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Investigation of the Transmission Loss Issue in Bellhop

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Contract Scientific Authority: Dr. W.A. Roger, 902-426-3100 x292

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2008-054
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Canada

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Project Authority

Original signed by Dr. W. A. Roger

Dr. W.A. Roger
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Abstract

Gaussian beam models such as Bellhop have demonstrated a discrepancy in level and phase that occurs whenever the bathymetry changes slope. This report has examined this discrepancy and attempted to determine its consequences for typical model usage. The effect of both simple geometric bottom contours and complex bathymetries taken from real environments have been analyzed, along with a comparison of the model against a parabolic model and experimental data. It is concluded that the model output using incoherent averaging would smooth out and cover most phase discrepancies and therefore is recommended for tactical decision aids and other standard Transmission Loss applications. This report has also examined other Bellhop inconsistencies that were evident in the newest World Wide Web version. These include an analysis of the updated formula for choosing the number of rays and providing recommendations. In addition, the new ray-tracing algorithm and the new interpolation between sound speed profiles have been investigated, resulting in a correction to the method of extrapolation when multiple sound speed profiles are specified.

Résumé

Les modèles de faisceaux gaussiens, comme Bellhop, ont présenté un écart de niveau et de phase chaque fois que la pente du fond mesuré par le bathymètre variait. Le présent rapport a examiné ces écarts et a essayé de déterminer leurs conséquences sur l'usage de modèles typiques. On a analysé l'effet de reliefs géométriques simples du fond et des mesures bathymétriques complexes effectuées dans des milieux réels. On a aussi analysé une comparaison entre le modèle et un modèle parabolique et des données expérimentales. On a conclu que les résultats obtenus pour le modèle en calculant la valeur efficace lisseraient et couvriraient la plupart des écarts de phase, et, par conséquent, on recommande l'utilisation du modèle comme aide à la prise de décisions tactiques et pour d'autres applications relatives à l'affaiblissement de transmission typique. De plus, le présent rapport examine d'autres écarts du modèle Bellhop qui sont évidents dans la dernière version sur Internet, dont une analyse de la formule actualisée pour choisir le nombre de rayons et formuler des recommandations. Par ailleurs, on a étudié le nouvel algorithme de tracé de rayon et la nouvelle interpolation entre les profils de vitesse du son, et, par suite de cette étude, une correction a été apportée à la méthode d'extrapolation lorsque de multiples profils de vitesse du son sont précisés.

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Executive summary

Investigation of the Transmission Loss Issue in Bellhop

Dr. D. McCammon; DRDC Atlantic CR 2008-054; Defence R&D Canada – Atlantic; October 2008.

Introduction or background

Gaussian beam models such as Bellhop have demonstrated a discrepancy in level and phase that occurs whenever the bathymetry changes slope. This report has examined this discrepancy and attempted to determine its consequences for typical model usage. Both simple geometric bottom contours and complex bathymetries taken from real environments have been examined. The Bellhop model has been compared against a parabolic model called PECan, as well as against experimental data from the Scotian Shelf and from Emerald Basin.

Results

The comparison between the models Bellhop and PECan appeared to be inconsistent when there is a change in slope. For example, the models agree for frequencies above 1000Hz when using bathymetry and sound speed profiles from Sable Bank. For data near Emerald Basin, the model outputs disagree. At frequencies below 512Hz, in both cases Bellhop predicts a transmission loss that is lower than the reference model following a change in bottom slope.

When Bellhop is compared to experimental data from Sable Bank and Emerald Basin (which includes changes in slope), the model agrees quite well with the measurements. At Sable Bank there is about a 3dB RMS error over a wide frequency range from 50Hz to 1625Hz. In the Emerald Basin comparison, there is excellent agreement, particularly at the low frequencies.

It is recommended that the incoherent form of transmission loss be used for tactical decision aids and other standard Transmission Loss model applications. The noted discrepancy does not produce transmission loss predictions that are significantly different from the reference model when considering the models' differences from measured data.

Significance

Despite the discrepancy that appears following a change in bottom slope, the Bellhop ocean prediction model provides estimates of sound transmission loss that closely match experimental measurements in the cases investigated here. It is the core engine that provides acoustic predictions for the Environment Modeling Manager, a client-server system that can power a wide range of tactical decision aids for sonar operators and the command team.

Future plans

The Bellhop model will continue to be enhanced and tested against measured acoustic data.

Sommaire

Investigation of the Transmission Loss Issue in Bellhop

Dr. D. McCammon; DRDC Atlantic CR 2008-054; R & D pour la défense Canada – Atlantique; October 2008.

Introduction

Les modèles de faisceaux gaussiens, comme Bellhop, ont présenté un écart de niveau et de phase chaque fois que la pente du fond mesuré par le bathymètre variait. Le présent rapport a examiné ces écarts et a essayé de déterminer leurs conséquences sur l'usage de modèles typiques. Des reliefs géométriques simples du fond et des mesures bathymétriques complexes effectuées dans des milieux réels ont été examinés. Le modèle Bellhop a été comparé avec le modèle parabolique appelé PECan, ainsi qu'avec des données expérimentales prises sur la plate forme Scotian et dans le bassin d'Émeraude.

Résultats

La comparaison entre les modèles Bellhop et PECan a produit des résultats qui semblaient contradictoires lorsque la pente variait. Par exemple, les résultats des modèles concordent pour les fréquences supérieures à 1 000 Hz lorsque le bathymètre et les profils de vitesse du son dans le banc de l'île de Sable sont utilisés. Pour les données obtenues près du bassin d'Émeraude, les résultats des modèles ne concordent pas. De plus, dans les deux cas, après une variation de la pente du fond marin, aux fréquences inférieures à 512 Hz, le modèle Bellhop a prédit un affaiblissement de transmission inférieur à celui donné par le modèle de référence.

Lorsque l'on compare les données produites par le modèle Bellhop aux données expérimentales obtenues sur la plate forme Scotian et dans le bassin d'Émeraude (où le fond comporte des variations de pente), le modèle concorde assez bien avec les mesures. Au banc de l'île de Sable, l'erreur type est d'environ 3 dB sur une large gamme de fréquences de 50 Hz à 1 625 Hz. Dans la comparaison avec les données obtenues dans le basin d'Émeraude, la concordance est excellente, surtout aux basses fréquences.

On a recommandé d'utiliser la forme incohérente d'affaiblissement de transmission comme aide à la prise de décisions tactiques et pour d'autres applications relatives au modèle typique d'affaiblissement de transmission. En ce qui concerne les différences des modèles par rapport aux données mesurées, elles ne donnent pas lieu à des prévisions d'affaiblissement de transmission qui diffèrent considérablement de celles du modèle de référence.

Importance

Malgré les écarts qui apparaissent par suite d'une variation de la pente du fond marin, le modèle de prévision du fond de l'océan Bellhop produit des estimations de l'affaiblissement de transmission du son qui correspondent étroitement aux mesures expérimentales effectuées dans

les cas étudiés dans le présent rapport. Ce modèle est le moteur central qui fournit des prévisions acoustiques au gestionnaire de modélisation de l'environnement, un système serveur client qui peut faire fonctionner une vaste gamme d'aides à la prise de décisions tactiques pour les opérateurs sonar et l'équipe de commandement.

Perspectives

On continuera d'améliorer le modèle Bellhop et de le mettre à l'essai par comparaison avec les données acoustiques mesurées.

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1. Introduction

1.1 Description of Phase Discrepancy

In 2007, during a geoacoustic sensitivity study undertaken for Dr. Sean Pecknold of DRDC Atlantic, a distinct phase error was discovered in the acoustic modeling program called Bellhop, when compared to another model called PECan. A report was issued [1] and Bellhop was dropped from the repertoire of models pending further investigation. In [1], two problems with Bellhop were identified:

1. Inability to correctly model the change in bottom slope that occurs at a vertex. This problem appears to be inherent in the mathematics of ray-based modeling, because the Gaussian bundle models CASS/GRAB and SPADES exhibit very similar behaviour.

2. Extreme sensitivity of the Bellhop Fortran code to the precision of inputs and calculations.

An example of the phase error cited above is the case shown in Figure 1 taken from [1]. A double wedge is defined as shown, with source and receiver at 50m over a very slow bottom half-space. The transmission loss is computed at 250Hz and plotted in Figure 2. At the range point corresponding to the change in slope, (5 km), the two models begin to depart in both level and phase.

This study continues the investigation of the phase discrepancy in Bellhop in Sections 2 and 3.

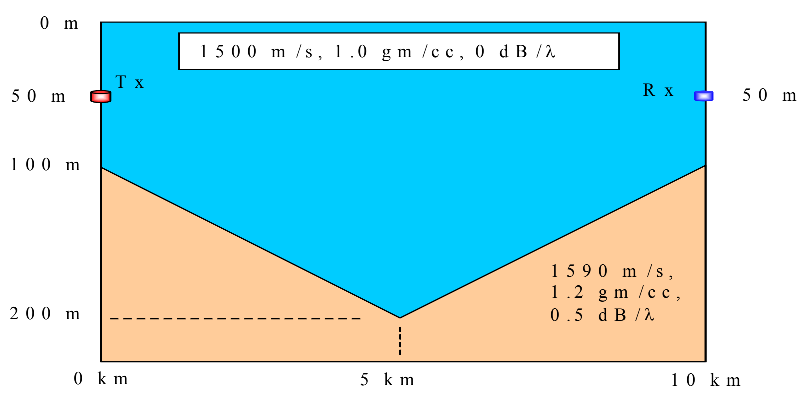

Figure 1. Double wedge bottom bathymetry from [1].

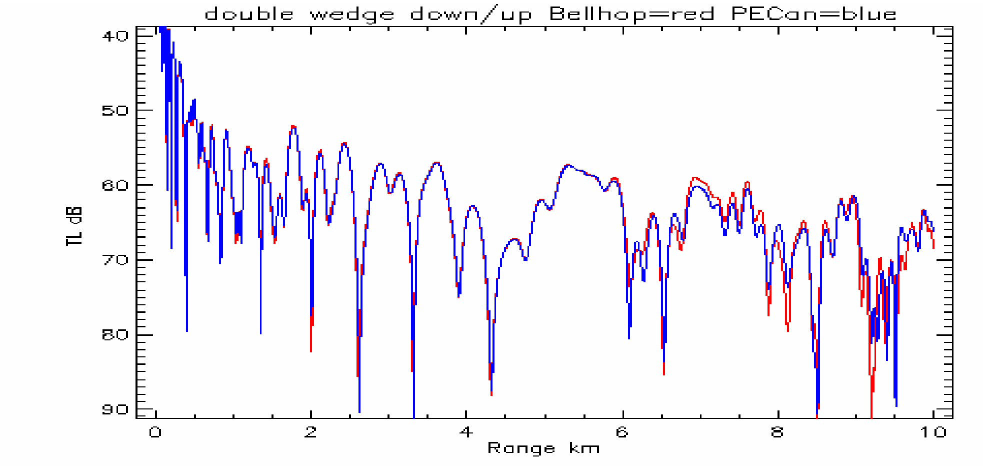

Figure 2. TL from PECan and Bellhop for the environment in Figure 1.

1.2 Other Bellhop Issues

1.2.1 Default Number of rays

The study began by bringing the newest version of Bellhop down from the website www.hlsresearch.com/oalib/. The new web model has a new default value for the #rays to be traced. The previous versions of Bellhop computed the default number of rays N_0 by the relation $N_o = \pi / 2 \sqrt{6FR/c}$, where F is the frequency in Hz, R is the maximum range in m, and c is the sound speed at the source in m/s. The new version computes the same quantity as $N_n = 3FR/c$. This is approximately the square of N_0. For example, for a 100km track at 1000Hz, $N_0=993$ while $N_n=200,000$. This increase in the number of rays has a big impact on the run time of the model; however, in some of the cases to be presented it is undeniably true that more rays gave better results. In what follows the quality of the predictions will be examined as a function of the number of rays used in Section 4.

1.2.2 'Boris' bug

In 2005, a problem with ray tracing in Bellhop was identified by the researchers at DRDC Atlantic. The problem, nicknamed the 'Boris' bug after the scientist who found it, manifests itself by trapping a surface reflecting ray in a near-surface path and propagating it to long distances before its reflection. The new web version mentioned in section 1.2.1 contains a new method of ray tracing, and so Bellhop was again tested for the 'Boris' bug. Unfortunately, exactly the same results were found; the newer method of ray tracing did nothing to help this problem, and actually slowed the runtime of the algorithm. This problem will not be studied further at this time.

1.2.3 Coherent, Semi-Coherent and Incoherent Output

In this study, the optimal type of output from Bellhop will be determined. In Section 5 an example of all the output choices will be presented and recommendations provided for their use.

1.2.4 Range dependent SSP's

The new web version mentioned in section 1.2.1 also accepts range-dependent sound speed profiles and performs a linear interpolation between them with range. In experimenting with this algorithm, it was found that the interpolation became an extrapolation beyond the last input profile, and was preformed incorrectly, leading to unphysical results further downrange. An example of this error is shown in Section 6.

