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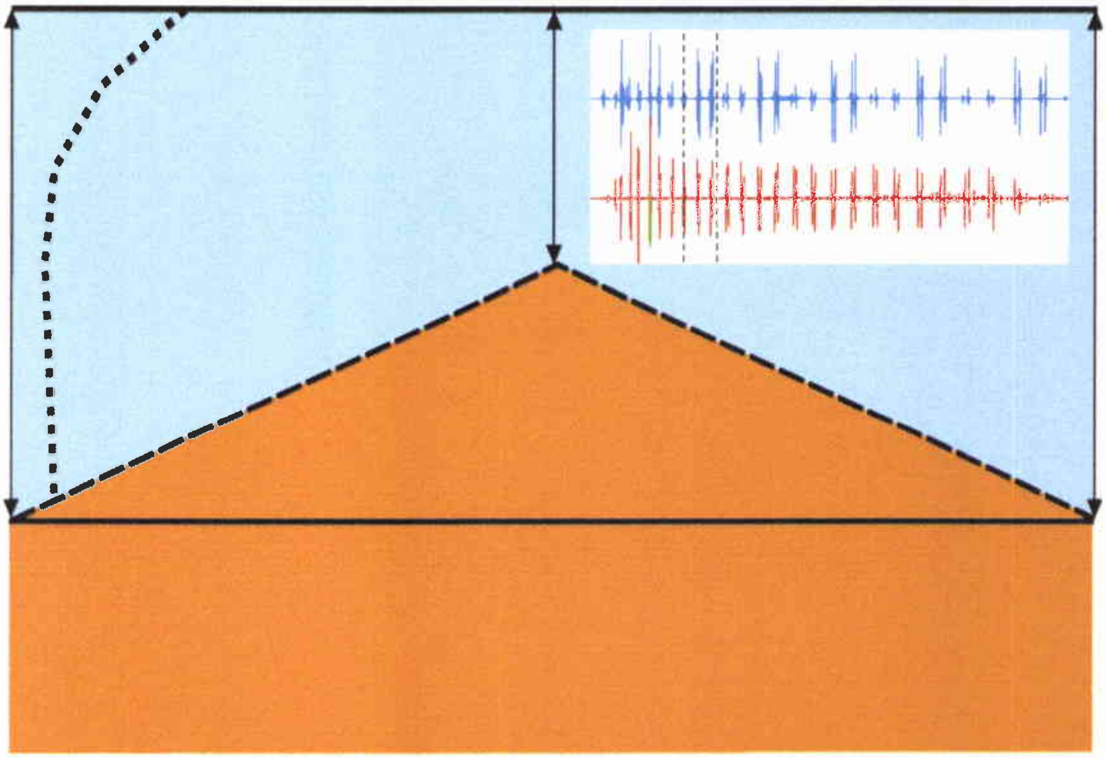
Broadband signal simulation in shallow water



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Jan L. Spoelstra
Director

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Broadband signal simulation in shallow water

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Executive Summary:

Broadband models have become indispensable tools for both data analysis and sonar system predictions in ocean acoustics. In particular, these models are used for Monte Carlo studies of acoustic signal fluctuations in the ocean, for tomographic time-domain inversions of ocean structures, for wideband geoacoustic inversions with global search algorithms, for designing underwater acoustic communication systems, and for testing signal processing algorithms in sonar systems in general. For many practical applications, the computational effort involved in using broadband models is still excessive and more efficient solution approaches are continuously being developed.

Today's minimum requirements for acoustic models are to be able to simulate broadband signal transmissions in 2D varying environments with an acceptable computational effort. Standard approaches comprise ray, normal mode and parabolic equation techniques. In this report we compare the performance of four broadband models (GRAB, PROSIM, C-SNAP and RAM) on a set of shallow-water test environments with propagation out to 10 km and a maximum signal bandwidth of 10–1000 Hz. It is shown that a computationally efficient modal approach as implemented in the PROSIM model is much faster than standard, less optimized models such as C-SNAP and RAM. However, the handling of range dependency in the adiabatic approximation is not always sufficiently accurate, and it is suggested that a mode coupling approach be adopted in PROSIM. Moreover, the interpolation of modal properties in range could lead to a further significant speed-up of mode calculations in range-dependent environments. It is concluded that coupled modes with wavenumber interpolation in both frequency and range remain the most promising wave modeling approach for broadband signal simulations in range-dependent shallow water environments. At higher frequencies (> 1 kHz) there is currently no alternative to rays as a practical signal simulation tool.

The military goal of this research effort is improved detection and classification (increase speed and accuracy) by reducing the uncertainty in sensor system performance caused by environmental factors. Modeling and simulation seek to explain, and ultimately predict, the factors that significantly alter operational effectiveness of ASW and MCM detection and classification systems.

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Broadband signal simulation in shallow water

F.B. Jensen, C.M. Ferla, P.L. Nielsen and M.G. Martinelli

Abstract: Today's minimum requirements for ocean acoustic models are to be able to simulate broadband signal transmissions in 2D varying environments with an acceptable computational effort. Standard approaches comprise ray, normal mode and parabolic equation techniques. In this report we compare the performance of four broadband models (GRAB, PROSIM, C-SNAP and RAM) on a set of shallow-water test environments with propagation out to 10 km and a maximum signal bandwidth of 10–1000 Hz. It is shown that a computationally efficient modal approach as implemented in the PROSIM model is much faster than standard, less optimized models such as C-SNAP and RAM. However, the handling of range dependency in the adiabatic approximation is not always sufficiently accurate, and it is suggested that a mode coupling approach be adopted in PROSIM. Moreover, the interpolation of modal properties in range could lead to a further significant speed-up of mode calculations in range-dependent environments. It is concluded that coupled modes with wavenumber interpolation in both frequency and range remain the most promising wave modeling approach for broadband signal simulations in range-dependent shallow water environments. At higher frequencies (> 1 kHz) there is currently no alternative to rays as a practical signal simulation tool.

Keywords: acoustic models ○ broadband models ○ Fourier synthesis ○ normal modes ○ parabolic equation ○ propagation loss ○ range dependence ○ ray theory ○ sonar simulation

Contents

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Introduction

Broadband models have become indispensable tools for both data analysis and sonar system predictions in ocean acoustics. In particular, these models are used for Monte Carlo studies of acoustic signal fluctuations in the ocean, for tomographic time-domain inversions of ocean structures, for wideband geoacoustic inversions with global search algorithms, for designing underwater acoustic communication systems, and for testing signal processing algorithms in sonar systems in general. For many practical applications, the computational effort involved in using broadband models is still excessive and more efficient solution approaches are continuously being developed. One such model based on normal modes, the PROSIM model, will be described in the following and benchmarked against standard signal models (GRAB, C-SNAP and RAM) both for accuracy and computational speed. We consider three shallow-water test environments with propagation out to 10 km at center frequencies of 250 and 500 Hz and a maximum signal bandwidth of 10–1000 Hz.

