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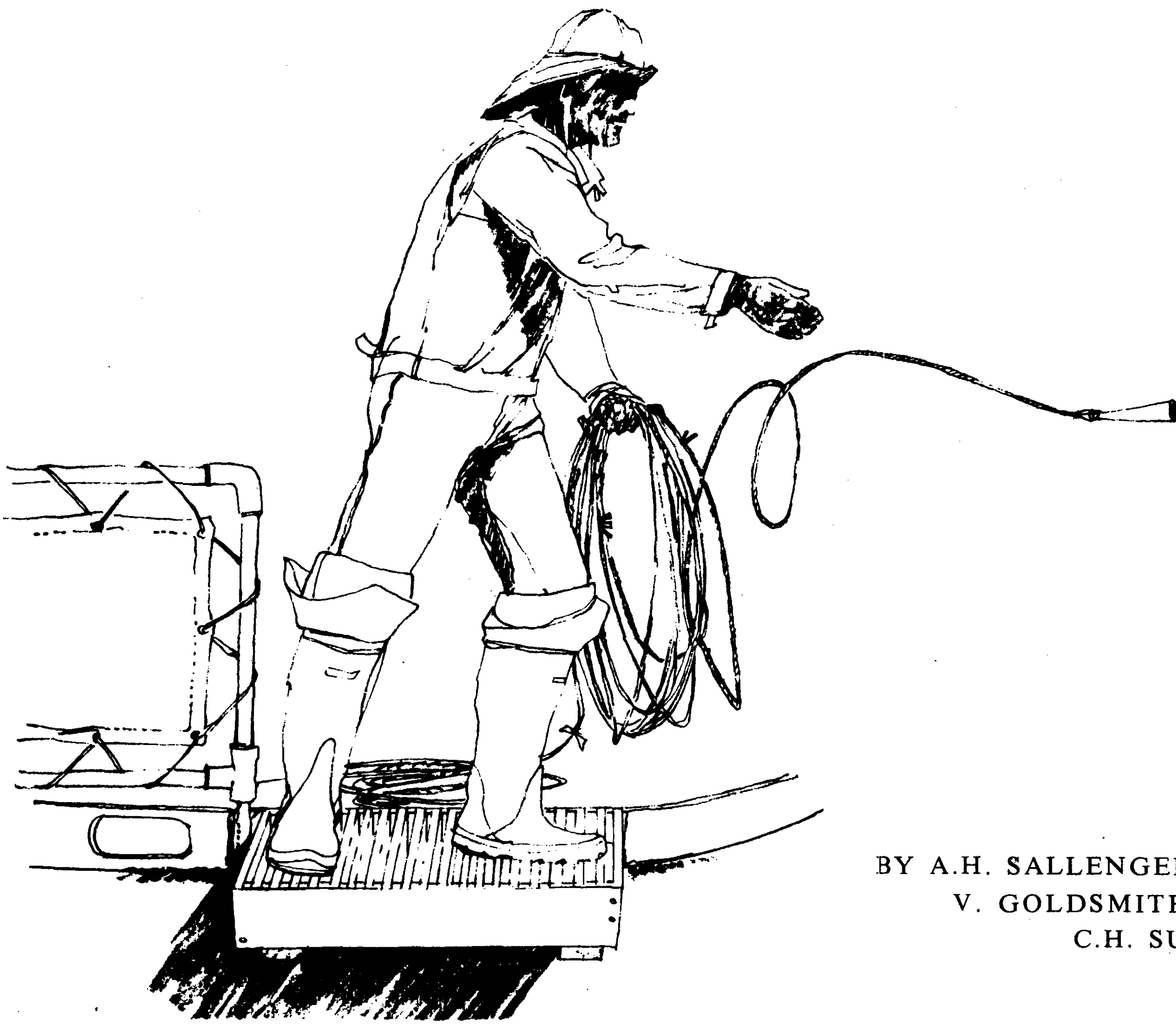

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FORWARD

(From National Ocean Survey Catalog
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In 1807, President Thomas Jefferson, in his message to the Congress, recommended the establishment of a national "Survey of the Coast," and this recommendation was implemented by the Act of February 10, 1807. Thus was born the nation's first cartographic bureau. When the Survey began its hydrographic work, the shoreline of the country included only the strip along the Atlantic coast comprised of about 15,000 statute miles. Ferdinand R. Hassler, an engineer and professor of mathematics, immigrated to the United States from his native Switzerland in 1805. He was encouraged by his sponsor, Benjamin Franklin, to seek and was then selected as the Survey's first Superintendent.

In 1816 two base lines, one in English Neighborhood, New Jersey, and the other at Gravesend Beach, Long Island, began the long history of charting America's waters. During the period from 1818 to 1832 surveying work of the agency came to a standstill due to a lack of funds. By the end of 1833 work was resumed and in 1836 the agency's name was altered to the "U.S. Coast Survey." Edmund Blunt, one of the first assistants to Hassler, headed a field party on Long Island which resulted in the first published charts by the Survey. By an Act of Congress March 3, 1871, a geodetic connection was authorized to be made between the Atlantic and Pacific coasts which enlarged the program work of the agency and caused the name to be changed in 1878 to the "U.S. Coast and Geodetic Survey." Additional areas of responsibility came with the Air Commerce Act of 1926 to produce aeronautical charts of domestic areas. October 1970 brought about the present organization under the National Oceanic and Atmospheric Administration to include charting of the Great Lakes, and the name "National Ocean Survey."

Nautical charts of a century or more ago were and still are works of art. The Coast Survey from 1850 until about 1916 pioneered in the copperplate technique of chart construction and reproduction. During its heyday in the second half of the Nineteenth Century, this technique reached levels of artistic expression not previously attained in cartographic pursuit. Its practitioners were skilled artists that included one of America's most famous sons, James McNeill Whistler.

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INTRODUCTION

By comparing bathymetric charts of the same region, but of different dates one can obtain net measurements of erosion and accretion. The measurements have numerous uses including computing sediment budgets for coastal waters (Stapor, 1971, 1973; Moody, 1964; Arnal, et al., 1973; Schubel, et al., 1972; Pierce, 1969; Stauble, 1974; and others), determination of general scour and deposition patterns (Nichols, et. al., 1972; Jordan, 1961; Hunter, 1914; and others), analyses of the mobility of subaqueous geomorphic features such as the ridge and swale topography (Moody, 1964; Swift, et al., 1972), measuring accumulations of waste material (for example, in the New York Bight, Williams and Duane, 1975), and many engineering applications dealing with design criteria of offshore structures such as pipelines (Rawn and Broverman, 1950), power plants (DeAlteris, et al., 1975), ports (Studds, 1950), drilling rigs, and others (Weeks, 1973).

In applying the results of a bathymetric comparison, however, it is essential to consider the errors involved. For example, consider the comparative profiles illustrated in Figure 1. The profiles (from Goldsmith, et al., in press) are drawn from soundings taken in 1852 and 1934 and extend offshore from an area encompassing Lat. 37°20' to Lat. 37°50' on the Eastern Shore of Virginia. The profiles show the ridge and swale topography which is a common component of the Mid-Atlantic inner continental shelf of the U.S. (Duane, et al., 1972). The comparisons indicate generally, that the ridges tend to build in height and that the swales tend to be scoured deeper. This type of response of the ridge and swale may be a result of helical flow systems confined between adjacent ridges (see Swift, et al., 1973 for discussion of helical flow in respect to ridge and swale). Questions, however, arise concerning the indicated changes in bathymetry. Could vertical errors in the measurement of the depths account for the indicated changes? Could horizontal position errors affecting the measured depths account for the changes? Since the soundings from one chart do not necessarily fall in the same location as the soundings from the chart to be compared, could errors due to interpolation to like positions account for the changes? Could distortion of the medium upon which the charts have been printed cause position errors in the soundings (Table 1)?

The purpose of this paper is to provide the worker with a manual of methodology for bathymetric comparisons, and techniques whereby the accuracy of such comparisons can be determined. An extensive literature survey is also included for the benefit of the interested reader. Altogether, this compendium is designed to fill a void in a field where chart usage is the basis for all other studies.

The study is subdivided into three basic sections. The first section (Methodology of Bathymetric Comparisons) discusses four methods by which charts can be compared and the limitations of each. The second section, entitled "Error Criteria for

TABLE 1: Distortion of Chart Paper

Type of paper or material	Percentage of distortion caused by a change from 27 to 89 per cent relative humidity	
	Across short dimension of sheet or roll	Along long dimension of sheet or roll
Cellulose acetate	0.29	0.19
White paper, Whatman	0.40	0.56
Buff paper, K. & E. No. 13322 M	0.51	0.25
Tracing paper, K. & E. Ionic No. 197 H	0.54	0.13
White paper, Weil No. 72	0.61	0.39
Chart paper (unmounted)	0.65	0.29
Buff paper, K. & E. Duplex No. 141 (in rolls)	0.65	0.40
Buff paper, K. & E. Duplex No. 141 (in sheets)	0.75	0.35
Tracing paper, Post No. 173	0.82	0.28
White paper, K. & E. Paragon	0.97	0.45
Tracing paper, K. & E. Doric	0.99	0.27
Tracing cloth, K. & E. No. 13303	1.00	0.28

(from Adams, 1942, p. 659)

Soundings" analyzes the two prime bathymetric data sources for the U.S. coastal waters (NOAA and U.S. Army Corps of Engineers) in terms of the accuracy of soundings published by each source. In the final section, varied applications of bathymetric comparisons are discussed utilizing the results of the first two sections.

METHODOLOGY OF BATHYMETRIC COMPARISONS

Four methods will be discussed (data point, contour overlay, contour overlay-data point, and grid point comparisons). The limitations of each method will be discussed independently of sounding accuracy, which will be dealt with in a later section.

DATA POINT COMPARISONS

Data Point comparisons involve comparing charts where the indicated positions of soundings are the same for each chart. The Corps of Engineers often gathers data of this character by measuring bathymetry along fixed traverses (i.e., repetitive surveys at the same locations). Accurate profiles can be drawn, and successive surveys compared, which provide accurate indication of local stability. The primary errors would concern the measurement of depth and depth changes due to horizontal positioning discrepancies (these errors will be discussed in a later section).

Volumetric changes of sediment can be calculated by interpolating between traverses (see for example Pierce, 1969). Error involved in volumetric computations can be quite substantial and is a function of the irregularity of bathymetry. An example of the error involved in the interpolation between traverses is presented in Fig. 2 which is taken from Saville and Caldwell (1953). The data are based upon computations of change from a number of traverses along Mission Beach, California. Spacing error is resolved by repeatedly computing the volumetric change along a set length of coast with different numbers of set traverses spaced evenly along the coast. In Figure 2 the probable volumetric error due to interpolation between traverses of various spacing is presented. Saville and Caldwell (1953, p. 1-2) point out that the data employed in the analysis were taken from "... a relatively long, straight beach, with essentially parallel contours, and no radical changes of bottom hydrography along its length, and as such, is representative of many of the southern California beaches." The analysis may well apply to other beaches of the same type, but should provide those working in other environments an indication of the magntidue of possible error that has to be considered in volumetric computations of sediment flux. It should, however, be remembered that in more complex bathymetry (typically much of the U.S. East Coast) the error can become significantly greater.

CONTOUR OVERLAY COMPARISONS

When utilizing National Ocean Survey (NOAA) data which are irregularly distributed from chart to chart of the same area, one method of comparison is the contour overlay. Each set of data is contoured to the same interval and plotted together at the same scale. An example of a contour overlay originally presented in Moody (1964) is shown in Figure 3. Volumetric measures of erosion and accretion can be determined by multiplying the change in area between the contours of the two dates by the average change in depth.

The three major limitations of this method, related to (1) Depth interpolation; (2) Medium distortion; and (3) Map projections, are discussed below:

1. Interpolation problems

Two types of interpolation are used in resolving volumetric changes. One limitation is the interpolation of drawing the contours between data points and the other limitation is involved in determining the average change in depth. These interpolations will affect the accuracy of comparison in the same way that the spacing of traverses affects the accuracy of data point comparisons; that is, generally the longer the distance over which an interpolation is made, the less confidence one can ascribe to the value. The confidence of course is also dependent on the complexity of bathymetry, that is a long interpolation in uniform bathymetry may well be more accurate than a shorter interpolation in orregular bathymetry. The accuracy of interpolations are discussed below in two parts: (a) Orientation of track lines; and (b) Depth density.

a) Orientation of track lines

The orientation of track lines may cause an error in interpolation. For example, until 1878 surveyors were instructed to orient track lines along the supposed contours (Shalowitz, 1942, p. 218). That the technique may have induced errors when applied to certain bathymetries is illustrated in Fig. 4. The earlier technique (track lines A, B and C) may have missed the deepest or shoalest points simply by not aligning along that singular deepest or shoalest contour. Since 1878 the general requirement for surveyors is to orient tracklines across supposed contours. In the present case this would yield the extremes in bathymetric fluctuation (tracklines 1, 2 and 3). The above case is provided only to be illustrative of possible errors since the surveyors most often resort to systems of tracklines that are designed to distinguish the maximum and minimums in depth. However, since all post 1878 tracks are not always aligned perpendicular to the contours (a situation which may become evident in more complex bathymetry) it is always worthwhile to peruse the charts to be compared for this type of error.

b) Depth density

Since we have assumed that the accuracy of a given interpolation is also a function of the spacing of the data points we must be concerned with the density of data on any given chart. The early criteria for data density usually were qualitative as is indicated in the instructions circa 1860. "The best test of whether they (the soundings) are sufficiently numerous is to ascertain if horizontal curves can be drawn by them, without leaving doubt as to their direction in any case" (quote from the original instructions, Shalowitz, 1964, p. 217). The survey criteria for trackline spacing, published in Jeffers (1960, plate 20), are plotted in Figure 5. These criteria, adopted in 1955 by USC & GS (now National Ocean Survey) indicate that hydrographic surveys equal or exceed these standards. It can readily be seen that the necessary density varies with scale, the larger the scale of the chart the more dense the data (remember 1:80,000 is a smaller scale than 1:10,000). This, of course, indicates that interpolations would tend to be more accurate on larger scale charts for the same bathymetric irregularity. Again, the accuracy of the interpolation can be to some degree estimated by the measured roughness along tracklines. The accuracy of this measure will decrease, however, with smaller chart scales, since we see in Figure 5 that data spacing along tracklines increases for smaller scale charts.

