A SEAMLESS VERTICAL-REFERENCE SURFACE FOR ACQUISITION, MANAGEMENT AND ECDIS DISPLAY OF HYDROGRAPHIC DATA

D. E. WELLS
A. KLEUSBERG
P. VANICEK

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PREFACE

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David Wells
Alfred Kleusberg
Petr Vaníček

Department of Geodesy and Geomatics Engineering
University of New Brunswick
P.O. Box 4400
Fredericton, N.B.
Canada
E3B 5A3

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Preface

This technical report is a reproduction of a final contract report prepared for the Canadian Hydrographic Service by David Wells, Alfred Kleusberg, and Petr Vaníček, and submitted on 6 February 1996.

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Executive Summary

This report addresses the question

> *What must the Canadian Hydrographic Service (CHS) do to bring their vertical datums into a consistent digital database, taking into account current and future Differential Global Positioning System (DGPS) capabilities?*

The approach taken is to carefully consider the transformations required for conversion among various surfaces (bathymetry, seamless reference surface, Chart Datum, instantaneous water level, etc.). Under this approach, the question is restated as:

What choices of

- *Seamless reference surface*
- *Transformation functions and their implementation*
- *Water level model*
- *Water level sensing technique*

will combine to provide depth information which jointly optimizes

- *Navigational safety*
- *Accuracy of final depth presentation to mariner*
- *Ease of realization and maintenance?*

Four kinds of vertical-reference surfaces are described: the tidal surfaces (e.g., LLWLT); hydrological surfaces used in rivers; equipotential surfaces (e.g., the geoid); and mathematical surfaces (e.g., a reference ellipsoid).

The nature of the transformations among these various vertical-reference surfaces are discussed.

Seven criteria are established for selection of a seamless vertical-reference surface, the transformations associated with that surface, the prescriptions (transformation functions) used to implement these transformations. These criteria are the impact on navigation safety; the accuracy of the final depth presentation to mariners; consistency across the land-sea boundary; seamlessness; the ease of realization and maintenance; the issue of datum stability versus utmost quality; and the impact on database management.

Based on these criteria, the seamless vertical-reference surface which is simplest, is time-invariant, and which involves the most reliable implementation of required transformations is proposed for adoption. That surface is a bi-axial reference ellipsoid of revolution.

A strategy to implement this seamless vertical-reference surface is proposed, which makes use of two tools: the Global Positioning System, and data from altimetric satellites. Conventional static baseline differential GPS positioning is recommended to tie existing Chart Datum points to a seamless surface. Altimetric satellite data should be used to determine the separation between the temporally averaged sea surface and the geoid (Sea Surface Topography) — however this will require improved accuracy of the marine geoid determination, and more complete temporal coverage of the oceans by altimetric profiles.

The issues affecting the accuracy with which final depths are presented to end-users are catalogued and described. These include the accuracy of the vertical-reference surface itself; depth measurement errors; water level measurement errors; water level prediction errors. It is concluded that for most purposes, vertical-reference surfaces established to decimetre uncertainties (at the 95% confidence level) would be adequate for most purposes. However, there are a few critical passages where the investment involved in establishing vertical-reference surfaces with an accuracy of a few centimetres may be justified.

A sequence of steps to be followed in implementing and maintaining a seamless vertical-reference surface are proposed. This involves, as a first step, the determination of the transformation between existing Chart Datum, and the new seamless datum, at each water level station for which Chart Datum has historically been established. The locations of existing Chart Datum points are summarized. Four priority levels for establishing this transformation are suggested: first priority is stations along the St. Lawrence River; second priority is stations for which ENC databases have already, or will soon be prepared; third priority is Chart Datum stations which have never been tied into a vertical network; ("floating" datums); and fourth priority is stations for which there are known problems concerning the Chart Datum attached to them. Specifications for the GPS survey work are proposed.

The most difficult "maintenance" issue, that of dealing with the inaccuracies of historical bathymetric data, is beyond the scope of this report. However, there are several maintenance issues which involve the transformations we propose, which should not be ignored. These include changes due to evolution of our understanding and **models** for the geoid; the instantaneous sea level; the tide; other sea surface dynamics; sea surface topography; vertical crustal movement; lake level; and river level. Also important are the physical rather than modeling changes due to eustatic sea-level rise.

The costs and benefits of implementing the proposed strategy are noted. The benefits range well beyond the immediate objective of improving navigational safety through adopting a more consistent vertical-reference surface. The impact of adopting the approach recommended here is discussed for three groups of "clients": the mariner; "virtual corporation" collaborators of the Canadian Hydrographic Service; and other end-users.

Thirty-eight recommendations are made throughout the report.

Acronyms Used in this Report

CARIS	Computer Assisted Resource Information System (a commercial GIS package)
CCG	Canadian Coast Guard (agency within DFO)
CCGLBHHD	Coordinating Committee on Great Lakes Basic Hydraulic and Hydrological Data
CD	Chart Datum
CHS	Canadian Hydrographic Service (agency within DFO)
COWLIS	Coastal and Ocean Water Level Information System (see SINECO)
CVGD	Canadian Vertical Geodetic Datum (?)
DFO	Canadian Department of Fisheries and Oceans
DGPS	Differential GPS
DHI	United States Defence Hydrographic Initiative
DMA	United States Defence Mapping Agency
DND	Canadian Department of National Defense
EC	Environment Canada
ECDIS	Electronic Chart Display and Information System
ECS	Electronic Chart System
ENC	Electronic Nautical Chart
FIG	Federation Internationale des Geometres
GALOS	Geodetic Aspects of the Law of the Sea
GIS	Geographical Information System
GPS	Global Positioning System
GRS	Geodetic Reference System
GSC	Geological Survey of Canada (an agency within Natural Resources Canada)
GSD	Geodetic Survey Division (agency within Natural Resources Canada)
HHWLT	Higher High Water, Large Tides
HHWMT	Higher High Water, Mean Tides
IAG	International Association of Geodesy
IERS	International Earth Rotation Service
IGLD	International Great Lakes Datum
IGS	International GPS Service for Geodynamics
IHO	International Hydrographic Organization
ISL	Instantaneous Sea Level
ITRF	IERS Terrestrial Reference Frame
LAT	Lowest Astronomical Tide
LLR	Lunar Laser Ranging
LLWLT	Lower Low Water, Large Tide
LLWMT	Lower Low Water, Mean Tide
LNT	Lowest Normal Tide
MLLW	Mean Lower Low Water
MLW	Mean Low Water
MSL	Mean Sea Level
MWL	Mean Water Level
NAD	North American Datum
NAVD	North American Vertical Datum
NAVOCEANO	United States Naval Oceanographic Office
NDI	Nautical Data International
NGS	United States National Geodetic Survey (agency within NOAA)
NOAA	United States National Oceanic and Atmospheric Administration
NOS	United States National Ocean Survey (agency within NOAA)
NRCan	Natural Resources Canada
ODIN	Ocean Data Information Network

OSL	Offshore Systems Limited
OTF	On-The-Fly carrier ambiguity resolution method of using GPS
PWC	Public Works and Administration Canada
RTCM	Radio Technical Commission for Maritime Services
SLR	Satellite Laser Ranging
SST	Sea Surface Topography
TALOS	Technical Aspects of the Law of the Sea
TOPEX	Topographic Experiment satellite
UHF	Ultra High Frequency
UNB	University of New Brunswick
UNCLOS III	Third United Nations Convention on the Law of the Sea
USCG	United States Coast Guard
VHF	Very High Frequency
VLBI	Very Long Baseline Interferometry
WGS	World Geodetic System

1. INTRODUCTION

In this chapter we define the problem to be addressed in this report: vertical reference surfaces and what to do about them. We also introduce the two main themes which we will follow throughout the report: the role of the Global Positioning System (GPS) in determining a new kind of vertical-reference surface, and the critical role of transformations in implementing any new strategy.

1.1 PROBLEM STATEMENT

The purpose of this report is to address the following question:

> *What must the Canadian Hydrographic Service (CHS) do to bring their vertical datums into a consistent digital database, taking into account current and future Differential Global Positioning System (DGPS) capabilities?*

In response to client demand, the CHS is aggressively converting from the production of paper charts to the production of a digital hydrographic database, which can be used either to produce paper charts or to supply data for Electronic Chart Display and Information Systems (ECDIS). There is a massive amount of existing digital and hard-copy data, referenced to the present vertical datums, which may be incorporated into a digital database for use in creating next-generation ECDIS. Depths used for such an ECDIS should ideally be referred to a "seamless" vertical-reference surface. Such a surface cannot easily be derived from the present set of Chart Datums (tidal datums, reference water levels along rivers, and reference levels for lakes).

The present set of Chart Datums in Canada are based on data from approximately 1200 water level gauge stations in Canada. At most of the tidal stations, the Chart Datum is based on a minimum of one month of tidal observations. For many of these stations, the tidal datum is only a local datum (the benchmarks which monument the tidal datum are isolated and not connected to any outside network). A weak connection may exist through water level transfer between gauges, or by reference to Mean Sea Level (MSL) values. Reference water levels along navigable rivers are generally based on water level observations spanned several years, so that seasonal and year-to-year averages The issues here are not restricted to vertical references in tidal waters, but also (perhaps even more critically) to reference water levels along navigable rivers.

1.2 THE ROLE OF VERTICAL-REFERENCE SURFACES IN NAVIGATION

This report is about vertical positions. There are two vertical positioning tasks aimed at preventing vessel groundings. These are to establish the vertical distances between

- the hydrographer's echo sounder transducer and the seabed, and
- the keel of a mariner's ship and the same seabed.

It is usually essential to also determine the draft of the transducer, and mariner's keel below the water level, and the water level referred to some datum, both at the time and location the soundings are made, and the time and location of the mariner's passage. The exception to these additional requirements would be if a sufficiently accurate three-dimensional navigation technique were to be used by both hydrographer and mariner.

There are two vertical positioning tasks aimed at preventing vessels from coming into contact with bridges, wires, and other overhead obstructions. These are to establish the vertical distances between

- the waterline and the obstruction, determined by the hydrographer, and
- the mariner's vessel mast and the same obstruction.

It is also essential to determine the relationship between the water level and the reference plane being used for the clearance.

All these distances depend on the water level at the time. In order to relate the hydrographer's soundings to the mariner's keel clearance, and the hydrographer's obstruction height measurements to the mariner's mast clearance, the following conditions must be satisfied:

- The vertical-reference surface used by the hydrographer to represent water levels (and thus depths to the seabed), must be the same as the vertical-reference surface used by the mariner to represent water levels and seabed depths.
- The vertical-reference surface used by the hydrographer to represent water levels and heights of overhead obstructions, must be the same as the vertical-reference surface used by the mariner to represent water levels and obstruction heights.

The traditional method of addressing this requirement is to use not one but two conservatively chosen ("near-worst-case") vertical-reference surfaces. The vertical-reference surface used for depths and keel-clearances is so low that the water level will seldom fall below it. The mariner should almost always have **more** water under his keel than that shown on the nautical chart. The vertical-reference surface used for heights and obstruction-clearances is so high that the water level will seldom rise above it. The mariner will almost always have **more** clearance above his mast than that shown on the nautical charts.

The conversion to Electronic Charts and digital databases on one hand, and increasing demands from the shipping industry on the other hand, are creating pressures to provide to the mariner a more realistic, perhaps time-varying, representation of keel-clearances and obstruction-clearances. Any such move away from the traditional conservative approach involves risk. **This risk must be made evident to the mariner.** It is important to build uncertainty information into **any** new representation of these depth and height clearances [e.g. Myres, 1990; Kielland and Dagbert, 1992; Kielland et al., 1993; Hare and Monahan, 1993; Hare and Tessier, 1995; Du, 1995; Zhou, 1995].

Recommendation 1: Systems designed to provide realistic (rather than near-worst-case) clearance information to mariners must also display easily understood information about the uncertainty with which these clearances are determined.

1.3 OPPORTUNITY PROVIDED BY GPS

The Global Positioning System (GPS) has become a predominant tool for horizontal positioning in hydrography [e.g. Wells et al., 1987; Leick, 1995]. GPS is widely used to provide horizontal positions for hydrographic surveying. It is also becoming widely used by mariners in navigating over these charted waters. It has been identified as one of the essential technologies which make feasible the widespread use of ECDIS. One of its attributes is that it provides seamless horizontal positions.

Typical goals for horizontal positioning are to place a hydrographic depth measurement within the first Fresnel Zone of the echo sounder beam pattern, and to place the navigating vessel within a safe channel. Each of these goals can generally be achieved with accuracies of a few metres. This accuracy is now, or soon will be, routinely provided by public and private differential GPS services. In Canada such a public service for mariners is being established by the Canadian Coast Guard.

Recently, the capabilities provided by GPS have improved to the extent that it is now feasible to seriously consider its use for vertical as well as horizontal positioning [e.g. Leick et al., 1990; Wells and Kleusberg, 1992; Lemmens, 1993; DeLoach et al., 1994a; 1994b; 1995a; 1995b; Lachapelle et al., 1994]. It has been possible for some time to interconnect isolated tidal benchmarks to accuracies of a few cm (for short baselines) and 1 part per million (ppm) of the horizontal distance between the benchmarks (for longer baselines), using standard static DGPS procedures. Better performance can be obtained using careful procedures to account for all error sources: vertical repeatability approaching 0.01 ppm (10 ppb) are possible for very long baselines (several thousand kilometres). These interconnections provide three-dimensional relative positions, the vertical coordinate of which is referred to a reference ellipsoid.

Now, however, it is possible to achieve instantaneous real-time three-dimensional GPS positioning accuracies of a few centimetres on board a hydrographic survey vessel, on a ship navigating through a difficult passage, or even on a water-level sensing buoy. These are positions relative to a shore reference station, and the relative vertical coordinates are referred, as above, to a reference ellipsoid.

The name given to this mode of using GPS is "on-the-fly differential GPS carrier phase integer cycle ambiguity resolution". In this report we refer to this simply as OTF (for "On-The-Fly").

OTF provides an opportunity to seriously consider the establishment and use of a seamless vertical-reference surface in hydrography. However in order for us to take advantage of this opportunity, some conditions must be fulfilled:

- The spatial data that defines the seafloor must use the same vertical-reference surface as the positions being used by the navigator for guidance.
- The accuracy of **both** the survey data and the navigation system must be compatible with the desired keel-clearance tolerances we wish to attain.

This report deals with this opportunity. It is perhaps useful to start with a short description of the OTF technique itself, as background.

1.3.1 WHAT IS OTF?

In contrast to the code-pseudorange measurements used by standard GPS and DGPS receivers, a GPS receiver capable of also measuring the carrier wave component of the GPS signal can only directly measure the fractional part of a single cycle, $\Delta\lambda$, of this carrier wave. The purpose of the OTF process is to compute the number, N, of complete carrier cycles, λ, between the observer and the satellite. This can be done while the observer is constantly in motion. Once N is determined, then the satellite-to-receiver distance ρ is given by:

$$\rho = \Delta\lambda + N\lambda \qquad (1.1)$$

This explanation is a little simplified, because in practice we do not actually determine N, but the difference in the N values for two receivers tracking the same satellite, or even the double-differences in N, involving two satellites and two receivers (see Abidin [1994]).

Considering that the carrier wavelength is about 20 centimeters and the satellites are about 20,000 kilometers away, it is impossible to know instantly how many full cycles, N (or full cycles in double-differenced Ns), there are between the receiver and the satellite, without some additional information. Useful additional information is provided by tracking as many satellites as possible; by tracking the carrier signal at both L1 and L2 frequencies; and by having as accurate a starting position (from the code pseudoranges) as possible. Many techniques have been introduced to resolve the ambiguities, with names such as kinematic, stop-and-go, pseudo-kinematic, and antenna swapping. Initially these techniques involved post processing (resolving the ambiguities **after** the project), but with appropriate differential radio links some can be made to operate in real time. However, all these techniques require that both reference and remote receivers be stationary for a brief period, in order to solve for the ambiguities (**before** the project). OTF still requires two observing stations, but one (or both) can be in constant motion, hence ambiguity resolution *on-the-fly*. OTF resolves the ambiguities **during** the project.

The ambiguity resolution process requires the creation of an initial search space from which to choose the correct set of integers. This search space is typically created from the differential code (DGPS) solution. The better the DGPS position, the smaller the search space, and the less computations required to solve for the correct integers.

After the ambiguities are resolved, whether using an OTF process, or one of the earlier techniques, the relative positions between the two GPS receiver antennas are computed using the same equations as for static differential GPS carrier phase position computations. The only difference is that one instantaneous relative position is produced for each data update, say once per second, versus a single relative position averaged over the observing time span.

1.3.2 STATUS OF OTF

OTF has been under development for a decade, based on an original suggestion that it was feasible, made by Remondi [1984]. Only recently, with the advent of the full GPS constellation, and the emergence of low noise, all-in-view, dual frequency receivers, and robust real-time OTF software, have reliable OTF results have become possible. The OTF technique is not without operational constraints. Real-time OTF requires higher differential message data rates (e.g. 4800 baud minimum) than does conventional DGPS (e.g. 100 baud), as well as higher reliability in the differential message link. Radio frequencies capable of handling this baud rate (VHF or UHF) have a more limited range than the lower frequencies used for many conventional DGPS services. OTF is susceptible to multipath errors. The maximum distance at which OTF will operate reliably has yet to be established, but it appears that operations at up to 100 kilometres may be feasible.

Like code DGPS before it, the full impact of the OTF method will only be felt once an infrastructure is in place, providing OTF to a wide range of users. The Radio Technical Commission for Maritime Services (RTCM) has included OTF differential data message structures in the latest version of their recommended format standard. The receivers presently being installed by the US Coast Guard at their differential GPS reference stations have the full wavelength L1 and L2 carrier phase capability required for OTF. With upgraded transmission facilities, it is possible to broadcast both code and carrier phase data. It is quite feasible, should the use of OTF become widespread, for this dual capability to be installed at all stations in DGPS reference station networks now being established in many countries.

At this stage in its development (unlike conventional DGPS) OTF equipment from different manufacturers are incompatible, and cannot be used effectively together. There are no agreed upon RTCM message standards as yet. Equipment from the same manufacturer must be used for both base and mobile stations, so far.

If and when such an infrastructure is established, OTF can then be used routinely for three-dimensional marine positioning, as well as for many other demanding three-dimensional positioning applications. Establishment of an OTF infrastructure will render such activities both safer and more efficient.

