DETECTION OF OBJECTS IN THE WATER COLUMN USING SHADOWS IN REVERBERATION

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ABSTRACT

Acoustic shadows have been used to aid object detection for many years with high frequency, narrow beam width sonars. This novel research shows that large objects displaced from ocean boundaries may be detected using mid-frequency sonars with wide beam widths. This allows the acoustic detection of very low target strength objects in highly reverberant shallow waters. A combination of modelling and sea trials data have been undertaken to develop and validate shadow detection algorithms.

1. INTRODUCTION

The detection of objects in the water column or on the seabed using sonar has a number of applications in both civilian and military operations. Conventional detection of stationary objects by active sonar (Doppler shift may be used for moving objects) relies on the object "highlight" (i.e. direct reflection from the object), or where narrow beam widths are possible a combination of acoustic highlight and shadow. However, for absorbent objects which possess a low target strength, the highlight may not necessarily be distinguishable from the background reverberation. This is particularly important in coastal regions, where shallow water means that close proximity to either the sea surface or seabed leads to a highly reverberant environment. The majority of civilian and modern military sonar applications occur within this environment.

Thus, in a scenario where the object highlight is absent or masked by reverberation, so that only the object shadow remains, conventional object detection techniques are rendered ineffective. This paper presents novel methods for detecting acoustic shadows within a reverberation background, where the shadows are not visible through amplitude-only detection techniques, and suggests how the range to an object may be estimated from shadow position.

This research has been conducted as part of the DERA Corporate Research Programme, also involving Dr. N.G. Pace and C. Bevan at Bath University, whose inputs are gratefully acknowledged. This paper presents the results of modelling studies and provides validation by comparison with sea trials data.

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2. MODELLING ACOUSTIC SHADOWS IN REVERBERATION

2.1 Modelling approach and development

The modelling presented in this paper stems from initial research by Coad [1], who calculated theoretical curves for the reduction in reverberation signal due to acoustic shadowing of an object against the sea surface (figure 1 shows curves for different sonar beam widths over a varying object range).

This initial modelling took the form of a 2-dimensional scenario, with a sonar and rectangular "plate" object existing in the same vertical plane. Figure 1 shows that the largest reductions are obtained using narrow beams. This is simply because there is less backscatter contribution from the sea surface outside the shadowed region for a narrow beam.

Whilst valuable in a deterministic sense, the family of curves represented in figure 1 are of no use in the development and training of shadow detection algorithms. To do this the model is required to generate synthetic receive signals.

Reverberation amplitudes are generated by modelling the sea surface subtended by the beam width as a set of randomly spaced point scatterers of normally distributed amplitude, such that the total scattering strength per unit area is determined by the model of McDaniel [2] for a given grazing angle and windspeed. All scatterers from within the shadow zone are excluded. The reverberation time series is generated by convolution of the backscattered amplitude series with a transmission signal.

2.1.1 SURFSHAD model

Although the above model served its purpose, it was inappropriate for modelling a generic sonar beam pattern, where relatively large beam widths can make the 2-D axial plane approach unrealistic, due to the reasons already pointed out by Coad [1]. Thus, the SURFSHAD model was developed, converting the above concepts in to 3-dimensions. The target object is no longer a rectangular plate, but a cylinder, and scatterers are defined within a conical beam rather than a linear strip subtended by a planar beam. This approach more accurately models wide beam widths, and allows modelling of off-axis objects. The object is modelled to be completely absorbent (having no target strength), so that there are no highlight returns generated, only an acoustic shadow.

The backscattering strength per unit area used to generate sea surface reverberation amplitude is calculated by the modified version of the McDaniel model, developed by the Applied Physics Laboratory, University of Washington (APL-UW) [3]. This model estimates the backscattering cross section of a laterally homogenous bubble layer, and from the sea surface roughness using composite roughness theory which interpolates scattering from small-scale roughness and from surface facets. Backscatter is generated as a function of windspeed and grazing angle. Bottom reverberation is generated in a similar fashion, applying the APL-UW bottom backscatter model [3], which accounts for a composite interface roughness in much the same way as the surface model, but also takes in to account scattering from within the sediment volume.

