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TEN YEARS OF EXPERIENCE IN CONVERTING CANADIAN HYDROGRAPHIC SERVICE CHARTS TO A WORLD-BASED GEODETIC DATUM

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Abstract

As long ago as 1975, North Americans realized that the North American Datum of 1927 (NAD 27) was becoming out-dated and that it would eventually have to be replaced by a geocentric datum. The Canadian Hydrographic Service (CHS) welcomed the idea but was also fully aware that some of its charts were not even based on NAD 27. In 1986, once the framework stations became known on the North American Datum of 1983 (equivalent to the World Geodetic System of 1984), CHS started the conversion of Canadian charts to that datum.

This paper describes why the work was necessary, the means by which it was done, the difficulties encountered and overcome and the progress made to date.

1. INTRODUCTION

For centuries, mariners have coped with imprecise charts. The inclusion of a geographic grid on a chart was a mere convenience to describe a certain position. Traditionally navigation was done by visual fixes near shore, or by dead reckoning (with its large error budget) when beyond the sight of land. Radio Direction bearings, radar fixes, and hyperbolic radio positioning systems are recent innovations. The capability to position a ship to an accuracy less than its length is a very recent phenomenon.

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Charts of Canada's coastline were needed as soon as the explorers made their first landfall and started to navigate the coast. The first dedicated hydrographic surveys started from astronomic positions, azimuths, baselines, and triangulated positions. As time progressed, the national geodetic framework developed and connected to the old hydrographic control or was used to start new surveys. It was, however, a slow process since Canada is a country of vast dimensions. The first-order geodetic triangulation commenced in 1907, but did not join up in central Canada until 1960. Control was extended into northern Canada from 1949 to 1958 by a line-crossing technique known as Shoran which provided one point of second order quality every 200 kilometres. Densification of that framework in the 1960s by Tellurometer traversing along the coasts and in a sparse but regular grid in the interior followed. The network had so few redundancies that it was impossible to locate blunders.

By 1968, the geodetic community realized that the first order framework in Canada was woefully inadequate for the 1970s. As a stop-gap action during the 1970s, the Geodetic Survey re-adjusted a large part of the Canadian survey framework piecemeal on NAD 27 to improve its point to point accuracy. However, this process created discordancies between the sections whose boundaries often occurred at bodies of water.

Globally, all national and regional horizontal datums then in place were classical non-geocentric coordinate systems. Doppler Satellite positioning in the 1970s and 1980s provided first order control at about 100-kilometre spacing throughout Canada and showed that a geocentric coordinate system would be preferable to a non-geocentric system. Forecasts as early as 1978 told of a marvelous new satellite-based equipment that would give metre accuracy, real-time, all the time. That system is now here, and is known as GPS.

2. STATUS IN 1986

The CHS has been Canada's national Hydrographic Office since 1883 and has acquired charts from American, British and French Hydrographic Offices that are based on surveys dating as far back as 1824. Many of these charts, and some charts derived from CHS surveys, are based on astronomic positions with local baselines and azimuths. An inventory of the situation was made in 1985 to establish the existing situation with respect to chart horizontal datum. At that time, insets without grids and harbour plans were not counted because they would not be affected so long as they remained without grids. The situation at the end of 1996 is offered as a comparison.

CHS now realizes that harbour plans and insets will require proper geographic referencing to be compatible with Electronic Chart usage.

	1985		1996	
Chart Horizontal Datum	Number of charts & insets	% of total	Number of charts & insets	% of total
North American Datum 1983	0	0.0	195	20.2
North American Datum 1927	722	74.5	572	59.4
United States Standard Datum	25	2.6	24	2.5
Astronomic/Unknown	192	19.8	155	16.1
No grid	30	3.1	17	1.8
Total	969	100.0	963	100.0

3. WHY CHARTS SHOULD BE PRODUCED ON A WORLD BASED GEODETIC SYSTEM

Mariners progressed from visual fixes and dead reckoning, to Radio Direction Finding (RDF) in the 1930s, to radar and hyperbolic radio navigation systems in the 1950s and Doppler satellite navigation systems in the 1970s. For each of these methods of navigation, the mariner did not have to know the horizontal datum of the chart. Navigation was relative to the charted information and positional error budgets were large. The mariner now has GPS with positioning accuracy in the order of 100 metres or less. And if real-time differential corrections are available from a shore station, metre accuracies are possible. In other words, the mariner has a more accurate positioning system than was available during the hydrographic survey.

