St. Pölten University of Applied Sciences, Matthias Corvinus-Straße 15, A-3100 St. Pölten

Safe Navigation with an Open Sea Chart

Bernhard R. Fischer

2048R/5C5FFD47 <*bf@abenteuerland.at*>

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Abstract

In today's open world the idea of making an open sea chart is obvious. Several projects started to apply the rules used for the OpenStreetmap to create a free editable sea chart of the whole world and it turned out to be much more difficult because of potential serious consequences in case of charting errors.
A sea chart contains a lot of vital information to a navigator but we cannot just survey every navigational important item on the world, we depend on third-party information.
Thus, data accuracy may be questionable but still valuable. The fact that unauthenticated people are editing data in an open database is a big challenge for an open community since safety and security of life heavily depends on it.
This paper covers basic surveying principles and specifically focuses on mapping lights and depths in open sea charts.

1 Introduction

Seafaring, surveying, and cartography has a very long tradition and in a time ages before today the term "global" had a far different meaning than it has today.
Many similar actions started at the same time in different places. This is true for seafaring. English, Spanish, Portuguese, Dutch people went out to discover the planet. Also thousands of years before them the ancient Greeks, the Romans and the Vikings sailed across their sea, their world.
And all of them started to chart the world to their best knowledge and with methods that have been as accurate as possible for that time. They roughly knew about the shape of our planet, that is that it more or less is a sphere.[1]

We know about famous explorers [1] like *Henry the Navigator* (1394 – 1460) who discovered the coast of Africa, *Christopher Columbus* (1451 – 1506) who accidentally discovered America on his voyage to find another way to India, Vasco da Gama (≈1460 – 1524) who actually found the way to India, *Ferdinand Magellan* (1480 – 1521) who circumnavigated the Earth, and *James Cook* (1728 – 1779) who was not just a great captain but also a brilliant scientist with excellent surveying skills. He charted all of his findings.
The methods used were fairly inaccurate. Various astronomic methods have been developed, most of which were dependent on exact chronometry and even precise measurement of time was a big challenge.[2]
But of course, not just those famous explorers discovered and charted parts of the Earth. Scientists started surveying the country, every city, village, mountain, river and so on.
All of those surveys share some kind of reference system. It defines the origin of measurement.

2 The Figure of the Earth

Defining the origin of a coordinate system is one thing but doing measurements somewhere outdoor and charting this later in such a manner that anyone can follow this is a complete different and difficult task. It was found that the knowledge of the shape of the Earth is imported. *Eratosthenes*[3] was the first who calculated the circumference of Earth with a more or less simple experiment (at least in theory). [12] His estimation was fairly accurate, which was about ±10% of its real circumference.

*Revision 807.

[1] Interestingly from a historic point of view is that this knowledge was lost in the Dark Ages. People thought (or were forced to think) that earth is a disk in the center of the universe.

[2] John Harrison (1693 – 1776) built then revolutionary accurate clocks but he was a misunderstood genius at his time. James Cook successfully used a copy of a pocket watch which was built after Harrison's design. [7]

[3] Eratosthenes of Cyrene, approx. 276 – 195 B.C., Greek mathematician, astronomer.

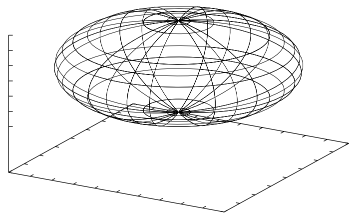

Figure 1: Ellipsoid of Revolution.

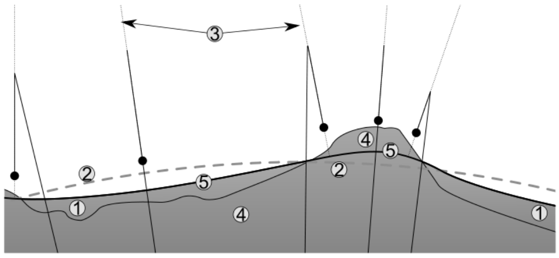

Figure 2: Figure of the Geoid. 1 ocean, 2 ellipsoid, 3 local plumb-line, 4 continent, 5 geoid.

Source: en.wikipedia.org/wiki/File:Geoida.svg

For a long time it was thought that Earth is a sphere. In the 17th century several scientists discovered some oddities which led to *Christian Huygens* (1629 – 1695) and *Isaac Newton* (1643 – 1727) developing oblate models of the Earth. This is basically called a *spheroid* or an *ellipsoid of revolution* (see Figure 1). This is mainly because of the rotation and the gravitation.