2. Distortion of the medium

A second major source of significant error is in the distortion of the medium upon which the charts are printed. Figure 6 shows a plot of the degree of distortion experienced by various mediums taken from data presented by Adams (1942, p. 658). The indicated changes refer to percent distortion in the across roll and along roll (of chart paper) direction due to a change in relative humidity of 27 to 80 percent. Figure 6 indicates that the distortion tends to be generally unequal in direction. The length of the solid line actually indicates the distortion of the medium since if the changes were equal in direction it would only amount to a scale change which could be readily corrected for. Prior to the comparison of charts the distortion of the chart should be determined. A method for determining distortion is to compare the scaled distances on the chart to the proper lengths as presented in the Polyconic Projection Tables , Special Publication No. 5 of the old U.S. Coast and Geodetic Survey (see Adams, 1942, p. 678). The distortion factor can be determined from the relation:

$$\frac{\text{Tabular value - Scaled value}}{\text{Tabular value}} = \pm \begin{matrix}\text{Distortion} \\ \text{Factor}\end{matrix}$$

This amounts to a measure of relative dispersion, and can be applied to measured distances that are to be plotted on the chart. Of course, several scaled differences should be measured and the mean calculated. In order to reduce distances on the chart to actual distances then the following correction factor should be used:

$$\frac{\text{Tabular value - Scaled value}}{\text{Scaled value}} = \pm \begin{matrix}\text{Correction} \\ \text{Factor}\end{matrix}$$

Should the distortion of the charts be extreme, then the validity of the comparison would be suspect. One should definitely consider employing the reduced form of the correction factor as an addition to position errors involved in obtaining soundings.

3. Map projections

Another source of error is to inadvertently employ two different types of map projections in a contour overlay comparison. Several types of projections have been utilized by the Coast Survey including the Bonne, rectangular polyconic, equidistant polyconic and polyconic (Shalowitz, 1964, p. 135-140). Of all of the charts published, however, the ordinary polyconic projection was used in the great majority of cases. It is now used exclusively. There is some evidence that the Bonne projection was used in some early surveys, such as the 1844-1945 charts of Delaware Bay and River (Shalowitz, 1942, p. 135). The rectangular polyconic projection was used for a period after 1853, but departs very little from the ordinary polyconic (Shalowitz, 1942, p. 138-139). The equidistant polyconic was employed earlier than 1853, and possibly to 1882 (Shalowitz, 1942, p. 139-140). The problem involved in utilization of this technique in chart making is that the charts distort the geometry of the contours depending on the projection. This distortion is greatly reduced when dealing with relatively large-scale charts (i.e., 1:10,000 or 1:20,000) since "... the curvature of the meridians never becomes sensible and the parallels only rarely so." (Shalowitz, 1942, p. 140). However, as long as the charts are corrected to the same datum, then the actual positions of soundings are correct in terms of latitude and longitude (which is, of course, uniform irrespective of projection). A method described at the end of this section (grid point comparisons) will illustrate how a comparison can be performed in terms of sounding position as opposed to the geometry of contours.

CONTOUR OVERLAY - DATA POINT COMPARISON

A prime problem involved in the contour overlay comparisons is in the necessary interpolations between soundings in order to develop a base of comparison. Two methods are: (1) contour overlay-data point comparisons; and (2) grid point comparisons.

A fairly simple method is outlined whereby one can qualitatively determine the influence of interpolation on indicated changes in contour position in a contour comparison. The method is illustrated in Figure 7. The contours and position of track lines from which the contours were determined are plotted. At point B and D the contour change indicates migration of the feature to the top of the diagram. At A and C, however, there is very little change. Since we have a good overlap of data at A and D which approaches a data point comparison then we should rely on these data to indicate a change to a greater degree than interpretations at B or C. We can conclude that a change does appear to have occurred with the topographic highs building higher and the lows remaining stable irrespective of any interpolation errors. Consequently, should a case arise where the data superposition indicates stability and the interpolated areas mobility then we might suspect a conclusion of stability.

The three limitations of this data point comparison method are briefly outlined below:

1) The method suffers from the limitations of the contour overlay method excepting that the interpolation error has been decreased somewhat.

2) The method is basically qualitative and intended primarily to aid judgements of the relative stability of the sea floor. A good application of this method would be in the analyses of the mobility of the ridge and swale topography.

3) The assumption that the data is continuous along track lines is of course not completely justifiable. Ideally, it would be necessary to have the original echo sounding records which would definitely provide a continuous data source. These, however are not generally available. It is suggested then that the track lines are the next best source.

GRID POINT COMPARISONS

A method of comparison based on the position of soundings in terms of latitude and longitude is provided below. Grids based on latitude and longitude are developed. Depths may be interpolated to the grid points for each chart to be compared depending on scale of grid and data density (Fig. 8). The interpolated or actual depths at the grid points can then be directly compared. The data could, however, first be transferred from the latitude/longitude grid to an equal-spaced grid to make the data amenable to computer processing of the changes in depths and contouring of the residuals (i.e., amount of depth change). Goldsmith, et al. (in press) utilized this depth transfer method in generating the bottom fluctuations (see in Fig. 9). To obtain volumetric results the area encompassed by contours should be multiplied by the average change in erosion or accretion derived from the grid point residuals.

The significance of four major limitations involved in bathymetric comparisons are discussed below with respect to the grid point comparison technique.

1) The method employs the interpolations of transferring to grid points, contouring results, and average change determinations. The previous discussions of interpolations on p. 3-6 will apply equally here.

2) The problems of the distortion of the medium discussed on p. 6-7 also apply here, but perhaps to a lesser extent. A depth that falls on the crossing of latitude and longitude lines is

correctly positioned with respect to latitude and longitude irrespective of the degree of distortion, so grids imposed on the originally drawn skewed rectangles of latitude and longitude (corrected for datum) will somewhat diminish the effects of distortion for the entire comparison as compared to trying to line up the contours of two charts at the widely spaced control points at the border of the charts.

3) The distorting influence of the projection becomes nonsignificant since the comparison is based on latitude and longitude.

SUMMARY OF LIMITATIONS AND REMEDIES OF METHODS

A summary of the limitations of each chart comparison method and suggested techniques by which the influence of each limitation on the chart comparison may be reduced or quantified, is presented in Table 2. The choice of one or another of these methods for a specific chart comparison depends on the type of data available, how well the limitations can be offset or quantified and, of course, the ultimate purpose of the comparison.

TABLE 2. Methods of Comparison: Summary of Limitations and Suggested Techniques for Offsetting or Quantifying these Limitations

Method	Basic Data Source	Limitations	Suggested Technique
Data Point	Corps of Engineers	1. interpolation between traverses for volumetric computations.	1. use of Fig. 2 with the knowledge that the computations may not be applicable to all environments.
Contour Overlay	N O A A	1. interpolation between soundings in drawing contours and interpolation in determining average change in depth for volumetric computations. 2. distortion of medium upon which chart is or has been printed (meaning the charts may have been copied several times). 3. use of two different map projections	1. peruse the chart for errors due to orientation of track lines and use largest scale chart available, questioning the results of smaller scale charts. 2. use of one of the following equations to check the $\pm \text{distortion factor} = \frac{\text{tabular value - scaled value}}{\text{tabular value}}$ or $\pm \text{distortion factor} = \frac{\text{tabular value - scaled value}}{\text{scaled value}}$ 3. ---
Contour Overlay - Data Point	N O A A	1. basically the same as contour overlay, yet the interpolation error in qualitative analysis has been decreased somewhat. 2. basically designed for qualitative analyses to determine the net movement of contours. 3. the assumption that data presented along a trackline is continuous is not completely justifiable.	1. same as contour overlay. 2. --- 3. use the largest scale charts which would have more dense data along tracklines (see Fig. 6); ideally it would be beneficial to obtain original echo soundings for the more recent charts, but this generally is not available.
Grid Point	N O A A	1. interpolation to grid points and determination of mean change for volumetric computations. 2. distortion of medium upon which chart is printed.	1. basically the same as contour overlay 2. same as contour overlay; the method, however, may decrease the influence of this somewhat.

ERROR CRITERIA FOR SOUNDINGS

In the previous section consideration was made of the methods of comparison, the limitations inherent in each method and proposed remedies for each limitation. In the present section we will devote our attention to the accuracy of soundings. As previously indicated the two prime data sources for U.S. coastal waters are NOAA and the Corps of Engineers. The accuracy of bathymetric data published by these two sources will be considered separately. The accuracy of the bathymetric data are best considered in terms of a vertical envelope about the survey line, i.e., a ± error.

NATIONAL OCEAN SURVEY (NOAA) DATA

Congress adopted a resolution on February 10, 1807 for a "Survey of the Coast". The organization that grew from this legislation was the Coast Survey which later became the hydrographic surveying branch of NOAA. One would assume that due to improved techniques and instruments the accuracy of surveys would have increased over the years from the Coast Survey's inception. Improvements in technique are not reflected in error criteria. Table 3 details the basic instruments and surveying techniques that have been employed by the Coast Survey for shore controlled surveys. The basic assumption is that surveys using the echo sounder and radar horizontal control are more accurate, generally, than surveys utilizing lead line and sextant, particularly the farther offshore one travels. The questions are then how much more

TABLE 3. Instruments and Techniques Employed by National Ocean Survey (NOAA) for Shore Controlled Surveys (basically after Shalowitz, 1964, p. 229-232).

S O U N D I N G

Approx. Dates	Instruments
inception to 1930's	(1) graduated pole to 10 or 15 ft. (2) leadline thereafter
1930's to present	(1) graduated pole in shoal water (2) echo sounder, thereafter*

P O S I T I O N I N G

Approx. Dates	Instruments
as late as 1894	(1) sextant angles on 3 shore stations (2) two shore theodilite angles on boat and verification by angle on shore bases (3) running ranges from shore and fixing position by time and velocity
1930's	RAR - Radio Acoustic Ranging; timed velocity of sound between boat and shore
during and post WW II	electronic fixes on shore stations, Shoran, E.P.I. (Electronic Position Indicator) and Raydist

* echo sounder first placed on a survey vessel in spring of 1925 (Hawley, 1931, p. 55-56) and used at depths greater than 15-20 fathoms through the early 1930's.

accurate are the recent surveys relative to the early surveys, and what is the absolute accuracy of each?

Discussions of the limitations of the NOAA data is divided into three subsections, as follows. The first is a discussion of the accuracy criteria employed by surveyors of NOAA over the years (Historical Review of Accuracy Criteria). The second section, on Maximum Error, discusses the criteria published in the Hydrographic Manual of 1960 (Jeffers, 1960) in terms of its general application to NOAA data. The third section is devoted to describing techniques whereby the absolute accuracy of specific charts can be determined.

1. Historical Review of Accuracy Criteria

The earlier instructions issued to surveyors were in manuscript form circa 1844 (Shalowitz, 1964, p. 215). The first instructions to include sounding accuracy criteria were presented circa 1860. Various accuracy criteria issued to surveyors are presented in graphical form in Figure 10 and the accompanying wording and general application of criteria in Table 4. The criteria since applied at track line crossings includes both vertical and horizontal discrepancies. Assuming that the sounding accuracy has improved over the years due to better equipment and and techniques, then one would expect that generally more stringent instructions to the hydrographers would accompany this increase in accuracy. As seen in Figure 10 this is not universally true. What is apparent, however (see Table 4) is that the more recent in-

TABLE 4. Historical Review of Sounding Accuracy Criteria Required of Hydrographers

Date of Criteria	Criteria	Notes
1860	"allowable error at sounding-line crossings was not to be more than 3 percent of the depth, with a limiting error of 5 percent" (quote from Shalowitz, 1964, p. 218)	requirement is based on "Observations made expressly for the purpose have shown that in the smooth water and moderate depths of harbors the accuracy attainable is to fractions of a foot, and in offshore soundings to fractions of a fathom" (from Shalowitz, 1964, p. 218 quoting the original instructions)
1878 and 1883	depth at sounding line crossings were not to exceed "in depths of 15 feet and under, two-tenths of a foot; between depths of 15 and 30 feet, three-tenths; 30 and 48 feet, five tenths; between 48 and 72 feet, three-fourths of a foot; between 72 and 96, one foot and a half; and between 96 and 150 feet, two feet. In the sea depths the limit of error should not exceed 1 percent" (from Shalowitz, 1964, p. 221, quoting original instructions)	
1894	the allowable error at sounding line crossings was 1.5 percent of the depth (Shalowitz, 1964, p. 224)	based upon observations made in smooth water (Shalowitz, 1964, p. 224)
1942	"In general, in the lesser depths the differences at sounding line crossings should average not more than 5 percent of the depth and in greater depths not more than 2 percent of the depth". (Adams, 1942, p. 275)	in inspecting the smooth sheet "The allowable difference in any case should not be based on a percentage of the depth, but rather on the lateral displacement of the depth curves." (Adams, 1942, p. 733)
1960 A	"In areas of smooth bottom and depths less than 11 fathoms, the discrepancies should not exceed 2 feet or .4 fathom. In areas of irregular bottom and in depths greater than 11 fathoms, discrepancies should not exceed 3 percent in the lesser depths and should decrease to 1 percent or less in ocean depths". (Jeffers, 1960, p. 158)	boat sheet criteria, which is for predicted tides and in which minor corrections are ignored; again as in 1942 emphasis is placed on displaced contours.
1960 B	"In areas of flat or gently sloping bottom and depths less than 11 fathoms, discrepancies of one unit in feet or .2 unit in fathoms can be expected occasionally, and, except where these differences affect a natural delineation of depth curves, they do not justify extensive investigation". (Jeffers, 1960, p. 222)	smooth sheet criteria

structions have been designed to be generally applicable to varying field considerations, unlike the early instructions. In the 1942 and 1960 instructions emphasis is placed upon the degree to which discrepancies displace the bottom contours. For instance from Adams (1942, p. 733) we find stated:

> In comparatively even bottom, such as exists in the Gulf of Mexico, a difference of 2 or 3 feet may be excessive, because of the amount of depth curve displaced. On the other hand, in areas of steep slopes a difference of several fathoms may be readily allowable since the position of the depth curve may not be affected appreciably.

