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OFF-LINE CONTOURING OF THE DATA FROM THE MULTIBEAM SEA BEAM

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The development of the Sea Beam processing system was undertaken in 1977. We now have available a complete system for off-line play-back of the Sea Beam data right up to precise isobath contouring along the ship's track. The problem of combining the data from several profiles has not been tackled, but nevertheless a notable improvement has been made over the real-time output of the system.

Although most of the algorithms do not deserve detailed description, it seems of interest to present the method used for contouring separately, endeavouring to show its advantages and disadvantages by concrete examples. We will then try to draw some conclusions which may be of help in furthering our programme. Finally, other applications are given which describe the processing system's results without going into details about the algorithms used.

1. THE SEA BEAM SYSTEM

The Sea Beam multibeam sonar system has been previously described in the *International Hydrographic Review* by J. P. ALLENOU and V. RENARD [1]; we therefore give here only a summary of its characteristics pertinent to a discussion of its processing sub-system.

Sea Beam allows simultaneous measurement on either side of the vessel of up to 15 depths on 16 beams, 2 2/3° in width, aligned perpendicular to the ship's axis.

The system measures round trip pulse travel times which can be transformed to oblique distances provided that the speed of sound in the water column is known. These oblique distances are then converted—after compensation for roll (pitch is allowed for at the time of transmission)—into horizontal distances and depths, the speed of sound being always taken into account; the depths are computed using a constant sound speed of 1,500 m/sec. The measurements considered by the system to be erroneous or non-existent are replaced by zero.

The data are recorded on magnetic tape, annotated with the time and the ship's heading, and then utilized in practically real-time contouring. The magnetic tape generated, together with navigational data, permits later off-line processing. The limited performance of the real-time contouring can be improved by more sophisticated software and therefore a detailed description of it will be given for purposes of comparison with our off-line processing development.

Real-time contouring by the Sea Beam system

The real-time system has a very heavy workload, and this necessitated a certain number of simplifications. Some matters were not treated in the manufacturer's manual and thus remain uncertain. The general principle, however, would appear well known.

The ship's heading is taken as constant—and this permits use of a narrow-width plotter and facilitates the generation of a rectangular grid of soundings. There are resulting errors in position and in contouring when the vessel yaws or drifts, and the plot is rendered completely useless when the vessel makes a major course change.

Speed was initially manually input and remained constant throughout fairly long intervals of time. A recent modification allows us to introduce automatically the speed through the water (log speed) every second. This speed is not of course the ground speed, for the wind or current drift is not exactly known until later.

The grid used for contouring has a fixed interval of 5 mm in both directions—one being parallel to the axis of the vessel whose direction is taken as constant (i.e. the longitudinal direction), and the other perpendicular to this axis (i.e. the transversal direction). In the latter direction a 5 mm interval is too small and some interpolation between measurements is necessary. However, in the longitudinal direction the interval is too large and the system has to average the data, and the results are thus smoothed. An example will illustrate this point.

Given a survey at 8 knots in depths of 2,000 m and at a scale of 1:10,000. The Sea Beam sweeps a swathe about 1,500 m wide, over which 15 soundings are obtained. The interval between two soundings on the plot is thus more than 10 mm, and so in the transversal direction every other value has to be interpolated. In the longitudinal direction, however, there is an interrogation every 3-4 seconds, representing about 16 m at a speed of 8 knots, i.e. 1.6 mm. There are thus 3 soundings per 5 mm interval, and we are obliged either to average these or to neglect two thirds of them. In both cases, the result is a loss of data.

When the density of contours is too great the system does not have enough time to plot everything and it leaves blanks.

The principle of contouring within the grid is very simple, as the lines are fairly angular, and it is probably very close to a linear interpolation.

The major disadvantage of exploiting the data in real time is that we are obliged to work at the maximum scale, otherwise we would lose accuracy. Thus, for example, if we are working at 1:20,000 in depths of 1,000 m, we obtain a sounding every 2.5 mm on the plotter. Therefore in the transversal direction we would need to take the average over two soundings, and this is unacceptable. We should thus work at 1:10,000.

2. THE PRINCIPLES ADOPTED FOR DEVELOPMENT OF SOFTWARE FOR OFF-LINE CONTOURING ALONG A SINGLE TRACK

THE MAIN ALGORITHMS

2.1 Definition of objectives

2.1.1 The accent was first of all put on computational speed and on minimizing memory use, as we wish to implement our programs aboard ship and to avoid overloading the office computer when the routine is finalized.

2.1.2 Plotting time was considered unimportant, in the first phase at least.

2.1.3 The chosen algorithms should allow contouring of raw data as well as the possibility of smoothing when required.

2.1.4 We considered that it would often be necessary to redraw the contours by hand, mainly in order to ensure that the swept swathes are correctly placed alongside two adjoining profiles. An angular plot and an irregular arrangement for the ticks indicating the slope direction is therefore permissible.

2.1.5 In view of the great number of soundings, a certain proportion may be neglected, provided that this proportion remains very small.

2.2 Algorithms

2.2.1 GENERAL

We chose to work cycle by cycle (*) in order to minimize memory time, the considerations mentioned in 2.1.4 making it possible to plot the contours as and when wanted, without taking account of their continuity.

(*) A complete sequence of transmission and reception is termed a cycle; by extension the term here designates the total number of soundings taken during one whole cycle.

It can be seen that the soundings form an irregular grid; but it is quicker to contour in this irregular grid than to form a more regular one.

The problem then arises of the intersection of two cycles within the swept swathe, the result of the ship's heading not remaining constant. It is simpler to delete the soundings which fall behind the preceding cycle for the problem does not often occur when sea conditions are good. However, when conditions are poor there are usually other disturbing features (e.g. bubbles under the hull) which degrade the soundings to a much greater degree. We have thought to minimize this deficiency by the creation of an artificial cycle based on soundings from a cycle that would fall between the preceding cycle and the one before that. Information would then only be lost in extreme cases, e.g. during turns. The number of intersections of successive cycles can also be reduced by averaging several cycles, which has the effect of smoothing the contours but also of reducing the slopes of smaller undersea features.

2.2.2 SMOOTHING

It seems desirable, for some areas at least, to smooth out the irregularities of bottom relief. This is done theoretically, by averaging positions and soundings for individual beams from several successive cycles. This smoothing is also necessary when plotting at small scales (less than 1:25,000).

In practice we used a slightly different method in order to optimize computing time. The unsmoothed data at the final stage appear as the values of soundings and the corresponding distances to the ship, together with the ship's position and the sine and cosine of ship's heading. Instead of averaging the positions of all soundings, we average the ship's positions (central beam), the sines and cosines of successive headings and the corresponding distances. This is valid to within second order accuracy, as is shown below.

Let X_N be the ship abscissa and X the average of n successive soundings which are at distances d_i ($i = 1, n$) from the corresponding X_{Ni} ship positions on cycles having azimuth α_i ($i = 1, n$).

Strictly, we should compute:

$$X - X_N = \frac{1}{n} \Sigma d_i \cos \alpha_i \quad \text{with} \quad X_N = \frac{1}{n} \Sigma X_{Ni}$$

But in fact we compute:

$$D = \frac{1}{n} \Sigma d_i \quad \text{and} \quad C = \frac{1}{n} \Sigma \cos \alpha_i$$

The d_i and the $\cos \alpha_i$ are close to D and C. Let us now put:

$$d_i = D + \epsilon_i \qquad \cos \alpha_i = C + \eta_i$$

$$X - X_N = \frac{1}{n} \Sigma (D + \epsilon_i)(C + \eta_i) = DC + \frac{D}{n} \Sigma \eta_i + \frac{C}{n} \Sigma \epsilon_i + \frac{1}{n} \Sigma \epsilon_i \eta_i$$

The $\Sigma \eta_i$ and $\Sigma \varepsilon_i$ are both zero. The error is thus:

$$\frac{1}{n} \Sigma \epsilon_i \eta_i$$

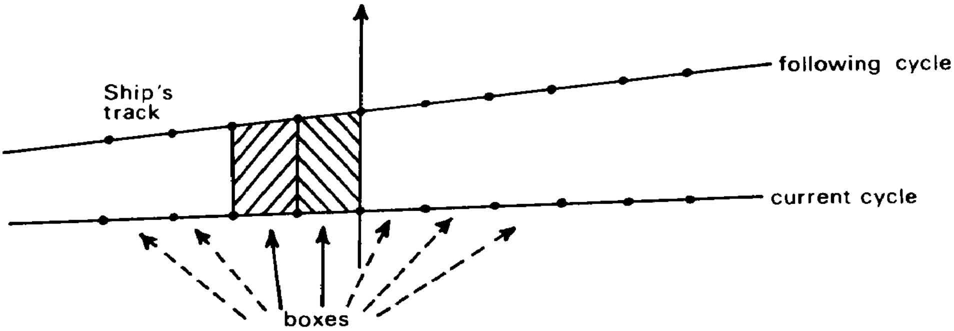
which is of second order. The same demonstration applies to the product of the $d_i \sin \alpha_i$.

