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Assessment of Hydrographic Data Uncertainty for Seamless Reference Surface

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The development of a seamless vertical reference surface is accompanied by a number of challenges pertinent to the availability, volume and uncertainty of bathymetric and topographic data. Data uncertainty, which is by far the most difficult to deal with, is attributed to various sources of errors including those of geodetic and hydrographic origin. The uncertainties in the geodetic measurements originate mainly from the limitations in the geodetic technique employed, i.e. terrestrial or space. Old nautical charts and topographic maps were based on terrestrial techniques, which are far less accurate than modern space techniques. In addition, the distribution of the positioning uncertainty is not expected to follow a consistent pattern across the chart (map). This is mainly due to the inconsistent datum distortion as well as the discrepancies in the measuring techniques in the subsequent chart (map) versions. The existing paper (and digitized) charts in many areas of the world were also based on old hydrographic surveying methods, for example the lead-line, which are far less accurate than modern techniques such as multibeam echo-sounding surveys. This creates inconsistent depth uncertainty across the chart. As uncertainties are propagated into the estimated transformation parameters, estimated positions and their covariance matrix, it is of utmost importance that they are properly modelled. This paper addresses the issue of uncertainty in hydrographic data and suggests ways to account for it.

KEY WORDS

1. Geodetic measurements. 2. Bathymetric data. 3. Hydrographic data.

1. INTRODUCTION. Bathymetric and topographic measurements have traditionally been collected independently to serve different purposes. In addition, depth and height data were referred to different vertical datums, namely chart datum and the geoid, respectively, which created inconsistency across the land-sea interface. Inconsistency also existed as a result of technological evolution of measurement techniques, old datum distortions and other factors (El-Rabbany, 2003). With the growing number of coastal and offshore applications, it is necessary that a seamless vertical reference surface be established.

The establishment of a seamless vertical datum could simply be carried out through the development of a transformation function between the present datums and the seamless reference surface. This, however, is accompanied by a number of challenges

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pertinent to the availability, volume and uncertainty of bathymetric and topographic data. Data availability addresses issues such as data coverage, both historic and recent. It is known that many regions of the world were either inadequately surveyed or had never been surveyed (see for example Barritt, 2001). This creates a geometrical weakness, which affects the determination of the transformation function. Digital data volume is another challenging problem, which requires appreciation. As stated by Gesch and Wilson (2002), a 50-gigabyte dataset was used for the development of a seamless model covering a small region such as the Tampa Bay. Data uncertainty, which is by far the most difficult to deal with, is attributed to various sources of errors including those of geodetic and hydrographic origin. The uncertainties in the geodetic measurements originate mainly from the limitations in the employed geodetic technique, i.e. terrestrial or space. Old nautical charts and topographic maps were based on terrestrial techniques, which are far less accurate than modern space techniques. In addition, the distribution of the positioning uncertainty is not expected to follow a consistent pattern across the chart (map). This is mainly due to the inconsistent datum distortion as well as the discrepancies in the measuring techniques in the subsequent chart (map) versions. In addition, the existing paper (and digitized) charts in many areas were based on old hydrographic surveying methods, for example the lead-line, which are far less accurate than modern techniques such as multibeam echo-sounding surveys. As such, when merging various sounding data sets inconsistent depth uncertainty would be expected across the chart. Furthermore, uncertainties in the tide measurements, tide prediction and spatial variations in chart datum must be considered in the development of the seamless reference surface.

As uncertainties are propagated into the estimated transformation parameters, estimated positions and their covariance matrix, it is of utmost importance that they are properly modelled. This paper addresses the issue of uncertainty in hydrographic data and suggests ways to account for it. A case study is presented, which shows hydrographic data quality for the Red Sea.

2. DATUM TRANSFORMATION.

Datum transformation establishes the relationship between two different coordinate systems (Hofmann-Wellenhof et al., 2001). A Cartesian terrestrial coordinate system $(X, Y, Z)^{NG}$ is transformed to another $(X, Y, Z)^{GEO}$ by a three-dimensional similarity transformation, as (see Figure 1):

$$\vec{r}^{\,GEO} = (1+sf)\; R(\varepsilon_x, \varepsilon_y, \varepsilon_z)\vec{r}^{\,NG} + \vec{r}_E^{\,GEO} \tag{1}$$