On the other hand the early criteria were most often based on the ability to sound in relatively quiescent and shallow water (see for instance Table 4 for 1860 and 1894 Criteria, Notes Section). We might then conclude that the late instructions were more generally applicable for various conditions and environments than were the early instructions. At any rate, it would be difficult, and probably erroneous to generally apply these criteria to charts surveyed in the respective years, at least for the early years. The later criteria may also be difficult to handle since at least for 1960 the smooth sheet (which is basically the final product which we might use) criteria include only relatively shallow and smooth bathymetry.

2. Maximum Allowable Error Criteria

In 1955 the American Nations adopted Accuracy Standards for hydrographic surveys at the 7th Cartographic Consultation of the Pan American Institute of Geography and History. These were published as part of the Hydrographic Manual in Jeffers

(1960, p. 19-20). The vertical and horizontal error criteria are discussed individually below.

a) Vertical criteria--The criterion cited for maximum allowable error in measurement of depth is plotted in Figure 11 for depths up to 200 feet. Table 5 provides the wording of the criteria for all depths. Also plotted in Figure 11 and text presented in Table 5 is the additive error due to adjusting soundings to the same datum plane (i.e. tidal corrections). These criteria may be put in terms of ± error (which is only partly dependent on total depth). As seen in Figure 11, the errors are fairly large relative to the criteria previously presented in Figure 10 (and which are more directly dependent on total depth). A reasonable assumption would be that the criteria were an attempt to include all environments that are surveyed and most all conditions under which surveys are conducted. These then are broadly applicable criteria unlike those presented in Figure 10. Furthermore it may be reasonable for the relatively shallow depths here considered, that the criteria may to some extent apply to the early surveys. This is supported somewhat in the early observations of the fairly good accuracy of the leadline in the tests in quiescent waters, and further by comparative experiment between leadline and echo sounder by Roy (1970, p. 17) who found no significant difference. However, on the open coast where significant wave activity might occur, the ability of the leadline operator to pick a mean water level should be poorer than doing the same operation from the results of an echo sounder. At any rate, we might say that the

TABLE 5. Maximum Allowable Accuracy Criteria for Vertical and Horizontal

CRITERIA		VALUES
Vertical:	Measurement of Depth	"(1) 0 to 11 fm. (0 to 20 m): 1.0 ft. (0.3 m); (2) 11 to 55 fm. (20 to 100 m): 5 fm. (1.0 m); (3) 55 fm. (100 m) and deeper: one percent of depth."
Vertical:	Reference of Sounding to Vertical Datum	"Location and duration of water stage observations to be such that each sounding can be referenced to the selected vertical datum with an error no greater than one-half that specified for measurement of depth."
Horizontal:	Error of plotted position (relative to a shore control)	.05 in. (1.5 mm) ; (for measurements on the scaled charts)

(taken from Jeffers, 1960, p. 19-20)

standards apply to maximum errors of the recent surveys and may be a minimal estimate of maximum error in the early surveys.

There are, however, two problems involving vertical corrections that may affect the accuracy of surveys. These problems are concerned with the paucity of precise tidal information on the shelf, and the effect of long period waves on the survey accuracy.

First, since tidal corrections applied to sounding data are based on measured tides at a shore base, the variation in tidal heights offshore are not accounted for in surveys that extend off the coast. For example, Sturges (1974) has suggested that a sea level slope exists over the continental shelf; Pattullo (1963) has measured seasonal changes in sea level (which may not be uniform across shelf); and Meade and Emery (1971) have suggested that shelf sea level can be locally affected by river runoff. Since little is known about tidal heights on the continental shelf this could produce a significant source of error that cannot at present be remedied. Since surveys run at different times employ different tidal corrections, crossline comparisons could be severely affected by faulty tidal corrections (as well as other sources of error). "Offshore tidal information can best be acquired by installation of a bottom-mounted tide recorder. Thus, offshore soundings could be reduced to a local low water which could then be correlated with a shore-based tide recorder. Moreover, an "absolute" depth check would be available at the recorder site. Such improvements might eventually lead to more stringent accuracy criteria." (R.J. Byrne, personal communication).

With respect to the second problem, Magoon, et al. (1970) reported the effect of long period waves on the accuracy of surveying. In Santa Cruz Harbor, California it was reported that since the tide station and surveying boat were located on different portions of the wave at any given instant the sea level correction could approach an uncertainty of ± 1.5 feet. Cross (1974) has studied the problems of wave-generated "wiggles" on the record, and vessel rollings and has suggested ways by which the survey errors introduced by these phenomena can be recognized and negated.

b) Horizontal Criteria--The horizontal error criteria is provided in Figure 12 and the exact wording in Table 4. The criteria refer to the horizontal error of the plotted soundings on charts relative to the shore control. The error will increase with decreasing chart scale. What we are actually interested in, however, is in exploring how this error will effect the value of soundings and this, of course, is dependent on the slope of the bottom. In Figure 13 the influence of horizontal error in affecting the sounding is plotted versus the slope of any particular bathymetry or localized area. This, of course, would be in addition to the total vertical criteria plotted in Figure 11.

c) Limitations--The use of the maximum vertical and horizontal error criteria may be somewhat limited in terms of bathymetric comparisons in the sense that it provides only the maximum chart and sounding error where the charts may indeed be more accurate, or where there may be other errors involved. Take for instance a two-dimensional case of comparing profiles as shown in Figure 14. Error envelopes are plotted around each profile. These envelopes should include possible errors due to sounding correction to datum, horizontal discrepancy and interpolation. What can be concluded from such a comparison is that:

(1) Where the envelopes surrounding the two profiles overlap the indicated change may be due to lack of measurement accuracy, but since maximum end criteria are being employed there is the possibility that the envelopes for the specific charts should be less wide (i.e., the charts are more accurate) and that a change has actually occurred.

(2) Where the envelopes do not overlap a change is indicated, but this may be attributed to other causes (i.e., tidal aberrations, long waves, etc.) and the possibility remains that the envelopes should be thicker.

Absolute Error Criteria

The standards adopted in 1955 by the American Nations at the 7th Cartographic Consultation of the Pan American Institute of Geography and History included the assertion that track lines on charts must cross at intervals of 3.0 in. (7.5 cm) or less (Jeffers, 1960, p. 20) which for a 1:20,000 chart is a maximum spacing of .82 nm. All regular surveys have included the crossed tracklines as a way of checking soundings, but not always at the interval specified above. The availability of soundings at nearly the same horizontal location provides the basis of determining the absolute (as opposed to maximum) accuracy of any specific chart. This is done by calculating the difference of the soundings at all available cross points, calculating the mean and standard deviation of the differences and then employing standard statistical/probability procedures on the mean error. Roy (1970) used this procedure to investigate the sedimentation in a tropical environment (Kaneohe Bay, Oahu). The differences at crosslines were calculated as were the means and standard deviations of differences for each chart to be compared. The 95% confidence interval for the error is given by:

$$(\sigma_1^2 + \sigma_2^2)^{\frac{1}{2}} 1.96 = \text{absolute sounding error}$$

where σ denotes the standard deviation of the differences at crosspoints and subscripts refer to specific charts. The results are interpreted as follows: a change in depth equal to the calculated error has a 5% probability to be due to survey error and a change greater than the calculated error is considered a real change. The absolute error does, of course, include depth errors due both to vertical and horizontal discrepancies.

CORPS OF ENGINEERS DATA

Saville and Caldwell (1953) repeatedly surveyed the same track line over a five hour period using an echo sounder mounted on a DUKW at depths ranging from 50 ft. to where the DUKW grounded, and they used a leadline for inshore. Two types of analyses were performed on the data: a) all profiles were compared with the mean profile, and b) successive profiles were compared. The analyses include the sounding error due both to vertical and horizontal surveying discrepancies.

For the echo sounding data the results were nearly the same for each analysis. For a) analysis the standard deviation of the average differences in profiles was .102 ft. and the probable error (the 50% confidence limit indicating average error) was .07 ft., and for analysis b) the standard deviation was .118 ft. and the probable error .08 ft. As Saville and Caldwell (1952) point out the very low indicated error is probably smaller than what would be expected for most applications since "the comparative profiles were taken on the same day with the same personnel and equipment and with relatively small tide variation and also any constant error that might have been effective on the day of the soundings, such as in the instrument, is not included (in the analysis)." Also, continuous rerunning is a lot easier than re-occupying an exact line after a considerable period of time. The leadline data analysis showed under a) a probable error of .11 ft. and b) a probable error of .2 ft. It is readily apparent that the echo sounder data are more accurate than the leadline data. This may be the result of the great difficulty in determining mean sea level in the surf with the leadline.

In Figure 2 the influence of the sounding error in calculating volume changes of sediment is plotted. However, the spacing error (based on distance between traverses) is far more significant than the sounding error.

With respect to the small sounding error Saville and Caldwell (1953) comment as follows (p. 3-4):

> "In considering this indication of an 0.07 to 0.08-foot uncompensated error it should be kept in mind that this figure is probably an optimistic one due to the fact that the comparative profiles were taken on the same day with the same personnel and equipment and with a relatively small tide variation. These factors would tend to make the error somewhat less than would be the case if the surveys were taken several weeks or months apart. Also, any constant error that might have been effective on the day of the soundings, such as in the instruments, the submergence of the sounder, or the tide adjustment, is not included in the 0.07-foot figure."

A more recent error evaluation of Army Corps of Engineers' profiles was made by Hands. In this study, the combined profile error is mathematically related directly to the distance from shore, which is considered to be the most important source of profile error. Also in this study, position error, which is the most important component of the total error, is presented in terms of probability (Hands, in publication).

FUTURE SURVEY METHODS

Engineering advances may result in a vastly new surveying technology. The use of helicopters for surveying has been suggested by Fontes and Casanova (1964). Also, the remote sensing use of lasers and other devices from fixed-wing aircraft and satellites is a future possibility.

Irrespective of such future advances, comparisons with the older data will still require the type of bathymetric analyses outlined here.

APPLICATIONS

The applications of bathymetric comparisons are numerous (see Introduction for specific references). The purpose of this section is to outline the techniques in which error analyses can be employed in several specific types of comparisons.

SEDIMENT BUDGET

Scientists and engineers have often employed bathymetric comparisons in deducing sediment budgets for specific areas. Net sediment transport rates, directions and long-term history of scour and fill can be deducted and then employed in design criteria for structures, coastal protection, etc. The basic idea is to identify the sources and sinks of sediment and then quantify with respect to time the volume of sediment flux. A hypothetical case in point is presented in Figure 15. Sediment has been eroded from area A and deposited in area B. As in most cases of sediment budget studies, however, we cannot say it is a closed system, that all of the sediment deposited in B necessarily comes from A, or that some sediment bypasses the sink, etc. The final interpretation is, of course, dependent on the absolute values of erosion and accretion and it is here where a knowledge of the accuracy of measures of erosion and accretion become critically important, so that errors of interpretation might be minimized.

For sediment budgets using NOAA data one approach would be to calculate the absolute error of each chart and determine the minimum amount of change between charts that would be considered a real change at a specific confidence interval. Then perform the comparison, using either the contour overlay or data point methods and calculate the volume flux of sediment. Adjust the soundings using the error criteria to yield the maximum amount of change and recalculate the volume change. Then readjust the soundings for least change, and again recalculate. This will provide a measure of the error limits of the comparison. For Corps data, Figure 2 should be employed in cognizance of the limitations of the error measures.

MOBILITY OF SUBAQUEOUS FEATURES

An analysis of the mobility of the ridge and swale topography off the coast of Delaware was performed by Moody (1964). Moody utilized the original fathograms and calculated the difference in the ridge crest positions as indicated on the fathograms and the crest positions indicated from equally-spaced soundings taken from the fathograms. The equal spaced soundings were what are normally available on NOAA charts. Assuming that the position indicated by the fathogram was the true position it was concluded that the error due to picking off the data at even intervals at the 95% confidence interval was + 9.4 m (the mean difference, positive denotes seaward movement) ± 30.6 m (two standard deviations). This indicates that a movement of 40.0 m or greater in the seaward direction is a real change and a movement of 21.2 m in the shoreward direction is a real change (Moody, 1964, p. 18).

Without the benefit of the fathograms the contour overlay-data point comparison (described in the section on Methodology, see in particular Figure 7), may be particularly useful in this type of analysis. Even though the error due to misplaced crests related to taking data at discrete intervals is not considered, the error concerned with interpolation between track lines (which may be much larger) is to some degree accounted for.

BATHYMETRIC STABILITY FOR DESIGN CRITERIA ON SHELF

In designing offshore structures such as pipelines and platforms a knowledge of the local scour and fill is critically important. As a portion of the analysis one can construct comparative profiles (for example see Figure 1) along the proposed site of the structure. Utilizing the techniques for absolute error, confidence limits can be plotted around the profiles as was done in Figure 14 for maximum error. This should provide a good basis for interpretation of local scour and fill.

MINERAL DEPOSIT EXPLORATION

An interesting possibility arises if we make the general assumption that difficult to transport material (i.e., heavy minerals, gravel, etc.) would tend to be concentrated in areas of scour. Constructing comparisons for given areas using grid point or contour overlay methods would reveal general areas of scour (see for instance Figure 9). Those areas exhibiting a degree of scour exceeding the error limits could then be further investigated for quantities of economically valuable material.

INDIRECT COMPARISONS

An additional type of study that depends on how the bathymetry of one data affects wave patterns as opposed to bathymetry of another data was presented by Goldsmith, et al. (in press). Wave climate models for 1852 and 1934 were developed for a portion of the continental shelf in the area of Wachapreague Inlet, Virginia in order to investigate the relationships between changes in wave patterns (due to bathymetric changes) and shoreline fluctuation. The relationship is shown specifically in Figure 16 and diagrammatically in Figure 17. It is evident that the greatest shoreline erosional zones correlate with short period erosional wave fields of 1852 and accretional zones with the long period accretional wave fields of 1934.