In the context of this report, OTF provides a means to improve the quality of the reference water levels used in creating a digital hydrographic database, and for users to accurately recover these reference water levels in real-time.

1.3.3 GPS ACCURACY LIMITATIONS

GPS can be used for positioning in a variety of modes leading to positioning accuracies anywhere between 100 metres and a few millimetres. The accuracy level of interest in the context of this study (one decimetre and better) is achievable only through the use of differential GPS carrier phase measurements with fixed phase ambiguities.

The position errors in this mode of operation result from

- measurement noise,
- signal multipath interference,
- atmospheric refraction, and
- satellite ephemerides errors.

Carrier phase measurement noise is typically at the few mm level for modern GPS equipment. Signal multipath errors depend on the conductivity in the GPS receiver environment, and are below 5 cm with typical values at the 1 - 2 cm level for reasonably ‘clean’ antenna environments.

Atmospheric refraction effects are usually separated into ionospheric effects and tropospheric effects. The ionospheric effects can be eliminated through the use of dual frequency GPS receivers. It cannot be compensated for in single frequency receivers. In such systems ionospherically induced position errors are to a large degree of approximation proportional to the distance between the GPS receivers. The range of these errors is from about 1 part per million (ppm) of the distance for periods of low solar activity up to about 10 ppm during periods of maximum solar activity.

Tropospheric refraction effects are usually compensated through atmospheric models. Such models are usually accurate to a few cm. Satellite ephemerides errors lead to distance dependent position errors similar to the uncompensated ionospheric refraction effects. Typical position errors resulting from errors in the ephemerides broadcast by the GPS satellites are below the 1 ppm level.

All of the above error sources combine to produce resulting errors in the vertical and horizontal position components. The vertical position errors are about 2- 3 times the size of the horizontal position errors. This is a consequence of two facts: First, the GPS geometry is not as good for the vertical position as it is for the horizontal position. Second, the residual tropospheric errors contaminate primarily the vertical position and to a lesser degree the horizontal positions.

The following may serve as a rule of thumb for GPS horizontal position errors in the above described mode of operation.

2 - 4 cm	for short distances (<20 km), single or dual frequency equipment, single epoch measurements
1 - 2 cm	for short distances (<20 km), single or dual frequency equipment, measurement data collected for 30 minutes
1 - 2 cm + 1 ppm	for long distances, dual frequency equipment, measurement data collected for a few hours

For vertical position errors, these numbers must be multiplied by a factor of 2 - 3. The distance dependent part in these estimates can be reduced by a factor of more than 10 by using post mission computed precise orbits instead of the broadcast GPS ephemerides. Such precise orbits are available from a number of GPS processing sites, one of them being the Geodetic Survey Division in Ottawa.

1.4 THE ROLE OF TRANSFORMATIONS

The approach we will take in this report is to consider the problem of selecting an appropriate seamless vertical-reference surface from the point of view of the transformations required. We will be concentrating on the vertical-reference surface used for depths, but will discuss the other vertical-reference surfaces used in hydrography as well.

Let us start by defining five terms:

$b^c(\varphi,\lambda)$ = database of bathymetry, below Chart Datum (e.g. as on paper charts)

$b^s(\varphi,\lambda)$ = database of bathymetry, below a seamless reference surface

$w^c(\varphi,\lambda)$ = water levels, above Chart Datum (e.g. as predicted from tide tables)

$w^s(\varphi,\lambda)$ = water levels, above a seamless reference surface

$d(\varphi,\lambda,t)$ = water depths

Note that the bathymetry is assumed to be time-independent, while water levels (and therefore depths) vary with time due to tides, seasonal river flow variations, and many other reasons. This assumption is not always true, due to sediment build-up and crustal movements. Time-varying water depths are the measurements upon which time-invariant bathymetric databases are built. The mariner would benefit most if instantaneous water depths at (and ahead of) the vessel were available for navigation, in real time. However, at present only the time-invariant bathymetry below Chart Datum is usually available. Figure 1.1 illustrates the relationships among these quantities.

A possible scheme for the flow of information into and out of a time-invariant bathymetric database, which uses a seamless reference surface, is illustrated in Figure 1.2. Existing (time invariant) bathymetric data, referred to Chart Datum, is contained in database $b^c(\varphi,\lambda)$. Some form of transformation must be performed in order to convert these data to a seamless database $b^s(\varphi,\lambda)$. New bathymetric data can be provided to $b^s(\varphi,\lambda)$, as long as the water levels used to "reduce" the measured soundings $d(\varphi,\lambda)$ are referred to the same seamless reference surface as is used for $b^s(\varphi,\lambda)$. At present, the only bathymetric data product available from the bathymetric database $b^c(\varphi,\lambda)$ is b^c itself (bathymetry referred to Chart Datum). From database $b^s(\varphi,\lambda)$, four possible data products are shown:

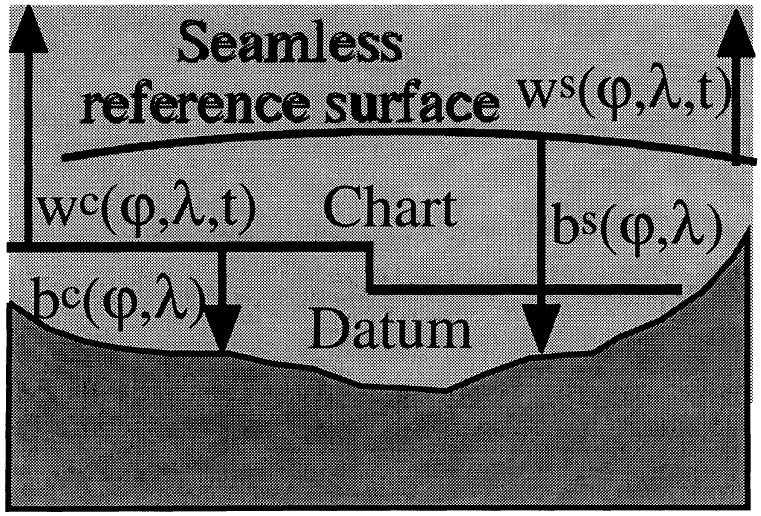
- $b^s(\varphi,\lambda)$ itself (not useful for marine navigation, but may have other applications)
- $b^c(\varphi,\lambda)$, which is obtained by applying the inverse transformation used to convert $b^c(\varphi,\lambda)$ to $b^s(\varphi,\lambda)$. This would be used for paper charts, which are likely to remain in use for some time.
- A model for the instantaneous water depth, $d(\varphi,\lambda,t)_{predicted}$, obtained by adding $b^s(\varphi,\lambda)$ to a water level model $w^s(\varphi,\lambda,t)_{model}$. These predicted depths could be used for future 3D electronic charts for non-critical users, for example, to display the time variability of the "critical contour."
- Actual instantaneous water depths, $d(\varphi,\lambda,t)_{actual}$, obtained by adding $b^s(\varphi,\lambda)$ to real-time water level measurements, $w^s(\varphi,\lambda,t)_{measured}$, referred to the same seamless reference surface as is used for $b^s(\varphi,\lambda)$. These water level measurements may be provided as a service, or from measurements made on the vessel itself. The resulting actual water depths could be used by critical users today, to indicate actual water under the keel. They could also be incorporated into future 3-D electronic charts, initially for critical users, and perhaps eventually, if demonstrated to be cost-effective, for a broader class of mariners.

Note that a "transformation" may be realized in practice by a mathematical algorithm or function, requiring computation but little storage; it may be realized by a list of numerical values requiring storage, but little computation; it may be realized by direct measurements (perhaps in real-time); or some combination of these may be used. The actual implementation of any transformation which may be required is deferred to Chapter 5.

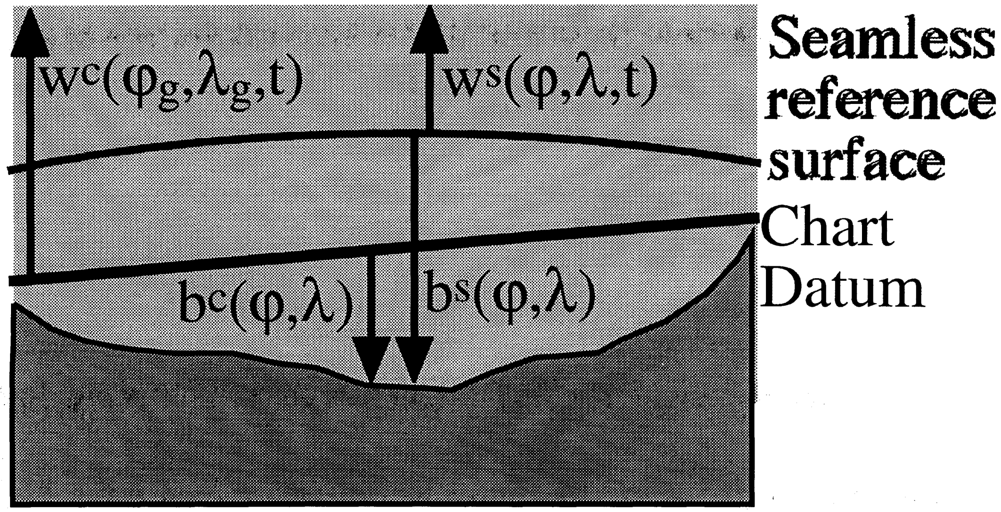
1.5 RESTATEMENT OF THE PROBLEM

In order to select the "best" seamless vertical-reference surface for hydrographic digital databases, we must establish some criteria by which we can judge one alternative against another. Ideally there would be just one such criterion, and we could assign it some numerical value for each alternative. The selection would then be simple: pick the alternative with the "best" (highest or lowest) value for that criterion. The process is an example of what is often called optimization.

Our problem is not quite so simple. There is no single overriding criterion. It may not be easy to assign numerical values to any of the criteria we come up with. However, following the "optimization" structure as closely as this problem permits us to do will still be beneficial.



$$\begin{aligned} d(\varphi,\lambda,t) &= w^c(\varphi,\lambda,t) + b^c(\varphi,\lambda) \\ &= w^s(\varphi,\lambda,t) + b^s(\varphi,\lambda) \end{aligned}$$



$$\begin{aligned} d(\varphi,\lambda,t) &= w^c(\varphi_g,\lambda_g,t) + b^c(\varphi,\lambda) \\ &= w^s(\varphi,\lambda,t) + b^s(\varphi,\lambda) \end{aligned}$$

Figure 1.1: Water depth, using Chart Datum, and a seamless vertical-reference surface.

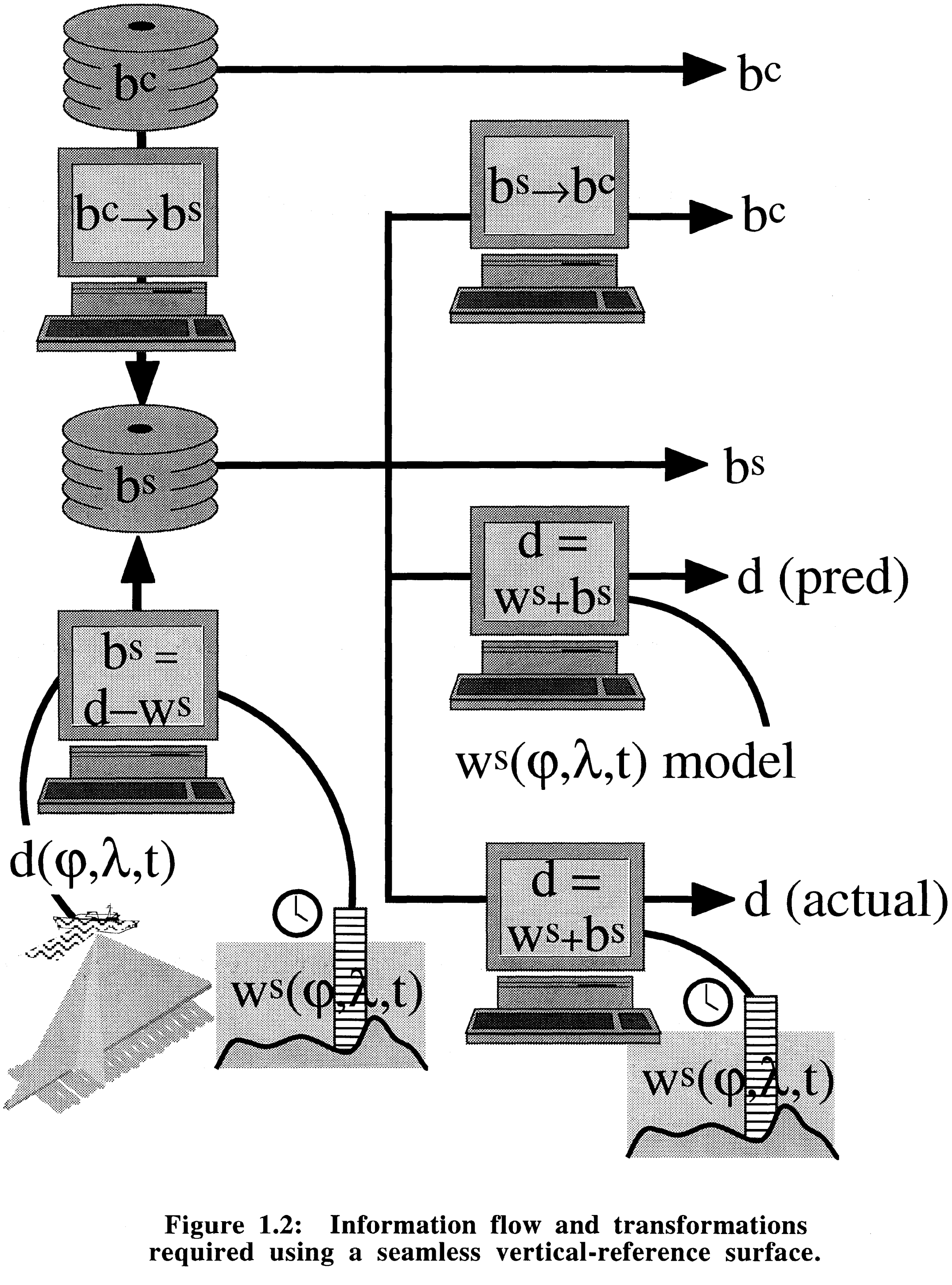


Figure 1.2: Information flow and transformations required using a seamless vertical-reference surface.

The criteria which we propose be used in selecting the "best" seamless vertical-reference surface for the CHS are discussed in detail in Chapter 6. In order of priority (or "weight" in our optimization) they are: the impact of this selection on navigational safety; the resulting accuracy with which depths are finally presented to the mariner; and the ease with which the selected surface can be realized in practice, and subsequently maintained or re-established. We have taken for granted the criterion that it must be a seamless surface, and consider that to be a "pre-filter" of the alternatives, rather than an optimization criterion. There are some other subsidiary criteria which we discuss in Chapter 6, but to which we do not accord the same priority as the three listed above (e.g. consistency across the land-sea boundary).

Based on this set of criteria, and our earlier mention of the role of transformations, we can now restate the problem posed first in §1.1:

What choices of
- *Seamless reference surface*
- *Transformation functions and their implementation*
- *Water level model*
- *Water level sensing technique*

will combine to provide depth information which jointly optimizes
- *Navigational safety*
- *Accuracy of final depth presentation to mariner*
- *Ease of realization and maintenance?*

Of the choices involved in this statement, the most important will involve those concerning transformations. Some transformations will be time-invariant, some will vary with time. Various choices for transformations will have different accuracies, will involve different modeling techniques (ranging from purely geometrical to purely physical), will be represented by mathematical expressions of varying complexity, and thus require different amounts of computer time to evaluate. These issues form one of the main themes of this report.

The formulation of some of the transformations will require some additional information, not readily available, which will have to be collected either via field observations, or through further analyses of existing data.

Finally, there will be several possibilities for implementing each particular transformation which is required, at different stages in the information flow. A transformation may be performed externally, before data is entered into an Electronic Nautical Chart (ENC) database. It may be imbedded as an ENC database input or output routine. It may be performed externally again, but this time after data has been extracted from an ENC database (possibly by the CHS, possibly by some other organization). It may be that the ECDIS system used by the mariner or other end user would perform the transformation. Choice of by whom and when each transformation required is performed is an important issue in establishing the "best" solution to the problem as stated above.

1.6 OUTLINE OF THE REPORT

In this chapter we have attempted to introduce the problem, briefly review the opportunity provided by OTF in addressing the problem, and introduce the approach which we plan to take in this report. The rest of the report can be divided into three sections: first we discuss in detail the issues surrounding selection of a seamless vertical-reference surface (Chapters 2 and 3); then we discuss the selection criteria in detail, recommend our choice for the "best" surface based on these criteria, and outline how it may be implemented (Chapters 4 and 5). Finally we discuss the impact of this choice on various CHS clients (Chapter 6).

2. VERTICAL-REFERENCE SURFACES

There are five applications for vertical-reference surfaces in hydrography. Depths and heights on paper charts are each presented in a conservative or "near-worst-case" manner, and therefore use different vertical-reference surfaces. The analysis and prediction of tides has the built-in assumption of some kind of mean water level about which the tide is sometimes lower and sometimes higher. Water levels in rivers and lakes are seldom governed predominantly by tides, and therefore have their own kinds of reference levels.

In this chapter, we review various kinds of vertical-reference surfaces, and consider them as members of four distinct groups. The first two of these are reference surfaces defined through functions of water levels. The **tidal surfaces** discussed in section 2.1 are defined for tidal waters. The reference surfaces for inland waters are discussed in section 2.2 under the heading **hydrological surfaces**.

The next two sections describe two types of reference surfaces which are not directly related to water levels. As a consequence, these reference surfaces are defined globally, and are not limited to oceans, lakes and rivers. The **equipotential surfaces** of section 2.3 are defined in terms of the gravity potential of the earth. A particular choice of the equipotential surface, the geoid, has a certain relation to tidal surfaces. The **mathematical surfaces** discussed in section 2.4 are defined through a number of numerical parameters to be used in a mathematical equation. Increasingly complex equations with increasing numbers of parameters can be used to approximate more and more detailed mathematical surfaces.

Finally we look at non-hydrographic applications of vertical-reference surfaces. In section 2.5 we consider land-based uses. In section 2.6 we mention the role of vertical-reference surfaces in sea surface topography (SST) studies; marine boundary delimitations; gravity field studies; and eustatic indicators of global change.

