SUPREMO: A Multistatic Sonar Performance Model

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ABSTRACT

The threat posed by diesel-electric submarines remains significant, especially in shallow littoral waters. The detection capabilities of existing passive sonar sensors are limited by the low levels of radiated noise from modern submarines. Detection using existing active sonars is difficult, especially in littoral waters, because of the low target strengths of modern submarines and high levels of scattering from features such as wrecks and rocky outcrops on the seabed.

An attractive solution to the problem of submarine detection in littoral waters is offered by the use of multistatic sonar systems in which a diversity of source and receiver locations is used. This approach increases the possibility of obtaining a high-amplitude reflection, or 'glint' from a target. Furthermore, the use of many receiver locations increases the number of detection possibilities and offers a reduction in false alarms and improvements in tracking.

The NATO Undersea Research Centre at La Spezia has a programme of research directed at producing prototype multistatic sonar systems and demonstrating their capabilities. To optimise experimental design and interpret measured data, some method of predicting system performance is required but the complexity of multistatic sonar makes this a difficult problem. SUPREMO, a model for the prediction of the performance of multistatic sonar systems, has been developed at the centre and is described with details of its novel features given. Model validation via comparison with reference solutions is reported and comparisons between model predictions and measured data are discussed.

1.0 INTRODUCTION

NATO's undersea research centre, SACLANTCEN, has an ongoing programme of research in the area of multistatic sonar for ASW in littoral waters. Part of this programme involves the development of SUPREMO, a computer model for the prediction of the performance of multistatic sonar systems.

SUPREMO [1] is designed to take advantage of the best available propagation models and databases. It calculates seabed reverberation, sea surface reverberation, direct blast between bistatic source/receiver pairs, ambient noise and target echo level. These can be combined at the display stage of the model's operation and viewed individually or in combination. Total intensity received can be displayed to simulate the data received by a sonar or signal-to-noise ratio calculated and displayed.

A considerable amount of the model's computational effort is directed towards the calculation of bistatic reverberation. In the context of the model, "reverberation" refers to random, diffuse reverberation and the

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model makes no attempt to predict features beyond the total reverberation intensity. Descriptors such as reverberation coherence and statistics are not considered. The model can include the presence of seabed scatterers that might act as false targets and echoes from these are calculated in the same way as echoes from actual, mid-water targets.

SUPREMO's calculations finish with the production of predictions of reverberation, background noise, echo level and consequently signal-to-noise ratio. The model does not include calculations of detection threshold. The "noise" referred to in "signal-to-noise ratio" here is the sum of surface reverberation, seabed reverberation, ambient noise and direct blast.

While the model is initially being designed to satisfy the requirements of SACLANTCEN's own research programme, it may be released to NATO nations in the future. Model run times on a standard desktop PC can be as low as a minute or less for reasonable numbers of sonar platforms and targets.

The operation of the model is now described and some examples of its output are given.

2. MODEL OPERATION

SUPREMO uses existing state of the art propagation models and environmental databases and is modular in structure so that future improvements in, for example, propagation models can be incorporated with minimal impact on the structure of the model (Figure 1).

After extracting the relevant environmental information from the chosen data source, the model calculates acoustic arrivals at all relevant scatterers from all source and receiver platforms. In the context used here, "scatterer" refers to environmental features such as the seabed and sea surface. Acoustic arrivals describe the incident field at a scatterer in terms of arrival intensity, arrival angle and travel time. While it is easiest to think of arrivals in terms of individual ray paths between platform and scatterer, research carried out under the SUPREMO project has shown that such a description can also be produced using propagation models based on normal modes [2]. As such, SUPREMO is neither a "ray model" nor a "mode model" and simply requires a propagation module that produces acoustic arrivals.