2. Comparisons with Ideal Double Wedge

The parabolic equation model PECan was chosen for the model comparisons in this paper because it was by comparison with this model that the problem first surfaced. While PECan is not an exact solution and its output is dependent on user choices of range and depth step, pade terms, bottom densities, and source functions, it is considered by the modeling community to be reliable over range dependent bathymetry and can thus serve to pinpoint the Bellhop discrepancies in these simple academic style problems.

To begin the comparison between Bellhop and PECan, the two models must be grounded in the same environment. To mimic PECan's calculations, the Thorpe volume attenuation and the surface loss algorithms are removed from Bellhop and the coherent output is chosen. To facilitate the level comparisons at high frequencies where the models oscillate very rapidly in phase, a simple range average is preformed over both Bellhop and PECan. In most cases, the incoherent output from Bellhop is also plotted.

Beginning with the simple case of an isovelocity sound speed profile and bottom parameters of 1590m/s sound speed, 1.2g/cc density and 0.5dB/λ attenuation, the transmission loss is computed over a variety of bottom slope configurations as shown in Figure 3. All bathymetries except the bump follow the same slope for the first 5 km.

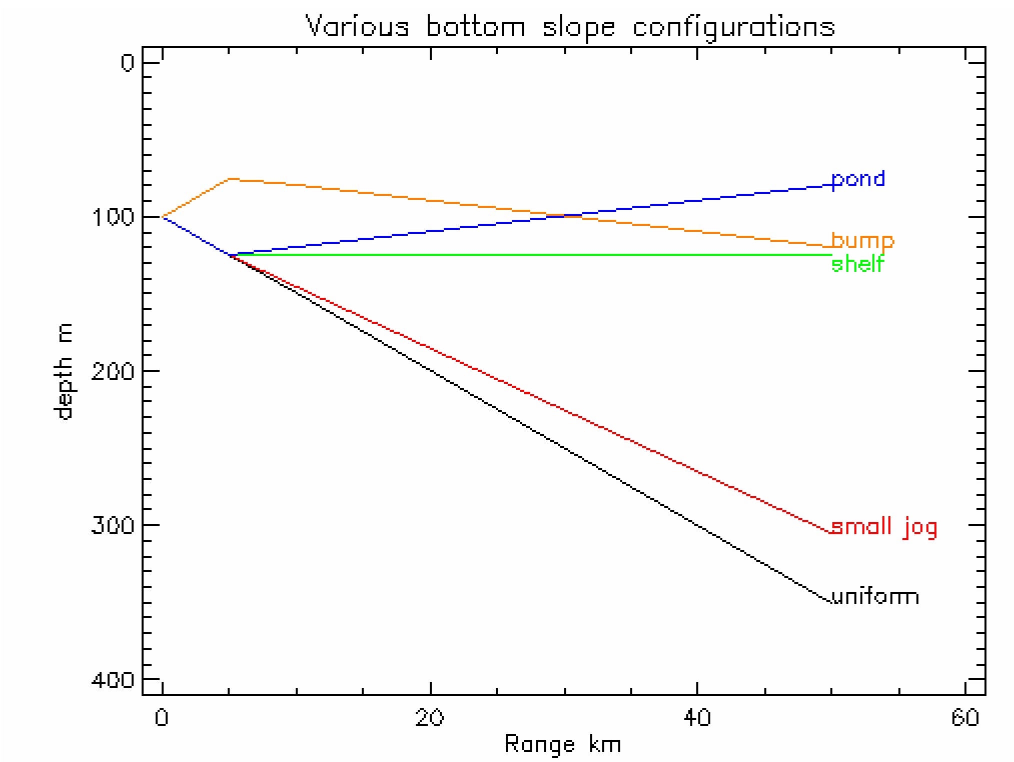

Figure 3. Various bottom slope configurations.

In the uniform slope case, Figure 4 shows very good agreement between PE and Bellhop at 250 Hz. Figure 5 shows a detail of this propagation between 30 and 40km, and the range phase is quite accurate.

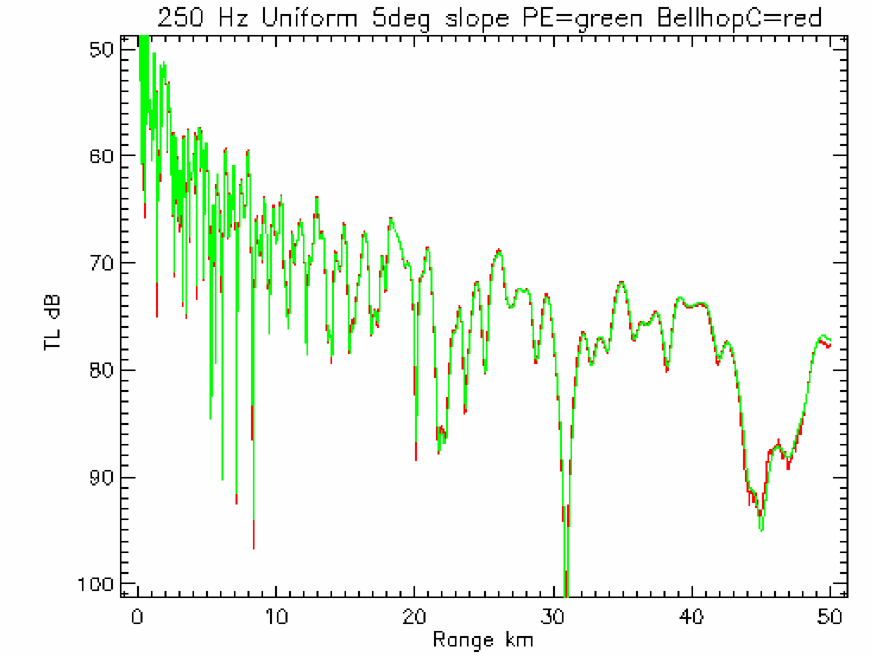

Figure 4. TL comparison, uniform slope bathymetry.

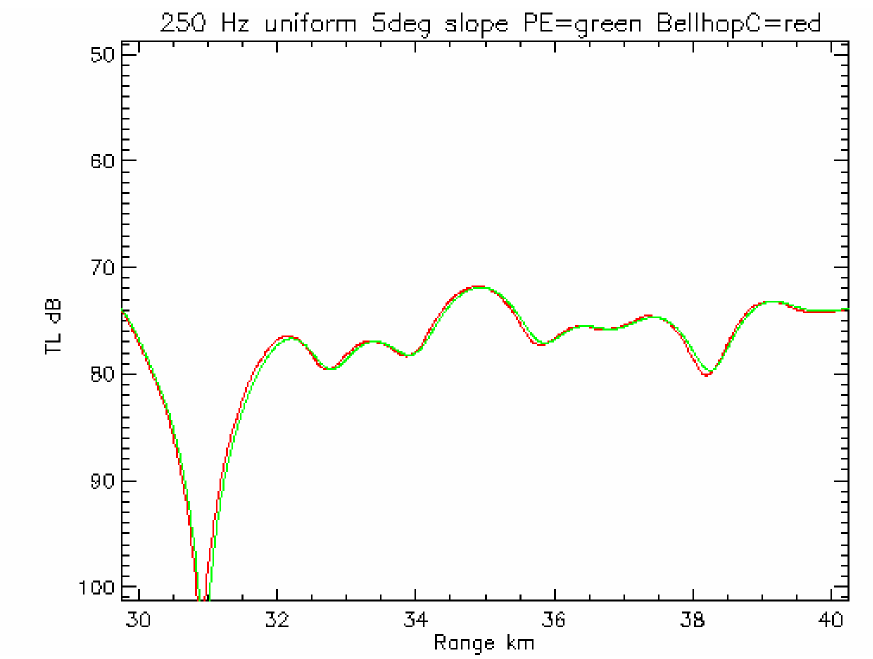

Figure 5. Uniform slope, detail of TL from 30 to 40km, 250Hz.

Now a slight jog is introduced in the bathymetry wedge, by changing the slope from 5º to 4º at 5km. The phase and level of Bellhop now depart from the PE and become obvious at ranges beyond 35km, as shown in Figure 6 and Figure 7.

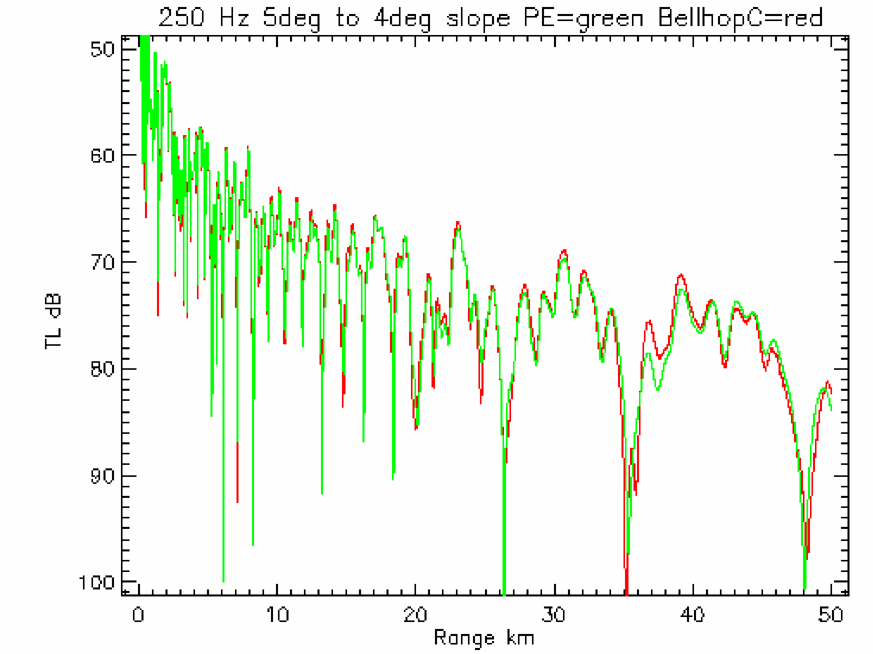

Figure 6. TL comparison, slight jog in slope at 5km.

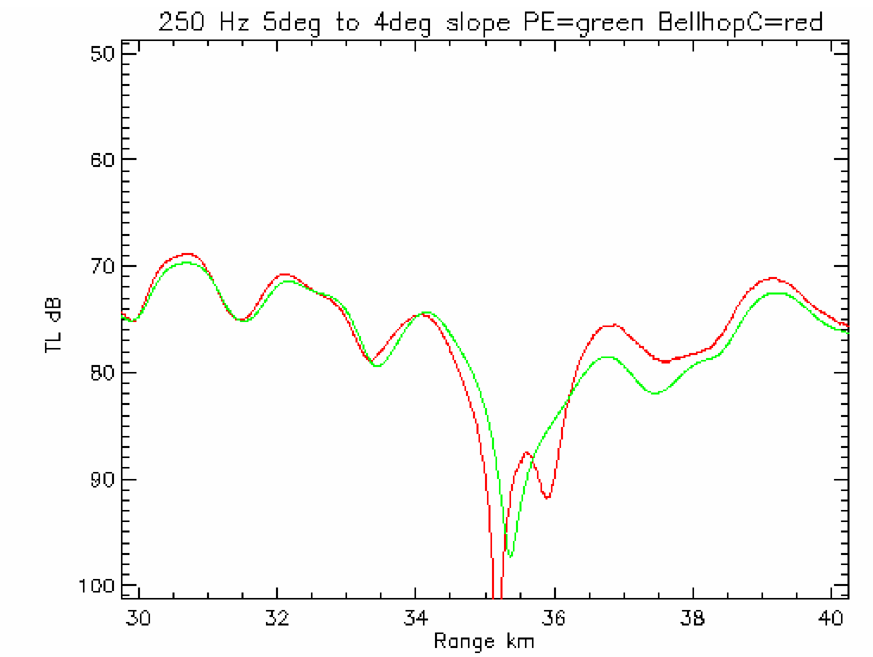

Figure 7. TL over jog bathymetry, detail between 30 to 40km.

Changing the problem slightly, the initial slope is left at 5º out to 5km, and then changed to a flat bottom thereafter in the fashion of a shelf (as shown in Figure 3). Figure 8 displays the TL between 30 and 40km, and shows a phase shift and a level shift of several dB.

