Closed-form and Numerical Reverberation and Propagation: Inclusion of Convergence Effects

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LONG-TERM GOALS

The flux formulation of propagation has already been used to calculate bistatic, range-dependent reverberation, target echo, and signal excess very efficiently in a model developed by Harrison called Artemis. This model is used in the operational planning aid MSTPA at CMRE. Propagation in this formulation behaves like acoustic energy flux and falls off monotonically with range. The goal of the ONR-funded work is to improve the propagation accuracy by including convergence and focusing effects in a range-dependent environment without compromising the simplicity and efficiency of the approach.

OBJECTIVES

The objective has been first to write out the theory for the range-independent case, i.e. start with the modulus-square of the coherent mode sum and reject rapidly oscillating terms to leave fluctuations on a scale of a ray cycle distance. These formulations have been evaluated in Matlab and compared with each other and with runs of other well-established models, in this case the normal mode model Orca. In the second part of this work the theory is extended to range-dependnet environments and to include reverberation. The final goal is to document the work and supply updated code for the Artemis model.

APPROACH

The flux method is exactly equivalent to an incoherent mode sum with only the smooth amplitude of WKB modes and a high mode density (i.e. treated as a mode continuum). One can start the derivation instead with the modulus-square of the coherent mode sum but retain some of the cross-terms instead of rejecting them all, as in the incoherent sum. It can be shown that the ray cycle distance is related to the difference between adjacent mode eigenvalues, so retaining just these terms adds a ray convergence peak structure to the otherwise monotonic decay. This theory with some examples was documented in Refs 1 and 2.

The major task now is to extend this theory to operate in range-dependent environments, to include reverberation, and finally to embed it in the model Artemis.

WORK COMPLETED

In the first year several approaches were developed for rapid calculation of propagation in a range-independent environment. The task completed in 2012 was:

Subask 1 - *Extend the theory of the energy flux solutions to include convergence effects.*

In addition, the theory, comparisons, and findings were documented in a CMRE report and published in a JASA paper (see Publications).

During 2013 the propagation and bistatic reverberation theory has been extended to range-dependent environments. This has been incorporated in a version of Artemis which underwent tests and comparisons by the author and also by the MSTPA team at CMRE.

Subtask 2 - *Develop an efficient numerical scheme for evaluating the fluctuating part of the propagation intensity corresponding to this convergence*

Part of this effort involved improving the scheme for the existing flux version of Artemis.

Subtask 3 - *Extend the scope of the numerical model ARTEMIS (fast reverberation, target echo, and signal excess for arbitrary environments) to include convergence effects in* [*range-dependent*] *monostatic and bistatic target echo and reverberation calculations.*

A new version of Artemis including convergence effects exists and some examples are shown below.

Subtask 4 - *Test the results against known solutions supplied by K. LePage (CMRE/NRL), P. Nielsen (CMRE).*

A number of tests against independent models have been completed but these are ongoing. A further CMRE report on range-dependence and reverberation and the Artemis implementation is currently in draft form.

Subtask 5 - *Feed the extensions of the flux approach into the US's operational reverberation models through Charles Holland (Penn State).*

A copy of Artemis and documentation has been handed over to CMRE (MSTPA team) and to Charles Holland.

RESULTS

In Subtask 1 the mathematics was successfully developed into three efficient approaches for calculating one-way propagation each of which was implemented in Matlab, and all were favourably compared with each other in several environments. Figure 1 [a copy of Fig 6 from Harrison (2013)] demonstrates the accuracy of this approach in a range-independent upward refracting environment by comparing results with the wave model Orca.

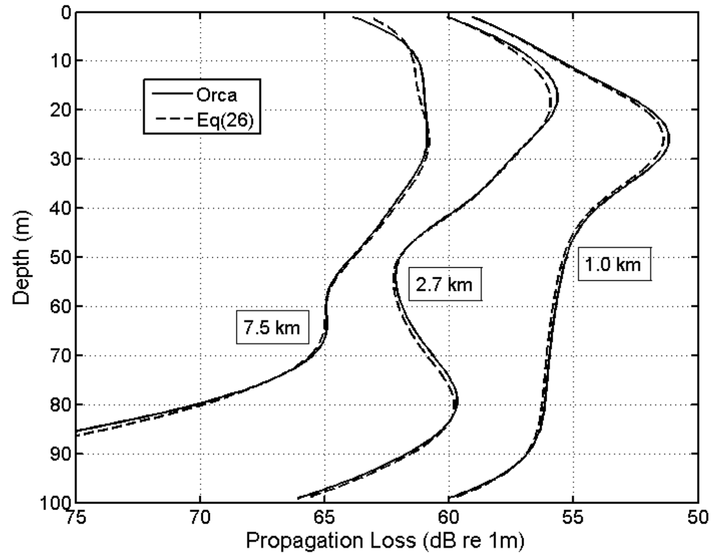

Fig. 1: Comparison with Orca of range-averaged propagation loss vs depth at selected ranges in an upward refracting stratified environment [taken from Fig 6 of Harrison(2013)].