Acoustic arrivals are used to calculate the intensity measured at each receiver from all scatterers due to transmissions made by all sources. This calculation can be computationally intensive and for range-independent environments it is the dominant factor in determining run time. For this reason, SUPREMO includes a series of novel features [1] designed to minimise the effort required for this calculation. For example, scatterers located on the seabed are distributed evenly, not in latitude and longitude but in travel time and bearing, as measured at the receiver (Figure 2). This ensures that the number of scatterers used is as small as possible while avoiding unrealistic gaps in predicted values of intensity versus time and bearing. Uniform distributions of targets in latitude-longitude can only avoid such gaps by using a considerably higher number of scatterers. Although this approach requires the re-calculation of scatterer distributions for each source-receiver pair, the gains in efficiency associated with the reduction in scatterer numbers have been found to outweigh this factor. This is, in part, because SUPREMO's use of interpolation over range of acoustic arrival properties means that propagation calculations do not have to be re-done when scatterer locations are changed.

The arrival intensities as a function of bearing and time calculated for each receiver are stored in a single matrix with a user-specified number of bins in time and angle. Provided that a sufficiently large number of scatterers have been used, the correct levels of intensity in each time-bearing bin can be calculated by this method without the calculation of the scattering area associated with the bin. Bins with larger areas simply have more scatterers contributing to the intensity within them and consequently contain higher final intensities.

A matrix of intensity in time-bearing bins represents a form of impulse response function with individual arrivals having an intensity amplitude but infinitely small duration in time. Before a realistic picture of the signal received can be produced, some post-processing in time must be performed. This is achieved in SUPREMO by convolving the “impulse response function” at the receiver with the envelope of the transmitted pulse, after replica correlation (Figure 3). This results in a smearing of arrivals over time and accurately takes into account the effects of finite transmission bandwidth. Similarly, post-processing in bearing is required to introduce the effects of finite array length, i.e. finite beam width. This is efficiently achieved in SUPREMO for line arrays by the ordering of bearing bins such that they cover equal steps in the sine of the bearing angle, measured from broadside to the array. This ordering means that beamforming can be carried out using FFTs with associated high speed of calculation.

After post-processing, the resulting arrays of intensity versus time and bearing are simulations of the basic output of a sonar that might be displayed on a screen to an operator. SUPREMO can also display the same data on geographic axes, i.e. as a function of latitude and longitude. This feature is particularly useful with bistatic geometries where the non-unique relation between travel time and range from receiver makes difficult the interpretation of data displayed on time-bearing axes.

An important factor in the design of deployment patterns for multistatic sonars is the need to minimise the impact of mutual interference. Transmissions made by one source may mask echoes from a previous transmission that would otherwise have been received. Usually, this effect would be avoided by spreading transmissions in time and frequency, i.e. by scheduling transmissions and spreading signals across the frequency band available. SUPREMO allows mutual interference to be investigated by giving the user the option to display the intensity received on a single receiver from all transmissions. Such a plot on geographic axes indicates which areas of the region under investigation would be masked by mutual interference.

SUPREMO calculates the result of a sonar using a specified matched filter, receiving a signal that does not match the filter. In this way it allows the quantification of measures that might be taken to reduce mutual interference by spreading transmissions over the available frequency band. This may be an important factor because a direct blast from a mismatched transmission may still result in the masking of weak echoes from the transmission matched to the receiver’s filter.

SUPREMO can handle targets in either high detail or as a grid of simple targets. In the first approach, the propagation module calculates propagation to specified target locations from all source/receiver platforms with the user allowed to specify the number of multipaths. In this approach, targets can be described as a cylinder with hemispherical end caps of user-specified length and radius. Simple geometric calculations are then used to predict target strength as a function of incident and outgoing angle. Alternatively, but still using the high level of detail, a user-specified file of target strength versus incident and outgoing angle can be used to calculate the strength of the echo. Both these methods require that the user specify the target heading. The high-detail calculations put the echo intensity from all targets as a function of time and bearing into a matrix similar to the one used for reverberation. This allows a simulation of the intensity received on the sonar in the presence of targets, including time smearing (due to both finite signal bandwidth and environmental multipaths) and bearing smearing due to finite array length (Figure 4).

Gridded targets use a necessarily lower level of detail and are simple point targets with single target strength. Echoes from these targets are calculated in a manner similar to that used for reverberation, with targets distributed evenly in time and bearing for each source-receiver pair. The resulting echo intensities cannot be displayed as a simulation of what might be received on a sonar unless the user feels that it is realistic to expect a grid of such targets to actually be present in the ocean! Instead, the calculated echo levels can be combined with reverberation predictions on geographic axes to give signal-to-noise ratio estimates as a function of target latitude and longitude. This type of plot is quite different from a plot of predicted echo and reverberation on geographic axes using the high-detail target description. The latter is a simulation of what might be received on a sonar. The value displayed at a particular position for gridded targets is the peak value of SNR that would be received if a target were present at the position and no other. As such, the plot includes many, single target locations all on the same plot (Figure 5).

