Translated Article

Determination of the Insonification Area of a Multi-beam Echo-sounder Using a Front Propagation

By Nathalie Debese, SHOM, France

By providing simultaneous depth measurements, Multi-beam Echo-Sounders can achieve swath coverage of the sea floor along the survey line with higher density and better resolution than single beam echo sounders. For example, the SIMRAD EM12-dual can cover a swath width up to seven times the depth.

The coverage of a multi-beam echosounder (the insonification area) depends on the swath width, which is a function of the depth and system opening angle. It also depends on the ship yaw, since perturbations of the heading act as a lever and can result in an irregular coverage. In order to perform a complete insonification, the line spacing is chosen accordingly to avoid 'holes'. However, the bottom being generally unknown, a control in real time acquisition remains necessary. This relies on a synthetic representation of the insonification area. The coverage is described using two contourlines. The first one is outside the soundings set, the second one contours the holes. Both lines are generated for a given control radius, which enables a partial account of the insonification area of each beam, which depends, at the same time, on the system and the depth measured.

Currently, the coverage is computed with the assumption that the insonification area of each beam (called the footprint of the beam) is constant. However, it increases proportionally with the depth, and thus can be very different between the central and the lateral beams of the same system.

The coverage of a set of soundings is defined as being the sum of the beam 'footprints' for each depth measurement.

Building the insonification area is ideally reduced to a standard morphological operator: a dilation. The originality of the approach described here, relies on the implementation of this family of operations, expressed in terms of propagation of fronts at uniform speed.

The first argument explaining this methodological choice in the method relies on the fact that morphological operations processed by fronts propagation (Ragnemalm, 1992) allow an optimisation of the processing time. Another advantage, essential to this application, is that operations of different sizes can be performed simultaneously, giving then an adaptive coverage.

As for a coverage with a fixed radius, the adaptive coverage is used during a survey to optimise its management. It can also be used during the processing phase by reinforcing (forbidding the over-extrapolations) of the resulting terrain elevation model.

The coverage is also used for the survey planning, to define the navigation profiles. Currently, this step is done manually; this study proposes this be done automatically. To do so, it is necessary to define a second type of coverage, a simulated coverage. Unlike the computed coverage, as defined above, the simulated coverage of a navigation route is defined as the theoretical bottom area seen by the sounder along the route. Like the computed coverage, the simulated coverage depends both on the characteristics of the echo-sounder and the seabed relief. The relief is described through a rough digital elevation model generated with available soundings on the area to be surveyed. The characteristics of the system are its aperture angle and the physical limits. Both types of coverage are defined below. After a short introduction to the algorithm of fronts propagation, the application to the adaptive coverage is then presented. Finally, the last paragraph focuses on the gain in time and accuracy of the technique, as well as on the contributions to the adaptive coverage.

Definitions

Two types of coverage have been defined:

- A computed coverage: generated, during the survey, from the acquired soundings (x,y,z)
- A simulated coverage: generated, during the planning of the survey, from a rough model of the sea-bottom

As illustrated below, in Figures 2.1 and 2.2, the processing of these coverages is based on a description of both the seabed, and the features of the echo-sounder used.

Computed Coverages

A sounding attached to a beam corresponds to a mean depth computed on its insonification area, namely designated as its footprint, even if it is usually represented by a triplet (x, y, z).

Two modes of computation are considered depending upon the type of the retained model of the characteristics of the beam footprint:

- Fixed: the insonification surface area is identical for all the beams
- Adaptive: the insonification surface area depends on the beam features

In the fixed cover case, a sounding is represented by an insonification area which is the same whatever the beam or its depth measurement. In other words, each sounding of the data set is dilated so as to cover the same area. The retained model is a disc whose radius R can be *a priori* fixed or obtained from the features of the data set.

The adaptive coverage takes into account the characteristics of the sea bottom and those of the echo-sounder. It is particularly suited to surveys carried out of large areas with great depth relief disparities. Moreover, it also allows the footprint deformation of the outer beams to be considered. In order to preserve reasonable processing time, the retained models leave aside the roll and pitch angles of the ship. The effects related to the local slope of the seabed are also supposed to be negligible. Two models are proposed depending on the sounder used.

