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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 included:

- to continue development of a *new* low frequency (LF) geoacoustic inversion method (Tolstoy, '10) with extension to slightly higher frequencies (up to 100Hz) and longer ranges (up 5km);
- to *apply* the new LF geoacoustic inversion method to additional simulated SW06 scenarios (such as three layered sediments).

APPROACH

Consider the simulated SW06 scenario with a "true" bottom consisting of 3 sediment layers (totaling 22m in depth extent – a medium thickness) where all three sediment layers are each defined by a linear sound-speed profile (and constant densities) all over a half-space (constant sound-speed and density) as seen in Fig. 1. For the inversion processing we shall (as in earlier work) 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}),
- all water depths D will be 78 to 86m ("true" D =79.7m),
- the ocean sound-speed $c(z)$ will vary with depth only (no inversion on $c(z)$),
- z_{sou} will be fixed and approximated by 30m (true value is 31.2m, no inversion done on z_{sou}),
- the fixed ranges rge will each be less than 5km (known within 50 meters, no inversion done on rge), and

- the array will be vertical consisting of 16 phones spaced at 3.75m apart with array element localization (AEL) assumed to be accurate within 1m in depth. The "true" array still has no tilt and has 3.75m spacing, but the true top phone depth z_{ph1} =14.6m. We shall (as in earlier work) assume z_{ph1} =15.6m (no inversion done on z_{phi}).

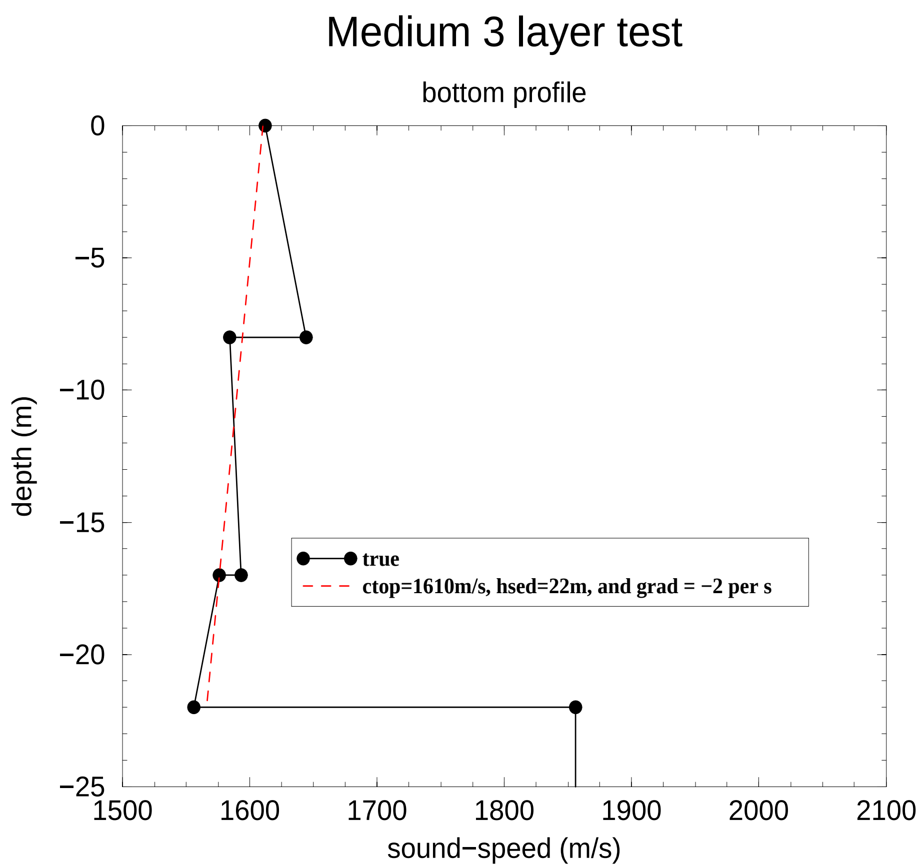

Figure 1: *Simulated 3 layer environment assuming the linear sound-speed profiles shown for each sediment layer. The top sediment layer is 8m thick, the next is 9m thick, and the last is 5m thick.*

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. 2, while for the inversions we will again assume the approximate (but incorrect) $c(z)$ as shown by the dashed curve of Fig. 2. As before we shall continue to generate the synthetic acoustic fields via RAMGEO (Collins, '94) where this code has the potential for range dependence (although we do not yet use this feature).