Circa 1980, the considered opinion at the U.S. National Ocean Survey and at CHS was that charts should be converted to the North American Datum of 1983 (identical to World Geodetic System for all practical purposes) because:

a) It would bring charts to a common horizontal datum so that there would be no need to transfer positions between charts by range and bearing from a common point,
b) GPS would produce positions based on that geodetic datum,
c) Survey information would be submitted on that datum, and
d) The fulfillment of a commitment to adhere to an International Hydrographic Organization resolution to convert charts to the World Geodetic System which, in itself, was based on the first three reasons. [MONTEITH & GRAY, 1981]

Although an immediate conversion of the grid and borders of all charts was desirable, it was just not practical with the available resources. The methodology employed by the CHS was to provide a datum note on existing charts whenever a chart was being printed as a New Edition or Reprint. The datum note took the form of an instruction to mariners to add, or subtract, specified quantities in latitude and longitude to the observed GPS position. If the chart information was already in digital form, as was the case for New Charts under construction and ones that had just recently been released, then the chart could be converted to NAD 83 by the addition of the translation components in latitude and longitude to all positions. The chart, including the border and grid lines, would be redrawn using the ellipsoid parameters associated with NAD 83. In December 1986, CHS chart 4201, *Halifax Harbour - Bedford Basin*, was the first CHS chart published on NAD 83. Work on issuing New Charts on NAD 83 and transformation notes on New Editions and Reprints progressed only as fast as charts were printed over the next 8 years and at the end of 1994, the projected completion of the provision of horizontal datum information was estimated to require a further ten years.

But a change was in the air. The 1990s has seen the development of the real-time integrated navigation system which incorporates the real time GPS position against a video display of the chart, commonly known as the Electronic Chart. This has caused a whole re-evaluation of the need for charts on a world-based geodetic system since GPS positioning is at the heart of the system. In Canada, this development went, almost overnight in 1993, from "Possible" to "Reality" when a major Canadian shipping company wanted to install, and have operational, Electronic Chart equipment on eleven (11) ships that ply the St. Lawrence Seaway and Great Lakes before the 1994 shipping season.

It became timely to specify all these electronic navigation charts on NAD 83 as the digital information was being assembled. The pace had to increase, and there was a need to provide a transformation for charts that had even large random errors in the datum shift. The first Electronic Navigational Chart (ENC) released by CHS was in July 1994. During 1994-96, the following numbers of vector and raster scanned ENCs have been issued by CHS through its distributing agent, Nautical Data International of St. John's Newfoundland.

	1994	1995	1996
Vector ENCs	90	249	247
Raster ENCs	6	211	143

At present, ENCs are constructed by digitizing or scanning the existing paper chart. Therefore it has been necessary to determine the datum shift for each paper chart, and its insets. The annual number of paper charts analyzed from 1986 to 1994 was, on average, 125. But in 1995 and 1996, there were 250 charts analyzed annually, mostly for ENC production requirements. It should be noted that ENCs produced by Canada were in NTX format until late 1996. The conversion of these charts and the construction of new ENCs in S-57 Edition 3 format did not begin until early 1997.

4. DETERMINING THE DATUM OF THE EXISTING CHART

The first step in determining the translation values for a chart is to determine what values had been used during its construction. The date of the First Edition is the first clue. Obviously, the chart could not have been constructed using coordinates that had not yet been computed. Most often, the coordinates were those computed in the field and used in the drawing of the field sheet (the large scale plot of all the measured soundings).