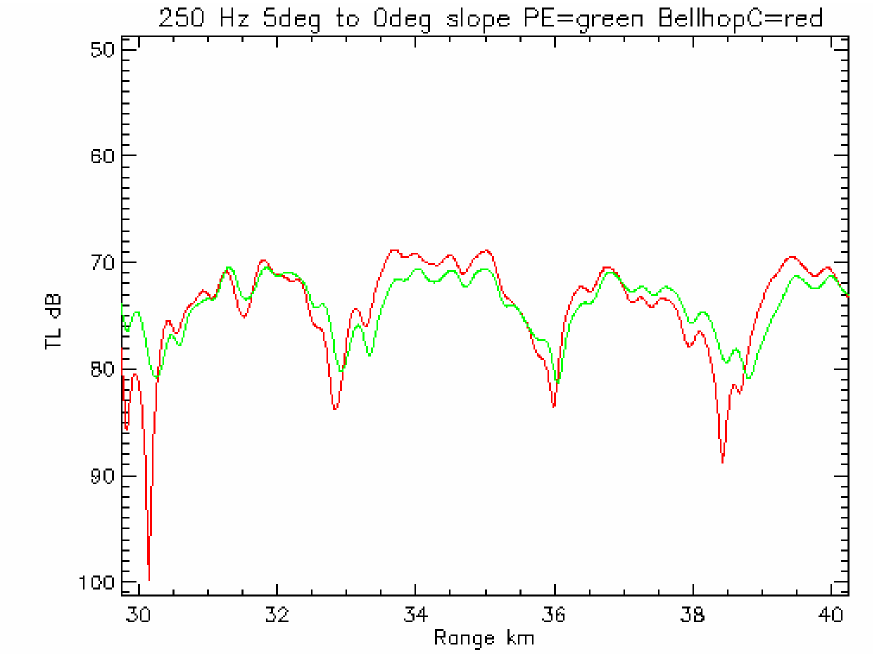

Figure 8. TL over shelf bathymetry, detail between 30 and 40 km.

Now, a double wedge is defined to represent a sediment pond (as shown in Figure 3). In this case, the phases of Bellhop and PECan are similar, but there is a level difference of several dB, as illustrated in Figure 9.

Making the bottom very lossy will remove energy from the field, but the shift in phase remains evident as indicated in Figure 10 for a pond sediment with a sediment speed of 1490.

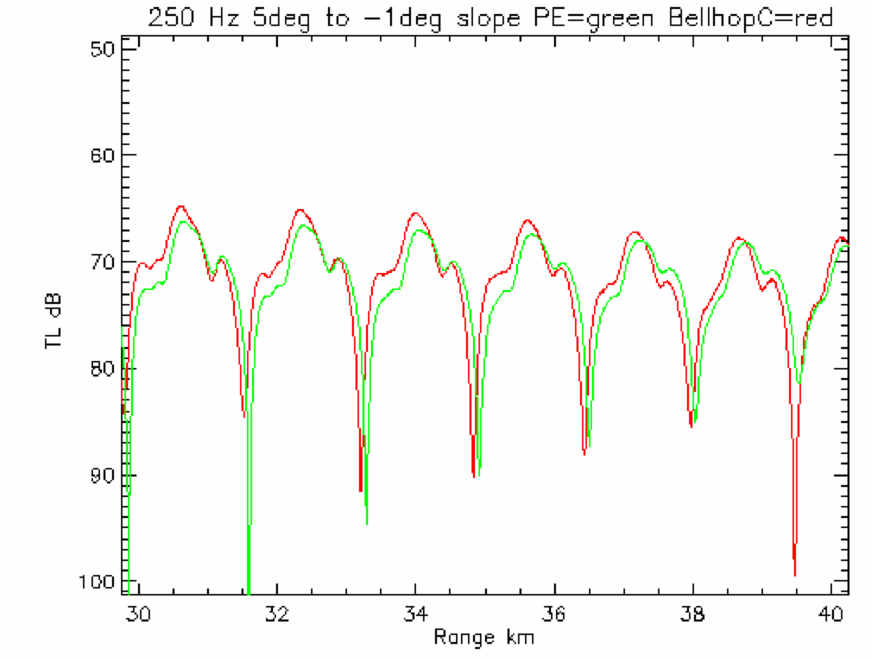

Figure 9. TL over a pond bathymetry, detail between 30 and 40km.

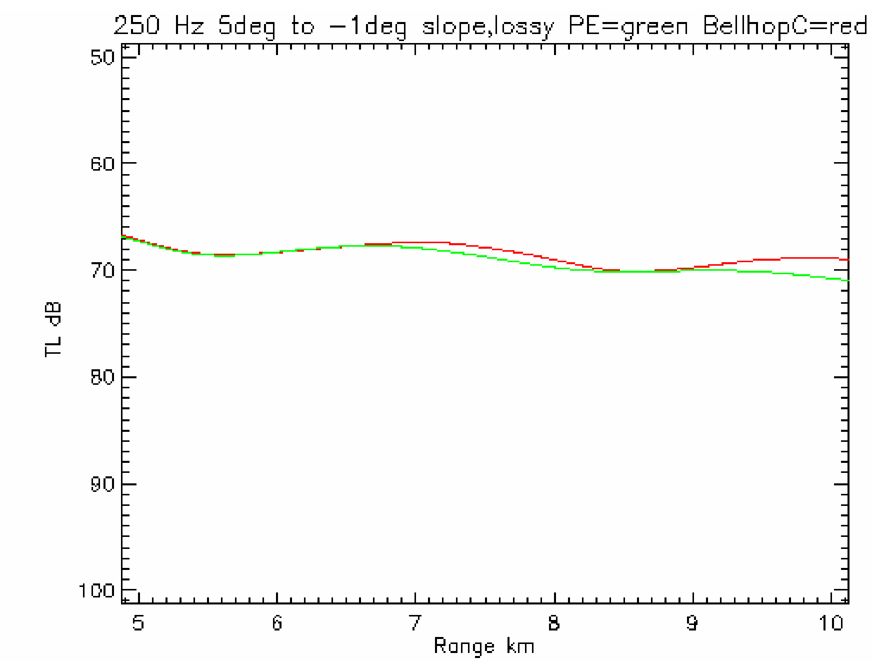

Figure 10. TL over pond bathymetry, high loss bottom, detail from 5 to 10km.

Figure 11 shows the same differences when using a very hard, highly reflective bottom with a sound speed of 2000m/s.

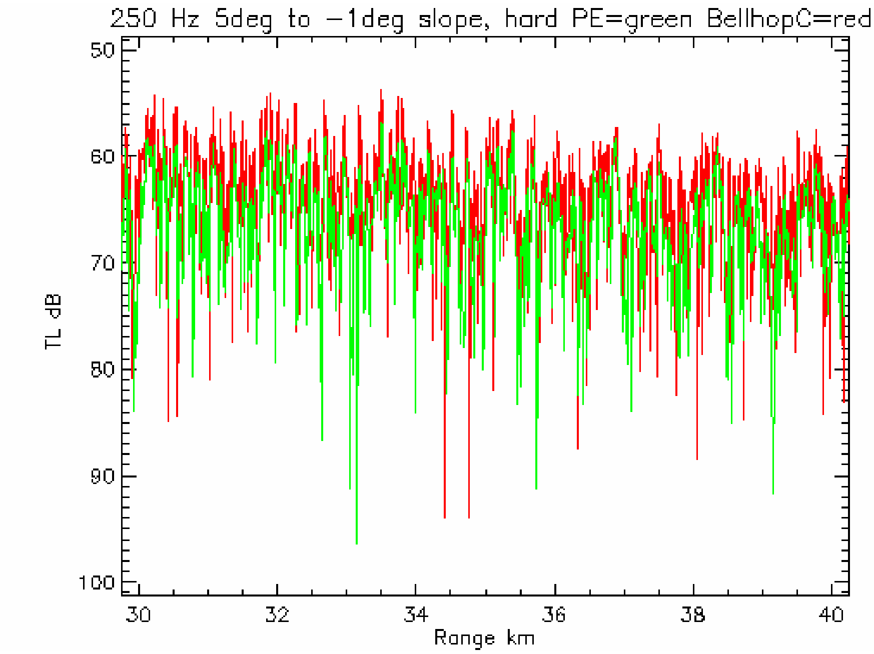

Figure 11. TL over pond bathymetry, hard highly reflective bottom, detail from 30 to 40km.

And finally, the bottom slopes were inverted to turn the topography into a bump (Figure 3), with the resulting TL differences being shown in Figure 12.

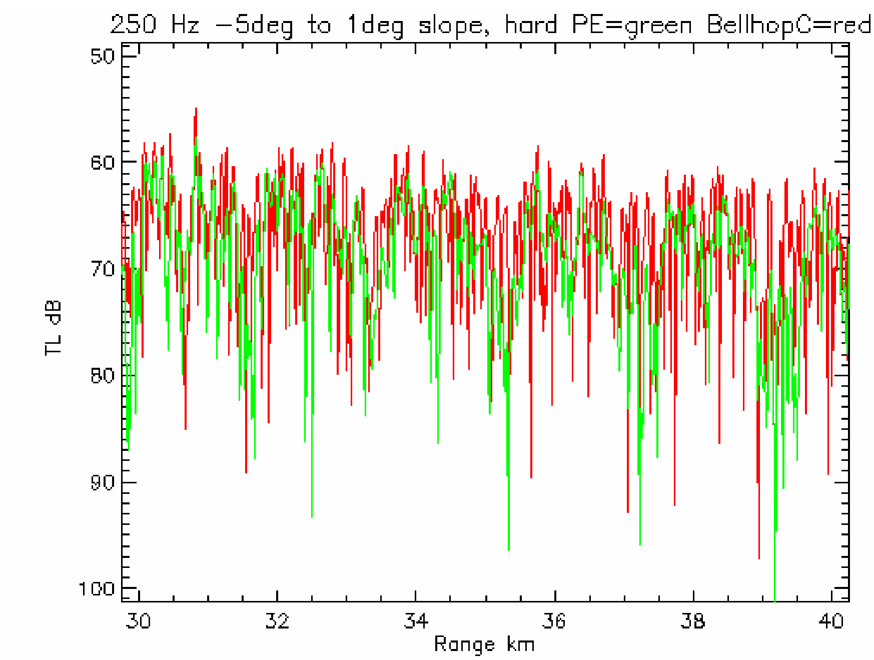

Figure 12. TL over bump bathymetry, detail from 30 to 40km.

It is observed that all Bellhop results appear to be range and/or level shifted slightly as compared to PE. All the Bellhop results appear to have less loss than PECan predicts. And these changes occur whether the change in bathymetry is small or fairly large, whether the slope change is positive or negative and whether the bottom is reflective or lossy.

3. Comparisons with Real Environments

It is all very academic to examine artificially constructed bathymetries and environments when comparing two models, because this allows us to concentrate on just one factor at a time. Unfortunately, this does not address the question of the quality of predictions in real-world environments. In this section, three geographic areas are examined where DRDC has obtained transmission loss data. Bellhop is compared with PE over these bathymetries at different frequencies. Then, in the Sable Bank and Emerald Basin cases, the match of Bellhop to the measured TL data is presented.

3.1 Sable Bank

3.1.1 Sable Bank bathymetry, PECan versus Bellhop

The first example is a comparison between Bellhop and PECan over a bathymetry measured in the shallow water Sable Bank region at 512 Hz. The average depth of the bathymetry in this region was 70m and the sound speed profile was downward refracting. First, Figure 13 shows the TL of the two models over a perfectly flat bottom but with the Sable Bank downward refracting sound speed profile at a frequency of 512Hz. Then follows, in Figure 14, the same comparison but using the actual Sable bank bathymetry, with depth vs. range drawn at the bottom of the plot.

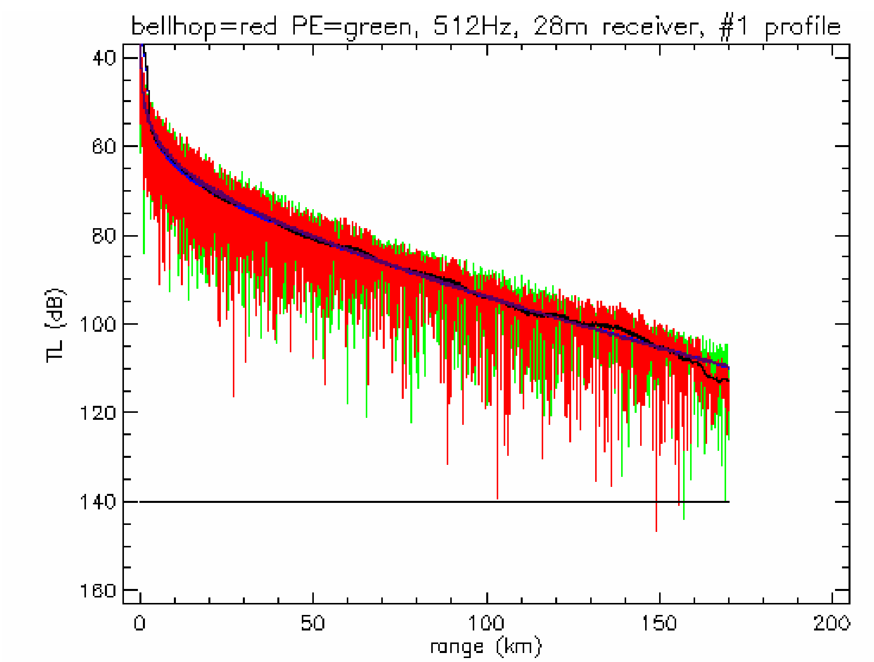

Figure 13. Bellhop(red) and PE(green) over flat bottom with Sable Bank SSP, 512 Hz. The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves.