Two kinds of surfaces which we have chosen not to consider are the cadastral surface determined by evidence of vegetation used for marine and river boundary delimitation, and the steric surfaces (ocean depths at which no motion is assumed to exist) used by oceanographers.

2.1 TIDAL SURFACES

In the absence of waves and other non-tidal phenomena, the water level of the oceans will at any instant in time form a continuous and smooth surface. Conceptually, tidal surfaces can be defined in terms of averages or extremes (or both) of this surface over a specified interval of time. Because of the continuity and smoothness of the water level, any such tidal surface will be continuous and smooth as well. However, since tidal extremes occur at different times for different locations, the actual water level will in general never coincide with any of these tidal surfaces.

Tidal surfaces are realized at discrete locations through tide gauge observations. In principle, the height determined with a tide gauge represents only a spot value of the tidal surface. The use of this spot value in the vicinity of the tide gauge requires spatial extrapolation. The simplest such extrapolation may assume a constant horizontal surface.

The tide gauge needs to be connected through levelling to at least one benchmark. These benchmarks may or may not be connected to the vertical geodetic network. If they are connected, the orthometric height of the tidal surface can be calculated.

2.1.1 PRESENT SET OF TIDAL SURFACES

The present set of tidal surfaces in Canada is described by Forrester [1983]. It includes:

MWL	Mean Water Level: The average of all hourly water levels over the available period of record
HHWLT	Higher High Water, Large Tide: The 19-year average of the highest annual predicted high waters.
HHWMT	Higher High Water, Mean Tide: The average of all the higher high waters from 19 years of prediction.
LLWMT	Lower Low Water, Mean Tide: The average of all the lower low waters from 19 years of prediction.
LLWLT	Lower Low Water, Large Tide: The 19-year average of the lowest annual predicted low waters.
LNT	Lowest Normal Tide: In present usage in Canada it is synonymous with LLWLT. Its meaning is different in other countries.

MWL is directly calculated as the mean value of a number of hourly tide gauge recordings over the period of data availability. In contrast, the calculation of all other tidal surfaces requires the prediction of tidal variations over the 19 year period specified. In Canadian tidal waters, LLWLT is used as a datum surface for depth representation; HHWLT is used as the datum surface for the representation of land elevations and vertical clearances in coastal charts.

2.1.2 OTHER TIDAL SURFACES

In principle, there are infinitely many other tidal surfaces. Some of these are in use in other parts of the world:

LAT	Lowest Astronomical Tide: The lowest water level predicted for a 19 year interval. LAT is used as a Chart Datum in Great Britain.
MLLW	Mean Lower Low Water: The average of all the lower low waters over a specified 19 year period. MLLW is used as a datum surface for depth representation in United States tidal waters. MLLW is close to LLWMT, and always above LLWLT.
MLW	Mean Low Water: The average of all the low waters over a specified 19 year period. MLW was Chart Datum for the U.S. Atlantic coast before 1980. By definition, MLW can never be lower than MLLW

2.1.3 REPRESENTATION OF DEPTHS

Depths are shown on paper charts as the distance the seabed lies below Chart Datum. Chart Datum is variously defined as "that level below which the water will but seldom fall" [Forrester, 1983], or "a plane so low that the tide will not frequently fall below it" [Admiralty, 1977]. The official definition used by the Canadian Hydrographic Service is as follows:

> *Chart Datum is the plane of reference for soundings and is stated in the title of each chart. Supplementary information may be given in a table, note or graph. Chart Datum is the low water plane to which are referenced the depths of water over features permanently covered by the sea and the elevations of those features which are periodically covered and uncovered. Some low waters can be expected to fall below the Chart Datum. This only occurs under certain astronomical conditions, but, where the range of tide is small, meteorological disturbances may cause even average tides to fall below Chart Datum. In tidal waters the CHS uses the level of either Lower Low Water, Large Tide or Lowest Normal Tide as its reference plane for Chart Datum.* [CHS, 1992]

These definitions presume that all tidal records have been accumulated over a full 19 year cycle before Chart Datum is established.

For some countries (e.g. the United States), this is a reasonable presumption. Over 100 continuously operating tidal observation stations have been established along the coastline of the continental United States. The tidal behavior at temporary gauges operating between these permanent gauges can be inferred to be similar to that at the nearest permanent gauges. Procedures for transfer of Chart Datum from a permanent to such a temporary gauge are routinely used.

In Canada, the harsh operating conditions and inaccessibility of the Arctic Ocean and northern waters make establishment of any continuously operating gauge very difficult and expensive, and the variable tidal behavior of the Bay of Fundy and Gulf of St. Lawrence on the Atlantic Coast, and within the Strait of Georgia on the Pacific Coast, is only sparsely sampled by the Canadian network of permanent gauges. Therefore procedures for simple transfer of Chart Datum from permanent to temporary gauges are not as effective as in the United States. Rather, more modeling is required to supplement the short (typically 30-day) tidal time series from temporary gauges, in order to establish Chart Datum.

2.1.4 REPRESENTATION OF HEIGHTS

Hydrographic charts also display elevations for visible objects on land, the sighting of which may assist in navigation, and display the vertical clearances under possible hazards to navigation, such as bridges and power lines. "Near-worst-case" elevations and clearances are normally used - on Canadian Hydrographic Service charts these are normally given above Higher High Water, Large Tide (HHWLT) for tidal waters. However, in non-tidal waters, elevations and clearances are normally given above Chart Datum [CHS 1992]. Therefore, during flood conditions in a river, for example, the clearance under bridges and power lines will be MORE restricted than would be shown on the chart.

The issues surrounding the practical implementation of this Height Datum are similar to those for Chart Datum.

2.1.5 TIDAL ANALYSIS AND PREDICTION

The analysis and prediction of tides is generally based on the harmonic model. This model assumes that the actual tidal variations can be represented by the summation of a series of sinusoidal functions, each describing the departure of the water level from the Mean Water Level, due to particular tidal constituent, or forcing frequency. Thus the reference level for tides is Mean Water Level, the average of all the values in the time series available at the tidal station.

2.2 HYDROLOGICAL SURFACES

Hydrological surfaces are defined through water levels (or averages / maxima of these) in non-tidal waters.

2.2.1 PRESENT VERTICAL-REFERENCE SURFACES IN RIVERS

Chart Datum in rivers should also be a water level "below which the water but seldom falls". However in this case water level variations are usually not primarily due to tidal variations, but to seasonal variations in precipitation and runoff. On rivers dammed for hydroelectric power generation or flood control, the river water level both upstream and downstream of the dam will vary according to decisions made on flow rates through the dam or generator.

As well as these temporal variations at a point, the (spatial) slope of the river level will also depend on the topography of the river banks and the flow rate.

The reference surfaces used in rivers are based on elevations established for a set of reference points along the river. These elevations are established by analyzing water level records from gauges established for some period of time at each reference point. These discrete points are used to establish a the vertical-reference surface for the river by some form of interpolation. Two interpolation approaches can be (and are) taken.

The first approach creates a “stepped datum” by holding the elevation of the Chart Datum at a reference point constant throughout some “reduction zone” surrounding that point. The location of the “steps” between these reduction zones is usually mid-way between the reference points. Sometimes the step is at another explicitly defined location: for example a Chart Datum step occurs at the Mackenzie River constriction known as The Ramparts, even though it is not mid-way between two water level stations [Hare, 1995]. This approach may be appropriate where the steps are small, either due to a flat river slope, or closely-spaced reference stations.

The second approach is to assume a linear slope to the river, determined by fitting the slope to pass through the elevations at the reference points. This approach is used in most navigable rivers in Canada, and is appropriate where the size of steps using the first approach would be navigationally significant.

The practical implementation of Chart Datum on a river requires water level time series of some duration, perhaps 10 years, at a number of locations along the river. From the time series for each location, monthly means are computed. Chart Datum for a particular location, is the lowest monthly mean water level, for all months in the time series for that location. To provide water level information to the mariner somewhat equivalent to that provided by tide tables in tidal waters, the lowest, highest and average monthly means for each month in the year, averaged over the duration of the time series, are plotted as a "hydrograph" for each measurement station along the river, shown as heights above Chart Datum. The orthometric height of the Low Water mark can be obtained through levelling from a benchmark which has been tied to terrestrial vertical control.

2.2.2 OTHER VERTICAL-REFERENCE SURFACES IN RIVERS

Other hydrological reference surfaces in rivers can be defined as horizontal planes through reference points at heights different from the low water mark; e.g. a high water level defined analogously to the low water level.

More complicated reference surfaces are obtained as inclined planes passing through two subsequent low water marks along the river. Such reference surfaces would account for the (linear part of the) slope of the river surface, and thereby approximate the river surface more closely.

Further refinements of the reference surface are possible by taking into account the level of salinity at different locations along the river, and by also accounting for slopes in the river surface across the river profile.

2.2.3 PRESENT VERTICAL-REFERENCE SURFACES IN LAKES

Present reference surfaces in lakes are horizontal planes through reference points. Typically, per lake one such reference point is established at the Low Water mark, and the resulting Low Water surface serves as Chart Datum in that particular lake. An example for this is the International Great Lake Datum (IGLD) of 1985 [CCGLBHHD, 1992], which defines Chart Datum for the Great lakes and the upper St. Lawrence river. "Horizontal surface" in the present context means a surface of constant gravity potential, a level surface. Such a surface is not a surface of constant orthometric height.

2.2.4 OTHER VERTICAL-REFERENCE SURFACES IN LAKES

Other hydrological reference surfaces in lakes can be defined by level surfaces through reference points different from the Low Water mark. In principle, also surfaces of constant orthometric height can serve as reference surfaces in lakes. In this latter case, lines of constant depth in a hydrographic chart referred to this datum would be also lines of constant height in a topographic map.

2.3 EQUIPOTENTIAL SURFACES

Equipotential surfaces are surfaces of constant gravity potential V, i.e. the sum of the gravitational and the centrifugal potential of the earth. The gravitational potential of the earth depends on the distribution of mass density throughout the earth. This distribution undergoes changes over geological time scales, leading to similar changes in the geopotential and its equipotential surfaces. The centrifugal potential results from the rotation of the earth with respect to inertial space. This rotation undergoes minor periodical changes at all time scales, and also non-periodical changes over geological time scales. In the present context, i.e. the definition of a vertical datum for the next few centuries, these changes in the gravity potential are negligibly small. For all practical purposes, the equipotential surfaces therefore can be considered invariant with respect to time. Their descriptive equation is

$$V(x, y, z) = constant \tag{2.1}$$

x, y, z are geocentric Cartesian coordinates. Equipotential surfaces are by definition seamless and smooth, i.e. the surface and its spatial derivatives are continuous. They are globally defined surfaces and can therefore be used both for height representation over land areas and for depth representation at sea and in inland waters.

2.3.1 GEOID

The geoid is *The equipotential surface of the Earth's gravity field which best fits, in the least squares sense, mean sea level.* [NGS, 1986]. This definition in principle implies, that for the exact realization of the geoid the gravity potential and the mean sea level must be known all over the oceans. In practice, the average of mean sea level samples as observed by a finite number of tide gauges over finite time intervals is used to approximate the global mean sea level.

The practical representation of the geoid is not in terms of the numerical value of its gravity potential, but rather in terms of its separation from a reference ellipsoid which is usually chosen to be rotationally symmetric. This separation is referred to as the *geoid height N*, sometimes called geoid undulation or geoidal height. The geoid height is the height of the geoid above the reference ellipsoid. On a global scale, the geoid heights remain in the range $-100 \text{ m} < N < +100 \text{ m}$.

Such geoid approximations have been used in the past as the reference surface for the topography. The distance between the topography and the geoid, measured along the plumb line is the *orthometric height*, commonly called the height above sea level.

The accuracy of the geoid depends primarily on the correct knowledge of the gravity field of the earth. This gravity field is fairly well known in flat land areas and in continental shelf areas with extensive gravimetric measurements. It is known to a lesser accuracy in the open oceans, and in mountainous land areas. Correspondingly, the accuracy of the geoid varies between better than 10 cm and worse than one metre. A major portion of the geoid errors is of long wave length nature, i.e., it changes rather slowly with geographical position. As a consequence, the accuracy of the geoid height difference between two points will be generally better than the geoid accuracy at a single point.

The mean sea level undergoes secular and long periodic variations. Therefore the geopotential value associated with the geoid, and thereby the geoid itself are changing accordingly. In the present context, i.e. the definition of a vertical datum for the next few centuries, these changes in the mean sea level and the geoid will amount to 20 - 40 cm.

The geoid is described by its deviation from an appropriately chosen reference ellipsoid either in a closed mathematical form representing a continuous surface, or in terms of discrete geoid heights on a regular grid in longitude and latitude. Such a gridded geoid is available for the Canadian territory on a 5 arcminute grid [Mainville, 1994]. The grid values of the geoid height, together with an interpolation procedure approximate the geoid.

Closely associated with the geoid heights are the *deflections of the vertical*, the angles between the ellipsoidal normal and the direction of the gravity vector. The gravity vector is normal to the geoid. The deflection of the vertical are usually split into an east-west component, and a north-south component. The size of the deflections of the vertical can reach several tens of arcseconds in mountainous areas.

2.3.2 OTHER EQUIPOTENTIAL-RELATED SURFACES

Other equipotential surfaces of the gravity potential are based on a numerical value for the potential which is different from the potential value associated with the geoid. There are infinitely many such surfaces, completely enclosing each other and never intersecting. All such surfaces are related to the geoid in a purely mathematical sense. And this relation is not a simple one. It requires global integration.

Any such equipotential surface can be specified by either selecting a numerical value for its potential, or by requiring that it contains a particular point, e.g., a point on the shore line of a lake. The accuracy of any such a vertical datum is comparable to the accuracy of the geoid.

A reference surface that has been in use in many countries in the former Soviet Union's sphere of influence is the *quasigeoid.* It coincides with the geoid over the oceans and is above the geoid over land areas. The deviation from the geoid depends to a certain degree on the distribution of topographic masses, and can be up to a few metres in high mountains. Over land areas, the quasigeoid is not an equipotential surface.

2.4 MATHEMATICAL SURFACES

The geometry of mathematical surfaces is described through equations which do not necessarily relate to physical phenomena. The most general type of such a mathematical relation may be expressed by

$$F(x, y, z, \mathbf{p}) = 0 \tag{2.2}$$

x, y, z are geocentric Cartesian coordinates and $\mathbf{p}$ is a number of parameters specifying the exact shape of the surface. Requiring that the surface is seamless and smooth (continuous $F(x, y, z, \mathbf{p})$ and its first gradients) restricts the number of allowable surfaces (no reference cube allowed!). Requiring further that the mathematical surface follows, to a certain extent, the shape of the earth leads to a class of surfaces called *spheroids.* A spheroid is *any surface differing but little from a sphere* [NGS, 1986].

Different spheroids will be defined through different parameters $\mathbf{p}$, both as far as the number of parameters and their numerical values are concerned. These parameters are not depending on any physical phenomena and therefore the spheroid will not change if its physical environment changes.

Spheroids are globally defined surfaces and can therefore be used both for height representation over land areas and for depth representation at sea and in inland waters. The simplest spheroid is the sphere itself. A terrestrial reference sphere that globally best fits to the geoid would deviate from the geoid (and mean sea level) by about 10 km at the equator and the poles. Therefore the sphere seems to be inappropriate for a reference surface for hydrographic data.

2.4.1 REFERENCE ELLIPSOID

The spheroid with the least difference from the sphere is a geocentric bi-axial reference ellipsoid described by

$$\frac{x^2 + y^2}{a^2} + \frac{z^2}{b^2} - 1 = 0 \tag{2.3}$$

with the two parameters $\mathbf{p} = \{a, b\}$. The two equatorial axes are equal to a, and the polar axis b is shorter by about 1/300.

Reference ellipsoids can also be non-geocentric. In this case, the centre of the reference ellipsoid is shifted by an offset x_o, y_o, z_o with respect to the geocentre. Such non-geocentric reference ellipsoids have been chosen in the past to give a best local or regional fit to the geoid. An example is the North American Datum 1927 (NAD27) reference ellipsoid with approximate values for the offsets $x_o \approx$ -9 m, $y_o \approx$160 m, $z_o \approx$ 176 m.

The reference ellipsoid fitting the geoid best in a global sense is always geocentric. A properly chosen bi-axial geocentric reference ellipsoid like the one underlying the North American Datum 1983 (NAD83) approximates the geoid within ± 100 metres.

A reference ellipsoidal surface is *realized* by assigning ellipsoidal coordinates to a selected number of reference points. Various realizations are presently in use including the series of World Geodetic Systems (WGS) as determined and maintained by the U.S. Defense Mapping Agency (DMA), with its most recent realization being the WGS84, and the reference ellipsoid underlying NAD83.

At the top of the hierarchy of such realizations are those produced by the International Earth Rotation Service (IERS). This is a series of realizations called the IERS Terrestrial Reference Frame (ITRF), each of which attempts to achieve the highest accuracy, and which is updated annually.

These solutions are based on four kinds of measurements — Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), and GPS — made at over 100 stations distributed around the world. Tectonic plate motions are both measured and modeled. Coordinate values of the ITRF stations are established with an uncertainty of less than 5 cm. The most recent ITRF realization is ITRF93.

2.4.2 OTHER MATHEMATICAL SURFACES

A general representation of spheroids can be obtained using a spherical harmonics representation of the geocentric distance of the spheroidal surface as a function of spherical latitude and longitude. Such a representation describes the geocentric distance of a surface point as a function of its spherical coordinates and reads:

$$r(\varphi,\lambda) = R + \sum_{n=2}^{N} \sum_{m=2}^{n} P_{nm} (\cos\varphi) [A_{nm} \cos m\lambda + B_{nm} \sin m\lambda] \tag{2.4}$$

where

$r(\varphi,\lambda)$ is the geocentric distance of the spheroid

R is the radius of a mean sphere

φ is the spherical geographical latitude

λ is the geographical longitude

P_{nm} are associated Legendre functions [Abramowitz and Stegun, 1964] of degree n and order m

A_{nm} and B_{nm} are numerical constants

N is the degree of the spheroidal surface.

Different sets of numerical constants describe different spheroids. The bi-axial geocentric reference ellipsoid belongs to a subset of spheroids obtained by omitting all B_{nm} and retaining only the A_{nm} of even degree n and zero order m, and by extending the summation up to infinity according to:

$$r(\varphi,\lambda) = R + \sum_{n=2}^{\infty} A_{no}\, P_{no}\,(\cos\,\varphi) \qquad (2.5)$$

Spherical harmonics representations according to equation (2.4) can be used to approximate any spheroidal surface. In particular, the geoid can be approximated through an appropriate choice of the constants A_{nm} and B_{nm}. Such sets of constants for the approximation of the geoid are available from various sources.

