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ACCURACY OF CARTOGRAPHIC PROCESSES IN THE CONSTRUCTION OF NAUTICAL CHARTS

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ABSTRACT

How precise is the portrayal of information on Canadian charts? When and how are errors introduced during the chart construction process? What is the magnitude of these errors? This paper will attempt to answer these questions. The evaluation is based on a production path which includes computer-assisted cartographic techniques. For a proper evaluation, it will be necessary to examine the subject matter in three stages: Stage One deals with the accuracy of the 'Source Data'. This paper deals mainly with Stage Two, which will cover all cartographic and chart production activities from the time the cartographer receives the source documents to the point where the chart is printed and released. Stage Three involves the nautical chart user. The goal, in that case, would be to establish what degree of accuracy the user needs and expects.

INTRODUCTION

'Accuracy' is defined as 'the extent to which a measured or enumerated value agrees with the assumed or accepted value', or as 'the condition of being accurate', and should not be confused with 'Precision', which relates to the quality of the operation by which the result is obtained (the degree of refinement).

The main concern of a nautical chart user is the magnitude of positional (two-dimensional) errors, involving a tolerance factor, defined by two variables: distance and/or direction. Two types of positional accuracy will be considered in this paper.

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The positional comparison between the charted information and the calculated value of the ground level coordinates will define the 'absolute accuracy' of the data. The absolute accuracy of the Digital Chart File is usually higher than that of a printed chart. Therefore, if the absolute accuracy of the Digital File is known, a comparison with a printed graphic can be made in order to obtain an indication of its absolute accuracy.

The nautical chart user is more concerned with another type of accuracy, the 'Relative', or 'Positional Accuracy' of charted information rather than absolute accuracy. For instance, as a result of humidity, temperature changes and printing processes, the scale of a printed chart may not conform to the information given in the chart title (scale). These discrepancies can be quite large, but might not be of a concern to the chart user, because the relationship (distance and direction) between the points remains relatively unchanged. Relative accuracy errors are usually created during manual cartographic processes (registration). These types of errors, if present in the Digital Chart File, should be eliminated before a File is utilized for construction of reproduction materials.

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Chart Construction Errors

Some errors introduced during chart construction are so small that they are, for all practical purposes, insignificant; for example, mathematically calculated 'X' and 'Y' coordinates in the computation of automatically generated graphics.

In order to eliminate or reduce errors, changes to the present production process may be necessary. These changes include modifications to techniques and/or methods as well as upgrading hardware. Primarily, however, the extent of the errors must be established and an evaluation has to be made in order to justify any or all improvements.

There are several different types of errors which can be introduced during the construction of nautical charts. They are:

— 'Systematic Errors', also called 'Cumulative errors', are ones that invariably have the same magnitude and the same sign (+ or −) under the same given conditions. Systematic errors are attributable to known conditions and vary with these conditions. There are three types of systematic errors:

1. 'Natural Errors' arise from natural phenomena, and prevent the observer from seeing or reading directly the quantity being sought. For example, temperature, relative humidity and aging can change the size of a hard copy document.
2. 'Instrumental Errors' are the effects of imperfections in the construction or adjustment of the instrument used in making the measurements. For example, hardware errors in the digitizing system.
3. 'Personal (Human) Errors' depend on the physical limitations and habits of the cartographer, who may have, for example, a tendency to see the scribed line more to the right (or to the left) when digitizing.

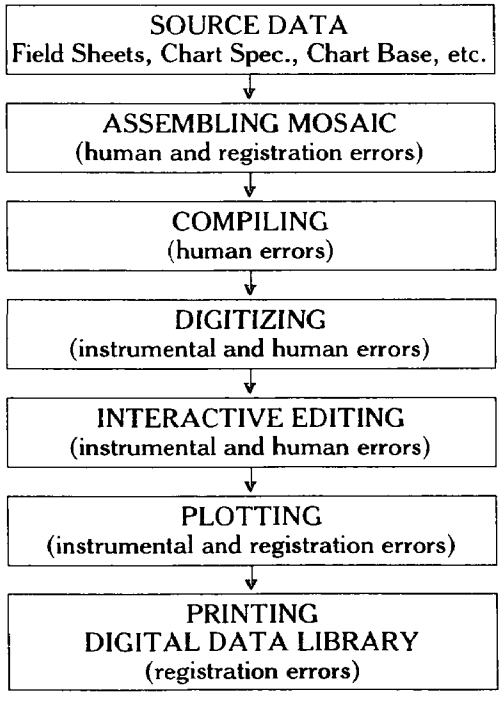
Although systematic errors are generally cumulative, it is sometimes possible to employ precautionary procedures to limit their accumulation. For example, changes in dimensional stability of the film base and emulsion, due to changes of temperature and humidity, will compensate for each other. The possibility that a particular systematic error exists may be detected by careful analysis of the cartographic techniques employed and by comparison with results that are known to be accurate.