Throughout SUPREMO's calculations, the user is given control of factors such as the density of seabed scatterers, maximum number of multipaths and the extent of interpolation used. This is done so that the user can control the trade-off between model fidelity and run time. High scatterer densities and many multipaths lead to results including much detail but require more computation time than calculations with lower densities and fewer multipaths. The user control over these model parameters allows SUPREMO to be used by those interested in very rapid calculations or those for whom a high-fidelity result is important. In this way the model will be suitable for use by a wide spectrum of users from spheres such as operation analysis and sonar performance prediction.

SUPREMO has the ability to accept either range-independent or range-dependent descriptions of the environment and this choice has a major impact on program run times. The inclusion of range dependence in seabed scattering strength does not require the use of a range-dependent propagation model and this parameter can be made range dependent with no impact on run time. All other parameters, if allowed to vary with latitude and longitude, require the use of a range-dependent propagation model. This generally increases the time taken for a single run of the propagation module because propagation models that include range dependence tend to be slower than those that do not. For the two models currently used within SUPREMO (GAMARAY for range-independent environments and GRAB for range-dependent) this can lead to a factor of up to ten increase in run time.

For a range-independent environment, a single run of the GAMARAY model can be used to determine the arrivals at a receiver from all scatterers after transmission by a source. However, if the environment varies with position, many such runs are required. The actual number of runs is given by the product of the number of platform positions and the number of radials traced from each platform to cover the full 360 degrees of azimuth. Thus, the total increase in run time when changing from a range-independent to a range-dependent environment for a ten-platform system with sixteen azimuthal radials used would be a factor of 1600.

This increase is unavoidable if full range-dependent calculations are required but is likely to be prohibitively high for some, if not all, users. There is therefore advantage to be gained if a method could be developed whereby some of the most important effects of range dependence could be included while still using range-independent propagation calculations. This is an area of ongoing research but one method that has been developed simply modifies incident angles of acoustic arrivals by the local seabed slope. In this way, enhanced reverberation is associated with regions in which the seabed slope is high.

This approach contains an inconsistency in that the seabed slope is used to modify reverberation but not propagation angles. It should, however, provide a reasonable solution for gently range-dependent environments.

3. MODEL VALIDATION

Predictions of reverberation made by the model have been compared [2] with reference solutions and analytic formulae [3]. These comparisons have shown good agreement and validated the core calculation scheme of the model (Figure 6). Future comparisons with reference solutions and analytic formulae will be carried out in bistatic geometries.

While comparison with reference solutions and analytic formulae is a good first step in the process of validating a sonar performance model, final validation must compare model predictions with experimental data. Ideally, this process would take predictions made by the model using the best available environmental data and compare them with measurements made in the area covered by the environmental data. However, it is widely accepted [4] that existing databases of environmental information are of insufficient quality to allow this comparison process to quantify model validity. Instead, differences between predicted and measured performance are most likely to stem from inadequacies in the environmental input information. Therefore, the major problem to be solved before meaningful model versus measured comparisons can be carried out is the acquisition of sufficiently detailed environmental data in experimental areas. An approach has been developed [5] that attempts to fill this gap by deriving environmental data from the reverberation measurements themselves and initial results of this limited but useful method are shown in Figure 7. The figure shows that the model predictions of reverberation agree reasonably well with measured data, both qualitatively and quantitatively.

4. POST-RUN ANALYSIS TOOLS

The core calculations performed by SUPREMO finish with predictions of intensity and, consequently, signal-to-noise ratio. However, potential users of the model may require further processing to produce, for example, probability of detection or area coverage plots. Such calculations can be performed using SUPREMO results by MATLAB programs run during a SUPREMO session. Because SUPREMO is run from MATLAB, all the sonar and environment variables are available for use and can be passed to user-written routines to produce higher-level measures of sonar effectiveness or performance.

