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THE USE OF SPATIAL STATISTICS IN HYDROGRAPHY

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Abstract

This paper describes ongoing efforts by the Canadian Hydrographic Service to devise geostatistical techniques for optimizing the nominal line spacing used on bathymetric surveys. This survey planning parameter has a great impact on both the cost of a survey and the confidence that a mariner can have in the resulting chart. Current methodology establishes initial line spacing quite subjectively. The main advantage of the geostatistical method being implemented is that it can estimate both depths and an estimate of their variance for all points within the survey area, regardless of whether they lie on or between sounding profiles. The geostatistical software under development (called "Hydrostat") evaluates the roughness of local bathymetry using available data. It then computes and displays the additional sounding coverage required to map the area to any desired level of confidence. The ideal line spacing for each small zone within the survey area is computed after specifying a maximum allowable standard deviation for interpolated depths lying between the sounding profiles. Developing algorithms for estimating the standard deviation of interpolated depths and ground truthing their accuracy forms the bulk of the work being done. While conceptually identical to the age old rules of thumb used to select and examine shoals, the geostatistical routines being developed can lead to more objective data quality standards and a more efficient deployment of survey resources.

INTRODUCTION

The principal mandate of the Canadian Hydrographic Service is to provide navigators with charts that are as safe as possible given its limited resources. To

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fulfill this mandate, much emphasis has been placed on insuring that position and depth measurements are made as accurate as possible. Consequently, improvements to sensors and processing software have consumed the bulk of the development efforts over the years. CHS now has data collection equipment and procedures that allow objective standards to be set and enforced on measurement accuracy. But how important is measurement accuracy in determining the overall safety of bathymetric data? While accurate measurements are obviously a prerequisite for safe bathymetric data, an examination of survey results quickly reveals that measurement accuracy is in fact much less critical than measurement completeness.

The distinction between measurement accuracy and measurement completeness is worth illustrating since it underlines the fundamental problem facing hydrographers when collecting data. Measurement accuracy refers to the performance of depth and position sensors at any single measurement epoch. Measurement completeness, on the other hand, refers to the spatial distribution of these measurements with respect to the spatial characteristics of the bathymetry being measured.

The accuracy of sensor measurements is relatively simple to evaluate statistically and control through appropriate calibration procedures. Evaluating it depends on having redundant data to analyze for consistency. An example might be the calibration of a positioning system or the detection and quantifying of depth errors in overlapping swath sounding data.

Measurement completeness is more complex to evaluate statistically since, by its very nature, no redundant data is available. Indeed, most of the potential data points have yet to be measured and what CHS wishes is to quantify the danger or uncertainty arising from their absence. The requirement for measurement completeness is a function of the roughness of the bottom topography. In practice, the hydrographer's control over measurement completeness depends on the choice of line spacing or scale of a survey.

THE HYDROGRAPHER'S DILEMMA

The hydrographer's dilemma revolves around just how densely soundings should be measured in order to insure an acceptably complete picture of the bathymetry. Simply stated, the problem is that it is not possible to see between the sounding lines.

Depths have to be interpolated within the survey area using the relatively few soundings actually measured along sounding profiles. Thus, due to interpolation errors, CHS might measure very accurate depths, yet obtain an incomplete or inaccurate picture of the bathymetry. If the bottom is rough, and the lines are far apart then the line density cannot resolve potentially dangerous details. Conversely, if the bottom topography is smooth, CHS wastes time and money if it collects soundings that are closer together than need be for adequate definition of the bottom topography.

Figure 1 illustrates the problem. If proper care is taken, the depth soundings obtained along the survey profiles (lines A and B) might have a measurement accuracy of +/- 1 decimetre. Interpolation errors are the difference between the true depths and the depths that can be interpolated using the soundings along A and B. Along the midpoints between the sounding profiles (line C), positions are at a maximum distance from any known depths so the interpolation errors along this line are statistically at a maximum. Common sense tells that if the terrain in this area is smooth and the profiles are close together then the interpolation errors will be unknown but small. If the terrain is rough and the line spacing is wide then the interpolation errors are both unknown and possibly very large.

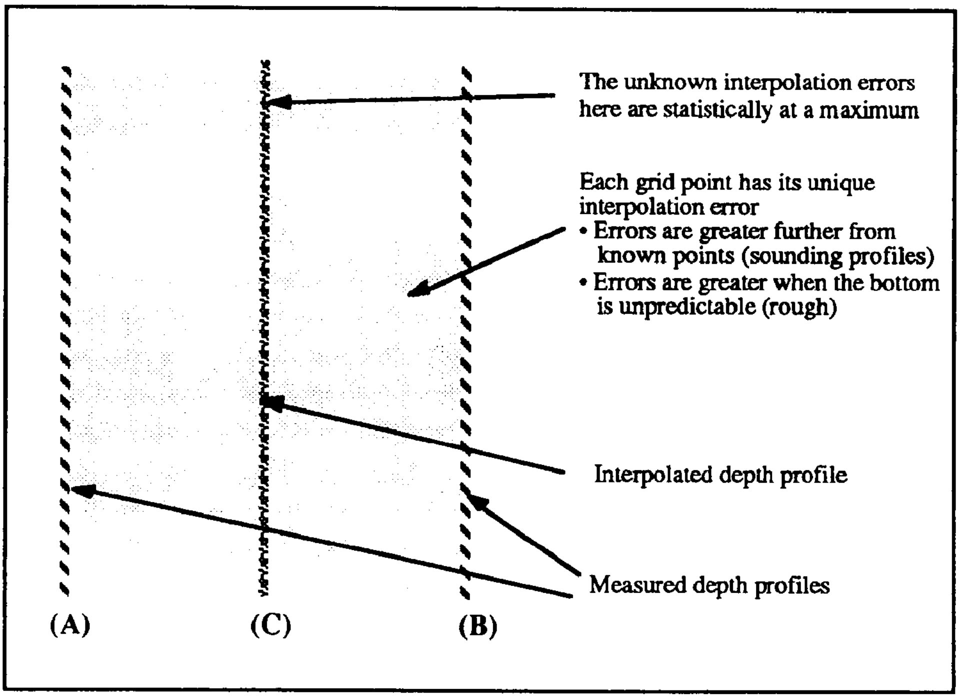

FIG. 1.- Interpolation errors between soundings lines.

It is also evident from Figure 1 that the unknown magnitude of the interpolation errors:

a - Can be much larger than the measurement errors.
b - The interpolation errors vary continuously over the whole survey area.
c - The interpolation errors are solely dependent on two factors:

  1 - The spacing of the sounding lines
  2 - The roughness of the bottom topography

If the line spacing is decreased so as to obtain total acoustic coverage of the bottom, then the interpolation errors will be eliminated due to the fully complete data set. The accuracy of the survey will then depend solely on the measurement errors associated with the depth and position sensors. Unfortunately it is not economically feasible to obtain total bottom coverage using conventional single transducer sounders. Even on very large scale wharf surveys most of the bathymetry still remains unmeasured between the sounding lines.