Such ellipsoid models come very close to the true figure of the Earth but still do not match precisely. The important mathematician and scientist *Carl Friedrich Gauss* (1777 – 1855) described in 1828 [4] that the true figure of the Earth is expressed by a surface of equal gravitation. Every plumb-line subtends this surface perpendicularly. It is the mean ocean surface with the assumption that the oceans are in an equilibrium. This true figure is called the *geoid*.

Unfortunately, the geoid is an irregular surface and cannot easily be described mathematically and it can be surveyed just by doing lots of gravity measurements all around the globe. It is important and a big advantage to have a mathematical model because it can be used for calculation, like distances, areas, and similar parameters.

Figure 2 shows the difference between a mathematically perfect ellipsoid (2) and the geoid (5). The ellipsoid and the geoid diverge. It is important that there are exact definitions for ellipsoids being used. Obviously, because different ellipsoids would lead to different charting and calculation results. Scientists and nations agreed on ellipsoid parameters. Such an ellipsoid is called *reference ellipsoid*. Of course, different reference ellipsoids have been used in history. Some well known reference ellipsoids are [10] the *Bessel*[4] ellipsoid of 1841, mainly used in Europe, the *Krassowsky*[5] ellipsoid of 1940, mainly used in the Sovjet Union, and the international ellipsoid of 1924 after *Hayford*.[6] All those reference ellipsoids are partially in use today.

Another very well known System is the *World Geodetic System 1984* (WGS84). It defines a reference ellipsoid and currently uses the *Earth Gravitational Model 1996* (EGM96) for expressing the divergence between the ellipsoid and the geoid.[7].

The ellipsoid defines a mathematical shape but for description of exact positions, reference points are necessary. Surveying and charting is done in respect to those reference points. The ellipsoid together with the reference points are called the *geodetic datum*. On a national basis, countries usually have their own reference point(s) and they might rotate the reference ellipsoid being used to the locally best fit.[8] The method based on a geodetic datum to describe a location of a specific object using coordinates is called *spatial* or *coordinate reference system*.

As previously explained datums of countries may differ. Thus, positions may deviate up to several hundred meters from one system to another one (see also Section 3).

Positions are usually defined in *geographic coordinates* given in *latitude* φ and *longitude* λ. The latitude is the angle between the equator and the desired position north- and southwards. It has a range from -90° to 90°. The longitude is the angle between the *prime meridian* and the desired position. It ranges from -180° to 180°. Southerly latitudes and westerly longitudes are defined to be negative. The exact location of the prime meridian is defined by the reference system. It is approximately the meridian which crosses the Royal Observatory of Greenwich. Even though positions are usually given just by latitude and longitude which is two-dimensional, all positions in fact also have a third dimension. This is the elevation. For its definition, a virtual reference plane of 0 meters elevation is necessary. Again, this actually is the geoid. That is why WGS84 includes EGM96 since the reference ellipsoid of WGS84 diverges about ±100 meters from the geoid.

To create maps which are usually drawn on paper,

[4] Friedrich Wilhelm Bessel (1784 – 1864). German mathematician, astronomer, and geodesist.

[5] Feodossi Nikolajewitsch Krassowski (1878 – 1948). Russian geodesist and mathematician.

[6] John Fillmore Hayford (1868 – 1925). US-American geodesist.

[7] WGS84 was revised several times since its introduction. [5]

[8] Germany traditionally used the Bessel ellipsoid with the reference point "Rauenberg". This is the *Potsdam-Datum*.

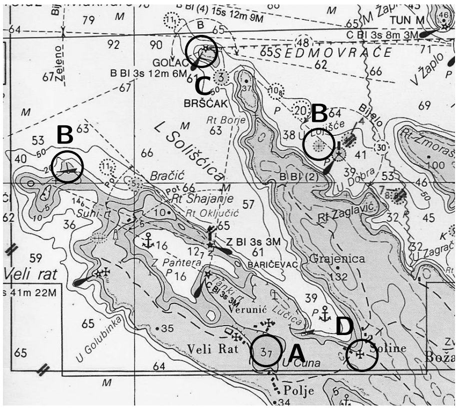

Figure 3: Map section of sea chart. [6]

a map projection [8] is used. It represents a three-dimensional surface (of a sphere, an ellipsoid or another three-dimensional shape) on a two-dimensional plane. Various methods of projection are available but, unfortunately, there is no perfect method. The process of projection always results in some distortions of distance, direction, and area.
One method is the *Mercator*[9] projection. It is a cylindrical map projection and preserves angles and distances in small scales. Thus, the Mercartor projection is used for nautical charts.

Summary

Reference ellipsoids are used because it has mathematical advantages but they differ from the true figure, the geoid. Reference points are positioned to fix the mathematical figure and a coordinate system. This may differ from one country to another one, hence, same coordinates might refer to different real positions. Projections are used to represent three-dimensional shapes on a two-dimensional plane. Distortions always occurs.