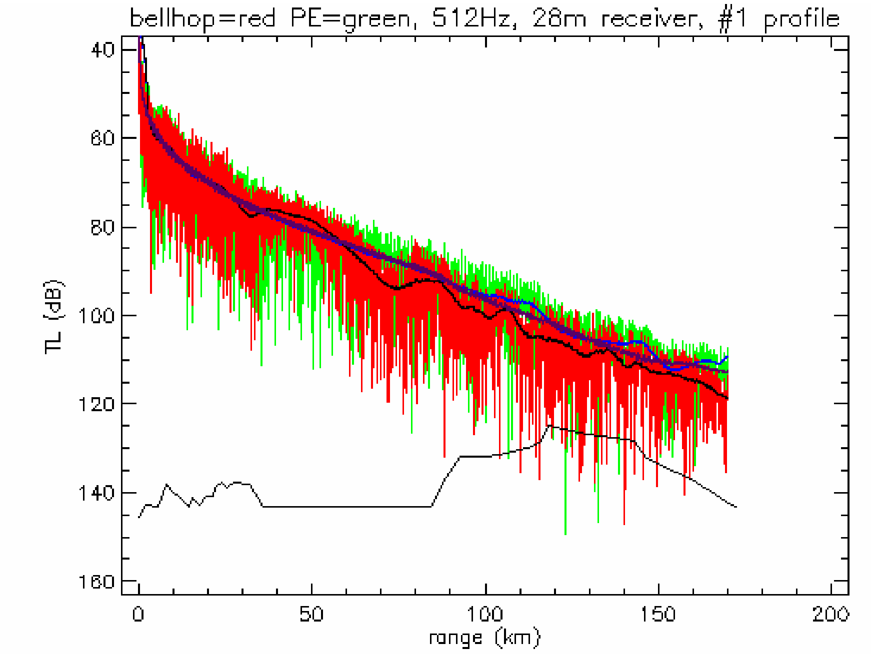

Figure 14. Bellhop (red) and PE (green) over Sable Bank bathymetry and SSP, 512 Hz. The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves.

In this comparison, the phase is oscillating so rapidly that it is necessary to use a range-average of the TL (boxcar filter) to achieve a smooth result. The PE range-average (in blue) and the Bellhop range-average (in black) are very close in agreement over the flat bottom, but Bellhop shows more loss when using the actual bathymetry. The purple line that more closely matches the PE range-average is the incoherent output from Bellhop.

There was almost perfect agreement between PE and Bellhop over both the flat and structured bottoms at frequencies of 1000 and 2000 Hz, so their figures will not be shown.

In Figure 15 and Figure 16, the frequency is lowered to 128 Hz. In this case, coherent Bellhop is not able to match the PE either over the flat or structured bathymetry. However, the incoherent Bellhop (purple line) is much closer to the range-averaged PE result. In this case, the frequency may be too low for an accurate result from Bellhop, which is, of course, a ray based solution. Another reason for disagreement may be the treatment of the sound speed profile interpolations: linear in Bellhop and $1/c^2$ linear in PECan. This lower frequency may be ducting in the $1/c^2$ linear profile because the PECan result changes very little between the flat and structured bottom.

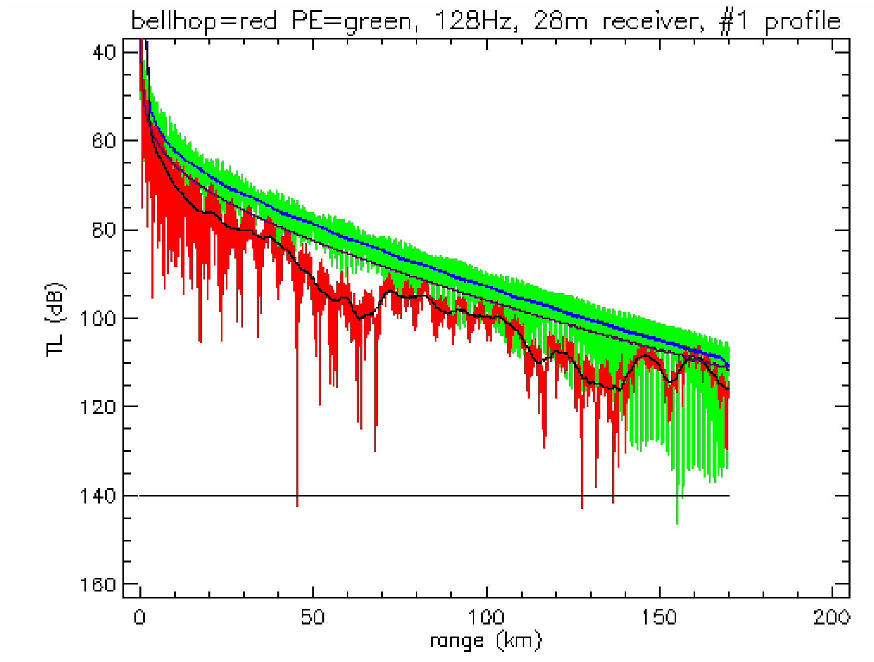

Figure 15. Bellhop (red) and PE (green) over flat bottom with Sable Bank SSP, 128 Hz. The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves. The purple curve indicates Bellhop's incoherent averaging.

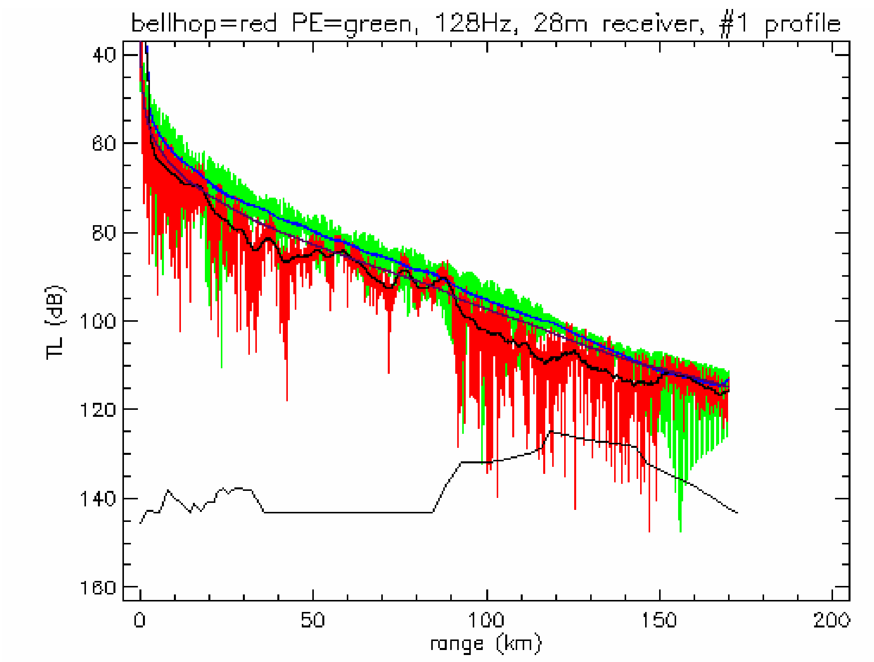

Figure 16. Bellhop (red) and PE (green) over Sable Bank bathymetry and SSP, 128 Hz. The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves. The purple curve indicates Bellhop's incoherent averaging.

3.1.2 Sable Bank Measured Data versus Bellhop

While the comparisons in the previous section show the TL from Bellhop is lower than that from PECan in these environments at low frequencies, it is important to remember that the PE is not an exact solution either, and in particular, it must smooth the transition into the bottom because of the density discontinuity at the sediment interface. In this case, in Sable Bank, the water is shallow and the bottom is an important factor in the propagation. The best comparison, therefore, is between Bellhop and the measured data in this region.

Shown in Figure 17-Figure 19 are the measured TL (black triangles) and modeled TL (red triangles) and their range-averages (black and red solid lines) for three typical frequencies and receiver depths in a Sable Bank data set with a slightly different bathymetry from the examples above. The model results are computed coherently but only for the same ranges as the measured data, therefore the large phase oscillations with range are not evident. Both sets of data are also range-averaged to facilitate their comparison. In this case, the 322Hz and 128Hz comparisons are showing that the transmission loss from Bellhop is about 5dB less than that of the experimental data.

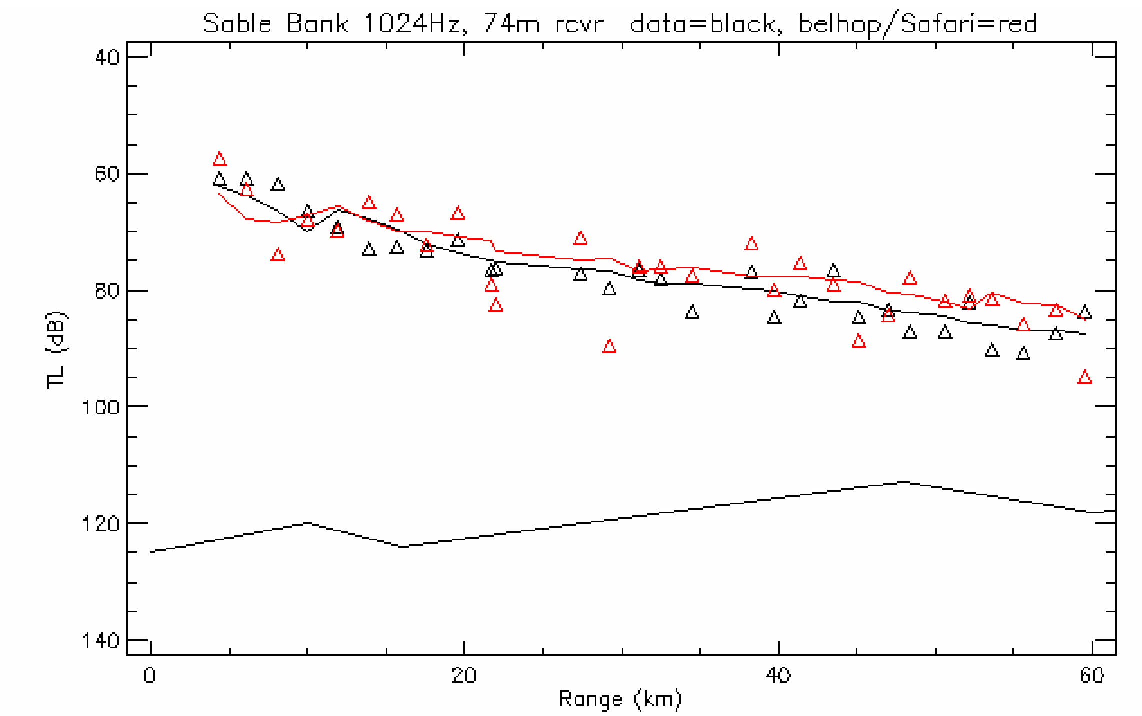

Figure 17. Sable Bank transmission loss at 1024Hz. Black triangles indicate measured data and red triangles the modeled data. Black and red curves show the smoothed data curves. The bathymetry is shown at the bottom of the graph (not to scale).

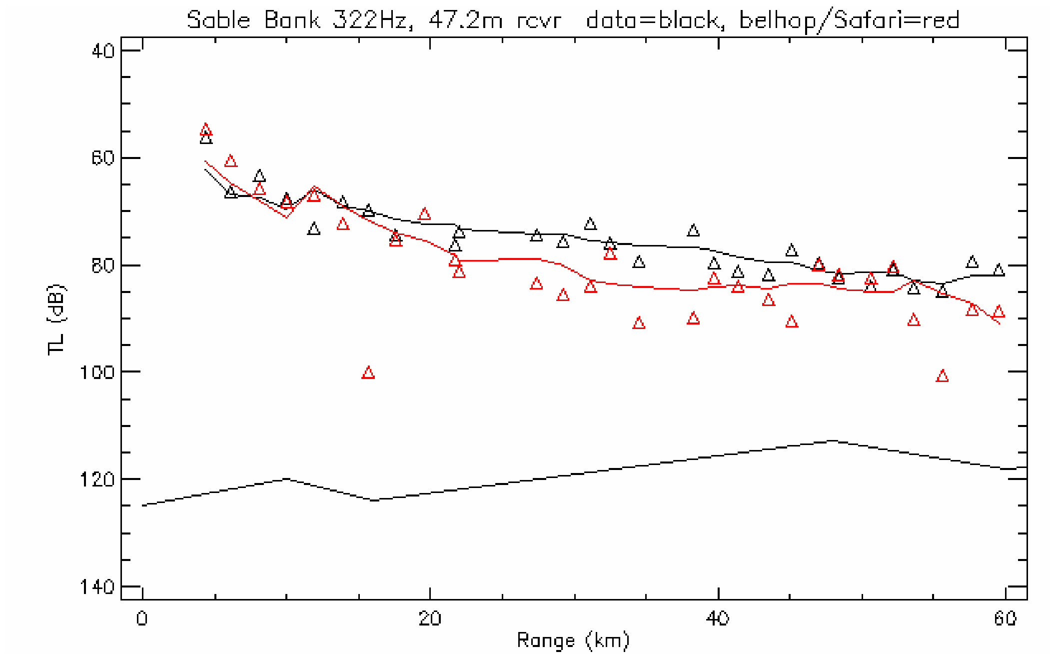

Figure 18. Sable Bank transmission loss at 322Hz. Black triangles indicate measured data and red triangles the modeled data. Black and red curves show the smoothed data curves. The bathymetry is shown at the bottom of the graph (not to scale).

