TOBI SIDE-SCAN PROCESSING WITH EDGE SEGMENTATION

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ABSTRACT

Digital side-scan sonar image processing techniques have been developed over the last ten years and successfully implemented on several sonar systems, such as the Mini Image Processing System (MIPS) for GLORIA imagery. Following the first trials of the Towed Ocean Bottom Instrument (TOBI), image processing of the sonagraphs has been a priority, converting and creating new software, whilst taking into account the different resolution, radiometry, geometry and other system characteristics of the TOBI vehicle. Correction for time-varying gain errors, slant-range and directivity are applied. Vehicle height above the seafloor is taken from the profiler record and cross-checked with an altitude obtained from the side-scan imagery using a small edge detector, thus improving the slant-range correction. Line dropouts and noise can be a major nuisance and distraction in the imagery.

The precise geographic positioning of the TOBI vehicle is an error-prone calculation. An initial estimate of position in the along track direction can be obtained using a cross-correlation of the ship's echo-sounder profile against the vehicle's profiler record. Good match of the profiles suggest the vehicle has passed over the same track as the ship but at a later time. This is shown to be quite reliable in areas of high bathymetric relief and with long straight tracklines. Prewitt and Deriche digital edge segmentation methods are used to find imagery boundaries. Thresholding, line following and line thinning techniques are used to tidy the segmentation pictures before the results are used for geological interpretation and further processing.

1. INTRODUCTION

TOBI (Towed Ocean Bottom Instrument) was developed by the Institute of Oceanographic Sciences Deacon Laboratory in the late 1980's and represents a new development in deep-ocean geological mapping. Since its first successful cruise in February 1990 it has been used extensively and large volumes of acoustic imagery created. The vehicle is towed at depths of up to 6000 metres at an altitude of about 400 metres above the seafloor. The two side-scan sonar arrays operate at 30-32kHz with a pulse repetition period of 4 seconds and a sampling rate of 1kHz, Murton [1]. This gives a nominal across-track pixel resolution of 0.75 metre and a total swath width of 6km. The vehicle has a variety of additional sensors, in particular a 7.5kHz sub-bottom profiler which has a sampling rate capable of providing 3.75cm vertical resolution.

As a compromise of the difference between sonar footprint resolution and the pixel resolution, the side-scan sonar imagery is averaged across-track and subsampled by a factor of eight. This has the effect of decreasing the otherwise extremely large dataset filesize. A further advantage is that it also increases the signal to noise ratio and produces a pixel size of 6 metres across-track. This latter property is consistent with the horizontal beam width of 0.8°, which combined with the 2.8ms pulse length, gives a footprint resolution of 9x4 metres at 100 metres range and 2x42 metres at far range (3km). If the ship surveying speed is 2 knots, the along-track pixel resolution is 4.11 metres and thus a 6 metre resolution mosaic grid is an attainable scale with better signal quality.

2. TOBI SIDE-SCAN PRE-PROCESSING

The TOBI side-scan sonar imagery when first acquired is recorded in the time-domain, each sample being 1millisecond wide and 4 seconds long. Interpretation by geologists requires the data to be in geographic map form at a known scale. The pre-processing stage is designed to remove as many of the acquisition system characteristics as possible without altering the information within the imagery. Most of the individual processing techniques are described in detail elsewhere, Le Bas [2]. A summary, however, is provided here together with the latest correction technique for vehicle altitude.

Following the initial acquisition of the data, it is transferred to the image processing host computer in a form averaged and subsampled by a factor of eight as mentioned above. As a consequence, this provides a width of 1000 pixels across-track, each pixel retaining its 12 bit precision. All pre-processing is carried out using the 12 bit data so as not to lose valuable detail during numerical analysis.