Figure 8 shows the results of one such routine that takes the SUPREMO signal-to-noise data for gridded targets and applies a threshold, in this case 10dB, to give a “cookie cutter” detection value. That is, any location where the signal-to-noise ratio is greater than the threshold is taken to indicate detection and any location where it is below the threshold indicates that the target would not be detected. The figure shows three separate signal-to-noise ratio plots for three receivers with a common source. The figure also includes a plot of the number of receivers that cover each position in the area of interest. The region around the source is shown to be multiply covered while large areas around each receiver are singly covered.

5. SUMMARY

The SUPREMO model predicts the intensity of reverberation, direct blast, ambient noise and target echo for multistatic sonar systems. It achieves this using existing propagation models and databases and can accept range-dependent or range-independent descriptions of the ocean environment. Targets can be described either singly in high detail including broadside glints, or as a grid of point-like targets with a single target strength. Intensities can be displayed singly or as a combined signal-to-noise ratio. Validation of the model has taken the form of comparison with reference solutions and measured data and agreement so far has been good. The usefulness of comparison with measured data, however, is severely restricted by the poor quality of environmental description data that is generally available.

REFERENCES

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[4] Ferla CM., Jensen FB. “Are current environmental databases adequate for sonar predictions in shallow water?” Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance. Pace NG and Jensen FB (Eds.) Kluwer 2002.

[5] MK Prior, “Reverberation Model Validation Using Measured Data”, To be presented at ECUA 2004, Delft, The Netherlands.

FIGURES

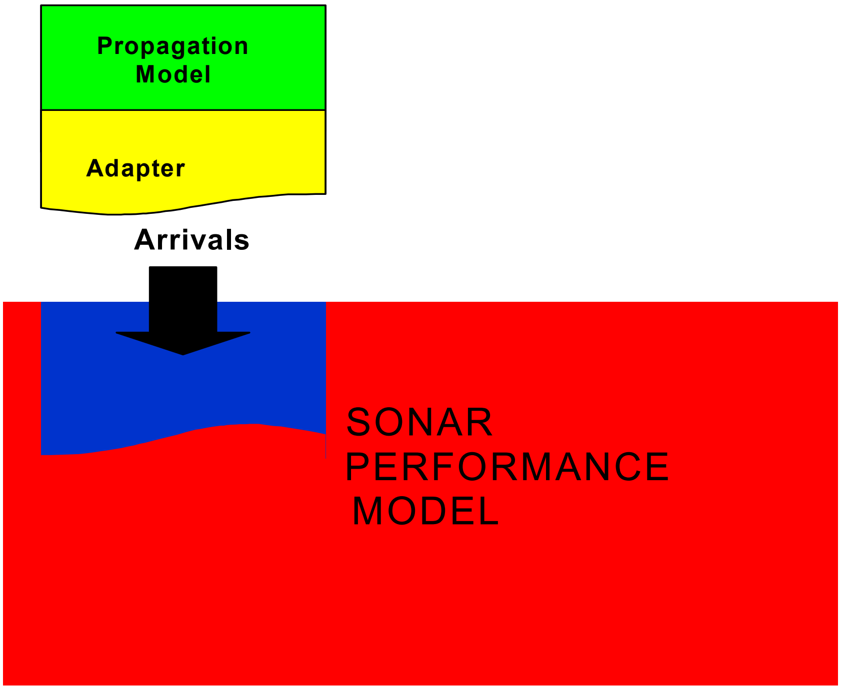

Figure 1. Schematic representation of modularity of propagation algorithms in SUPREMO. Any model can be used, when fitted with a suitable adapter to convert its output into acoustic arrivals