It was pointed out in refs 1 and 2 that the existing flux integrals (over angle) are modified by the simple insertion of an extra convergence term. In the range-dependent case no change is required to the boundary loss calculations, but the convergence term needs to account for the slowly changing complete ray cycle distance, and the partial cycle distances are evaluated only at the source and receiver locations. Together they operate like a variable wavelength and phase offsets to the ray cycling. The detailed changes to be applied to the theory in order to allow for range-dependence and reverberation are discussed in Ref 3. These changes have now been incorporated in a version of the Artemis code and have undergone tests.

However an additional complication in the coding for a range-dependent environment is that the wavenumber interpolation that is essential in the original flux approach can lead to erratic behaviour of the final intensity integral. A way round this has been found by careful choice of the set of wavenumbers (or angles) in relation to source depth, receiver depth and turning point depth.

The plot format of Refs 1 and 2 (i.e. propagation intensity (or loss) vs. depth and range) is a useful diagnostic, but Artemis is not designed to produce them since one of its advantages is that it does not require accurate calculations at intermediate points between source and receiver (or source and target). However since it already caters for an arbitrary set of target depths at each range it is possible to do the calculations with the actual Artemis code though with plotting code added as a diagnostic. The plots below were done in this fashion.

Convergence examples using modified Artemis implementation

- ***Range-independent refracting duct***

Figure 2 shows a range-independent refracting duct similar to those shown in Refs 1 and 2. It merely demonstrates the old maths but implemented in Artemis.

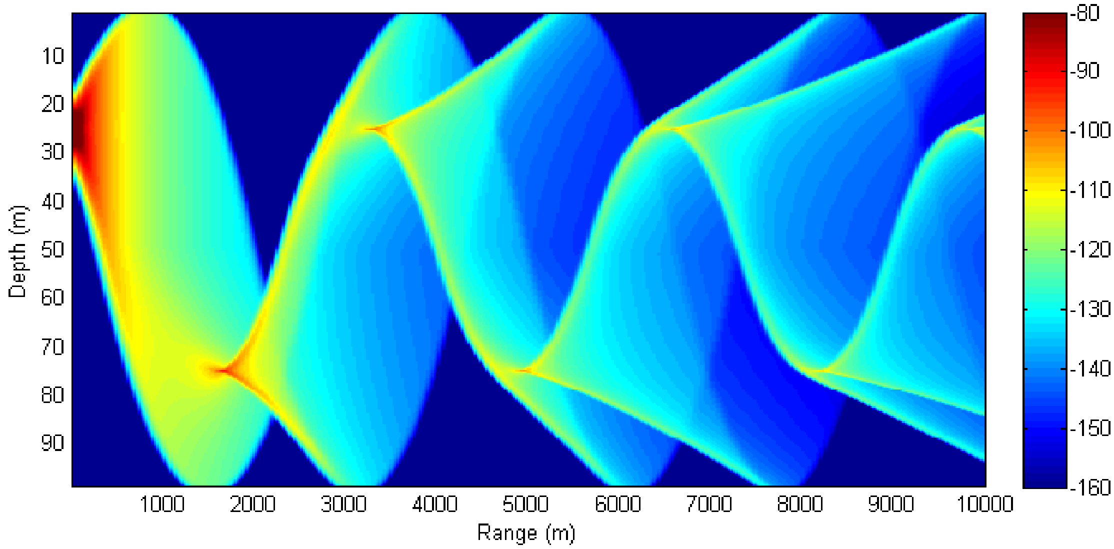

Fig. 2: Range-independent refracting duct

- ***Downslope with downward refraction***

Figure 3 shows a downward refracting (linear) profile with 25m source on a shelf followed by downslope bathymetry where ray arcs follow the bottom, as expected. In tests it is possible to select (a) waterborne paths only or (b) all paths. Also one can show the effect of reverting to flux, as in Fig 3(c) (waterborne paths only), by simply taking out the convergence factor.