This type of application would, of course, be of value in predicting shoreline changes in the future. The results are, however, dependent on the accuracy of the bathymetry from both dates. Conceivably, one could determine the wave characteristics from bathymetry that represents both the plus and minus error envelope involved for both dates (interpolation, absolute) and then compare the results to that of Figure 17. The results employing the extremes of the accuracy envelopes, however, may not be totally representative of possible errors. This is because the errors would tend to occur at random on the charts and affect the wave climate in one way, where we would artificially raise or lower the bathymetry to account for the computed error over the whole region which would tend to affect the waves in yet another, non-correlative manner. Another approach would be to randomly employ errors to the depths where the frequency of application of any one error would correspond to its probability of occurrence.

SUMMARY

This paper was designed to provide useful methods by which bathymetric comparisons can be conducted, to consider various aspects of accuracy criteria for soundings, and to discuss the utilization of methods and error criteria in specific applications.

Four methods of comparison have been discussed. The data point comparison involved comparing soundings that are in the same horizontal position and pertain primarily to Corps of Engineers data. The contour overlay method involves plotting the contours of one year over the contours of another and by measuring the relative displacement of like contours the change in bathymetry (volumetric) can be calculated. The data point-grid point comparison is a method whereby one can investigate the displacement of contours while minimizing the possible error due to interpolation. The grid point comparison involves comparing soundings that have been interpolated to grid points where the grid points lie at the same horizontal position for different charts. The limitations inherent in each method and techniques to offset and quantify these limitations were discussed, and are summarized in Table 1.

Accuracy criteria required of hydrographers for soundings, for both NOAA and Corps of Engineers data, is presented. Historical review of NOAA criteria is provided in Figure 10. The criteria are unusual in the fact that the criteria did not always become more stringent coincident with the advent of more sophisticated

instrumentation and techniques. Maximum error criteria for both vertical and horizontal control are provided in Figures 11 and 12, respectively. The maximum allowable error criteria adopted by the 7th Cartographic Consultation of the Pan American Institute of Geography and History appears to be more universally applicable than criteria based on instructions to C & GS surveyors detailed in Figure 10. A method by which the absolute error of a given chart can be determined is presented and concerns simple statistical analyses of the depth differences at track line crossings. The probable error for sounding (Corps data), as determined by Saville and Caldwell (1953) is quite small and its influence in volumetric computations is presented in Figure 2.

Sediment budget studies, analyses of mobility of subaqueous features, bathymetric stability for design criteria and mineral deposit exploration are a few of many applications of the techniques of bathymetric comparisons discussed in this manual. The methods and sounding error criteria particularly suited to each of these particular applications are discussed in order to illustrate the applications of these techniques to particular problems.

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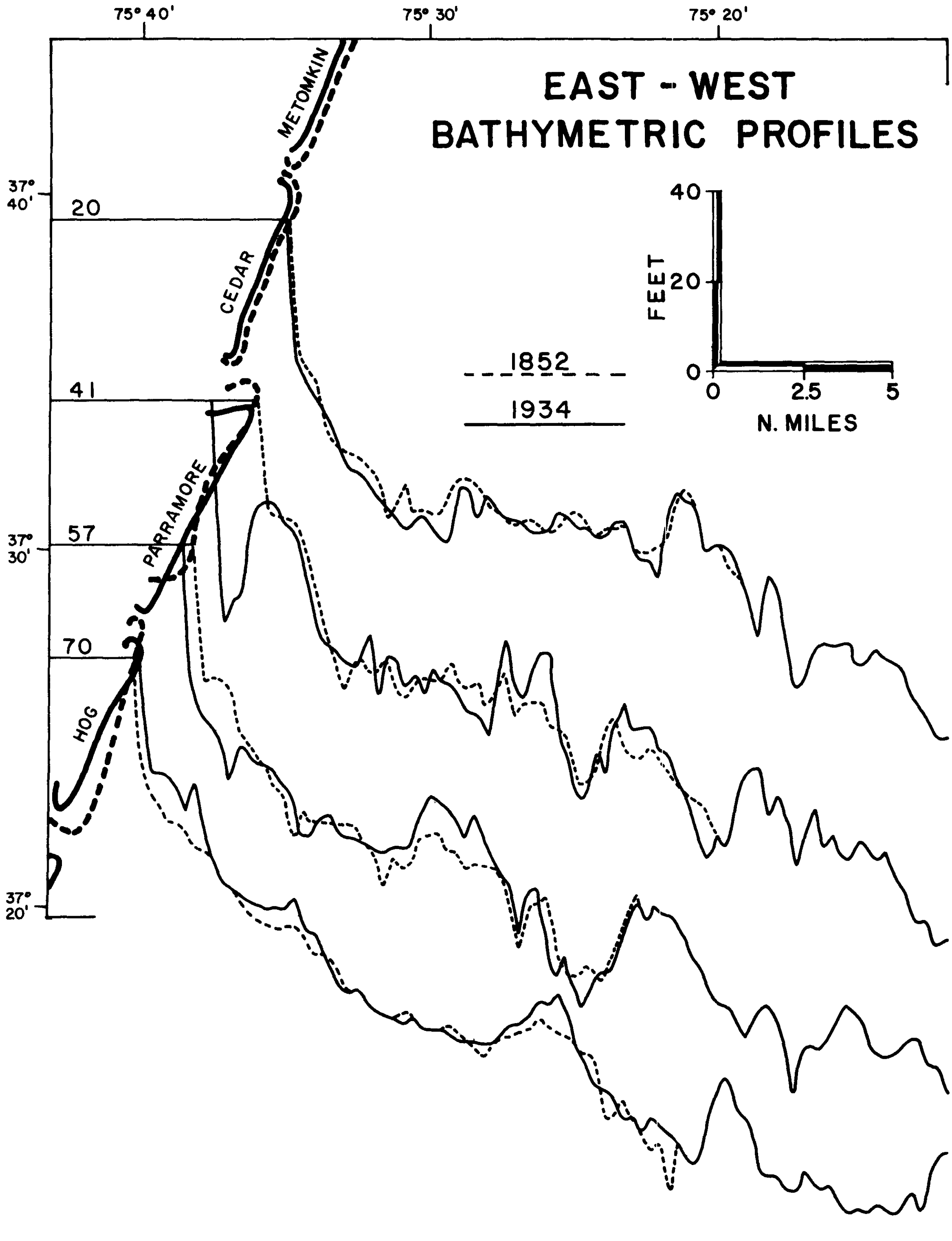
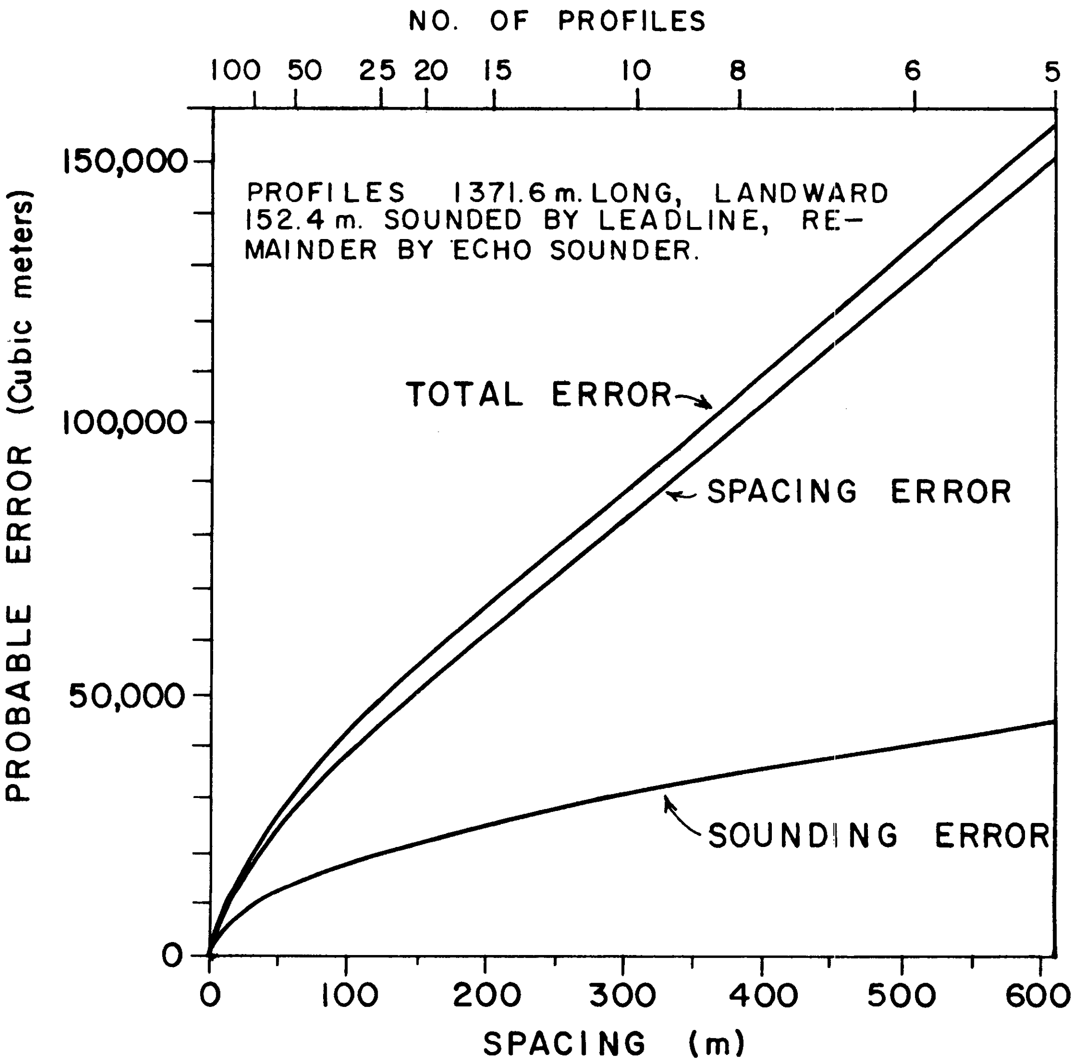
Figure 1. Comparison of four east-west bathymetric profiles (out of 100), plotted from 1852 and 1934 original hydrographic sounding sheets (from Goldsmith, et al., in press). The location is the inner continental shelf adjacent to the Eastern Shore of Virginia, Hog Island to Metomkin Island.



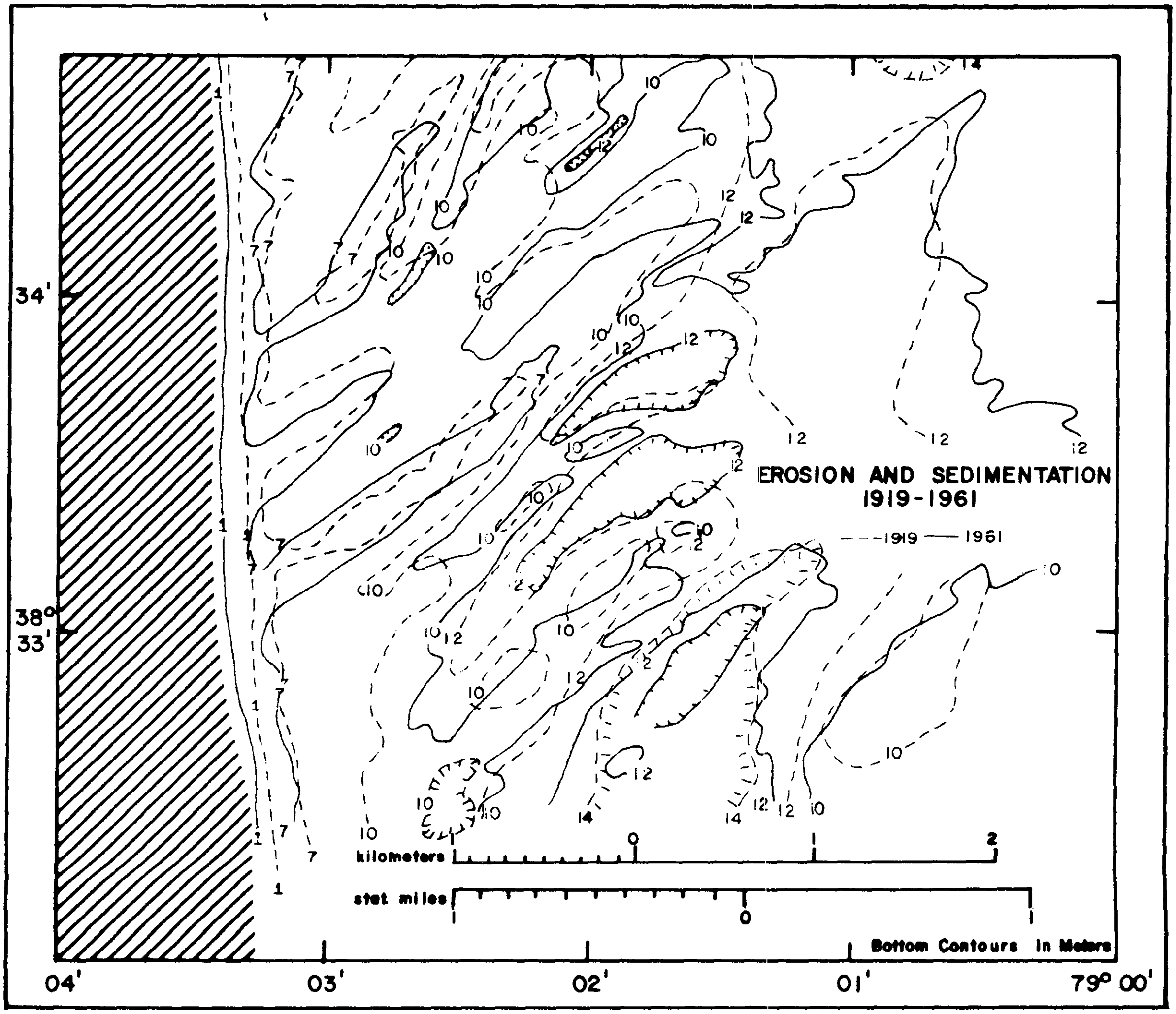
EAST - WEST
BATHYMETRIC PROFILES
75° 40'
75° 30'
75° 20'
37° 40'
37° 30'
37° 20'
20
41
57
70
METOMKIN
CEDAR
PARRAMORE
HOG
1852
1934
FEET
40
20
0
0
2.5
5
N. MILES

Figure 2. The probably volumetric error due to interpolation between traverses at various spacings is presented. Two types of errors are considered. The Spacing Error refers to the errors due to distances between traverses. The Sounding Error refers to volumetric error due to measurement of depth where the volume is calculated over various distances. The combination of the two is provided and termed total error.