When some of the soundings are zero, that is, when the values are considered by the system as erroneous or non-existent and are replaced by zero, we average the non-zero soundings if they constitute more than half the number of averaged cycles. This introduces a filtering that eliminates some of the erroneous data, which are often spot soundings.

2.2.3 PLOTTING OF CONTOURS

Organization of cycles

We work on two successive cycles and in each we successively explore each "box" (the quadrilateral whose corners are the adjacent soundings for two successive cycles, as illustrated below).

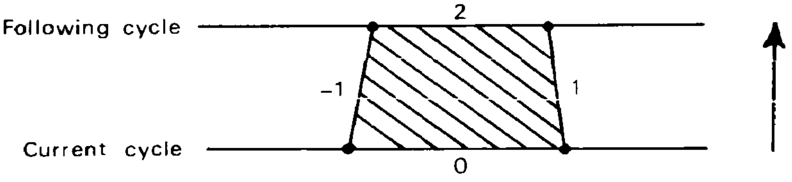


The boxes are numbered by the sequence of their port corner in the current cycle.

Each cycle contains a maximum of 15 soundings, but the ship may roll and this displaces the vertical beam. We therefore worked on a buffer with two more beams on each side, but this limit is rarely reached. Furthermore, for facilitating the algorithm computations, we added a zero sounding to each end of all cycles, so as to automatically stop plotting without an additional test. We are in fact obliged to make a systematic search of the box soundings to see that none of them are zero. If one at least is a zero, the contours are not plotted. The cycles are swept alternately from port to starboard and from starboard to port in order to optimize the plotting.

Plotting the contours within a basic "box"

It is obvious that a contour entering the box on one side must necessarily exit by at least one other side. If there is only one other point of exit, there is no problem. However, if there is more than one exit, then there will perforce be three, i.e. we are dealing with a "saddle" point. There are then two possibilities, according to whether the area between the two segments of isobaths contains high or low points. We chose the first alternative, high points, following usual hydrographic practice. The real-time software, however, crosses the contours, which is physically quasi-impossible. In any case the density of the information provided by the Sea Beam reduces the gravity of this problem whose solution would have little influence on plot quality. For ease of programming a code has been attributed to each side of the 'basic' box, as illustrated below:



First the 0 side is explored to find the exit of each entering contour; this exit may be on any of the other three sides. In the case of a "saddle" point there are exits on the other three sides. The positions of the intercept extremities are calculated by linear interpolation of the positions in proportion to the number of sounding values shown. The two extremities are joined by a segment of a straight line which is plotted as soon as the coordinate computations are completed. The numbers for the contours that exit on each side are recorded.

Side 1 is next explored for additional contour intercepts, but without going back over the already plotted contours (those from side 0). The exit sides can only be sides − 1 and 2.

Finally side − 1 is explored, without going back over the already plotted contours (those from sides 0 and 1). The exit side can only be side 2.

Preparation of contours

The ticks, which indicate the slope direction (i.e. downwards) are drawn from the intercept ends every other cycle to avoid having two sets of ticks with different directions at the same point. The rectangularity of the ticks and the contouring is to within 22° 30′ (trigonometric function computations are thus avoided).

The contour values are labelled at least every other cycle, alternately on one side and then the other of the contoured swathe (or else in a blank caused by a lack of data). The straight line joining the base of the labelling figures is an extension of the corresponding contour.

The problem of turns

The preceding algorithms work well when the ship follows a fairly straight course. At the turnings, those parts of cycles located inside the bend fall behind the preceding cycles, and this means that the contours

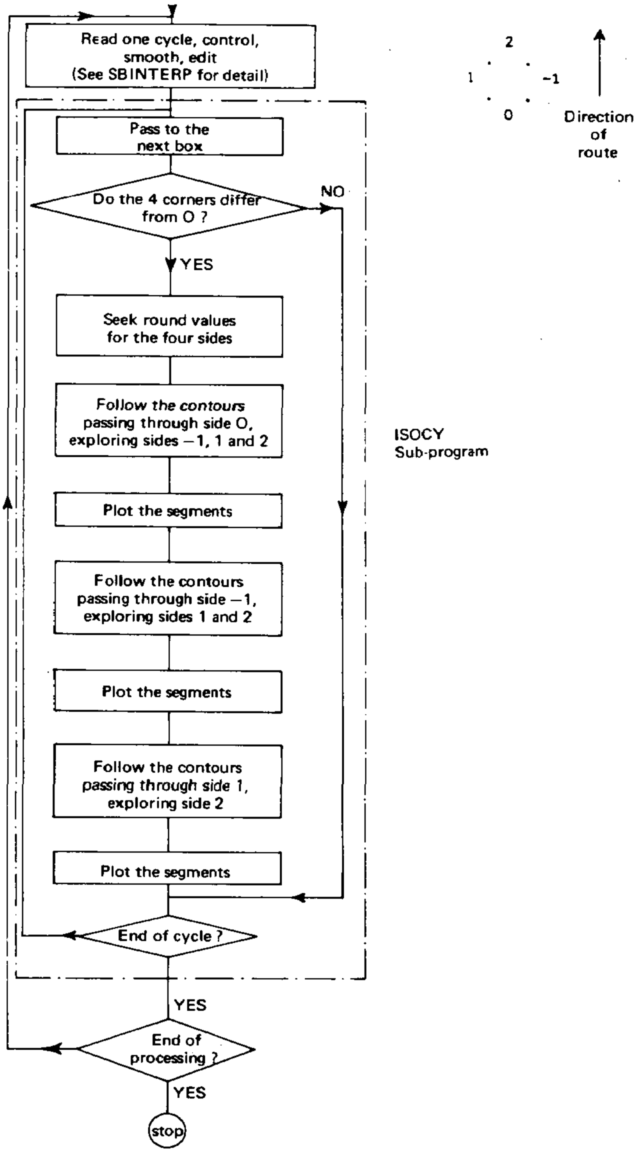


FIG. 1. — Flow diagram showing contouring principle.

are superimposed. Since navigation is relatively poor in turns, it is impossible to combine the various soundings that have been obtained around one and the same point. We therefore added an additional test routine, which does not figure in the standard program so as not to increase the computation time. This test consists of a search to determine whether the soundings are forward or behind the so-called "extreme" cycles that are retained in a buffer. These "extreme" cycles are defined by the following criteria:

— The subsequent cycles cut them at points closer to the ship than their own point of intersection with the last cycle retained in the

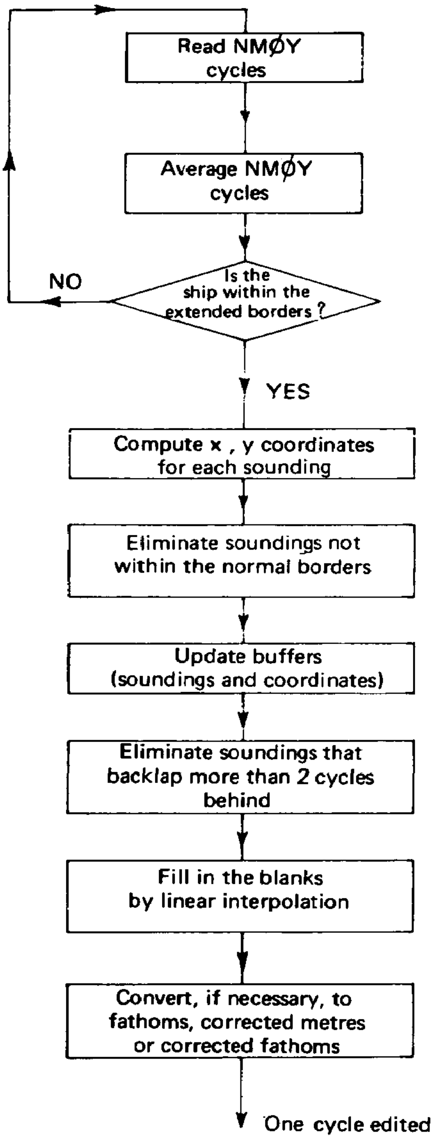


FIG. 2. — Flow diagram showing principles of reading and editing (SBINTERP sub-program).

buffer; all these points of intersection are closer to the ship than the half-width of a cycle; the half width of a cycle is fixed at 0.4 × P, where P is the depth of the vertical beam.

