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# MODELLING THE PERFORMANCE OF SONAR ARRAYS IN COMPLEX, RANGE DEPENDENT ENVIRONMENTS

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## ABSTRACT

There has been growing interest since the end of the Cold War in expendable underwater acoustic surveillance systems that can be deployed rapidly and at short notice to new areas of operation. The systems would be laid on, or be moored up from, the sea-bed. The fixed nature of these systems introduces the possibility of complex array configurations which exploit the arrival angle structure of the acoustic field. A number of new models have recently been developed to predict the acoustic response of such arrays in shallow and deep water environments. Models for the level and directionality of ambient noise in complex range and azimuth dependent environments, and response of arrays to noise and signal sources, have been developed. Environmental data for these models can be extracted automatically from databases. A model for predicting the echo and reverberation on a receiver in an active system has also been developed. The model calculates echo and reverberation in the time domain. This approach requires a different form of the sonar equation but allows the dispersion of pulses in shallow water to be quantified. The various models that have been developed are described. Examples of results obtained are presented.


## 1. INTRODUCTION

There has been a shift of emphasis in the sonar research field since the end of the Cold War, from open ocean scenarios involving nuclear-powered submarines, towards operations in littoral waters against small and quiet conventional submarines. A large number of nations now operate such submarines which could pose a significant threat to Allied shipping in a regional conflict. Conventional submarines in noisy and reverberant environments are difficult to detect using conventional ship and submarine mounted sonars. Expendable undersea surveillance systems that could be deployed rapidly and at short notice to new areas of operation as a conflict developed have been proposed as a means to meet the new challenge. These would be barrier systems consisting of a number of arrays laid on, or moored up from, the sea-bed. The short detection range of each array would be overcome by the large number distributed along the length of the barrier.

The fixed nature of these systems introduces the possibility of complex array configurations. These include vertical line arrays spanning a large fraction of the water column, large aperture horizontal line arrays (the configuration on the sea-bed of which could be determined accurately after deployment), two-dimensional horizontal planar arrays on the sea-bed, or compound arrays with both vertical and horizontal sub-apertures processed coherently. Array configurations that best exploit the arrival angle structure of the incident acoustic field must be identified. A vertical aperture, for example, can take advantage of the noise notch (the absence of horizontally arriving energy) which is predicted to occur with downward refracting sound speed profiles and has been observed in experiments in some environments. A horizontal aperture has azimuthal discrimination and can provide enhanced performance against targets in low noise directions.

Models for predicting the performance of candidate array configurations are required so that optimal systems for particular environments can be identified and an estimate of their performance obtained. In the work reported here, improvements have been made to two noise models so they can be used for the assessment of the detection performance of passive systems. The use of the deployed arrays as receiver arrays in bistatic active systems is also being investigated. A model for these systems must be able to treat arbitrary array configurations and ideally should use a similar representation of the environment to that used in the models for passive systems to facilitate the comparison. It should also be able to model the dispersion of pulses in the time domain due to multipath effects encountered in shallow water environments. Most active sonar performance models use a propagation loss model designed for continuous source (as in a passive system) which is incapable of modelling dispersion. A model for active systems has been developed which satisfies these requirements.

# 2. MODELS FOR PASSIVE SYSTEMS

## 2.1 CANARD MODEL

A ray-based model, CANARD, for calculating the response of an array to surface noise sources in a complex range and azimuth dependent environment has been developed. The model was developed under contract to DERA by Chris Harrison and his team at BAeSEMA. This was a development of earlier work on CANARY, a model that calculated the coherence between noise on two spatially separated elements (and hence array response) in a range independent environment. In CANARY, the simplified assumptions on the environment and on the distribution of noise sources mean that most of the integrals required to evaluate the noise response can be performed analytically.

For the more realistic range dependent problem, CANARD performs a ray trace in the vertical plane along a number of the azimuths out from the receiver. This is not a full ray trace calculation of propagation loss. Ray tracing in a range dependent environment is difficult because the rays are chaotic at long ranges. The method used here exploits the fact that, for distributed sources, the reduction in intensity from the surface noise sources in a ray bundle due to geometrical spreading is exactly balanced by the increase in the area of contributing sources. Ray tracing is simply a method of accounting for boundary reflection (surface and bottom) losses, and volume absorption loss.