While multi-beam sounders are exciting new tools, they still only collect a fairly narrow band of data. CHS has estimated that swath surveying all Canadian waters using a Simrad EM100 would require over 120 years of continuous steaming. This economic reality will probably mean that the majority of hydrography in Canada and around the world will continue to be collected by profiling sounders for the foreseeable future. The hydrographer's dilemma cannot be resolved solely by hardware tools such as swath sounders. Strategic tools will also be needed that can help determine where to concentrate sounding energies for maximum effect and also to tell what effect these efforts are having on the safety of the product.

TRADITIONAL METHODS OF DETERMINING LINE DENSITY

The distance between sounding profiles or scale of a survey is the single most important planning decision a hydrographer can make. It is fair to say that halving the line spacing will double both the cost of a survey and the confidence that navigators can place in the resulting chart. In other words one gets what one pays for.

Over the years hydrographers have developed rules of thumb for determining what level of measurement completeness is appropriate for each survey. Line spacing is tied directly to survey scale. CHS Standing Orders for example require that line spacing result in 2 soundings/cm. being inked on the field sheet. Survey scale is in turn related to chart scale by approximately a 3 to 1 ratio. Thus, the decision on chart scale strongly affects the nominal line spacing for surveys carried out within the chart limits.

Establishing chart scale is a planning decision that juggles many factors in an intuitive manner. Efforts are made for a chart scale that both meets user needs and is consistent with our ability to carry out the required surveys. Some of the factors considered are:

- the draft of vessel traffic using the chart
- the frequency of vessel traffic using the chart
- proper illustration of traffic separation schemes
- onshore features that need to be shown on a single chart
- required overlap between adjacent charts
- the number of charts sold for the area
- the size of paper used to publish a chart
- the roughness of the bottom (subjective evaluation of the entire charted area)

Since the roughness of the bottom, in fact, varies constantly from point to point within the charts' limits, it follows that any rule of thumb which establishes a single line spacing over a large area is either inefficient (if the lines are too dense) or dangerous (if they are not close enough). From this it follows that the line spacing rules currently lack flexibility and objectivity.

To address this weakness, CHS has been conducting a small scale R&D program over the last 2 years entitled "Survey Design Tools". Its Industrial Partner has been Geostat Systems International of Montreal. Geostat personnel have experience in the mining industry and as a result have developed a line of geostatistical software aimed at orebody estimation from sparse bore hole data. Geostat have modified some of their software to satisfy the specific needs of hydrographic surveyors. Results from this new software, called "Hydrostat", are presented in this paper.

THE GOAL OF HYDROSTAT R&D

The principal goal of the "Survey Design Tools" project has been to design and implement a statistical method for determining an optimal line spacing that satisfies a standardized safety requirement and is tailored to the local bathymetry. This involves computing a statistically valid confidence value for the knowledge of the real depth at any point within a conventionally surveyed area. These computed confidence values are roughly analogous to the error ellipses geodesists compute for control points and similarly allow statistical criteria to direct the data collection process.

Two design rules are guiding this R&D project. The first ground rule is, that hydrographic expertise built up over time must serve as a guide in developing any automated method of determining line spacing. The software must strive to emulate the same decisions that an experienced hydrographer would make given the same data. The only advantage that the computer can bring to this process is the ability to perform repetitious mathematical operations. The output of Hydrostat must always be subordinate to human judgment while at the same time augmenting good planning decisions with reliable statistical estimators.

For example, Hydrostat might predict that the maximum interpolation uncertainty arising from using a given line spacing over a specific small area of bathymetry to be +/- 1 metre at the 95% confidence level. The hydrographer might choose to accept this risk level and the survey would then be complete in that particular area. However if this risk is considered unacceptable the hydrographer could then choose to go to the time and expense of densifying the sounding pattern as directed by Hydrostat so as to attain the desired level of confidence. If zero interpolation errors at the 100% confidence level is required, then swath sounding techniques would have to be employed.

The second ground rule for this project is that statistical error estimates must be extensively validated using real observations. The real value of interpolation errors can only be determined with certainty by densifying soundings and differencing the new observations with the values that were interpolated from the original sounding lines. These misclosures, observed at a great number of points must agree statistically with the Hydrostat error estimates in order for the Survey Design Tools to be considered useful.

GEOSTATISTICAL CONCEPTS BEHIND HYDROSTAT

As its name indicates, geostatistics characterize data that are spatially distributed. Geostatistics originated in the mining industry to service the need for accurate estimates of mineral bodies from sparse bore-hole data. Bathymetric, meteorological, ecological and even demographic data also tend to be spatially distributed in a semi-random fashion suitable for geostatistical modeling. Two geostatistical methods are being investigated in the Survey Design Tools project: the variogram and kriging.

THE VARIOGRAM

Modeling roughness is the foundation of Geostatistics, be it the roughness of bathymetry or the variability of grade data in an orebody. The roughness model used is called the "variogram". The variogram relates the average squared difference between measured values as a function of the distance between their measurement locations.

In practice the variogram appears as a simple XY graph with distance between measurement points along the X axis and average squared difference between measured values along the Y axis. It is computed in the following way:

1 - A data sampling window onto the survey area is established (Fig. 2).

2 - The distances between all soundings inside this window are computed and groups of all possible sounding pairs are formed according to distance (eg. pairs from 0-10 metres apart, pairs from 10-20 metres apart, ... pairs from 990-1000 metres apart, etc.)

3 - Within each distance group, the average squared difference in depth among the member pairs is computed (the groups variability) as well as the average distance between the sounding pairs in the group.

4 - The average squared depth differences are then plotted against the average distances between soundings to form the variogram which characterizes the spatial variability of the data within the window.

Figures 3 and 4 show examples of two windowed depth profiles on the left and their resulting variograms on the right. The rougher terrain in Figure 3 results in a variogram that is more than twice as steep as that computed from the subjectively smoother terrain in Figure 4. While this may seem trivial or merely common sense, it does provide a statistical basis for predicting estimates of uncertainty out into the unsounded zones between sounding profiles.