As before, the LF method performs an *exhaustive* search through a *limited* parameter space. In particular, we shall first search at a single LF (25Hz, $\lambda \approx$ 60m) over all possible values while for the unknowns testing over *crude* increments:

- c_{top} in [1550,1700]m/s with Δc_{top} =50m/s,
- γ in [-10,10]/s with $\Delta\gamma$ =2/s,
- h_{sed} in [5,55]m with Δh_{sed} =5m,

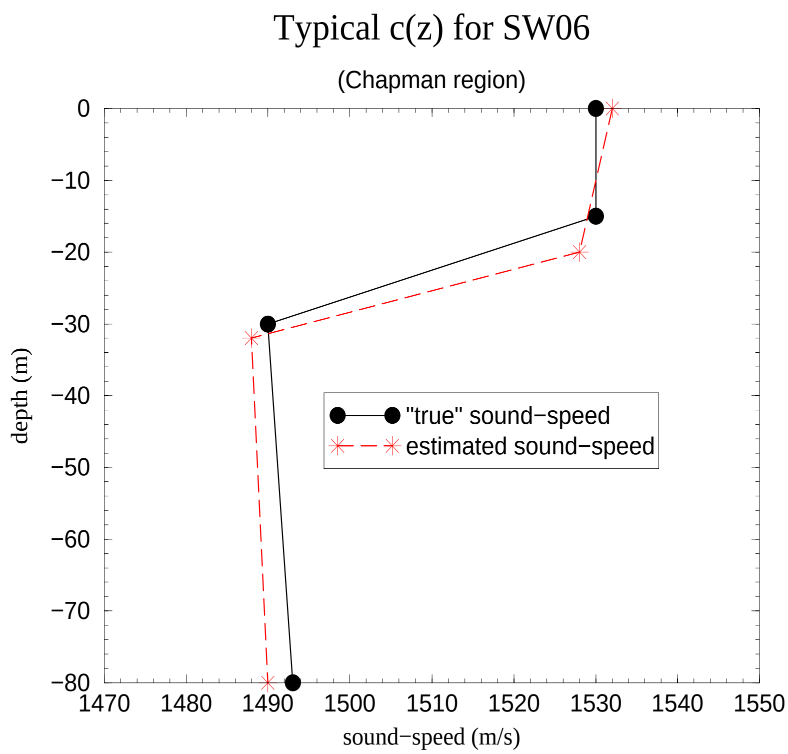

Figure 2: *The ocean sound-speed profiles for the simulated SW06 scenario. "True" is the solid curve, the dashed curve is used in the inversions.*

- c_{hsp} in [1700,2100]m/s with Δc_{hsp} =50m,
- D in [78,86]m with ΔD =2m.

This gives nearly 22K parameter sets to examine, and for each set we will compare the field predicted with that of the simulated "data" via the MFP linear correlation value (see Tolstoy, '93).

A new feature for this effort includes software to check if the sampling has been fine enough to catch the "true" peak. In particular, all the sets of parameters for which MFP $\geq$ 0.8 are examined to ensure that at least 99% of the sets for which MFP $\geq$ 0.9 have a neighbor for which the MFP value is at least 0.8. That is, all the strong peaks should have a neighbor which has only a slightly lower MFP value. A neighbor N of a point $P = (p_1, p_2, ..., p_n)$ with n parameters (we have n =5) is defined as a point where one of the coordinates (parameters) is next to P, e.g., $N = (p_1, ..., p_i + \Delta_i, ..., p_n)$ for some i. If this criterion is not met, then the computation is redone at a finer sampling for the parameter(s) indicated.