— Also retained are the cycles where the point of intersection with the subsequent cycle changes side, but always within a half-width of a cycle.

— The last cycle processed will systematically replace the last cycle in the buffer when their intersection is at more than a half-width of a cycle from the ship.

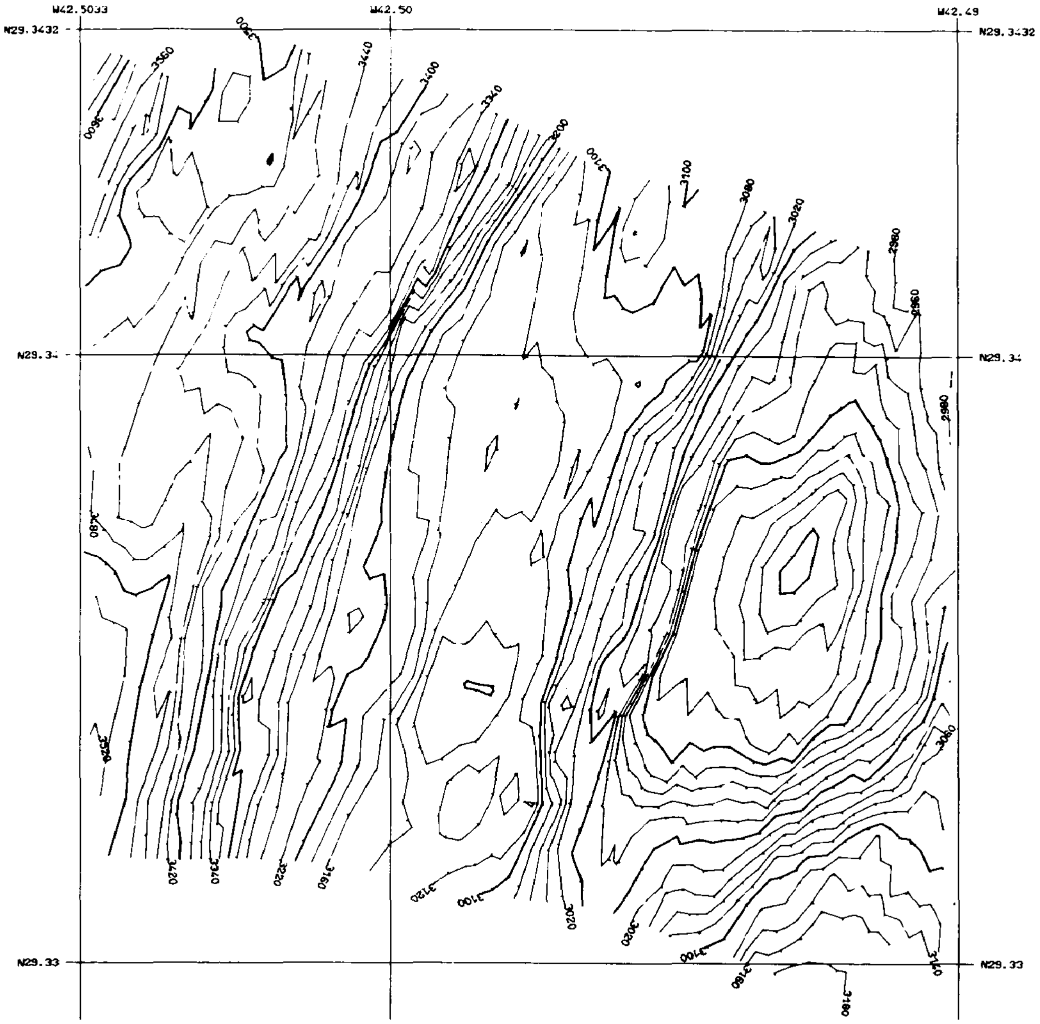


FIG. 3. — Contouring of raw data in an area of steep slope. Original scale 1:10,000.

2.3 Development

The program input consists of the positions and headings of the ship at each cycle and the tables of soundings and distances perpendicular to the ship's axis (the X, Y file). First the geographic grid is plotted (using an ALTAS cartographic plotter), and then the contours, according to the flow diagram presented in figure 1. The principles of reading and editing are described in a second flow diagram (fig. 2).

The only point not mentioned in the preceding section is the test on "extended" borders. In order to speed up processing, we define these "extended" borders as the initial borders increased by the maximum width of a cycle, and we know that if the ship is not within these borders there can be no soundings within the "normal" borders.

3. APPLICATION TO SOME EXAMPLES

The examples given here are all from the VEMA campaign which was one of the first to truly exploit the Sea Beam [2]. It has been necessary to reduce the illustrations in size, and thus the scales mentioned are about twice too large.

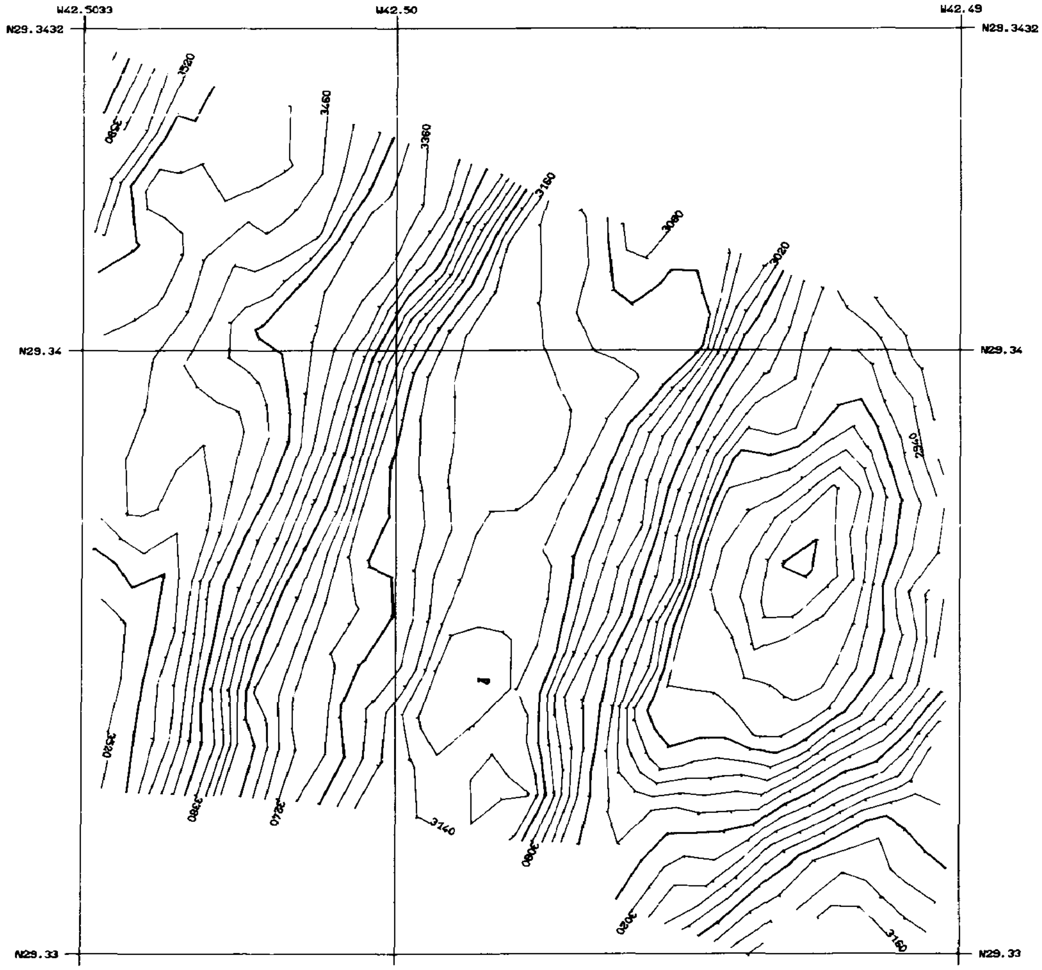


FIG. 4. — Same area as fig. 3. Smoothing by averaging over two cycles. Original scale 1:10,000.