The 3-D nature of the model makes the effect of the transmit and receive beam sensitivities more important. For ease of calculation, a Gaussian bell function is used to model both transmit and receive sensitivities. The fall-off of a sinc function beam pattern follows an exponential decay which

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may be approximated by a Gaussian bell, all that is lost are the beam pattern nulls. Thus, the Gaussian bell accurately models the main lobe of a true beam pattern, but becomes less accurate at wider angles where side lobes exist. The 3-D nature of the model also increases the number of scatterers subtended by the beam, increasing the computational load. This problem has been overcome by limiting the maximum number of scatterers and averaging over half the pulse length.

2.1.2 Simple complete model

This model, developed by Bath University evolved from a volume reverberation model to include sea surface and bottom reverberation, becoming a "complete" reverberation model. However, this model is more simplistic in its approach than the SURFSHAD model, assuming a 2-D scenario. The functions used by this model to calculate sea surface and bottom backscatter are also less complex than those incorporated in the SURFSHAD model. The expression used to calculate sea surface backscatter is that of Chapman and Harris [4], whilst Lamberts Law is used to calculate backscatter from the seabed.

Although somewhat simplified, this model is nonetheless a powerful tool to model the ensemble average of total reverberation. It is always a concern that in certain environments with certain sonar parameters an acoustic shadow may be swamped by scattering from other boundaries. This unified approach ensures that this has been taken into account. This is particularly the case with volume scattering.

2.2 Model performance

The two models discussed above were combined to operate in tandem, as it was found that each complimented the other. Figure 2 shows a comparison of each model with sea trials data gathered at the DERA Loch Goil facility. Evident from this plot is that both models have predicted the amplitude of the signal very well (note that the peak of the reverberation in the Bath University model is not aligned with the real data as it modelled the object as being in the beam axis when in fact it was off axis).

The Bath University model provides a look over a longer range than the SURFSHAD model, and predicts the position of the object shadow correctly, but over-predicts the amplitude reduction with the shadow because it is a 2-D model. The SURFSHAD model correctly models the subtle amplitude reduction within the shadow because it is a 3-D model accounting for off-axis scatterers. Thus, the combined use of both models provides a complete picture.

Figure 3 shows modelling of different bottom scattering environments by the SURFSHAD model. . A cylinder is modelled on a seabed in 200m of water with a sonar at the surface. The sonar beam employed has –3.0dB beam widths of 12.5°×6.0°. The plan range of the cylinder is 500m from the sonar and centred perpendicular to the beam axis, which is depressed 21° from the horizontal. The cylinder is 120m long and 15m in diameter, and casts a shadow in the reverberation accordingly. The cylinder has also been given a point target strength of -15.0dB to demonstrate how reverberation from certain sediments will mask an object highlight, so rendering conventional detection impossible.

Against the mud/clay sebed, the object highlight spike is clearly visible above the bottom backscatter. However, against a "harder" gravel bed, with increased backscatter strength (increased

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reflection coefficient, increased roughness, and less penetration), the return becomes lost within the reverberation (in the lower plot, the dashed line labelled "TS" marks the signal level of the highlight return). It is important to note however, that irrespective of the relative highlight level, an acoustic shadow is easily visible in each case, and in fact becomes more pronounced within stronger background reverberation.

3. METHODS OF DETECTING ACOUSTIC SHADOWS IN REVERBERATION

In practice, for a moving sonar and target object, acoustic shadow detection methods are required to operate on a single ping basis. With this as a governing objective, the following strategy evolved.

3.1 Initial investigation

Initial 2-D modelling highlighted the difference in probability density functions (PDFs) between shadowed and non-shadowed reverberation. Shadowed reverberation, which possessed reduced amplitudes, produced taller, thinner distributions, showing that the variance and kurtosis of the distribution had changed. This statistical difference was then pursued as a method of detecting an object shadow in a reverberation time series. However, when the surface scattering model started dealing with a 3-D scenario, it was found that this method became highly unreliable, largely because the contribution from off-axis scatterers within the shadowed reverberation made it very difficult to distinguish the difference between the PDFs of shadowed and non-shadowed reverberation. Thus, new shadow detection algorithms were required.