— 'Random (Accidental) Errors' are usually small and have a tendency to be mutually compensating. Accidental errors may be either a plus or a minus. The + – sign cannot be determined, and there is no relationship known between the sign and the magnitude of the error on the one hand and any conditions of measurement on the other. They are truly random in occurrence and size.

— 'Blunders (or Mistakes)' are not errors in accuracy since they are caused by a lack of experience in compilation procedures, a lack of drafting skills, inattention or carelessness on the part of the cartographer or system's operator. Blunders are usually easy to detect (Quality Control) and to correct. A typical example of a blunder is an erroneous sounding value or incorrect specification for a base plot.

During compilation, when contour interpolation, data interpretation, line generalization, etc., are performed, the cartographer must exercise his judgement based on a knowledge and experience of chart compilation. This judgement is very subjective. Each cartographer may present the chart information in a slightly different manner, and therefore, it is usually difficult at this stage of chart production to detect the existence of any errors or blunders. The concept of cartographic generalization, selection and interpretation is not part of this report.

Chart Production Path



In order to list all error sources and their impact on chart construction, familiarity with cartographic techniques and procedures is necessary. This generalized production path diagram describes the general flow of data during construction of CHS nautical charts. The manual drafting functions are replaced by computer-assisted techniques. Because each chart is unique, considerable variations in the order of the production steps exist. Several steps have to be repeated due to the editing, technical limitations or reproduction requirements. In this diagram, major sources of error are listed against each production stage. It should be remembered that factors affecting dimensional stability of hard copy documents should always be taken into consideration. Each time a new hard copy document is generated, there is a danger of introducing dimensional changes.

It is not the cartographer's responsibility to check the accuracy of the source data. The cartographer must, however, be aware of the reliability of the source documents. Usually, all available data is assembled in a mosaic regardless of the age of the document, of the method by which the data was collected and of the type of material on which the document was supplied. When source information overlaps, the cartographer has to decide which information is more reliable and which can be disregarded. Often a hydrographer has to be consulted in order to make the final decision. When data is available in digital form (Digital Field Sheet, Qualified Digital Data Base or Digital Chart File), the amount of errors and blunders generated by the cartographer will decrease (elimination of digitization and some data processing, reduced number of photo-reproduction steps).

Dimensional Stability

The dimensions of a printed chart often differ from the values given in chart specification (scale) by as much as 1/8th of an inch, or even more. Fortunately, this error usually affects only absolute accuracy of a chart, and therefore, the chart can be safely used by the navigator, who is only concerned with the relative relationship between points. The dimensional stability of a film depends on both the film base and the emulsion applied to that base. It is mainly affected by four factors: temperature, relative humidity (RH), age and stress. For example, changes of 20°F will change the length of an AO, 0.007" film by 0.010" (0.021%), and changes in RH by 20% will change the length of that film before processing by 0.011" (0.023%) and after processing by 0.009" (0.019%). In practice, therefore, the effects of temperature and humidity tend to cancel each other out. For example, rising air temperature, which would cause an increase in size, is often offset by a lower relative humidity, which normally would cause decrease in size.

During transportation, cartographic material is exposed to extreme variations of temperature and humidity which can seriously affect the documents.

Due to the 'plastic flow', or 'creep' of the plastic base, films tend to shrink with age. They start shrinking immediately after processing and will continue for about five years. The maximum shrinkage will occur in the first year (40%). The maximum shrinkage (after 5 years) will be about 0.02% (this will cause a 0.01" change in a 50" sheet).

In addition to the dimensional changes associated with humidity and temperature, there are also small dimensional changes due to film processing. These are not completely reversible. The reason for these small changes in resin base films involves the

interplay between the gelatin layers and the support base, and their creep characteristics. If the film processing techniques are controlled, the perfect size can be obtained.