or

$$\vec{r}^{\,GEO} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}^{GEO} = (1+sf)R_1(\varepsilon_x)R_2(\varepsilon_y)R_3(\varepsilon_z)\begin{bmatrix} x \\ y \\ z \end{bmatrix}^{NG} + \begin{bmatrix} x_E \\ y_E \\ z_E \end{bmatrix}^{GEO} \tag{2}$$

where, $(\vec{r}^{\,GEO})^T = (x, y, z)^{GEO}$ and $(\vec{r}^{\,NG})^T = (x, y, z)^{NG}$ are position vectors of P_i in the two systems, $R(\varepsilon_x, \varepsilon_y, \varepsilon_z)$ is a rotation matrix composed of three successive rotations $(\varepsilon_x, \varepsilon_y, \varepsilon_z)$ about the coordinate system axes, $(\vec{r}_E^{\,GEO})^T = (x_E, y_E, z_E)^{GEO}$ is the translation vector between the two systems, and sf is a scale factor. If the seven

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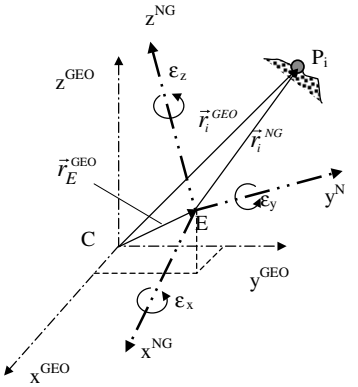


Figure 1. Coordinate Transformation.

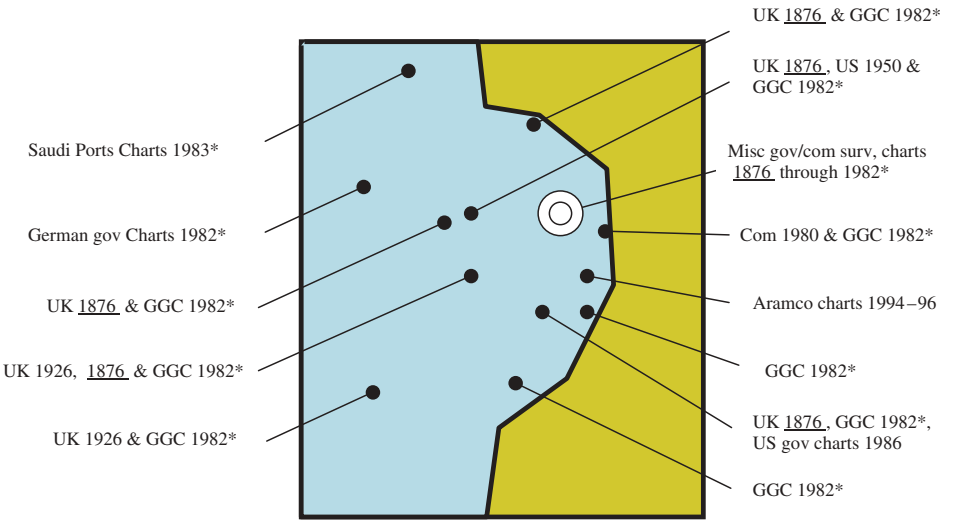


Figure 2. Approaches to Jeddah, Saudi Arabia – Publication date: 08/1987; new edition: 06/2000. (source: Admiralty chart #2599)

parameters (translation vector, rotation angles, and scale factor) of the 3D similarity transformation are known, the coordinates of a point in the NG-system can be transformed into the GEO-system by (2). In general, however, the transformation parameters are not precisely known. In such cases, the transformation parameters can be obtained by comparing the coordinates of common points in both systems. In an ideal world, the determination of the transformation parameters is possible if two common points and an additional common coordinate component are available. In practice, however, redundant, well-distributed common points are used in a least-squares estimation to determine the unknown parameters along with their covariance information. To do this, the non-linear mathematical model (2) must