Beginning at the 250m rge (the true rge = 265m) we have the initial LF inversion with 25Hz where we find about 14K sets of parameters for which MFP $\geq$ 0.8, i.e., for which the correlations are respectable. Next, these values are checked for sampling where we find that the crude intervals suggested above are fine. In Fig. 3a we see a plot of the MFP values for 2 parameters (γ and h_{sed}) where the other 3 parameters have been fixed at "true" values, i.e., c_{top} =1600m/s, D =78m, and c_{hsp} =1850m/s. If we continue to increase frequency and require that *all* the frequencies have MFP $\geq$ 0.8, we arrive at Fig. 3b. Next, increasing the rge to 500m (we need to change D to 80m since we have overestimated the rge where the true rge = 480m) we arrive at Fig. 3c. Continuing, we see Fig. 3d at 50Hz (and below), rge = 500m. Additionally, at rge = 750m ($\boldsymbol{D}$ is now set to 78m again since the true rge = 780m) we have Fig. 3e for 25Hz, Fig. 3f for 50Hz (and below). We notice that:

- there are still a lot of parameter sets for which MFP $\geq$ 0.8, including the "true" values (the true set is around $\boldsymbol{h_{sed}}$ =22m, γ = -2 per s) as well as some severely false values (such as $\boldsymbol{h_{sed}}$ =45m, γ = 8 per s);
- the most improvement seems to occur for changing range rather than for changing frequency.

However, if we also plot these parameters while fixing the others at *incorrect* values, e.g., $\boldsymbol{c_{top}}$ =1700m/s, $\boldsymbol{D}$ =78m, and $\boldsymbol{c_{hsp}}$ =2100m/s, then we see the plot of Fig. 4 where we still have many false data fits but there is now more improvement for the multiple frequencies. Thus,

- using multiple frequencies *does* significantly reduce the false data fits and is worth doing.

Next, let us add 100Hz to the mix. First, we find that $\boldsymbol{h_{sed}}$ and γ need to be more finely sampled at this frequency according to the neighbor test[1]. In particular, $\Delta \boldsymbol{h_{sed}}$ =1m, $\Delta\gamma$ =0.5 per s resulting in 1035 MFP values $\geq$ 0.8 at $\boldsymbol{c_{top}}$ =1600m/s, $\boldsymbol{c_{hsp}}$ =1850m/s, and $\boldsymbol{D}$ =78m with the results at 250m rge shown in Fig. 5b. Proceeding to increase rge to 500m and to 750m we see the results on the right in Fig. 5 where adding the higher frequency has significantly improved the selection of the peak. Moreover, there are no high MFP values at 100Hz at rge=500 and 750m for the "wrong" values of $\boldsymbol{c_{top}}$ =1700m/s, $\boldsymbol{c_{hsp}}$ =2100m/s, and $\boldsymbol{D}$ =78 or 80m. Unfortunately, there are still other wrong values (such as $\boldsymbol{c_{top}}$ =1700m/s, $\boldsymbol{c_{hsp}}$ =1750m/s, and $\boldsymbol{D}$ =78m, not shown) giving high MFP values at 100Hz and at all rges as well as at all lower frequencies.

Thus, we see so far that:

- we can add the 100Hz component at ranges 250, 500, and 750m but only with *finer* sampling,
- the addition of 100Hz helps a lot but does *not* guarantee a unique solution since a number of incorrect data fits are still possible.

Work is now ongoing to examine the simulated scenarios at longer ranges such as 1, 3, and 5km. To date such work has shown that even finer sampling is needed at the longer ranges even at the lowest frequency (25Hz) resulting in much longer CPU times, particularly if a complete search is done rather than the partial search used to plot values as shown in Fig. 3-5.