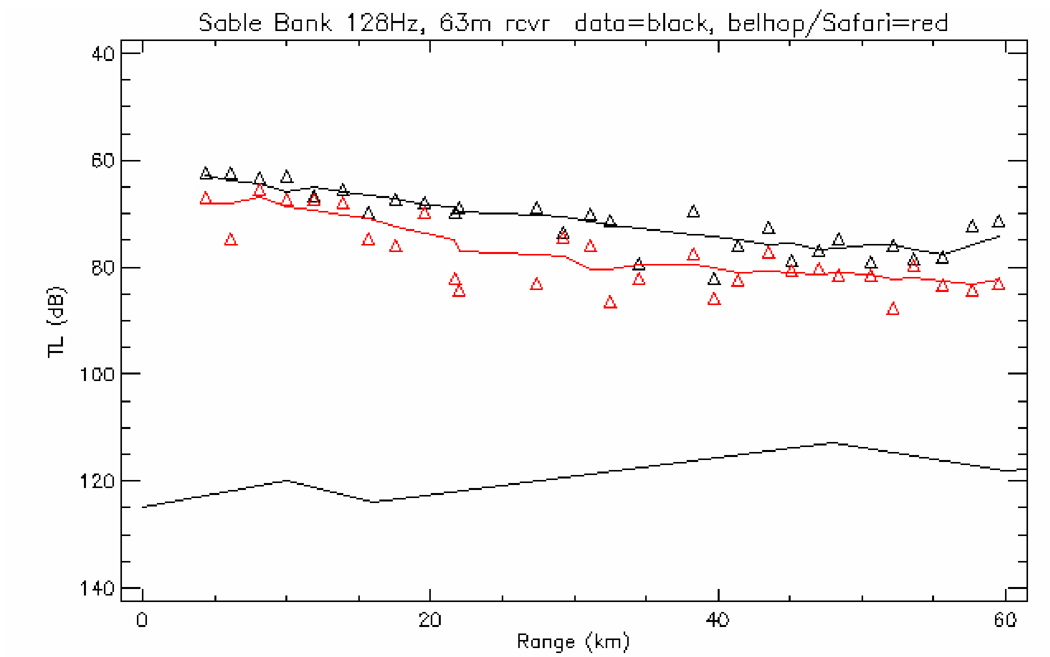

Figure 19. Sable Bank transmission loss at 128Hz. Black triangles indicate measured data and red triangles the modeled data. Black and red curves show the smoothed data curves. The bathymetry is shown at the bottom of the graph (not to scale).

Table 1 shows the RMS error between the measured range-averaged data and the coherent range-averaged Bellhop for a range of frequencies and receiver depths. The largest errors occur at the low frequencies where Bellhop is too low, but overall, the agreement with Bellhop is good.

It can be concluded from these comparisons that the Bellhop coherent range-averaged output is doing a reasonable job of predicting the level of sound in the Sable Bank area in the 203-1625 Hz range, and it is low by about 5dB in the 50-161 Hz range. The phase errors are not evident in the range-averaged output.

Table 1. Errors between measured data and Bellhop in Sable Bank.

Data used in Sable Bank Analysis	**RMS Error (dB)**
6 frequencies from 512Hz to 1625 Hz, 4 receiver depths, 29 range points	2.5
4 frequencies from 203 Hz to 406 Hz, 5 receiver depths, 29 range points	3.2
3 frequencies from 50 Hz to 161 Hz, 3 receiver depths, 29 range points	5.04

3.2 Atlantic Sea Trial Q290

The sea trial Q290 featured a very rough bathymetry with an average depth of 90m and a downward refracting sound speed profile. The bottom was a hard, reflective sediment with a mean depth of 90m. Using a flat bottom but with the Q290 sound speed profile at 1400Hz, Figure 20 shows rather good agreement between the models in level, but the phases do not track each other. These differences may also be affected by the different treatments of the interpolation between measured sound speed profiles. Figure 21 shows the same comparison over the actual rough bathymetry. The agreement is about the same as in the flat bottom case, so it cannot be concluded that the rough bottom was responsible for the differences.

Lowering the frequency at site Q290 to 150Hz gives the following comparisons in Figure 22 and Figure 23. In this case, Bellhop is not able to match the PE result due to the low frequency, not even over the flat bottom. However, the incoherent Bellhop is surprisingly close to the range-averaged PE, especially over the rough bathymetry.

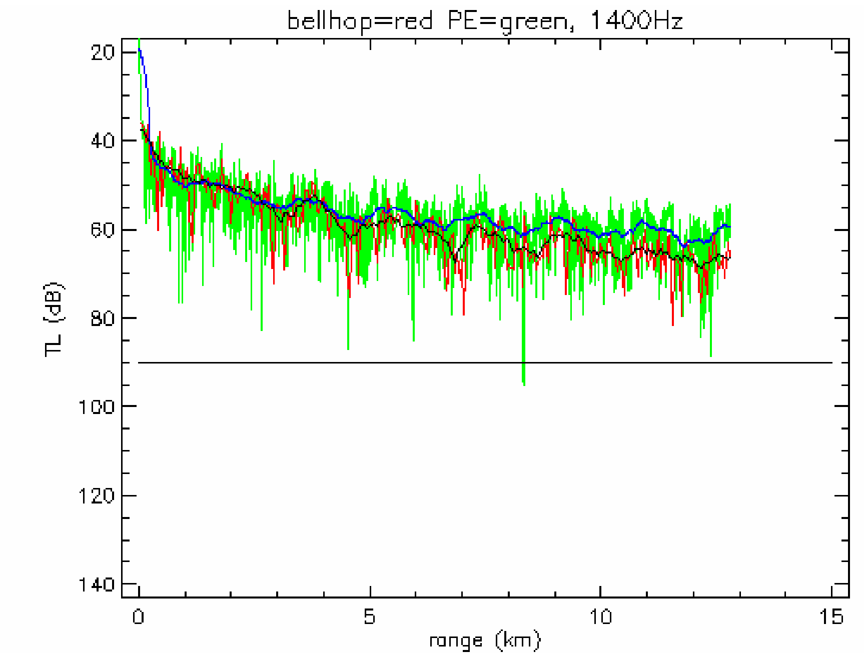

Figure 20. Site Q290, 1400Hz. TL comparison of Bellhop (red) and PE (green) over flat bathymetry. The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves.

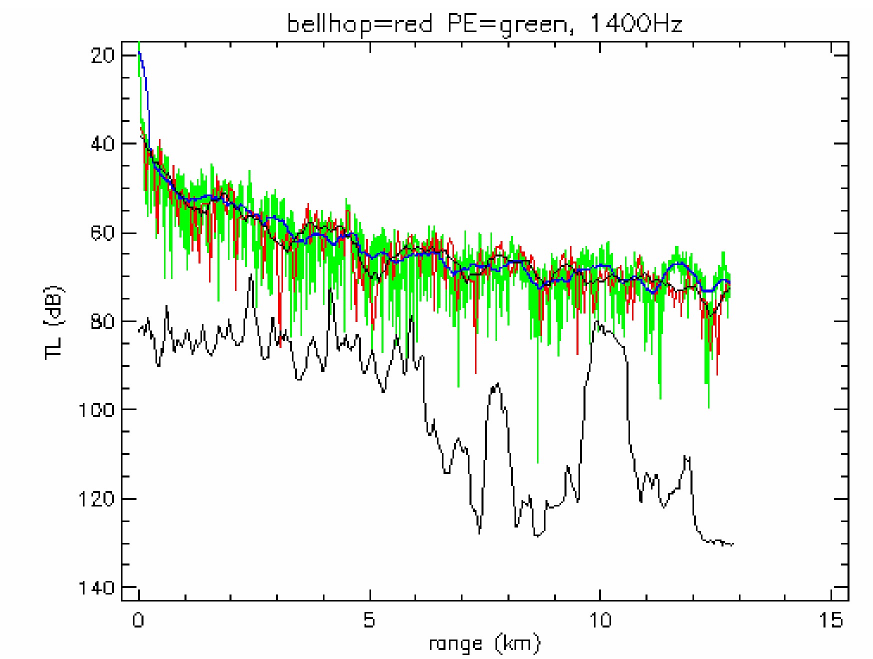

Figure 21. Site Q290, 1400Hz. TL comparison of Bellhop (red) and PE (green) over rough bathymetry. The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves. The bathymetry is shown at the bottom of the graph (not to scale).

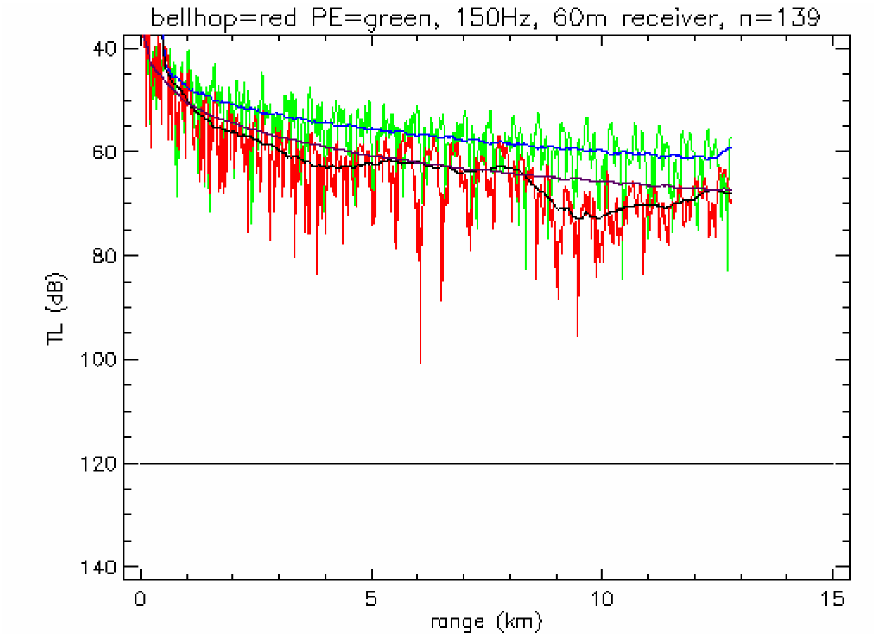

Figure 22. Site Q290. TL comparison of Bellhop (red) and PE (green) over flat bathymetry at 150 Hz. The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves. The purple curve indicates Bellhop's incoherent averaging. The bathymetry is shown at the bottom of the graph (not to scale).

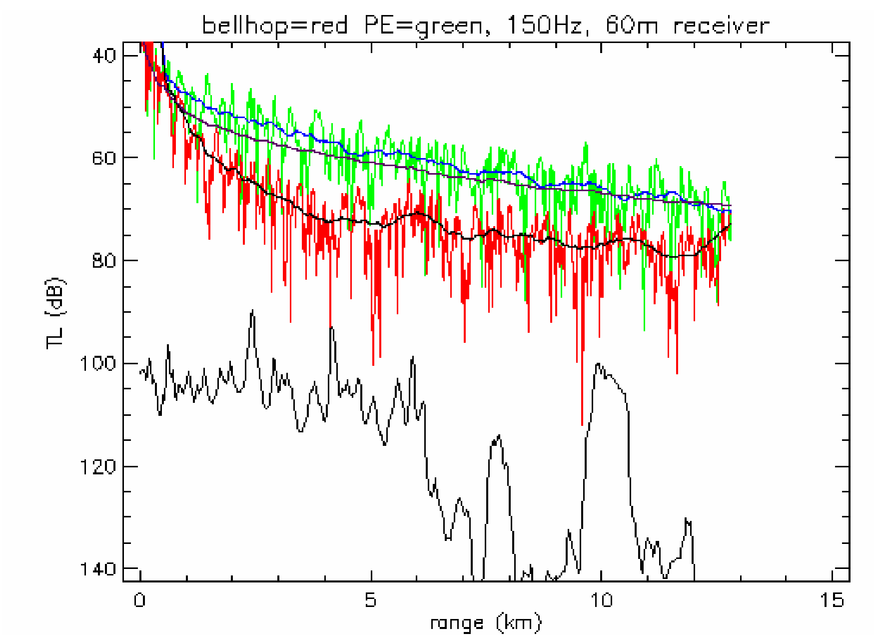

Figure 23 Site Q290. TL comparison over rough bathymetry at 150Hz. The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves. The purple curve indicates Bellhop's incoherent averaging. The bathymetry is shown at the bottom of the graph (not to scale).

Finally, lowering the frequency even more to 50 Hz results in the curves of Figure 24 and Figure 25. It is obvious that Bellhop does not match the level of PE, even over the flat bottom, although the short range-scale phases are remarkably similar. Again, the incoherent Bellhop transmission loss (purple line) is much closer to the PE result.