The series of processing stages start with the removal of the step-function in the time-varied gain (TVG) which was applied during acquisition. A smooth TVG is interpolated digitally and the data corrected, removing any background 'steps'. If TOBI operates at a depth of less than 1.5km, a direct reflection from the sea-surface is sometimes seen, appearing as a bright narrow linear feature parallel to the ship track on either side of the ship track. As the depth of the vehicle below the surface can be calculated from the water pressure, the position of the feature can be predicted, detected and removed. The surface reflection is replaced by interpolated data, using pixel values immediately adjacent to the reflection. It is possible that some slight information loss may occur due to real features being hidden by the surface reflection.

The TOBI vehicle has, as part of its main acquisition hardware suite, a high frequency (7.5kHz) sub-bottom profiler. It not only gives a high resolution profile of the seabed but also a value for the altitude of the vehicle above the seafloor. To be of useful resolution the profiler does not record a single sweep of 4 seconds sampling at one millisecond but windows the data down to 4000 samples in 200 milliseconds. In this way the 50 microsecond samples give a very high vertical resolution of 3.75cm. To achieve this resolution the first large return of the ping must be detected accurately using first break routines in order to window in correctly on the sub-surface returns. This must be done in real-time (during acquisition) otherwise the amount of data would be unmanageable. Most of the time this is achieved successfully, but occasionally the first large return is indistinct. Loss of lock is due either to seafloor sediments with low reflectivity or to suddenly changing altitude (such as a cliff face). The profiler therefore rapidly searches (digitally) for reduced altitudes in case the vehicle may be approaching the seafloor. User intervention on board ship usually redirects the windowing software but not without an intervening loss of altitude data.

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Part of the current image processing package is to correct the altitude data by passing a 280 second median filter across the altitude values. This removes most of the lost lock values, but unfortunately if the window loses lock for more than 280 seconds then this method fails and errors occur in the slant-range correction stage of processing. Thus another source of altitude data must be used to correct the profiler altitude dataset.

The raw TOBI side-scan imagery can provide a coarse resolution value for altitude by looking for the first large reflective return from either side. This first break should represent the seafloor directly beneath the vehicle, unless there is some interfering noise present. The precision of resolution of these data is 6 metres whereas the profiler is 160 times better. However this is not a problem as the required resolution for slant-range correction in this case is 6 metres. If both port and starboard side-scan images are used, the accuracy can be enhanced by correlating the two sides.

The depth provided by the profiler is taken as a starting point for the edge detection of the first break. A total range of ca. 330 milliseconds about this point is then used to predict the altitude and with this value the method tests for first break. Any differences greater than this must be altered manually; though fortunately this is very rare. A series of ratios (r_t) for all possible times is created by the product of the three pixel values before the predicted time for both sides divided by the product of the three pixel values after the predicted time for both sides. Mathematically the formula for the ratio at time t is:

$$r_t = \frac{\sum_{i=1}^{3} s_{t-i} \sum_{i=1}^{3} p_{t-i}}{\sum_{i=0}^{2} s_{t+i} \sum_{i=0}^{2} p_{t+i}}$$

where s_t is the starboard reflectance pixel value at time t, and p_t is the port reflectance pixel value at time t. A ratio value of 1.0 will mean that there is little change in reflectance values at time t, but a small ratio value means an increase of reflectance values at time t, and thus possibly being the first return. The best estimate for the first return is when the ratio is at a minimum. This therefore produces an altitude value for every swath. It is possible that single values in the imagery caused by system noise or ambient noise may create erroneous ratio values and thus spurious altitude values. If a non-recursive smoothing filter is applied to this series, the results are improved.