3.2 Acoustic shadow detection algorithms

3.2.1 Scattering function modulus

This technique was initially developed by Bath University [5] as means of detecting an acoustic shadow within volume reverberation. The modulus of the reverberation time series (scattering function) is taken and split into a series of N time series/range bins. The mean of each bin is then used to create a series of N local means, which was then smoothed to produce the smoothed SFM.

Bath University successfully used the gradient of the SFM as a detection method [6], the onset of shadowing in volume reverberation occurring where the gradient became sharply negative. This method did not prove successful in detecting acoustic shadows in surface reverberation, so the SFM technique was adapted as follows.

A signal loss thresholding function is generated, based on the spherical spreading and absorption characteristics (assuming an isovelocity water column):

$$\text{Signal loss function} = 20\log_{10}(\text{range}) + \alpha(\text{range}) \tag{1}$$

where α is the absorption coefficient, taken as 0.007 for generic cases.

The signal loss function is then adjusted to take account of the given sonar and sonar geometry, i.e. the Gaussian beam sensitivity function along the subtended beam axis becomes progressively skewed as the grazing angle decreases. Both signal and SFM are then normalised by their maximum values

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for ease of comparison The signal loss function is then multiplied by a threshold value. The choice of threshold must take into account the identification of shadows when they exist, but must also identify the fact that a shadow is not present when an object is absent. The threshold best suited to this discrimination was found to be 0.85 × the peak smoothed SFM of reverberation in the case of Loch Goil trials data. (Note that when direct object returns occur within the data, care should be taken to threshold the signal loss function against the peak of the reverberation, and not the peak of the highlight spike, as the amplitude reduction within the shadow is unaffected by target strength).

The shadow is then taken to be the region where the thresholded signal loss function exceeds the smoothed SFM (figure 4), for a given distance. This minimum distance is defined as the smallest possible shadow which could be cast by a cylinder flush against the surface, and is given as

$$\text{Minimum shadow length} = \text{cylinder diameter/tan(sonar elevation)} \tag{2}$$

3.2.2 Signal "blanketing"

This technique has been based on algorithms used to discriminate seabed textures in sidescan sonar images, and to detect bottom objects due to changes in texture [7]. Taking the reverberation signal r(x), consider all points within a distance, ε , about the signal data point (figure 5). These points form an upper "blanket", $u_\varepsilon(x)$, and a lower blanket, $l_\varepsilon(x)$, to the signal, defined as:

$$u_\varepsilon(x) = \max_i\left[r(x+i) + \varepsilon - |i|\right] \;\; \forall i \in \{-\varepsilon,\dots,0,\dots,\varepsilon\} \tag{3}$$

$$l_\varepsilon(x) = \min_i\left[r(x+i) - \varepsilon + |i|\right] \;\; \forall i \in \{-\varepsilon,\dots,0,\dots,\varepsilon\} \tag{4}$$

where x is range or time, i are steps in range/time

The value of ε used during modelling was equal to the binsize, the minimum value being related to the transmit frequency (any smaller and the blanket will simply follow the signal sinusoid). Thus, the optimum value of ε will depend on the sonar frequency and nature of the scattering environment. The blankets are then divided into range/time-series bins, and the area between the upper and lower blanket calculated for each bin. This blanket area data is then smoothed and compared to a signal loss function as described above for the smoothed SFM routine. A similar thresholding is applied to the signal loss function to optimise positive and negative detection. The threshold best suited to this discrimination was found to be 0.75 × the peak smoothed blanket area for Loch Goil trials data.

3.3 Performance of shadow detection algorithms

Both SFM and blanket algorithms have been proven to detect acoustic shadows in a number of difficult environments, including under ice [8]. Figure 6 shows the overall performance of the algorithms when applied to the Loch Goil sea trials data [9]. Performance is quantified by comparing the detected shadow start and shadow end with that calculated from the known experimental geometry. These results confirm the intuitive assumption (and modelling output) that

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acoustic shadow detection is best for narrow beam widths. Performance is particularly good, considering that many of the runs had the object situated off the sonar beam axis.

3.4 Object ranging using acoustic shadow detection

Once a shadow has been detected, the range to the object is required to for location. Within volume reverberation, the object range is simply taken as the range at which the start of shadowed reverberation occurs. However, the shadow cast on to the surface or bottom is a projection of the real object position. This complicates the situation somewhat, in that the same shadow may be generated by a large object at long range, or a smaller object closer in (although there is a minimum object size at which diffraction becomes important).