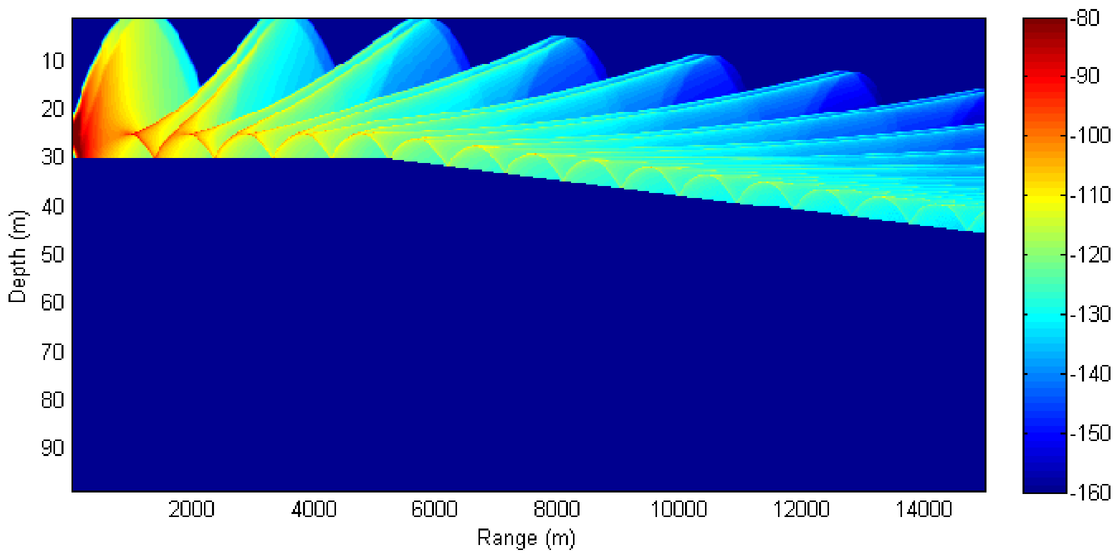

Fig. 3(a): Downslope with downward refraction – waterborne paths alone

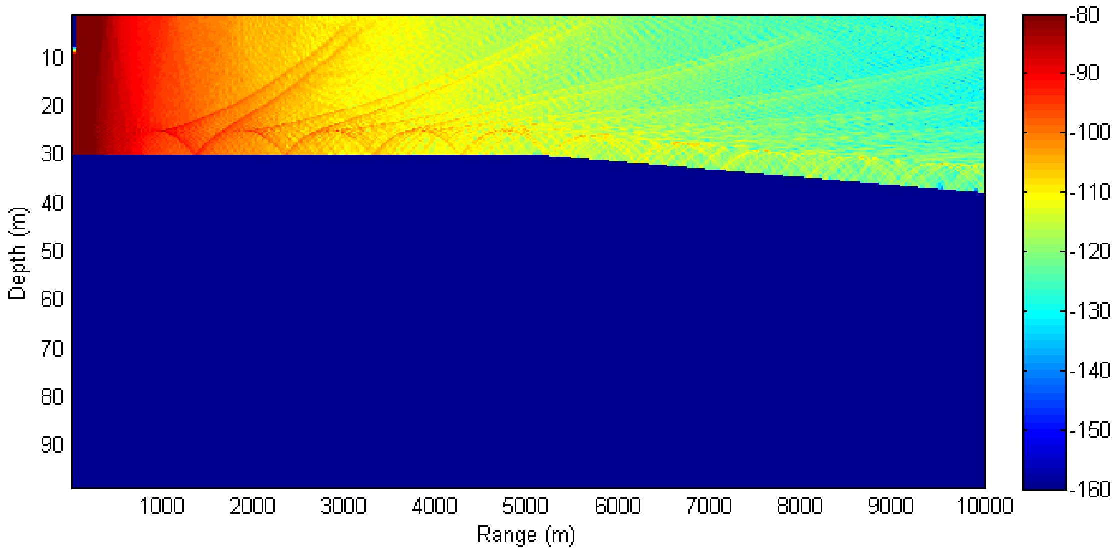

Fig. 3(b): Downslope with downward refraction –all paths

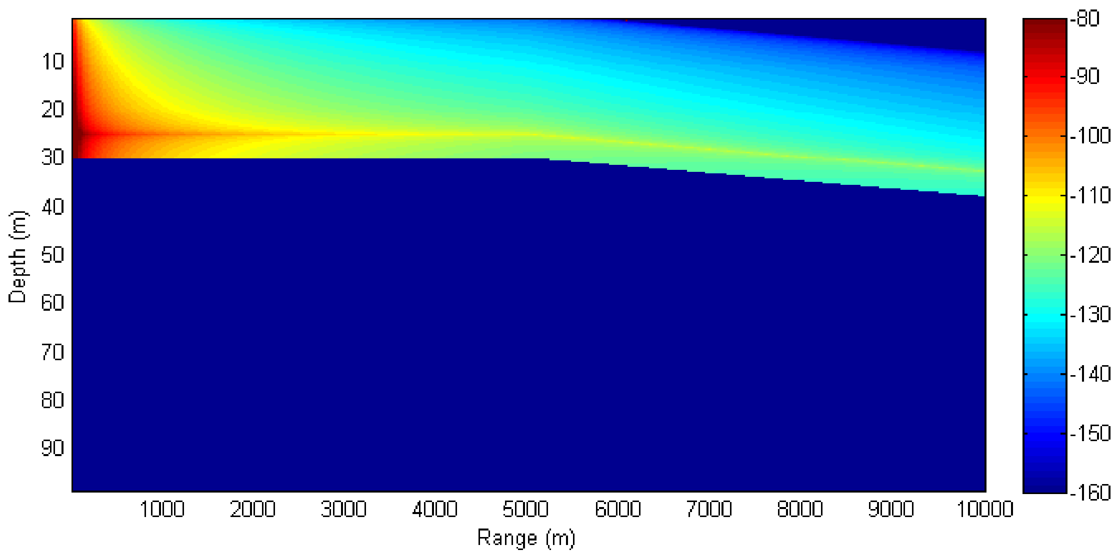

Fig. 3(c): Downslope with downward refraction – flux

- ***Downslope with fixed SSP ('V'-shaped refracting duct)***

Figure 4 shows a shelf with steeper slope and a symmetric 'V'-shaped profile centred on 50m. The caustics are seen to settle