The two altitude datasets may then be compared. If the two values are similar then the minimum of the two is chosen. This shows that there is good control on the altitude and therefore any discrepancy is likely to be due to off-nadir bathymetric peaks or bad first return estimation. Thus the minimum value is thought to be more reliable. If the two altitude values differ by more than a threshold value then the maximum of the two values is used. This is done because if the profiler loses lock on the bottom, it will always underestimate the altitude. Taking the maximum of the two values ensures that the low altitude values given by the profiler will not be used. In the same way if noise in the water

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column gives a falsely low altitude value, this will be removed by using the maximum of the two values. Noise in the imagery that may give too low an altitude value is less likely, as the background level is relatively bright and thus, the noise value would have to be very high. Once the new set of altitudes is created from the minima and maxima calculations, it is again smoothed with a small non-recursive filter to remove any instabilities in the series.

Slant-range correction is the next image processing technique to be applied to the raw imagery data. The results now produced show a marked improvement on the shipboard imagery, having no 'footballs' and near-nadir pixels that match well on port and starboard sides.

It is at this stage that the full swath of imagery can be viewed. Several system artefacts are immediately recognisable and thus processing is required to remove them. Single pixels are seen that are considerably brighter than their surrounding eight neighbours. This is caused by ambient noise in the water column such as slip-ring squeak and speckle. Using a median filter and threshold curve, these points can be removed easily. Line dropouts are also

Figure 1. Fully pre-processed TOBI imagery of the Reykjanes Ridge about 58W and 32W showing the axial spreading ridge and associated rifting. The data have been slant-range corrected, together with removal of line-dropouts and speckle noise. A surface reflection has been removed at mid-range from both sides and data interpolated to fill the gap.

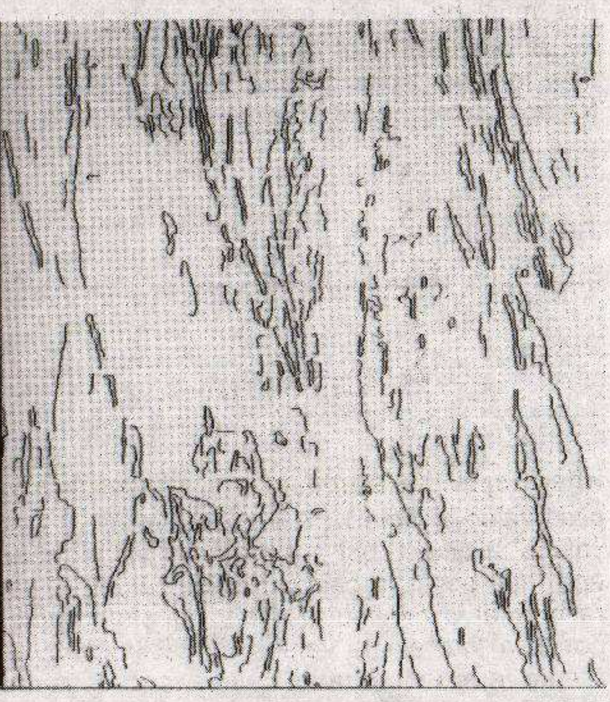

Figure 3. Edge segmentation image created by the Prewitt edge detection algorithm, using a mask size of 7 pixels (ca. 40metres). The image has been refined using edge strength and edge structure, which removes false-edges and makes sets of connected lines. This can now be used as an interpretational aid for the geologist. The source for this image can be seen in Figure 1.

removed using a thresholding technique utilising Otsu's criteria, Le Bas [2]. Shading corrections similar to techniques used on GLORIA imagery, Searle [3], are then used to equalise the illumination over the whole swath. These results show marked improvement near-nadir but as the range is much reduced and the directivity pattern is significantly better for TOBI than GLORIA, little difference is seen at far-range. The final pre-processing results are seen in Figure 1.

3. PROFILE MATCHING

Positioning of the TOBI vehicle can be error-prone, there being no absolute positioning variables available for the vehicle such as satellite navigation systems. Errors of up to two kilometres on vehicle position have been experienced. Acoustic beacons can be placed in a small network on the seafloor but this also has disadvantages, having only a small areal extent and being costly in time to deploy and calibrate. In some areas of high bathymetric relief, even this method is not viable as the beacons can be hidden in small valleys and canyons. However, one way of approximating the position of the vehicle is by calculating the relative distance between ship and vehicle, the former having relatively reliable positional data provided by satellites (e.g. GPS).