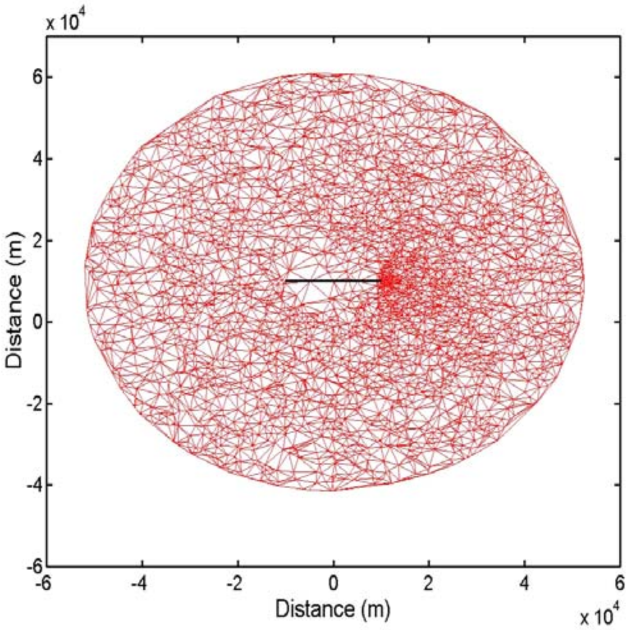

Figure 2. Scatterer locations for one source-receiver pair. Source is at the left of the black line, receiver at the right. Actual scatterer locations are at the centres of the triangles shown. Triangles generated using the Delauney algorithm to map from locations uniformly spaced in time-bearing, as measured at the receiver, into x and y position.

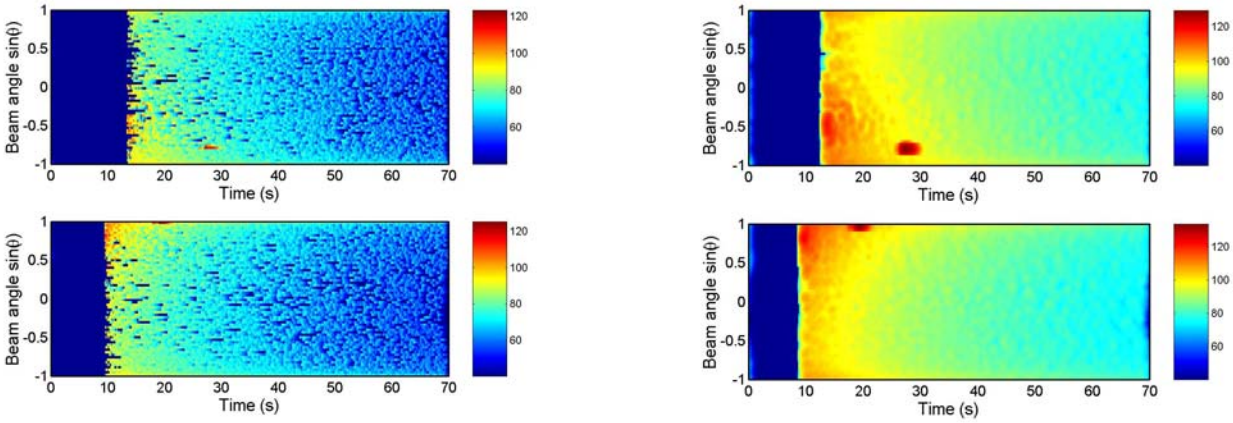

Figure 3. Intensity versus time and bearing for two receivers after transmission by the same source. Left hand side shows results before time and bearing post-processing. Right hand side shows results after post-processing to include finite pulse duration and non-zero angular beamwidth.