The closeness of approximation is directly related to the degree N of the spheroidal surface. Low degree ($N = 20$) spheroids approximating the geoid have been determined from measurements to artificial satellites [Vaníček and Krakiwsky, 1986]. The maximum deviation of such surfaces from the geoid and the mean sea level is less than 10 metres. More recently, the coefficients of approximating spheroidal surfaces of very high degrees ($N = 360$) have been computed. Maximum deviations of these high degree surfaces from the geoid are of the order of several metres. Generally, the higher the degree, the less the spheroid departs from the geoid. Remaining differences are caused by insufficient accuracy and insufficient coverage of the gravity data used in the approximation.

It should be noted that the amount of numerical computations for the evaluation of equation (2.4) increases rapidly with increasing degree N, thereby limiting the feasibility of high degree spheroids as a reference surface.

2.5 VERTICAL-REFERENCE SURFACES ON LAND

On land we use topographical heights (heights of the earth topography) which are referred to one of the following reference surfaces: the geoid, quasigeoid, or a reference ellipsoid. The first surface, the geoid, is one of the equipotential surfaces of the earth's gravity field, selected so that at sea, it approximates most closely the mean sea level (MSL). This is why the heights, referred to this surface (the "orthometric heights" H) are known as "heights above mean sea level". These heights are used almost exclusively in mapping and they are the quintessential practical heights. They show the height of the (mean) coastline to be equal to zero — up to the difference between the geoid and the MSL. (This difference is called "sea surface topography" (SST), a term that mimics the "land surface topography" at sea.) To see the coastline associated with a zero height is what practically all the users of heights are accustomed to.

We note that other kinds of heights, such as "dynamic heights" or "geopotential numbers", are also referred to the geoid. Dynamic heights are used in special applications such as hydrological studies, oceanography, etc. Geopotential numbers are used in theoretical geodesy where they are thought of as being the generic heights.

In the countries of the former Soviet sphere of influence, quasigeoid is used as a reference surface for heights instead of the geoid. Quasigeoid coincides with the geoid at sea but under the land it may deviate from the geoid by as much as a few metres. Under the land, quasigeoid is not an equipotential surface; rather, it is defined in an artificial way which, some theoreticians believe, makes the quasigeoid somewhat easier to compute. Quasigeoid serves as a reference surface for heights known as "normal heights" H^n. Normal heights serve the same practical purpose as orthometric heights do; they can be regarded as heights above sea level (or mean sea level) the same way as orthometric heights are. It is questionable if normal heights will ever be used on this continent but the possibility should not be ruled out completely.

The last reference surface for heights on land is a reference ellipsoid, also called a horizontal datum or a reference spheroid — the latter terminology should be avoided since a spheroid (a sphere-like body or surface) is a more general term used for other sphere-like bodies or surfaces. The heights referred to a reference ellipsoid are measured along the normals to the ellipsoid and are called "geodetic heights' or "geometric heights" or simply "heights above the reference ellipsoid". These heights have no relation to reality; geodetic heights of a coastline may vary from — 100 metres to + 100 metres and they are not heights above the sea level. This makes the geodetic heights unacceptable for practical use. They are used, however, in transforming three-dimensional Cartesian coordinates obtained by satellite or other non-terrestrial positioning to the curvilinear geodetic coordinates, i.e., latitude ϕ, longitude λ, and geodetic height h, and vice versa. In the future, the Geodetic Survey Division (GSD) intends to make available the geodetic heights of points precisely positioned by GPS. These heights will be referred to NAD83 [GSD, 1995].

There is a very simple relation between geodetic and orthometric heights. As we have already mentioned, geodetic heights are measured along ellipsoidal normals and orthometric heights are measured along the vertical lines of the earth gravity field. These two directions are almost identical and the difference between the two kinds of heights is nothing else but the difference between their respective reference surfaces, i.e. the so called “geoid / reference-ellipsoid separation” or simply the “geoid height” N above the reference ellipsoid. We thus have:

$$H = h - N \tag{2.6}$$

The geoid height is becoming quite well known. The standard deviation of a global geoid model (N given as a function of ϕ, and λ globally) is better than 1 metre. Regional solutions are usually much better, particularly at the sea level. There, even when the total value of N may have an error of a few decimetres, the geoid height differences ΔN, which are more important for applications, would be known with a sub-decimetre error.

2.5.1 LAND-BASED HEIGHT CONTROL

For mapping and other uses, geodesists have established networks of (control) points on land, the accurate orthometric heights of which are known. These points, known as "levelling benchmarks", have been surveyed by geodetic levelling. This technique guaranties a very good accuracy in height differences; in Canada, orthometric height difference ΔH of two first-order benchmarks S kilometres apart should be good to between 0.9 mm * $\sqrt{S}$ and 1.3 mm * $\sqrt{S}$ — one standard deviation reflecting random errors.

The main problem with orthometric heights of benchmarks in Canada is the way the levelling network is referred to the geoid, i.e. the sea surface topography (SST). This should be done in theory by a set of fundamental tide gauges at which the MSL height can be determined from the analysis of long-term records. These MSL heights should then be corrected for the SST to give us the elevation of the geoid at the location of these tide-gauges [Vaníček, 1991: see external appendix]. The MSL heights that define the datum of the levelling network, the Canadian Vertical Geodetic Datum of 1928 (CVGD28), to which the published orthometric heights refer, are not corrected for SST. SST was not known in 1928 and even now is known only at few places in Canada. Even the latest adjustment of the Canadian levelling network (which is still going on and was initiated as part of the North American Vertical Datum of 1988 (NAVD 88) project) can not yet be corrected for SST. Efforts at the GSD are directed at improving the modeling of the geoid and at determining SST using GPS and the geoid model. Details are found in GSD [1995].

The datum for land topography used up to now (MSL at gauges) doesn't extend itself away from the levelling network. That is why the future of land-based height control is also to connect the levelling network to the reference ellipsoid surface using GPS and use the geoid model to extend the datum away from the levelling network [GSD, 1995]. It can be seen that GSD has some of the same needs has CHS, the knowledge of the geoid and SST.

It should be emphasized that the NAVD 88 heights are not adopted in Canada (while they are adopted in the United States). They will be adopted in Canada only when proven to provide more accurate heights than the official heights referring to the Canadian Vertical Geodetic Datum of 1928 (CVGD 28). One of the requirements is to determine SST. The main problem is determining accurate SST and an accurate geoid model.

A preliminary determination of SST using only the levelling network was obtained in the latest adjustment of the Canadian levelling network (NAVD 88 project). One gauge, that at Pointe au Père near Rimouski, Québec, was held fixed to determine the height of the other gauges all around Canada. The MSL (actually the mean river level) of the St. Lawrence River at Pointe au Père was chosen to define the zero height, i.e. to coincide with the geoid. As SST and a worldwide geoid model becomes available as described in GSD [1995], this value, the zero height, can be revised accordingly. Actually it is known to be about 10 cm above the MSL in Halifax, N.S. and 20 cm above the MSL in Yarmouth, N.S. [Merry and Vaníček, 1983] and thus presumably, about the same amount above the MSL of North Atlantic Ocean. This elevation of 10 to 20 cm should be considered to be a part of the SST at Pointe au Père; the values of SST at Halifax and Yarmouth are not yet known. The sum of these two values, one known and one unknown, should be added to all heights obtained in NAVD 88 to make them referred to the geoid.

The other problem with the Canadian levelling network is the presence of systematic errors [GSD 1995; Vaníček, 1995: see external appendices]. The NAVD 88 results show, for instance, that the height of the zero-mark of the tide gauge in Prince Rupert, B. C. is about 180 cm above the MSL at Pointe au Père [Zilkoski et al., 1992], i.e. some 200 cm above the MSL at Yarmouth. This height difference is impossible to explain by the difference in the SST at the two places [Maul, 1994] and the explanation must be sought in the presence of systematic errors. We note that the random error over the distance between Saint John and Prince Rupert should not amount to more than some 15 cm — one standard deviation.

2.6 REFERENCE SURFACES FOR OTHER PURPOSES

Topographical heights and bathymetry are not the only kinds of information that have to be based on a reference surface. As noted in §2.2, the sea level, mean or otherwise, used in oceanography, is normally referred to the geoid — this is the SST we have been talking about earlier. Hydrological studies of the Great Lakes behavior also use the geoid for a reference surface.

Perhaps we should mention one specific application here, i.e. that of marine boundary delimitation. According to UNCLOS III [United Nations, 1983], the selection of straight baseline turning points is based on bathymetric data referred to a low water level reference surface. This reference surface is usually defined locally; yet there is a perceived need to use heights, or height differences determined by satellite positioning techniques such as the GPS in determining heights of these turning points. Consequently, there is a movement among the professionals interested in marine boundary delimitation to tie the turning points to a global datum [Vaníček, 1994]. This global datum will probably be the geoid.

The geoid is also used as the reference surface in the investigations of earth gravity field. This geoid is however defined differently from the geoid we have been talking about. It is understood as the equipotential surface that has a specified value of potential, W_0. This potential value W_0 is, to be sure, selected so that the geoid follows approximately the MSL, but the tie with the MSL is not of primary importance in this context. As a result, the two geoids behave differently in the temporal sense. While the geoid defined through the MSL changes with the eustatic rise of the MSL [Emery and Aubrey, 1991] as well as with the internal redistribution of masses, the geoid defined by W_0 changes only in response to the latter.

Which brings us to the temporal aspect of reference surfaces. Description of temporal (historical or contemporary) behavior of MSL and topography (crustal motion studies) also require a selection of reference surfaces. In both cases, geoid, either instantaneous or fixed in time, is normally used.

The contemporary behavior of MSL seems to be of an intense interest nowadays, because it is the only reliable indicator of the global budget of water in liquid form. This budget, in turn, is one of the best indicators we have on secular climatic changes deemed responsible for the "global change". We note that these MSL changes (eustatic) are relatively minute, somewhere between 1 and 2 mm per year. Hence the accuracy with which the pertinent data have to be acquired has to be relatively high, higher than that required by the standard hydrographic practice.

To study the global temporal behavior of MSL one needs a reference surface fixed in time. The geoid fixed in time would appear to be a good choice for the reference surface.

3. TRANSFORMATION ISSUES

In this chapter we discuss how we can move between several surfaces which are vertically separated from each other. These surfaces include the following:

- The surface represented by the present set of Chart Datums.
- A seamless vertical-reference surface which is the subject of this report.
- The time-varying shape of the water surface.
- The Mean Sea Level surface.
- The geoid.

These discussions consist in identifying the transformations between these surfaces. We consider that each transformation is defined by an associated *transformation function* , which is used to execute the transformation.

These transformation functions can take several forms: perhaps a set of analytical functions (for example a set of harmonic tidal constituents), or a set of observed values (for example readings from a tide staff), or numerical values from some other source. Combinations of these forms also occur.

Eventually each transformation function will be *evaluated*, that is the set of numerical values to be used will be determined. For analytical transformation functions these numerical values are obtained by evaluating the known functions for a given position and / or a given time. For transformation functions which are already in numerical form, evaluation often requires some kind of spatial or temporal interpolation between the values given in a table.

Evaluation of a particular transformation function may result in a single constant value (for example a shift in Chart Datum at one station), or a single time series (for example the transformation from instantaneous sea level to Chart Datum at a single point, for a set of specified time epochs), or a set of values which are constant in time, but represent spatial variations (for example the transformation from all Chart Datums in Canada to a seamless vertical-reference surface), or a set of values which represents the time-varying shape of a surface (for example the changing shape of the water surface).

Towards the end of this chapter, we consider some additional kinds of transformations, between horizontal datums.

3.1 VERTICAL-REFERENCE SYSTEM TRANSFORMATION CONCEPTS

The information (depth or height) referred to a specific reference surface should be transformable to another reference surface. Any such transformation involves the vertical displacement of the two reference surfaces. A transformation we have already discussed is from a height above the geoid to a height above the reference ellipsoid. The vertical displacement in this case is the displacement of the geoid with respect to the reference ellipsoid, i.e. the geoid height N.

Since the reference ellipsoid is considered fixed in time, and the geoid changes only very slowly with time (a few millimetres per year at most), the "transformation function" N can be considered to be a function of only the horizontal position:

$$N = N(\varphi,\lambda) \tag{3.1}$$

When one of the reference surfaces changes with time more rapidly (e.g. the instantaneous sea level surface) then the transformation function becomes also a function of time. For instance, the water level above the Chart Datum, w^c, can be considered to be the transformation function from the instantaneous sea level reference surface to the Chart Datum. This function must be considered a function of not only the horizontal position, but also of time:

$$w^c = w^c(\varphi,\lambda,t) \tag{3.2}$$

3.2 CHART DATUM TO A SEAMLESS DATUM

In this section we consider the transformation needed to establish a seamless vertical-reference surface, given the present set of Chart Datums.

The present reference surface for bathymetry is the Chart Datum. In Canada this is LLWLT, as defined by a time series from a local tide gauge (often temporary). Chart Datum is considered fixed in time (except for changes due to eustatic and isostatic changes), but is spatially discontinuous at the border between two local tide gauge neighborhoods. As the name implies, a new "seamless" reference surface should be both fixed in time, and have no such spatial discontinuities.

Then the transformation function T from the present reference surface (Chart Datum) to such a seamless reference surface will also be spatially discontinuous, but not a function of time:

$$T = T(\varphi,\lambda) \tag{3.3}$$

The determination of this transformation function will be the major task in switching to the new seamless reference surface. The ease with which this function can be determined will be one of the main criteria in selecting the most appropriate seamless reference surface.

Once the transformation function T is known (for all φ,λ), bathymetric data, $b^c(\varphi,\lambda)$, referred to Chart Datum can be transformed to refer to the seamless reference surface by the following simple equation

$$b^s(\varphi,\lambda) = b^c(\varphi,\lambda) + T(\varphi,\lambda) \tag{3.4}$$

3.3 SEAMLESS SURFACE TO CHART DATUM

In this section we consider the transformation required to extract information from a digital bathymetric database which uses a seamless vertical-reference surface, and to provide users with the same kind of depths they now find on paper charts — depths below Chart Datum.

The transformation function T in equation (3.4) is required to convert the existing bathymetry to a seamless database.

However, in order to be able to draw upon this seamless database for the maintenance and production of existing paper charts, we must be able to "undo" this transformation, using the inverse transformation (– *T*). Therefore, *T* (or its inverse) must be retained for continual use. This does not preclude maintenance (improvement, correction, extension) of *T*. In fact, it is our contention that such maintenance will be facilitated, not impeded, by using a seamless vertical-reference surface.

The transformation function *T* is **not** required for new surveys based on a seamless vertical-reference surface. However, the inverse transformation function – *T* will still be required, to allow this new data to be used to produce paper charts, or to verify the content of existing paper charts.

3.4 CHART DATUM TO SEA LEVEL

In this section we consider the transformation required to convert depths below Chart Datum into depths below (instantaneous) sea level.

The common source of information about instantaneous sea level, in tidal waters, is from Tide Tables. These tables represent one example of the transformation from the present vertical-reference surface (Chart Datum) to instantaneous sea level:

$$w^C = w^C(\varphi,\lambda,t) \tag{3.5}$$

Other implementations of this transformation, in tidal waters, are available from commercial tide-prediction software programs, for example.

Mariners use this transformation, together with charted depths, to obtain more realistic keel-clearance information than using the chart alone:

$$d(\varphi,\lambda,t) = b^C(\varphi,\lambda) + w^C(\varphi,\lambda,t) \tag{3.6}$$

For non-tidal waters (rivers and lakes), $w^C(\varphi,\lambda,t)$ is not as easily modeled as for tidal waters, and is therefore not as accessible as the Tide Tables. However, where conditions warrant, it is possible to provide users with this transformation along rivers or in lakes as well.

3.5 SEAMLESS SURFACE TO PREDICTED SEA LEVEL

In this section we consider the transformation required to move directly from a digital bathymetric database which uses a seamless vertical-reference surface, to provide users with depths below (instantaneous) sea level, where no real-time water level sensor data is available. The transformation must therefore be based on models and predictions driven by historical records of water level variations.

For some mariners, it is important to know the depth referred to instantaneous sea level. To present the mariner with the information needed, depths (bathymetry) referred to the seamless reference surface in the database have to be transformed to the reference surface of the instantaneous sea level. The transformation function, $w^S(\varphi,\lambda,t)$, the instantaneous water depth / height with respect to the seamless reference surface, is a function of not only the horizontal position but also of time:

$$w^s(\varphi,\lambda,t) = w^c(\varphi,\lambda,t) - T(\varphi,\lambda) \tag{3.7}$$

Bathymetric data based on the seamless reference surface can then be referred to the instantaneous sea level reference surface — giving the instantaneous water depth, $d(\varphi,\lambda,t)$, the mariner needs — by the following equation:

$$d(\varphi,\lambda,t) = b^s(\varphi,\lambda) + w^s(\varphi,\lambda,t) \tag{3.8}$$

For most applications, $w^s(\varphi,\lambda,t)$ will be determined from *predictions* based on tidal, hydrological and other models. In this case we denote it as $w^s{}_p(\varphi,\lambda,t)$ and rewrite equation (3.8) as:

$$d(\varphi,\lambda,t) = b^s(\varphi,\lambda) + w^s{}_p(\varphi,\lambda,t) \tag{3.9}$$

3.6 SEAMLESS SURFACE TO INSTANTANEOUS SEA LEVEL

In this section we consider the transformation required to move directly from a digital bathymetric database which uses a seamless vertical-reference surface, to provide users with depths below (instantaneous) sea level, where real-time water level sensor data is available. The transformation will therefore be based on models and predictions driven by real-time measurements of water level variations.