WORK COMPLETED

Recent work (FY08) completed includes:

- further development of a new LF geoacoustic inversion method. In particular, software has been created to test that sampling at each step (each frequency or range) is sufficiently fine;

[1] Work earlier in the year suggested that a more accurate $c(z)$ would also result in improved MFP results at the higher frequency but with the crude sampling.

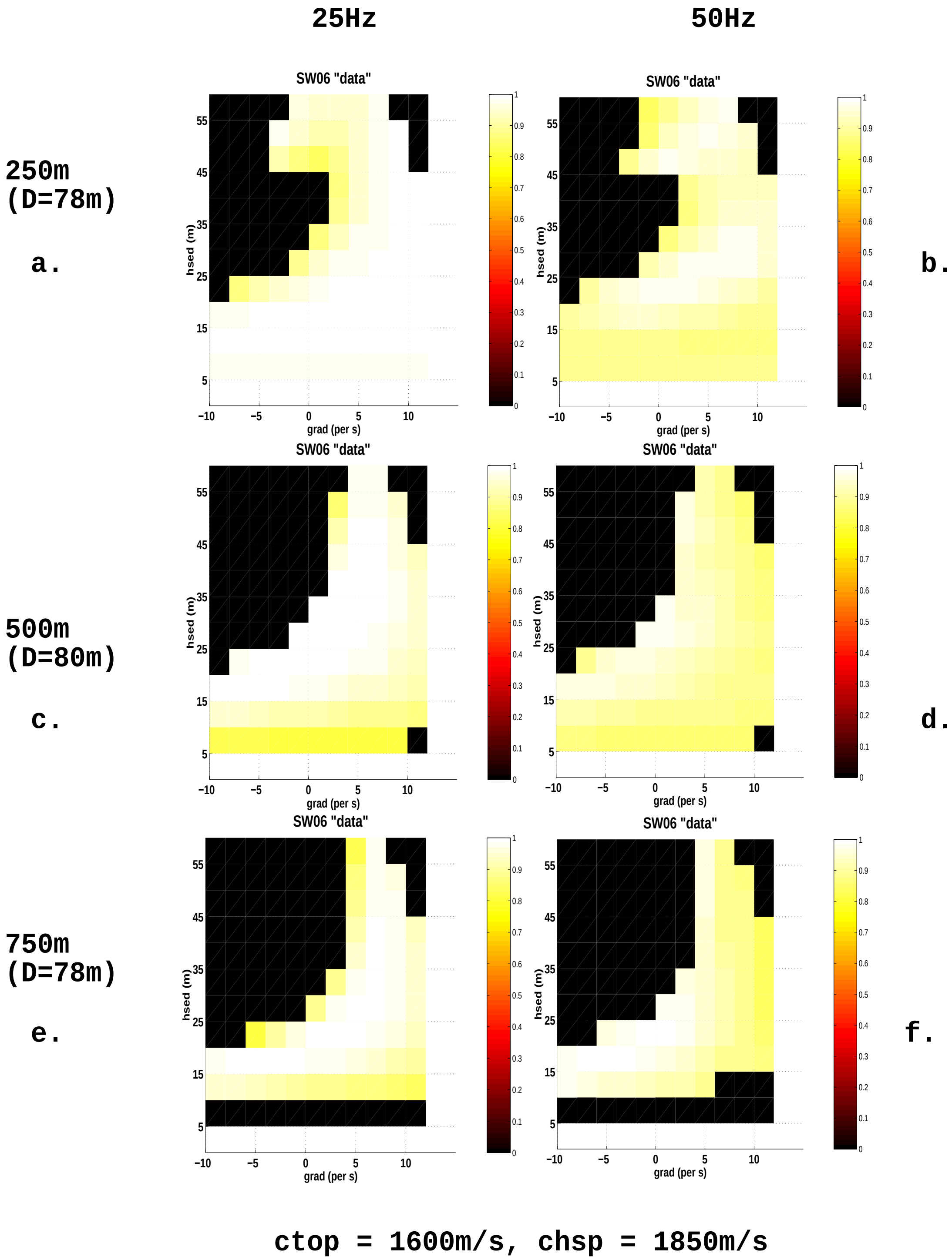

Figure 3: *Plots of the MFP values higher than 0.8 (light shades) for multiple frequencies as shown and multiple ranges as shown. The fixed parameters have been set to the "true" values:* c_{top} *=1600m/s,* c_{hsp} *=1850m/s, with* D *as indicated per subplot.*