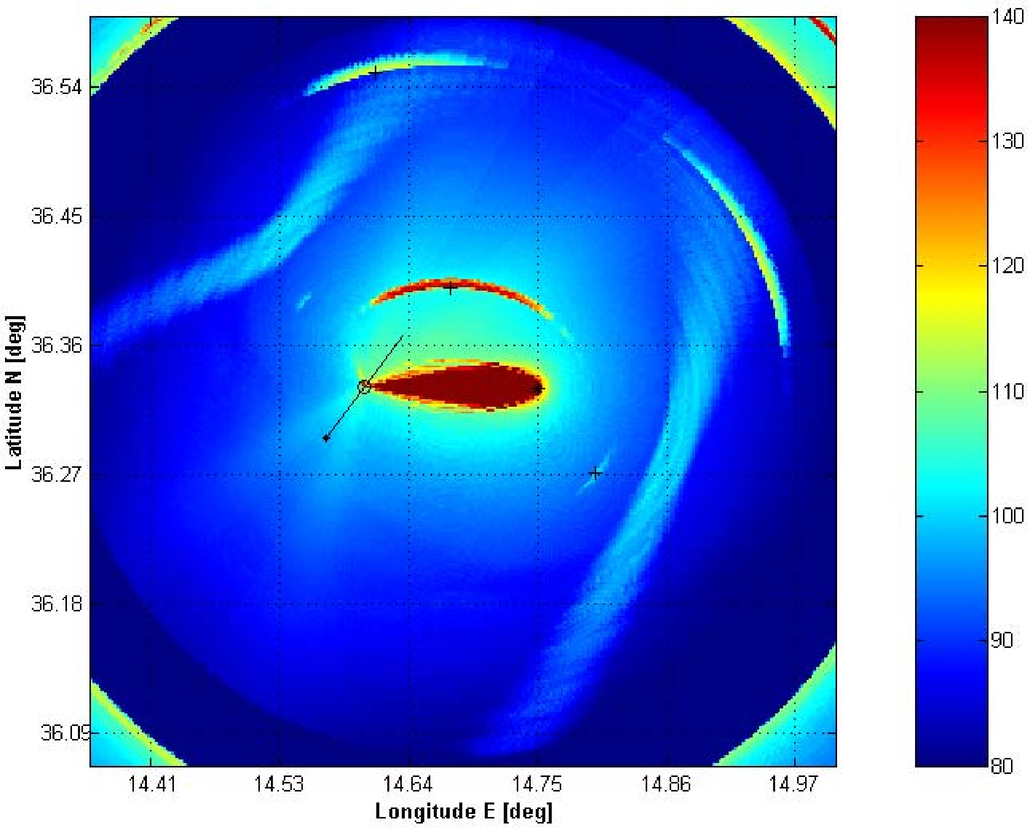

Figure 4. Received intensity plotted on geographic axes for bistatic sonar. Receiver location shown by black circle with line indicating array heading. Source location shown by asterisk. Single target locations shown by crosses. High detail target modelling results in prediction of large amplitude echo due to target glint for middle target. "Cloud" of reverberation arises from region of rocky outcrops on the seabed.