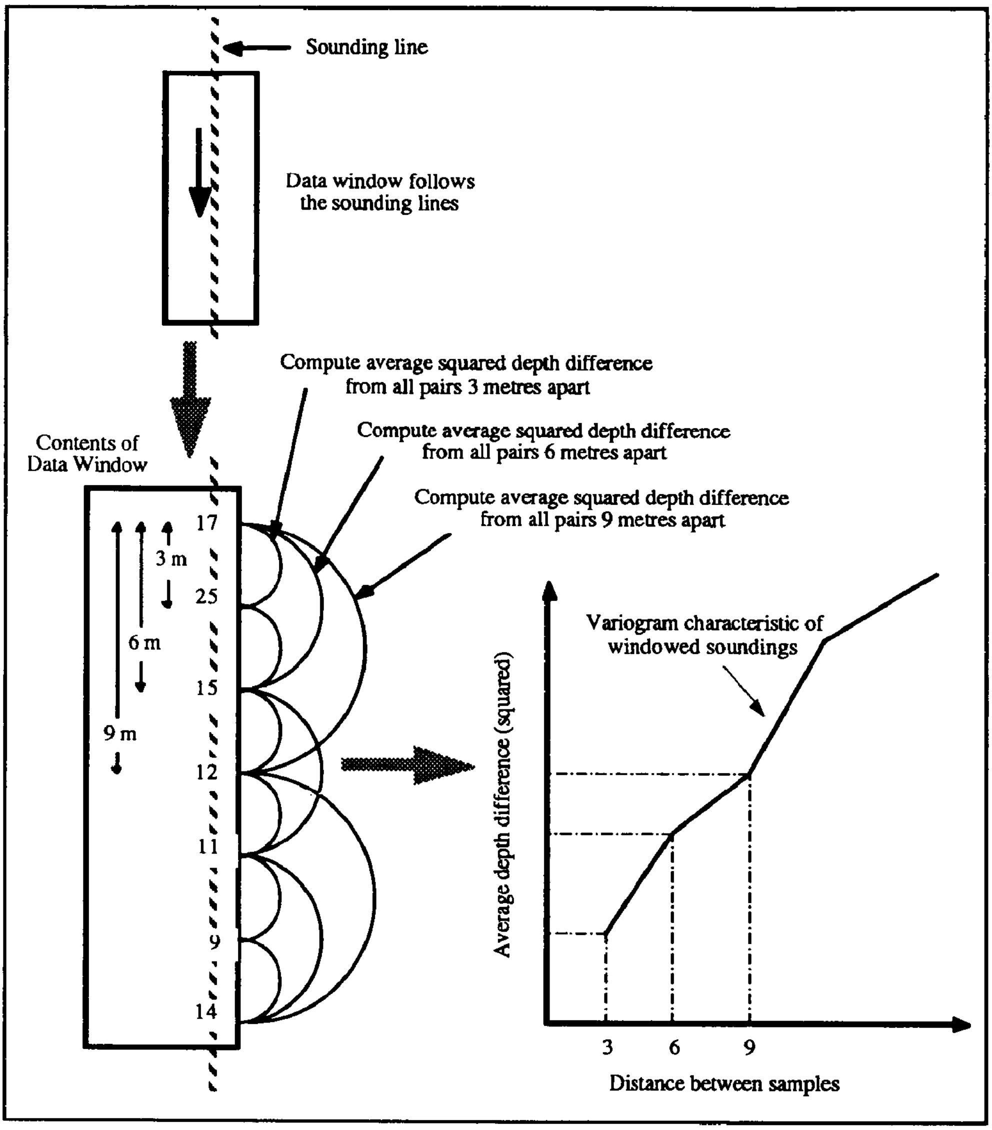

FIG. 2.- Example of how a variogram is computed to characterize the roughness along a sounding line.

There are a few constraints on the variogram worth noting. The first is that the general slope of the terrain (called the trend) will falsely exaggerate the roughness of the terrain if it is not taken into consideration. In Figures 3 and 4 we see that the bottom has a considerable slope superimposed on both the rough and smooth terrain samples. The straight line drawn over the profile is a linear regression Hydrostat uses to cancel out this trend effect. To do so the depth differencing is done, not on the absolute depths but on the residuals from the line fit.

Another proviso for obtaining a realistic variogram model is that there needs to be at least 30 to 50 soundings in the sample window. This is so that the curve

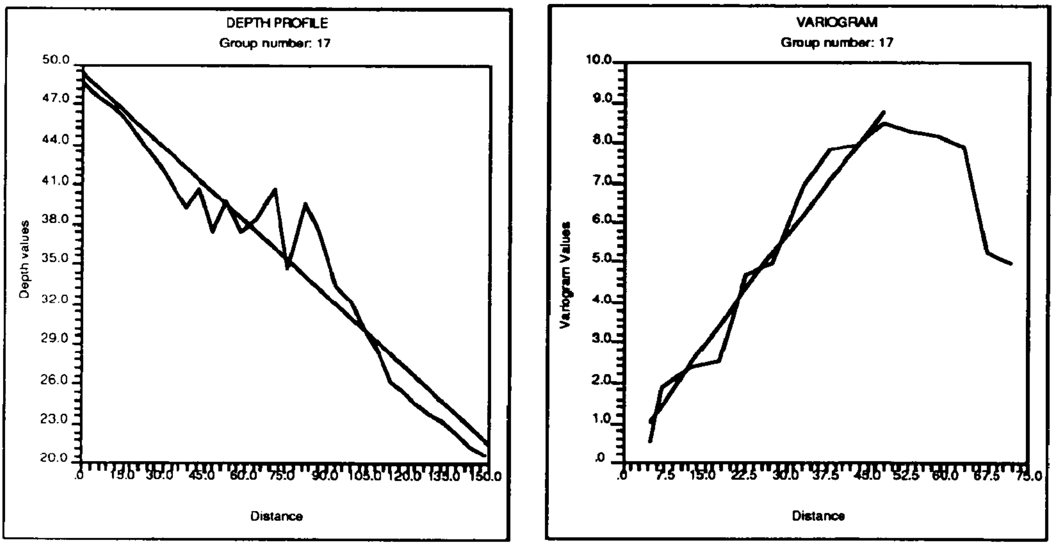

FIG. 3.- Rough terrain and resulting variogram.

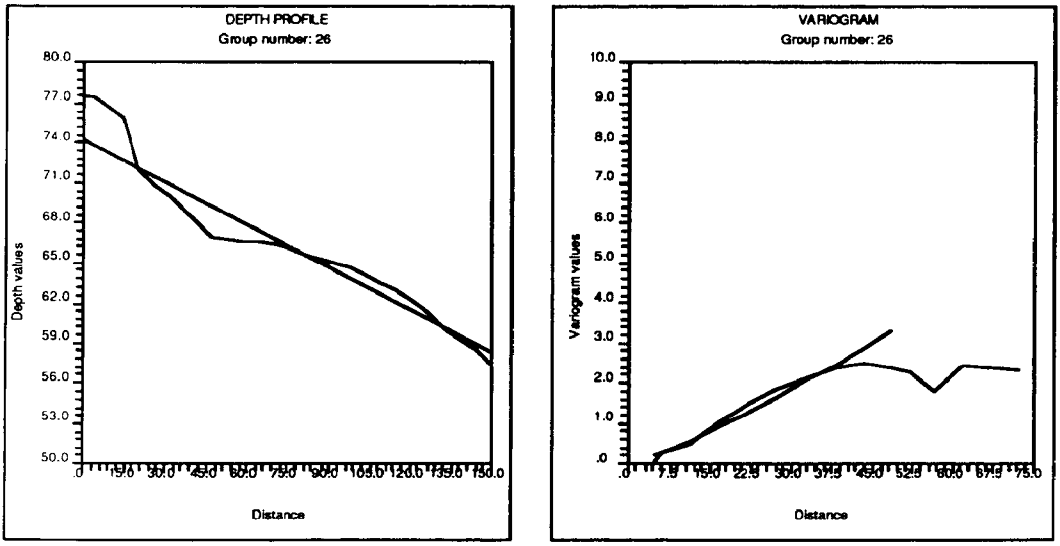

FIG. 4.- Smooth terrain and resulting variogram.

will be well defined by a large number of depth comparisons and thus have statistical significance. If too few soundings are used in the computations, then the graph will be noisy. Fortunately hydrographers collect data very densely along sounding profiles so this does not pose a real problem provided raw, un-decimated sounding data is used for the analysis.