For some critical applications, the historically-predicted instantaneous sea level $w^s{}_p(\varphi,\lambda,t)$, may not be accurate enough. If available, a value actually observed in real time, $w^s{}_a(\varphi,\lambda,t)$, can be used instead. Then the instantaneous water depth can be determined as:

$$d(\varphi,\lambda,t) = b^s(\varphi,\lambda) + w^s{}_a(\varphi,\lambda,t) \tag{3.10}$$

In practice, it may be that the difference between $w^s{}_p(\varphi,\lambda,t)$ and $w^s{}_a(\varphi,\lambda,t)$ is smaller than the value of each. In such cases it may be advantageous to use a correction to $w^s{}_p(\varphi,\lambda,t)$, rather than replacing it entirely:

$$\Delta w^s(\varphi,\lambda,t) = w^s{}_p(\varphi,\lambda,t) - w^s{}_a(\varphi,\lambda,t) \tag{3.11}$$

Then equation (3.10) changes to:

$$d(\varphi,\lambda,t) = b^s(\varphi,\lambda) + w^s{}_p(\varphi,\lambda,t) + \Delta w^s(\varphi,\lambda,t) \tag{3.12}$$

In some critical applications, knowledge of the instantaneous water depth is needed up to an hour ahead of time. Under this circumstance, we can no longer talk about an instantaneous depth, but we may still be able to improve on the value $w^s{}_p(\varphi,\lambda,t)$ predicted from measurements taken in the past by evaluating at least a predicted value of the correction $\Delta w^s{}_p(\varphi,\lambda,t)$ based on some more recent information. The desired water depth then results from an extrapolation forward both in time and in vessel position:

$$d_p(\varphi,\lambda,t) = b^s(\varphi,\lambda) + w^s{}_p(\varphi,\lambda,t) + \Delta w^s{}_p(\varphi,\lambda,t) \tag{3.13}$$

which would be the most accurate solution we can come up with.

A mariner wishing to use instantaneous water depths for navigation, must also account for ship's draught, and changes in ship's draught. The "draught" of large vessels can have complex behavior — being affected by the depth of water under the vessel, even the shape and composition of the seabed. As well, such large vessels will drag a large parcel of water along with them which will be similarly affected by seabed interactions, so that any "local" draught measurement may not represent the true change in the vertical position of the vessel with respect to an undisturbed water level [Loncarevic, 1995]. Further discussion of these issues is beyond the scope of this report.

3.7 TRANSFORMATIONS BETWEEN HORIZONTAL DATUMS

Horizontal positions (φ,λ) in North America are reckoned either on the North American Datum of 1927 (NAD 27) or on the North American Datum of 1983 (NAD 83). It is thus necessary to know, which datum are the geodetic coordinates (φ,λ) of the point of interest referred to. The two pairs of coordinates, referred to the two datums, may differ by as much as several arc-seconds, indicating an apparent position shift — the shift is only apparent because there is, of course, no real position shift involved — of up to a few hundreds of metres. If the appropriate horizontal datum for the coordinates of the point of interest is not indicated, then the horizontal position given by these coordinates is good only to a few hundreds of metres.

A position given on NAD 27, $(\varphi,\lambda)_{27}$, may be transformed into the corresponding position on NAD 83, $(\varphi,\lambda)_{83}$, by applying the appropriate transformation equations. These equations consist of two parts:

- the transformation from the reference ellipsoid of NAD 27 to the reference ellipsoid of NAD 83, involving the "datum transformation parameters"
- a correction to the transformed position due to the deformation (systematic errors) of the original geodetic network of points $(\varphi,\lambda)_{27}$ on NAD 27.

Transformation software for Canada which implements equations for both these steps is available from the Geodetic Survey Division, and is described by Junkins [1991].

The NAD 83 represents a geocentric reference ellipsoid, which for all practical purposes coincides with the geocentric reference ellipsoid of WGS 84 and that of GRS 80. Horizontal, as well as vertical positions determined by GPS, are referred to WGS 84 and thus to NAD 83. There is no transformation required between the GPS determined horizontal coordinates and the existing coordinates referred to NAD 83.

3.8 TRANSFORMATIONS OF GEODETIC HEIGHTS BETWEEN HORIZONTAL DATUMS

It is difficult to imagine the set of circumstances under which such a transformation would be required. Geodetic heights, h, above the NAD 27 reference ellipsoid have never been determined. They have not been needed in the past, and there is no real need for them now, other than for distance reduction from the earth surface to the reference ellipsoid. Ellipsoidal heights are a direct product of 3D position determination by satellite and other space methods and are quite easily and most naturally referred to a geocentric horizontal datum such as the NAD 83 reference ellipsoid.

On the other hand, the horizontal positions of most of the existing CHS bathymetric data (and charts) holdings are referred to NAD 27. It would be dangerous, to have the horizontal positions and geodetic heights referred to two different datums. In principle, the transformation of geodetic heights from one horizontal datum to the other is simple. It only requires a knowledge of accurate values of the datum transformation parameters. But such accurate values are not known: the existing transformation parameters had been derived from deformed *horizontal positions* without consideration of heights. The use of the transformation equations for transforming horizontal positions cannot be recommended for the transformation of heights, because these equations contain the model for local *horizontal* deformation of the old horizontal terrestrial geodetic control network. These deformations would result in local vertical deformations (aliases) of the horizontal datum (we would have a corrugated ellipsoidal surface) with unfortunate consequences.

The solution is to use the geodetic heights referred to the NAD83 reference ellipsoid together with horizontal positions on NAD83. This would imply the necessity to systematically transform all the existing horizontal positions to NAD83 first.

Recommendation 2: The horizontal and vertical coordinates of data being placed in an ENC database should be consistent, and both should be referred to NAD 83 before being entered into the database.

4. SELECTION OF A SEAMLESS VERTICAL-REFERENCE SURFACE

In this chapter we first discuss the various criteria to be considered in selecting a seamless vertical-reference surface for hydrographic digital bathymetric databases.

We then propose a surface which, in our opinion, best meets these criteria.

4.1 CRITERIA FOR SELECTION OF A NEW REFERENCE SURFACE

The criteria which are relevant for selection of a seamless vertical-reference surface fall into two classes: those which are directly related to the operation and maintenance of a hydrographic digital bathymetric database, and those which are related to the effectiveness and reliability of the end-product presented to end-users of the information in the database.

As we will see later in this chapter, the first class of criteria leads to selection of an ellipsoid as the "best" vertical-reference surface to be used within the database itself.

However, the second class of criteria leads to the strong recommendation that this ellipsoid NOT be used in displaying information to end-users. A variety of other surfaces are suggested, each specifically tailored to the needs of a particular group of end-users. Transformations between the database vertical-reference surface, and the surfaces available to these end-users must become part of the overall system.

We discuss the end-user related criteria first, then turn to the criteria directly related to database issues.

4.1.1 NAVIGATION SAFETY

In a general sense, the most important type of information to the mariner is all information which may have an influence on navigation safety. The way in which critical information is delivered — its simplicity, freedom from ambiguity, and reliability — are as important as the information content itself.

In a more specific sense, related to the topic of this report, the most important type of information to the mariner is the depth of water under the vessel keel. However depth under the keel is information which is delivered too late if it refers to the vessel's current position (particularly if the depth is insufficient for safe passage).

To be most effective, depths need to be projected ahead of the vessel's current position (both a spatial and temporal transformation) by at least the interval required to manoeuvre the vessel, and preferably by an interval sufficient to allow safe and efficient route planning. In order to prevent confusion and mis-interpretation, such predictions must be based on the same vertical-reference surface and set of transformations as is used for the ENC database.

4.1.2 ACCURACY OF FINAL DEPTH PRESENTATION TO MARINERS

When the depths presented to the mariner are very conservative, such as depth below Chart Datum, then their "accuracy" is not the issue. They are by definition **inaccurate**, representing a near-worst-case value. At each stage in the processing of such depth values, the policy is to "shoal-bias" the value whenever there is some choice to be made. However, these depths are **reliable**, in the sense that the actual depth "should but seldom fall below" the depths presented: almost always, there will be more water available for safe navigation. If this limitation is acceptable to the mariner, then this is an appropriate way of representing depths. This is the tradition for paper chart presentations.

As a criterion for selection of a seamless vertical-reference surface, the capability must be retained for representing depths in this conservative way, referred to the same Chart Datums as have been used in the past, if only to maintain the capability of producing paper charts which have some uniformity with those which are now available. Maintaining this capability means maintaining the transformation function used to move between Chart Datum and the seamless vertical-reference surface.

There are good reasons for having the capability of representing the bathymetry with respect to both a reference ellipsoid, and the geoid. Assuming that either a reference ellipsoid or an approximation to the geoid is selected as the seamless vertical-reference surface, then the transformation between that seamless datum and the other of these two surfaces (reference ellipsoid or geoid) must also be maintained.

However, some critical users pay an economic penalty for this conservative approach. They need water depths which more closely represent the depth of water which will actually exist as they pass through a channel or up a river. In this case the accuracy of depth presentation becomes a much more important issue. Procedures and assumptions which are acceptable when shoal-biasing is used are no longer sufficient. A much more careful accounting must be made of factors which may influence the accuracy of depth presentation. Some of these factors are:

- Limitations in the bottom detection resolution of the echo sounder used in the hydrographic survey.
- Limitations in echo sounder bottom detection due to the presence of suspended sediments near the bottom (e.g. mud lenses).
- Limitations of the acoustic velocity profile used to convert the echo sounder travel time into a depth data point.
- Limitations of the sensors used to monitor water levels during the survey.
- Limitations in the assumptions made about the relationship between long wave period water level variations (such as tide and river flow) observed at the sensor, and those variations actually occurring at the survey vessel.
- Limitations in the sensing of local, or short wavelength, water level variations at the survey vessel (such as heave).
- Limitations in the sensing of changes in the vessel draught.
- Limitations in the monitoring of vessel roll, pitch and heading, particularly for modern surveys using multibeam sonar.

- Limitations in the effectiveness of eliminating "bad" depth data points (and no others) from sets of measured depth values.
- Limitations in the extent of coverage of the seabed (less than 100%), necessitating some conservatism in sounding selection.
- Limitations in the methods for selecting soundings, either for retention in a digital database, or for inclusion in an ENC, or for presentation to the mariner.
- Limitations in the methods used for contouring depth data points.
- Limitations in the methods used to transform measured water depth data points to refer to a time-invariant vertical-reference surface, that is to bathymetry.
- Limitations of the sensors used to monitor water levels, used to derive water depths for presentation to the mariner.
- Limitations in the assumptions made about the relationship between long wave period water level variations (such as tide and river flow) observed at the sensor, and those variations actually occurring at the mariner's vessel.
- Limitations in the sensing of local, or short wavelength, water level variations at the mariner's vessel (such as heave).
- Limitations in the sensing of changes in the mariner's vessel draught.
- Limitations in the methods used to transform bathymetry to instantaneous water depths to be presented to the mariner.
- Limitations in the methods used to present these water depths to the mariner.

As a criterion for selection of a seamless vertical-reference surface, we must take into account the effect of this selection, of the transformations associated with this selection, and the reliability with which these transformations can be implemented, in either reducing or exacerbating these many present limitations.

4.1.3 CONSISTENCY ACROSS LAND-SEA BOUNDARY

Here again, we should separate quite strictly the requirements on the datum used for data storage and on the one used for data display. Once again, when the appropriate transformation functions become available, the datum for data storage could be selected on the basis of simplicity, and the ease of realization and maintenance.

For the bathymetry / height data display it is indeed desirable to have the datum unified, to avoid an appearance of a step along the coastline. This desirability is particularly clear for coastal zone management, but not limited to this application alone. If the coastline is understood to be related to some high water level (or some low water level), then its height will differ from the geoid (geodetic zero height) by roughly half the tidal range. If the coastline in defined as the intersection of Mean Sea Level with the land, then its height will differ from the geoid by the Sea Surface Topography. It seems desirable to use the geoid as the data display datum because for this datum, one of the contour lines of the displayed bathymetry/height data would coincide with the coastline.

4.1.4 SEAMLESSNESS

Once we accept the idea that no ordinary user will be allowed to access the raw data, it does not seem to matter too much if the datum for the **stored** data is seamless. The main issue is that the bathymetry the user gets, be referred to a seamless datum. Any of the reference surfaces discussed above is seamless.

The advantage of the datum in which the bathymetry is **displayed** being seamless, appears to be so self-evident that it does not require any discussion. In other words, once we have the means to realize a seamless datum (always only for the display) it would seem ludicrous to even think of a datum plagued by discontinuities (steps).

4.1.5 EASE OF REALIZATION AND MAINTENANCE

Here we should distinguish between realization and maintenance of the database and that of the transformation functions. The realization of the bathymetric database is really equivalent to the formulation of the transformation function $T(\varphi,\lambda)$. The formulation of this transformation function is going to be a major task and the practicalities of this task are discussed in Chapter 6. After the database is in place, its maintenance is going to be relatively routine, consisting of correction of evident errors and registration of actual changes in bathymetry and, of course, addition of newly acquired bathymetric data. This should not be understood as saying that this maintenance will be easy, merely that the maintenance problems will be more or less the same as they have been up to now.

The realization of the other transformation functions, i.e. the transformation functions that the user is going to need to get the raw data in the desired form (referred to the appropriate reference surface), will again require a considerable effort. Depending on which transformations will be built into the system, the formulation of these functions may require an acquisition of quantities not readily available anywhere, e.g., the SST, the eustatic water rise rate, the instantaneous sea level heights, etc. Some of these quantities may, initially, be known only very approximately.

The maintenance of the retained (and realization of new) transformation functions will consist of improvements to their accuracy. As new observations and new data sources become available, the transformation functions will be formulated more accurately, both in the spatial and temporal sense. This is where the real challenge will be. This could become an important part of the mandate of the CHS in the future.

4.1.6 STABILITY VERSUS QUALITY

Like most datum issues, a balance must be struck between:

- Stability: it could require a lot of work to revise existing charts, digital files, databases or publications after adopting a new vertical datum strategy, and
- Quality: replacing the present isolated, non-uniform tidal datums with a seamless vertical-reference surface of known quality; providing the mariner with more accurate water depth information than is possible at present.

The selection of a seamless vertical-reference surface, of the transformations associated with it, and of the way in which these transformations are implemented, should be done in such a way to retain both stability (for the low and medium complexity end users), and enhance quality (for the critical end users).

4.1.7 DIGITAL DATABASE ISSUES

A large bathymetric database should contain data (bathymetry) which do not change over time, except for correcting real errors in the original data and recording real changes in bathymetry. These exceptions fall under the general category of "database maintenance" and should be understood as the inevitable changes faced by any database operator.

> **Recommendation 3**: Bathymetric data placed in an ENC database should be referred to a vertical-reference surface that does not change in time, such as one of the mathematically defined reference surfaces, for example a reference ellipsoid.

Practically, the geoid (defined in either of the two ways shown above) could also be used for this purpose since its temporal variations are slow and small, the variations of the geoid defined by W_O being slower. Alternatively, a geoid fixed at a selected epoch could be used. However, the geoid is not known accurately. We would have to use an approximation to the geoid. This approximation would change (improve) as data improves.

The transformation functions of different kinds will have to be stored in one form or another. These will be numerical tables ordered according to horizontal positions, parameters in functional prescriptions, temporal variability descriptors, etc.

In addition to the database itself, these transformation functions may require considerable maintenance (updating). The maintenance of the transformation functions may even be, conceptually and intellectually, a more demanding task than the maintenance of the bathymetric data themselves. Although there may be some time variations in the transformations, the main reason for this maintenance effort is to improve and update the transformations, as additional measurements are accumulated, and better understanding is reached. For example, the relationship between some Chart Datums and the seamless vertical-reference surface may not initially be precisely known. There is an ongoing effort to better define the relationship between the geoid and the reference ellipsoid. As these relationships become better defined, the transformations should be improved (maintained).

> **Recommendation 4**: Provision should be made for convenient and efficient assessment, updating and maintenance of the transformation functions used to convert data entering and being extracted from an ENC database.

An important question that should be asked and answered is: where should these functions be stored? They may be a part of the database, they may be distributed to the users, they may be treated as being an indivisible part of the retrieval system. More thought will have to be addressed to these practical issues.

Whatever the final choice is going to be, the CHS should make sure that any bathymetric data retrieved from the database by the customer make sense. For instance, if the reference ellipsoid is adopted as the best reference surface (datum) for bathymetric data storage then no "ordinary" user should be allowed to retrieve these data in their raw form; the default retrieval option should be to have the data referred to the equivalent of the existing Chart Datums, or to the geoid, through an appropriate transformation. Thus the datum for data storage, and that for data display shall, in all probability, be different.

Recommendation 5: Provision should be made in the implementation of a seamless vertical-reference surface to prevent possible misinterpretation of data extracted from the system, by, for example, applying a default transformation which refers all data to a more conservative vertical-reference such as Chart Datum.

4.2 PROPOSED STRATEGY

Perhaps the most important point which has emerged so far in this report is that the main issue is **not** the selection of which seamless vertical-reference surface should be used in an Electronic Nautical Chart (ENC) database. In principle any of a wide variety of surfaces could be used.

The main issue surrounds the realization and implementation of the transformations required: from the present reference surfaces to a seamless one; and from the seamless database bathymetric values to what is presented to various kinds of users.

The important criteria for defining a total strategy are the impact the selection of a seamless vertical-reference surface and its associated transformations have on navigational safety, accuracy of final depth presentation, and ease of realization and maintenance.

4.2.1 SELECTION OF A SEAMLESS VERTICAL-REFERENCE SURFACE

However, in our opinion, the most important criterion, as far as the selection of a seamless reference surface itself is concerned (without regard for issues involving the associated transformations) is the ease of its realization and maintenance.

The most important aspect of realizing and maintaining bathymetry referred to a seamless vertical-reference surface in an ENC database is, in our opinion, the human factor. Every effort should be taken to minimize the risk that someone involved in inserting or extracting vertical data into such a database may misunderstand the nature of the seamless reference surface being used.

According to this line of reasoning, the important criteria for selection of the vertical-reference surface itself are that it be seamless, temporally invariant, and as simple to understand as possible.

Of the surfaces which we have considered in Chapter 2,

- It would not be a simple matter to create a seamless surface from the tidal and hydrological surfaces presently used to define Chart Datum. Such a seamless surface would be temporally invariant only if no additional water level time series were incorporated, in the form of new or improved estimates of Chart Datum at reference stations.
- There are many arguments for seriously considering the selection of the geoid as the seamless reference surface for an ENC database. It is seamless. It is a "natural" reference surface, closely associated with mean sea level. It is also closely related to many vertical reference systems already in use. However, realizing a geoid surface in practice requires an extensive collection of data of various types, and involves mathematical models of varying complexity. In the years ahead, geoid models will undergo a series of improvements and a number of versions will appear. Transforming the stored data from version to version, and monitoring the variations in accuracy from region to region involves a computational burden which may be significant, when

applied to terrabytes of ENC data, for example. On the other hand, the transformation between the reference ellipsoid and (any specific version of) the geoid would be well defined (but not necessarily correct) and easy to apply, to any desired subset of data being extracted from the database. There are also some questions concerning the temporal invariance of the geoid itself, due to global change (in particular eustatic variations).