It was the practice in CHS, and in many other Hydrographic Offices, to provide in the Title Block the coordinate value for one survey station as a reference point. This also provided a definite clue. But, there have been times when that position was updated on subsequent New Editions without making the corresponding changes in the location of the grid lines causing an erroneous assumption as to the real coordinates used.

During chart construction, a number of survey points are plotted on the final manuscript. The positions of these points can then be scaled off the existing chart, at a far inferior accuracy than the position quoted in the Title Block or in a listing left over from chart construction. Nevertheless, they do provide a clue to the position values that were used.

For charts that were surveyed and compiled by other Hydrographic Offices, or from the earliest days of CHS, it is necessary to obtain the description of *any* survey control point within the limits of the chart. The locations of these points have to be plotted according to their descriptions and then the latitudes and longitudes scaled from the chart. The positions can then be compared to the surveyed positions.

Yet, another approach is to convert photographically the National Topographic Map of similar scale to that of the chart. Then the shorelines or other features are matched and the two grids compared to determine the shifts in latitude and longitude. Several considerations have to be reviewed before this technique is used; namely:

- the coordinate values used for the construction of the Topographic map,
- the change from Transverse Mercator projection (as used in Canadian topographic maps) to Mercator, Polar Stereographic, Polyconic, or Gnomonic projection (whichever that chart is constructed upon),
- since Topographic maps are constructed using photogrammetric techniques, the stereographic models from the airphotos are less accurate if there are large water areas,
- Topographic maps generally portray the shorelines at Mean Sea Level, whereas charts have both the low water line and high water line,
- erosion and accretion have to be considered when Topographic maps are used.

5. CONVERSION OF CHARTS FROM CHART (HORIZONTAL) DATUM TO NAD 27 (FINAL)

The previous step just determined the coordinates used in the chart construction. The latest NAD 27 positions can be researched and compared to these values and, generally, the differences can be averaged. Sometimes the deviations from the mean are random and unacceptably large and these facts are noted. For a few charts, the differences appear similar in distinct areas of the chart, leading to the provision of different datum shifts for different segments of the chart.

Since only some of the hydrographic control surveys have been recomputed on NAD 83, it is necessary to take a multiple step approach:

1) chart to NAD 27 (CHS),
2) NAD 27 (CHS) to NAD 27 (final), and
3) NAD 27 (final) to NAD 83.

The local hydrographic control would have NAD 27 values, but these might not be the latest NAD 27 values in the region. This information would have to be researched. The Geodetic Survey might have re-adjusted the higher order control and maybe even some of the lower order control in the area. Thus, there would be a necessity to determine the shift between the older NAD 27 values used in the CHS control and the final NAD 27 values used by Geodetic Survey of Canada.

5.1 Datum Selection on a GPS Receiver

Some models of GPS receivers have the option of selecting the datum upon which the geographic coordinates will be displayed. Since the receiver has probably already computed the Cartesian X, Y, Z coordinates of the point relative to the earth's centre of gravity, it is a simple matter to add in the translation to make the X, Y and Z coordinates relative to the centre of the requested ellipsoid, and compute the latitude, longitude and height based on that datum's ellipsoid parameters. This sounds wonderfully convenient and can be used. But there are pit-falls that must be appreciated. The National Imagery and Mapping Agency (NIMA), formerly the United States Defense Mapping Agency has computed, and the International Hydrographic Organization has published a "User's Handbook on Datum Transformations Involving WGS 84" for the shifts between WGS 84 and many local or regional datums. [IHO, 1992] Since the NAD 27 was a sequential build up of control surveys, particularly in Canada, that datum is non-homogeneous. By the very nature of the types of survey observations that went into NAD 27, the datum has no direct relationship to the centre of the earth. Since the differences in the Cartesian coordinate values of control points vary by over 40 metres in the three directions, a mean value of ΔX, ΔY and ΔZ can only provide a position with about 20-metre accuracy, assuming the latest values of NAD 27. Shifts between old NAD 27 and NAD 27 (final) coordinates greater than 50 metres are known to exist. But as was discussed earlier, many CHS charts were compiled on NAD 27 of earlier epochs. Some charts whose datum of reference is astronomic, or just unknown, can be related by shifts in latitudes and longitudes but cannot be related to satellite coordinates by this ΔX, ΔY, ΔZ transformation method. Therefore, it is recommended to mariners that it is best to acquire the WGS position and to manually add or subtract the latitude and longitude shifts that are provided to obtain the most accurate charted position.