The size of the moving data window and its increment step along the sounding profiles are important Hydrostat variables that are currently up to the user to define. Another obstacle to stable results is that the linear trend model currently employed by Hydrostat may be inappropriate if the depth profile in the data window contains large structures which should be considered as trend. This second problem tends to exaggerate the predicted uncertainties so it is less objectionable to hydrographers than if the predicted errors were being minimized. More experience with real data will be required to develop rules and algorithms that automatically adjust these parameters to insure stable results for different bottom types. This iterative software development is part of the on-going validation process described later in this paper.

Hydrostat employs the variogram to compute and plot out "confidence envelopes" (Fig. 5). A confidence envelope is a lane of variable width centered along a sounding profile. The area inside these envelopes represents the zone in which depths can be interpolated within the error tolerance that was used to compute the envelopes. In Figure 5 for example, all points within the confidence envelopes can be interpolated to within +/-2 metres 95% of the time. The depth contours have been overlaid onto the confidence envelopes to illustrate how the envelopes become narrower as the bottom gets rougher thus opening "holes" in the interpolation confidence.

The width of the envelope at any window position along its length is "read off" the modeled variogram computed for that window. The width is equal to twice the horizontal distance that corresponds on the variogram to the maximum allowable interpolation error. Varying either the allowable error tolerance or its associated confidence level will result in wider or narrower envelopes: large allowable errors at a low level of confidence result in wide envelopes and vice versa. To prevent graphical confusion, Hydrostat can limit the maximum envelope width to the nominal line spacing (this was done for Figure 5).

Hydrostat computes confidence envelopes under the assumption that the terrain is isotropic i.e. the roughness encountered by a North-South sounding pattern is statistically similar to that of an East-West sounding pattern. Using this assumption permits the horizontal distance corresponding to the allowable interpolation error to be projected at right angles to the direction of the sounding profile. This defines the width of the confidence envelope at the location being analyzed. Isotropy is not always a valid assumption, however, it is as valid an assumption as the linear interpolation of depths between soundings. Linear interpolation is a common assumption in hydrography and simply reflects the fact that, in the absence of data to the contrary, one must assume that bathymetry lying between the sounding lines is highly correlated to that which we have actually measured. Traditionally hydrographers try to compensate for a lack of isotropy by running lines across the anticipated direction of contours. This common sense measure is equally necessary when using Hydrostat.

The Hydrostat process mirrors the logic used by an experienced hydrographer when selecting those shoal soundings which warrant a return visit for examination. The "10% of average depth" rule flags a regular sounding for shoal examination if it is shallower than the average of its adjacent soundings by more than 10%. In other words: "if a small zone is rough then its nominal sounding grid

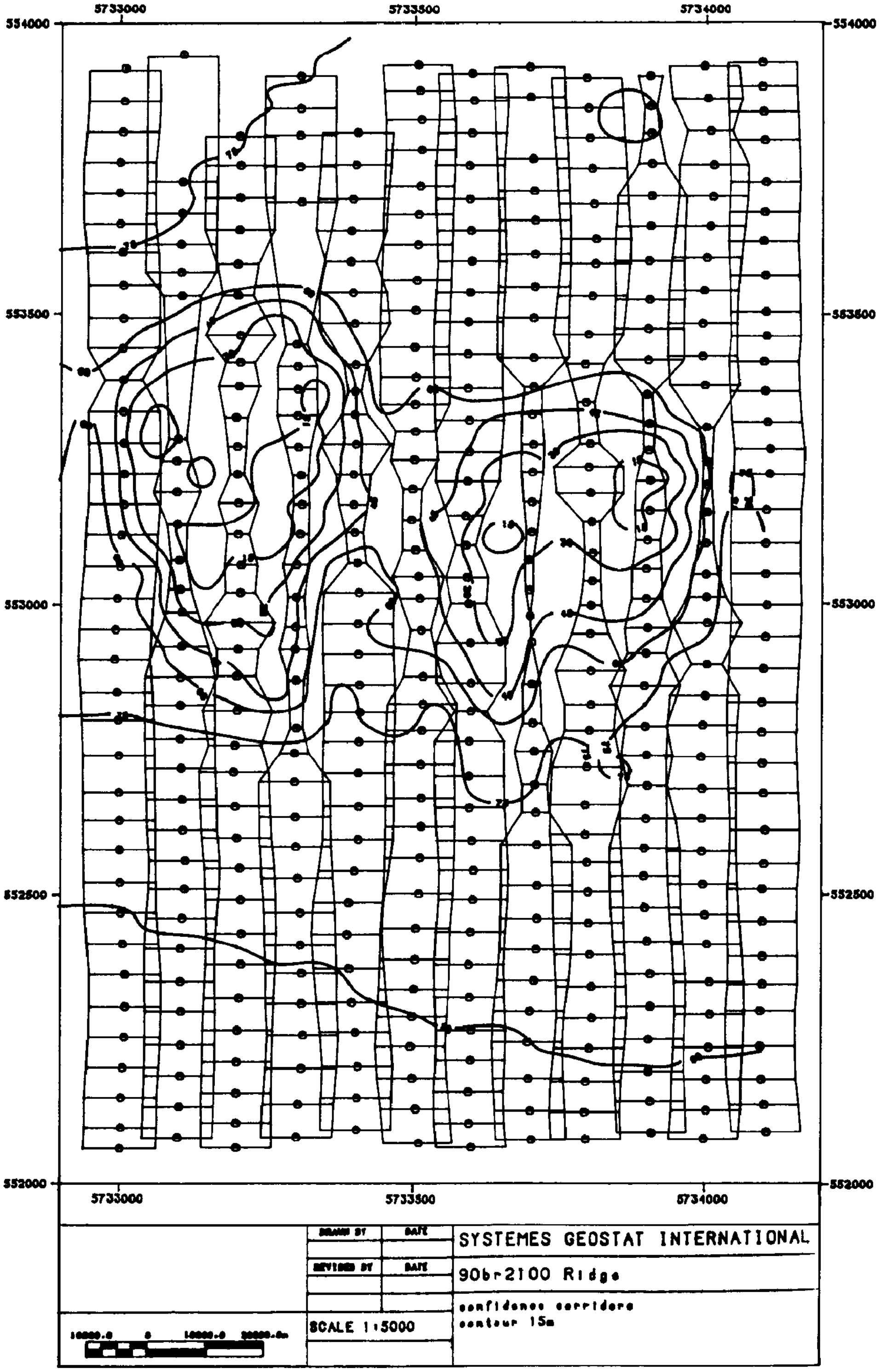

FIG. 5.- Plan view of confidence envelopes.

requires additional soundings to improve measurement completeness". The Hydrostat process differs from the 10% shoal selection rule only in that it can be applied earlier in the data collection process. There's no need to wait until the regular lines are completed before applying Hydrostat adaptive sampling.