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first be linearized around the approximate values of the unknown parameters, which takes the form (Vanicek and Krakiwsky, 1986):

$$\boldsymbol{w} + \boldsymbol{A\delta} + \boldsymbol{Br} = \boldsymbol{0}, \boldsymbol{C}_\ell \tag{3}$$

where, $\boldsymbol{A}$ and $\boldsymbol{B}$ are the design matrices, $\boldsymbol{w}$ is the misclosure vector, $\boldsymbol{\delta}$ is the unknown vector of corrections to approximate parameters, $\boldsymbol{r}$ is the vector of residuals, and $\boldsymbol{C}_\ell$ is the covariance matrix of the observations. The least-squares solution for (3) is given by:

$$\boldsymbol{\delta} = -[\mathbf{A}^T(\mathbf{B}\ \mathbf{C}_\ell\mathbf{B}^T)^{-1}\ \mathbf{A}]^{-1}\mathbf{A}^T(\mathbf{B}\ \mathbf{C}_\ell\mathbf{B}^T)^{-1}\mathbf{w} \tag{4}$$

$$\mathbf{C}_{\boldsymbol{\delta}} = [\mathbf{A}^T(\mathbf{B}\ \mathbf{C}_\ell\mathbf{B}^T)^{-1}\mathbf{A}]^{-1} \tag{5}$$

where, $\boldsymbol{C}_{\boldsymbol{\delta}}$ is the covariance matrix of the estimated parameters. As can be seen from (4) and (5), the covariance matrix of the observations, which represents the quality of sounding data and others, directly affects the estimated parameters (i.e., the establishment of the seamless reference surface) and their covariance matrix (i.e., how well the seamless reference surface is established).

3. DATA UNCERTAINTY – A CASE STUDY.

To examine the quality of available hydrographic data, the Red Sea region is selected as a case study. In general, hydrographic data is obtained through one or more of the following sources:

a. National Hydrographic Offices (HOs).
b. Non-government organizations, including private sector, universities, research institutions, and others.
c. Data collected by another country – a number of countries collect and maintain hydrographic data of other nations through bilateral agreements.

The most important source of hydrographic data is the British Admiralty, which maintains charts and navigational publications for the whole world (Hecht et al., 2002). To the author's knowledge, British Admiralty charts are the only source of "complete" hydrographic data, at the commercial level, for the Red Sea. Therefore, the analysis of data uncertainty is essentially based on the British Admiralty charts for the Red Sea. In examining the 50 charts covering the Red Sea, it was found that (see British Admiralty charts of the Red Sea for more details):

- the data used by the charts were collected by many agencies, including local and foreign governments, commercial companies, local or foreign government chart info, which usually lacks important information such as survey details. An example showing the approaches to Jeddah (Admiralty chart #2599) – the busiest port on the Red Sea – is shown in Figure 2. As shown, the chart is composed of 20 different zones; each was surveyed by one or more agencies at different date and scale factor. (N.B. The multi site titled "Misc gov/com …" include 8 very small zones.)
- various scale factors were used for various areas on the same chart (one area is horizontally shifted by 0·1′ on two charts with different scales). In Figure 2, each of the 20 zones has one or more scale factor.
- chart scales varied from 1:7,500 to 1:750,000.

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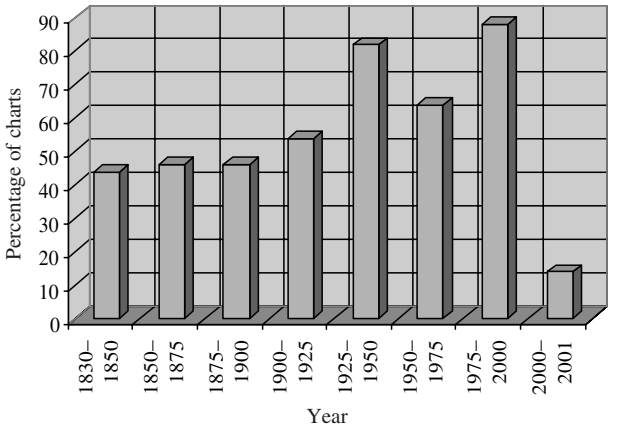


Figure 3. Survey age.