Photo-reductions are utilized when source data must be reduced for the purpose of assembling a mosaic. The total instrumental and human error during photo reduction should not exceed ±0.005".

All photographic films will take a 'set' if stored in 'roll' form. This is due to flow or creep. This curl is greater with thicker base films and also with smaller diameter rolls. The 'set' increases with time and temperature. All photographic films should be stored flat, if possible.

When moving repro-materials from the cartographic office to the printing shop, negatives are subjected to different environmental conditions. This can affect the dimensional stability of the documents, and the results are unpredictable. The absolute accuracy of the actual printing process is affected by the type of printing press, the quality of paper, the number of copies printed, the number of runs (colours), and how the printed charts are stored. Quite often, the size of a printed chart exceeds by more than 1/8" (0.263%) the size of the reproduction-negatives.

The above mentioned 'Natural Errors' can be effectively reduced by maintaining proper environmental control in the work and storage areas. Only dimensional changes resulting from exposure to extremely high or low thermal or RH conditions (below −20 and above +100 degrees C, and below 20% and above 70% RH) are not reversible. It is important, therefore, that before reproducing any hard copy document, this document be conditioned, so its size will remain stable. Depending on the type of material, this conditioning may take between 10 and 750 minutes. When unstabilized documents are used to make a combined copy, there exists the danger of introducing a relative error.

Accuracy of Digital Data stored on tape or disc is not affected by any of the previously discussed factors, but the storage medium has to be handled carefully to avoid loss of digital information.

CHS Computer-Assisted Cartographic System

The CHS Computer-Assisted Chart Production System consists of four Cartographic Work Stations:

1. Digitizing Station,
2. Interactive Editing and Compilation Station,
3. Digital Data Processing Station,
4. Accurate Plotter.

There are over a dozen programs used during construction of CHS charts. Generally speaking, only software which makes alterations to a file can degrade the accuracy of the digital data, but blunders in programming, usage and data entry could cause very serious errors.

Checking is a very important aspect of chart production. The objective is to verify the cartographer's work, its correctness with respect to data selection and compilation procedures, the accuracy of cartographic presentation, and conformity with drafting standards. Checking, as such, does not affect accuracy of a chart. Every time a new digital file, or copy of a file is generated, or is going to be processed, the integrity of the data file must be checked. This will assure smooth runs and eliminate future processing

problems. Programs used for checking digital files will not make any changes to the file, as this is only a 'read' operation.

Mathematically-Generated Graphics

For the last thirteen years, CHS cartographers have been utilizing 'Computer Generated Graphics'. The following graphics are generated by the CHS Computer-Assisted System during chart construction: grid and graticule lines, borders, lattices, control points, bar scales, magnetic roses, neatlines and registration crosses. The accuracy of the computation of the 'Mathematically-Generated Graphics' on the CHS system is very high. The data is calculated to the nearest 1 dm at the ground level, which at the very large scale of 1:10 000 converts only to 0.0004". At a smaller scale, the error is proportionally smaller. The CHS system can generate files in a format based on a 0.0004" grid, and, therefore, has a precision of ±0.0002". The maximum combined error is so small that for practical purposes it can be ignored. At the present time, there are no known bugs in these programs.

The mathematically-generated graphics should be used as a benchmark for comparison and error evaluation at a later stage of chart production.

Digitizing System

The CHS digitizing system has been designed to effectively convert any graphical information into the Interchange (NTX) format. In recent years, the CHS has committed its resources to the Altek based 'Digitizing System'. The Altek is a solid state digitizing table with an accuracy of ±0.003" and a resolution of 0.001". The absolute value of every point digitized will be in error by no more than ±0.003". The largest error occurs when a line is digitized at a 45 degree angle. It is the responsibility of the operator to ensure that the accuracy of the table is within the required tolerance. The cursor is used to measure 'X' and 'Y' coordinates of the feature to be digitized. During digitization, the cartographer has to check whether the rotational error of the cursor is within the recommended tolerance, which is ±0.002". This rotational error can be reduced if the operator avoids rotating the cursor during digitization.