To differentiate between the shadow cast by a small, close range object or a large distant object either requires assumptions about the object size, or requires a ping history from a moving sonar or object to track the moving shadow. Thus, for an assumed relative object velocity, there is a unique shadow motion. An estimate of the relative object velocity is required to correctly range and size an object from its surface or bottom shadow. Whilst this is not ideal, clues to the range of an object may be combined with tactics to manoeuvre to a position where direct detection is possible.

The detection and ranging techniques described provide good discrimination between the desired object and synthetically generated signatures, as they rely on the physical dimensions of the object.

4. CONCLUSIONS

As a result of this research it has been successfully shown that acoustic shadows can be automatically detected within reverberation in a wide range of environments.

At present, neither of the algorithms developed appears any better than the other. It is therefore recommended that until further research has explicitly gauged their performance in different conditions, that both algorithms be used in tandem.

Further work is required to investigate what other objects or biota in the water column, if any, may cause acoustic shadowing in reverberation, so forming a "shadow clutter" hindering object detection. The shadowing from fish shoals may produce significantly different shadows from solid objects and so may be distinguisable. Similarly, spatial variability of sea surface and bottom roughness may produce false alarms. Smooth regions (such as a calm patch on the surface, or a muddy area on the seabed) within surrounding rougher surfaces may appear shadow like in the reverberation time series.

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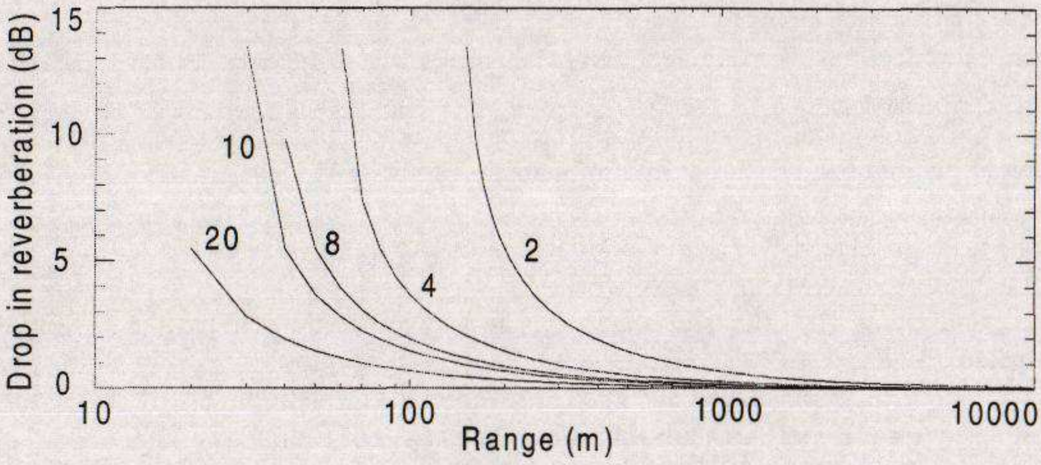

Figure 1. Drop in surface reverberation with range due to on-axis plate object shadowing for beam widths 2, 4, 8, 10, and 20 degrees (after Coad [1]).