3 About Sea Charts

Sea charts contain a lot of vital information to navigators. This is general information about the chart and the charted area, topography (e.g. natural features, landmarks, ports), hydrography (e.g. tides, currents, depths, rocks, seabed), and navigational aids and services (e.g. lights, buoys, beacons). [2]
Figure 3 shows a section of a Croatian chart. It shows depths in meters (A), obstructions (B), lights (C), conspicuous landmarks like churches (D), and many other items. It may be important to point out that the scale of this map is 1:100 000. The black circles used for annotation within the image have a diameter of about 0.3 nautical miles which corresponds to 556 meters. Different from road maps, it is of extreme importance that positions and depths are highly accurate because navigation of vessels is not limited to roads. Underwater obstructions are invisible to the navigator, hence, accurate navigation is used to prevent damage of the vessel, goods, and passengers. Accurate navigation is only possible if the chart is accurate. Nowadays, one might think that global navigation satellite systems like the *Global Positioning System* (GPS) solved the problem of nautical navigation. But this is only partly true. GPS is based on the WGS84 reference system and allows to accurately determine ones geographic position but this position is useless without accurate charts.
To gather accurate positions, all these items are subject to national surveys acquiring exact geographic coordinates. Finally, they end up in a national sea chart. As explained in Section 2 several different geodetic systems exist. This leads to the fact that navigation must be done carefully, specifically in respect to geographic coordinates. The chart in Figure 3 uses a Croatian reference system based on the Bessel ellipsoid[10] which is different from the WGS84 system. A further note on the chart clearly says *"Positions obtained from satellite navigation systems are normally referred to WGS-84 datum; such positions should be moved 0.01 minutes northward and 0.28 minutes eastward to agree with this chart."*. This corresponds to an offset of about 370 meters.[11]

4 Creating Free Sea Charts

Official sea charts are usually copyright protected (like the one of Figure 3), hence, projects aiming to create free sea charts are not allowed to copy items out of the chart. But it is still obvious today to create a free sea chart like it is done with road maps at the OpenStreemap (OSM) project.[12]
Projects that aim to create a free sea chart are the Freie Tonne[13] and the OpenSeamap[14] project. The author currently contributes to the OpenSeamap.
In the previous sections the importance of sea chart accuracy and some reasons for deviation of geographic coordinates have been discussed. Creating a free sea chart by volunteering poses a trust problem. Of course, an official sea chart may also contain errors, thus, a good navigator will not just blindly

[9] Gerardus Mercator (1512 – 1594), Flemish cartographer.

[10] This is pointed out on the notes to this chart which are not part of Figure 3.

[11] The construction parallel of this Mercator chart is N 44° 25', thus, $1852 \cdot 0.28 \cdot \cos 44°25' \approx 370$.

[12] www.openstreetmap.org

[13] www.freietonne.de

[14] www.openseamap.org

trust the chart but he can usually trust that the chart was seriously created. The OpenSeamap is based on the OSM database which basically allows everybody to edit map details anonymously. To our best knowledge, currently no fraud is known but it is supposable that this may happen. Accidental damage of the data may happen also. The necessity for users to register with their real identity would clearly scale down the community contributing to the map data. We think about the *Web-of-Trust* model [3] which seems to be a feasible solution but this is not sufficiently investigated yet. This model allows to establish trust relations to other users without knowing them personally and without the necessity of a central trust center.

Lights

Since sea charts contain many different items, they are split into groups and considered separately. Of high importance are the lights which are absolutely essential. All lights are collected world wide, enumerated with unique identifiers, and published in tabularly organized books. It is the *List of Lights.* The *US National Geospatial-Intelligence Agency*[15] publishes the list as PDF documents without copyright protection. It is obvious to import this list into the OSM database. Unfortunately there are several problems.

- PDF documents do not have any semantic information, hence, data extraction needs a highly sophisticated text processor.
- The list of lights contains errors and the text processor might detect information incorrectly.
- Geographic coordinates are are not highly accurate by default. The list of lights clearly says about positions: *"Approximate latitude and longitude of a navigational aid to the nearest tenth of a minute, intended to facilitate chart orientation (use column 2 and the appropriate chart for precise positioning).".* [9]
- Geographic coordinates usually refer to national reference systems.

Data extraction of the PDF document is done in several steps. First, it is converted into an HTML document with the tool pdftohtml by Ovtcharov and Dorsch. Then the major text extraction is done with a perl script which heavily uses regular expressions and some rules that define dependencies. This is possible because the document still has a loose structure. the result is a flat tabular file (CSV) which is then ready for post processing. Data is checked for integrity where applicable and then imported into an SQL database from which an OSM[16] file can be generated.