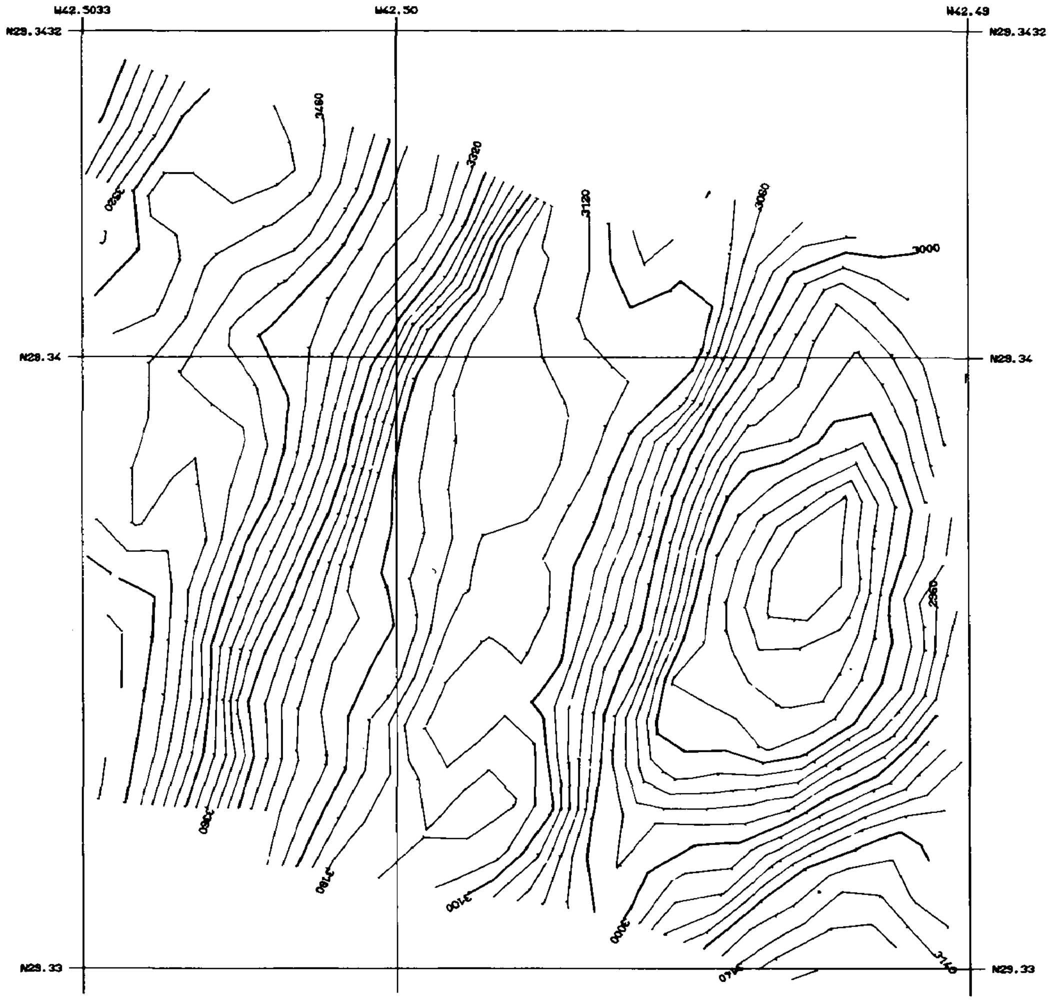


FIG. 5. — Same area as fig. 3. Smoothing by averaging over three cycles. Original scale 1:10,000.

3.1 Smoothing at large scales

GOOD QUALITY DATA IN AREAS OF STEEP SLOPE (Atlantic Rift)

Figure 3 gives an example of off-line contouring with raw data and without smoothing (scale 1 : 10,000). Figures 4, 5 and 6 give the contours at 1 : 10,000 in the same area, averaged on 2, 3 and 4 cycles respectively (the number of averaged cycles is NMØY). Figure 7 is an enlargement at 1 : 10,000 of the real-time plot.

Sharp variations of slope can be noted on figure 3, but these are completely smoothed out on figures 4, 5, 6 and 7. On the other hand figures 4, 5 and 6 show no important morphological differences. Such sharp variations of slope could be attributed to measurement errors,

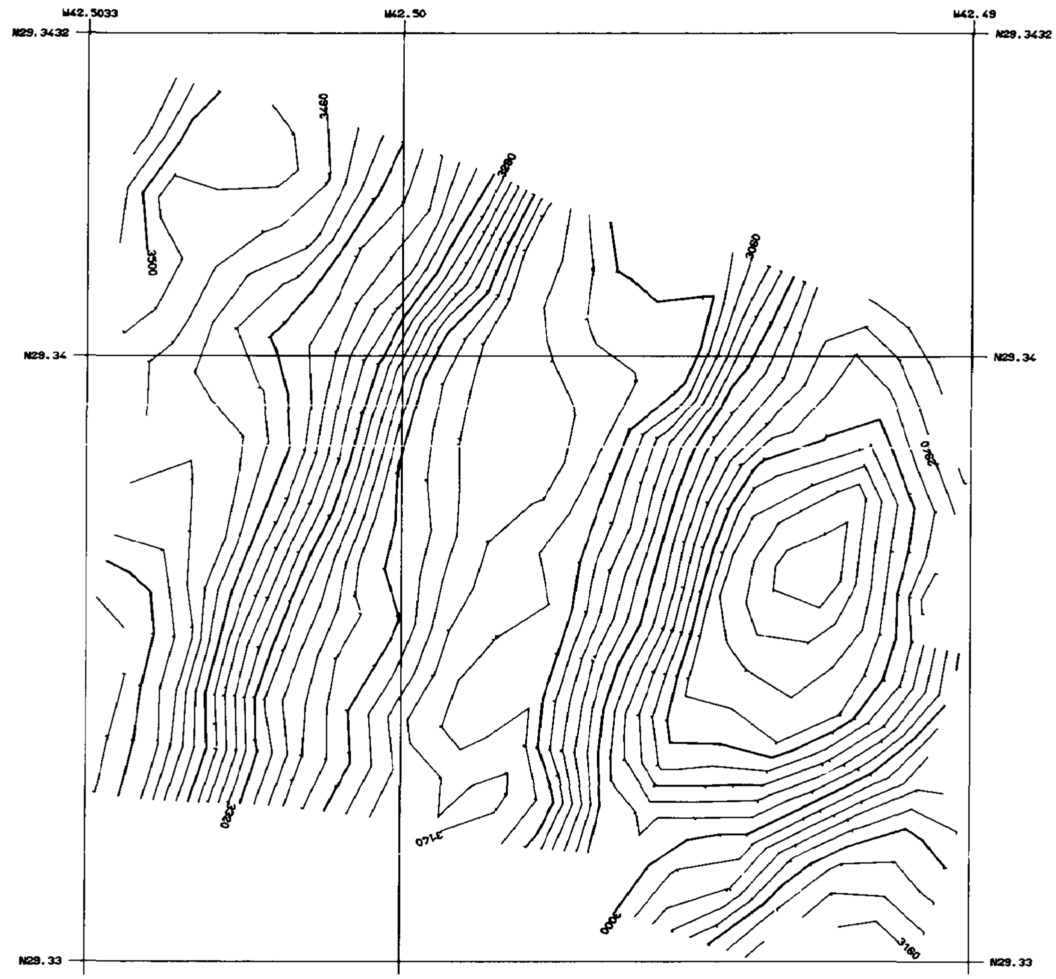


Fig. 6. — Same area as fig. 3. Smoothing by averaging over four cycles. Original scale 1:10,000.

since a whole cycle can fairly often be in error, and when the sounding has a constant error this leads to an effect similar to the one we are seeing here. This effect can be better observed over a flat bottom. It is however probable that in this particular case the irregularities observed correspond to the actual bottom relief. This is because this type of relief is characteristic of the internal valleys of mid-ocean rifts, and also because some of the features run obliquely to the cycles and are also noted on at least two cycles (see figure 3). This means that their origin cannot be attributed to an erroneous cycle. These effects are discussed in more detail in reference [2].

In brief, it will be seen in this example that off-line contouring of the raw data leads to a better definition than real-time contouring (fig. 7). This is chiefly the case when the ship's route is perpendicular to the principal structural directions.