MOSAIC

The primary function of the 'MOSAIC' program is to register data digitized in cartesian (table) coordinates to that of a geographical system. The 'Graticule Record' supplied by the digitizing system is utilized for this purpose and MOSAIC will calculate the proper distance between given Latitude and Longitude values for each of these digitized points and, if necessary, will adjust the data to obtain the best fit between these points. The accuracy of the registered file will depend on how accurately the 'Graticule Record' has been entered. Because MOSAIC is implemented on the NTX (Interchange) Format, all information is based on a 0.0004" grid, and therefore, the precision is ±0.0002". In the case when MOSAIC has to rotate the digital file, an additional error of ±0.0004" can be introduced. MOSAIC is also used to convert soundings from imperial units to the metric system, or vice versa. When fathoms (larger units) are converted to meters (smaller units), some precision is lost (round-off error) and this may generate some errors.

Interactive Chart Compilation and Editing System

'CARED' allows the user to view and manipulate digital hydrographic data using a graphic terminal. At the present time, the system is mainly used for editing digitized data. Interactive compilation is only at the experimental stage. When a CARED file is built, discrepancies may occur between a border and other files being concatenated. This registration error should be within ±0.001". Incorporating new information via the CRT terminal was a limiting factor, therefore, an 'Accurate Pointer' (Altek table) is connected to the CARED system. In addition to all the errors which arise from the software, the hardware, and from the operation of the digitizing system, the accurate pointer will also generate errors when a hard copy is being registered to the digital chart file on the CRT display. Cartographers should be able to position the cursor within a 0.002" radius from the center of a point used for registration, and, therefore, the relative error in this case should not exceed ±0.004".

Symbolization

'STARS' is a program used to symbolize digital hydrographic data. Symbolization should not introduce additional errors to the Symbolized Data File (with a very few exceptions, such as a Rocky Ledge Symbol). Because of its unique presentation, the outside limit of a symbolized line has at present a tolerance of about 0.010". Only unsymbolized digital information is kept in the Digital Data Library for future use (new editions, smaller scale charts, etc.), and, therefore, this file is not affected by symbolization.

Plotting

During chart construction, several hard copy documents are generated. Some copies are used only to facilitate the digitizing and compilation processes, while others are produced as verification manuscripts. The last set of reproduction film positives, the 'Final Chart Overlays' are used for reproduction purposes.

The Calcomp Plotter is used at any time during chart production to draw verification paper plots. Because of the poor dimensional stability of the paper, these Calcomp plots are not used for reproduction, and, therefore, they do not affect the accuracy of the Digital Chart File or the Printed Chart.

In the CHS, a Kongsberg Flat Bed Table is utilized for the production of high quality film plots. These plots are made for accurate verification purposes, as well as for the production of 'Final Chart Overlays'. Plots are usually produced as film positives and can have features plotted in symbolized or unsymbolized form. Plotting the information in negative form will eliminate some reprographic steps that can introduce errors (including the time consuming process of spotting negatives) and subsequently shorten production times. Unfortunately, problems related to the exposure time, speed of the film, symbol disc, registration, do not always make this process efficient. The accuracy of the Kongsberg table depends on four factors:

1. Plotting Resolution (0.0004").
2. Plotting Repeatability (±0.0006") — which is the ability of the machine to repeatedly position the drafting implement at any specified point, within a certain specified tolerance.

3. Absolute Static Positioning Accurary (±0.002") — which is the ability of the machine to position the drafting implement at a desired coordinate position.
4. Dynamic Accurary — this is the ability of the machine to follow a programmed curve within a certain tolerance. The CHS system reduces velocity and acceleration in order to maintain dynamic accuracy within ±0.001".

The accuracy of the Barr and Stroud Light Head Projector is a factor in the positional tolerance of the Dove Prism and the Symbol Disc and includes:

— Repetition error (Inner Row = ±0.00012", Outer Row = ±0.00024"),
— Positional error (Inner Row = 0.0004", Outer Row = 0.0008"),
— Coaxiality error (between Inner Row Symbols and Outer Row Symbols 0.0004"),
— Positional error due to Image Rotation (0.0006"),
— Positional error due to Symbol Disc change (Inner Row = 0.00008", Outer Row = 0.00016"),
— Positional error due to the change of Magnification System (Medium Power = ±0.0006", High Power = ±0.0012").

The NTXKNG program changes the data format from NTX to the Kongsberg plotting format. Because the NTX grid is based on imperial units and the Kongsberg is metric, a scaling factor is utilized. One Kongsberg unit is equal to 0.01mm (0.0039") and, therefore, the error introduced during this transformation is so small (1/2 of a Kongsberg unit) that it can be ignored. A smoothing 'Look Ahead' routine is also implemented in the NTXKNG program. A larger 'look ahead' outputs smoother, more generalized lines. As a result, the line can be shifted by as much as ±0.010". Small island-type features and lines containing sharp outgrowths are the most affected.