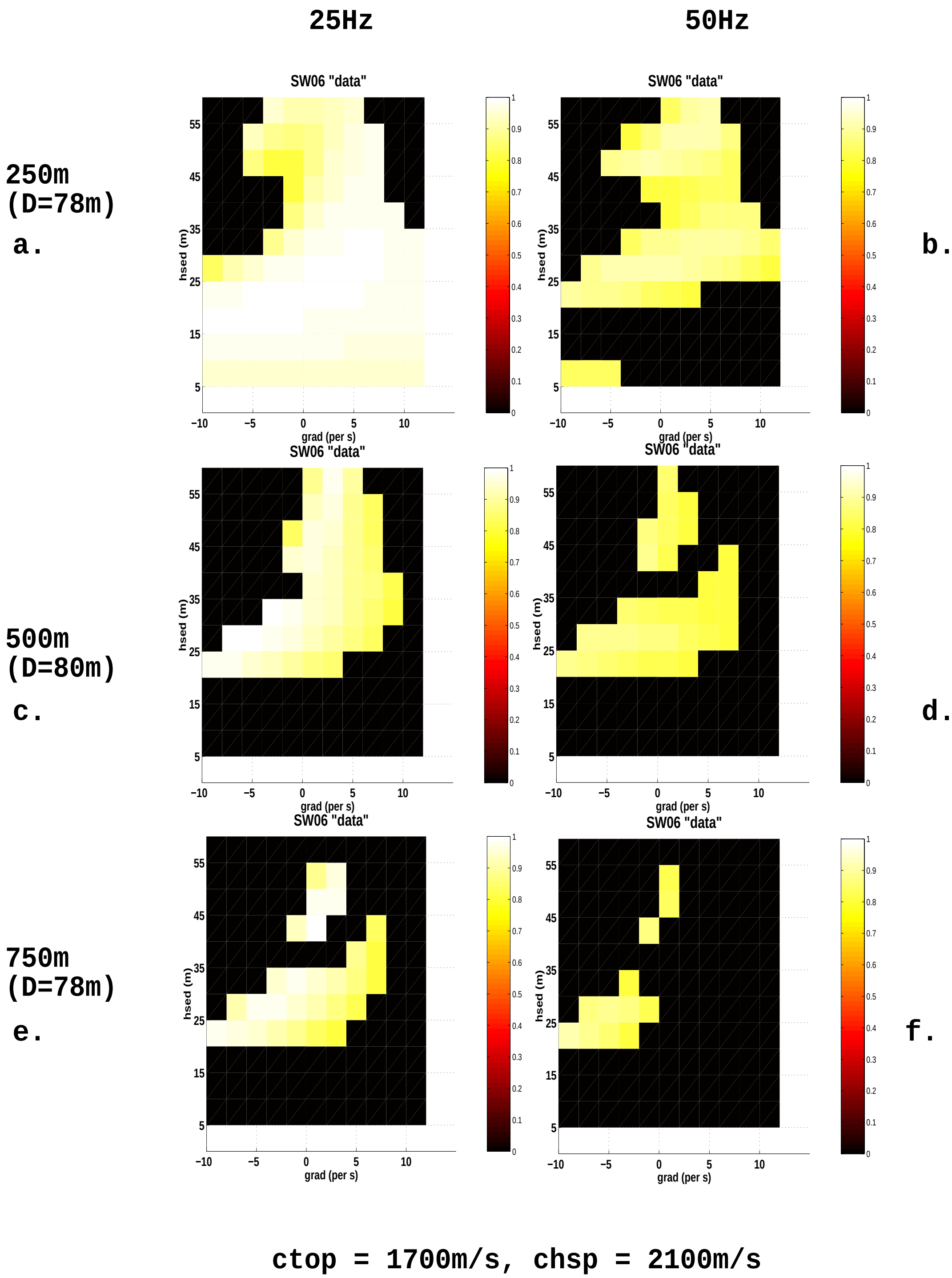

Figure 4: *Plots of the MFP values higher than 0.8 (light shades) for multiple frequencies as shown and multiple ranges as shown. The fixed parameters have been set to false values:* c_{top} *=1700m/s,* c_{hsp} *=2100m/s, with* D *as indicated per subplot.*