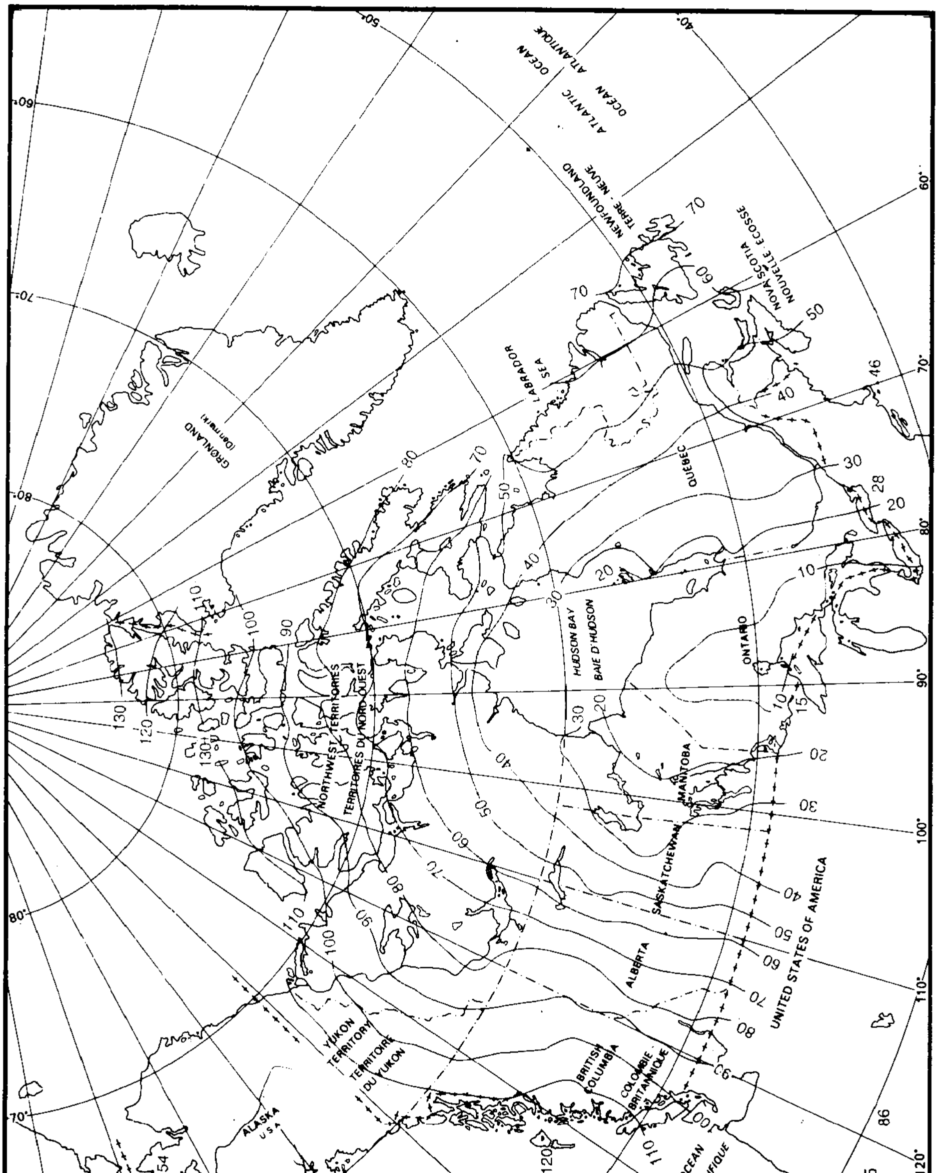

FIG. 1.- Coordinate shift in metres between NAD 27 and NAD 83.