- The simplest practical mathematical vertical-reference surface is the bi-axial reference ellipsoid. This is seamless, as simple to understand as any of the surfaces considered here, and can easily be made temporally invariant by convention, since it is defined by adopting numerical values for certain parameters. However, even if new values for these parameters were to be adopted by convention in the future, the transformation required to move to the new ellipsoidal reference surface so defined is a simple one. One advantage of selecting a reference ellipsoid is that the transformation from the present set of Chart Datums to a reference ellipsoid could take advantage of the capabilities of the OTF mode of Differential GPS positioning. There are, however, some disadvantages in selecting a reference ellipsoid. Bathymetric values referred to a reference ellipsoid will be useful in their un-transformed state only to a very small fraction of the end users of the bathymetric data. And this emphatically does **not** include the primary users, concerned with navigational safety. Therefore, default transformations to some other, more useful, reference surface will be required, should a reference ellipsoid be selected as the vertical-reference surface for ENC databases.

Based on the above summary, we recommend the following:

Recommendation 6: The CHS should adopt a reference ellipsoid as the seamless vertical-reference surface for ENC databases.

Recommendation 7: The CHS should use this reference ellipsoid as the vertical-reference surface for both bathymetry and height data.

Recommendation 8: The CHS should develop transformation functions to relate the present set of Chart Datums to this reference ellipsoid.

Recommendation 9: The CHS should use geoid models developed elsewhere to relate the geoid to this reference ellipsoid.

Recommendation 10: The CHS should collaborate with other agencies in improving geoid and SST models.

4.2.2 SELECTION OF A SPECIFIC ELLIPSOID

We turn now to selection of the specific reference ellipsoid to be used. The vertical-reference surface should be closely related to the ITRF coordinate system. There is no particular reference ellipsoid associated with ITRF, since it is concerned only with Cartesian coordinates of points (x, y, z). However, the reference ellipsoid chosen as a vertical-reference surface should be positioned (realized) so that its centre coincides as closely as possible with the origin of the ITRF system.

The reference ellipsoid chosen for a seamless vertical-reference surface should be one which is in common use. The sizes and shapes of several reference ellipsoids in use are [Leick, 1995]:

Acronym	semi-major axis (m)	flattening (1/f)
NAD 27	6 378 206.4	294.978 698 2
WGS 72	6 378 135.0	298.26
GRS 80	6 378 137.0	
NAD 83	6 378 137.0	298.257 222 101
WGS 84	6 378 137.0	298.257 223 563

The reference ellipsoid which is most closely related to (recently issued) existing CHS charts is NAD 83. The reference ellipsoid which is most closely related to the GPS system is WGS 84. Fortunately, both of these ellipsoids were deliberately chosen [Schwarz, 1989; DMA, 1987] to agree with the Geodetic Reference System ellipsoid recommended by the International Association of Geodesy [IAG, 1980]. Therefore the sizes and shapes of these three ellipsoids (GRS 80, NAD 83 and WGS 84) are practically identical. That is, in converting from a set of Cartesian coordinates to ellipsoidal coordinates, the heights obtained by using each of these three reference ellipsoids would differ from each other by less than one millimetre.

Recommendation 11: The GRS 80 reference ellipsoid (or its nearly identical clone, NAD 83) should be chosen as the seamless vertical-reference surface for bathymetric and other data in ENC databases.

It is important to draw a distinction between the choice of reference ellipsoid size and shape, as we have just done, and the choice of coordinate system. The NAD 83 and WGS 84 coordinate systems, which happen to use reference ellipsoids which are identical to better than a millimetre, do not provide coordinate values which are as closely related as are the reference ellipsoid sizes and shapes. Differences in the data and observing stations used to define each of these coordinate systems will lead to discrepancies between them at the metre, rather than millimetre, level. While these differences may not be significant when considering horizontal coordinates, they do become important when considering vertical coordinates.

There is (in our opinion) a widespread misconception that the bond between GPS positions and the WGS 84 coordinate system is stronger than it actually is. DGPS (OTF or otherwise) provides, in the simplest case, Cartesian coordinate differences in three dimensions, between the base station and mobile station. These can be transformed to relative ellipsoidal coordinates on any reference ellipsoid which we wish to use. There is nothing special in this sense about the WGS 84 reference ellipsoid. The resulting coordinates for the mobile station will be in whatever coordinate system we have used to set the “known” coordinate values on the base station. There may be arguments (such as international acceptance and consistency) in favour of adopting the WGS 84 coordinate system. But its bond with GPS is not such an argument.

However, the CHS is strongly committed to NAD 83 coordinates. This may be a more important consideration than the possible international acceptance associated with WGS 84 coordinates.

Recommendation 12: The CHS should carefully weigh the relative advantages between maintaining NAD 83 coordinates, or converting to WGS 84 coordinates, for data entered into its ENC database.

4.2.3 OTHER INITIATIVES

We are aware of the following:

- Organizations other than those involved in nautical charting and ENC databases have a vested interest in the selection of a vertical-reference surface for bathymetry. This is being addressed by including members of Geomatics Canada in the project of which this report is a part.

- At the FIG Congress in Melbourne Australia in February 1994, FIG Commission IV (Hydrography) established the following Working Group:

WG420a Vertical Chart Datum determination using GPS
This group will study the issues involved in using GPS for water level sensing. The Chair is:
Stephen DeLoach
US Army Corps of Engineers
Topographic Engineering Center
7701 Telegraph Road
Alexandria VA USA 22310-3864

- We understand that the IHO has circulated a request for information from member states on activities related to vertical-reference surfaces in hydrography, and that the date by which responses were requested was 1 April 1995. We have not, however, actually seen this circular letter.

- NOAA and DMA are jointly considering the adoption of a reference ellipsoid as a vertical-reference surface for bathymetry. The motivation in this case is a global one — the variety of Chart Datums presently used by various countries and agencies around the world presents difficulties in ensuring that the bathymetry obtained from each of them is consistent.

- At its meeting on Bali in 1992, the IAG GALOS (Geodetic Aspects of the Law of the Sea) Committee passed a resolution urging the adoption of a global vertical datum to facilitate a more consistent international maritime boundary delimitation. This resolution was then addressed in Vaníček [1994].

- The IAG Special Study Group 3.124 on *Global Vertical Datum* was established in 1987 with Erwin Groten of the Technische Hochschule in Darmstadt, Germany as Chair. During its eight years of existence, this SSG has accumulated a wealth of information and ideas on this topic, which should be tapped.

Recommendation 13: The CHS should take into account the intense interest and activities ongoing elsewhere on the issue of hydrographic vertical-reference surfaces.

5. IMPLEMENTATION OF A SEAMLESS VERTICAL-REFERENCE SURFACE

In this chapter we discuss some details of how to implement the seamless vertical-reference surface selected in the previous chapter, together with all the associated transformations.

We first discuss two of the tools available for this implementation: GPS and altimetric satellites. We then look at what kinds of information we are able to obtain from each of these tools.

We consider the accuracy issues involved in presenting final depths to end-users, and the role which vertical-reference surface establishment and maintenance plays in this context.

We then propose the steps and strategy which should be followed in implementing and maintaining this seamless datum.

Finally we look at the costs and benefits involved in moving to a seamless vertical-reference surface.

5.1 TOOLS AVAILABLE FOR IMPLEMENTATION

In this section we will look at various tools for the implementation of the seamless vertical-reference surface selected in the previous chapter. Implementation in the present context means establishing the connection between the chosen reference surface, the GRS 80 reference ellipsoid, and all reference points for historical Chart Datums.

5.1.1 GPS

The GPS can be used in a variety of different ways. One way is the On-The-Fly (OTF) methods described elsewhere in this report. These methods yield positioning accuracies between 100 m and a few mm. The accuracy achieved depends mainly on the sophistication of the receivers and the data processing software which is used. For an overview, see Wells et al. [1986]. The highest level of accuracy is obtained in conventional static differential GPS (DGPS) positioning, using carrier phase measurements.

In principle, DGPS requires the simultaneous operation of two GPS receivers, referred to as monitor and remote receivers. The data processing then determines the geocentric position of the remote receiver based on the a priori known position of the monitor receiver, and the DGPS phase measurements collected at both receivers. In other words, DGPS determines the relative position of the remote receiver with respect to the monitor receiver. This relative position can be expressed in geocentric Cartesian coordinate differences Δx, Δy, Δz, or in differences in geodetic coordinates $\Delta\varphi$, $\Delta\lambda$, Δh.

Recommendation 14: Conventional static differential DGPS positioning should be used to establish the transformation between Chart Datum and an ellipsoidal seamless vertical-reference surface.

Geodetic height differences from DGPS can be transformed into absolute geodetic heights, if the geodetic height of one or more reference stations is known. A total of five such reference stations are available in Canada as part of the global network of GPS stations belonging to the IERS GPS Service for Geodynamics (IGS). The coordinates of these stations are known to a greater degree of accuracy than any other stations in Canada. These stations provide a fundamental frame of geodetic heights for the implementation of a seamless ellipsoidal vertical-reference surface.

Recommendation 15: Chart Datum reference points should be tied to IGS stations, in order to determine absolute geodetic heights at the Chart Datum stations.

The Geodetic Survey Division (GSD) is involved in the data collection and processing of the Canadian IGS sites. GSD has acquired GPS data collection and processing expertise over the past decade, and appears to be the appropriate partner for CHS and CCG, in determining the ellipsoidal heights of Chart Datum points with respect to the chosen vertical-reference surface.

Recommendation 16: CHS and CCG should seek collaboration from GSD in the determination of ellipsoidal heights for Chart Datum points.

5.1.2 TOPEX AND OTHER ALTIMETRIC SATELLITES

There have been several satellite missions launched with the main goal of determining the sea surface and its temporal variations, namely GEOS 3 [AGU, 1979], SEASAT [AGU, 1982; 1983], GEOSAT [Frain et al., 1987], TOPEX-POSEIDON [AGU, 1994] and others. The instrument that actually measures the sea height (with respect to the satellite position) has been the altimeter, based on short-wavelength radar. The accuracy of the employed altimeters has steadily increased from a few metres in the first mission to a few centimetres in the latest mission (TOPEX-POSEIDON). Also, the accuracy of the requisite satellite orbits has increased significantly, reaching a few decimetres in the latest (ongoing) mission.

The final data that a user gets from any altimetric mission are profiles of instantaneous sea surface with respect to a geocentric reference ellipsoid, typically the GRS 80. These profiles, consisting of points a few kilometres apart, are obtained from the measured sea level heights and the computed satellite orbits through an adjustment process, after having applied a series of various corrections; the largest is normally the correction for the tide.

The profiles criss-cross the world oceans in a pattern of south-west and north-west heading lines which intersect to form diamond-like configurations. Different missions resulted in different diamond-like patterns depending on the satellite inclinations and orbital periods. With the TOPEX-POSEIDON, the profiles repeat themselves approximately every 10 days and adjacent profiles are 315 km apart at the equator. The diamonds get gradually smaller with growing latitude and there is no coverage above the latitude equal to the inclination of the satellite orbit — 66 degrees for the TOPEX-POSEIDON mission.

Since the sea surface varies in time, due to seasonal effects and the changing dynamics of the sea, typically by many decimetres, the collected data can be used in two, conceptually very different modes. One can study the temporal variations of the sea level along a profile (or in an area) or one can average the sea surface values over a specific epoch (a year, several years) and look at the spatial variations of the sea surface.

If one is interested in looking at a specific area, one must somehow bridge the sizable gaps between adjacent profiles. While the sea surface heights along a profile are only a few kilometres apart, the profiles are separated by tens of kilometres. Hence, the areal reconstruction of the surface is always much less accurate than the sea heights along a profile, no matter what mathematical technique one uses for the reconstruction. In addition, the short wavelength information along the profiles is somewhat better (about 5 cm in the TOPEX-POSEIDON case) than the long wavelength information (about 15 cm in the TOPEX-POSEIDON case).

If it were not for the SST, the temporally averaged sea surface would represent the geoid to a good degree of accuracy. In reality, altimetric data are used together with the geoid to study the SST (the difference between temporally averaged sea surface and the geoid). Because of the limited accuracy of our knowledge of the geoid at sea, the derived SST also has a limited accuracy of several decimetres (up to a metre or so).

As the accuracy of the marine geoid and the temporal coverage of the oceans by altimetry profiles increase, satellite altimetry will become a more practical tool for SST determination. At the moment, satellite altimetry should be used only for mapping the sea surface heights (with respect to the geocentric reference ellipsoid) averaged over the time span of the altimetry mission.

5.2 APPROPRIATE MAPPING FUNCTIONS

In this section we consider the role that two complementary measurement technologies may play in the establishment and future maintenance of the transformations associated with adopting a seamless vertical-reference surface. These are GPS and satellite altimetry.

The use of GPS is straightforward. The GPS employed in differential mode gives geodetic height differences (differences of heights above the geocentric reference ellipsoid) with a sufficient accuracy for the establishment, maintenance and recovery of vertical-reference surfaces.

In order to establish absolute geodetic heights at Chart Datum reference points, it is necessary to tie the Chart Datum points to other points for which the absolute geodetic height is known. There are a few such points in Canada, maintained by the GSD, for which the absolute geodetic height is known with commensurate accuracy.

If the geocentric reference ellipsoid is selected for the seamless datum, GPS can be used to construct various transformation functions point by point. For instance, if the position (height) of a local Chart Datum is known at a point (φ,λ), then the value of the transformation function $T(\varphi,\lambda)$ is determined, by comparing the geodetic and Chart Datum heights for that point.

Satellite altimetry data complements GPS data. Satellite altimetry may be of some (limited) use in designing two of the various transformations needed. The first of these transformations is between sea level, averaged over the life span of the altimetric mission, and instantaneous sea level (ISL). The second of these transformations is between sea level, averaged over the life span of the altimetric mission, and Chart Datum.

The first transformation requires knowledge of not only the tide but a host of other dynamic phenomena such as seiches, waves, wind driven variations, etc. These must be known one way or another if the instantaneous depth $d(\varphi,\lambda,t)$ is to be computed. The averaged sea level $w^S(\varphi, \lambda)$ obtained from satellite altimetry through time averaging, can be used in constructing the transformation function $w^S(\varphi, \lambda,t)$ by adding to it the temporally variable part $\delta w(\varphi, \lambda,t)$ obtained from models of the sea tide and other dynamic phenomena to obtain:

$$w^S(\varphi,\lambda,t) = w^S(\varphi,\lambda) + \delta w(\varphi,\lambda,t) \tag{5.1}$$

We note that even though the information on instantaneous sea level $w^s(\varphi,\lambda,t)$ can be obtained from satellite altimetry for the instants of time when the data have been collected, the temporally variable part $\delta w(\varphi,\lambda,t)$ has to be modeled separately to be usable for prediction in time.

The second transformation is more problematic. First, we would have to know the difference between the averaged sea level from altimetry and the "true" MSL (sea level averaged over a much longer period of time). Then we would have to know the difference between the MSL and Chart Datum.

5.3 UNCERTAINTY MANAGEMENT

The following error sources contribute to the overall inaccuracy

a) sounding errors (including water level sensing, sounding datum definition, sounding datum extrapolation — particularly recovering these for historical data)
b) Chart Datum definition
c) Chart Datum extrapolation
d) accuracy of the transformation function to a seamless vertical-reference surface
e) accuracy of the water level sensing
f) accuracy of the Geoid (with respect to an ellipsoid)

Various combinations of these inaccuracy sources are important for the following four applications:

Application 1: Bathymetry below ellipsoid (error sources a,b,c,d)
Application 2: Water below keel (error sources a,b,c,d,e)
Application 3: Bridge above mast (error sources a,b,c,d,e)
Application 4: Water below geoid (error sources a,b,c,d,e,f)

Recommendation 17: The uncertainty contributions from all error sources should be established.

Recommendation 18: The uncertainty contributions from the various error sources should be made available to the users for display and interpretation.

5.3.1 VERTICAL-REFERENCE SURFACE ACCURACY ISSUES

Many factors will contribute to the accuracy with which keel-clearances and obstruction-clearances are presented to the mariner. Here we are concerned mainly with the role which vertical-reference surfaces play in those final uncertainties.

The total error budget will be dominated by depth measurement errors, water level measurement errors, water level prediction errors, and spatial variations in Chart Datum (away from Datum station). It will also contain contributions from the mariner's horizontal and vertical positioning uncertainties. There is no reason why the accuracy associated with the vertical-reference surface cannot be kept small in comparison with these other error sources.

Recommendation 19: Vertical-reference surfaces should be established and maintained with an accuracy that does not contribute significantly to the total error budget of the mariner's keel-clearance and obstruction-clearance information.

To place the accuracy issues in this report in perspective, it is worth reviewing what is known about the magnitude of each of these error sources.

5.3.2 DEPTH MEASUREMENT ERRORS

Hare, Godin and Mayer [1995] studied the accuracy with which the depth of the seabed can be established, using modern multibeam and multi-transducer echo sounders. They considered each of the many sources of error in swath and sweep surveys (e.g. uncertainties in acoustic velocity profiles, acoustic range measurement, vessel motion sensing, vessel draught, water level sensing, horizontal position, and time synchronization), and developed models for total depth error budget based on manufacturer's specifications for several swath and sweep systems, as installed on some specific vessels. This model was used to predict the operating conditions (vessel speed, line spacing, etc.) needed to meet the depth accuracy specifications in International Hydrographic Organization [IHO, 1987]. These IHO specifications demand a depth *measurement* uncertainty of less than 30 cm (at the 90% confidence level), for depths of 30 m or less, and a depth uncertainty of less than 1% of depth (at the 90% confidence level) for deeper water.

The IHO specifications demand the same uncertainty limits for tidal (or water level variation) reduction of the measured depths: the measurement of water level variations, and resulting reduction of measured depths should have errors less than 30 cm (at the 90% confidence level), for depths of 30 m or less, and less than 1% of depth (at the 90% confidence level) for deeper water. The uncertainties due to other reductions is not mentioned. Therefore the specification for total depth uncertainty is that

$$\sigma^2_{total} = \sqrt{\sigma^2_{depth} + \sigma^2_{tide}} = \sqrt{2} * \begin{cases} 30\ cm \\ 1\%\ depth \end{cases} = \begin{cases} 42\ cm\ if\ depth \leq 30\ m \\ 1.4\%\ of\ depth\ if\ d>30\ m \end{cases} \tag{5.2}$$

A new edition of these IHO specifications, now under preparation, is intended to address the use of modern swath and sweep survey techniques, and will likely provide for several "classes" of survey, including one which requires higher performance than that in the existing edition.