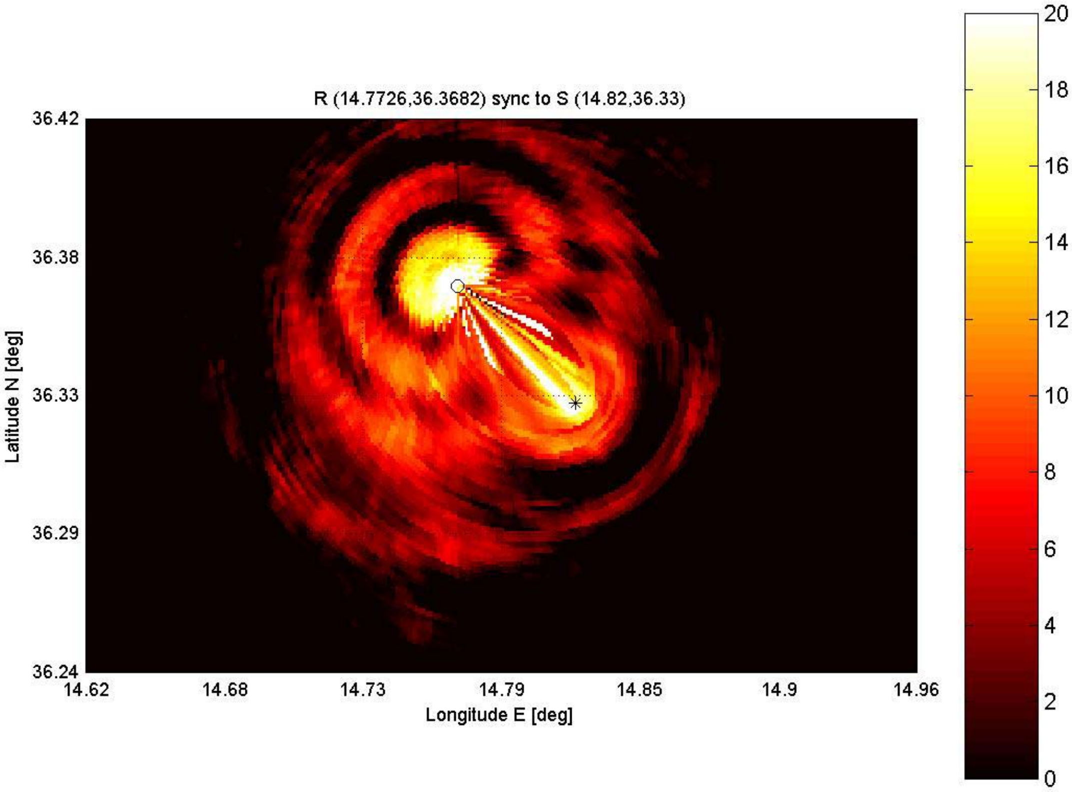

Figure 5. Signal to background ratio for a bistatic source/receiver pair with gridded targets. Receiver marked by circle in top left, source marked by asterisk in bottom right.

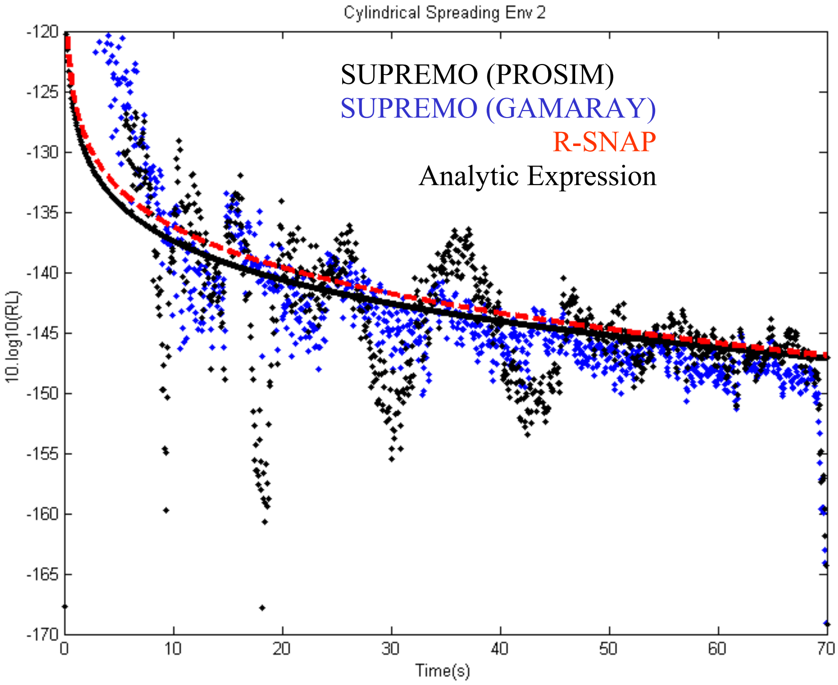

Figure 6. Comparison between SUPREMO reverberation predictions (using GAMARAY and PROSIM models as propagation modules) with reference solutions from RSNAP and analytic expressions developed by Harrison.