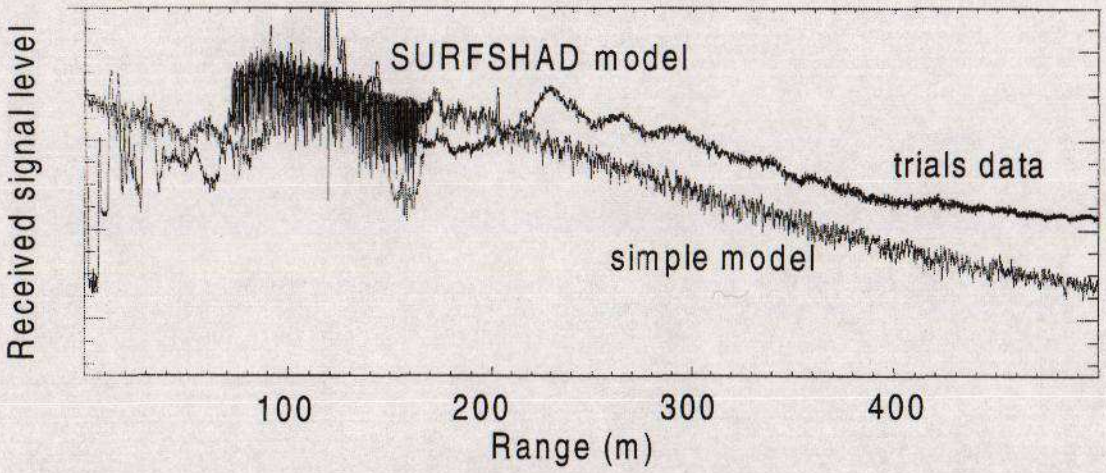

Figure 2. Comparison of the 3-D SURFSHAD model and the Bath University simple total reverberation model with sea trials data.

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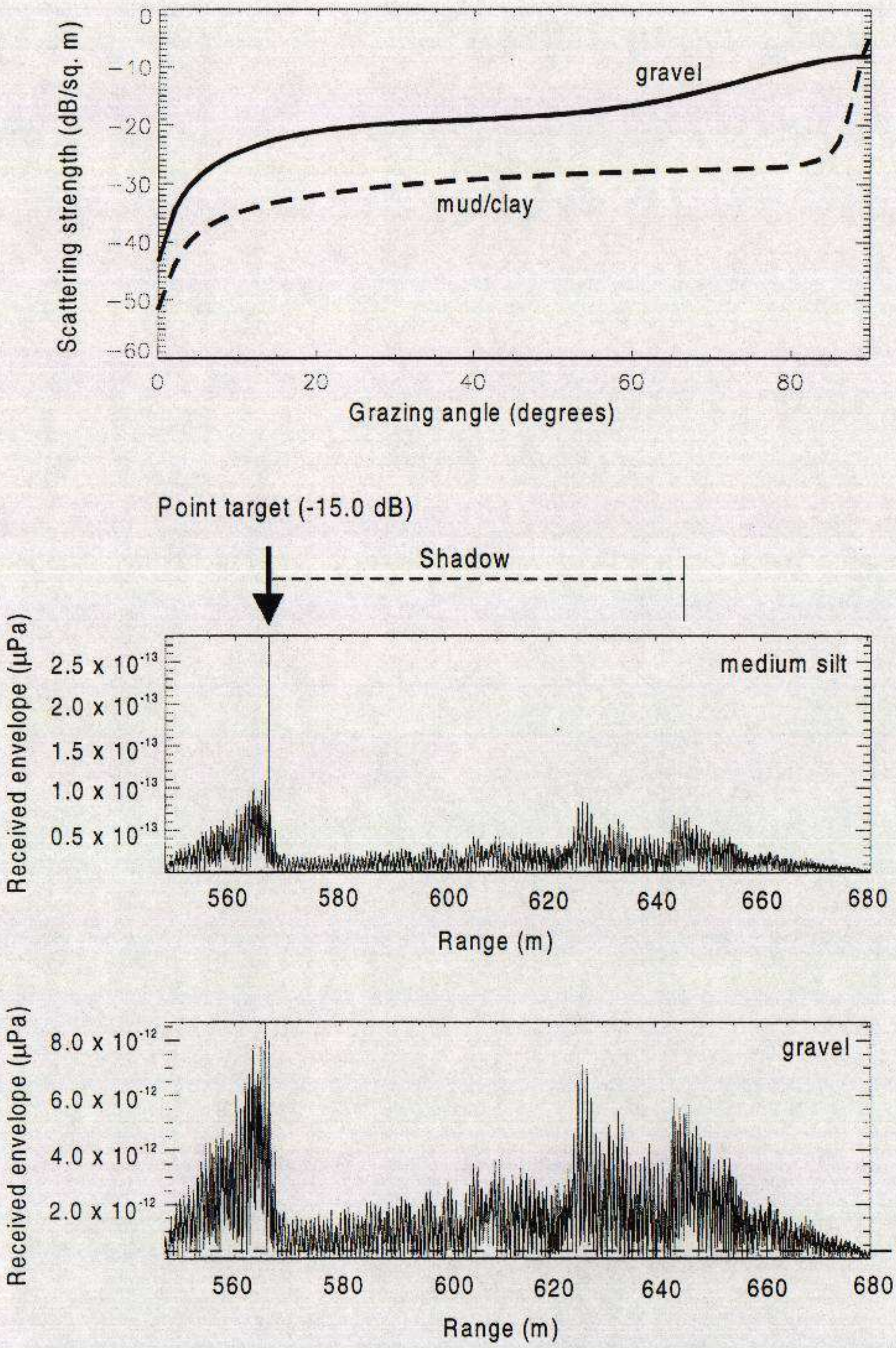