The CANARD model allows calculations of noise intensity at the receiver point from distributed shipping, wind and rain noise sources versus elevation and azimuth, and the noise response of an arbitrary array. The array response can be thought of as the omnidirectional noise level less the effective directivity index delivered by the array in the complex ambient noise field. The restriction to distributed shipping noise sources means that the calculation method is valid for distant shipping only. The response of an array to discrete local ships has to be calculated by a different method (see later).

Environments are specified on a cartesian or radial grid. Water depth is defined at each grid point, together with a specification of sound speed profile, bottom properties, and noise source densities (from a list of provinces). Environments with non-uniform distributions of sound speed profile, bottom conditions and noise source densities can therefore be modelled. Software has been written to generate input files automatically from databases. Bathymetry was taken from the DBDB5 database, sound speed profiles from the World Ocean Atlas 1994, and bottom properties from the LFBL database. The noise predictions obtained by this ray-based approach have been compared to analytic solutions (in some cases approximate) for a number of types of propagation conditions. Corrections to the basic ray method have been developed to account for duct leakage in weak ducts, and near-surface and near-bottom effects.

CANARD can not be used for calculating the response of an array to a point source in a range dependent environment as it is a noise model for distributed sources not a propagation model. The response of an array to noise from local ships and to submerged sources (such as submarines of interest) has been calculated in a range independent version of the environment local to the receiver using an eigenray propagation model. This approximation is acceptable in the signal calculation if the sea-bed is relatively flat and the ranges of the sources from the receiver are not large. If these conditions are not satisfied, the response of an array can be calculated using INSTANT, the range dependent propagation, echo and reverberation model (described later) which has been developed for the assessment of active systems but which also calculates noise from foreground ships. Calculation of ambient noise in a range independent environment is usually not acceptable, as the ranges to the contributing sources are large and range dependent effects are likely to be very significant over these distances.

Once predictions of the response of the array to ambient noise and to unit sources at various ranges have been made, appropriate source levels and detection thresholds are selected and sonar equation signal excess as a function of target range and steer angle calculated. Optimal steer angles and median detection ranges can then be deduced. Adaptive beamforming has also been considered. The minimum variance distortionless response method is used to determine the weights required to minimise noise output subject to the constraint that the response to a plane wave from a given azimuth and elevation is unity. Signal and noise response is then determined in the usual way. Note that this method allows the effect of mismatch between the signal field from the target and the plane wave assumption, which can be significant, to be assessed.

## 2.2 RANDI-2 MODEL

The RANDI-2 model was developed at the SACLANT Undersea Research Centre in the 1980s. It was produced as a research tool and has been improved and thoroughly documented during the course of the programme. It computes exact results by the coherent summation of individual hydrophone complex pressures within each propagation mode. It uses the SUPERSNAP propagation loss model to calculate the acoustic field. Various improvements to the SUPERSNAP model have been made in the UK in the past few years in its treatment of range dependent environments (the adiabatic approximation), and the approximate (faster) calculation of modes that do not contribute greatly to propagation loss. RANDI-2 has been modified to take advantage of the improvements. The improvements were carried out by Rachel Harrison at BAeSEMA.

RANDI-2 calculates shipping noise from source levels of individual ships and propagation mode data, and wind noise using the Kuperman/Ingenito (K/I) surface noise theory. Wind noise is made up of contributions from discrete modes and a continuous (virtual) spectrum. The latter was originally calculated by a Fast Field (wavenumber integration) method, which was very numerical intensive. The virtual spectrum is now calculated using discrete modes introduced by adding an artificial bottom below the substrate. Improvements were also made to reduce the size of the data files passed between different parts of the model, and in a number of other areas. The improvements mean that the model can now be used for higher frequencies and deeper water than was hitherto the case. The model is, however, still restricted to weakly range dependent environments.

Data files for RANDI-2 can be generated from the databases. Calculations of detection performance are made using the predicted signal and noise beam responses, as with CANARD.