6. CONVERSION FROM NAD 27 (FINAL) TO NAD 83

The final step is the conversion from the NAD 27 (final) values to NAD 83. In July 1986, the Geodetic Survey issued the NAD 83 coordinate values for the first 7800 primary stations. [PARENT & PINCH, 1988] It was not until 1990 that coordinate values became available for another 100 000 stations, and a re-adjustment of both the first order and many more lower order surveys in the NAD 83 system took place in 1993. Nevertheless, there are still many survey control networks that are not, and will not be, adjusted to NAD 83. At first inspection, NAD 83 positions generally appear farther from Chicago (U.S.A.) than their corresponding NAD 27 coordinates, as shown in Figure 1. In fact, the distances are very similar, the real reason the coordinates have spread outwards is because the NAD 83 coordinate system uses a slightly smaller ellipsoid.

There rarely are first order points that are directly related to CHS charts, and initially, seldom were there any points within the limits of a chart with both NAD 83 and NAD 27 values. It was necessary to do a transformation from NAD 27 to NAD 83 for the area of the chart. This was done mathematically by determining the ΔX, ΔY and ΔZ between the Cartesian coordinates of the NAD 83 position and of the NAD 27 (final) position of several nearby first order points which were then averaged. These ΔX, ΔY and ΔZ values would then be used to compute pseudo NAD 83 positions at several points throughout the chart and the mean value for the shifts in latitude and longitude computed. If, by chance, there were several points with both NAD 83 and NAD 27 values within the limits of the chart, the mean shifts in latitude and longitude could be computed directly.

After the 1990 publication of NAD 83 coordinates, the Geodetic Survey of Canada issued a data set of shifts in latitude and longitude at a grid of every 5 minutes of latitude and longitude in an interpolation program package, called INTGRID, that allowed the computation of shifts at any point in, or near Canada. The answers obtained had to be taken with caution because:

- what was used as the NAD 27 (final) because it is not always obvious which control points were used to establish the grid of data,
- the extrapolation off the coast was suspect.

After the 1993 re-adjustment, a second and much improved version of INTGRID was issued that was more meaningful.

Thus, the data for the conversion of charts to NAD 83 took these steps:

- identification of the charted positions of control points,
- the determination of the shift between charted position and latest NAD 27 position of CHS points,
- the determination of the shift between latest NAD 27 position of the CHS control and the final NAD 27 positions held by Geodetic Survey Division,
- the determination of the shift between NAD 27 (final) and NAD 83.

With the re-adjustment of the NAD 83 control in Canada in 1993, there is the necessity to revisit the datum shift computation for those charts where the shift was computed prior to 1993.

7. OTHER TECHNIQUES TO SOLVE THE DATUM PROBLEM

It is perhaps fitting at this stage to look at some of other methods of converting charts to NAD 83. Some have only been contemplated, others have been tested and used.

7.1 Least Squares Fitting

One method that has been proposed is the matching of features derived from the chart and from some other modern mapping, and to set up a series of observation equations for an affine transformation of the coordinates of one map (the CHS chart) onto those of the other map (usually a modern large-scale topographic map). The tests that have been done using this technique have shown the need for good conditioning of the observations, which is usually not present on charts. Most charts have the coast along the edge of the paper and great expanses of water everywhere else, or if there is a lot of land there is little accurately charted detail inland.

7.2 Rubber Sheeting

This technique is equivalent to printing the chart on a rubber (stretchable) sheet and then force fitting the rubber sheet to common points that appear on another map. This method assumes that every point that is picked, has been picked correctly. Again, there is the need to have a "well conditioned" situation.

This method has been used to convert the chart of the Welland Canal to NAD 83. The chart had previously lacked any grid lines since it really was a montage of engineering plans that had been converted into charting symbology. The Ontario Government had done Topographic mapping at about the same scale, and it was not a difficult matter to push and pull one to fit the other.