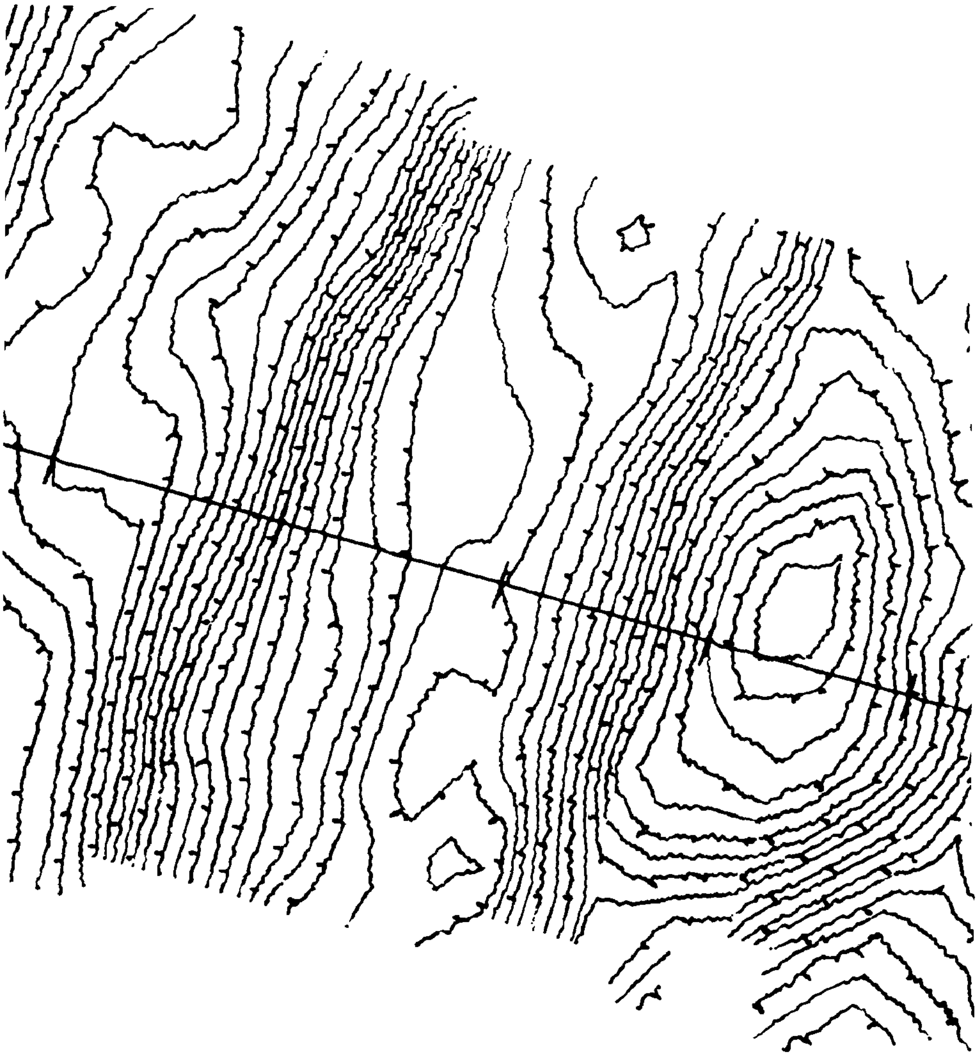


FIG. 7. — Same area as fig. 3. Enlargement of the real-time contouring. Original scale 1:10,000.

GOOD QUALITY DATA IN AREAS OF SMALL SLOPE

In areas where the slope is small the imprecision of the measurements will render the plotted contours highly variable and tangled—to the point of becoming unusable for interpretation (see figure 8). It is likely that some of these fluctuations do in fact reflect reality, but at present it is impossible to separate these errors from the real values we are endeavouring to measure. We can, however, highlight the mean directions of contours by a drastic smoothing (figure 9).

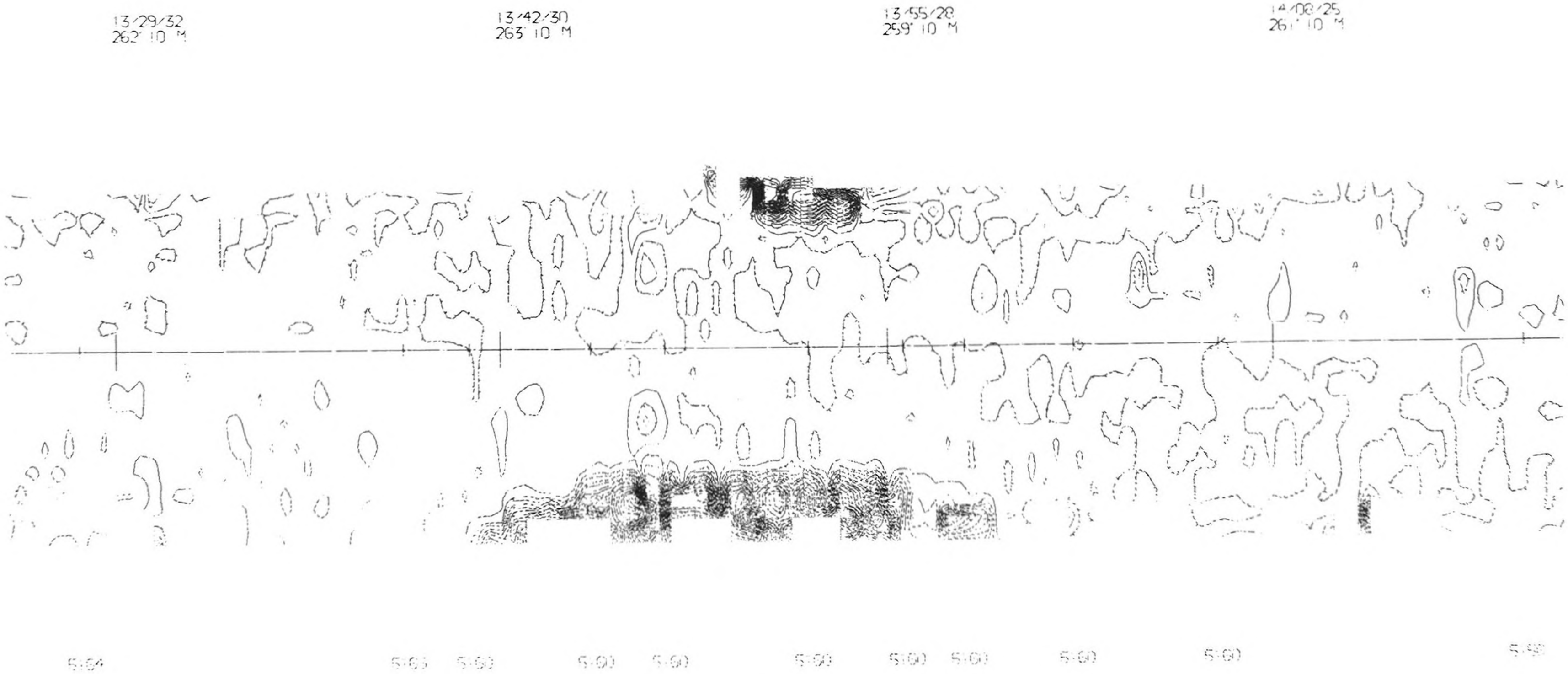


FIG. 8. — Small slope – The real-time plot.

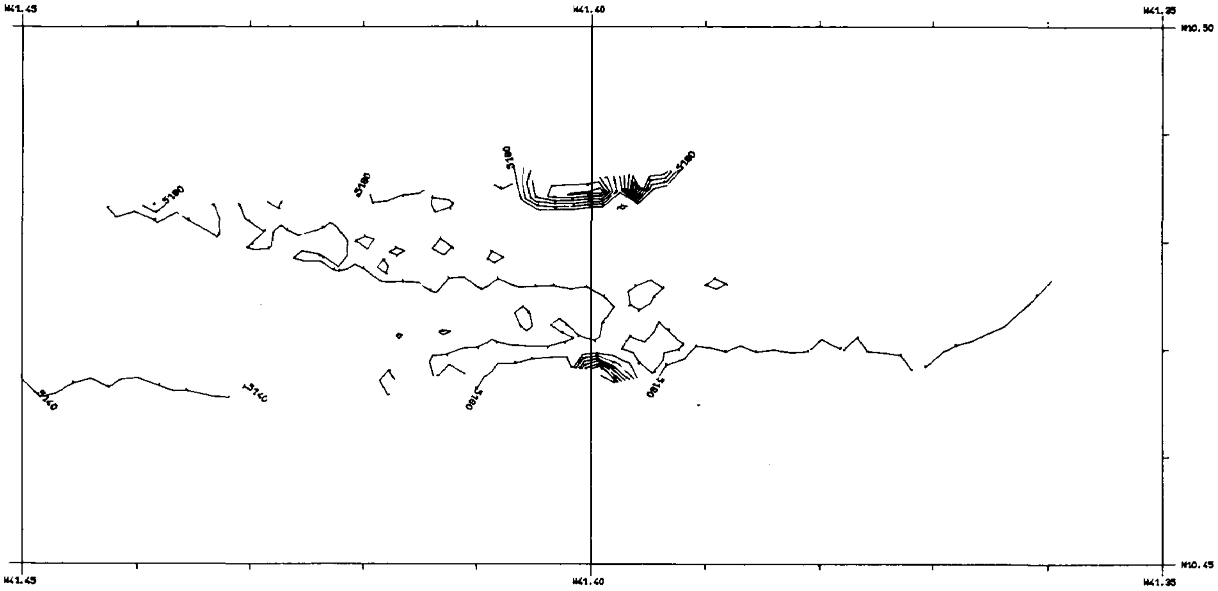


FIG. 9. — Same area as fig. 8. Smoothing by averaging over 50 cycles. Original scale 1:50,000.