2
GRAB

The Gaussian Ray Bundle (GRAB) model [1] was developed by the U.S. Navy for high-frequency applications in shallow water, but thorough testing showed excellent performance also at frequencies well below 500 Hz, and for deep-water applications in general. Two aspects of this model are unique: first, the use of Gaussian ray bundles, which causes a smoothing of the acoustic field and hence avoids the standard ray artifacts of infinite intensity near caustics; second, a careful treatment of ray reflections at boundaries using the concept of virtual rays. This is important for producing high-fidelity results in shallow water.

3
PROSIM

The broadband acoustic model PROSIM [2] developed at SACLANTCEN over the past few years is essentially a range-dependent version of the ORCA model developed by Westwood *et al.* in the mid 1990s [3]. The design criteria for PROSIM were to perform broadband signal simulations (10 Hz – 10 kHz) in range-dependent shallow-water channels with high computational efficiency. To that end an efficient modal solution involving hundreds of modes was required. Two approaches are commonly applied in the community: (1) Numerical integration of the depth-dependent wave equation resulting in computation times that typically increase quadratically with frequency (the number of modes increases linearly with frequency and so does the required numerical depth discretization). Examples of these types of models are KRAKEN and C-SNAP. (2) Analytical solution of the wave equation in a small number of layers where the sound-speed profile is either constant or varies linearly in $1/c^2$ with depth (Airy function solution). In this case the computation time increases linearly with frequency because the number of modes increases linearly with frequency. The ORCA model is an example of a layer model.

An illustration of the computational performance of ORCA versus KRAKEN on a propagation problem with 15 points in the sound-speed profile is shown in Fig. 1. The number of modes computed varies from around 10 at the lowest frequency to around 1000 at the highest frequency. We see that the cross-over point where ORCA becomes more efficient is around 50 modes, and that ORCA is 50 times faster than KRAKEN in computing 1000 modes. Clearly, for acoustic problems involving many hundreds of modes, the layer approach employed in ORCA provides significant savings in CPU time.

Apart from adopting the layer solution approach for PROSIM, it was decided to consider fluid environments only and to evaluate only real-axis modes. This implies that attenuation is handled as a perturbation, which is an approximation often employed in mode models. The advantage of solving a real-eigenvalue problem is increased speed and a more robust code which ensures that all modes are computed.

Range dependency in PROSIM is handled in the adiabatic approximation, i.e. no cross-mode coupling of energy. This approach works well for weak range dependence and is computationally faster than evaluating the mode coupling coefficients.

Finally, since broadband signal simulations via Fourier synthesis involves computing the acoustic field at many closely-spaced frequencies within the band of interest (often several

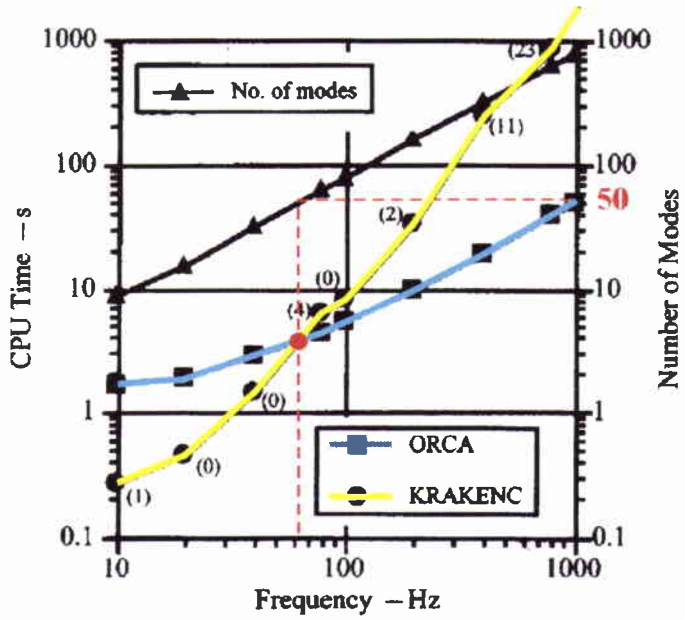

Figure 1 *Computational speed versus frequency for two mode models: A layer model (ORCA/PROSIM) versus a numerical integration model (KRAKENC/C-SNAP) [3].*

hundred frequency samples), the concept of frequency interpolation of modal properties was adopted from ORCA. The concept here is that modal eigenvalues and modal depth functions vary smoothly with frequency and that modal information can be obtained with sufficient accuracy by interpolation between computed properties on a coarse grid covering the frequency band of interest. The problem is to build a robust algorithm that ensures accurate modal properties at all frequencies for any sound-speed profile, even when double-ducts are present.

The frequency interpolation algorithm implemented in PROSIM [2, 4] has been thoroughly checked and has proven to permit a significant speed-up of broadband problems by computing only 1:20 or 1:40 of the required frequency samples and interpolating the remaining information. As a result the PROSIM model should be a factor 20 to 40 faster than other mode models based on brute-force, frequency-by-frequency calculation of the broadband transfer function. The scope of this report is to demonstrate the computational efficiency of PROSIM compared to less optimized broadband models such as C-SNAP and RAM.

4
C-SNAP

The SACLANTCEN coupled normal-mode model C-SNAP [5] has a modal solver similar to the one used in KRAKEN, i.e. numerical integration is used to solve the depth-separated wave equation. As in PROSIM only real-axis modes are computed and attenuation is handled via a perturbational approach. The range dependency in C-SNAP is dealt with through mode coupling, which should provide more accurate field solutions for strongly range-dependent environments. The approach is to divide the total range into a sequence of range-independent sectors (several tens or several hundreds, depending on the degree of range dependency and the frequency), compute the local mode properties for each sector, compute the acoustic field on a vertical slice at the sector boundary, project this field onto the new mode set in the adjacent sector to determine modal coupling coefficients, re-propagate the field through the next sector, etc. This is not an exact mode coupling procedure since we omit the continuous mode spectrum, which would account for energy propagating into the bottom beyond the critical angle.

Since C-SNAP performs brute-force frequency-by-frequency calculation of the spatial transfer function, this model is expected to be slower than PROSIM. The presence of mode coupling, however, should guarantee more accurate results for range-dependent problems.

5
RAM

The split-step Padé solution of the parabolic wave equation, as implemented in the RAM code [6], is considered the most efficient PE-based technique for solving range-dependent ocean acoustic problems. RAM provides more accurate results than any of the mode models, both because it includes complete coupling among all spectral components, including the continuous mode spectrum, and because losses are handled correctly. The field solution is obtained on a spatial grid $(\Delta r, \Delta z)$ which determines both the environmental discretization and the solution accuracy. In essence, a convergence test with decreasing Δr and Δz must be carried out to ensure stable numerical results. Since the required grid size is inversely proportional to frequency, a broadband RAM calculation increases approximately with frequency squared. As for C-SNAP, all frequency samples of the transfer function must be computed.

6

Test problems

To test the accuracy and computational efficiency of the above four broadband models, we have designed a series of simple shallow-water propagation problems as shown in Fig. 2. Case 1 is a flat-bottom situation used as a calibration case to see that all models give similar results. Cases 2 and 3 are symmetric upslope/downslope situations where the water depth varies from 200 m at the deep end to 100 m at mid range. This geometry corresponds to a bottom slope of 1.15°. The sound-speed profile is downward refracting and consists of 5 input values as shown in the table. This profile is taken to be unchanged along the track. The bottom is a homogeneous fluid halfspace with the properties given in Fig. 2.