The other important difference from the traditional densification algorithm is that the Hydrostat roughness estimator is "scaleless". The 10% rule uses only those soundings that can be inked onto the field sheet as its input data. Even on automated "digital" surveys, graphical limitations dictate that only the shallowest soundings are inked onto the field sheet. Visually analyzing these few depths masks much of the valuable roughness detail contained in the raw echograms.

The 10% rule essentially involves scanning the field sheet for soundings where a large change in slope occurs. While the depth differencing part of the algorithm uses absolute or scaleless data, the magnitude of the horizontal distance to the "nearest adjacent soundings" varies directly with the scale of the survey. Thus the slopes used by the 10% algorithm to detect shoals are more a function of the scale of the field sheet than any absolute slope changes in the bathymetry.

The variogram on the other hand uses only absolute positions and the total depth record as input to its roughness algorithm. The scaleless nature of Hydrostat is the key to making it a more objective standard for determining how to densify the sounding pattern.

HOW HYDROSTAT WORKS

Hydrostat works in the following manner. Upon execution it first asks the user to supply a desired error limit and confidence level, as well as parameters on window size and movement. It then sets up its moving window which follows the sounding lines as they were collected by the launches.

The window increments along the profile using the user defined window size and step value. At each increment stop along the lines, the soundings in the window are used to compute a variogram which is de-trended using a linear regression. This variogram is then mathematically modeled using a log-log linear curve fit. The variogram model is constrained at the origin so as to force Hydrostat to predict a zero interpolation error at zero distance from the sounding profile.

The confidence limit specified by the user is then used to "read off" from the modeled variogram the corresponding distance inside of which adequate interpolations can be made. This distance is presumed to be as valid across the vessels track as along it, i.e. there is a presumption of isotropy. A plotter or screen plot routine then draws the window's confidence envelope centered on the vessel's track. Hydrostat then increments to the next window position to compute and draw the next segment of the envelope. In this way the variable width envelopes are constructed along all of the sounding lines.

Hydrostat is meant to be used in near real-time, on-board sounding vessels. A feasible deployment scenario might be as follows: Nominal survey scale and line spacing would be established using the traditional planning technique. This "normal" sounding density would then be arbitrarily decimated. For example, only 1 in 4 of the normally prescribed lines would be run to seed the Hydrostat process. This degree of decimation is itself arbitrary and therefore represents a "rule of thumb" which must be determined through experience. The validation and software development cycle described later in this paper addresses just how such rules of thumb can be safely determined.

At the end of each of the seed lines, the raw sounding data logged since Start Of Line is passed through the algorithm just described and the line's confidence envelope displayed on a track plotter or CRT. The hydrographer then examines this graphical feedback and plans the next sounding line accordingly. In areas where the bottom is smooth, the envelopes will be wide enough to extend more than half way to the next planned seed line. In these areas, interlining of the seed lines will not be required to achieve the desired survey specification. If the envelopes do not overlap, then the seed lines will have to be interlined until all the gaps between confidence envelopes have been eliminated.

In rough terrain complete envelope coverage may well require running lines much closer together than would have been the case had the "normal" line spacing been used. In practice these high density lines will be sounded over the same areas where shoals would normally be identified using the 10% rule. When using Hydrostat however, some of the effort involved in return trips to examine shoals will be eliminated since the required density will have been acquired the first time out.

Figure 6 illustrates Hydrostat results on a test data set. The area is a 1:20,000 field sheet off the northern tip of the Magdalen Islands which encompasses both smooth and rough terrain. Hydrostat was run using a +/- 1 metre error tolerance at the 95% confidence level. Hydrographers who are used to thinking that all their bathymetric data is accurate to +/- 1 decimetre might find that using a 1 metre allowable error limit for the interpolated depths is not good enough. Since the sounding profiles used for this plot are 200 metres apart, 1 metre interpolation errors, given the variability of the bottom, is however all that can be expected at the 95% confidence level.

It must also be noted this envelope plot was created with data that is sub-optimal and not representative of what is typically available on a real survey. The Magdalen Islands data used here was "field sheet" data at a density of only 1 sounding every 100 metres along the profiles. This eliminated much of the detail that's necessary for good definition of the variograms. As a result, the sample window had to be very large in order to contain enough points to process. This diluted the effect of local bottom features on the envelopes. Despite this handicap the confidence map gives results that agree well with a qualitative evaluation of the bathymetric contours. On-going tests are now using raw data files containing 1 depth every 3-5 metres along the profile. This will result in confidence envelopes which are much more sensitive to local changes in the profiles roughness.