However, little of the world's navigable waters have so far been surveyed using modern swath and sweep systems. The accuracy of depth measurements obtained during older surveys is not well established, and likely varies considerably. The horizontal positions attached to earlier depth measurements is often less accurate than the positioning systems now available to mariners. More significant than these measurement errors is the fact that earlier survey techniques (single beam echo sounders and lead lines) often sampled only a small fraction of the seabed. The depth uncertainties associated with undetected depth anomalies likely dominate the error budget for most existing nautical charts. It is safe to say that the vast majority of seafloor models resulting from hydrographic surveys have absolute vertical uncertainties in the 10's of decimetres, or greater [Kielland, 1995].

5.3.3 WATER LEVEL MEASUREMENT ERRORS

The accuracy with which water levels can be established with respect to Chart Datum (by hydrographers and by mariners) depends on a number of factors. Hare and Tessier [1995] have studied the accuracy with which water levels can be established in the St. Lawrence River. They considered errors in water level measurement (including biases which may occur), errors due to data filtering, differences in timing between water level sensor and vessel, and most significantly, errors in spatial prediction of water levels away from the sensor site. They concluded that, at the 95% confidence level, water levels can be established in the St. Lawrence River with an uncertainty of 4 cm, where there is no tidal influence or spatial prediction problems, but that this uncertainty grows to 40 cm where there is a tidal influence, and to between 2 m and 3 m where there is a spatial prediction problem (the water level sensors are spaced too far apart and / or the hydrological model for the river is inadequate).

5.3.4 WATER LEVEL PREDICTION ERRORS

Carrera [1995] recently studied the accuracy with which predictions contained in the CHS Tide Tables agree with tidal measurements made at 23 tidal stations in Eastern Canada. The criterion used for "acceptable" prediction accuracy was that the predictions agree with the measurements to within 15 cm, 60% of the time. The predictions at nine out of eleven primary tide stations met this criterion, using measurements spanning all of 1994. However, only three out of twelve secondary ports met this criterion, using measurements scattered over the past two decades, and two to eight weeks in duration. At Hantsport, N.S., with a tidal range of 16 m, the differences between predicted and observed water levels was almost uniformly distributed between ± 1.2 m, with 15% of these differences exceeding 1 m.

5.3.5 VERTICAL-REFERENCE SURFACE ACCURACY

We now return to the question: with what uncertainty must vertical-reference surfaces be established and maintained so they do not contribute significantly to the total error budget of the mariner's keel-clearance and overhead obstruction-clearance?

Assume a total error budget, σ_{total}, of 50 cm for depth determination, which includes the water level uncertainty contribution [Myres, 1990]. Using the relationship

$$\sigma^2_{\text{total}} = \sigma^2_{\text{vrs}} + \sigma^2_{\text{other}} \tag{5.3}$$

(which assumes we are dealing only with random errors), if the uncertainty in establishing and maintaining the vertical-reference surface, σ_{vrs}, was 10 cm, the contribution from all other sources, σ_{other}, would have to be reduced to 49 cm $\cong \sqrt{(50\text{ cm})^2 - (10\text{ cm})^2}$. Due to undetected depth anomalies and horizontal positioning errors, many historical surveys may not meet this 50 cm total error budget. Therefore, decimetre uncertainties (at the 95% confidence level) in the establishment and maintenance of vertical-reference surfaces will be adequate for most purposes.

However, there are a few critical passages where the investment is justified in performing carefully controlled modern surveys, and providing an adequate water level monitoring network and prediction model. Assume the total uncertainty associated with determining the mariner's keel-clearance and overhead obstruction-clearance can be reduced to 10 cm (at the 95% confidence level). Note this assumption has certainly not yet been realized in practice. Then, if the uncertainty in establishing and maintaining the vertical-reference surface, σ_{vrs}, was as low as 3 cm, the contribution from all other sources, σ_{other}, could remain close to 10 cm (e.g. would be greater than 9.5 cm). Therefore, in these cases, uncertainties in the establishment and maintenance of vertical-reference surfaces should be reduced to a few cm (at the 95% confidence level).

A final note regarding such critical cases. The important total error budget is that for the determination of the mariner's keel-clearance and overhead obstruction-clearance. This includes contributions which come from the operation of the mariner's vessel, and beyond the control of any other agency. It is important that the mariner have a good grasp of the uncertainties associated with the depth and water level data upon which these clearances are based. Failing to keep these uncertainties foremost in mind could result in an over-confidence. This over-confidence has been of concern to Hydrographic Offices for the past five years in dealing with mariners using DGPS for **horizontal** positioning. This potential over-confidence becomes a more serious safety concern when moving from horizontal positioning to vertical positioning.

Recommendation 20: The uncertainties (from all sources) which are involved in navigating using either DGPS or OTF should be made as clear as possible to the mariner.

5.4 INITIAL IMPLEMENTATION STEPS

In order to relate individual existing Chart Datums to a new seamless vertical-reference surface, the transformation parameters need to be established. Therefore this section deals with the "initial" problem of converting historical data to a seamless vertical-reference surface.

5.4.1 DETERMINE TRANSFORMATION AT WATER LEVEL STATIONS

The most straightforward starting point in connecting existing vertical-reference surfaces to the seamless datum is to determine separate transformation parameters for each of the discrete reference stations which are used to determine the existing datum surfaces. If GPS is to be used to determine the parameters, then the benchmarks associated with each Chart Datum reference station must be occupied by a GPS receiver, to determine the height difference of that Chart Datum with respect to the seamless vertical-reference surface.

Interpolation of the transformation values between these Chart Datum reference stations depends upon the vertical-reference surface variations from one location to another. If these variations are smooth and continuous, the transformation can be interpolated by continuous functions of latitude and longitude.

If the variations are smooth and continuous, it may even be possible to avoid measuring the transformation values at every known Chart Datum reference station. The minimum number of reference stations would have to be at least as many as the number of coefficients required to model the transformation function (polynomials, trigonometric functions, splines, etc.). The advantage of this approach is a significant reduction of field work. The disadvantage is that a priori knowledge about the degree of smoothness of the transformation parameters is required.

Any (navigationally significant) steps in the existing Chart Datum surface will have to be taken into account in determining the transformation. The extreme example of this are the steps involved in locks. St. Lawrence Seaway locks have standard steps of 7.15 m (23.5 feet). Chart Datum in some regions of Canada is stepped due to the variation in range of the tide. Because such steps are to be expected at various places in the Canadian marine areas, this simplified method should not be used.

Recommendation 21: The transformation function should be determined by using GPS to measure the ellipsoid height of each station for which a Chart Datum has been established.

5.4.2 CHART DATUM BOUNDARIES AND SPATIAL EXTRAPOLATION OF CHART DATUMS

Existing values for Chart Datum have been established for locations which have at one time been occupied by a water level sensor. These values have then been used to reduce depth soundings over some region surrounding this sensor location. The boundaries of such regions must be recovered, in order to implement the conversion to a seamless vertical-reference surface. Recovering these boundaries may or may not be a difficult task.

Recommendation 22: The CHS should devote the resources needed to recover the boundaries used in applying data from water level sensors to reduce historical depth soundings.

When reducing soundings which are within the above boundaries, but which are some distance from the water level sensor, there may be appreciable differences in the water levels between sensor and survey vessel. These can be considered to be spatial variations in Chart Datum, and some attempt may have been made to model these variations during historical surveys [Myles, 1990; Luynenburg and van Gent, 1981].

The treatment of such spatial variations (even where they are navigationally significant) varies. In some cases, spatial variations were ignored when depth soundings were reduced to Chart Datum: that is the separation between instantaneous sea level and Chart Datum, measured at the location of a water level gauge, was applied at the location at which the sounding was measured.

However, in some cases it may be that some form of spatial extrapolation for Chart Datum (e.g. a linear river slope, or a co-tidal model for Chart Datum)was used at the time of depth reduction. In such cases, the method and values used for extrapolating Chart Datum away from the water level sensor must be recovered, in order to incorporate them into the transformation function used to convert from Chart Datum to a seamless vertical-reference surface. This recovery may or may not be a difficult task.

Recommendation 23: The CHS should devote the resources needed to determine, for each Chart Datum, whether spatial extrapolation (other than horizontal plane) was used, and if so, to recover the extrapolation method and values used in applying data from water level sensors to reduce historical depth soundings.

Some Chart Datums are known to be wrong: that is they do not coincide with LLWLT, even at the water level sensor location. For example, the Chart Datum at Sheet Harbour is 0.3 m below LLWLT, and the Chart Datum at Cape Tormentine is 0.5 m below LLWLT [O'Reilly, 1995]. Correcting these errors would involve a revision of both the paper chart, and the corresponding Tide Tables, a major undertaking. It is worth noting here that the move to electronic charting (ENC and ECDIS) will greatly simplify making such corrections (although the arguments we have made concerning the balance between stability and accuracy should be kept in mind).

Recommendation 24: Known errors in Chart Datum should be taken into account when the transformation function between Chart Datum and the seamless vertical-reference surface is defined.

5.4.3 APPLYING TRANSFORMATIONS

Once the transformation functions and their spatial validity have been established for each existing datum surface, the depth values in the data base can be transformed to the seamless datum. For each existing datum surface, this step involves the identification of all data points and adding to the depth values the difference between the old and the new datum, calculated from the transformation formulas as a function of horizontal position.

The numerical values of the transformation function can be stored in a look-up table. A particular value is then used within its grid cell. The grid size to be used for this table depends on the degree of variability of the transformation function and the desired accuracy of the transformation. Example: Assuming a variation of 1 metre over 100 km in the transformation function and a required accuracy of the look-up table of 5 cm, the resulting grid size is 10 km. Different grid cell sizes might be appropriate for different areas in Canadian waters.

5.5 PROPOSED IMPLEMENTATION STRATEGY

Establishing a seamless vertical-reference surface requires, as a first step, finding some way to convert historical bathymetric data so that they refer to such a seamless surface. That is, to establish a transformation function which relates the existing Chart Datums to the seamless surface.

The seamless surface recommended in this report is a reference ellipsoid. If this recommendation is adopted by the CHS, the transformation function can be established by determining geodetic heights (heights above the reference ellipsoid) for each of the benchmarks for which Chart Datum heights are presently known. A convenient tool for determining such geodetic heights is GPS.

The strategy we propose is to conduct a GPS campaign (or series of campaigns) to determine geodetic heights for these benchmarks. Since GPS is a three-dimensional positioning tool, this will also result in placing latitude and longitude values of the same accuracy on these benchmarks. Such a campaign may provide benefits to other agencies.

Recommendation 25: The CHS should seek collaboration with other agencies who may benefit from the establishment of geodetic heights (and horizontal coordinates) on benchmarks.

5.5.1 WHERE ARE THE EXISTING CHART DATUM POINTS?

We understand that there are about 1200 Chart Datum points in Canada. A campaign to survey each of these 1200 stations is a major undertaking. Priorities must be set as to which areas may be most critical, or yield the lowest cost / benefit ratio. In this section we look at where the Chart Datum stations to be surveyed actually are.

The only detailed information about these points which is available to us for this study, is a CHS **Bluefile** (a database containing the "official" harmonic constituents for all tide stations in Canada) for 874 stations. Our copy of the Bluefile was obtained several years ago. Unfortunately, we do not have any information about Chart Datum stations in non-tidal waters, that is rivers and lakes. We presume that there are about 325 (1200 minus 874) such nontidal Chart Datum stations in Canada.

We have constructed a directory of Chart Datum stations consisting of the header records from this Bluefile, and have imported this directory into a Geographical Information System for display and analysis. The 874 Bluefile stations can be broken down regionally as follows:

- 377 are on the Atlantic coast
- 283 are on the Pacific coast
- 214 are in the Arctic (which we defined as starting at the Strait of Belle Isle)

The Atlantic coast stations can be further broken down as

- 53 are on the Newfoundland coast
- 242 are on the coasts of the Maritime Provinces
- 82 are in Quėbec, on the banks of the St Lawrence River, and the north shore of the Gulf of St Lawrence.

5.5.2 SETTING PRIORITIES

Criteria must be selected for setting priorities on which subsets of these Chart Datum stations should be surveyed with GPS first.

Recommendation 26: The two criteria which should be considered in setting priorities for GPS surveys of Chart Datum points are urgency or need, and ease of survey or cost.

Four groups of Chart Datum stations should be given a high priority under the criterion of need:

- First priority: stations along the St. Lawrence River. The shipping industry is demanding an enhanced capability for real-time three-dimensional navigation in the St. Lawrence River. We contend that establishing a reference ellipsoidal vertical-reference surface is an important component to achieving real-time three-dimensional navigation.

- Second priority: stations in areas for which ENC databases have already, or will soon be prepared. If the concept of a seamless ENC vertical-reference surface is accepted by the CHS, the earlier it is implemented, the fewer difficulties may occur at conversion.

- Third priority: Chart Datum stations which have never been tied into a vertical network, and which therefore supply only local "floating" Chart Datums.

- Fourth priority: Chart Datum stations for which there are known problems concerning the Chart Datum values attached to them.

The cost of the GPS campaigns we propose will depend primarily on the transportation mode used to travel between adjacent Chart Datum points (and on the season of the survey). The three priority classes we have established, according to the cost criterion, are

- Chart Datum stations which can be accessed by land (road) will be the lowest cost, and thus have the highest priority.

- Chart Datum stations which cannot be accessed by land, but can be by sea (boat) will be more expensive to survey, and should have second priority.

- Chart Datum stations which can only be accessed by air (helicopter) will be the most expensive to survey, and should have lowest priority.

The Canadian winter can be both a hindrance and an advantage. When lake (and perhaps some river) surfaces are frozen, access to Chart Datum stations may be easier (less costly) by snowmobile over the ice. On the other hand, finding benchmarks under snow cover can be very difficult.

Over time there may be other activities which will involve visits (by boat or by air) to locations at or near the more inaccessible Chart Datum stations. Collaboration with other agencies may permit these opportunities to be used to establish geodetic heights at Chart Datum stations.

Recommendation 27: Implementation of the transformation from Chart Datum to a seamless vertical-reference surface should be done in a carefully planned, phased region-by-region sequence, taking urgency and cost considerations into account.

Recommendation 28: A pilot project should be implemented first, using the St. Lawrence River from Montréal to Trois Rivières (or perhaps Québec) as the test site. This pilot project should be carefully coordinated with the work proposed to be done in the same area by the CCG, in setting up a real-time OTF DGPS broadcasting facility.

Recommendation 29: Once the transformation function has been determined, the actual conversion of the ENC to seamlessness should involve all relevant conversions simultaneously (ENC, water level sensing, Tide Table generation, new paper chart products, ECDIS capabilities, etc.)

5.5.3 SPECIFICATIONS FOR GPS STATIC BASELINE SURVEYS

The accuracy requirements for a vertical-reference surface were discussed in §5.3. Since this accuracy will not be better than the accuracy with which geodetic heights are attached to benchmarks, we will start with the specification in §5.3:

Recommendation 30: Geodetic heights should be established at Chart Datum stations with an accuracy of 10 cm, at the 95% confidence level.

GPS is a relative positioning tool. A GPS survey generally determines only relative geodetic heights. However, there is a hierarchy of three-dimensional control distributed throughout the world, for which accurate absolute ellipsoidal heights have been determined, and are been maintained (as station locations change due to motions of the earth's crust). A GPS network which is part of this hierarchy is managed by the International GPS Service for Geodynamics [IGS, 1994]. The following five Canadian stations are operated by Natural Resources Canada, as part of the IGS network:

Station #	Name	Longitude	Latitude
1	Alberthead	-123.48	48.38
2	Algonquin	-78.07	45.95
54	Penticton	-119.62	49.32
61	Saint John's	-52.68	47.60
73	Yellowknife	-114.47	62.47

Three other stations may be of some value as well

Station #	Name	Longitude	Latitude
18	Fairbanks	-147.48	64.97
70	Westford	-71.48	42.62
P30	Thule	-68.73	76.56

Recommendation 31: The CHS should arrange with GSD to tie Chart Datum points to IGS stations, in order to establish absolute geodetic heights at the Chart Datum stations.

Directly tying all Chart Datum points to these IGS stations will involve baselines over 1000 km in length. To achieve 10 cm accuracy at 1000 km requires relative GPS positioning performance of 0.1 parts per million (ppm) of the station separation. Such accuracy can only be obtained with very long observation sessions, and very careful (and expensive) GPS surveying procedures. A better alternative would be to tie a small number of "reference" Chart Datum stations to the IGS stations, and then position the majority of the Chart Datum stations relative to these "reference" Chart Datum stations. Since Reference Ports in the tidal network are likely more stable and accessible than other Chart Datum stations, we have selected a set of 11 Atlantic coast and four Pacific coast "reference" stations, at least one of which is within 200 km of every other Chart Datum station on those coasts. For the Arctic, the situation is much worse.

Recommendation 32: The CHS, with collaboration from GSD and other agencies, should tie benchmarks at about 15 Reference Ports to the IGS network, using GPS procedures designed to provide the highest possible accuracy.

It is important that critical users using OTF vertical navigation obtain keel-clearance depths with the best possible accuracy. This can be achieved only if bathymetric surveys and OTF navigation are referenced to the same datum. To ensure that, the GPS reference stations used to provide vertical control for both bathymetric surveys and OTF navigation should be tied into these 15 Reference Ports.

Tying the remaining Chart Datum stations to these Reference Ports will involve baselines of up to 200 km, or relative GPS accuracies of 0.5 ppm (10 cm in 200 km). This GPS performance requires careful procedures with good quality control checks.

Recommendation 33: The CHS, with collaboration from other agencies, should tie benchmarks at other Chart Datum stations to these selected Reference Port benchmarks.

5.5.4 MEETING THE GPS SPECIFICATIONS

The goal of the GPS survey is to establish geodetic height for each Chart Datum. This implicitly defines the transformation from each Chart Datum to the seamless reference surface. As outlined in the previous section, it is proposed to establish the geodetic heights in two steps: first, about 15 Reference Ports are tied into the IGS network, and then all Chart datums are connected to these Reference Ports. Comparing the accuracy specification to the accuracy limitations of GPS as outlined in section 1.4.3, it can be seen that

- dual frequency GPS receivers are required for all survey operations,
- precise ephemerides must be used in the position calculations, and
- several hours of data needs to be collected for each baseline.