The conclusion of this comparison is that Bellhop, being a ray model, is not very accurate at 150 Hz and lower, although the incoherent TL is a better match to PECan at these frequencies. It can also be concluded that the phase error is not critically important at higher frequencies when the rapid phase oscillations obscure any differences.

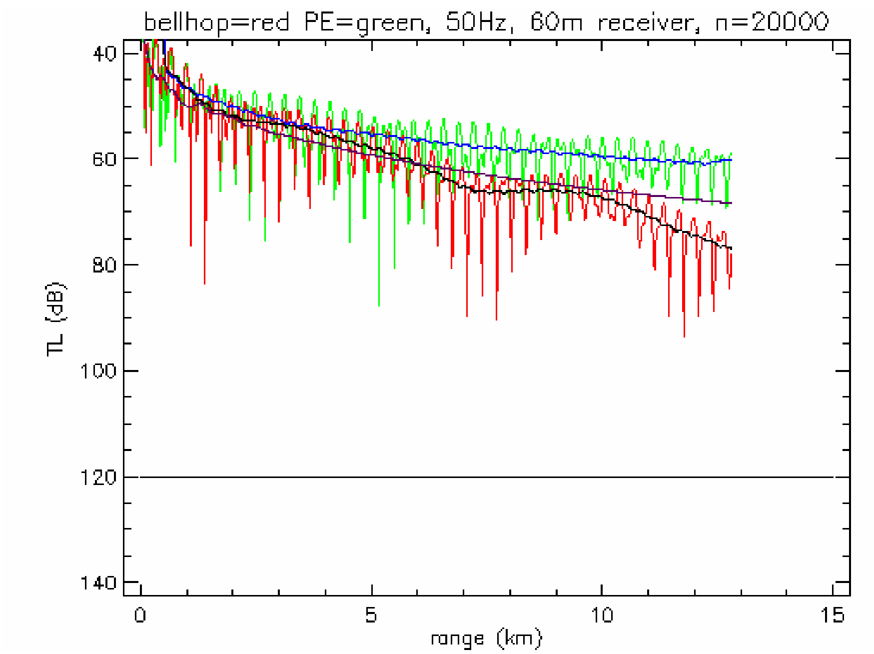

Figure 24. Site Q290, 50Hz. Transmission loss for Bellhop (red) falls below that from PE (green). The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves. The purple curve indicates Bellhop's incoherent averaging. The bathymetry is shown at the bottom of the graph (not to scale).

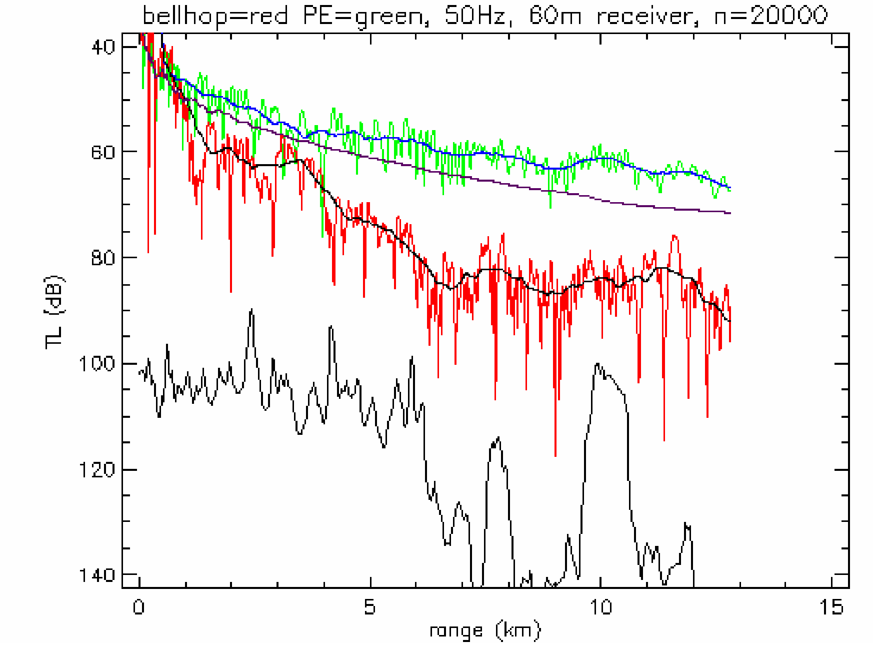

Figure 25. Site Q290, 50Hz. TL comparison over rough bathymetry. The result of averaging the PE and Bellhop transmission loss with range produced the blue and black curves. The purple curve indicates Bellhop's incoherent averaging. The bathymetry is shown at the bottom of the graph (not to scale).

3.3 Emerald Basin Measured Data Versus Bellhop

Shown in Figure 26-Figure 28 are the measured TL (black triangles) and modeled TL (red triangles) and their range-averages (solid lines) for three typical frequencies and receiver depths in an Emerald Basin data set. The bathymetry is drawn at the bottom of each figure (not to scale). The model results are computed coherently but only for the same ranges as the measured data, therefore the large phase oscillations with range are not evident and in particular, any phase differences are impossible to determine. Both sets of data are range-averaged to facilitate their comparison. In this data set, the model is very close to the data, even as low as 80 Hz.

Subsequent to this analysis, it was found that there may have been a source level error in the Emerald Basin data. This was detected by the simple experiment of inserting 0dB bottom loss into Bellhop and comparing the resulting TL with the data, whereupon, at some of the receiver depths and frequencies, the model was still slightly more lossy than the data. It has been postulated that since the shots were detonated on the bottom, the actual source level would probably have been affected by the proximity of the sediment, and the true source level could be different by as much as 3dB. Therefore, the comparison presented here should have error bars on the data to represent this unknown source level.

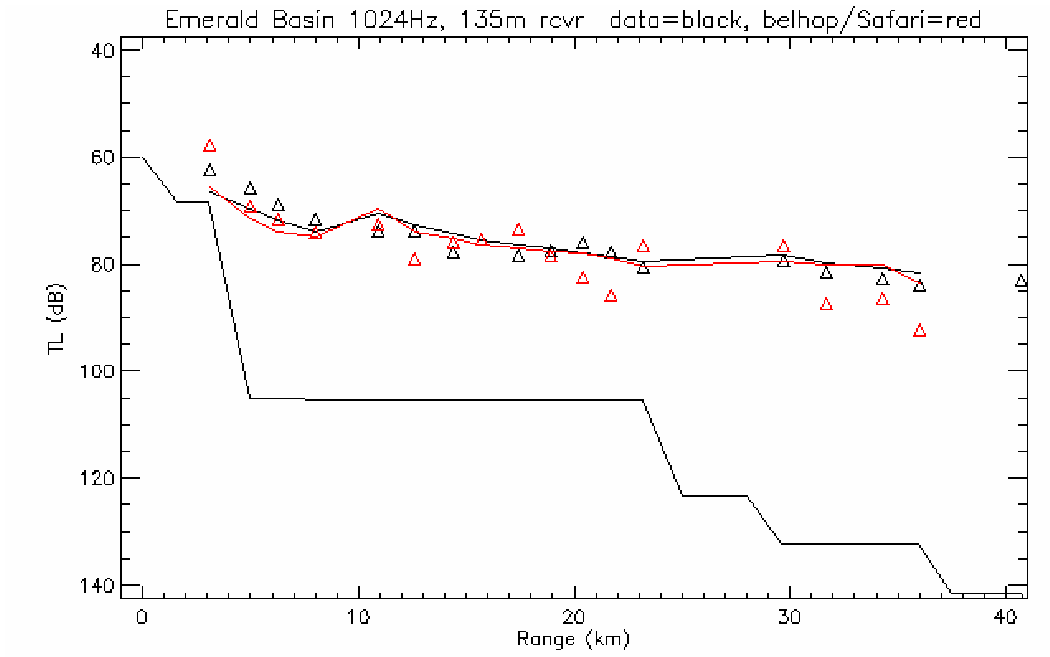

Figure 26. Emerald basin data/model comparison at 1024Hz. Black triangles indicate measured data and red triangles the modeled data. Black and red curves show the smoothed data curves. The bathymetry is shown at the bottom of the graph (not to scale).

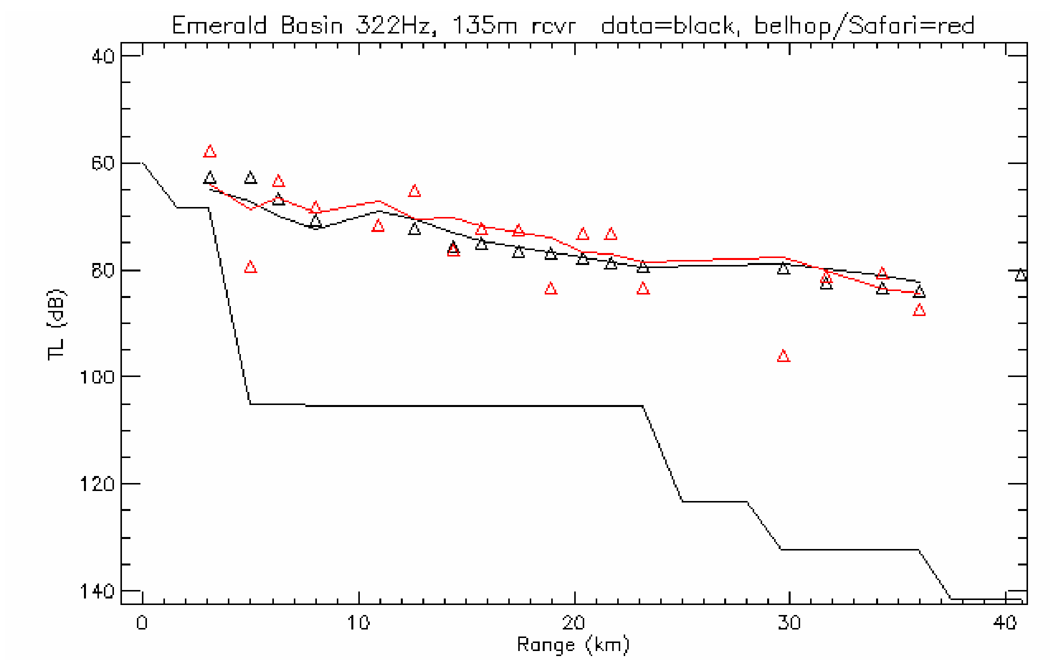

Figure 27. Emerald Basin data/model comparison for 322Hz. Black triangles indicate measured data and red triangles the modeled data. Black and red curves show the smoothed data curves. The bathymetry is shown at the bottom of the graph (not to scale).

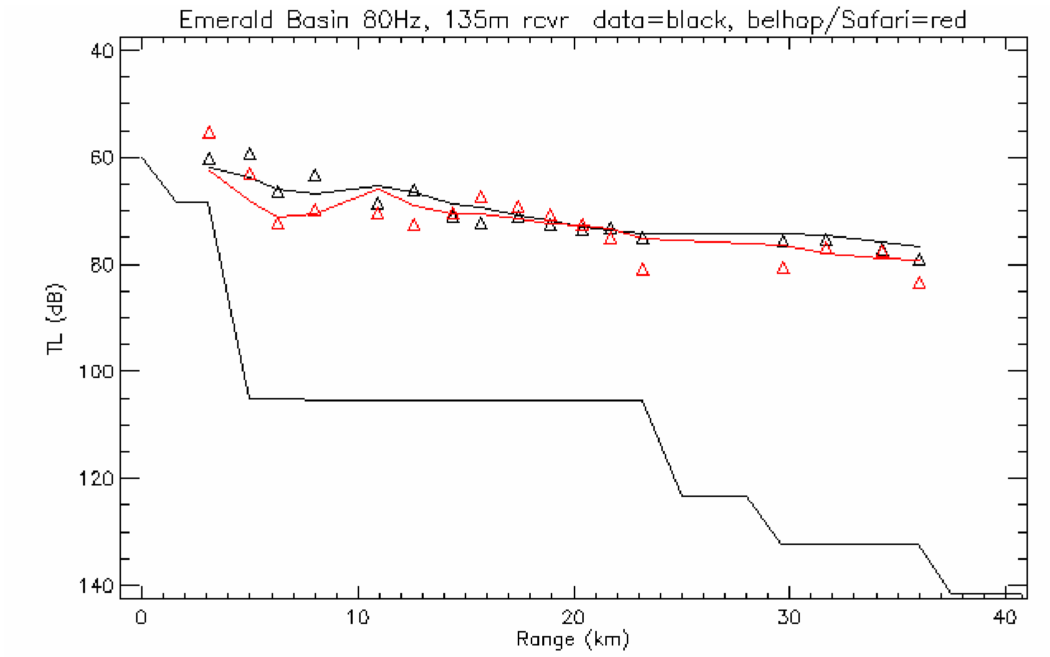

Figure 28. Emerald Basin data/model comparison for 80Hz. Black triangles indicate measured data and red triangles the modeled data. Black and red curves show the smoothed data curves. The bathymetry is shown at the bottom of the graph (not to scale).