into a pair of conjugate depths in deep water (Fig 4(a)). Figure 4(b) shows all paths, and Fig. 4(c) shows surface and bottom reverberation. The propagation in Fig 4(b) shows why the surface reverberation falls off slightly more quickly than the bottom reverberation. The flux plot (Fig. 4(d), waterborne paths only) makes an interesting comparison with Fig. 3 (c).

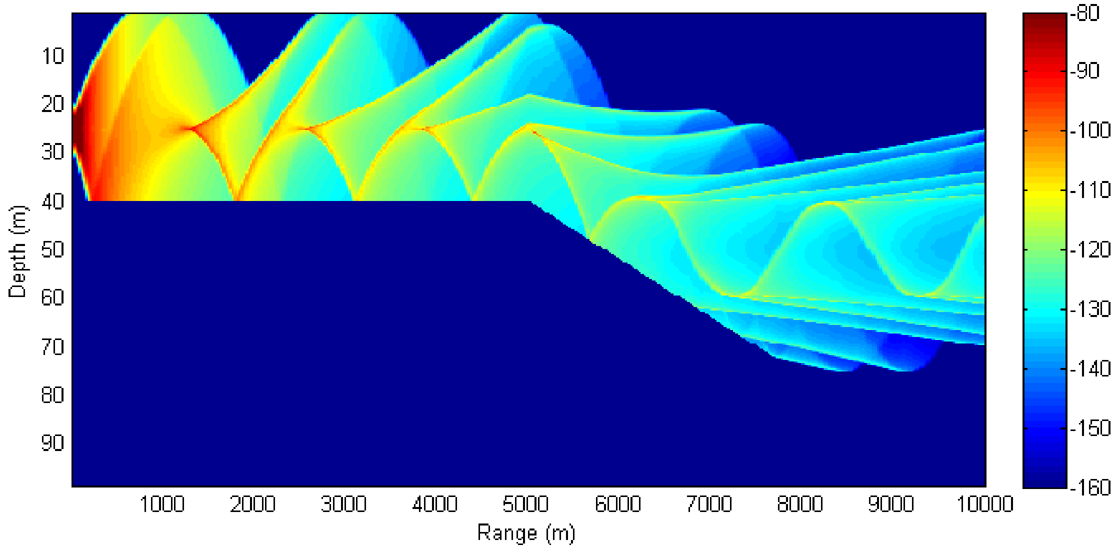

Fig. 4(a): Downslope with fixed SSP ('V'-shaped refracting duct) – waterborne paths