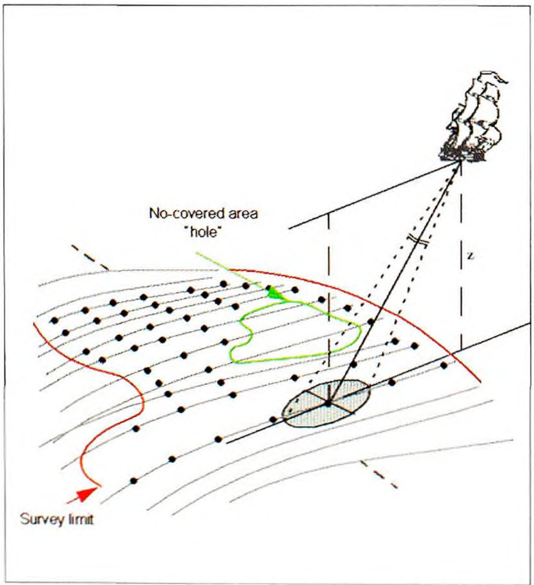

Figure 2.1: Computed coverage

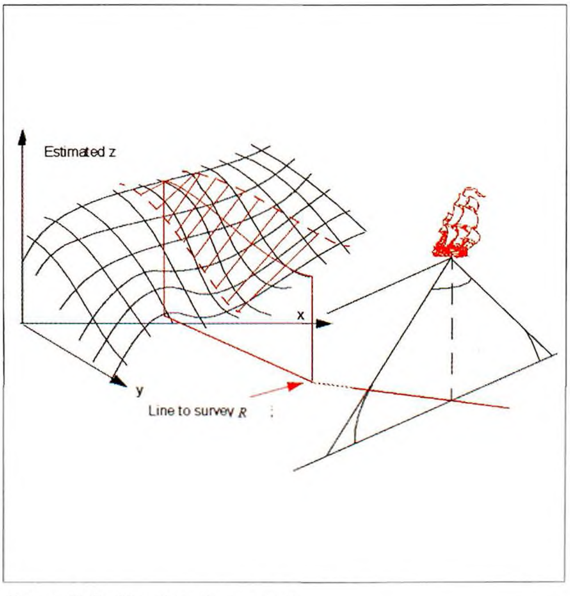

Figure 2.2: Simulated coverage

In the *Thomson-Lennermor* case, which is a shallow water echo-sounder (i.e. 5m – 300m) with 20 beams of identical lateral and longitudinal opening angles, the deformation of the outer beam footprint is weak. Consequently, the model is the same whatever the beam. It is defined as a disc whose radius depends on the measured depth, on the observed angle, and on the opening angle of the beam.

In the SIMRAD EM12-dual case, which is a deep water echo-sounder (i.e. 200m – 12,000m), the opening angle of the 162 beams depends on the operating mode of the system. The deformation of the outer beam has to be modelled as the opening angle can be up to 150°. The footprint of an outer beam will be represented by a set of discs each having a variable radius. In practice, the geometrical model of the outer beams footprint is similar to adding virtual soundings to the initial set.

Simulated Coverage

The simulated coverage associated to a route R is an estimation of the theoretical insonification area along this route. It is obtained from a description of the seabed features of a coarse Digital Elevation Model (generated from the soundings provided by the bathymetric data base of the SHOM) and the sounder features.

This estimated coverage is used to optimise the planning of a survey. Its accuracy is the one of the Digital Elevation Model used to generate it.

Fronts Propagation Processing

General Principle

In two dimensions, the temporal evolution of a wave front can be represented by a curve according to its normal directions with a speed that depends on extrinsic or intrinsic front criteria. It becomes an advection process when all of the front points are moving at the same orthogonal speed (Jacq 1997). A special case of advection process is the linear one thus called because the module of the propagation speed is invariant in time.

Performing the dilation in a binary graph - which is our goal here - corresponds to the simplest algorithmic form of the linear advection. In that case, the temporal evolution of the initial front verifies Huygens principle, which says that a front being propagated at a unit speed is, at t time, only made up of points located at distance t from the initial front.

In the graph theory, the propagation of a front by linear advection is similar to generating a tree structure from the nodes that describe the initial fronts at a uniform cost. The main part of the processing cost of the uniform distance propagation algorithm lies in the search step of the open node (not visited) having the lowest cost. The list of open nodes has to be ordered so as to efficiently find this node. As cost values are integers, Verwer (1989) has suggested the use of a simple bucket sorting technique. The front propagation starts by storing all of the nodes describing the initial front in bucket 0. Then, buckets are inspected, one by one, in ascending order. A bucket inspection comes down to inspect each of the nodes that belong to it. No order is assigned to a node in a bucket. In practice, a bucket is implemented as a linked list, and its scanning order is the same as the one of a list management. When a node is inspected, two scenarii can occur:

- The node p is closed, meaning that it has already been observed with a lower cost. In that case it is simply discarded from the list
- The node p is open. In that case, it is noted that it has just been observed (and it is labelled closed). Then, it generates its successors. A successor *p*' of a node is a node adjacent to *p*, regarding the neighbourhood defined over the graph and not marked closed yet. The cost associated to the successor *c*(*p*') is the sum of the cost associated to *p* and the cost of the arc between *p* and its successor *p*'. The successor *p* is thus stored in the bucket *c*(*p*')

The checking of the buckets list in the ascending order guarantees that the successors of the nodes

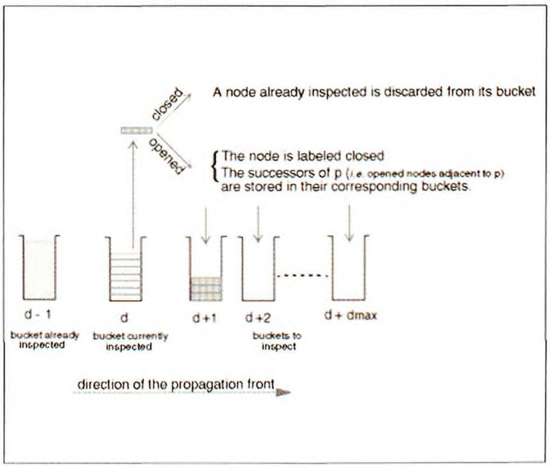

Figure 3.1: Front propagation with a uniform distance implemented as buckets list – case of bucket d

attached to a bucket have always costs strictly higher to the index of the retrieved bucked (the propagation is entropic).

The resulting distance is non-Euclidian. Ragnemalm shows (Ragnemalm, 1992) that this technique can be extended to the case of the Euclidian distance by indexing the buckets with the square Euclidian distance value, computed from the position vector (v_i, v_j) connecting the node to the closest one in the initial front.

Application to the Computation of a Coverage

As previously mentioned, the coverage implementation is based on a standard operation in the binary mathematical morphology field: the dilation (extension of the areas of an image). It is possible to propose a post-filtering option of the resulting coverage, by carrying out a closing (dilation followed by erosion – contraction of the areas – of the same size). This operation takes place in the dynamic process of a front propagation. To proceed to an opening of δ size, the front has simply to be propagated onto a supplementary distance of δ, then propagated onto the same distance in the reverse direction. The observed effect is a selective or partial smoothing of the cover limits – gaps are attenuated; In the same way, the 'holes' having a size lower or equal to the closing are filled. These two operations are processed using a front propagation algorithm, with a uniform distance implemented as a buckets list.

In this framework, the determination of a coverage assumes the creation of a previous binary image built from the initial set of soundings (a pixel of 0 will represent an empty cell for the image – and a pixel of 1 will represent a cell containing at least one sounding). The size of the pixels defines the accuracy of the coverage. It is a crucial parameter of the algorithm, which is deducted from the size of the dilation.

Determination of a Fixed Coverage

The front is propagated from cells containing at least one sounding. In the case of a Euclidian distance propagation, each bucket is indexed according to the square distance value of the position vector of its belonging nodes p. The propagation of the front requires the storage of the co-ordinates (i,j) of each node as well as the co-ordinates (vi, vj) of its associated position vector.

Determination of an Adaptive Coverage

In the case of an adaptive coverage, the size of the dilation depends on the characteristics of each sounding (depth and angle of incidence of the measuring beam). The propagation at uniform speed of fronts started at the same time results in a uniform dilation of the set of soundings. A simple way to adapt the dilation size to the features soundings is to generalise the previous algorithm to the case of the uniform propagation of fronts started at different times (Debese, 1999). As before, the dilation operates over a grid. Each grid cell is then assigned to the maximal depth of its belonging soundings in order to calculate the starting times of the different fronts. The starting times of the fronts attached to each sounding are deduced from the histogram of the depth over the whole grid. The histogram step takes into account both of the grid accuracy and the longitudinal opening angle of the beams.