As the ship proceeds it collects data firstly from the TOBI vehicle and secondly using an onboard 10.5 kHz echo sounder, and the proposal is to compare the data from these two separate sources. The TOBI profiler and the TOBI pressure sensor can be used to provide a total water depth at every point as the vehicle proceeds. Similarly the echo sounder produces a seafloor bathymetric profile below the ship. The method is to correlate the two bathymetric profiles and to calculate the time lag between the TOBI vehicle and the ship passing over the same piece of seafloor (see Figure 2). An assumption made here is that the

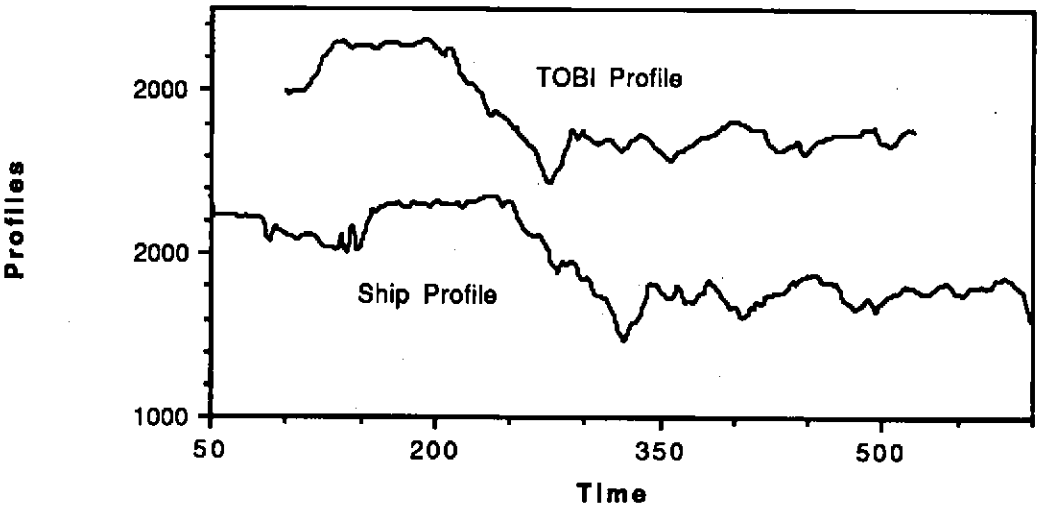

Figure 2 The ship's profile of the seafloor compared with TOBI's profile. Good correlation is seen between the two profiles. The variations in time lag of the TOBI vehicle behind the ship is also evident when the peaks and troughs in the profiles are compared.

vehicle follows the exact path of the ship. This is generally acceptable so long as the ship does not deviate from a straight line and there are no ocean bottom currents pushing the vehicle sideways. The first of the assumptions is relatively simple to check by looking for changes in bearing on the ship's track. Unfortunately little is known about ocean bottom currents which may push the vehicle sideways. Times when the ship is going round a corner or there are known ocean bottom currents, other positioning methods must be used.

The two bathymetric profiles are obtained from their separate sources. The profiles are sampled every two minutes, as the speed of the vehicle is unknown. As the ship travels in front of the vehicle both profiles will not start at the same instant. An extra 90 bathymetric values are taken at the beginning of the ship's profile, allowing a maximum time lag of the vehicle behind the ship of three hours. The TOBI profile is used as the movable template on a fixed ship-profile. A cross-correlation of the two profiles is taken, and the least squares difference taken to provide the best fit is:

$$CC_d = \sum_{i=1}^{n} \frac{\left(s(i+d) - v(i) \right)^2}{n} \qquad \text{and}$$

$$d^* = \text{Arg Min } CC_d$$

where d is the time interval between the ship and vehicle passing over the same piece of ground, which can be anything from 2 to 180 minutes, CC_d is the cross-correlation coefficient at time interval d, s(i) is the ship's bathymetry value at time i, v(i) is the vehicle's bathymetry value at time i, n is the number of profile points on the vehicle profile and d^* is the optimum time interval for the whole pass.