7.3 Satellite Imagery

Satellite imagery is not so much a method to correct charts to NAD 83, as a method to identify charts that are off datum by significant amounts, particularly in a non-systematic way, and to quantify that amount. This has been attempted in some of the Arctic regions. [TOMLINS, WAINWRIGHT & WOODS, 1995] Fortunately, the satellite imagery does not have to be the most recent (which is costly), but rather the imagery has to be clear of cloud cover so that good identification of the shore is possible.

Another use of satellite imagery is the detection of islands, small rocks and shoal areas in remote areas. Mariners, for obvious reasons, prefer not to navigate in uncharted waters and since the waters are not used, the priority to survey the area is low. Nevertheless, the legal definitions of the outer limits of the territorial sea, exclusive economic zone, etc. are based on the most seaward rocks, islands and drying rocks. Therefore, there is a need to establish whether these features exist. Surveys are required to position these features in the same coordinate system as being used by the mariner up to 200 miles away.

8. PROBLEM AREAS

The above description covers most situations, from oldest surveys, foreign originals, and latest surveys. But there are a few special problem areas in Canada that are worth describing.

8.1 Lake Superior

Lake Superior is the world's largest freshwater body by surface area. It has a rugged coast of granitic rock sculptured by glaciers with a bottom just as rugged. Most of the Canadian charts for the Lake were surveyed by lead line and rowing gig about 100 years ago. It is presumed that there is little difference between the natural conditions of shore and bottom then and now. Therefore, if the charts are brought to the modern datum, they can be used with modern navigation equipment. The problem is the conversion of the horizontal datum to NAD 83. It was necessary to recompute the United States Lakes Survey triangulation of 1865-95 from the pre-NAD 27 datum values onto NAD 83, add the 1910-20 CHS control and compare the resulting NAD 83 coordinates against old listings to determine the shifts in latitude and longitude. [GRAY, 1997]

8.2 South Coast of Newfoundland

The charts of the south coast of Newfoundland from Cape Ray, at the southwest corner, to the French islands of Saint Pierre and Miquelon, are reproductions from the United States Navy which were based on British Admiralty surveys. The longitude was proportioned between the pre-NAD 27 position of a light at the southwest corner of Newfoundland and an astronomic position in Placentia Bay. After plotting the existing control points by their descriptions, scaling the coordinates, comparing their positions with their surveyed values, errors in position of one minute (1') in longitude and ten seconds (10") in latitude were measured. With a little creative thinking, it was realized that the longitude and latitude errors were a function of the longitude. See Figure 2.

8.3 Arctic

During the 1950s, the United States and Canada established some 70 Distant Early Warning radar stations, known as the DEW Line, from western Alaska to eastern Greenland, with over 40 of them on Canadian soil. It meant the delivery of

CANADA

NEWFOUNDLAND—SOUTH COAST

RAMEA ISLANDS TO BONNE BAY

Reproduction of U.S.N.O.O. Chart No. 2416, April 1943, edition

From British surveys between 1872 and 1885

Outlines in hairline and soundings in slanting figures are from a smaller scale chart

The longitudes on this chart are based on a pro-rated adjustment of values depending upon Cape Ray Lighthouse being in Long. 59°18'16".80 W. and Coopers Cove Obs. Spot being in Long. 53°59'29" W.

Bearings refer to the True Compass and are given from Seaward (thus 295° etc.)

SOUNDINGS IN FATHOMS

HEIGHTS IN FEET ABOVE HIGH WATER OF SPRING TIDES

Water areas with depths of 3 fathoms and less are tinted blue

Underlined figures on drying banks or in brackets against drying rocks express heights in feet above the datum of soundings

For complete list of Symbols and Abbreviations see Chart No. 1

SCALE 1:75 000 AT LAT. 47° 35'

Projection: Mercator

CAUTION

Not all the aids to navigation are shown on this chart. For details of inner waters the larger scale charts must be consulted.

HORIZONTAL DATUM: Unknown datum. Positions on North American Datum 1983 (NAD 83) and those taken from GPS, SATNAV or Loran - C co - ordinate conversion after ASF correction must be moved "C" seconds northward/southward and "D" seconds eastward/westward to agree with this chart. With the exception of Pass Island, these values are a linear function of longitude.