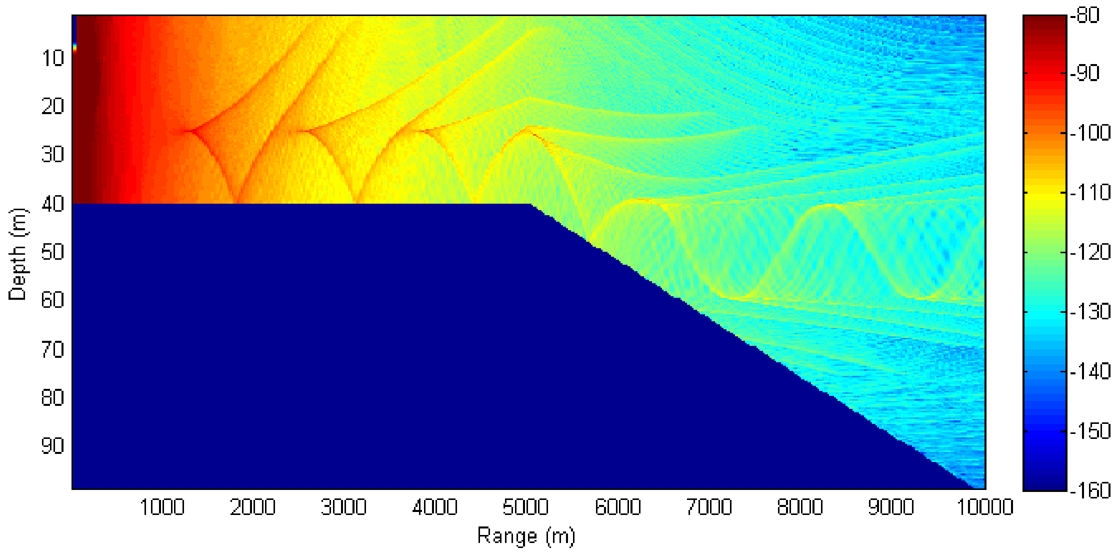

Fig. 4(b): Downslope with fixed SSP ('V'-shaped refracting duct) – all paths

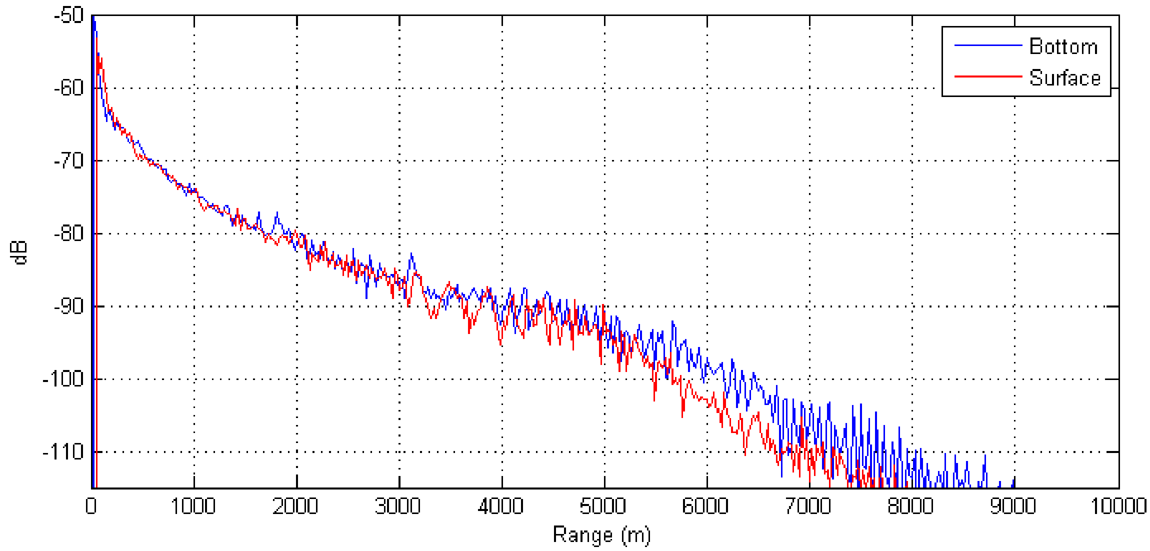

Fig. 4(c): Downslope with fixed SSP ('V'-shaped refracting duct) – bottom reverberation (blue), surface reverberation (red)