An assumption here is that the time lag of the vehicle is constant during the pass. Two difficulties arise here: firstly the cable deployed is being altered periodically and secondly the ship speed is not constant. Both of these alter the geometry of the towing system and hence the distance of the vehicle behind the ship. Thus the value of d^* can be taken as a guide-line for recalculating the individual time lags with a smaller window. The window size is tempered by the maximum physical cable haul speed and ship's acceleration. Cross-correlation indices are then calculated for every point and the resulting time-lags recorded. Inconsistencies in these data, due to mis-correlation of features and the breakdown in the initial assumptions, are minimised by reducing the amount of freedom on the cross-correlation. A set of time-lags is now available that can then be used to position the vehicle using the vehicle time minus the time-lag giving a ship time and thus a position. The geographic data are then copied from the ship's navigation file onto the header information of the TOBI imagery and in this way the positional data are available for further processing and analysis.

4. EDGE DETECTION

There are two objectives to edge detection. Firstly it is to provide quantitative control on the usual interpretation maps created from shipboard mosaics by the geologist. This cannot completely replace the interpreter but is a major addition in data confidence. The second, and possibly more important, objective of edge detection is to implement edge feature based registration methods, thus co-registering two segmented images such as TOBI imagery and Hydrosweep bathymetry. Several edge detection techniques have been developed for remotely sensed images, mainly for region extraction, line extraction, calculation of region attributes and region merging. A range of algorithms are readily available for the extraction of regions. An edge detecting algorithm is the first processing technique required and include the Sobel, Nevatia, Prewitt and Deriche algorithms, of which the latter two have been found successful in sonar imagery because of the paucity of the signal-to-noise ratio.

The edge detection task can be divided into three main stages: (1) initial edge detection; (2) refinement on edge strength; and (3)refinement on edge structure, Swayer [4]. These are explained briefly here. The Prewitt algorithm, Prewitt [5], is relatively simple to compute, calculating the magnitude and direction of edge gradients from a grey level image by applying the convolution of two masks of the form:

$$\begin{matrix} 1 & 0 & -1 \\ 1 & 0 & -1 \\ 1 & 0 & -1 \end{matrix} \qquad\qquad \begin{matrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{matrix}$$

The mask shown here is 3x3 but can be variable to any size. The total magnitude of edge is taken as the mean square of the sums of the vertical and horizontal gradient magnitude images. The direction is computed by the tangent of the ratio of magnitudes of the horizontal and vertical gradient images. The Deriche algorithm, Deriche [6] is more computationally intensive but calculates the two orthogonal gradient images as with the Prewitt method. With the Deriche algorithm, Canny's design for a solution for precise formulation of detection and localisation for an infinite extent filter, Canny [7], leads to an optimal operator which can be efficiently implemented by two recursive filters. It can provide good localisation, good detection and a single response to an edge. One parameter (α) is required to balance the criteria of localisation and detection. A value of 2.0 for a would give better positioning though worse actual detection. However, a value of 0.5 for a provides better signal to noise ratios and thus better detection but worse positioning. The optimal edge detector used has an impulse response of:

$$g(x) = k.x.e^{-\alpha|x|}$$

which when extended to the 2D case gives two masks (of size m by n):

$$X(m,n) = \frac{-c.m.e^{-\alpha|m|}.k.(\alpha|n|+1).e^{-\alpha|n|}}{\alpha^2}$$

$$Y(m,n) = \frac{-c.n.e^{-\alpha|n|}.k.(\alpha|m|+1).e^{-\alpha|m|}}{\alpha^2}$$

$$\text{where } c = \frac{(1-e^{-\alpha})^2}{e^{-\alpha}}$$

and $$k = \frac{(1 - e^{-\alpha})^2 \cdot \alpha^2}{(1 + 2\alpha e^{-\alpha} - e^{-2\alpha})}$$

The resulting horizontal and vertical gradient images, X(m,n) and Y(m,n) are then combined to make magnitude and direction images.