Longitude	"C"	"D"
Pass Island	5.8" northward	4.4" westward
56°20'W	12.4" southward	52.9" westward
56°40'W	11.9" southward	46.7" westward
57°00'W	11.5" southward	40.6" westward
57°20'W	11.1" southward	34.5" westward

Even incorporating this data, positions plotted from navigation systems such as GPS, SATNAV, Loran-C, Omega may be in error by 0.3 miles because the horizontal reference datum for this chart is unknown. Positioning methods such as range and bearing should therefore be used.

FIG. 2.- Portion of Title Block of CHS Chart 4633 (Ramea Islands to Bonne Bay). Note reference to the pre-NAD 27 position of Cape Ray Lighthouse and an astronomic position at Coopers Cove. The translation components from NAD 83 to chart horizontal datum are a function of longitude.

thousands of tons of equipment and supplies to points along the north coast of continental North America. Up to that time only two shallow draft ships had transited the Northwest passage; and it was necessary to send in heavily laden ships supported by icebreakers. Charts were constructed on the fly, with ships navigating through areas surveyed by a few track lines only days, if not hours, before. These surveys are still part of the Canadian complement of charts.

CHS recognizes that ships may navigate these waters using an ENC and GPS but, in some cases, the paper chart is off datum by several minutes in latitude and longitude for a total error of up to 4 miles. One method to convert these charts to NAD 83 is to use the Topographic map as an intermediate step, as described in Section 4 (See Figure 3).

9. SPIN-OFFS

There are a number of advantages to re-examining CHS charts in a comprehensive manner that were not recognized at the outset, but have certainly produced benefits.

9.1 Quality Control

Many organizations are evaluating the quality of their products and establishing discrete methods to maintain those standards. The re-evaluation of the horizontal datum of CHS charts has led to finding steps in some procedures that had been overlooked and specific errors have since been corrected. Hopefully, the procedures have been tightened up as well. The recognition that one chart was woefully off datum in a very non-systematic manner lead to its abrupt cancellation, forcing mariners to use the smaller scale chart of the area. Fortunately, it was in a lightly travelled area.

9.2 Territorial Sea Baselines

The baselines of the territorial sea have, for the past 30 years, been based on the geographic feature as shown on CHS charts, even if on a local datum. The geographic position is quoted, but strictly as an aid in knowing what feature is being described. The problem comes in drawing the Territorial Sea and Exclusive Fishing Zone outer limits from these positions. The limit is drawn on one chart whereas the control point that defines the limit is derived from another chart on a different datum. During 1995-97, the CHS has been re-evaluating the baseline points, and determining the charted position as well as the NAD 27 and NAD 83 coordinates of such points.

9.3 Global Positioning System/Differential GPS as a survey tool

Thirty years ago, it was estimated that CHS spent 15% of its field time establishing the survey control fabric that was necessary to execute a hydrographic