From US Army Corps of Engineers (1953) TM 32

Figure 3. An example of a contour overlay comparison taken from Moody (1964).



SOURCE: D. W. MOODY (1964)

Figure 4. Possible sounding discrepancies due to orientation of track lines is shown. The solid lines indicate the contours. A, B and C are track lines oriented parallel to contours. 1, 2 and 3 are tracklines oriented normal to contours. Since B does not align along the contour 4 then the extreme in depth is not revealed, but since track lines 1, 2, 3 are oriented normal to contours extremes are well represented.

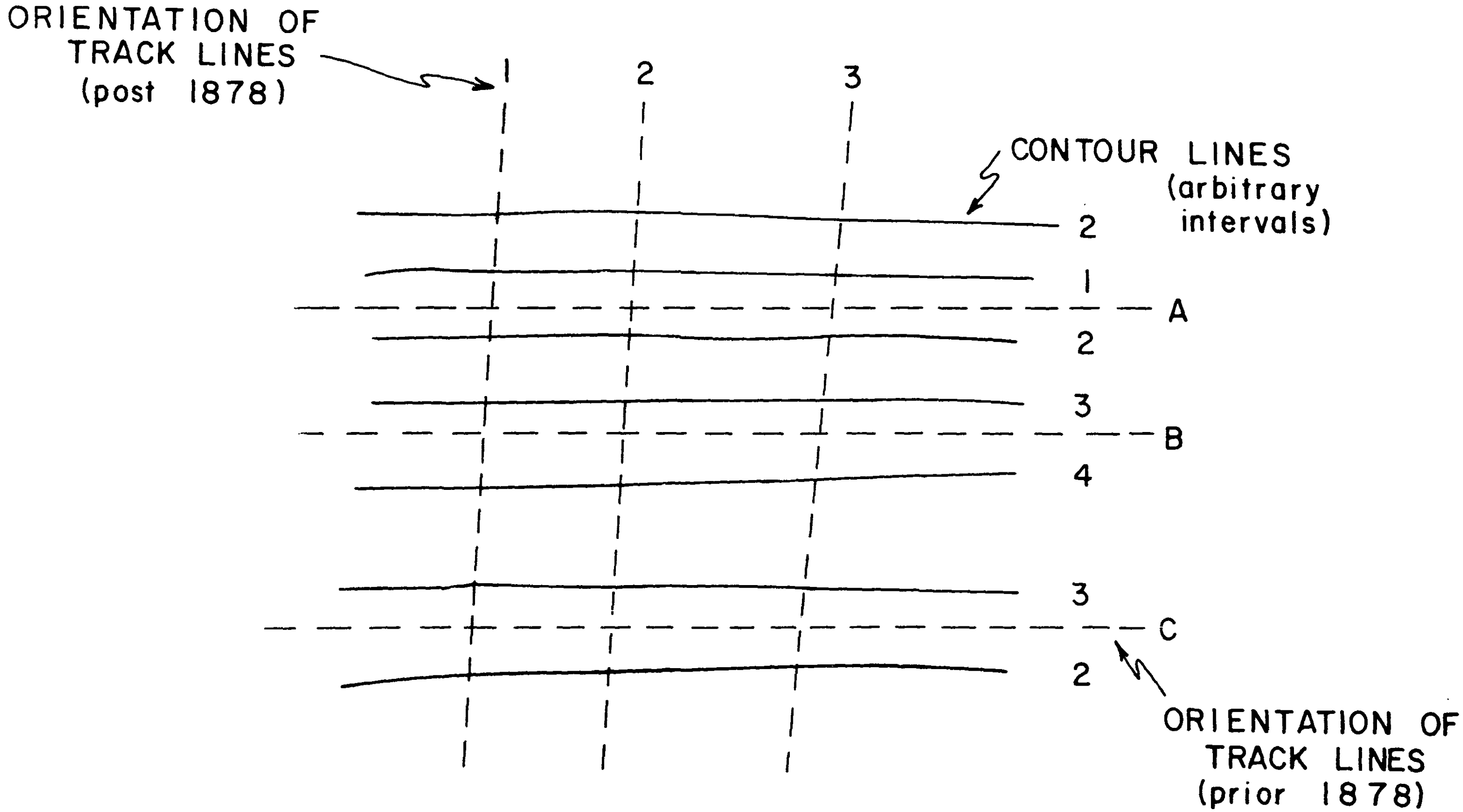

ORIENTATION OF
TRACK LINES
(post 1878)
1
2
3
CONTOUR LINES
(arbitrary
intervals)
2
1
A
2
3
B
4
3
C
2
ORIENTATION OF
TRACK LINES
(prior 1878)

Figure 5. The criteria for spacing of tracklines and data frequency along lines is provided. These criteria, adopted in 1955, are presented in Jeffers, 1960, p. 20.

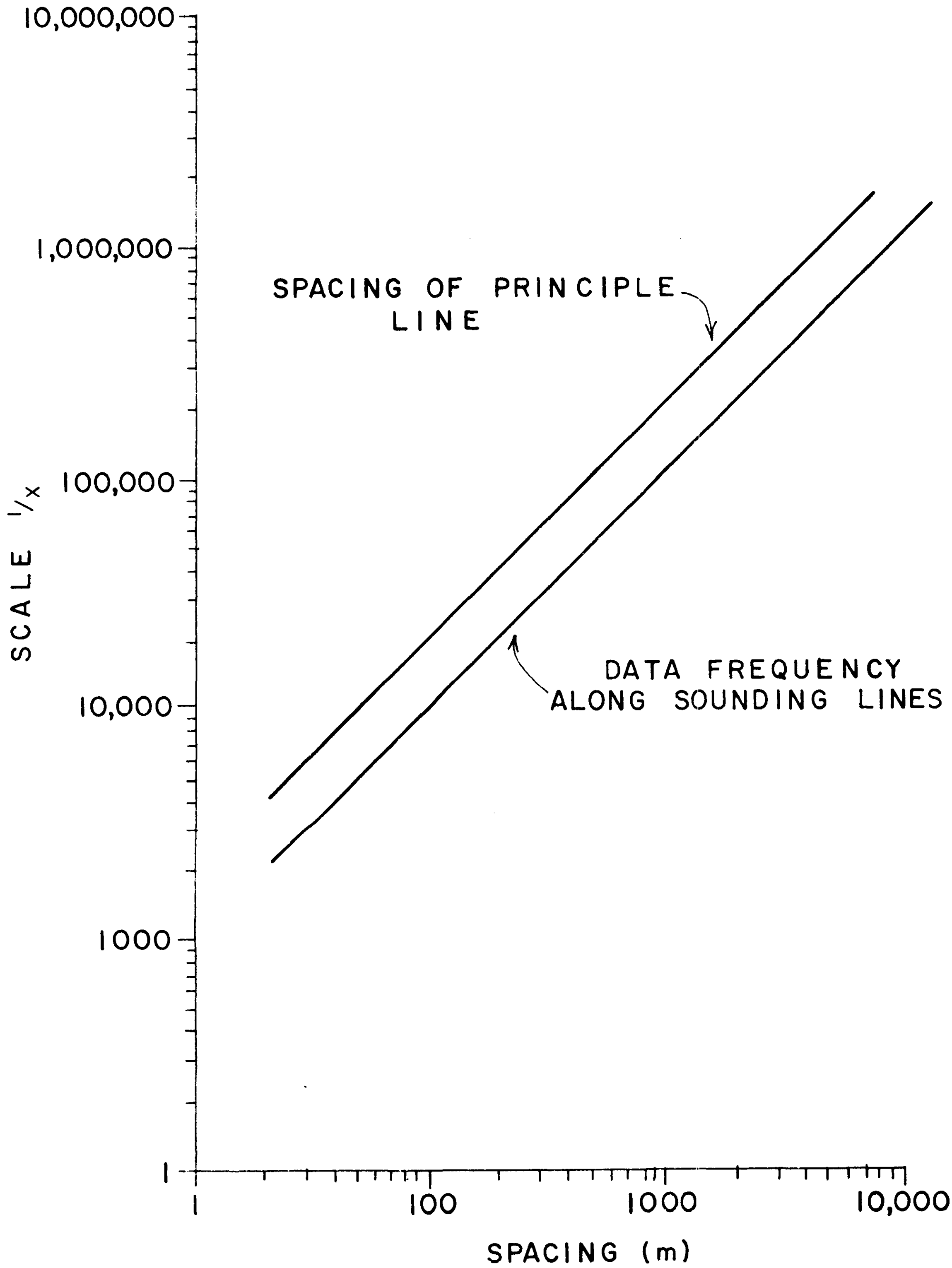
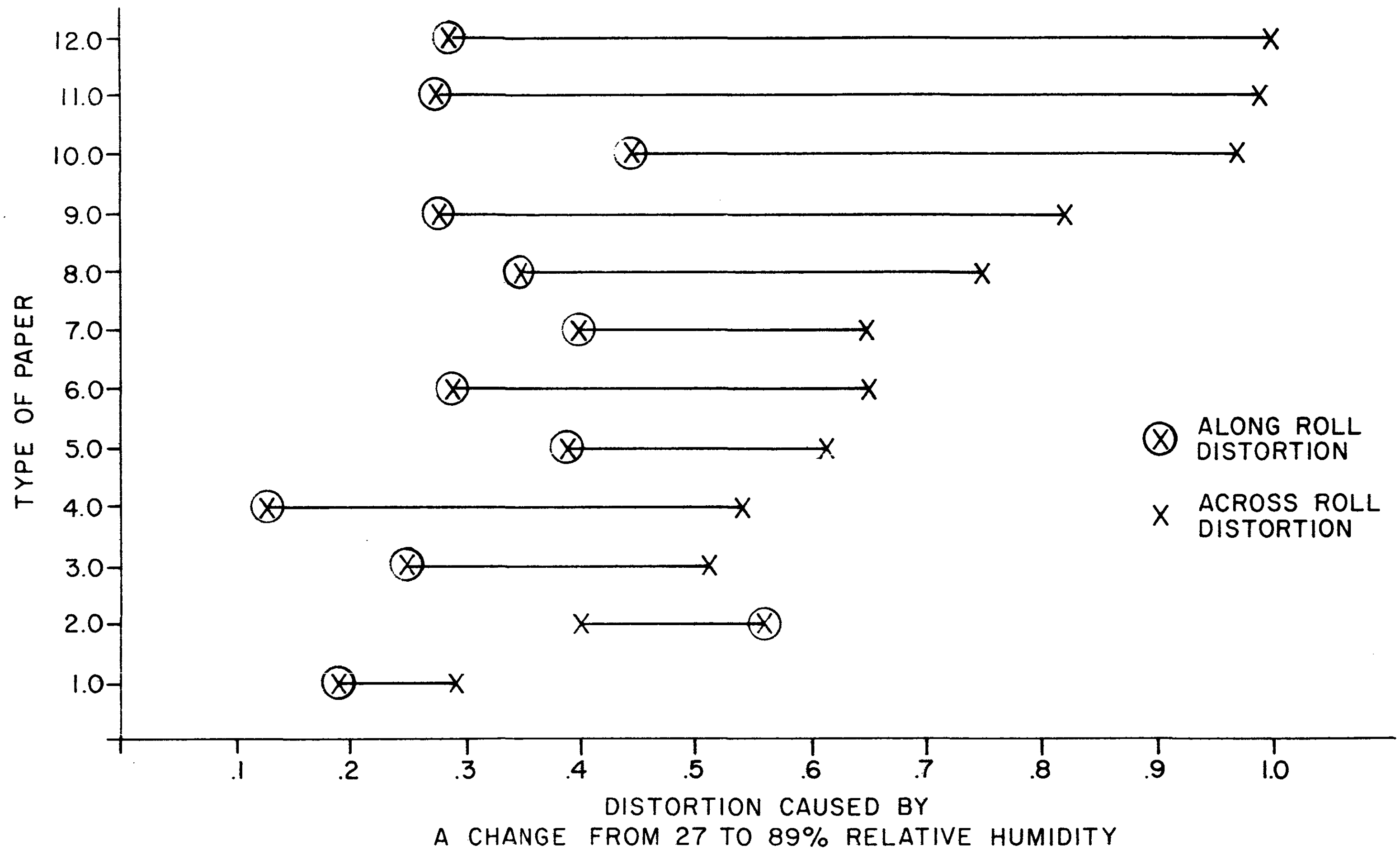

10,000,000
1,000,000
100,000
10,000
1000
1
SCALE 1/x
SPACING OF PRINCIPLE LINE
DATA FREQUENCY ALONG SOUNDING LINES
1
100
1000
10,000
SPACING (m)

Figure 6. The percent distortion of various types of chart paper caused by differences in humidity. The length of the solid line indicates distortion (difference in expansion or contraction between along the roll, and across the roll direction. The types of paper are listed in Table 1 (data from Adams, 1942, p. 678).



TYPE OF PAPER
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
ALONG ROLL DISTORTION
ACROSS ROLL DISTORTION
DISTORTION CAUSED BY
A CHANGE FROM 27 TO 89% RELATIVE HUMIDITY

Figure 7. A hypothetical example of a contour overlay--data point comparison is presented.