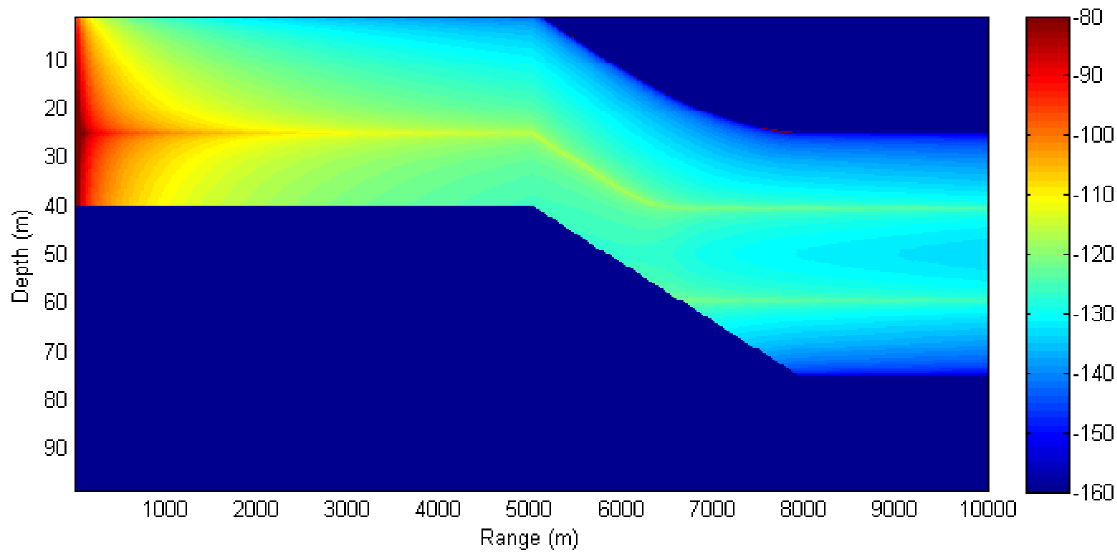

Fig. 4(d): Downslope with fixed SSP ('V'-shaped refracting duct) – flux

- ***Ridge with fixed SSP ('V'-shaped refracting duct)***

Here the shelf is replaced by an upward slope forming a ridge, retaining the same 'V'-shaped SSP. Figure 5(a) shows waterborne paths, and (b) shows all paths. Figure 5(c) shows the corresponding reverberation. Note the drop-outs on the far side of the ridge caused by a limited set of rays being able to cross the ridge.