# 3. MODEL FOR BISTATIC ACTIVE SYSTEMS

An existing model INSTANT which calculated transmission loss and reverberation in weakly range dependent environments was available at the start of the work. The technique used was tracking of rays from the transmitter using the invariance of the ray invariant. The model has been improved so that echo is calculated in the time domain. Modifications have also been made so that arbitrary array configurations, range dependent environments and bistatic geometries can be considered. The work was undertaken by Mike Ainslie and colleagues at BAeSEMA. The model is at present still only valid in weakly range dependent environments although work is in progress to relax this restriction.

The beampattern of an arbitrary array is calculated as a function of azimuth and elevation, and used to weight the incident field. Echo from a single frequency source of unit source level and infinitesimal duration, and a scatterer of unit target strength, is calculated as a time series by integrating over all the ray paths on the outward and return paths. The time series of the reverberation from a similar source is also calculated. Ambient noise can be calculated either by assuming an isotropic or horizontally axisymmetric noise field, or by reading in beam responses from another model (for example CANARD). Monostatic systems can be modelled in a sectored range dependent environments with the environmental data generated for the passive models. Bistatic geometries can as yet only be considered in range independent environments although an extension to the full range dependent case would be relatively straightforward.

The echo, reverberation and noise results created by INSTANT are then used in a detection model. Effective (postcorrelator) source levels and pulse lengths for continuous wave (CW), frequency modulated (FM) pulses, and explosive transmissions are defined. An approximate treatment for the reduction in effective reverberation level due to Doppler in a CW system is used. The pulse at the receiver in the real environment is extended over a duration longer than the initial pulse due to multipath effects. The maximum value of the echo relative to the noise and reverberation integrated over the effective pulse length, for different start positions of the integration period within the time series, is calculated. Start positions where the echo is received within the direct blast are ignored. With the total energy form of the sonar equation and effective (postcorrelator) reverberation level notation adopted here, the definition of the detection threshold required is different from that normally used. The output of the detection model is a prediction of signal excess for a specified steer angle.

# 4. EXAMPLE RESULTS

Examples of results from the new models are now presented. The environment considered was a shallow water environment on the edge of the Scotian shelf off Halifax, Nova Scotia. Water depth at the receiver location was 100m, but depths increased rapidly to the south east. The bottom is sand and gravel (relatively reflective). Fig. 1 shows the bathymetry of the area. The radials are 500km radials centred on the receiver array. Data on a representative distribution of ships in the area were obtained from the HITS database. Positions and courses of the ships are shown.

Fig. 2 shows the bathymetry, sound speed profiles and bottom types along a radial to the east of the receiver position. The dotted lines mark the areas where the sound speed profiles apply. Bottom provinces are shown by shading. Note the segments on this radial where the sound speed profile from the database does not extend to the water depth in the other database. In the model the sound speed profile is extrapolated assuming isothermal conditions. This is an illustration of one of the problems with the database approach. The resolution of any database is finite so there are likely to be inconsistencies between the different environmental parameters. The use of averaged or smoothed data can also introduce problems. Features of a sound speed profile (number of ducts etc) at a particular time of year may be destroyed by averaging over different months or seasons.