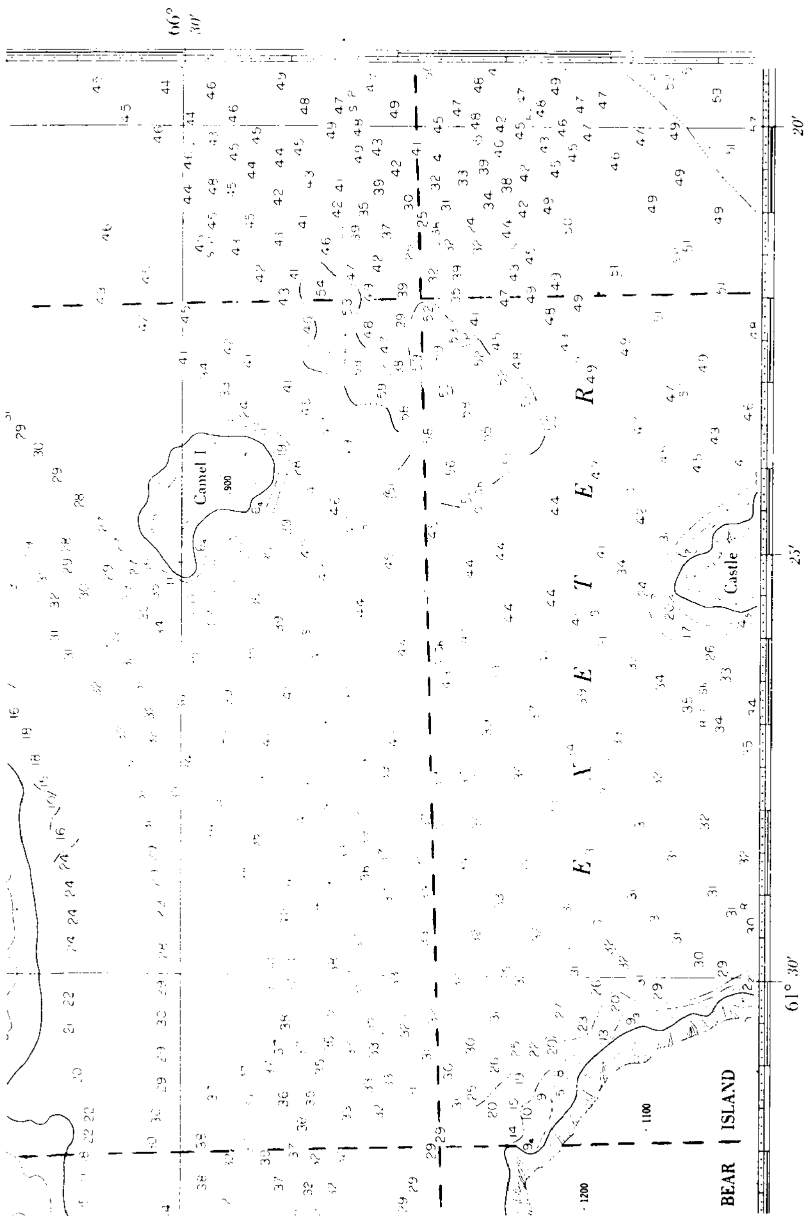

FIG. 3.- Portion of CHS Chart 7170 of Exeter Bay and Approaches showing placement of NAD 83 grid lines (dashed lines). Note positioning error in excess of 1 nautical mile and orientation error.

survey. Now, with GPS and DGPS, there is significantly less time spent on survey control and more flexibility as to where to survey as the only need for terrestrial survey control is the differential monitor site. Also, the use of GPS controlled hydrography means that these surveys can be directly added to a chart on NAD 83 with no conversion to the chart's horizontal datum. It will mean that mariners, using GPS, will be using a chart surveyed using the same system.

9.4 Field Sheets

During 1996, CHS began a process to evaluate the datum shift for individual field sheets so that they could be converted to NAD 83 on an individual basis. It is very much a case of converting the old survey data to NAD 83 at the earliest possible stage, rather that at the last stage of chart production. The necessity to do so is dependent on the requirement of using that field sheet again in chart or ENC construction.

10. Conclusions

In ten years of converting charts to a world based geodetic datum, CHS has accomplished sizable inroads into the conversion. Some charts have been completely converted, many have instructions to mariners to correct their GPS position by specified amounts, a few have a caution to mariners that their GPS position might be in error by up to a specified amount due to the horizontal datum of the chart, and there are 30% that are still to be addressed. The production of 946 Electronic Navigation Chart digital files is exclusively on a world based geodetic system.

When the CHS managers first considered the horizontal datum problem, they considered that the anticipated 100 metre difference in position between NAD 27 and NAD 83 as either insignificant or capable of being handled by a simple translation, either of the grid or of the GPS position before plotting. Little did they realize that almost 15% of the CHS charts had fundamental horizontal datum problems that had to be overcome. It was a true case of opening Pandora's Box. Since then, the easy ones have been accomplished, the more difficult ones are still to come.

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