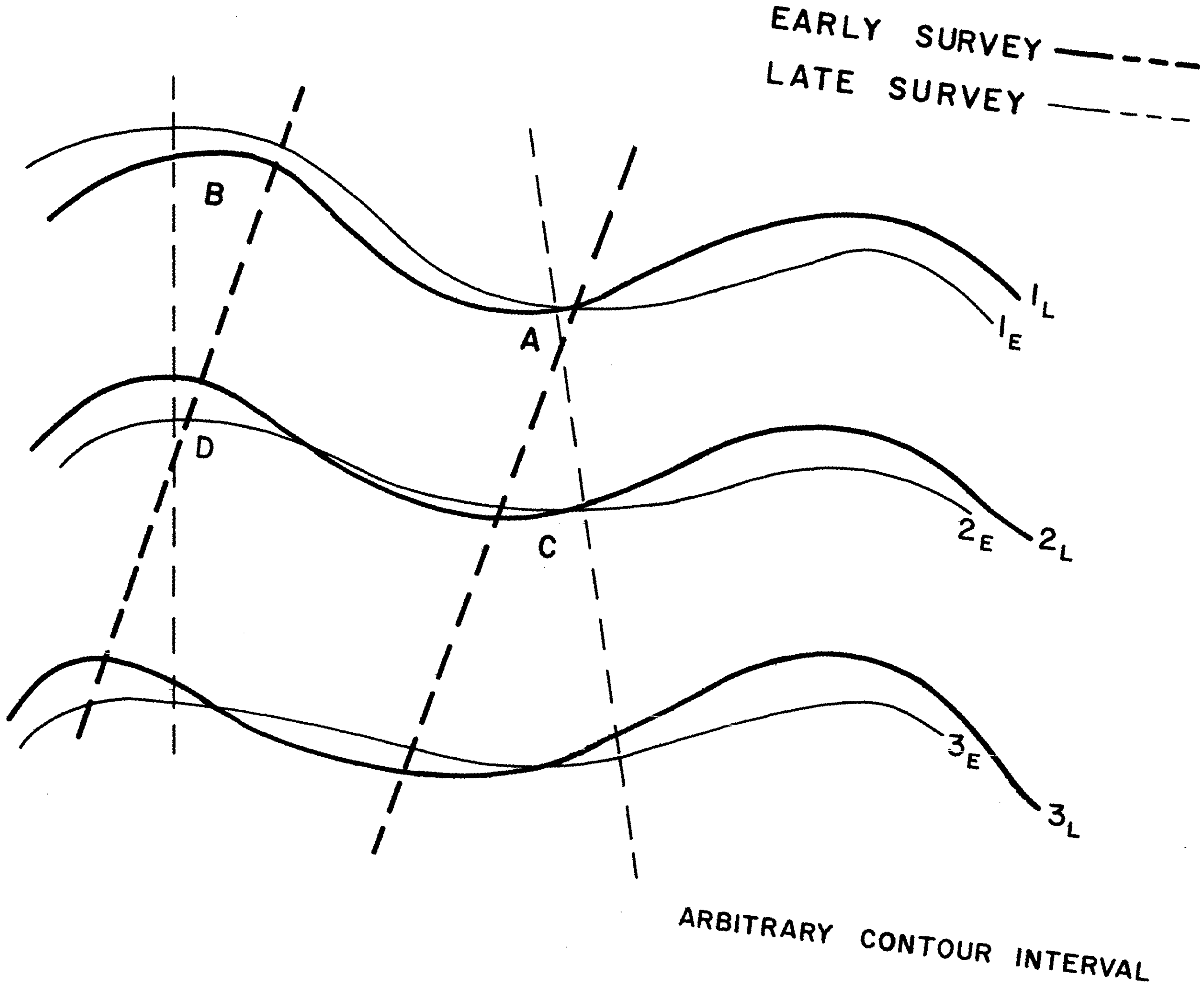
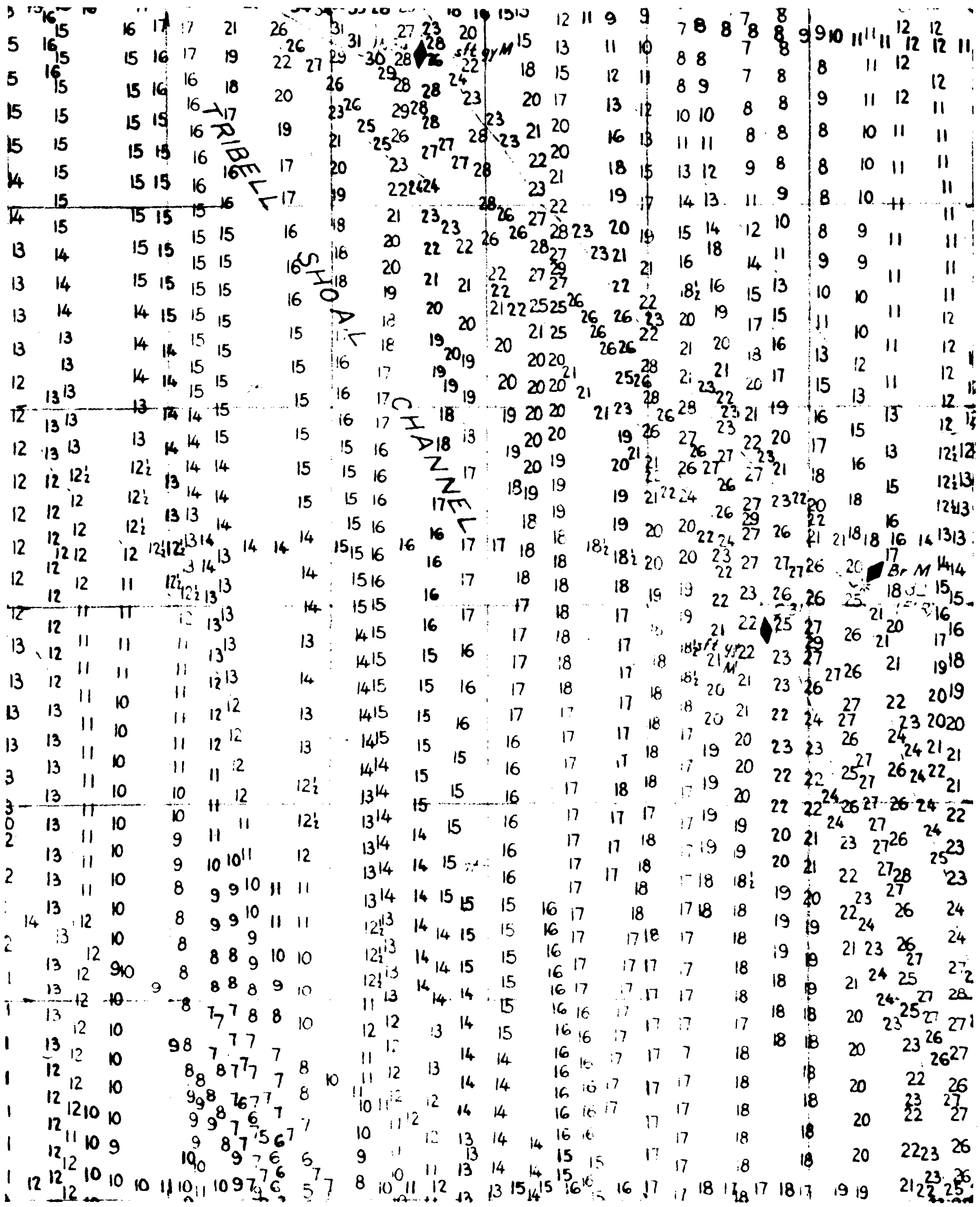

EARLY SURVEY
LATE SURVEY
B
A
D
C
1L
1E
2E
2L
3E
3L
ARBITRARY CONTOUR INTERVAL

Figure 8. The method of constructing a grid point comparison is presented. The soundings chosen for each chart either fall on the grid points or are interpolated to the grid points. The grid is based on latitude and longitude. The data is then compared in terms of latitude and longitude.



TRIBELL
SHOAL CHANNEL
sft gy M
Br M

Figure 9. Results of a grid point comparison (from Goldsmith, et al. (in press)).

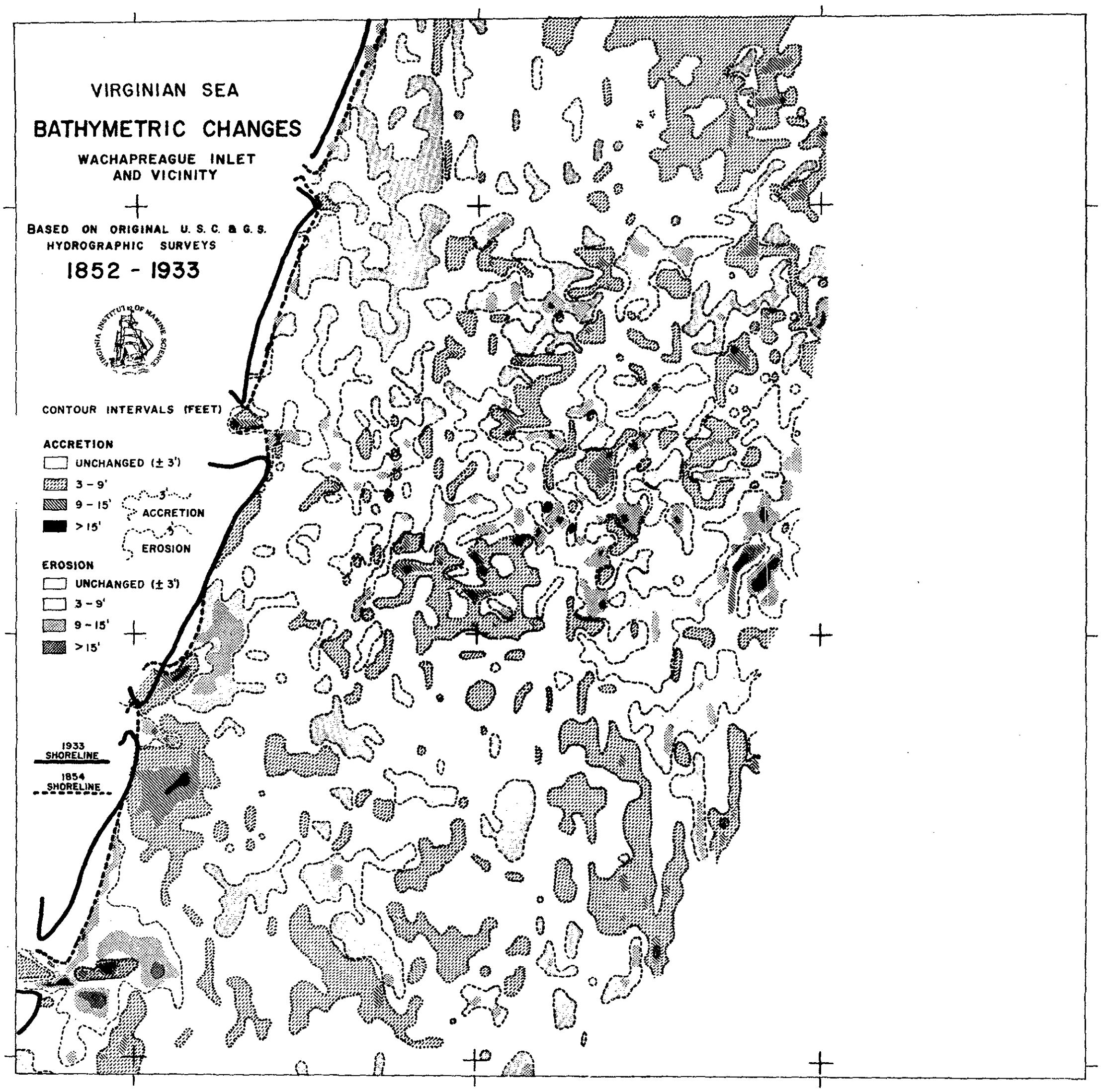

VIRGINIAN SEA
BATHYMETRIC CHANGES
WACHAPREAGUE INLET
AND VICINITY
BASED ON ORIGINAL U. S. C. & G. S.
HYDROGRAPHIC SURVEYS
1852 - 1933
CONTOUR INTERVALS (FEET)
ACCRETION
UNCHANGED (± 3')
3 - 9'
9 - 15'
> 15'
ACCRETION
EROSION
EROSION
UNCHANGED (± 3')
3 - 9'
9 - 15'
> 15'
1933 SHORELINE
1854 SHORELINE

Figure 10. Various required accuracy criteria issued to hydrographers over the years. Sources and wording of the criteria are presented in Table 4.