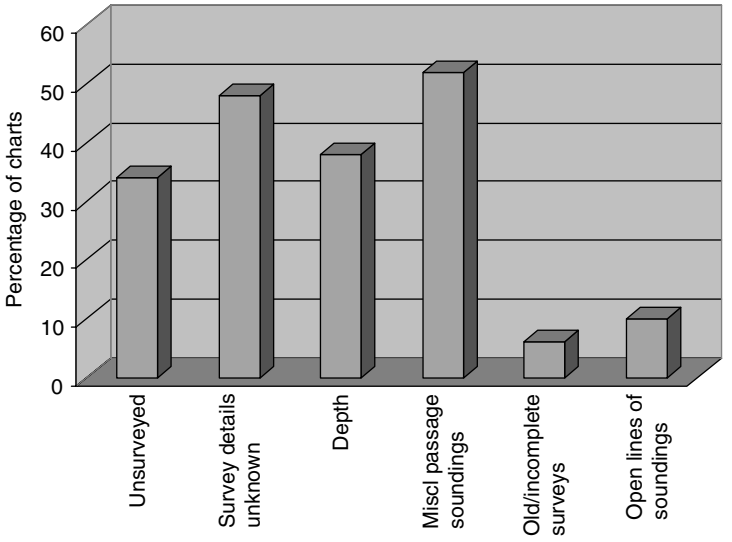


Figure 4. Survey classifications.

- chart publication dates range from 1981 to 2002, while *actual survey* date can go back to 1830 (about 175 years old). Figure 3 shows the age of the survey data for the Red Sea region. It can be seen that over 40% of the charts contain hydrographic data that were collected between 1830 and 1850. It can also be seen that the Red Sea region lacks modern multibeam data.
- none of the charts was shown to have a 100% bottom search.

Other important information, which can be extracted from the British Admiralty charts for the Red Sea area include survey classifications (see Figure 4). It can be seen that 48% of the charts contain areas with unknown survey details, while 6% contain areas with old or incomplete surveys. As well, 52% of the charts contain areas where the soundings were obtained from miscellaneous passages and 10% contain areas

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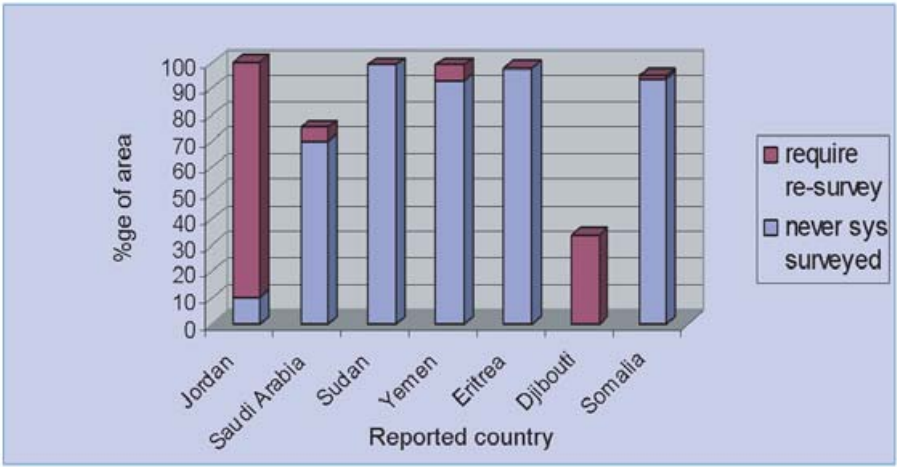


Figure 5. IHO S-55 – Status of hydrographic surveys for the Red Sea (depths 0–200 m).

with open lines of soundings. Obviously, estimating the uncertainty values for those areas would be very subjective. Additionally, 38% of the charts have depths notes, which warn mariners of possible navigation hazards (i.e., large uncertainties) due to one or more of the following (see British Admiralty charts for the Red Sea for more details):

- Most (other words such as *much* or *some* have also been used) of the region covered by the chart has not been systematically surveyed.
- Depth information is obtained from miscellaneous passage soundings, old lead-line surveys, or foreign government charts with unknown details.
- Uncharted hazards/shoals and/or patches of coral may be present.
- Specific areas of charts have not been completely surveyed or derived from a chart based on a general survey, etc.

Although depths notes provide mariners with useful navigational information, they provide a very subjective level of uncertainty information which is not good enough for the development of a seamless reference surface. Figure 4 also shows that 34% of the charts contain completely unsurveyed areas, which means that the uncertainty values for those areas would be infinity. According to the latest IHO report on the status of hydrographic surveying and nautical charting (S-55), the Red Sea is largely unsurveyed. Figures 5 and 6 show the status of hydrographic surveys, as reported by the various Red Sea nations, for areas with depths between 0–200 m and greater than 200 m. As can be seen, only a small fraction of the Red Sea coasts is surveyed.