Depth (m)	Sound speed (m/s)
0	1491
30	1480
60	1476
100	1474
200	1475

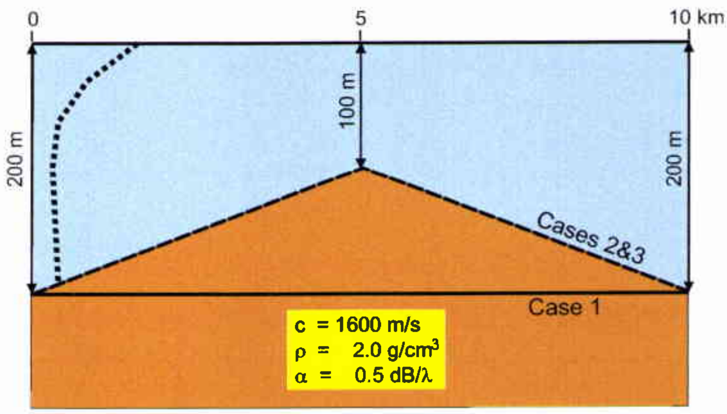

Figure 2 *Shallow water test environments. Case 1 is a constant water depth of 200 m whereas Case 2 is a symmetric upslope/downslope environment. Case 3 has the same geometry as Case 2, but a faster bottom ($c = 1800$ m/s, $\rho = 2.0$ g/cm^3, $\alpha = 0.1$ dB/λ).*

We consider a broadband pulse emitted by a source at 100-m depth and calculate the received signal on a hydrophone at 20-m depth and at ranges of 5 and 10 km. The emitted signal is a Ricker pulse with center frequency of 200 Hz and covering the band 10–450 Hz. Since the received signal at 10 km is found to have a total time dispersion of nearly 1 s, a frequency sampling of 1 Hz is required to avoid signal wrap-around in the Fourier transformation ($\Delta f = 1/T$) [7]. Hence 441 frequency samples must be computed to synthesize the received signal at 10 km.

When timing different acoustic models on a particular test problem, it is important to

Table 1 *Test problem summary. NM_{max} is the maximum number of modes computed, NSEG the number of range segments used in the modal computations, NF the number of frequency samples computed, $\mathcal{R}$ the peak cross-correlation relative to the* RAM *result, and CPU is the execution time for a full 10-km run on an 850-MHz PC.*

Test	Model	NM_{max}	NSEG	NF	$\mathcal{R}_{5km}$	$\mathcal{R}_{10km}$	CPU
Case 1 – RI (10–450 Hz)	GRAB	±23°	$\Delta\theta = 0.05°$	441	0.86	0.39	13 min
	PROSIM	47	1	441(23)	0.99	0.99	1 s
	C-SNAP	47	1	441	0.99	0.99	5 s
	RAM	N = 4	$\Delta r = 10$ m, $\Delta z = 0.25$ m	441	1.00	1.00	20 min
Case 2 – RD (10–450 Hz)	GRAB	±23°	$\Delta\theta = 0.05°$	441	0.92	0.25	12 min
	PROSIM	47	100	441(23)	0.95	0.82	1 min
	C-SNAP	47	256	441	0.96	0.98	15 min
	RAM	N = 4	$\Delta r = 10$ m, $\Delta z = 0.25$ m	441	1.00	1.00	20 min
Case 3 – RD (10–1000 Hz)	GRAB	±35°	$\Delta\theta = 0.5°$	1981	0.87	0.56	10 min
	PROSIM	155	200	1981(50)	0.90	0.49	20 min
	C-SNAP	155	1024	1981	0.94	0.95	40 h
	RAM	N = 4	$\Delta r = 5$ m, $\Delta z = 0.05$ m	1981	1.00	1.00	20 h

establish uniform convergence criteria for model solutions, i.e. the relative solution accuracy should be the same for all models. We decided to run each model to a convergence of $\mathcal{R}_{10km} = 0.99$ for the peak cross-correlation between a super-accurate model solution and the one determined to be just accurate enough, still with the same model. Hence, model convergence was done independently for each of the four models, but only for the particular source/receiver depths investigated here. The pertinent numerical parameters for each model and for each test problem to obtain stable solutions with $\mathcal{R}_{10km} = 0.99$ are summarized in Table 1.

6.1 Case 1 – RI/LF

This is the flat-bottom calibration case where the three wave models (PROSIM, C-SNAP, RAM) are expected to provide accurate pulse solutions. In fact, as shown in Table 1, the peak cross-correlation between the PROSIM and RAM results are better than 0.99 at both ranges and so is the correlation between C-SNAP and RAM. It is also evident from the stacked signal plots in Figs. 3 and 4 that the three wave-model solutions are virtually identical.

The ray result provided by GRAB is less accurate, with a peak correlation compared to RAM of 0.86 at 5 km and only 0.39 at 10 km. This problem was identified as being due to