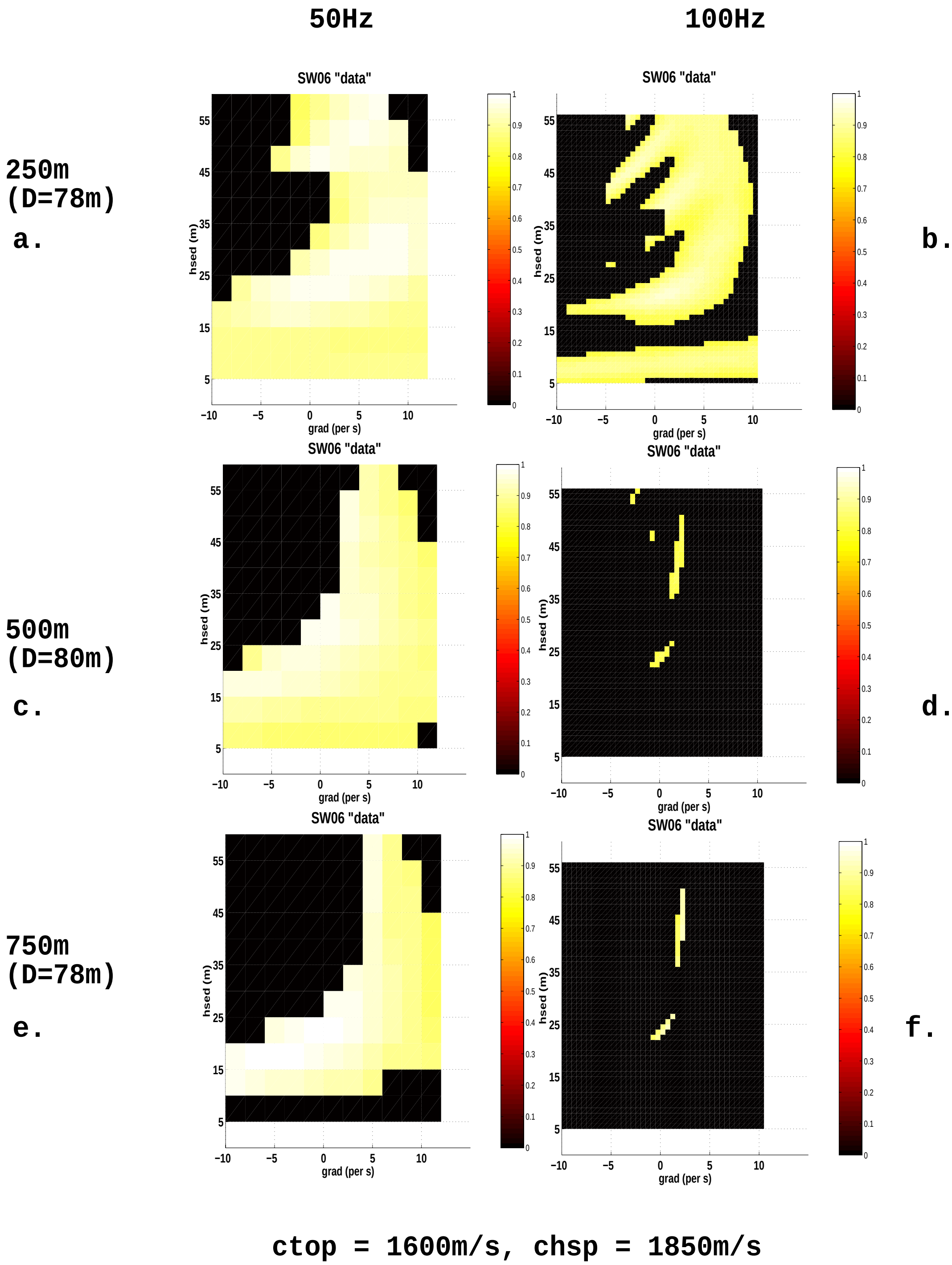

Figure 5: *Plots of the MFP values higher than 0.8 (light shades) for multiple frequencies (50 and 100Hz) and multiple ranges as shown. The fixed parameters have been set to "true" values:* c_{top} *=1600m/s,* c_{hsp} *=1850m/s, with* D *as indicated per subplot.*

- application of the method to more complicated simulations (such as a 3 sediment layer bottom) for selected SW06 scenarios;
- partial application of the method to higher frequencies such as 100Hz;
- partial application of the method to longer ranges such as 3 and 5km.

RESULTS

We find a number of results reconfirmed using more complicated scenarios than in earlier work. In particular, for 3 layer sediments:

- the LF method (at the shorter ranges and at 25 to 50Hz) need assume only rather crude values for many environmental and geometric parameters such as source depth, source range, phone locations (assuming some AEL), and ocean $c(z)$;
- the LF method can still find *all* distinct data fits;
- the LF search is *not* random;
- the LF search improves with sequential searches using information from earlier results;
- only a few unknowns need be sought (particularly when assuming a simple, linear, single layer sediment sound-speed profile);
- the LF method can approach convergence to a unique "solution" only through the use of multiple frequencies, multiple ranges, and multiple realizations, as available;
- there are *no* guarantees that a unique "solution" will actually be found even using higher frequencies and longer ranges;
- distributions of parameters can only indicate *intervals* within which the solution will lie – they cannot indicate the solution itself. Thus, intercomparison of methods relying on such distributions to indicate final parameter values needs to be performed, e.g., benchmarking seems to be needed for confirmation that simulated annealing and genetic algorithm based methods are finding "the solution".