4. DATA UNCERTAINTY – OTHER PARTS OF THE WORLD. The IHO S-55 report provides more information on the status of hydrographic surveys for other parts of the world, which in turn provides some information about the expected uncertainty levels (see IHO, 2004 for more details). The report shows that there are major deficiencies on the west and east coasts and inland waters of Africa. Other regions with major deficiencies include areas of the South China Sea and

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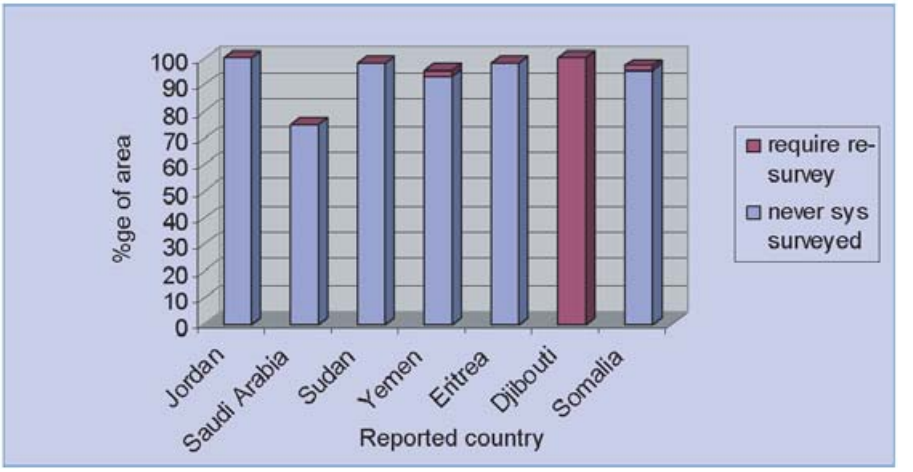


Figure 6. IHO S-55 – Status of hydrographic surveys for the Red Sea (depths >200 m).

Java Sea, areas of the Caribbean waters, and the oceans. In addition, it is reported that there exist large areas of un-surveyed waters in the Persian Gulf. Other reports show that even in developed nations there are areas of low-quality (i.e., large uncertainty) hydrographic data. Examples of those reports are:

- Over 50% of inshore hydrographic data shown on NOAA charts was acquired prior to 1940, which was based on old lead-line and sextant surveys (Wells, 2004).
- Canadian Coast Guard ship, Gordon Reid, went aground in September 2003. The area of the grounding was surveyed in 1923 using old lead-line and sextant with sounding lines of 400 metres apart (Wells, 2004).
- A series of recent ship groundings in the southern Baltic Sea, mostly due to poor navigation and use of inadequate chats (Hecht et al., 2002).
- North Sea area between Britain and Norway was last surveyed in early 20th century (Hecht et al., 2002).
- Charted positions along Norway's north coast are offset by about 400 m (Hecht et al., 2002).

5. ACCOUNTING FOR DATA UNCERTAINTY. As indicated earlier, for a reliable seamless reference system to be developed, it is of utmost importance that data uncertainty is properly modelled. The following are proposed ways to account for hydrographic data uncertainty:

- Conduct new multibeam hydrographic surveys at selected key areas, which would be compared with old surveys to extract statistical information.
- Conduct bathymetric/topographic LIDAR surveys at inter-tidal zone. This helps extract uncertainty information, improve accuracy of shoreline determination, and strengthen datum transformation solution.
- Obtain a reliable regional tidal model, which minimizes tidal uncertainty, through e.g., artificial neural networks or a hydrodynamic model.

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- Install continuously-operating acoustic arrays/GPS-equipped buoys at key locations offshore. Such a system ensures the availability of control soundings at high accuracy and helps map offshore ocean floor and derive global tidal information when combined with data from satellite altimetry.

It should be pointed out that the above list is in no way complete. Other ways to account for hydrographic data uncertainty could be used.

6. CONCLUSIONS. Hydrographic data uncertainty must be accounted for if a reliable datum transformation solution is sought. As shown earlier, existing hydrographic data suffer from a high level of uncertainty, which does not follow a consistent pattern, even within a small area. In addition, current uncertainty representations on nautical charts are very subjective and are not enough for the development of a seamless reference surface.

Extracting uncertainty information of old data is possible with the help of auxiliary data. As a result of unmodelled uncertainty and geometrical weakness in data distribution, a solution for a global seamless reference system would not be reliable. It is recommended that a regional, rather than a global, seamless vertical reference surface be developed, which would be allowed to grow as data becomes available.

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