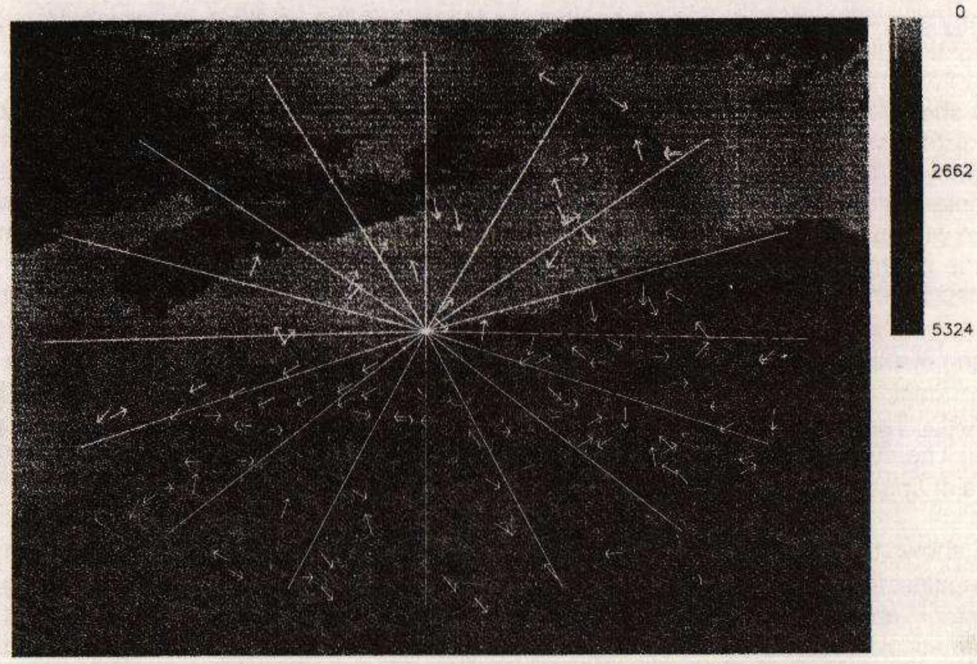


Fig. 1. Map of the Scotian Shelf showing bathymetry, radials from receiver position, and ships

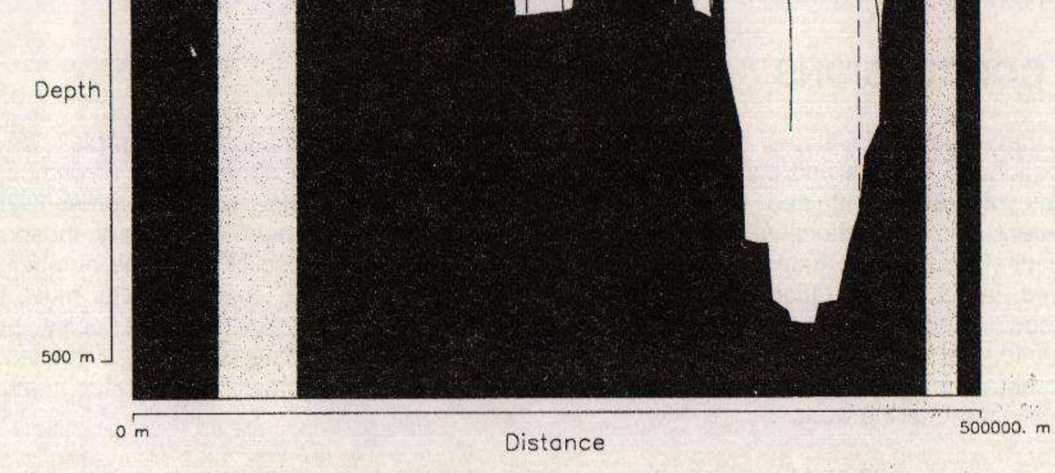


Fig. 2. Bathymetry, sound speed profile and bottom provinces along a radial to north east

Similarly averaging over an area may obscure features in the environment which are significant to propagation (and hence ambient noise and sonar performance).

Fig. 3 shows the predicted directionality (intensity versus azimuth and elevation) of ambient noise from distant shipping and wind noise calculated by CANARD for a receiver on the sea-bed and a frequency of 150Hz. Note the concentration of energy from distant shipping above and below the horizontal (with a narrow notch in the horizontal direction itself), and the variation of the width of this feature with azimuth due the different upslope and downslope conditions in different azimuths. Note also the energy from local wind noise sources arriving from vertically above and the lower levels reflected from the sea-bed. Fig. 4 shows the beam response of a 32 element horizontal line array on the sea-bed with a heading of 340° (approximately perpendicular to the shelf edge). In the shipping distribution adopted there are two relatively local ships at a bearing of 60° and a number of distant ships. The contribution of the distant ships to the beam response is calculated within CANARD. The contribution of the local ships is calculated here using the eigenray propagation model. The sum of the contributions is shown. The high level from the local ships is seen at steer angles of approximately 60° above a more uniform background from distant shipping.

Fig. 5 shows the signal to noise ratio in the beam outputs for a submerged source on a bearing of 110° against the total ambient noise field. Signal to noise is displayed as a function of source range and steer angle. Steer angles are defined as an angle anticlockwise from east (as in a mathematical coordinate system). The steer angles plotted are therefore endfire to endfire. In this case an arbitrary source level of the submerged source has been used. The results give an indication of how detection performance can be deduced from the model. High signal to noise is observed at steer angles where the source is in the main beam of the array. Lower signal to noise levels are observed at other steer angles. Greater detection performance is obtained for targets which are in lower ambient noise directions as in this example, and poorer performance for targets in high noise directions such as the directions of local ships.