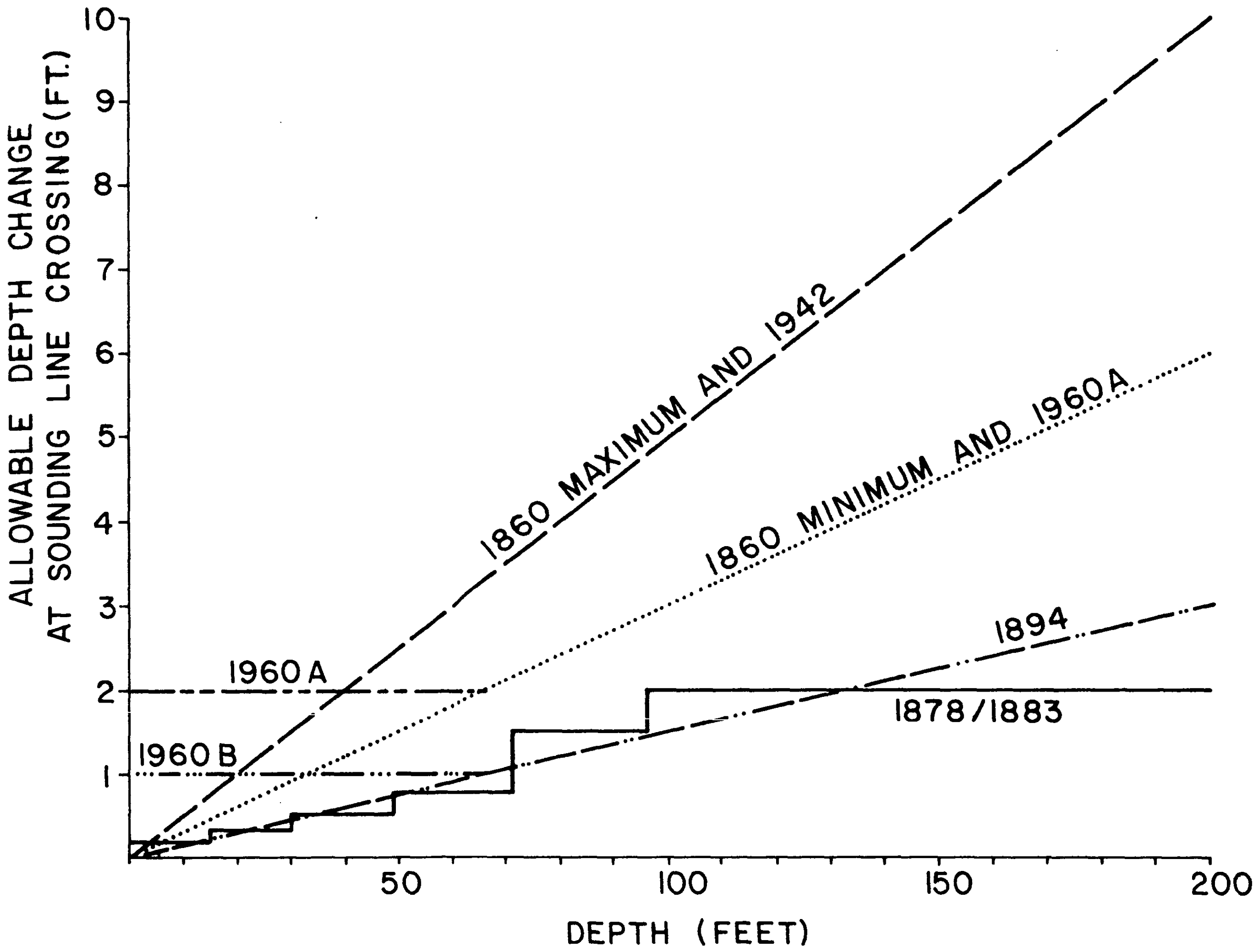
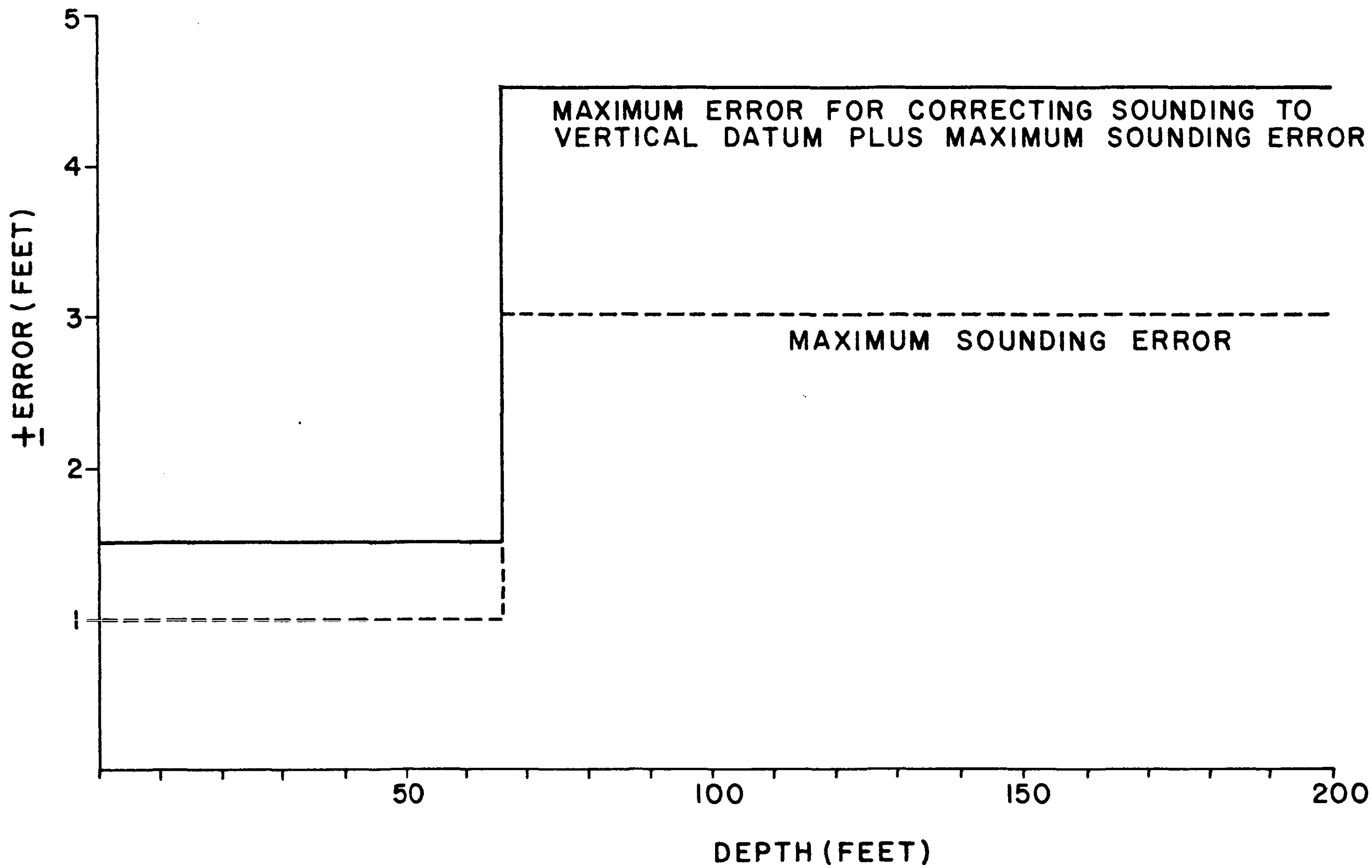

ALLOWABLE DEPTH CHANGE
AT SOUNDING LINE CROSSING (FT.)
10
9
8
7
6
5
4
3
2
1
50
100
150
200
DEPTH (FEET)
1860 MAXIMUM AND 1942
1860 MINIMUM AND 1960 A
1894
1960 A
1960 B
1878/1883

Figure 11. Maximum sounding error, and combined sounding plus correction to datum plane error, adopted at the 7th Cartographic Consultation of the Pan American Institute of Geography and History are presented. The source and wording of these criteria are presented in Table 5.



MAXIMUM ERROR FOR CORRECTING SOUNDING TO VERTICAL DATUM PLUS MAXIMUM SOUNDING ERROR
MAXIMUM SOUNDING ERROR
± ERROR (FEET)
DEPTH (FEET)
5
4
3
2
1
50
100
150
200

Figure 12. The maximum horizontal error is plotted versus scale. The source and wording of the criteria is provided in Table 5.

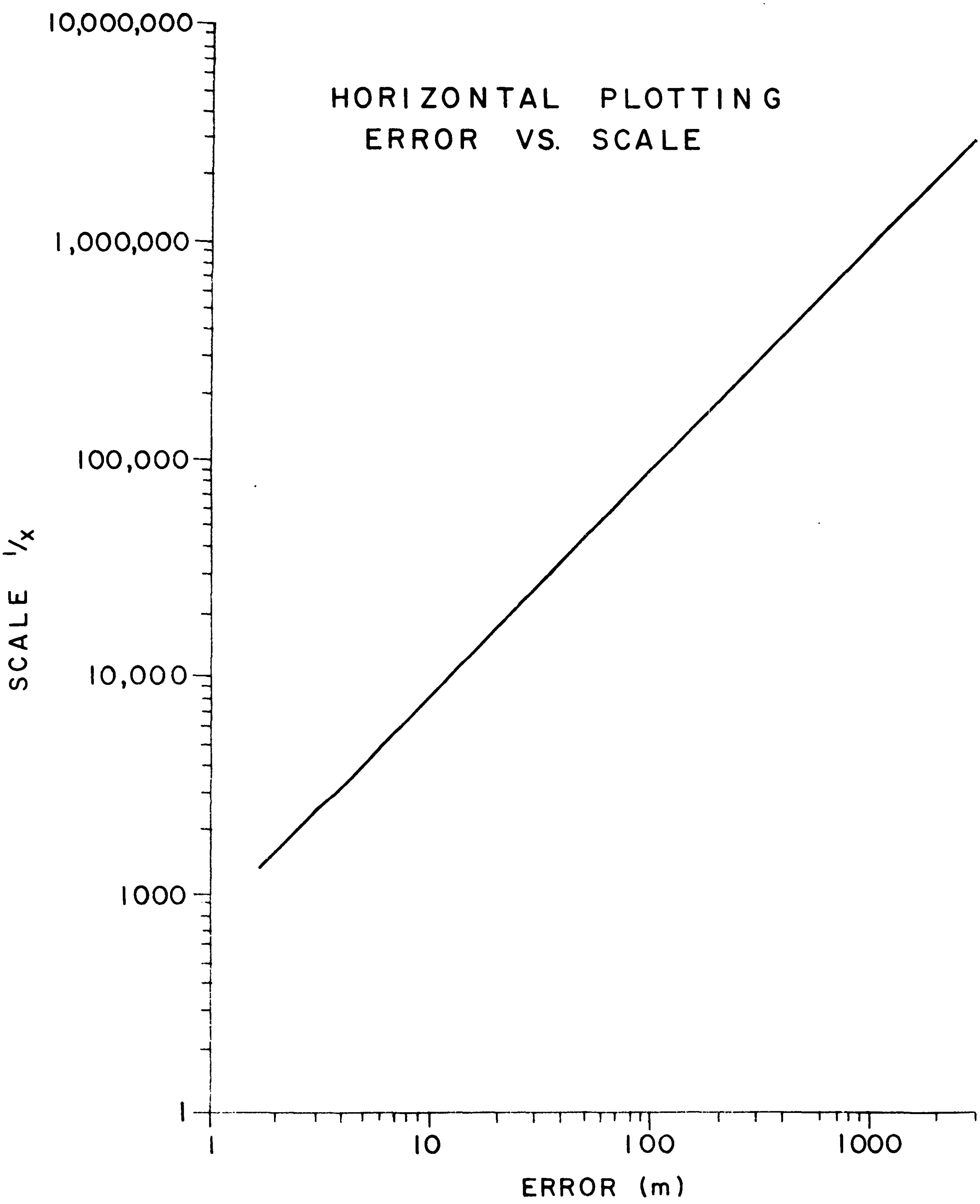
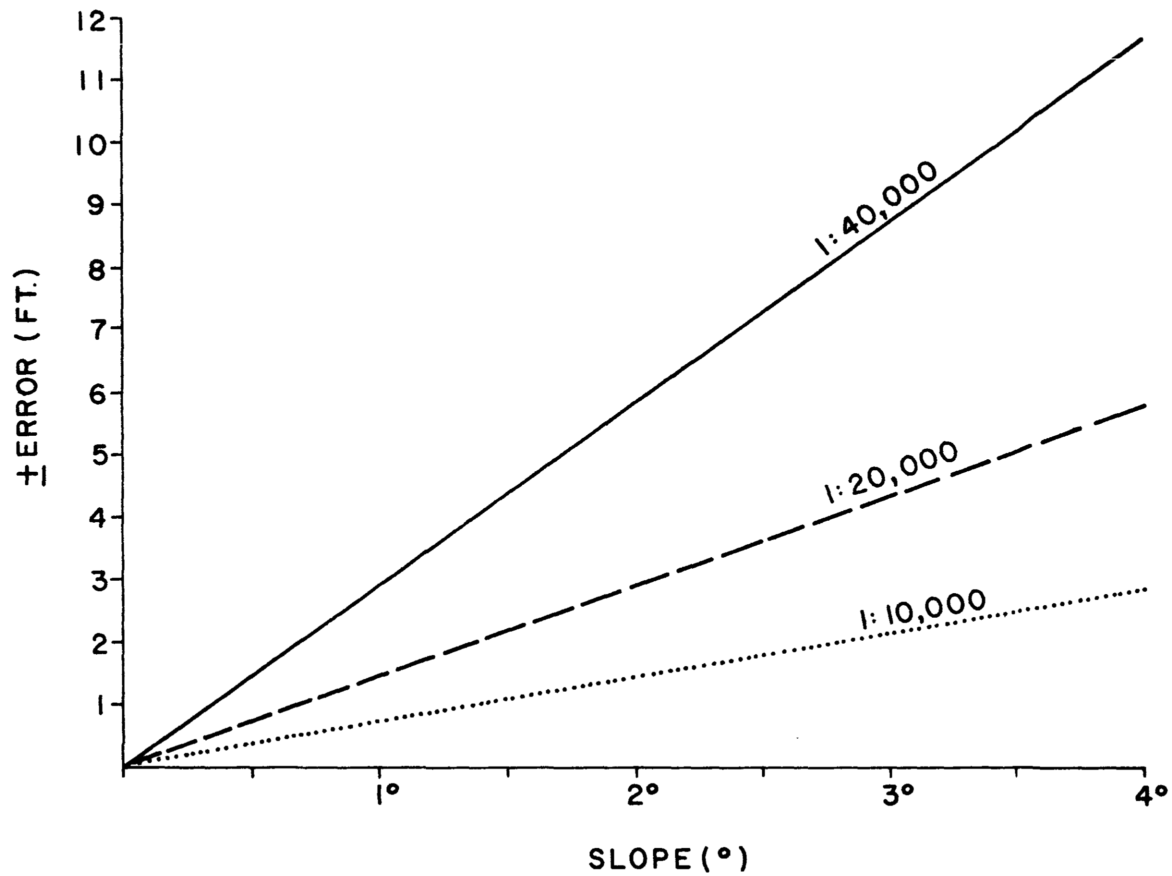

HORIZONTAL PLOTTING
ERROR VS. SCALE
10,000,000
1,000,000
100,000
10,000
1000
1
SCALE 1/x
1
10
100
1000
ERROR (m)

Figure 13. The influence of horizontal errors on soundings for various chart scales is plotted relative to slope.



12
11
10
9
8
7
6
5
4
3
2
1
±ERROR (FT.)
1:40,000
1:20,000
1:10,000
1°
2°
3°
4°
SLOPE (°)

Figure 14. An example of the utilization of maximum error criteria (see text, p. 23).