Registration errors may occur if more than one file is plotted on the same film.

Human Factors

The major source of Human Errors occurs during the programming, and compilation-drafting procedures.

During digitization, the document (usually correct reading, blueline on 0.007" scribe coat) is taped flat onto the digitizing table 12 hours prior to digitizing, in order to minimize dimensional stability errors. Using a magnifying glass and the freehand scriber, the operator makes holes through the document to mark the origin, the corner points and the points for the graticule record. The precision in positioning the cursor on these points should be ±0.002". The four accuracy points are re-entered every time the operator wishes to change the cursor and every time he restarts the digitizing session. The acceptable tolerance is ±0.004". This signifies that the data digitized in one session can be shifted by as much as 0.004" from data digitized on a previous occasion.

It is essential that the mainheader information be entered correctly to assure smooth processing by MOSAIC and other utilities. All the hydrographic information digitized for production purposes must be registered to geographic coordinates, and, therefore, the first digitized information must be the graticule record. A minimum of four points must be entered. Each point contains the exact geographical position, and 'X' and 'Y' table coordinates. The cursor position of 'X' and 'Y' values of the graticule record should be within a tolerance of ±0.002". These values are used by the MOSAIC program to register the Digital Chart File to the geographical coordinate system.

Blunders in the mainheader or graticule record may force MOSAIC to output data in an incorrect scale, projection and limits.

In line digitization, the operator is tracing the line, and entering a stream of 'X' and 'Y' coordinates. During line digitization, an experienced draftsman should be able to split the line with the cursor's scribe point. The error introduced would average ±0.004". When a crosshair cursor is used, point information with a well defined center point can be positioned with a precision of ±0.002". Soundings and other point information, where the center point of the symbol must be interpolated, can be positioned with a precision of ±0.010".

Mistakes made during the digitization process are usually easy to spot, and are usually corrected later on the interactive editing system.

The primary functions of the Interactive Editing System are to display on a CRT terminal any portion of a data file at a reduced or magnified scale, and to give the user the ability to add, delete, move and change information. The most convenient magnification is four or eight times the original chart scale. At this scale, users can position the cursor at the nearest grid intersection, which will give them an accuracy of ±0.001". In line editing, a curve fitting routine is implemented; however, the operator must carefully select the proper number of points in the right location to accurately reproduce the graphical input. If proper judgement is used, lines can be drawn with an accuracy of ±0.001".

Registration is the process of assembling several cartographic documents (digital or hard copies) for mosaicking, compilation, drafting, checking or reproduction. In the manual construction of a 'Compilation Mosaic', the source information is pasted to the chart base in such a way that the registration marks will overlay each other. The average error should not exceed ±0.002", assuming that both documents are on the same scale and projection. When a digital mosaic is produced, MOSAIC will take care of the registration, which should be within tolerance of ±0.0004". The Mosaic program is designed to generate registration crosses at specified graticule intersections. This set of registration marks remains in the Digital Chart File and can be output every time a plot is required. The registration marks are identical to the grid intersections generated by the border program and their accuracy is ±0.0004". When final reproduction overlays are generated by the Kongsberg plotter, each positive will have exactly the same set of registration crosses. Even with registration marks, the correct superimposition (better than ±0.002") of several pieces of reproduction overlays is not easy, especially when negatives are involved. In order to maintain correct registration, a Harris registration strip is attached to each overlay. During the registration to the Harris system, an error of approximately ±0.002" should be expected. Manual mosaicking will affect the relative accuracy of chart information. Poorly registered reproduction overlays or printing plates will affect spatial and directional relationship between points (features).

Printing

Checked and approved reproduction negatives are submitted for printing. By moving repro-materials from the cartographic office to the printing shop, the negatives are subjected to different environmental conditions. This can affect the dimensional stability of the documents, and the results are unpredictable if the environment is not controlled. The next step is the construction of printing plates.

The accuracy of the actual offset printing process is affected by:

— type of printing press and quality of ink,
— quality of paper (it should be 'map paper'),
— how well printing plates are registered,
— number of copies printed,
— number of runs (of colour runs),
— and how printed charts are stored.