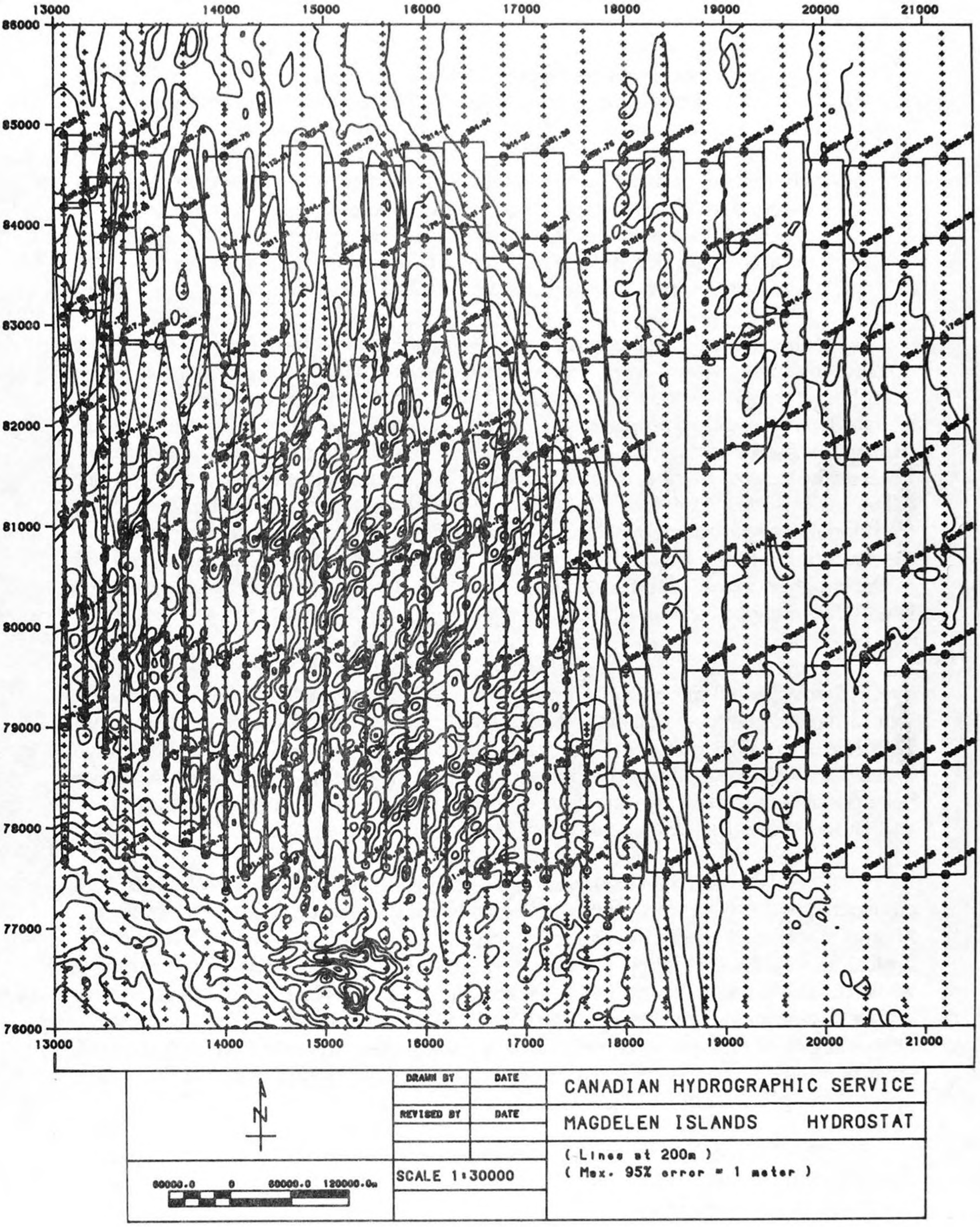

FIG. 6.- Magdalen Islands confidence envelopes.

Using this plot as a guide, a simulation of the Magdalen Islands survey was carried out. Lines were eliminated or added as the envelopes dictated with the following results:

- in the smooth area of the survey 345 kilometers of sounding lines were eliminated since they were not required to achieve the desired confidence (+/- 1 metre, 2 sigma).
- in the rough sector of the survey 970 kilometers of extra sounding lines were deemed necessary in order to achieve the desired confidence level. It should be noted that this shoal patch is one of the roughest areas in the whole Magdalen Islands region and that a great many shoal exams were carried out in this region during the CHS survey.

If this entire field sheet had been as smooth as its North-East sector then a 400% cost savings would have been experienced compared to the regular 1:20,000 sampling strategy. Since the Magdalen Islands took 3 years and over a million dollars to survey, this potential for saving money is certainly interesting. The principal reason however for using statistics to control the sampling pattern is not necessarily to save money, it is to achieve a higher quality product. As the test example illustrates, a Hydrostat survey may actually cost more to do than one using traditional line spacing methodology. By sounding to a standard level of confidence, the sounding effort not required in the smooth zones of a survey can be re-directed to the rougher zones. The result in such cases will not necessarily be cheaper but it will definitely be safer.

In the example, one can see that while the rough zone was actually sounded by CHS using a 100 metre initial line spacing, the Hydrostat confidence envelopes would have demanded that lines be run at 20 metres over most of the this zone. This raises the possibility that the traditional survey may well have missed any indication of a potentially dangerous shoal. Using Hydrostat, it would at least have been possible to statistically qualify the survey as being lower in safety than desired and show where the inadequate coverage exists.

The Hydrostat R&D software is Fortran code running on a 386PC. In this environment, it can compute confidence envelopes at the rate of about 7 seconds per kilometre sounded when depths are logged every 3-5 metres along the profile. On typical survey lines, this represents a turn-around delay of about 1 or 2 minutes while the latest line of soundings is processed. If the software were operating in a higher performance environment such as the ISAH data logger, then processing delays at end of line would be negligible. In such an environment Hydrostat could even be modified to run as a real-time task so the hydrographer could then plan optimal sampling strategy as the launch is under way.

One feature that is not yet implemented in Hydrostat is a depth variable confidence standard. Traditionally CHS's concern about errors in the bathymetry decreases as the average water depth increases. For example, if the average water depth is 10 metres then 2 metre rock outcroppings are of great concern and need to be completely and accurately measured. The same rocks in 100 metres of water are of much less concern to navigation so they can be measured with less certainty.

The 10% shoal selection algorithm used by hydrographers takes this reality into account when each sounding is differenced with the average surrounding water depth. Hydrostat currently determines envelope width irrespective of water depth, only desired confidence and the bottom roughness are taken into account. This can easily be changed and will be in a later version of Hydrostat. A sliding confidence requirement option will allow error limits and confidence levels for each window along the envelope to be dependant on the average depth in the window. This function will be implemented using a table of user-definable depth intervals with their corresponding confidence requirements. For example, from 0 to 30 metres might require a tolerance of +/- 5 dm at a 95% confidence level while in water deeper than 30 metres, +/- 8 dm at a 68% confidence level might be used to compute envelope width.

KRIGING

The Hydrostat confidence envelopes are a rudimentary implementation of geostatistics. They are merely a useful graphical representation of the information contained in the variogram. No attempt is made to make use of soundings collected on adjacent lines nor can the confidence envelopes be used to actually estimate qualified depths for points between the profiles. To do so, Hydrostat extends the use of the variogram to an interpolation process called "kriging".

Kriging can be used for automated contouring since it interpolates an arbitrarily dense grid of depth values. Lines can then be drawn between grid points of equal value to produce a contour map. Kriging uses a linear combination of depth values from the nearby survey lines to produce its depth estimates at grid points. Weights used in the linear combination depend not only on the distance between each grid point and the measured depths being used but also on the distances between the depth measurements themselves. The variograms, which reflect the roughness of the bathymetry, play a strong role in computing the weights used in this process.

One attractive feature of kriging is that it honors the data points. Some gridding algorithms will deform the observations to fit onto a "best fit" grid surface. Kriging will not. If a grid point is interpolated at the exact location of a sounding then its value will be identical to that sounding. This property is desirable in hydrography where observed values must be preserved. Of prime importance however is the fact that kriging can estimate not only grid depths, it can also estimate a confidence value (estimation variance) for each of the grid depths. The maximum estimation variance between sounding profiles gives an objective indicator of the fidelity between the data we measured along our sounding lines and the infinitely dense set of points that form the real bathymetry.

The variance values for grid points can be contoured in exactly the same way as the interpolated depth values themselves. This produces a "confidence map" as opposed to a "confidence envelope". These contours can be used in the same way as the more approximate confidence envelopes. Zones of rough topography will produce high contours of estimation variance. These areas will require further sampling in order to smooth these peaks in the "confidence surface" down to the desired level.