Table 2 shows the RMS error between the measured range-averaged data and the coherent range-averaged Bellhop for a range of frequencies and receiver depths. Overall, the agreement of Bellhop with the experimental data is good, notwithstanding the uncertainty in the source level.

Table 2. Errors between measured data and Bellhop in the Emerald Basin..

Data used in Emerald Basin Analysis	RMS Error (dB)
4 frequencies from 512Hz to 1024 Hz, 4 receiver depths, 17 range points	4.0
4 frequencies from 203 Hz to 406 Hz, 4 receiver depths, 17 range points	3.0
4 frequencies from 50 Hz to 101 Hz, 4 receiver depths, 17 range points	3.2

3.4 Summary of model-to-model comparisons

Table 3 summarizes the model-to-model comparisons using real-world environments. The error reported is the mean dB difference (not RMS as was used above) between the range-averaged PE and the range-averaged coherent Bellhop over the range of the prediction.

Table 3. Summary of Bellhop/PE error comparisons.

Tests	dB Error over Bathymetry	dB Error over Flat bottom	Change	Comments
Sable Bank				
128 Hz	4.75	8.9	+4.15	Frequency too low for Bellhop accuracy?
512 Hz	2.18	0.15	-2.03	Models very similar
1000 Hz	2.0	0.57	1.43	Models very similar
2000 Hz	2.5	2.6	+0.1	Models very similar
Atlantic Sea Trial Q290				
50 Hz	16.7	6.5	-10.2	Frequency too low for Bellhop accuracy?
150 Hz	10.8	4.5	-6.3	Frequency too low for Bellhop accuracy?
1400 Hz	17.2	14.1	-3.1	Bellhop low in both

It appears that the Bellhop and PE comparisons are inconsistent. In the Sable Bank case, the models seem to agree at frequencies above 1000Hz, while in the Q290 tests there is disagreement. At frequencies below 512Hz, in both cases Bellhop predicts a transmission loss that is lower than the reference model.

3.5 Summary of model-to-data comparisons

Comparing Bellhop to real measured data in the Sable Bank and in the Emerald Basin, we find that the model agrees reasonably well with the data, having about a 3dB RMS error over a wide frequency range from 50Hz to 1625Hz. In the Emerald Basin comparison, the low frequencies are matching the data quite well, notwithstanding the uncertainty in the source level. It is impossible to discern any phase errors in this comparison because the data are sampled about 4km apart.

4. Free parameter issues and number of rays

Both the PECan and Bellhop models contain at least one free parameter; that is, a variable that is not specified by their theories but can be chosen at the user's whim. These parameters are explained below.

Parabolic solutions: In PECan, the free parameters are the choice of source function, the choice of pade terms, the choice of sampling depth and range step and the reference sound speed c_0, which controls the base phase in the solution, $\exp(-i\ \omega/c_0\ r)$. After the model's creator, Dr. Gary Brooke pointed out a big mistake I had made in my choice of range step that was creating erroneous output, I did not experiment any further with these parameters, and just used the suggested values from Dr. Brooke.

Gaussian beam models: In Bellhop and other Gaussian beam models, the free parameter is the standard deviation of the Gaussian. It is not directly available for user experimentation, but is computed deep within the program to be a function of either the beam radius computed during the tracing or the range in wavelengths or $\pi\lambda$. There have been some attempts by mathematicians to derive a theoretical justification for these choices, but nothing rigorous has yet been proposed. The user can experiment with this free parameter to some extent by choosing different numbers of rays to compute, since that will change the beam radius. As mentioned in Section 1.2.1, the default number of rays was increased in the new web version of Bellhop (it is the square of the old value), perhaps in an attempt to provide more accuracy.

The sensitivity of this free parameter was investigated by comparing calculations using different numbers of rays in the Sable Bank environment at 512Hz (with a different sound speed profile than was used above). It was found that the larger the number, the more the TL level was decreased until it converged on a final solution. In Figure 29, the red curve is using the old default value of 280 rays. The green curve results from increasing the number of rays by a factor of 10 (2800) while 30 times the default value (8400) was required to achieve the dark blue result. Increases over that (10000) did not change the result.

The second case used the Q290 environment at 50 Hz, and changing N from the default 81 rays to 810, 2430, and 10000. The result in Figure 30 shows a rise in level when the default value is increased by a factor of 10, but there was no noticeable change at still higher numbers of rays.

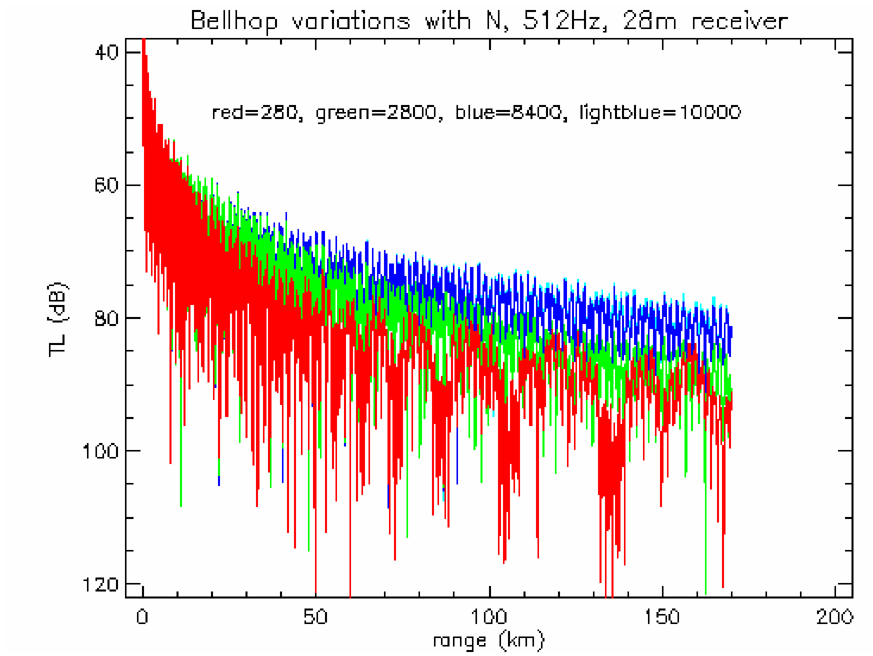

Figure 29. Variations in transmission lass with number of rays, for the Sable Bank environment at 512 Hz.

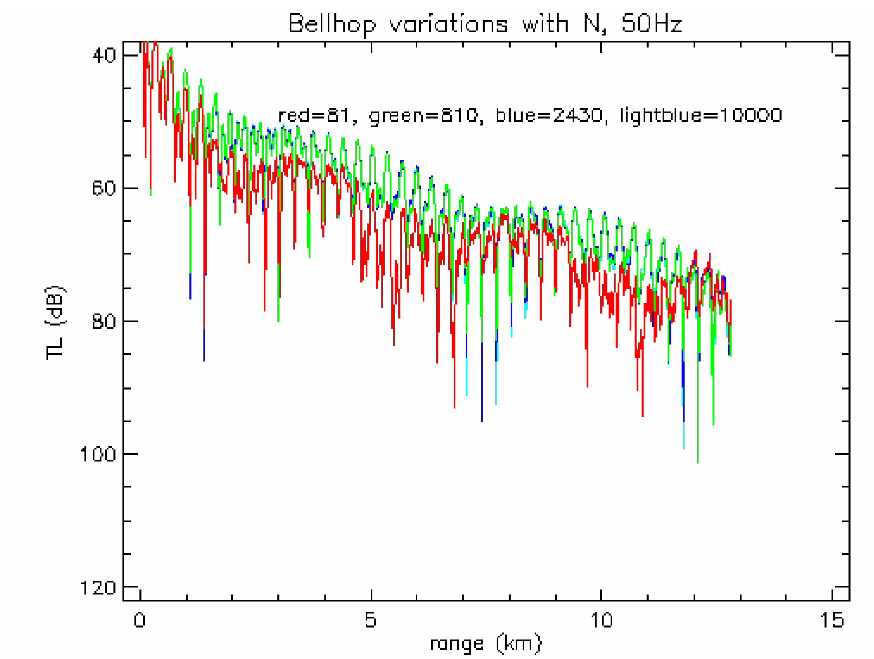

Figure 30. Variations in number of rays in Q290 environment at 50Hz.

At frequencies of 1000 Hz and above, there was no noticeable difference when N was increased above the old default value.

The increase in the number of rays actually affects the width of the Gaussian that defines the Gaussian ray technique. Thus, increasing the number of rays means that the spatial extent that each ray represents is decreased, theoretically making the result more accurate. However, there is always an upper limit to the accuracy than can be achieved by any technique, and we can see in the above figures that beyond a certain limit (10x or 30x) no change is found.

A better way to compute the number of needed rays does not exist at present. It is recommended that if the frequency is below 1000Hz, and if the user has the luxury of time, he should test his prediction by increasing the number of rays until the result approaches a limit that is independent of the ray number.

5. Coherent, Semi-coherent and Incoherent comparisons

In Bellhop, rays are traced out in range and the accumulated amplitude and phase along the ray path is stored. When the transmission loss is computed, these ray paths are assembled according to their position in the water column with respect to the range and depth of the moving point receiver. The coherent transmission loss output is obtained by adding all the amplitudes A_j and phases $\omega t_j - \varphi_j$ of the rays together in a complex storage array of pressure,

$$p = \sum_j W_j A_j \, e^{-i(\omega t_j + \varphi_j)} \tag{1}$$

weighted by the Gaussian amplitude factor W_j. The incoherent transmission loss comes from the sum of the squared amplitudes without regard to the phases and weighted by the Gaussian amplitude factor, in terms of intensity, $p^2 = \sum_j W_j A_j^2$.

The particular output in Bellhop called the semi-coherent transmission loss is given by the intensity

$$p^2 = \sum_j W_j S_j^2 A_j^2 \tag{2}$$

where S is a sinusoidal factor $S_j = \sqrt{2}\,\sin(\omega z_s \sin\theta_j / c)$ for the source depth z_s and launch angle θ_j. This is not really a Lloyd's Mirror factor because it does not decay with range.

In Figure 31, the four outputs are plotted from Bellhop at very close range using the "pond" (Figure 3) bathymetry at 250Hz. The coherent transmission loss is in black, the incoherent TL is in green, and the semi-coherent TL, as described in the equation above, is in blue. Note the small sinusoidal oscillations of the blue line with range about the green incoherent line. There has been some experimentation by changing the definition of the semi-coherent output. The orange line indicates a combination of coherent summations of all rays with just one bottom bounce or less added to the incoherent summation of all higher-order bounce rays. This result maps over the coherent output to the first 0.3km, then it oscillates with larger intervals until it eventually dies back to the incoherent result at about 40km. There appears to be no justification for using either form of semi-coherent output from a physics point of view, and so their use is not recommended at this time.

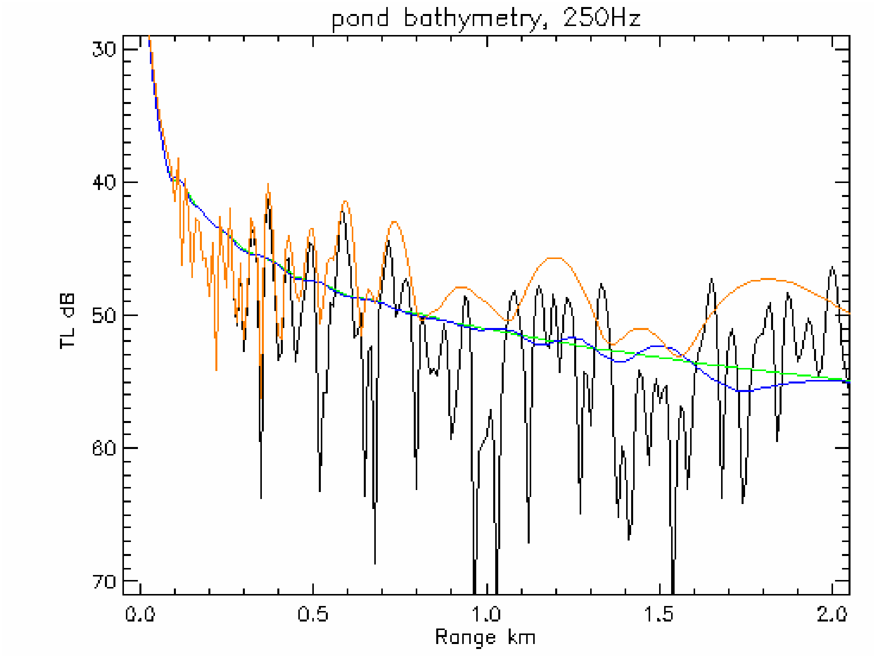

Figure 31. Coherent (black curve), Semi-coherent (blue and orange curves) and Incoherent (green curve) TL from Bellhop.