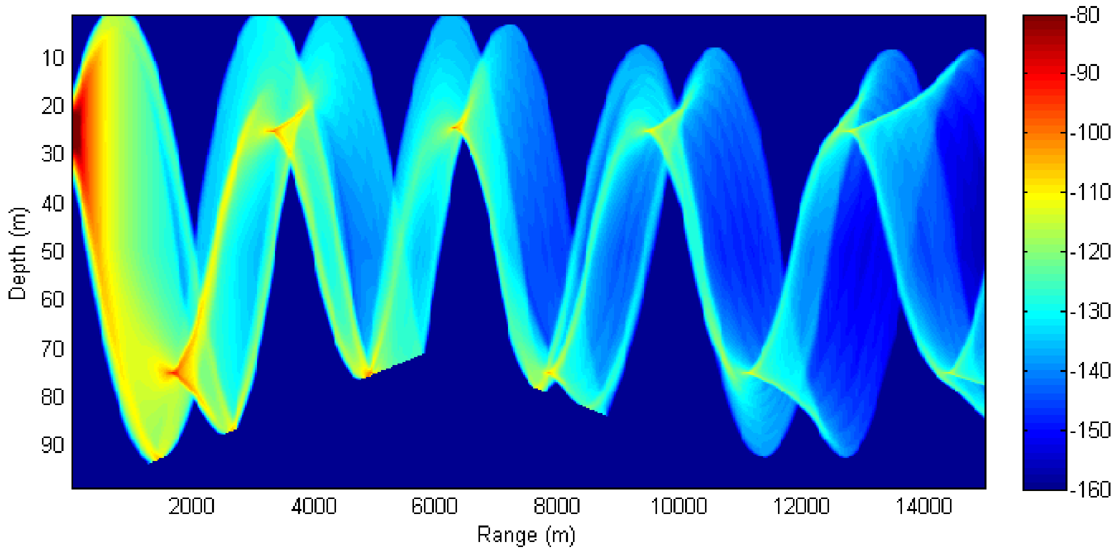

Fig. 5(a): Ridge with fixed SSP ('V'-shaped refracting duct) – waterborne paths

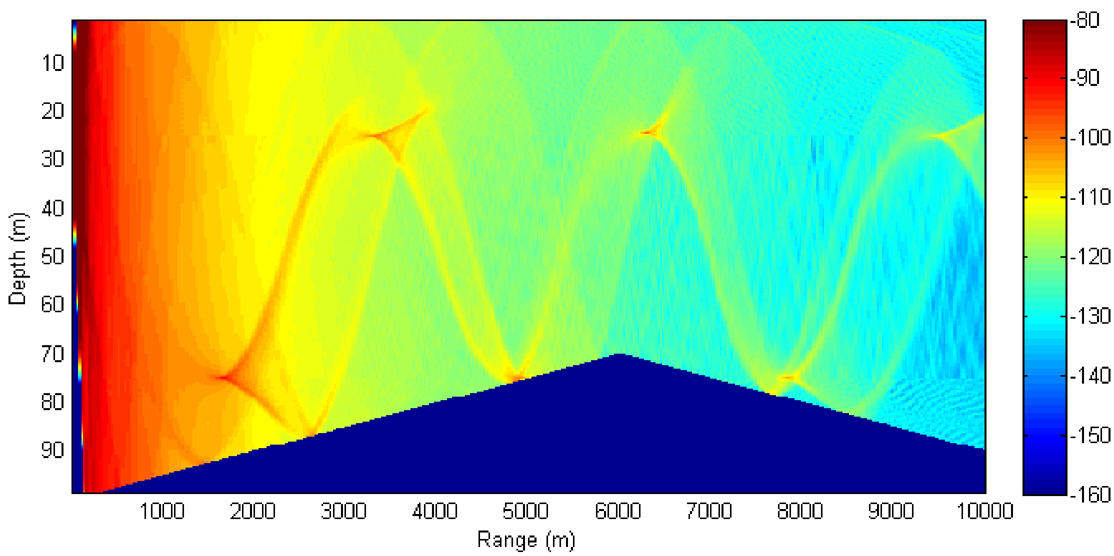

Fig. 5(b): Ridge with fixed SSP ('V'-shaped refracting duct) – all paths

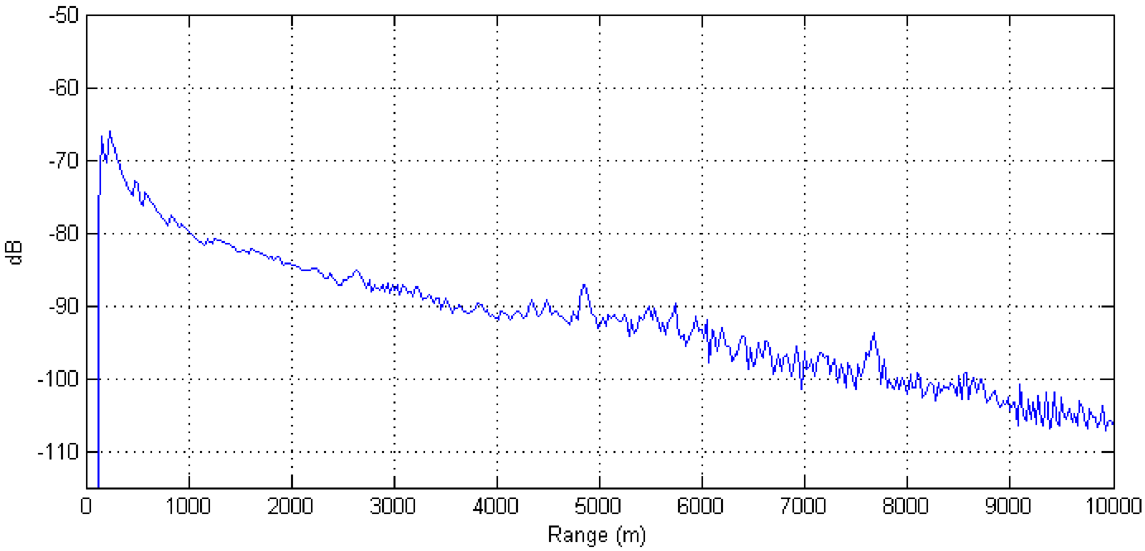

Fig. 5(c): Ridge with fixed SSP ('V'-shaped refracting duct) – bottom reverberation

- ***Fixed water depth with varying SSP***

In Fig 6 there is a 'V' shaped SSP of [1500 1498 1500] m/s on the left, increasing in contrast to [1500 1496.8 1500] m/s on the right. Energy is squeezed into a narrower depth range.