Figure 3. Model pings against a –15.0dB object against clay gravel seabeds. 'TS' on the lower plot represents the return highlight signal level masked by reverberation. Note that the upper plot shows backscatter per unit area, and not values that can be directly related to the -15.0db target strength.

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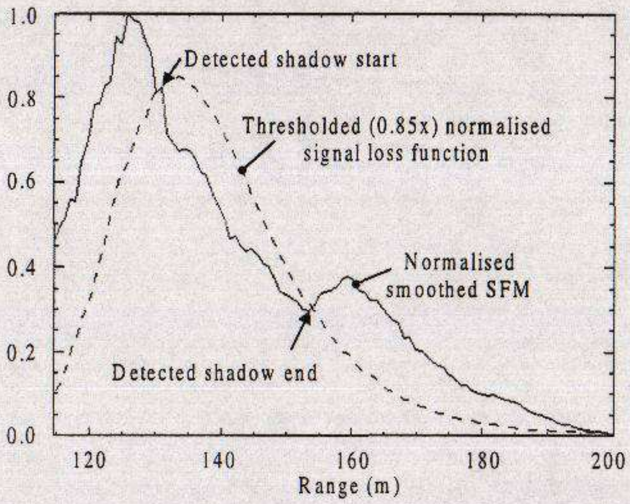

Figure 4. Acoustic shadow detection by comparison of a signal loss function with smoothed SFM algorithm.

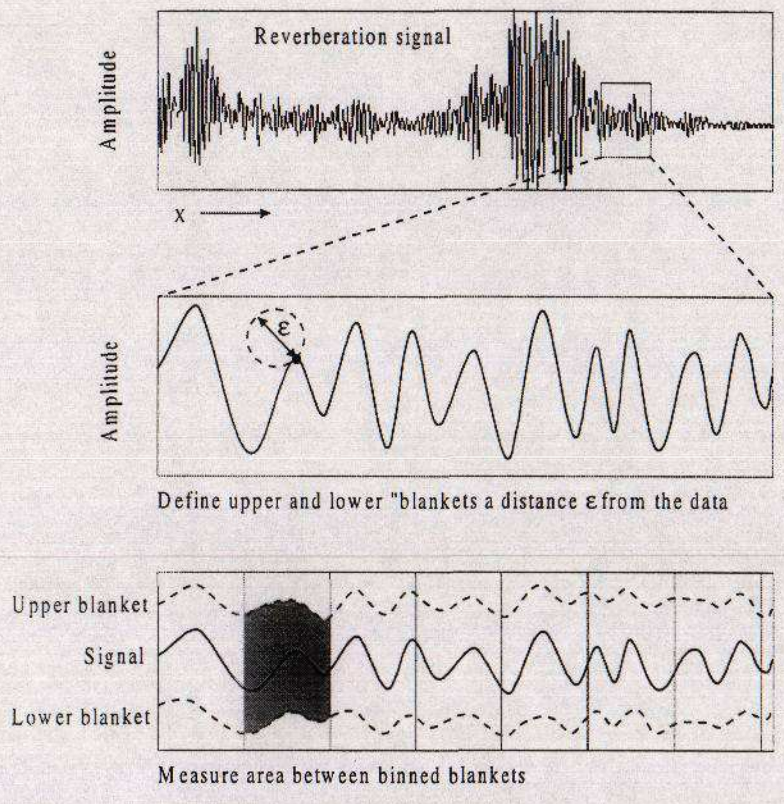

Figure 5. Graphical representation of how the signal “blanket area” is defined.