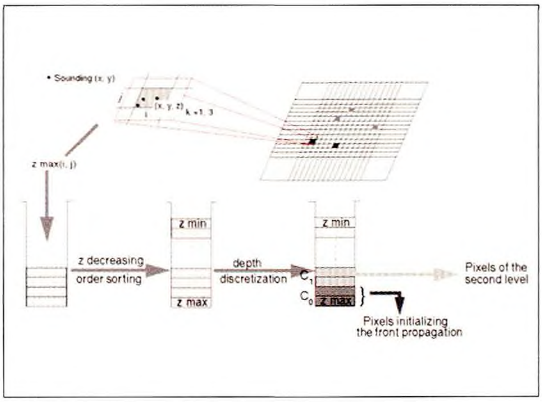

Figure 3.2 (a):Time delaying process of the different propagation fronts – case of an adaptive coverage

At the start time t_0, corresponding to the initialisation of the creation of the adaptive coverage, the initial fronts are constituted with pixels of the maximum depth class Z_{max} (see Figure 3.2(a)).

As illustrated on Figure 3-2 (b), the 0 vector is attached to each of these pixels. At the first step, each pixel - in black – of the initial front generates a set of successors, which are either assigned to bucket p[1] or to bucket p[2]. The pixels describing the new fronts have to be placed into the current bucket before the front progresses by generating the successors of the pixels contained. Bucket p[1] also contains the successors of the pixels of bucket p[0] as well as those coming from the class C_1 of the depths histogram. The position vectors of

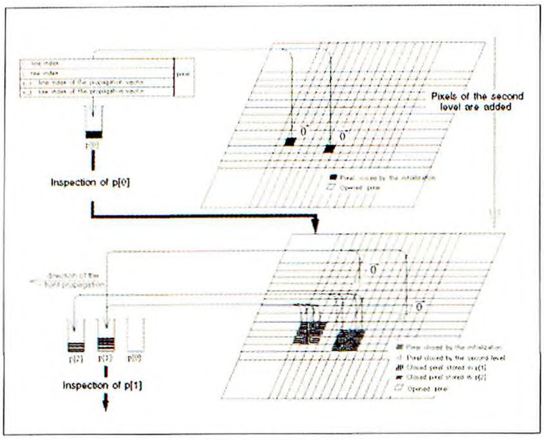

Figure 3-2 (b): Propagation of the initial front and then initialisation of the second front – case of an adaptive coverage

the pixels describing the new front are set to the 0 vector. As the front propagation is a causal process, the calculation of the index bucket, in which the successors of the pixels will be stored, has to take into account its time delay. From a practical point of view, the initialisation time of the front attached to the pixel has to be stored along with its co-ordinates (*i,j*) and the co-ordinates of its position vector (v_i, v_j).

Determination of a Simulated Coverage

The front propagation technique used to generate a fixed or adaptive covered area is analogous to an efficient construction of a distance map. Applied to the simulation of the coverage attached to the navigation line *R*, it consists to propagate a front starting from the pixels of the navigation line *R*. The front gradually progresses including the bordered pixels of the built area as long as they verify the opening constraints of the sounder defined.

Application

Traditionally, a dilation is achieved by sequentially moving a structuring element (i.e. an image of smaller size) over the whole image. The proposed approach allows the generation of the fixed covered area of a more than a one million soundings set in less than 3 seconds on a Sun-Ultra Sparc workstation, thus 6 times quicker than the standard technique. This time ratio is given only for information: the spatial configuration of the soundings has to be taken into account in a processing time evaluation. Indeed, Ragnemalm, in (Ragnemalm 1992), has compared the complexities of each approach. For a *n* x *n* binary image, the complexity of the conventional raster scanning algorithm is in O(n^2). As for the front propagation technique, its complexity only depends on the influenced area of the morphological operation (the increased surface area resulting from the dilation). Figure 4(a) underlines the contribution of an adaptive coverage compared to the one of a fixed and a minimal (fixed coverage which radius is deducted from the minimum depth of the set of soundings) ones according to their accuracies. The data used for this comparison come from a flat bottom, acquired by the SIMRAD EM12 Dual echo-sounder operating in mode 150°.

By taking into account the characteristics of each sounding, the adaptive coverage greatly improves the accuracy of the insonification area of a multi-beam echo-sounder. In the case of a sea mount, as depicted in Figure 4(b), the fixed coverage leads to an under-estimate of 10 per cent of the survey limits which appears prejudicial as holes located near a relief increase are filled. A coverage generated by fixing the radius disc according to the minimum depth cannot solve this problem. In presence of a too short erroneous sounding in the data set, the minimal coverage has no meaning at all, as it generates a high density of holes. The density of holes the adaptive coverage generates can be, on the opposite side, interpreted and thus used as a survey guide