ANOMALOUS DATA

It can happen that the data are anomalous, principally when heavy seas are running. Figure 10 is an example. Note in particular that the errors are aligned by cycle, as shown by the direction of the anomalous contours which run perpendicular to the ship's route. A smoothing over two cycles (figure 11) reduces these anomalies almost entirely.

CONCLUSIONS REGARDING SMOOTHING

The spectral density of the variance of measurement anomalies is concentrated around the cut-off frequency (1/2 × cycle width). Relief features in the same frequency band (taking speed into account) can be masked by a strong noise or confused with a weak noise. The most "realistic" features are those which are perpendicular to the ship's track. The step-type features are the most plausible, especially when they "mark" several successive cycles. On the other hand, isolated peaks or blanks are most improbable, on account of the beam width.

3.2 Smoothing at small scales

Smoothing with the aid of the algorithms presented permits plotting for scales of up to about 1:300,000. At smaller scales, the ticks become too dense and too long. Figures 12 and 13 show examples at 1:100,000 and 1:300,000. The validity of the smoothing method is evident at the

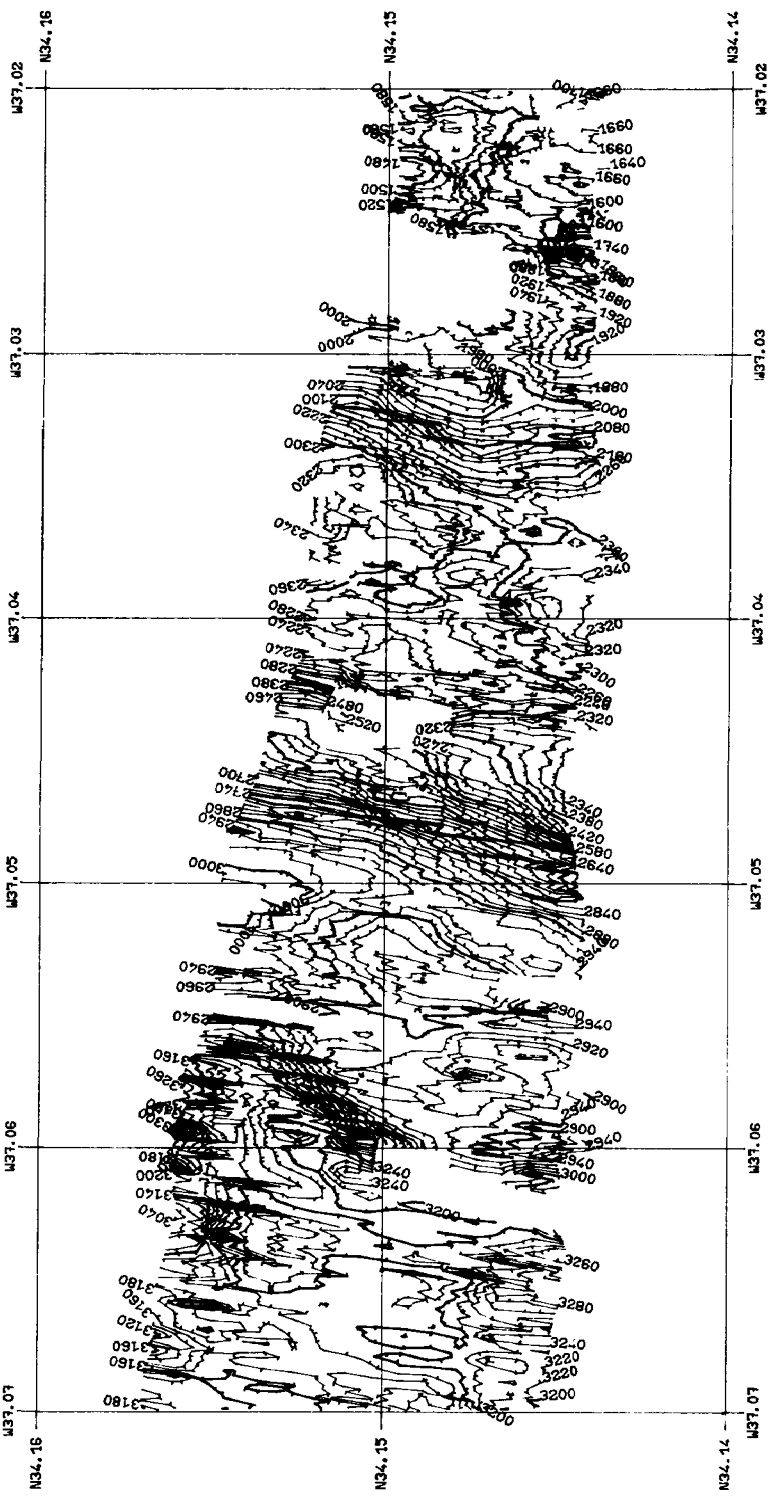


FIG. 10. — Anomalous data. Contouring of raw data. Original scale 1:25,000.

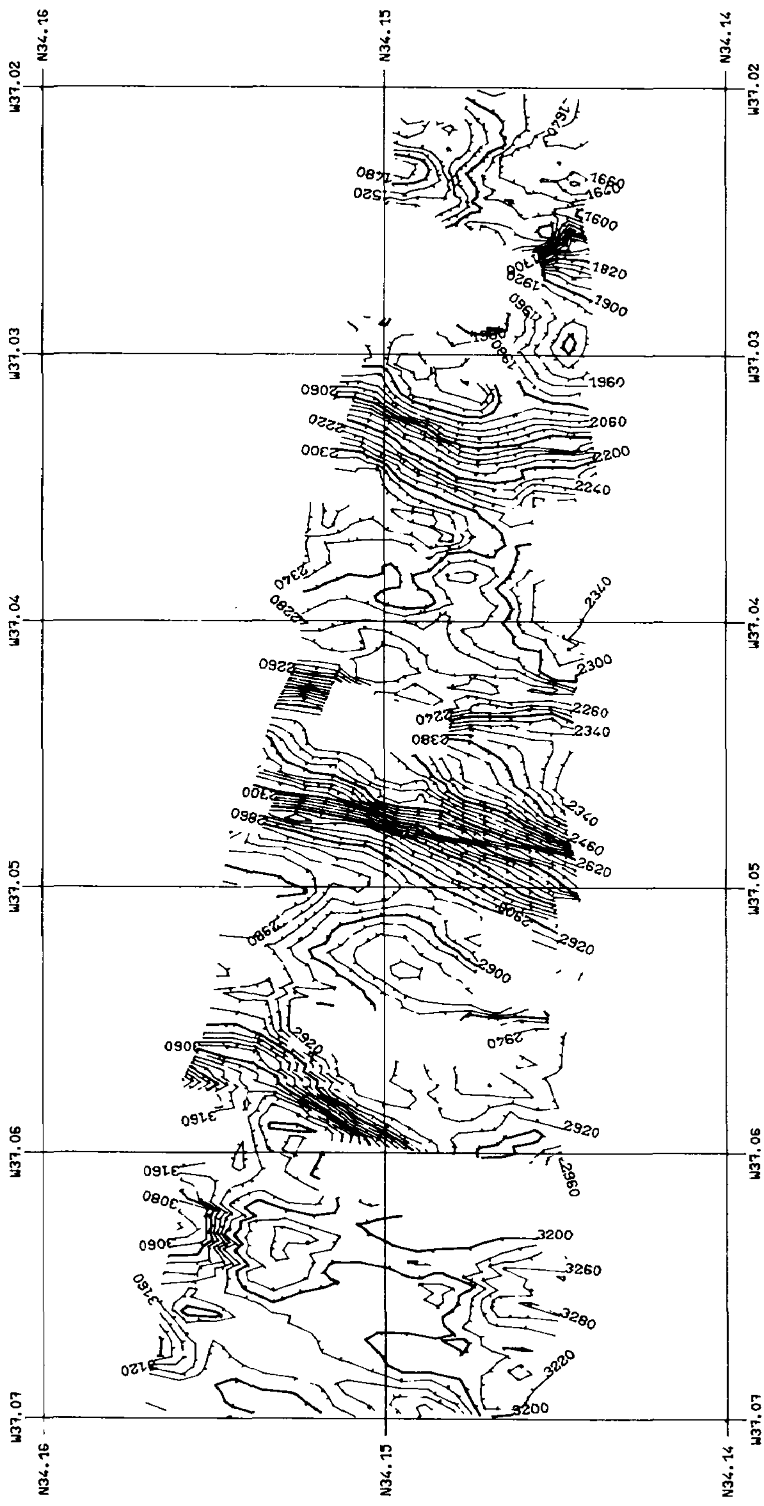


Fig. 11. — Same area as fig. 10. Smoothing by averaging over two cycles.