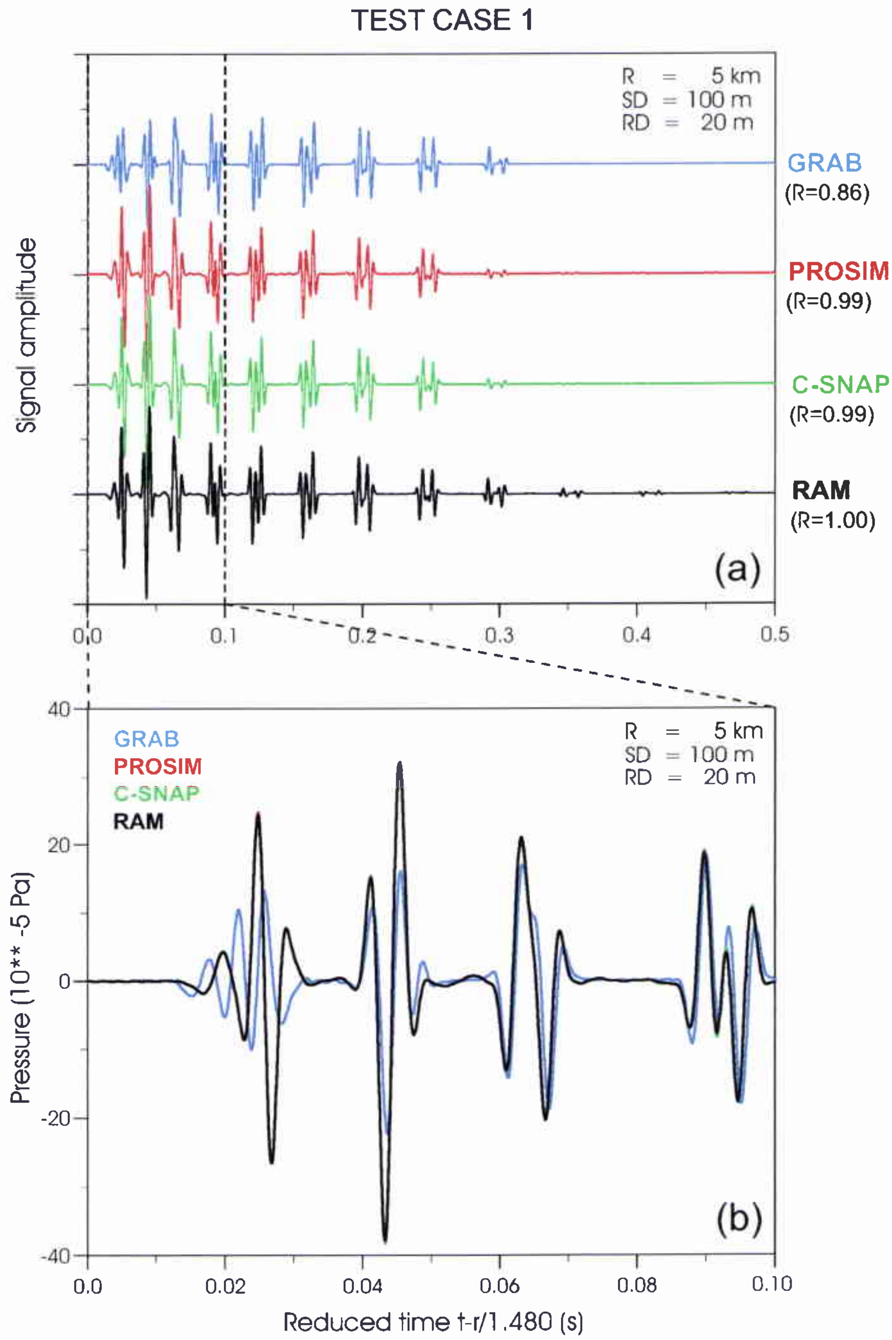

Figure 3 *(a) Comparison of broadband pulse solutions for Case 1 at a range of 5 km. The source signal is a Ricker pulse with center frequency 200 Hz. (b) Expanded overlay of model solutions for the initial 10 ms.*

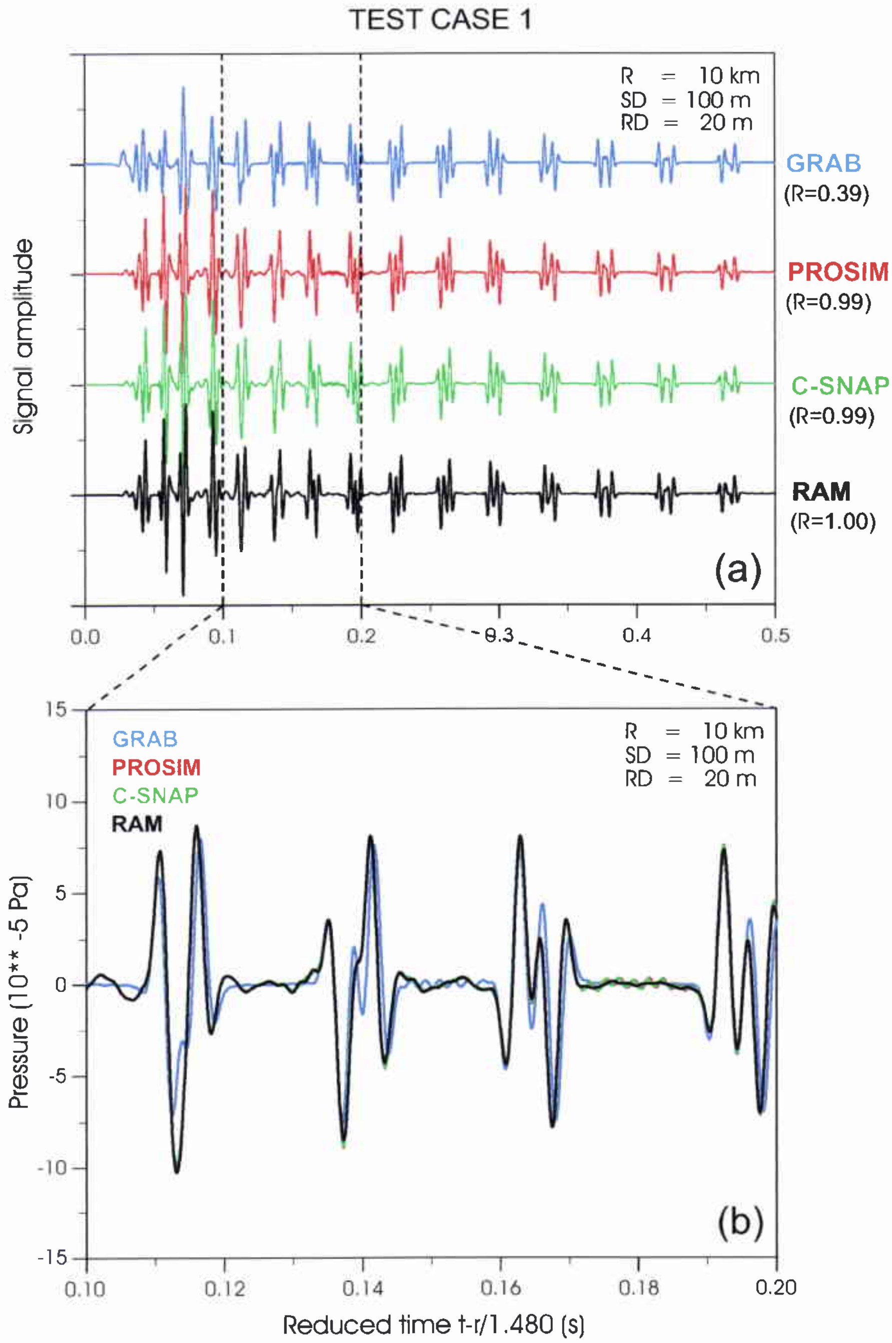

Figure 4 *(a) Comparison of broadband pulse solutions for Case 1 at a range of 10 km. The source signal is a Ricker pulse with center frequency 200 Hz. (b) Expanded overlay of model solutions for a 10-ms time window.*

refractive effects in the water column not handled accurately by this particular ray code. Thus, if we re-run this case for an isovelocity profile in the water column, we obtain much more accurate pulse solutions with correlations close to 0.99. As shown in Fig. 3, it is the initial part of the ray solution which is in error. This is particularly evident in the expanded overlay in Fig. 3(b), where the GRAB solution is seen to differ significantly from the RAM reference solution for the first couple of pulses. This is understandable as the early arrivals correspond to horizontally propagating rays which are affected the most by a refracting profile. Steeper rays arrive later and are less affected by refraction. As a result the GRAB solution improves in accuracy towards the tail of the signal. It is also clear that an inaccuracy in handling refraction will lead to error accumulation with range, and hence cause lower correlations at 10 km than at 5 km.