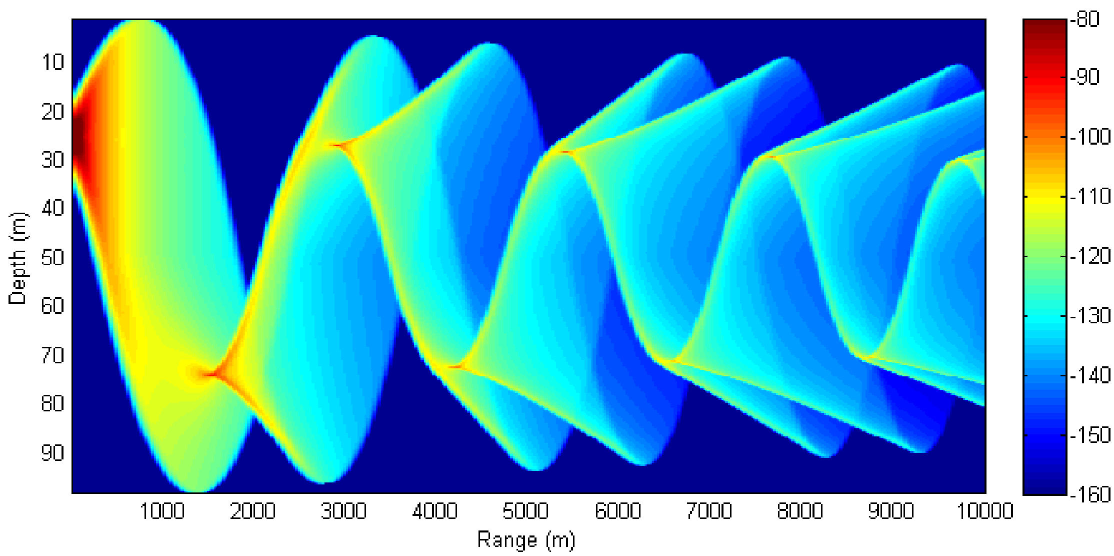

Fig. 6: Fixed water depth with varying SSP

- ***SSP squeezed to varying water depth***

Here the water depth reduces from 100m at left to 80m at right, and the SSP is squeezed (but with the same sound speed values) in the same ratio. The ray turning points can be seen to shift in depth in a corresponding fashion.

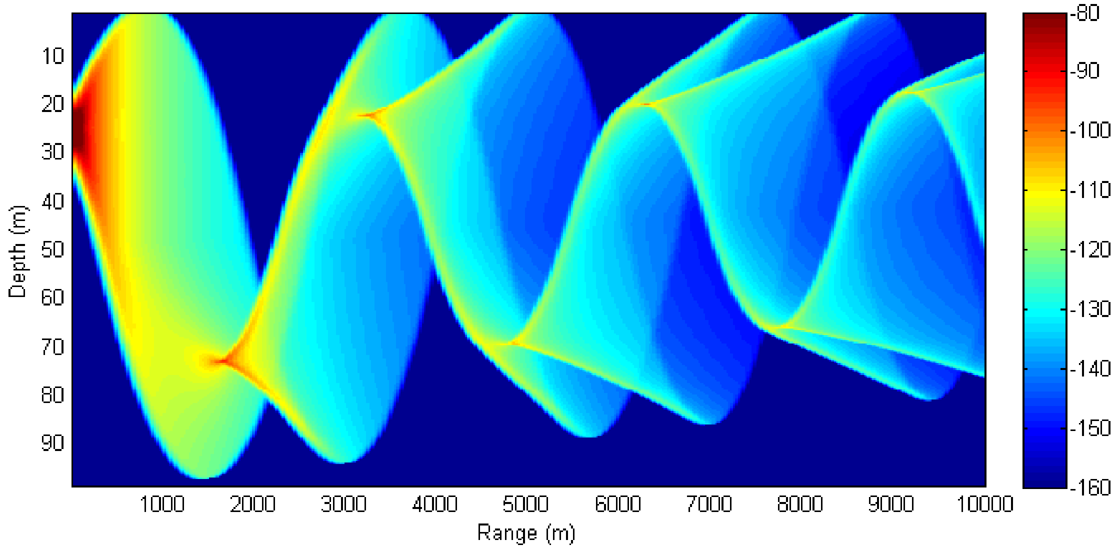

Fig. 7: SSP squeezed to varying water depth

IMPACT/APPLICATIONS

The potential and existing Naval application of this work is in fast operational sonar models, operational assessment, sonar assessment, tactical decision aids, operational planning aids. The sonar performance model Artemis is embedded in the operational planning tool MSTPA and handles propagation and reverberation in a general environment but, to date, is restricted by using the energy flux formulation of propagation which ignores convergence effects. The scope of MSTPA will be greatly increased by allowing realistic modelling of the convergence leading to caustics in deep or shallow water, and above all, without compromising computational efficiency.

PUBLICATIONS

1) C H Harrison, "Retrieving ray convergence in a flux-like formulation", Centre for Maritime Research and Experimentation Technical Report, CMRE-FR-2012-006, NATO Unclass, October 2012.

2) C H Harrison, "Ray convergence in a flux-like propagation formulation", J. Acoust. Soc. Am., **133**, 3777-3789, (2013).

3) C H Harrison, "Propagation and bistatic reverberation with convergence in a range-dependent environment (?)", Centre for Maritime Research and Experimentation Technical Report, CMRE-FR-******, ***.