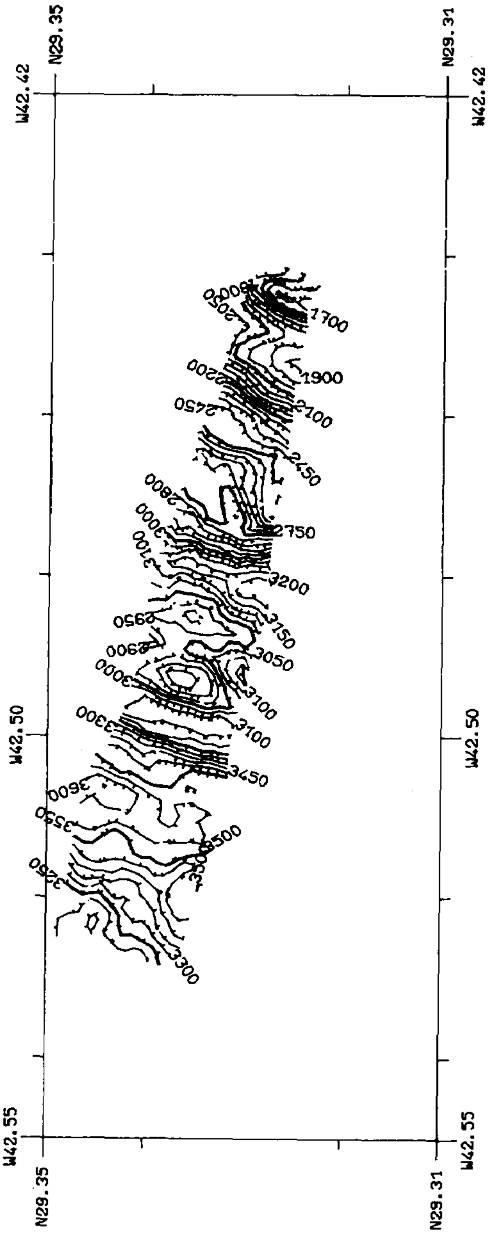


FIG. 12. — The plot at 1:100,000 (Original scale).

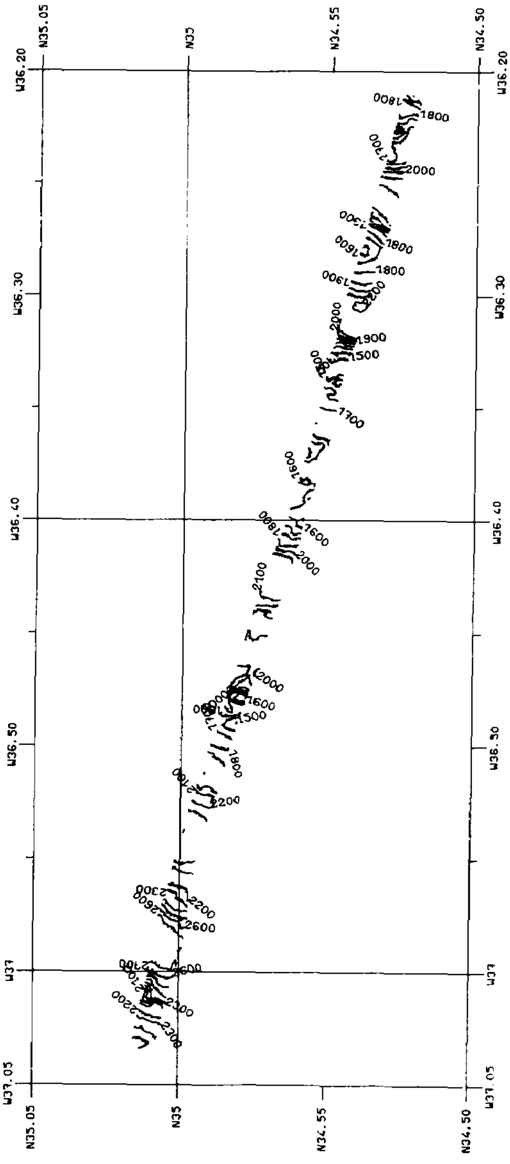


FIG. 13. — The plot at 1:300,000 (Original scale).

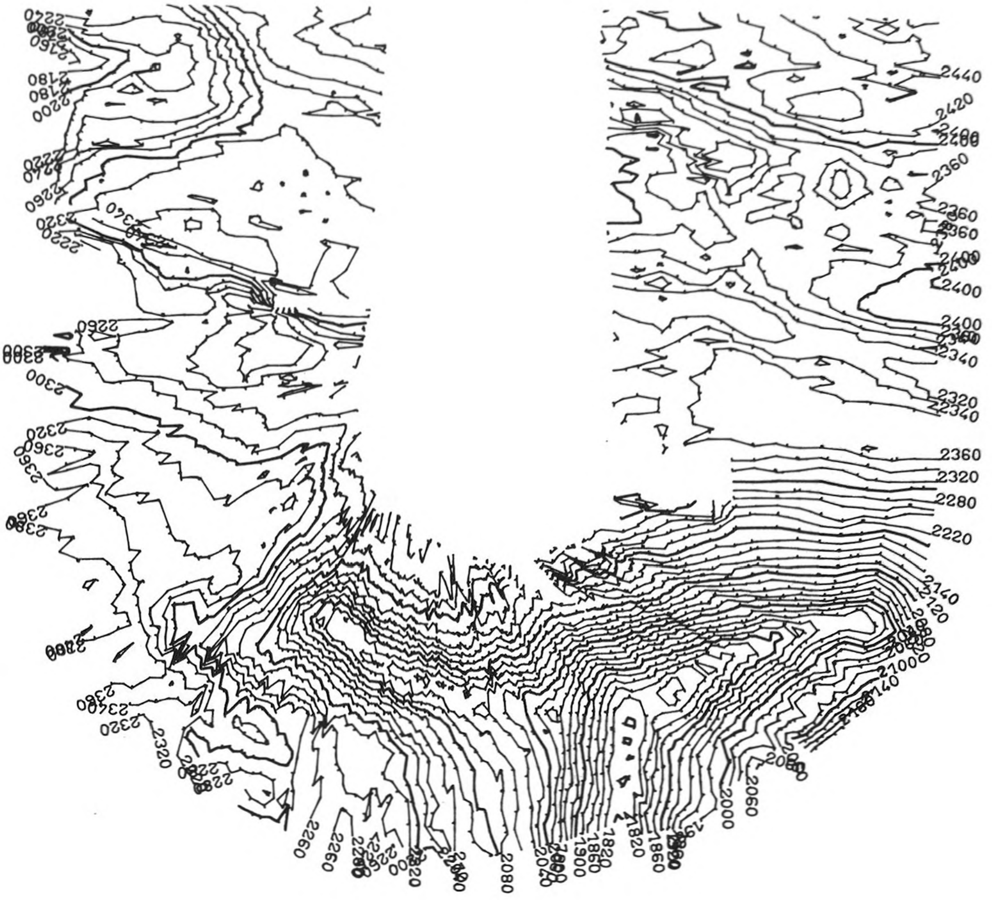


FIG. 14. — A progressive turn. Original scale 1:25,000.

profile intersections. This is also verified by the real-time software which uses a similar kind of procedure.