The calculation times for Case 1 are given in the last column of Table 1. We see that the two mode solutions are several orders of magnitude faster than the ray and PE solutions. Clearly, a range-independent case favors the modal approach since only one mode set is required to compute the acoustic field anywhere in the waveguide. The number of modes is just one at 10 Hz but increases to 47 at 450 Hz. Hence, the C-SNAP model must compute a total of (47-1)/2 x 441 = 10,143 modes to generate a broadband transfer function. PROSIM, on the other hand, uses frequency interpolation in 20-Hz bands and therefore only needs to compute 23 frequency samples. As a result, PROSIM is 5 times faster than C-SNAP for this case.

Both GRAB and RAM are intrinsically range-dependent models. GRAB traces rays within an aperture of $\pm 23°$ in steps of 0.05° (461 rays) and ray paths are constructed based on triangular sectors in which $1/c^2$ varies linearly with depth and range. The result is that the computation time of GRAB has little dependence on the environmental complexity, and, more importantly, is *independent* of frequency.

RAM marches the solutions out in range on a computational grid (Δr, Δz) which relates to the frequency (inversely proportional) but has little dependence on the environmental complexity. Hence, also RAM solutions take essentially the same time for range-dependent and range-independent cases. However, the RAM CPU time increases with frequency squared. Accurate RAM solution were obtained with Padé order N=4, using the computational grid size shown in Table 1 for all frequency samples. A potential time saving of a factor 3 could be obtained for this model by using a frequency-dependent computational grid, i.e. a coarser grid at low frequencies and a finer grid at high frequencies. This feature has not yet been implemented in our version of the RAM code.

6.2 Case 2 – RD/LF

This is the upslope/downslope situation with changing bathymetry along the entire track. As mentioned earlier this will not change the calculation time for GRAB and RAM, but the mode models will become slower, essentially in proportion to the number of range segments and, hence, additional mode sets required to obtain a stable solution. For this case with a 1.15° bottom slope the adiabatic PROSIM model requires 100 range segments for convergence, whereas the coupled C-SNAP model requires 256 segments. The calculation times (Table 1) are still in favor of PROSIM which is ten times faster than the other models.

The solution accuracy now becomes an issue since the mode models both treat range-dependence in an approximate fashion. The most accurate solution compared to RAM is seen to be C-SNAP with a peak cross-correlation of 0.96 at 5 km and 0.98 at 10 km. Less accurate is the adiabatic PROSIM result and the GRAB ray trace result. These differences are also evident in the stacked time plots in Figs. 5 and 6, where we see similar arrival structures in all traces, but with incorrect amplitudes on some arrivals in the PROSIM and GRAB solutions. We analyze the results separately for the upslope situation (Fig. 5) and the combined up- and downslope propagation (Fig. 6).

At a first glance the four pulse solutions in Fig. 5 look almost identical except for the coda, which dies out more quickly in the two mode solutions. The reason for this is that only the discrete modal spectrum, i.e. energy propagating below the critical angle [$\theta_{cr} = \cos^{-1}(1475/1600) \simeq 22.8°$], is included in the mode solutions. On the other hand, both GRAB and RAM include the high-angle energy, which, though rapidly attenuated, is still contributing significant arrivals beyond 0.15 s in Fig. 5(a). The expanded view in Fig. 5(b) show excellent agreement between all four curves except for the earliest part of the GRAB result — due again to the fact that refractive effects in the water column are not handled accurately by this particular ray code. In conclusion, all models perform well for upslope propagation with peak cross-correlations better than 0.92.

Turning now to the 10-km results in Fig. 6, we see a significant deterioration of the solution accuracy for GRAB ($\mathcal{R}$ = 0.25) but also some problems with PROSIM ($\mathcal{R}$ = 0.82). Note that the arrival times of individual pulses, each actually being a superposition of four multipaths with almost identical travel times, are accurately predicted by all four models. It is the detailed pulse shapes which are in error in the GRAB and PROSIM results. This is evidenced in the expanded view in Fig. 6(b) which shows six distinct arrivals in the time window 10–20 ms, with the first four GRAB arrivals being far too low in amplitude, and with the two middle PROSIM arrivals being too strong.

The reason for the wrong results in GRAB is again the incorrect handling of refraction in the water column which affects primarily the early part of the signal, i.e. the rays propagating near the horizontal. Since downslope propagation shifts ray angles towards the horizontal [7], it is to be expected that the GRAB result deteriorates at 10 km compared to the purely upslope condition at 5 km. In general, GRAB works best for upslope propagation where there is ray-angle steepening at each bottom reflection — and hence less refraction — and GRAB gives poorest results for downslope propagation where refraction effects are accentuated due to ray-angle flattening.

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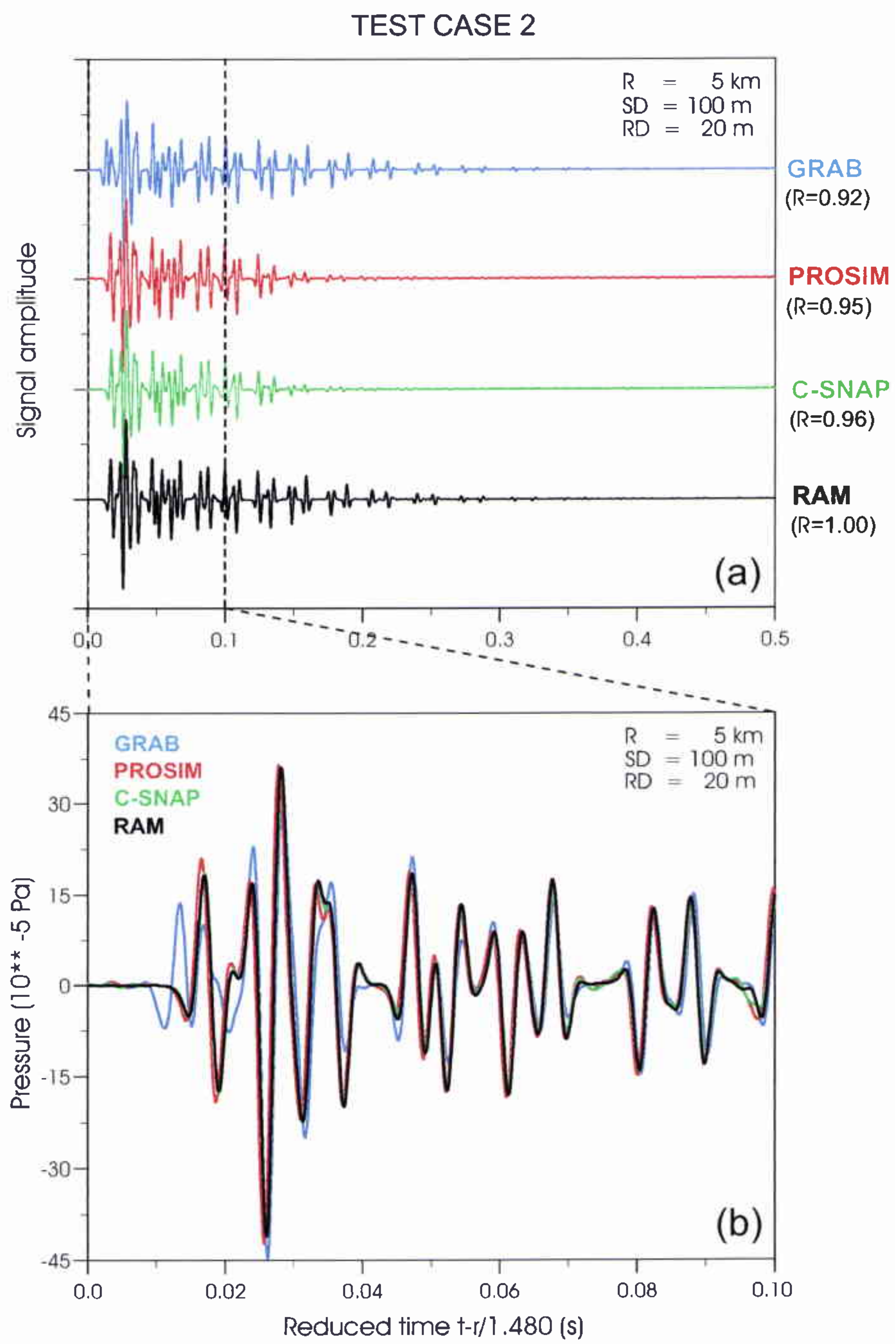