Figure 7 shows the confidence map for the same area near the Magdalen Islands as depicted in Figure 6. The effect of sampling with a constant 400 metre line spacing over very different bottom types is clearly seen in the contours of estimation variance. The contours range from less than +/- 5 dm in the smooth zone to over 20 dm in the rough zone.

Kriging is a numerically intensive operation that takes hours of CPU time to execute when high density profile data is being analyzed. It is only feasible to use it as part of the post-processing procedure. Typically the "quick and dirty" results of the real-time line density optimization done in the launch would be re-processed at the end of day. This would provide a more reliable picture of the confidence for that day's work and identify any areas in need of further densification.

The main improvement of kriging over the one dimensional "confidence envelope" method is due to the fact that soundings from adjacent sounding lines are also used in the computations. Since the presumption of isotropy which underlies the confidence envelopes is sometimes false, using data from adjacent lines can improve the reliability of the variograms and thus the variance estimates used to control the adaptive sampling. Another advantage of the post-processing environment is that we can use Hydrostat to analyze for measurement completeness after having screened the input data for inaccurate measurements (poor digitizing due to fish or weeds, bad positions, etc.). It would not be feasible to perform this screening process in real-time on the launches.

Kriging has three other potential applications for hydrographers other than the adaptive sampling techniques being implemented in Hydrostat. These other applications have yet to be explored however a brief explanation of their potential is worthwhile here:

OTHER POTENTIAL APPLICATIONS IN HYDROGRAPHY

Contouring

Many people feel that some form of machine contouring package will be needed in order for automated cartography to reach its full potential. Several commercial contour packages have been tested by CHS but none provided output acceptable to cartographers. The contours might look good to an engineering draftsman or even a hydrographer but they could not be used by a nautical cartographer without an unacceptable amount of graphical editing.

The problem stems from the need to both generalize and safety-bias charted contours. Current contour packages interpolate "the best" grid values using a strictly deterministic approach (linear interpolation or curve fitting to the data points). These values are meant to be the most exact interpretation of the data, not necessarily the safest interpretation of the data. The very word "safety" implies a

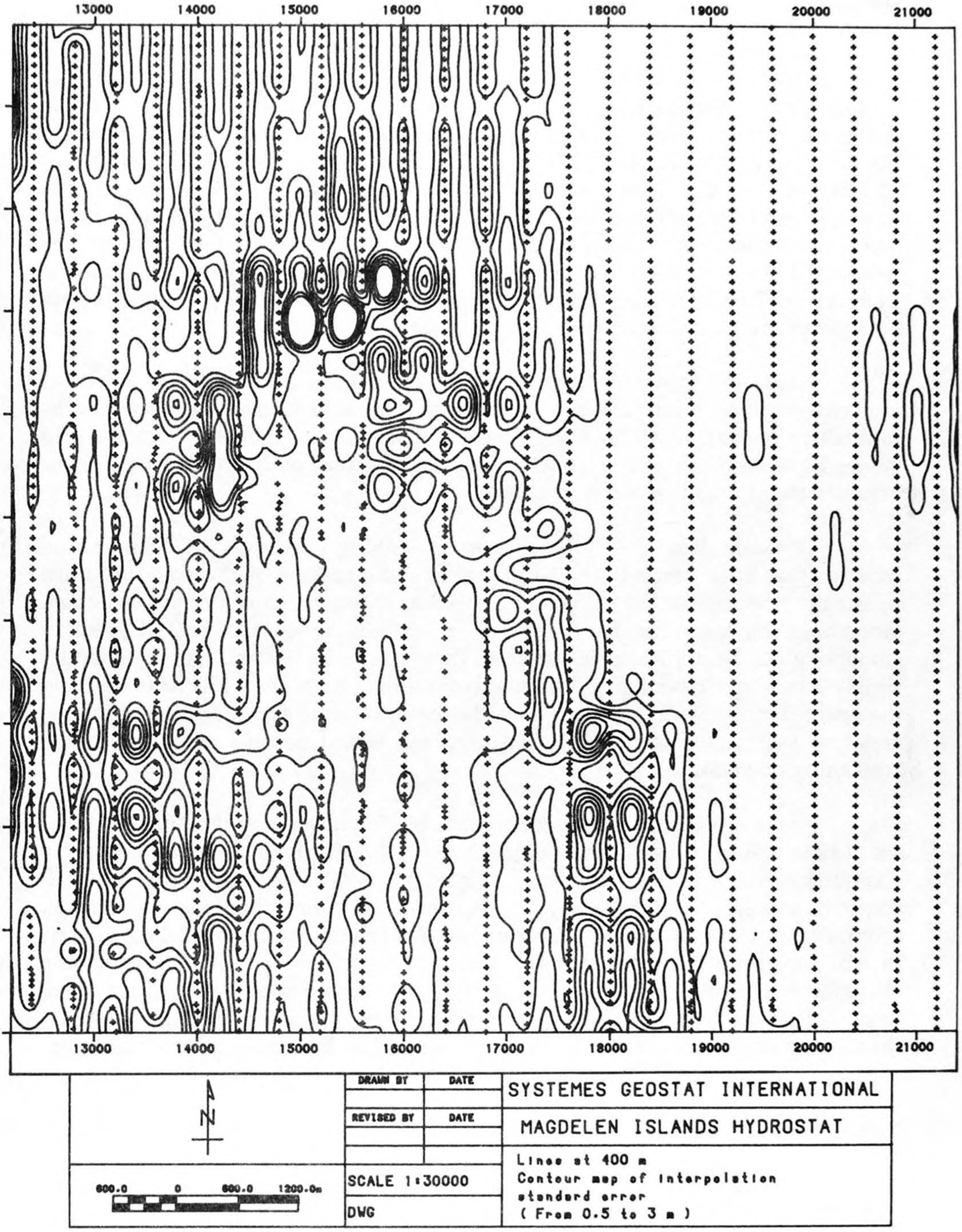

FIG. 7.- Magdalen Islands confidence map (end of month).

probabilistic or stochastic element which compensates for some uncertainty or danger. In the case of hydrography, this safety factor can be evaluated using geostatistics (kriging).

The benefit of a kriging based contour package could be realized by safety biasing the grid values which guide the drawing of the contours rather than moving the contours themselves. This approach is truly numerical rather than graphical. For example, a particular interpolated depth value might be estimated by kriging at 15.2 metres +/- 3 dm. If the uncertainty attached to this depth is 3 dm then a logical means of safety biasing the contour would be to simply subtract this uncertainty value from the depth which would otherwise be used. In the example just mentioned, the grid value used for drawing the contour would be safety biased at 14.9 metres. This logic is certainly not the same as that used in hand contouring but it might produce similar or equally valid results.