We also find that:

- higher frequencies can require finer sampling of the parameter search space;
- longer ranges, e.g., 3km and farther, do require finer sampling of the parameter search space even at 25Hz (thereby requiring longer CPU times).

IMPACT/APPLICATION

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

- a new LF inversion method and its success with simulated SW06 data;
- the difficulty of comparing inversion methods with a subsequent need for benchmarking such methods.

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).

REFERENCES

- Collins, M.D. (1994), "Generalization of the split-step Pade solution", *J. Acoust. Soc. Am.* **96**, 382-385.
- Tolstoy, A. (1993), *Matched Field Processing in Underwater Acoustics*, World Scientific Publishing, Singapore.
- Tolstoy, A. (2010), "A deterministic (non-stochastic) low frequency method for geoacoustic inversion", *J. Acoustic. Soc. Am.* **127**(6), 3422-3429.

PUBLICATIONS for FY10

- Tolstoy, A. (2010), "A deterministic (non-stochastic) low frequency method for geoacoustic inversion", *J. J. Acoustic. Soc. Am.* **127**(6), 3422-3429.
- Tolstoy, A. (2010), "Waveguide monitoring (such as sewer pipes or ocean zones) via matched field processing", *J. J. Acoustic. Soc. Am.* **128**(1), 190-194.
- Tolstoy, A. (2010), "Using low frequencies for geoacoustic inversion", in *Theoretical and Computational Acoustics 2009*, Dresden, to be published.
- 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).
- 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).
- 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)