Fig. 6 shows the signal excess in a bistatic active system predicted using INSTANT and the active detection model. The environment is a range independent version of the environment considered in the passive case. The source array is a 4 element vertical array at mid-water. A frequency of 900Hz is assumed. The receiver array is a 32-element horizontal line array on the sea-bed, oriented east-west, 10km east from the source array. The target is assumed to be due north of the receiver. An arbitrary source level, target strength and detection threshold have been assumed in these calculations. The figure shows signal excess as a function of range of the target from the receiver and target depth from which the detection performance can be deduced.

## 5. CONCLUSIONS

Models have been developed for predicting the detection performance of complex array configurations in passive and bistatic active systems in realistic, range dependent environments. Examples of results obtained from the models are presented. The models represent the environment and the detection process in greater detail than has been customary in sonar performance modelling to date. Such detail introduces problems because of the large number of array and target configurations which can be considered. However, these effects must be understood if expendable systems which exploit the directionality of ambient noise and reverberation fields are to be developed to satisfy the current demanding undersea surveillance requirement. The models developed for this specific application will eventually be exploited in more general sonar modelling work.

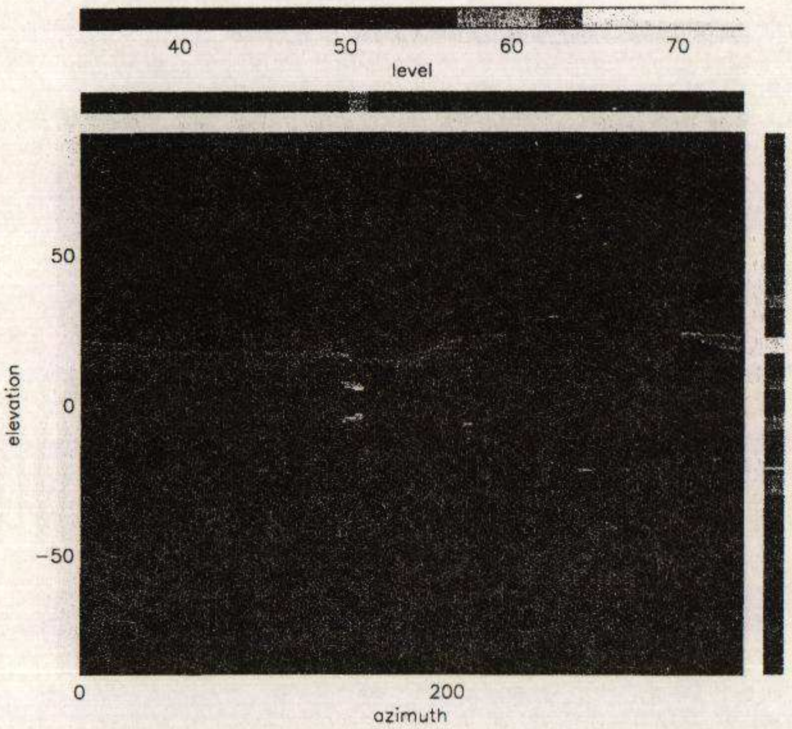


Fig. 3. Intensity of ambient noise at receiver position versus azimuth and elevation arrival angle

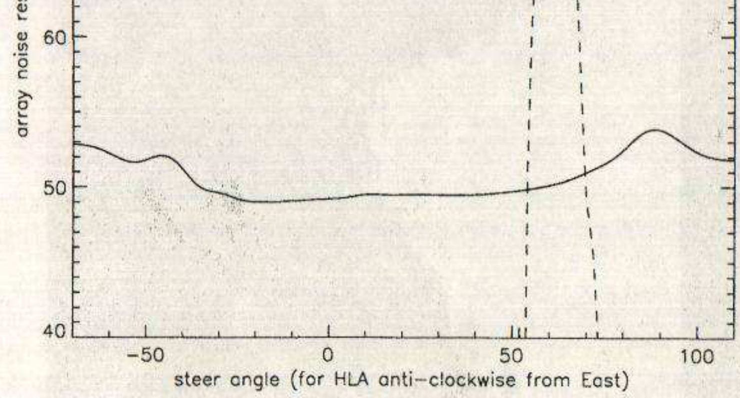


Fig. 4. Beam response (dB) of horizontal line array to distant (solid) and local (dashed) ships