Figure 5 *(a) Comparison of broadband pulse solutions for Case 2 at a range of 5 km. The source signal is a Ricker pulse with center frequency 200 Hz. (b) Expanded overlay of model solutions for the initial 10 ms.*

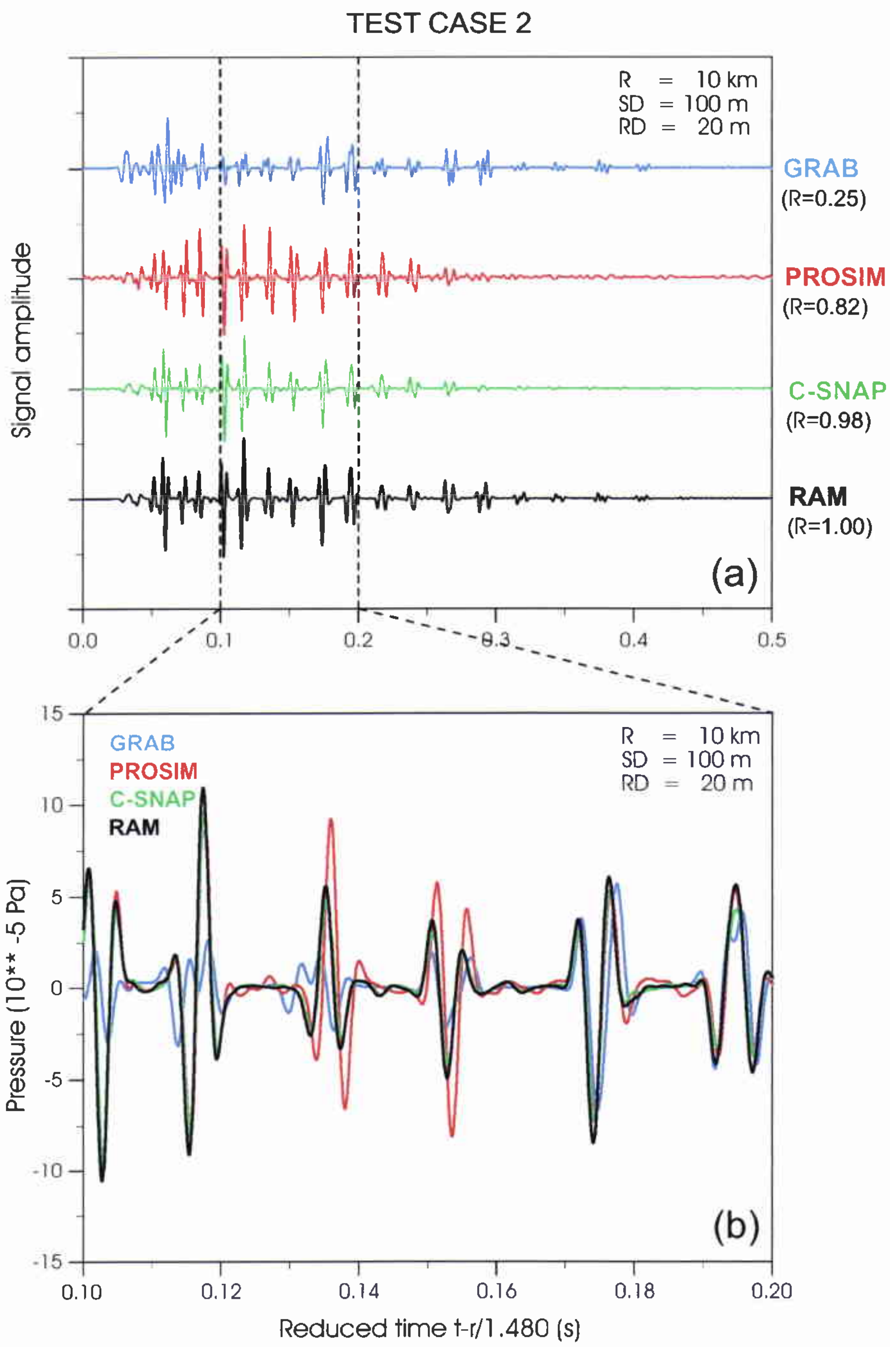

Figure 6 *(a) Comparison of broadband pulse solutions for Case 2 at a range of 10 km. The source signal is a Ricker pulse with center frequency 200 Hz. (b) Expanded overlay of model solutions for a 10-ms time window.*

Also PROSIM has poorer performance at 10 km than at 5 km, but for a different reason. Here it is the adiabatic approximation (no energy coupling between modes) which causes the problem. Again, downslope propagation accentuates the problem because the number of modes present at the apex (5 km) is the total number of modes being used for the whole downslope path, i.e. no extra modes are introduced even though the water depth doubles at 10 km. It is a quite common experience in the modeling community that the adiabatic approximation works better for upslope propagation (mode cutoff) than for downslope propagation [7].

6.3 Case 3 – RD/HF

In order to push computations to the limit for the wave models, we modify Case 2 to have a faster bottom (1800 m/s) and a lower attenuation ($\alpha = 0.1\,\mathrm{dB}/\lambda$) which causes more time dispersion due to late, steep-angle ray arrivals. As a consequence, the time window must be increased to 2 s, which, in turn, results in a 0.5-Hz frequency sampling of the transfer function. In addition, we increase the bandwidth to 1000 Hz. These changes result in more modes to be computed (max. 155), more range segments, and several more frequency samples.

As shown in Table 1, GRAB and PROSIM both provide convergent answer within 10 to 20 min whereas C-SNAP and RAM take 20 to 40 h. This case clearly favors the PROSIM interpolation scheme, since, by using 20 Hz interpolation bands, only 50 frequencies out of 1981 need to be computed. The numerical parameters used for getting convergent answer for all models are listed in Table 1.