All steps of above are not 100% perfect yet but it is still just a technical issue. A much bigger problem are the geographic coordinates. Coordinates given in tenths of a minute are just as accurate as about 185 meters.[17] While using official sea charts which are usually scaled at 1:100 000 this is not such a problem because of the large scale. But when using digital maps it is possible to zoom in into a much higher zoom level and it is annoying if mapped items seem to be completely dislocated even if this would actually be a misuse of the chart. The second problem of diverging reference systems is even a bigger one. This is due to the fact that it is actually not known which coastal regions are charted within which reference system.[18] This leads to position offsets by default. Some kind of automatic position correction seems to be necessary because the world wide list of lights contains roughly about 50 000 entries.

Depths

Compared to lights, an even bigger challenge is charting of depths. When approaching the shore or a port it is important to know depths at an accuracy of at least 0.5 meters. Specifically, this is true when cruising with yachts. Dependent on the type of boat their draft ranges from 0.5 meters up to 4 meters and it may be decisive if a port can be entered or not. Unfortunately, there is no such a "list of depths" available. Thus, the community itself has to survey the depths. It seems to be trivial but it is not.

In Section 2 the geoid was defined to be the plane of equal gravity which is equal to the surface of the oceans if they are in an equilibrium. Unfortunately, this is an ideal assumption which does not reflect reality. The true surface of the oceans depend on tide, winds, and currents which means that they are in permanent movement. Thus, depths of sea charts are usually referred to a virtual static sea level. In respect to sea charts this is called the *chart datum.* It may differ from one region to another one. In the Mediterranean sea it is common practice to refer to the *lowest astronomical tide* (LAT). It is the computational lowest value but together with winds and currents the actual sea level may in rare cases even be below this value. German charts of the north sea usually refer to the *mean low water springs* [11] which is above the LAT.

The navigator has to use the chart depths together

[15] www.nga.mil/maritime

[16] XML-based file ready for the OSM API.

[17] 1' along a meridian is defined to be a nautical mile which is approximately 1852 meters.

[18] At least at the time of writing of this paper even though we are in contact with the *International Association of Lighthouse Authorities* (IALA).

with a *tide calender*[19] to compute the actual depth at a specific position.
In the opposite case when sounding depths this means that the measured value has to be corrected back by using a tide calender to get a reference depth for this specific location. And this is not a trivial task, at least for somebody who is not highly familiar with this process. A further problem is that when using OSM everything is referred to WGS84 which includes a gravitational geoid model. Thus, it has its own plane of a virtual sea level which is different from what is common in specific regions. Of course, the depths actually depicted in the digital chart are just a matter of implementation of the renderer[20] but it would require that an "OSM geodesist" would have to correct his measured value up to WGS84. This further requires knowledge about the relation between the chart datum to which the tide calender refers to and the WGS84 system.
A further difficulty lies in the method of measurement itself. Modern yachts are always equipped with echo sounders and the navigator can easily just read the depth off a display. To interpret this depth correctly the reference point of the echo sounder has to be known. Specifically in the charter business it is common practice to set the reference of the echo sounder below the keel for safety reasons. Thus, the depth shown on the display is always too less and would require to be increased by at least the draft of the boat.
These obstacles clearly lead to the conclusion that adding simple nodes being tagged by a single depth value is negligent and would induce people to set such nodes without knowing the essential background.

5 Summary and Conclusion

Geodesy and cartography has a long history. Methods of surveying have been highly improved with evolving technology but there is still no perfect solution since it is not a trivial task to find a good model for the Earth but models are necessary for creating charts. Models are permanently refined and improved.
Nowadays, most people know and use GPS and have heard about WGS84. The ease of use of handheld GPS devices give the impression that surveying is a simple tasks. This assumption may be true if real accuracy is not critical but it is dangerous when surveying sea charts since accuracy is seriously important. Open source projects always may suffer from adversaries being destructive but in reality it is shown that open source tends to be "self-healing" since many people cross check code. Similar rules may also apply to *open data* projects like OSM or Wikipedia. Nevertheless some kind of a trust model in respect to user edits and data correctness seems to be necessary because of the mission critical information at least in respect to free (and open) sea charts. This is not enough investigated yet.
The OpenSeamap project is on the way to import the list of lights into the database after several steps of integrity checking. Charting of depths is a big challenge which is currently elaborated on. At this stage of research there is no solution ready but it seems to be feasible. It is clear that nodes with single depth tags are negligent and dangerous. We (the OpenSeamap depth project members) currently try to find a computer aided solution helping people to enter and correct sounded depth values. Currently it seems necessary to let those values end up within a separate depth database which is combined by overlay into the sea charts.

[19] A set of tables which allow to manually calculate the actual tide at a specific day and time.
[20] The piece of software that creates a visual map out of the database.

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