A printed chart is not checked for correct scale, but quite often it will exceed, by more than 1/8", the size of the repro-negatives. This is considered to be an acceptable error. Because these errors do not change locally, the relationship between features does not change enough to affect users' requirements. The entire printing process is largely outside of cartographers' control.

CONCLUSIONS

Most of the errors which may occur during the chart construction processes have been listed above. In order to answer the question 'Are the CHS charts accurate enough for modern navigation purposes?', further study is required. Stage 3 of the accuracy study will attempt to define the degree of accuracy required by the chart user and how precisely the user can read charted information. Regardless of the final conclusions from these studies, several improvements to chart production procedures can be introduced in order to eliminate or reduce errors. Some improvements can be implemented at no extra cost. In fact, by eliminating error-prone methods, the overall cost and construction time can be reduced. Computer-assisted cartography will, in this case, play a very significant role.

Dimensional stability of reproduction material is a major factor affecting accuracy of a cartographic product. With the utilization of computerized cartography, data can be stored in digital form and retrieved on demand in a relatively short time. Therefore, problems related to aging, storage and transportation of hard copy repro-materials can be completely eliminated in most cases. Changes to scales and projections are performed more accurately, faster and cheaper on digital data files than by using error-prone photo-reproduction techniques. When hard copy overlays are requested, they can be generated at the last moment, just prior to printing, and if produced in a controlled environment the results should be near perfect.

In the near future, we may experience the implementation of digital electrostatic printers which may further revolutionize chart production processes. Electrostatic printers and dry printing used in conjunction with smaller printing runs should improve chart accuracy and also could make chart construction more efficient. Future utilization of 'Electronic Charts' will simplify some problems of chart production accuracy, but may initiate others that are not anticipated at the present time. In addition, new materials for printing and the printing technology itself will evolve.

Digitization will remain, for some time, the main source of errors. Although every year more data is collected in digital form, thousands of graphics will still have to be converted into digital form. Automatic and semi-automatic line digitizers and character

recognition (not available for soundings) systems are costly and may or may not produce more accurate outputs

The objective of this paper is to bring to the attention of cartographers the possible sources of error and to suggest the means whereby they may be eliminated or minimized. The listing below attempts to summarize the errors occurrring in the chart production process. Because of the unique nature of nautical charts with the production path varying from chart to chart, a single value for cumulated or average errors cannot be calculated. Typical or maximum errors have been given for only some production phases.

1. Dimensional stability of hard copy documents can be affected by random errors at any time during chart construction. In a very well monitored environment these errors should be negligible. Typical cumulative errors will not make much sense, and therefore only an example of the error sources is listed below.

— RH change 20%, 0.007″ film:
  before processing 0.023%
  after processing 0.019%
— Thermal changes 20F, 0.007″ film 0.021%
— Aging:
  after 1 year ..... −0.008%
  after 5 years ..... −0.020%
— Photo-reductions ..... ±0.005″

2. When digital data is created, instrumental errors, registration errors and human errors are introduced. The maximum error introduced by Mathematically-Generated Graphics should not exceed 0.0006″ and, therefore, for practical purposes can be ignored. Information entered into the system via the digitizer or interactive editor may contain a maximum cumulative error of ±0.009″. A human error between ±0.002″ and ±0.010″ must be added to this value. This error is related to the drafting accuracy, and depends on the type of data being digitized (point, line or symbol).

3. Errors introduced by the MOSAIC program are so small (typical =±0.0002″, maximum = ±0.0006″), that they can be ignored for practical purposes.

4. Symbolization generally does not add any errors to chart information with the exception of a few symbols (rocky ledges ±0.010″; this will be improved in future symbolization subroutines).

5. Drafting errors can be introduced at two critical times during the chart construction process. They are the compilation stage and the final drafting (digitizing-interactive editing) stage. Typical errors depend on the type of information drawn and have a range between ±0.002″ for well defined points, ±0,004″ for lines and ±0.010″ for soundings and other symbols.

6. Manual registration, which takes place several times during chart construction (assembling mosaics, registering reproduction materials and during the printing stage), will affect the absolute accuracy of chart information. Typical accumulated error is ±0.009″.

7. Maximum cumulated error in accurate plotting is ±0.008″. When line smoothing is involved, this error may increase, for a certain type of line, up to ±0.018″.

8. During printing, chart dimensions may increase by as much as 0.25% or even more. This affects the relative accuracy of the document.

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