Gross errors must be avoided. Perhaps the most dangerous one in the present context of vertical GPS positioning is to record in the field notes an erroneous antenna height. Such an error cannot be detected during data processing and, if undetected, falsifies the transformation from Chart Datum to seamless reference surface. It would be worthwhile to investigate if GPS antennas with calibrated fixed antenna heights are available, or if such antenna support systems can be constructed for the purpose of this survey.

In order to detect any major problems with the collected data, individual baseline data processing should be performed with low accuracy broadcast ephemerides as early as possible, perhaps every evening. The result of this processing would not be the differential position but the Quality Assessment of the measurement data. Early detection of data problems might save considerable time and resources.

A critical issue in connecting a Chart Datum to a Reference Port is the proper identification of the benchmark defining the Chart Datum. For some Chart Datums the defining benchmarks may be lost, and will have to be re-established from new tide gauge readings. This invariably will contribute to a higher error budget for the transformation to the seamless reference surface.

5.6 MAINTENANCE OF THE TRANSFORMATION

Maintenance of a bathymetric database has many aspects. Here we are concerned with the aspect of maintenance which is central to the issues discussed in this report. This is to maintain the *transformation functions*, which will become part of the vertical-reference system. These functions will allow the CHS to satisfy the needs of all clients interested in the seabed, requiring that bathymetric information be available in different forms. These transformation functions will, in some areas, initially be known only approximately and the "maintenance of the system" should definitely include upgrading of these transformation functions to reflect increased demands on the accuracy of the output.

We should note that the most difficult aspect of bathymetric database maintenance is beyond the scope of this report. This aspect is due to inaccuracies in historical bathymetric data. Problems have arisen because DGPS (or even, in some cases, GPS) provides much more accurate positioning than the placement of historical bathymetric data. Problems have arisen because ECDIS bathymetric depiction permits closer scrutiny (and possible misuse) of existing data than do conventional paper charts. And there are potential problems which may arise from adoption of the vertical-reference surfaces discussed in this report, which will likely be more accurate and consistent than the methods used to reduce historical sounding data.

Re-surveying using modern methods may eventually reduce these problems. However, that is some time in the future. Meanwhile, very little can be done to improve the quality of existing bathymetric data. These deficiencies must be addressed somehow. The traditional approach is to provide users with bathymetric data which are referred to a “near worst-case” reference surface — to deliberately build in a safety factor. Another possibility is to provide more realistic bathymetric data, but to inform users of the magnitude of uncertainties due to potential errors. It may be possible to design some method of displaying such uncertainties as part of the chart presentation. An intensive public relations effort may be required to raise the level of awareness of the marine community, concerning the limitations and uncertainties of bathymetric data.

However, the maintenance topic which is relevant to this report, is what kind of improvements might be expected in the models used for the various transformation functions we have discussed. It is impossible to foresee exactly what these improvements may involve. We can only list some of the issues may have to be addressed. We consider these issues systematically in the context of the transformations discussed above.

- **Evolution of geoid models** — for users requiring bathymetry referred to the geoid, the transformation function between the geocentric reference ellipsoid and the geoid (geoidal height $N(\varphi, \lambda)$) will have to be used. The geoidal height as a function of position (as a point function for a regional geoid or as a series expression for a global solution) is known only approximately and is subject to a continuous improvement.

Recommendation 34: The best up-to-date geoidal height should be maintained in the system.

- **Evolution of instantaneous sea level (ISL) models** — for users requiring bathymetry referred to the ISL, the elevation of the ISL above the geocentric reference ellipsoid is needed. This quantity can be, to a certain extent, obtained from satellite altimetry, as discussed above. The maintenance of the new CHS system should keep an eye on the availability and accuracy of the data available from satellite altimetry missions, present as well as future.

- **Evolution of (sea) tidal models** — for users requiring bathymetry referred to the ISL, the tidal component of the sea level variation is, of course, crucial. Thus the tidal component of the transformation function $\delta w(\varphi, \lambda, t)$ will have to be a part of the system. As such, it must be a subject to continuous improvement as our knowledge of the tides improves in specific areas. This improvement is conditional on local tide measurements, improved tidal analysis techniques and the real change in tides in response to changing sea bottom and coastline. There is also the possibility that the character of the tide itself may change over time [Godin, 1992].

- **Evolution of other sea surface dynamics models** — again, for users requiring the ISL datum, the other sea surface phenomena such as the barometric pressure and wind induced variations, seiches, swells, etc., will be important. In certain areas models exists that can, to a certain extent, predict these phenomena (based on meteorological observations). The advantage should be taken of the existence of these models to improve the transformation function $\delta w(\varphi, \lambda, t)$. Inclusion of these models in the new system should thus be a part of the maintenance process.

- **Evolution of SST models** — for users requiring bathymetry referred to the ISL, the elevation of the MSL above the geoid (the SST) is another important part of the transformation function. This quantity SST(φ, λ) is known only very approximately at present, but is a subject of an intense study by both the geodetic and oceanographic communities. One must expect that the knowledge of SST will definitely increase in the near future and the CHS system should take a notice of this in the system maintenance program.

- **Evolution of vertical crustal movement models** — tide gauges are subject to elevation changes due to vertical crustal motions. When new, or existing tidal observations are brought into the system, it would be desirable to know just how much the tide gauge in question is changing its elevation vis-à-vis the MSL each year. The crustal motion, as a function of position, is, once again, not very well known and probably cannot be taken into account at this time. This situation is going to improve, however, and the CHS system maintenance may wish to take the new models into consideration.

- **Eustatic sea-level rise** — is another temporally varying part of the transformation between the geocentric reference ellipsoid and the ISL. It is a global parameter and its magnitude is so far not very well known. When it becomes better known, it may become an integral part of the appropriate transformation function.

- **Evolution of lake level models** — note that IGLD is expected to change every 25 years or so [CCGLBHHD, 1992].

- **Evolution of river level models** — navigation through critical passages along rivers requires real time river level information. For this reason the COWLIS / ODIN / SINECO network of water level and other sensors has been established along the St. Lawrence river [Tessier et al., 1993].

Clearly, some of the issues discussed here will look esoteric, even irrelevant to a hydrographer or a marine navigator. However, if CHS wants to capture a new set of clients, who will require more accurate and more up-to-date information, some of these issues may become important. Some may not. Whether or not they will be important depends on the expected accuracy and the projected lifetime of the system. If the expected accuracy of the output data (bathymetry referred to one datum or another) is to be, say 3.5 cm at a one sigma level [Hare and Tessier, 1995] and the lifetime of the system is, say 50 years, then even the eustatic water rise (estimated now to be between 1 and 2 mm per year) will have to be seriously taken into account. In 50 years it will amount to an estimated 5 to 10 cm!

Discussing the magnitudes of the individual effects described above and accuracies with which these effects are known at present, is considered beyond the scope of this report. Interested readers can find more details in [Vaníček, 1994] a copy of which is provided as an external appendix to this report. We hope, nevertheless, that the above discussion makes the point that the issues described require some attention from the designers of the new CHS system.

5.7 COSTS AND BENEFITS

In this section we consider the costs required to establish the transformation from Chart Datum to seamless vertical-reference surface, and the benefits which might be gained by (a) the CHS, (b) clients of the CHS, and (c) other agencies.

We have not considered the costs involved in maintenance of the seamless database itself, nor maintenance of the various transformations which are discussed in this report. The first of these involves mainly issues which are well beyond (and much larger than) than topic of this report. The second requires more information about how the seamless system would operate in practice than is at present available.

5.7.1 COSTS OF IMPLEMENTATION AND MAINTENANCE

The costs of establishing the transformation between the existing Chart Datums and a seamless vertical-reference surface will involve planning, algorithm design, and software development. However, the two main cost items, in our opinion, will be to search historical records to find out the details of how each Chart Datum was established and implemented, and to perform the field surveys required to measure the geodetic height of each Chart Datum.

Ideally, the historical search should include determining the boundaries of the "reduction zones" used to apply water level measurements from each Chart Datum reference station, at the time of each bathymetric survey in that area. The search should also determine what, if any, kind of spatial extrapolation methods were used in applying these reductions (linear river slope, co-tidal model, etc.)

In practice this information may no longer be available for many older surveys and Chart Datum reference stations. Therefore, it may be necessary to simply categorize the existing Chart Datum datasets according to how complete and reliable the historical records are. This categorization could then be used as one factor in prioritizing the need for modern re-surveys and water level records in that area.

Attaching actual costs to this exercise is beyond the scope of this report.

5.7.2 BENEFITS AVAILABLE TO CHS

A seamless vertical-reference surface provides the framework to prepare for a more consistent and reliable management and maintenance of vertical reference information. It also prepares the infrastructure for new capabilities like OTF surveying without need for water level gauges, and without the need to account for changes in vessel draught due to changes in trim, loading, squat, settlement and lift. OTF can also improve the performance of heave compensators, and perhaps potentially replace then, using a multi-antenna array. Finally, it provides the infrastructure for 3D ECDIS and thereby meets the needs of the critical users.

5.7.3 BENEFITS AVAILABLE TO OTHER AGENCIES

It seems to us that the main benefit of the new CHS system will be due to its flexibility, whereby all the agencies involved with sea bottom will be able to get the bathymetric information in the form in which they actually need it. This should result in in-house savings — less computer processing, fewer specialists formerly needed to design the appropriate transformations and computer programs — of uncertain magnitude. As an example, if lake bathymetry referenced to a fairly accurate (regional) geoid in the region of the Great Lakes becomes available from CHS then the job of the international Coordinating Committee on Great Lakes Basic Hydraulic and Hydrological Data (CCGLBHHD) will become much easier.

The other clear benefit should be in the increased accuracy and frequent upgrading of the various transformation functions used in the system. Also, as one assumes that there will be some error estimates associated with the data output, user agencies preoccupied with accuracy, such as the above mentioned CCGLBHHD will have a much easier time dealing with the data on a routine basis.

When talking about benefits let us also mention an obvious drawback of the new system. Because the new system will give the user more flexibility, i.e. more choices of the form in which the bathymetric information can be requested, the user will have to be more sophisticated and discriminating. This is, of course, true of any new system in any walk of life. Since some of the existing and potential user agencies may not have the requisite degree of sophistication, to even decide what it is that they need, a certain degree of coaching and training by CHS may be required, both in a written as well as spoken form.

6. IMPACT ON CHS CLIENTS

The CHS has traditionally had a predominant single client group: mariners who purchase and use CHS nautical charts (and related publications).

This will change dramatically, when the infrastructure to deliver ECDIS capabilities to these same mariners has been built. In principle, this infrastructure should also provide the capability for delivery of different levels of ECDIS capabilities to different classes of mariners. This infrastructure should also provide the capability to more effectively deliver hydrographic data products to clients other than mariners. Thus there will be major changes both in the supply of, and in the demand for, hydrographic information.

In this chapter we identify various CHS client groups, and assess the impact of selecting a particular seamless vertical-reference surface. Where appropriate, suggestions are made on how to most effectively implement such a surface, in order to meet client needs.

6.1 IMPACT ON NAVIGATION SAFETY

6.1.1 IMPACT ON NAVIGATION PROCEDURES

The issues associated with GPS OTF based navigation systems and the potential of such systems have been discussed in [Santerre and Parrot, 1995]. We would like to offer here the following comments.

A reliable real-time OTF service needs an accurate and reliable bathymetric database. It is important that the bathymetry must be referred to same vertical-reference surface as OTF heights. OTF heights are typically referred to an ellipsoid. This makes the same ellipsoid also the natural choice to refer the bathymetry to. The bathymetric coverage must be complete, to accuracies compatible with OTF performance (decimetre level).

A reliable real-time OTF service needs a reliable OTF infrastructure. This includes placing accurate ellipsoidal heights on all reference stations. These ellipsoidal heights can be derived from GPS measurements connecting the reference stations to the IGS network, cf. section 5.1.1. The reference station locations should be chosen to minimize environmental interference. They should be equipped with reliable low-noise dual-frequency GPS receivers, and proven commercially available software. To ensure network reliability, back-up equipment (GPS receivers, computers, radio link equipment) must be running in parallel at the reference stations. Reference station separation must be small enough to allow OTF throughout the service area. In designing the network it must be kept in mind that solar activity will peak in the year 2000. At that time ionospheric refraction effects on GPS positioning will be more pronounced then now, potentially decreasing the range of reliable OTF service.

A reliable real-time OTF service needs reliable OTF user equipment. This includes low noise, dual-frequency GPS receivers, reliable communications link receivers, and proven commercial OTF software. It is also necessary to ensure that the carrier phase ambiguities have been correctly resolved (e.g. through OTF with respect to multiple monitor stations, or through multiple GPS receivers on board). A display component, a well-integrated reliable 3D ECDIS showing keel-clearance (OTF water level minus ellipsoidal bathymetry) completes the user equipment.

6.1.2 LOW COMPLEXITY END USERS

Low complexity end users include the following:

- mariners who are presently compelled by law to carry and use paper charts, and who will continue to do so in the future
- mariners who will use an Electronic Chart Display and Information System (ECDIS), should that become legally acceptable
- mariners who will use a simpler Electronic Chart System (ECS) in conjunction with paper charts.

The common feature of all these users is that all such forms of nautical information represent only the time-invariant near-worst-case “depths” below Chart Datum.

In tidal waters, these users can perform the transformation from bathymetry to water depths using predicted Tide Tables. In rivers this transformation is generally not possible.

The selection of a seamless vertical-reference surface for the representation of depths in the CHS digital data base should be so arranged as to have **no** impact on these general end users.

Recommendation 35: The seamless vertical-reference surface, and its associated transformations, should be implemented in such a way that the present capabilities for presenting depths below Chart Datum are not compromised.

6.1.3 MEDIUM COMPLEXITY END USERS

Medium complexity end users are mariners who will use an ECDIS or ECS system which includes some facility for converting from time-invariant near-worst-case "depths" below Chart Datum to some kind of predicted depths. These predictions would not, in this case, be based on real-time, or near-real-time measurements. In tidal waters, these predictions could be a digital tide table, or tide prediction software with a database of tidal constituents. In rivers some seasonal variation model might possibly be implemented, but this is a riskier undertaking. The accuracy of the depths derived will differ substantially from that derived manually by the low complexity end user.

6.1.4 CRITICAL END USERS

There are certain shipping channels and harbour approaches in the world for which keel-clearances are a significant restriction to shipping. In Canada, the most important example is the St. Lawrence River between Trois Rivieres and the Port of Montreal. Other examples are the entrance to Port Phillip Bay and the Port of Melbourne, Australia, and the channel leading to Europort at Rotterdam, The Netherlands.

For these critical areas, vessels must limit the amount of cargo they carry, to enable them to safely clear the keel-clearance obstructions. Loading vessels to less than their carrying capacity translates into $10’s of thousands lost profit per trip, for each decimetre of reduced keel draught.

Therefore, the most critical end users will be large vessels, or those vessels carrying hazardous cargoes, for which the economic or environmental benefits justify the expense of installing or accessing some real-time tools to improve the accuracy with which depths can be presented on the vessel.

Recommendation 36: The seamless vertical-reference surface, and its associated transformations, should be implemented in such a way that critical end-users can access real-time and predicted keel-clearances which are as realistic and accurate as possible.

These critical end users are expected to interact with depth data in more sophisticated and risky ways than do the low and medium complexity end users.

Recommendation 37: Critical end-users should be provided with as much information as possible concerning the uncertainties of the water depths with which they will be dealing.

6.2 "VIRTUAL CORPORATION" COLLABORATORS

The supply-side infrastructure being built by the CHS and its collaborators has been likened to a corporate structure, but one which is not based on the formal bureaucracies of a traditional corporation. Hence the term "virtual corporation". We use the term here to include all those engaged, in collaboration with the CHS, in the supply of an ECDIS capability to mariners. This includes

- the various functions performed by the CHS itself.
- partners involved in developing database tools, such as CARIS, and Oracle MD
- partners involved in converting CHS data into marketable products, such as Nautical Data International (NDI), and Offshore Systems Limited (OSL)
- partners involved in providing real-time components for an ECDIS system, such as the Differential GPS network being established by the Canadian Coast Guard (CCG), and the ODIN / COWLIS / SINECO network of water level observing / predicting stations along the St. Lawrence River.

The relationship among these collaborators in supplying water depths to the mariner is an implementation issue, to be addressed in Chapter 5. The impact on these collaborators, in terms of changing capabilities and responsibilities is dealt with in Chapter 6.

6.3 IMPACT ON OTHER USERS

Other agencies are also concerned with water levels. For example, Public Works and Administration Canada (PWC) provides hydrographic surveying services to other agencies, for the purposes of monitoring channels, dredging, and port construction. The Canadian Coast Guard (CCG) is responsible for maintaining aids to navigation, which includes providing information on safely-navigable channels. In Québec, the CCG also provides the services PWC does elsewhere. The Department of National Defence (DND) has an interest in precise and repeatable bathymetry for mine-countermeasures and other applications. Environment Canada (EC) is responsible for modeling tidal (and other) currents for emergency response to a pollutant spill. A network of benchmarks exist in Canada, many of which have precise geodetic heights, as determined by the Geodetic Survey Division of Geomatics Canada. GSD is also in the process of redefining the North American Vertical Datum (NAVD). Some provincial governments are interested in the integration of CHS high-water line and foreshore information into their resource databases. What are the benefits and/or drawbacks to each of these agencies from an improved method of establishing and recovering water levels?

The needs of oceanographers, hydrologists and the use of vertical datums for gravity field, maritime boundary and global change applications has already been discussed. These users generally have stricter requirements for the accuracy and temporal invariability of the reference surfaces, although they often deal with slowly varying phenomena, which permits long-term averaging of vertical measurements. The use of the geoid as a vertical reference surface is usually required. The extent to which the CHS should cater to these needs was addressed in Carrera [1994].

In order that the seamless vertical-reference surface be fully understood and accepted in the user community, a stategy for advertising and for educating the prospective users is essential. CHS therefore must assume for some time an active educational role, infoming mariners and other users about the issues involved in the new system, its proper usage, and its limitations.

Recommendation 38: CHS should develop a strategy for information and education of potential users of the seamless vertical-reference surface.

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