The solution accuracy as reflected by the signal cross-correlation coefficients is seen to deteriorate only slightly at 5 km compared to Case 2, whereas GRAB improves significantly at 10 km and PROSIM gets worse. The four pulse solutions at 5 km are shown in Fig. 7. As for Case 2 they look identical except for the tail part which dies out more quickly in the two mode solutions because the high-angle energy propagating beyond the critical angle has been ignored (continuous mode spectrum) [7]. The expanded view in Fig. 7(b) show excellent agreement between all four curves except for the earliest part of the GRAB result — due again to the fact that refractive effects in the water column are not handled accurately by this particular ray code. In conclusion, all models perform well for upslope propagation with peak cross-correlations better than 0.87.

Turning now to the 10-km results in Fig. 8, we see a significant deterioration of the solution accuracy for PROSIM ($\mathcal{R} = 0.49$) but also some problems with GRAB ($\mathcal{R} = 0.56$). Again, arrival times of individual pulses are accurately predicted by all four models but not the pulse shapes and amplitudes. This is evidenced in Fig. 8(a) where the RAM reference solution shows a characteristic pattern of two strong arrivals followed by two weak arrivals, and so on. Three of the models reproduce this pattern, but not PROSIM.

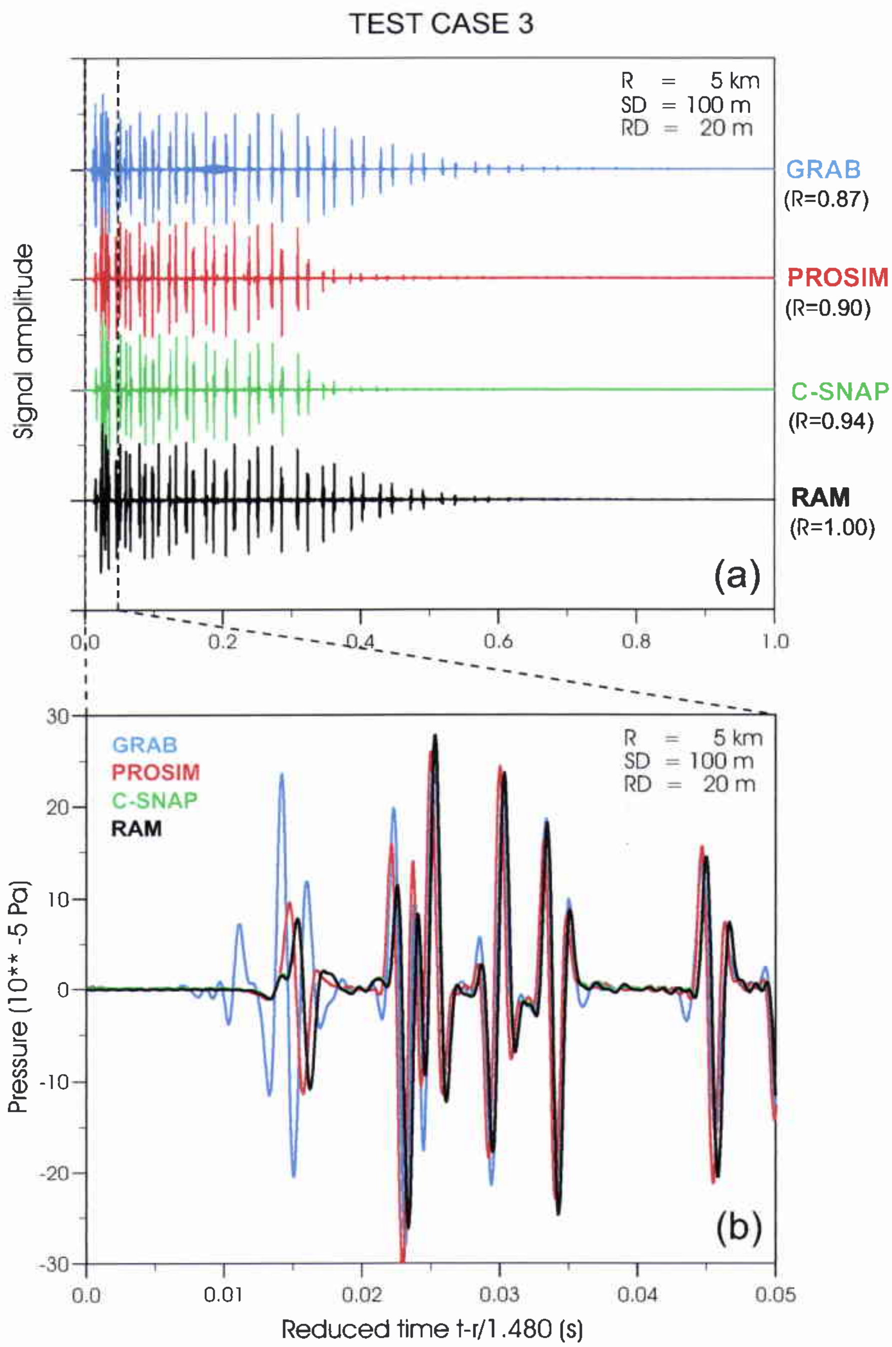

Figure 7 *(a) Comparison of broadband pulse solutions for Case 3 at a range of 5 km. The source signal is a Ricker pulse with center frequency 500 Hz. (b) Expanded overlay of model solutions for the initial 5 ms.*