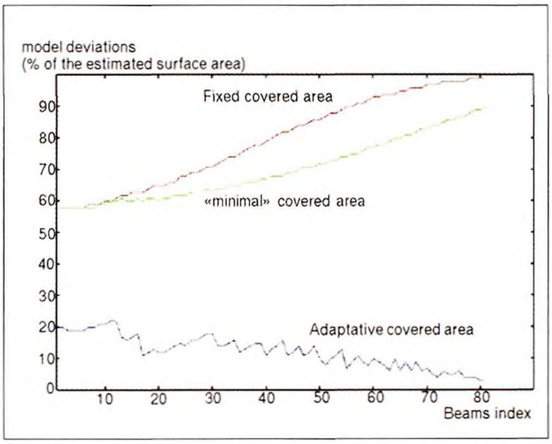

Figure 4(a): Surfaces deviations, in percentage of the estimated area per beam, Sounder Simrad EM12 Dual

Finally, this technique which is also used in the construction scheme of a hierarchical structure to store the coverage enables the classification and

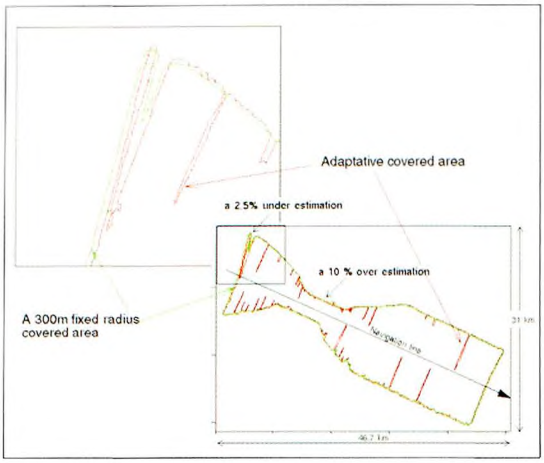

Figure 4(b): Comparison example between an adaptive and a fixed coverage. For more understanding, only the external contour lines are represented

extraction of 'holes' according to some specific criteria (surface area, maximal depth proximity, erroneous soundings rate ...).

Conclusion

The preparation, the management and the analysis of a bathymetric survey is based on a synthetic representation of the insonification area of a multibeam echo-sounder.

This article proposes an alternative construction scheme of a coverage based on a standard operation in mathematical morphology: the dilation. The originality of the approach here lies in its implementation. Using a uniform front propagation technique to process a dilation enables the running time to be optimised while increasing the accuracy. Its generalisation allows an adaptive coverage representation to be obtained, according to the relief and features of the echo-sounder in realistic processing time.

When used during a survey planning, it also allows the theoretical covered area, from a Digital Elevation model and the features of the echo sounder, to be simulated.

Finally, the hierarchical description provided is used to classify the doubtful (to some given criteria) areas of a survey. In the short-term, it will be useful to restrict the construction of terrain models.

References

1) Ragnemalm I. (1992), Fast Erosion and Dilatation by Contour Processing and Thresholding of Distance Maps. Pattern Recognition Letters, Vol. 13, No.3, pp. 161-166, Mar.

2) Jacq J. J. (1997), Elements de segmentation morphologique, Rapport interne Département Image et traitement de l'information de l'Ecole Nationale Supérieure des Télécommunications, pp-77 Dec.

3) Verwer B.J.H., Verbeek P.W., and Dekker S.T. (1989), An efficient Uniform Cost Algorithm Applied to Distance Transforms, IEEE Trans. on Pattern Analysis and Machine Intelligence, Vol. 11, No. 4, pp. 425-429, Apr.

4) Debese N. (1999), Détermination de la zone insonifiée par un sondeur multifaisceaux, Rapport d'étude du SHOM n°001/99 fév.

Biography

Dr Nathalie Debese received an engineer degree in Computer Science from the University of Technology of Compiegne (U.T.C. - France) in 1989, with an MSc degree in Statistics. She obtained a PhD in Systems Control in December 1992 for her research works at IFREMER (the French research for the exploitation of the sea), on the "learning registration of the navigation through bathymetric data". From March 1995 to September 2001, she has been involved into the 'multi-beam echosounder' project undergone with SHOM. In May 2000 she was awarded the Commodore Cooper medal of the OHI for her work on the detection of outliers in bathymetric data, and became in October 2001 an engineer (IEF) of the SHOM, assistant to the Chief of the multi-beam sounder project. Her research interests include automatic cleaning of bathymetric data, modelling of topographic surface, geometrical and morphological properties of digital terrain, algorithms for extracting feature information, for automatic cleaning of bathymetric data, and also algorithms dealing with registration problems.

E-mail: nathalie.debese@shom.fr