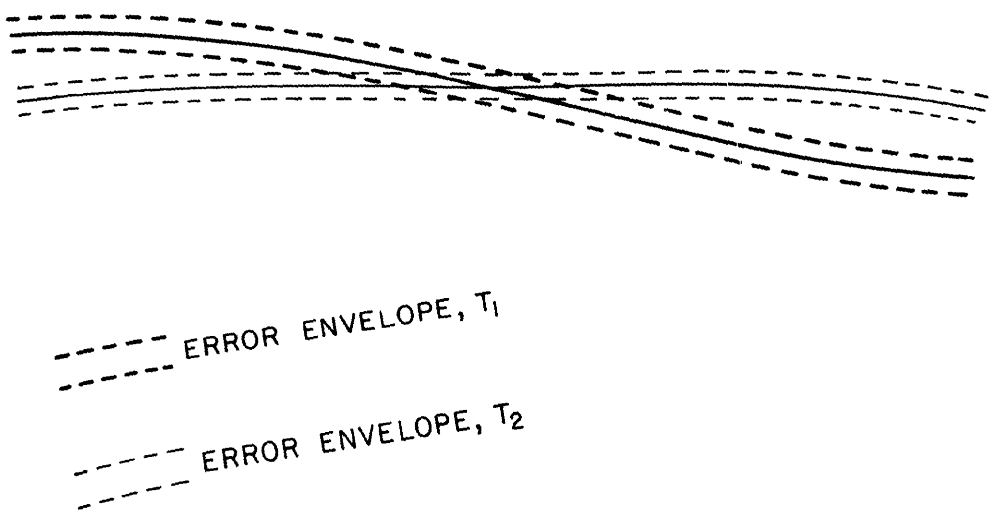

ERROR ENVELOPE, T1
ERROR ENVELOPE, T2

Figure 15. An example of a sediment budget study.

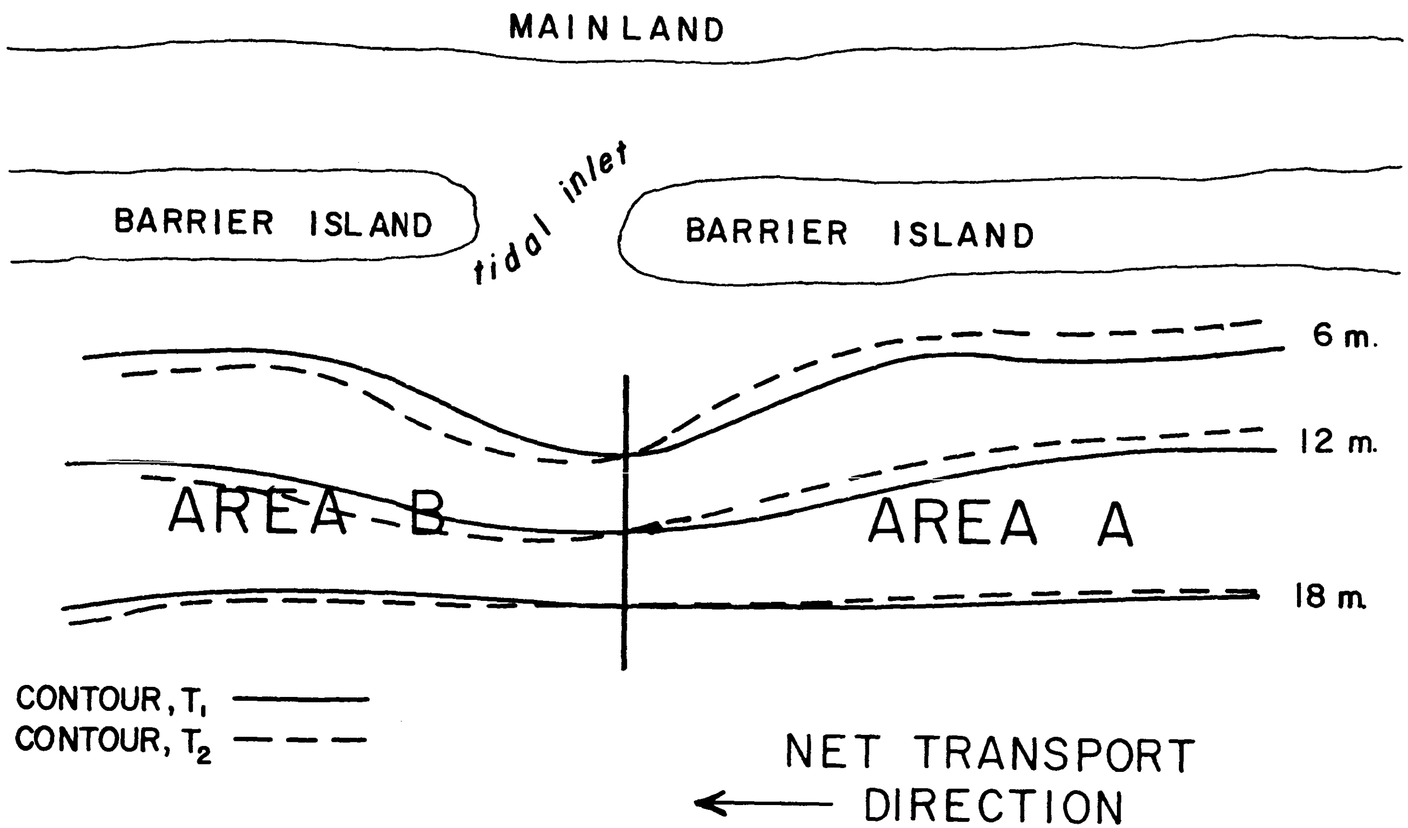

MAINLAND
BARRIER ISLAND
tidal inlet
BARRIER ISLAND
6 m.
12 m.
AREA B
AREA A
18 m.
CONTOUR, T_1
CONTOUR, T_2
NET TRANSPORT DIRECTION

Figure 16. Relationships between shoreline fluctuations and wave energy are depicted (from Goldsmith, et. al. in press).

SHORELINE and WAVE ENERGY CHANGES 1852 - 1934

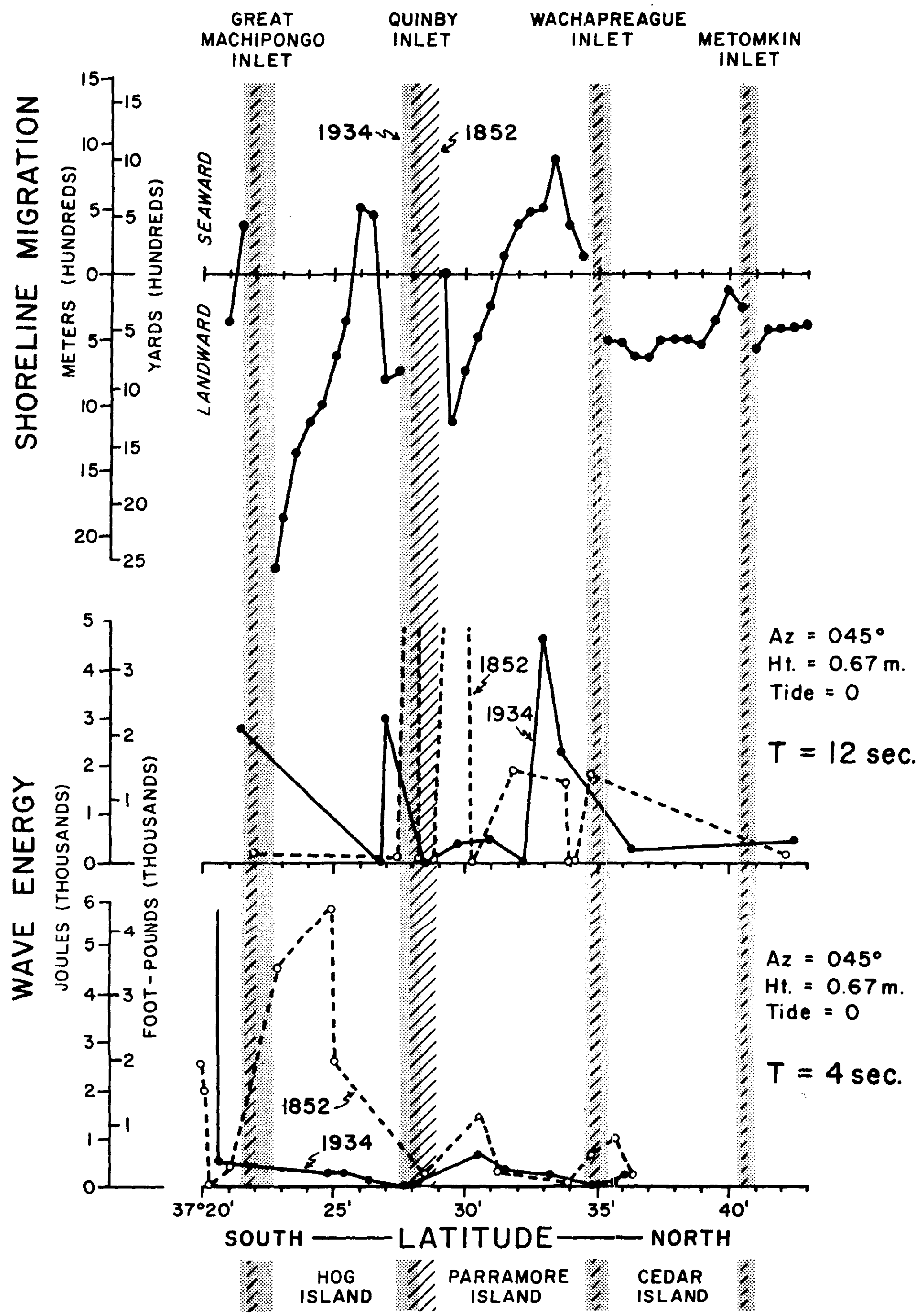
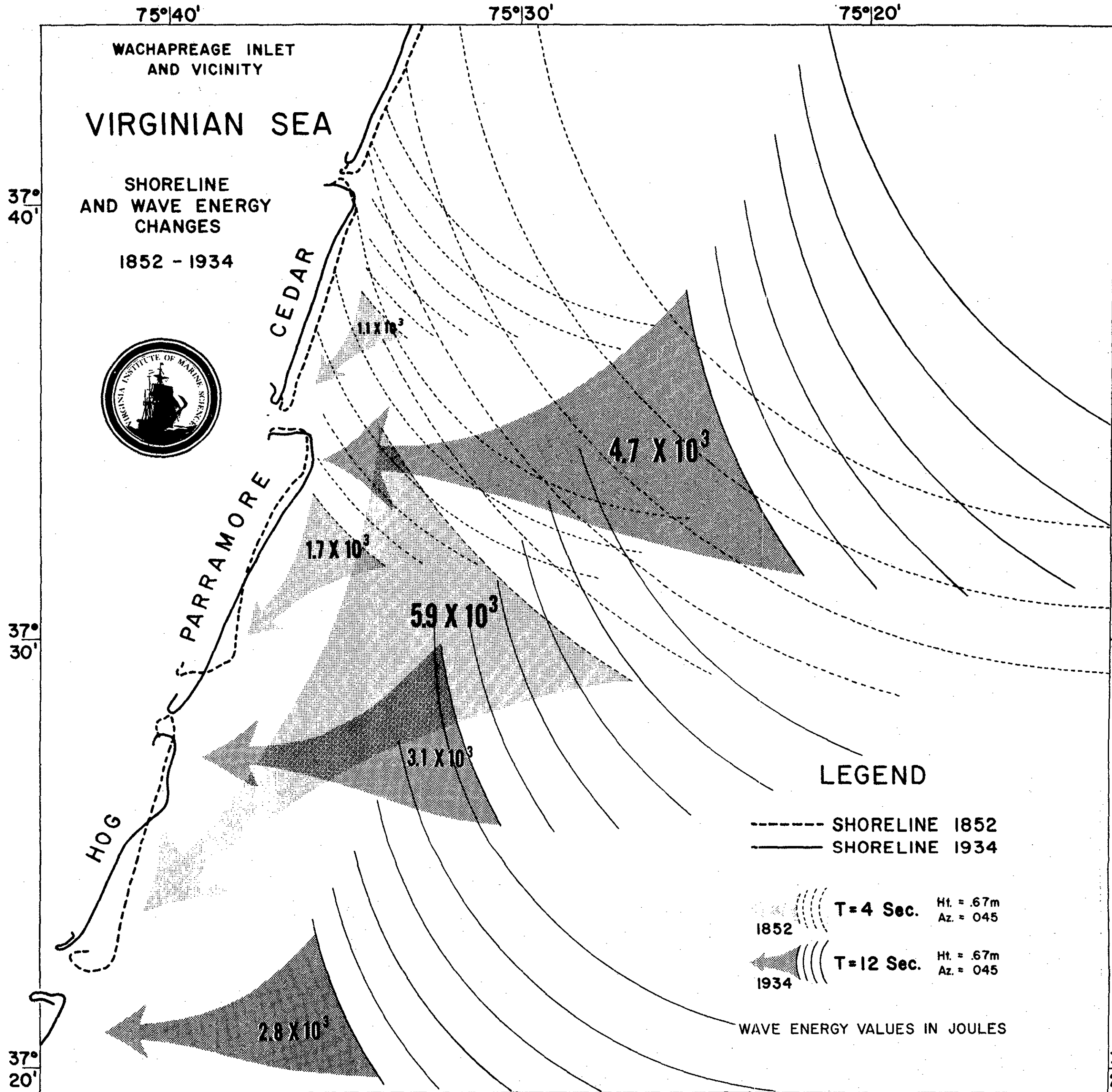


Figure 17. The relationships given in Figure 16 are diagrammatically presented.



WACHAPREAGE INLET
AND VICINITY
VIRGINIAN SEA
SHORELINE
AND WAVE ENERGY
CHANGES
1852 - 1934
CEDAR
PARRAMORE
HOG
VIRGINIA INSTITUTE OF MARINE SCIENCE
75°40'
75°30'
75°20'
37° 40'
37° 30'
37° 20'
1.1 X 10³
4.7 X 10³
1.7 X 10³
5.9 X 10³
3.1 X 10³
2.8 X 10³
LEGEND
SHORELINE 1852
SHORELINE 1934
1852
T = 4 Sec.
Ht. = .67m
Az. = 045
1934
T = 12 Sec.
Ht. = .67m
Az. = 045
WAVE ENERGY VALUES IN JOULES