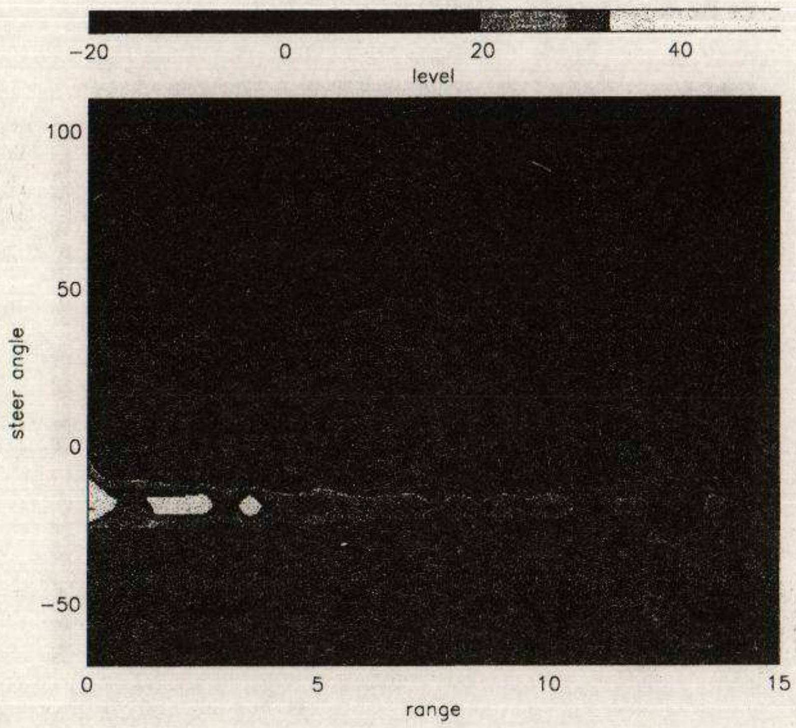


Fig. 5. Signal to noise versus source range (km) and steer angle

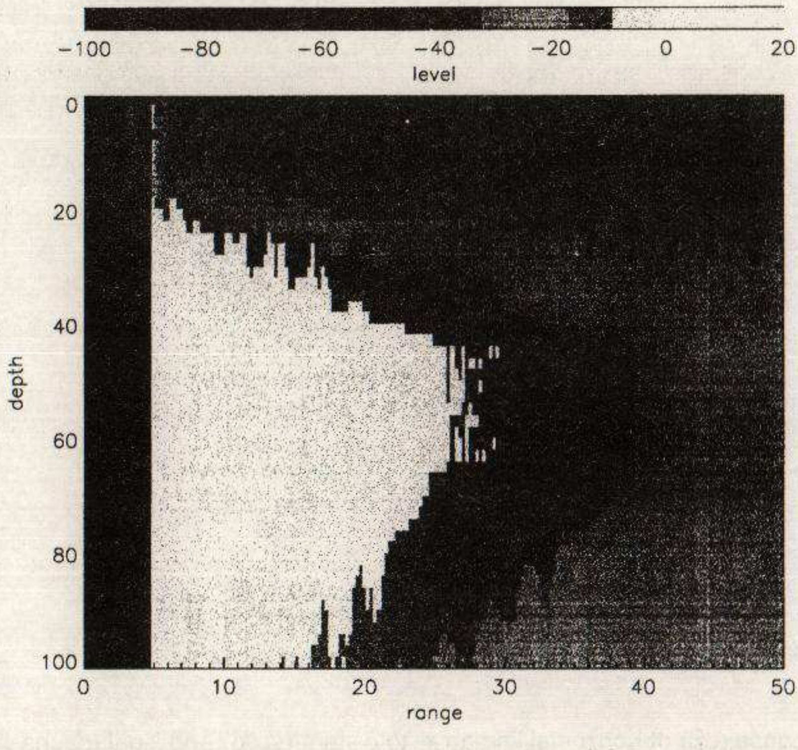


Fig. 6. Signal excess in bistatic system versus target range (km) and depth (m)