Refinement on the edge strength imagery is now required. Thus the edge magnitude image is initially non-maximum suppressed. This discards the false-edge pixels which are not a maximum according to their nearest neighbours along the gradient direction (across the edge line). Hysteresis thresholding can also be used to remove false-edge pixels. Instead of defining a single magnitude threshold, below which all points are discarded, two threshold values are defined. Any point above the higher threshold value is immediately kept. An entire connected edge segment is also retained as long as each point it contains lies above the lower threshold and has at least one point above the high threshold. All points below the lower threshold are discarded.

Edge structure can also be refined, to provide long thin webs of data, a web being a set of connected edges. Edge thinning provides edges of 1-pixel thickness by erasing elements if they do not belong to the medial line. A threshold is then applied to the lines and webs according to size. A minimum of points per line and a minimum of points per web are set to remove small dashes and dots from the edge image. During this stage the raster imagery (iconic data) is converted into a vector database (symbolic data). This aids the computation and allows easy editing. Conversion back into imagery is done so that the data can be viewed.

The output created by edge detection (see Figure 3) represents a more succinct and higher level description of the original imagery. All the images processed are of a size 256x256 pixels thus large images are sub-divided into tiles of this smaller size. The positions of the tiles are chosen so as to have overlapping edges and thus removing tile edge effects from edge detection process. At this stage geological interpretation is possible. The webs and lines, of course, only show lines of difference in reflectance. Topographic features such as ridges, slumps, and seamounts show up very well on the edge imagery. Lithological boundaries such as the edge of a lava flow over turbidities, and longitude shear patterns are also visible on the edge segmentation imagery. Interference fringes, Huggett [8], are also picked out by the segmentation process, which are a system artefact and must be ignored by the interpreter. However, it has been suggested that these interference fringes may be used to calculate isopach maps of the seafloor surface sediments.

5. CONCLUSION

The development of an image processing and analysis system for the TOBI dataset has proved to be a challenging task. So far over 200 programs have been created, containing over 8000 lines of Fortran and C code, running in either a VAX/VMS or UNIX environment. The final result is a software set which can provide a solid base for further development. The suite of pre-processing algorithms is now virtually complete. The system artefacts can now be filtered out, with the proviso that the information content of the imagery has been altered as little as possible, and this has been relatively successful. The slant-range calculation has been significantly improved by using the first-break on the side-scan imagery to aid altitude calculations. The assumption of level across-track topography that the calculations use is, however, more problematic for TOBI data than for GLORIA, as minor changes in bathymetry can now make major differences in range. The further addition of across-track bathymetry from a gridded Hydrosweep survey, for example, therefore could improve the slant-range correction. To gain registration of the two datasets is, unfortunately, not simple. This is mainly due to the error-prone calculations for TOBI positioning. Profile matching can account for over 80% of the variation in the position correlation. Much of the remaining percentage must be found using the bathymetry grid for data registration and advanced slant-range corrections.

The results produced so far show marked improvement on previous capabilities and have aided interpretation. Not only does processing allow a cosmetic improvement to the imagery it also provides data confidence and a degree of quantitative control. In this way two-way information transferral between the sonar community and the much wider remote-sensing community is eased and reinforced collaboration and cooperation. It is this collaboration that has led to great strides being achieved in edge detection. Continuing with this relationship, further goals are now being realised, such as data registration, region segmentation, texture processing, texture analysis and calculation of region attributes such as backscattering coefficients and speckle determination.

6. REFERENCES

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