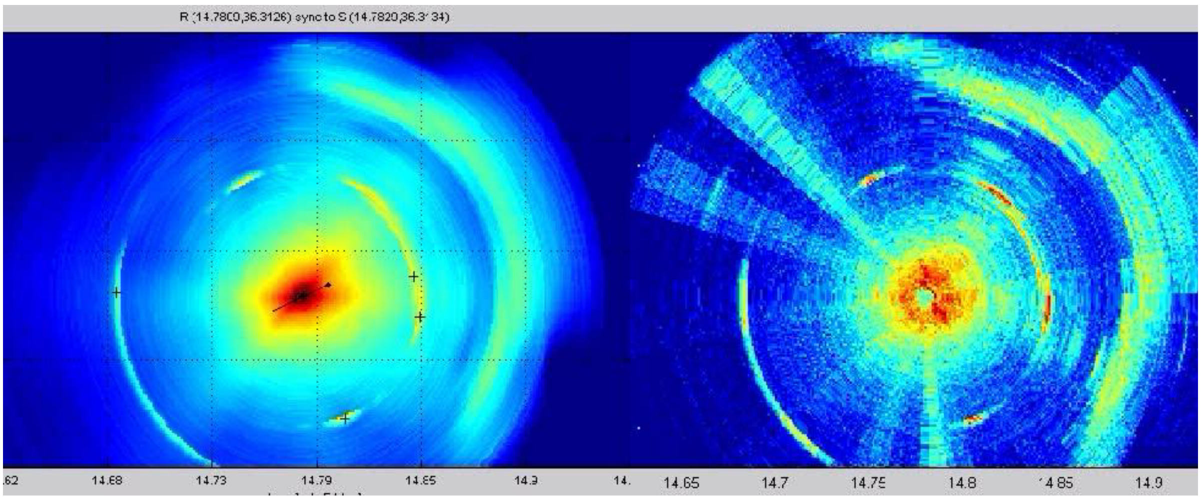

Figure 7. Contours of intensity received on an ambiguous horizontal line array predicted by SUPREMO (left) and measured at-sea (right). Data plotted on geographic axes to show apparent origins of echoes. Common dB colour scale used for both measured and modelled data.

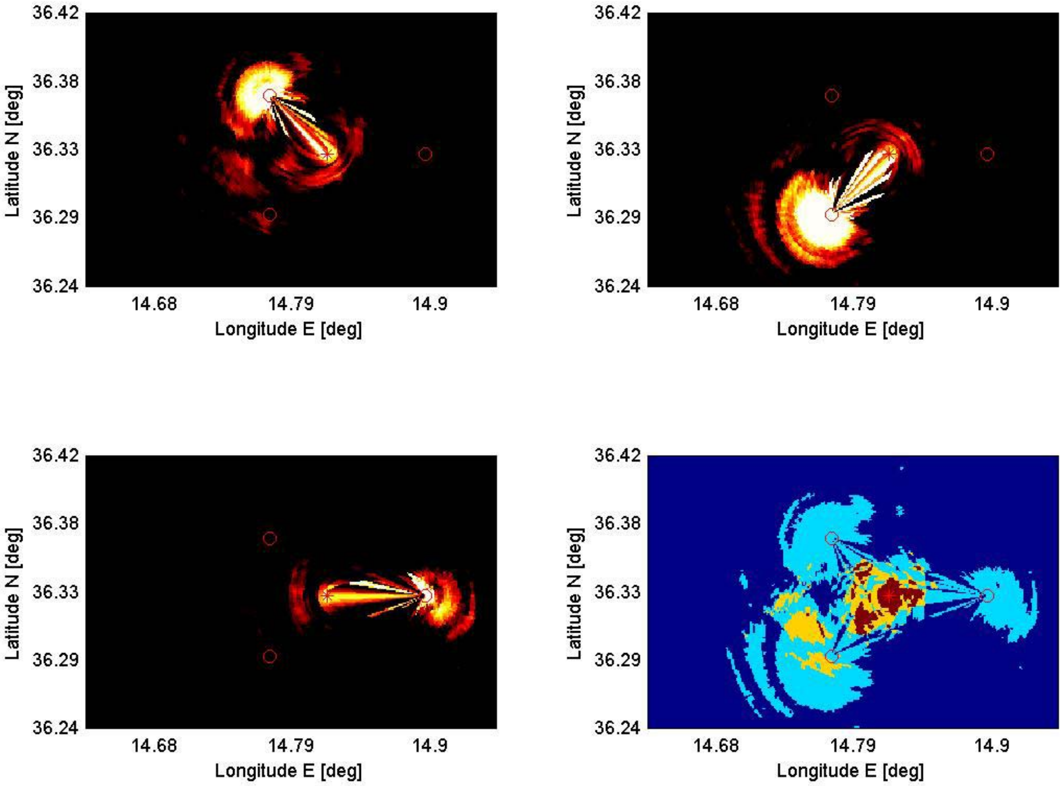

Figure 8. Signal-to-noise ratio for three receivers (shown by circles) with a common source (shown by asterisk). Colour levels start (black) at threshold value of 10dB and end (white) at 10dB higher than the threshold. Bottom right panel shows the number of receivers in contact with target as a function of position (Dark blue=0, light blue=1, yellow=2, dark red=all three.)