6. Range Dependent SSP

The problem of implementing range dependent sound speed profiles arises from how they will be interpolated over the intervening range. The latest web-based version of Bellhop provides for the input of multiple profiles with range – provided they are all defined at the same depths – and it linearly interpolates between each one. A question then arose as to whether there would be the same type of phase error at each change in SSP as was found when the bathymetry changed slope. Because the author's version of PECan does not handle multiple SSPs, this issue cannot be investigated further at this time.

However one can examine the general question of linear interpolation when the range change in the profile is a rise or fall of the axis of a duct. In Figure 32, four typical sound speed profiles from the Sable Bank area are plotted, with their ranges indicated beside each curve. Figure 33 shows a contour plot of the SSP as it would be computed inside Bellhop. The vertical lines indicate the ranges where the SSPs were defined. There is an error in the implementation of the interpolation in the current web-based Bellhop algorithm that causes it to continue to extrapolate beyond the last profile input, with rather large errors, in this case. The algorithm has been corrected so that now it produces an unchanging SSP beyond the last specified profile, as shown in Figure 34. To show what differences these make, Figure 35 presents a plot of TL in the Sable Bank area from 80 to 176km, using the four profiles shown in Figure 32. The incorrectly extrapolated plot (red) shows the TL being shifted upward by an RMS error of 7.9dB.

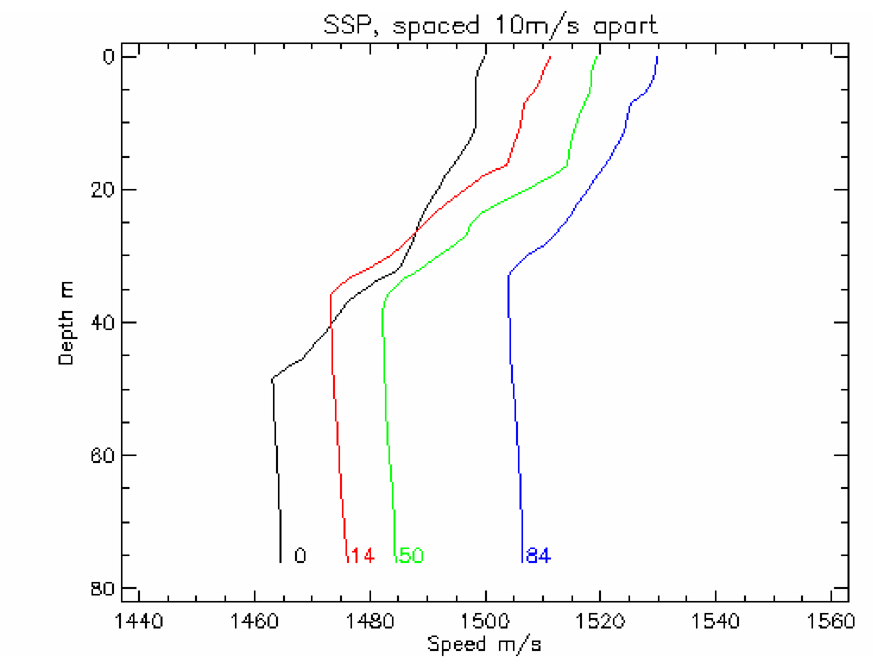

Figure 32. Four typical sound speed profiles with ranges noted.

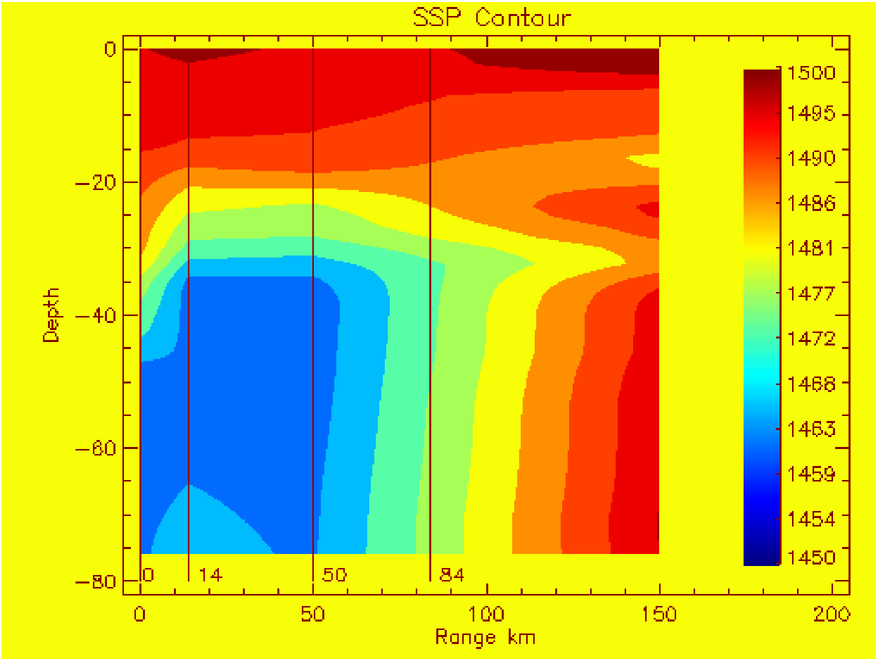

Figure 33. SSP interpolation and extrapolation in Web version of Bellhop.

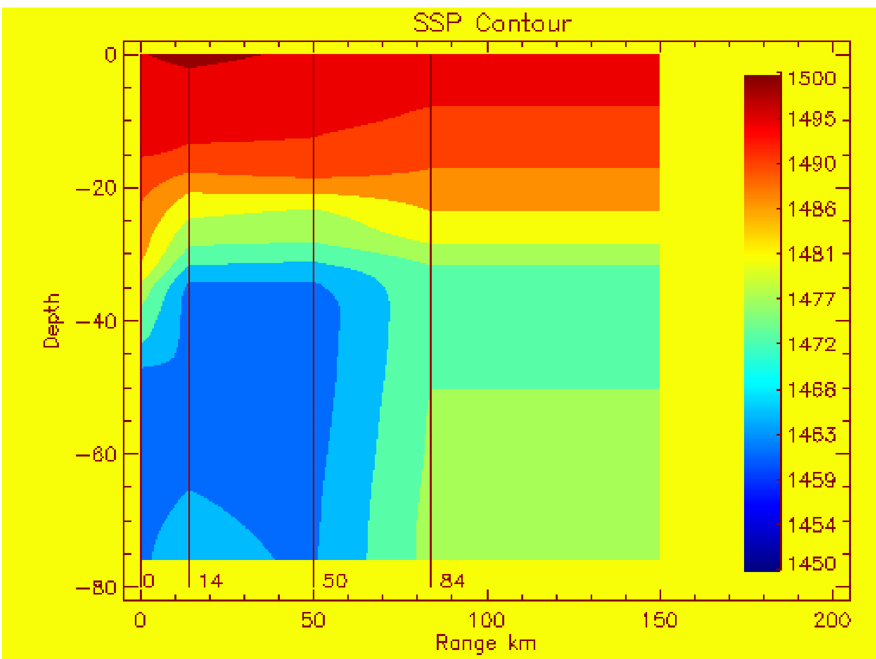

Figure 34.Corrected interpolation and extrapolation of SSP with range.

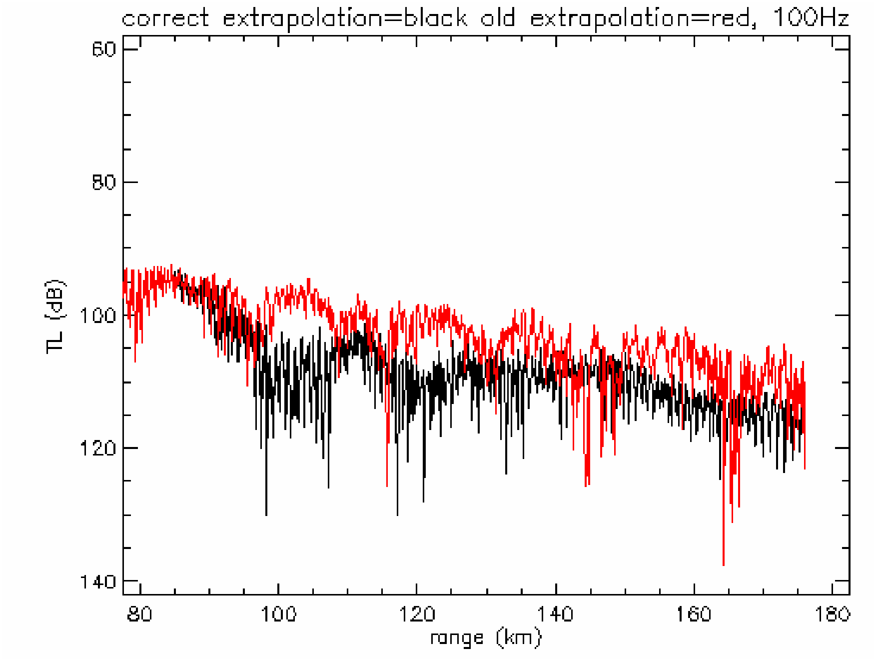

Figure 35. TL from two SSP extrapolations, detail from 80 to 176km.

7. Summary and Recommendations

This report has examined the phase discrepancy that the propagation engine Bellhop has exhibited when compared to the parabolic equation PECan over bathymetries that contain slope changes. It has been shown that a phase error exists, but it may not be damaging since the coherent phase oscillations normally present in typical ocean propagation problems tend to obscure any slight shifts in level and phase. The use of coherent range averaging, which is required for the PE in Naval applications such as TACAIDS, will, in Bellhop, smooth over any phase errors. Additionally, Bellhop can produce an incoherent output that will also smooth over any phase errors. The semi-coherent output offered by Bellhop is not based on any physics, and it is recommend that the user avoid it.

Although some large differences between the PE and Bellhop have been presented, it is uncertain whether they are truly an indictment of Bellhop or a function of the fundamental differences between the models for these difficult shallow water tests. The full extent of the discrepancy is not readily discernable by a simple comparison with the Parabolic Equation because there are potential differences in the employment of PE in shallow water, such as the treatment of the density discontinuity at the sediment interface, that may make the two models un-comparable. If we rely on the measured data to show Bellhop's phase failures, we also find difficulties because the measured data is spaced too far in range to show any phase discrepancies. And as far as low-frequency Bellhop weaknesses, in fact, in the Sable Bank and Emerald Basin cases presented, the range-averaged Bellhop was in quite good agreement, even as low as 50 Hz. Based on the evidence at hand, one should trust the comparison with measured data more than the PE comparisons.

Another issue examined was the number of rays to use in Bellhop. It was demonstrated that increasing the old default value by 10 times or more can, in some cases, change the result. It is recommended in the web-Bellhop instructions that the user experiment with the number of rays when using Bellhop to provide predictions. That is certainly to be recommended if the user has that luxury of time. Alternatively, one can de-facto increase the number of rays internally (simply raise the default value) for all applications, although there would be a run-time penalty. It is recommended that the present default value be used, and just encourage the user to experiment with it.

The newest version of Bellhop on the web contains a new algorithm for ray tracing. It was tested on the "Boris bug" (which is a ray tracing failure at high frequency discovered by a researcher at DRDC). Unfortunately, the new algorithm does not cure the 'Boris bug', while increasing the run-time. The resulting ray traces from the new algorithm seem identical to the old version's ray trace, therefore it does not appear to be worth the extra run time it consumes; it is recommended that the user stick with the current technique in BellhopDRDC.

The newest algorithm was examined for range dependent SSP interpolation and discovered that it was also extrapolating SSP's incorrectly downrange of the last input profile. A corrected interpolation code has been implemented.

To summarize the recommendations:

- Use Incoherent transmission loss in Bellhop whenever possible.
- Experiment with increasing the number of rays over the default value whenever possible.
- Stick with the current BellhopDRDC ray trace algorithm.
- Use the corrected interpolation for range-dependent sound speed profiles.
- Avoid model-to-model comparisons unless the two models are demonstrably using the same physics.

References

[1] Drs. Gary H. Brooke, Diana F. McCammon, Peter M. Giles and Stan E. Dosso, “Comparison between Bellhop and PECan for Range-Dependent Bathymetry: Errors Arising in Bellhop”, General Dynamics Contractor report under contract # W7707-06-3411/001/HAL, DRDC Atlantic, CSA: Dr. Sean Pecknold, March 2007

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Gaussian beam models such as Bellhop have demonstrated a discrepancy in level and phase that occurs whenever the bathymetry changes slope. This report has examined this discrepancy and attempted to determine its consequences for typical model usage. The effect of both simple geometric bottom contours and complex bathymetries taken from real environments have been analyzed, along with a comparison of the model against a parabolic model and experimental data. It is concluded that the model output using incoherent averaging would smooth out and cover most phase discrepancies and therefore is recommended for tactical decision aids and other standard Transmission Loss applications. This report has also examined other Bellhop inconsistencies that were evident in the newest World Wide Web version. These include an analysis of the updated formula for choosing the number of rays and providing recommendations. In addition, the new ray-tracing algorithm and the new interpolation between sound speed profiles have been investigated, resulting in a correction to the method of extrapolation when multiple sound speed profiles are specified.

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