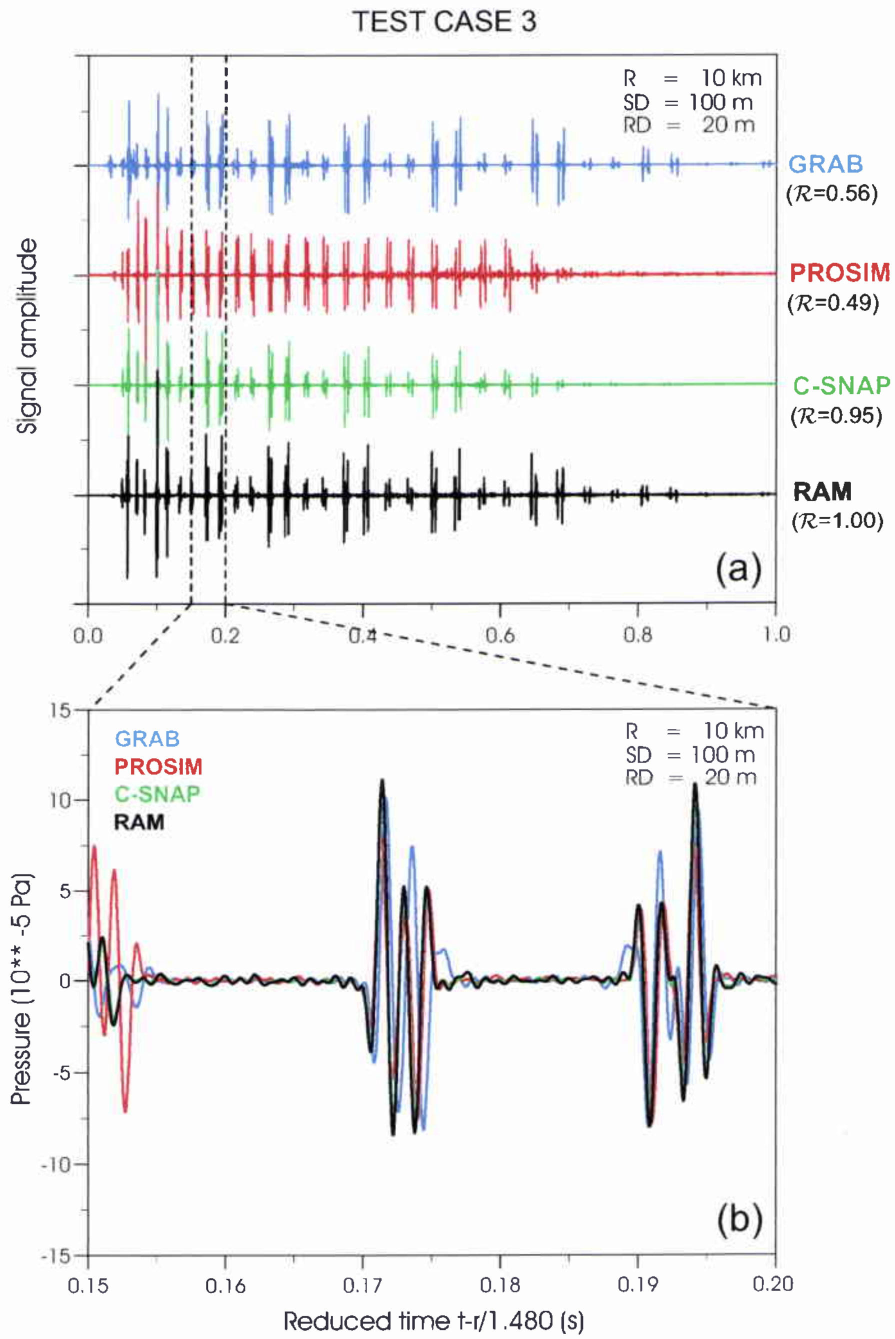

Figure 8 *(a) Comparison of broadband pulse solutions for Case 3 at a range of 10 km. The source signal is a Ricker pulse with center frequency 500 Hz. (b) Expanded overlay of model solutions for a 5-ms time window.*

Knowing that mode coupling becomes more important with increasing frequency, it is not surprising that the adiabatic PROSIM approach has its worst performance for Case 3. It is somewhat surprising that GRAB gives better results for Case 3 than Case 2. There are still problems in the earliest part of the signal due to refraction, but already after 0.2 s the pulse shapes are close to the RAM reference. There are two possible explanations for this improved GRAB result. Firstly, that this case has a higher bottom speed, i.e. a higher critical angle, which in turn allows for steeper propagation paths not affected by water-column refraction. Secondly, the higher center frequency of 500 Hz which may improve the accuracy of the ray results.

The curious signal structure of two strong and two weak arrivals interspersed throughout in Fig. 8(a) was investigated in detail with the ray code. It turned out that a single pulse consists of four eigenray arrivals, which may coincide in time to provide constructive interference, i.e. a strong pulse arrival. The weak arrivals are not associated with eigenrays, but can be considered diffracted arrivals from rays passing close to the receiver position. These contributions are included in the GRAB solution by associating a frequency-dependent Gaussian intensity distribution with each ray. If these rays are several wavelength away from the receiver, there will be no diffracted contributions, which was proved by increasing the center frequency to 10 kHz. Then the two weak pulse arrivals disappear all together. It is important to note that an accurate ray model (GRAB, Gaussian beam tracing [7]) will include these diffracted arrivals which become increasingly important at lower frequencies.

The general conclusion from Case 2 that GRAB and PROSIM work better for upslope than downslope propagation is confirmed for Case 3. It is expected that the GRAB solution accuracy will increase with increasing frequency, whereas the adiabatic PROSIM results will get worse. In principle, the C-SNAP (for low-loss environments) and RAM solutions should be accurate at any frequency, but calculation times are prohibitive. For all models the calculation time is proportional to the number of frequency samples required to synthesize the pulse. Hence, narrowband pulses are computationally faster. The calculation time for the wave models increase with frequency squared, making these models impractical for high-frequency applications. On the other hand, the ray model GRAB is seen to solve all of our test problems within 10 min, independent of environmental complexity and center frequency. Hence, only GRAB is a practical signal simulation tool for high-frequency applications (f_c >1 kHz).

7
Summary and conclusions

Much work has gone into the development of computationally efficient CW propagation models for use in ocean acoustics. These standard techniques, based on ray, mode, wave-number integration and parabolic equation solutions of the wave equation, can be straightforwardly extended to broadband signal simulations via Fourier synthesis of a spectrum of CW solutions. Clearly the computational effort in each model increases with the number of frequency samples required, but, as shown here, not always linearly with the number of frequencies.

Mode models have always been considered optimal for range-independent problems, whereas PE models have become the preferred choice for range-dependent problems. However, when moving to multi-frequency, broadband situations, the picture is not so simple. As shown in this report, the use of efficient modal solvers combined with frequency interpolation of modal properties across bands of 10–20 Hz can make the modal approach much more efficient than standard PE solutions.

The current implementation in PROSIM of range dependency in the adiabatic approximation is not always sufficiently accurate, and it is suggested that a mode coupling approach be adopted, which would not increase computation times much. Moreover, modal properties could also be interpolated in range, which would lead to a further significant speed-up of mode calculations in range-dependent environments. As to improving the efficiency of broadband PE codes, there is only one obvious way: introduce a frequency-dependent computational grid. This, however, can provide only a factor 3 reduction in computation time for broadband problems. Hence, coupled modes with wavenumber interpolation in both frequency and range remain the most promising wave modeling approach for broadband signal simulations in range-dependent shallow water environments. At higher frequencies (> 1 kHz) there is currently no alternative to rays as a practical signal simulation tool.

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Title

Broadband signal simulation in shallow water

Abstract

Today's minimum requirements for ocean acoustic models are to be able to simulate broadband signal transmissions in 2D varying environments with an acceptable computational effort. Standard approaches comprise ray, normal mode and parabolic equation techniques. In this report we compare the performance of four broadband models (GRAB, PROSIM, C-SNAP and RAM) on a set of shallow-water test environments with propagation out to 10 km and a maximum signal bandwidth of 10-1000 Hz. It is shown that a computationally efficient modal approach as implemented in the PROSIM model is much faster than standard, less optimized models such as C-SNAP and RAM. However, the handling of range dependency in the adiabatic approximation is not always sufficiently accurate, and it is suggested that a mode coupling approach be adopted in PROSIM. Moreover, the interpolation of modal properties in range could lead to a further significant speed-up of mode calculations in range-dependent environments. It is concluded that coupled modes with wavenumber interpolation in both frequency and range remain the most promising wave modelling approach for broadband signal simulations in range-dependent shallow water environments. At higher frequencies (>1 kHz) there is currently no alternative to rays as a practical signal simulation tool.

Keywords

Acoustic models – broadband models – Fourier synthesis – normal modes -- parabolic equation – propagation loss – range dependence – ray theory – sonar simulation

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