Numerical safety biasing of contours could be relatively easy to automate whereas graphical safety biasing, as practiced during hand contouring, would be difficult to implement without sophisticated artificial intelligence. Once the grid values have been numerically safety biased, the second problem (that of contour generalization) might be easier to attack.

Generalization is a sophisticated smoothing operation. Generalization requires real intelligence since the graphical deformations of the contours must reflect the priorities of the navigator, as well as the esthetics of the printed chart. Smoothing, on the other hand, is less context sensitive. Different degrees of smoothing can be applied using mathematical rules. Smoothing has the effect of simply removing or averaging graphical complexity. By numerically safety biasing the grid prior to drawing the contours, the job of contour generalization would be easier to automate since the graphics involved would become much more of a smoothing operation.

Another potential advantage of safety biasing using kriging is that the entire set of data values is biased and not just those values which happen to fall on the contour interval. On the current paper chart this is of minor importance since all contours are: 2m, 5m, 10m, 20m, etc. However, on a functional electronic chart, arbitrary and user selected contours must be displayed. Applying tidal corrections in real time would require that the contours continuously move to reflect the changing water level. If the entire grid of depth data has been safety biased using kriging, then each of these moving contour lines would be faster and easier to draw than if graphical generalization had to be performed each time the contours changed.

Swath Data Compaction

The vast amounts of data being generated by swath systems pose a problem. Real-life data processing systems require that the swath data be decimated in some way before processing. The approach generally taken is to "bin" the data onto a chosen grid size. For example, within each grid bin only the deepest, the shallowest and the average depths might be retained for processing after decimation. The crucial factor in this process is what size of bin is appropriate. CHS wants to filter out "excess data" so as to increase processing efficiency but at the same time it wishes to retain a "sufficiently detailed" Digital Terrain Model of critical topography.

If a 100% bottom coverage is achieved, the utility of kriging would appear at first to drop to zero since the uncertainty between sample points drops to zero. However the swath data decimation problem could be usefully approached from a geostatistical viewpoint so that the bin size could be optimized.

Project Priorization and Digital Data Qualification

Project priorization could be a by-product of the geostatistical process which would help management to identify areas that need to be re-surveyed. As older data is digitized, validated and loaded into the hydrographic data bank, confidence maps could be produced. This scaleless picture of the region would allow management to plan survey campaigns more efficiently with respect to the needs of shipping. Surveys could be dispatched to re-survey those specific areas which did not have sufficient confidence for the maritime activity in the region. Survey instructions could demand only the sounding effort needed to attain the required standard.

Related to this function is the increasing need for a standardized method of qualifying hydrographic data. This will be needed to realize the full potential of the Electronic Chart. Good error estimates for each data point in the hydrographic data base are required in order for the Electronic Chart to compute and present a safe representation of the data to the mariner. The IHO Committee on the Electronic Chart has recognized this need and a Working Group is now studying the problem of how to evaluate the quality of hydrographic data sets and how to use this information within the Electronic Chart.

Hydrostat evaluates data quality strictly in terms of interpolation errors caused by the discrete sampling of the irregular bathymetric surface. A more rigorous approach would also entail an evaluation of the instrumental errors associated with the data collection process itself. This is particularly important when considering older data sets which used less accurate sounding technologies. The two approaches: instrumental error evaluation and geostatistical evaluation of interpolation errors are very complimentary. Variances computed from a knowledge of the survey instruments used during a survey can be propagated through the kriging equations to arrive at an optimal estimate of data quality for all surveyed areas. Standardized software that can perform this data quality evaluation will be required by hydrographic offices producing data for use in the Electronic Chart.

CAVEATS

When considering the potential for using geostatistics in hydrography one should keep in mind the following truisms:

- "You don't get something for nothing".
- "You can make numbers say whatever you want".

The results given in this paper are preliminary. They definitely will require extensive verification before being relied upon. Real data will undoubtedly present cases where the statistical presumption of normal distribution of errors will be false. Strange geological situations such as pingos or man made structures such as wrecks will remain unpredictable. New survey rules of thumb will have to be developed to insure that the Survey Design Tools incorporated in Hydrostat are properly used in such situations.

The validation process using data sets has started from the Magdalen Islands, Lake Huron and the Queen Charlotte Islands. Other data sets will also be used to verify the Hydrostat confidence predictions. For each test site, the total data set from a completed survey will be used to ground truth statistical predictions. The data set will be edited to decimate the line density (half density, quarter density, etc.). So there will be multiple benchmark data sets for each area from which different survey scales can be simulated. The validation process will then proceed using two different test approaches.

The first approach will test for statistical validity. One of the decimated data sets (eg. every fourth line) will be interpolated, using kriging, onto a grid of the same density as the total data set. Thus along the lines that have been removed from the full data set many test points will be obtained. Each test point will give:

- The true measured depth
- The estimated depth from the kriging program
- The estimation variance predicted by the kriging program.

The estimation variance can then be verified by differencing the true depth from the estimated depth and comparing it to the square root of the predicted estimation variance (its predicted standard deviation). For the estimates to be statistically valid, the depth misclosure (the difference between the true and interpolated depths) should be smaller than the predicted standard deviation about 68% of the time. The misclosures should also be less than twice the predicted standard deviation about 95% of the time. Since thousands of test points can be considered in this analysis it should be quite simple to draw valid statistical conclusions.

The second approach to validation being done is more empirical yet probably more significant for hydrographers. A 95% confidence limit would be small comfort to a navigator who discovered an outlier the hard way. What needs to be verified is that the rules for using the Survey Design Tools do not result in unsafe conditions.

To test this, the decimated test sites are being "re-sounded" using the confidence envelopes as a guide. Each of these survey simulations is being started using the decimated data set of every fourth line actually sounded. Additional lines are being added from the total data set as dictated by Hydrostat. Once the simulated survey is fully densified as per the confidence envelope predictions, a visual check is made to note any dangers to navigation that were discovered by the regular CHS survey but were not detected on the Hydrostat pattern. Depth discrepancies will also be compared to see if they fall within the tolerance used to compute the envelopes. Statistics on the kilometres of sounding saved or additional lines required will also be compiled.

After doing simulations using existing data, the next step in validation will be to test performance during actual surveys. Hydrostat processing will be run in parallel with conventional methods. By being carried out in the field, these validations will be more thorough than simulations from archived data, since additional densification can be performed if it is required by the Hydrostat envelopes.

The results from these validation efforts will be compiled and submitted to the hydrographic community. The logistics of the test surveys (both savings and additional sounding required) can then be balanced against any increase or decrease in the perceived danger to navigation. Only then can instructions for using spatial statistics be formulated such that the safety requirements of navigators can be better met at the lowest possible cost. Ultimately experience and judgment will remain the most useful Survey Design Tools.

CONCLUSIONS

Hydrostat adaptive sampling offers the potential for a significant improvement to both the efficiency of data collection on conventional hydrographic surveys and the quality control of the resulting bathymetric data. Before any conclusions can be made on this potential, thorough ground truthing and further software development will be required.

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