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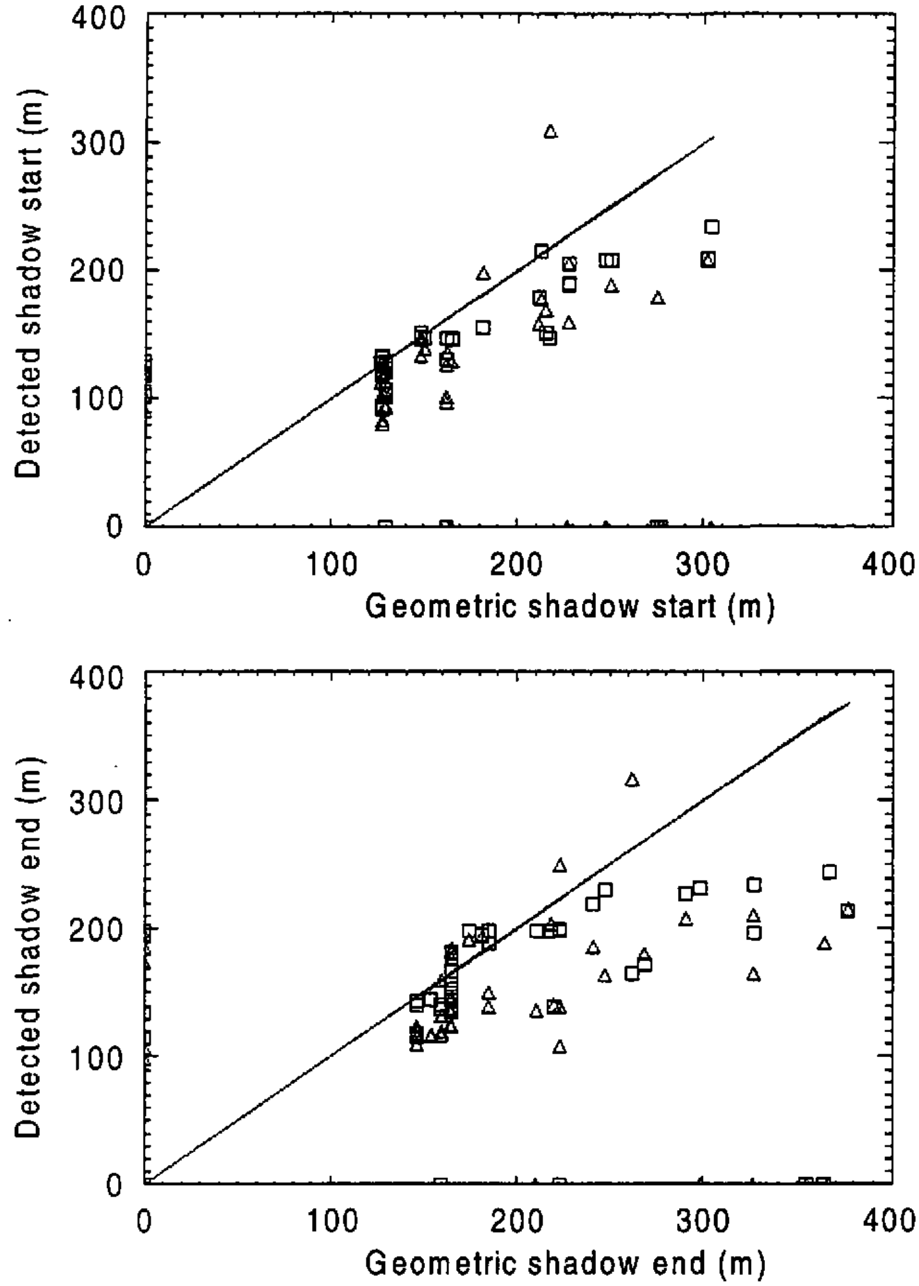

Figure 6. Detection of shadow start (upper plot) and shadow end (lower plot) during the Loch Goil sea trial. The blanket algorithm results are plotted as triangles, and the SFM results as squares. Filled symbols represent narrow beam (12.5° × 6.0°), open symbols broad beam (25.0° × 12.0°)