3.3 Application for turns

The procedure used gives an exploitable plot both for a progressive turn (figure 14) and a hard turn (figure 15). Distortions, probably due to poor navigation, appear at these points; in particular, the transverse log did not function, and this meant we were unable to evaluate the lateral displacement during turns. The method remains valid for smaller scales (see figure 16).

3.4 Comparison with other software systems

Comparison with a standard contouring software [3] has shown that our method is about eight times faster and requires half as much memory space, thus confirming our choice of algorithms.

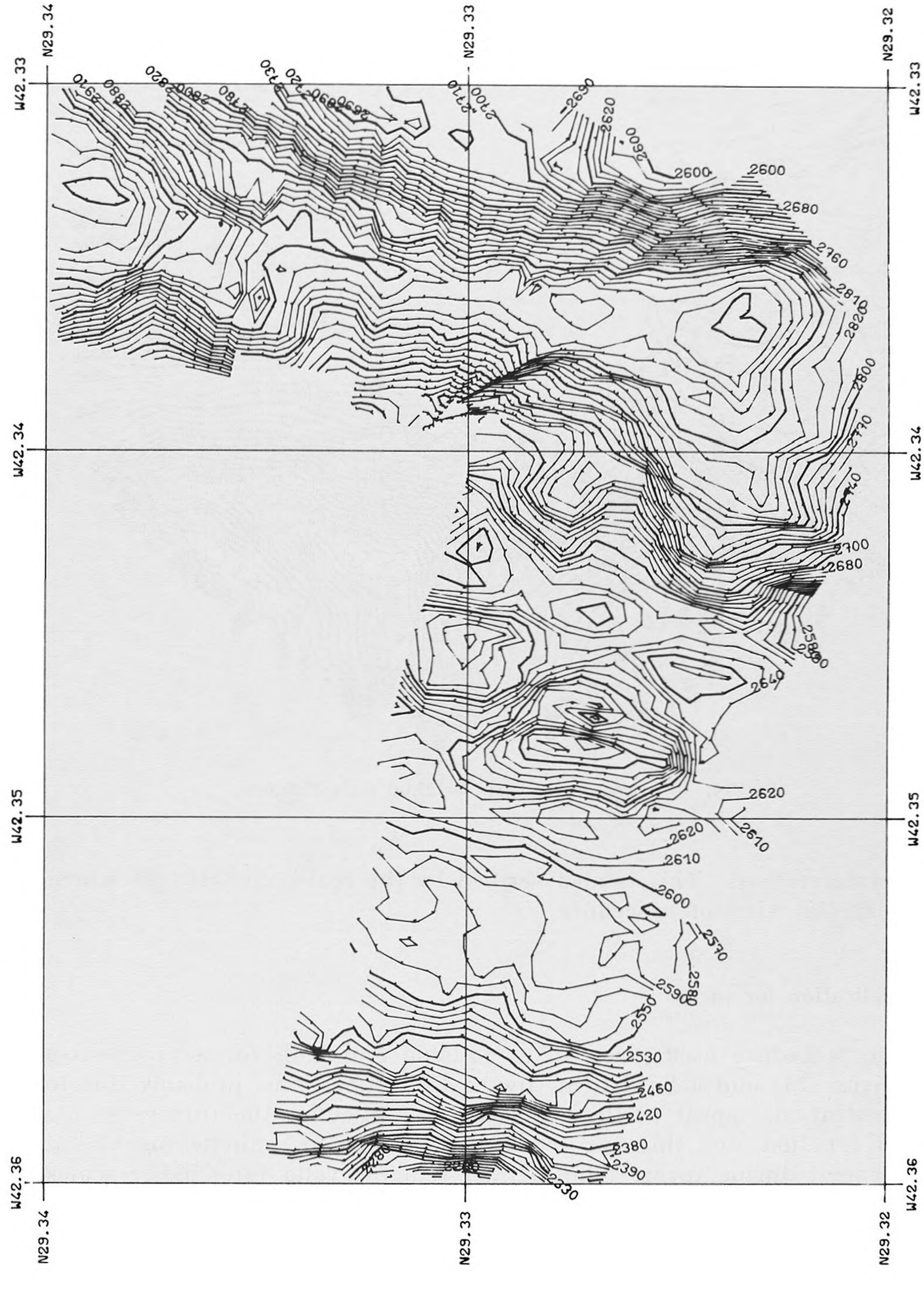


FIG. 15. — A sharp turn. Original scale 1:20,000.

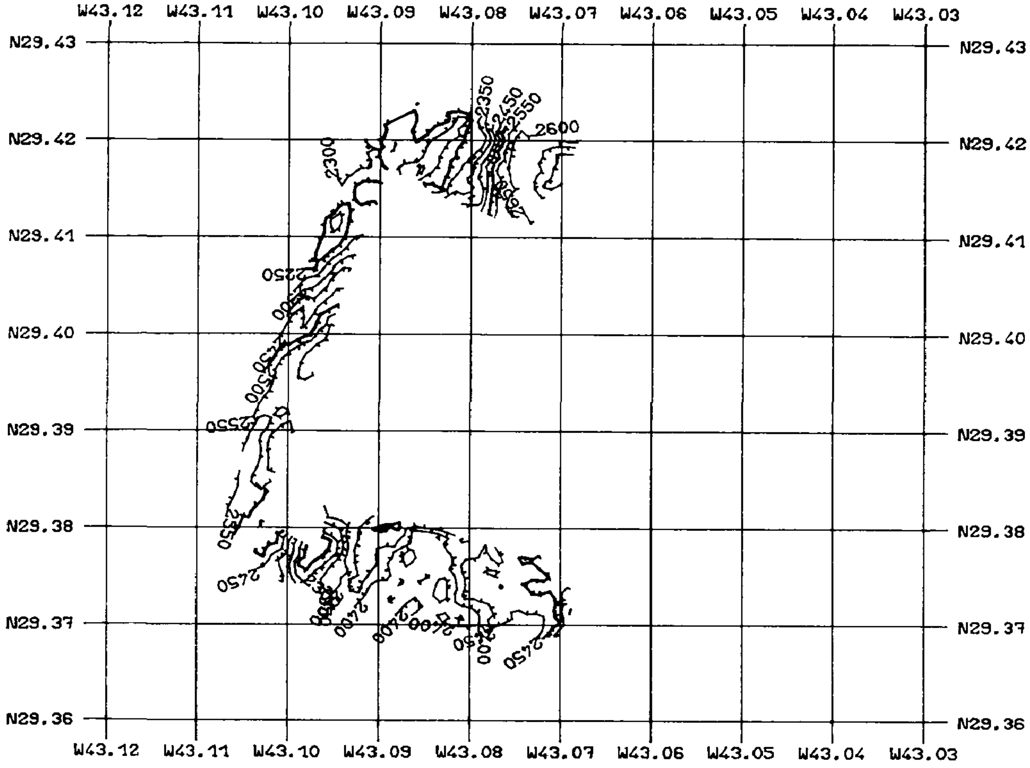


FIG. 16. — Turns at an original scale of about 1:100,000.

4. CONCLUSION

We have developed software that allows us to contour Sea Beam data in the main projections used in cartography and yet keep control of processing options, for we may either carry out a simple contouring or smooth the data in any way we like. Computer time is minimized, but plotting time is not optimized. A different version of the program is being written which will include a contour-follower. The result will be reduced plotting time and improved quality of line drawing, but the program will take longer and require a larger memory core.

The next stage will be the adaptation of programs for onboard mini-computers. However, the problem of onboard processing of navigational data will first of all need to be solved. Real time applications are already planned.

The final stage of contouring will be automatic plotting of charts where several profiles are combined, but this will firstly require an improvement in navigation and probably in survey methods.

Although we have only presented algorithms, it must be remembered that a large part of the work concerns the management of data, i.e. transcoding, selection and integration of both bathymetric and navigational data, creation of intermediate files, etc. Such a system is a very useful work-basis and new processing algorithms may be added to it without too much effort in order to include cross sections, perspectives, slope statistics, etc.

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IT IS STILL THE SURVEYOR'S RESPONSIBILITY

Good automated systems are expensive but can be very cost-effective when taking into account the speed of the survey and the immediate chart and (dredge spoil) volume presentations. The speed and accuracy of the survey itself still lies to a high degree on the surveyors undertaking the survey. For, without the correct configuration of positioning, calibration of the measuring instrumentation, quality control of the results and operation of the system itself, all that has been achieved by using automation could be lost by lack of basic knowledge of hydrographic surveying.

From "Analyses of dredge volumes obtained by automated surveys" by A.G. Stephenson published in *The Hydrographic Journal* (U.K.), No. 14, April 1979.