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HORIZONTAL DATUMS FOR NAUTICAL CHARTS

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INTRODUCTION

Marine navigation charts are based on many and varied geodetic datums in use throughout the world. These datums range from local datums to the DoD World Geodetic System (WGS) 1972. In many cases, the datums for adjoining charts will differ, although this difference will usually introduce only minor errors into the solution of navigational problems. There are times, however, when even small errors can be very disconcerting, if not dangerous, and it is under these conditions that it is advantageous for the navigator to possess some knowledge of the factors in datum selection and chart construction which lead to apparent discrepancies in position plotting.

It is equally important for the chart compiler or cartographer to understand the basic principles of navigation and, therefore, the need for establishing clearly definable horizontal datums on charts. For this reason, the author has aimed at tracing the evolution of datums on Defense Mapping Agency (DMA) nautical charts, mainly for the benefit of cartographers who must realize how the product they produce impacts on the safety of navigation in ways other than the portrayal of up-to-date information such as navigation aids, depths, etc. This paper discusses the differences between chart datums and coordinates determined by using various navigation systems, accuracy requirements for nautical charts, navigation system accuracy requirements as related to datums, and datum transformation methods.

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CHART DATUMS

Impact on Navigation

The navigator encounters differences too often when piloting and shifting his plot from chart to chart, each based on a different datum. The result usually shows the navigator's position relative to land as being different on the two charts. To avoid this problem, standard advice given in Notices to Mariners should be followed : namely, transfer or plot positions by range and bearing from a landmark common on both charts. In particular, with the increasing use of long-range electronic navigation systems, the discrepancies caused by difference in datums are quickly evident and require adequate correction techniques.

Plotting sheets and positioning tables for electronic systems (other than radar) are by necessity computed and plotted on a single datum for the entire area of coverage. Because most approach and coastal charts use a local datum, the projected track, which is determined at intervals by the electronic system and transferred to the chart, will contain the datum error. For this reason it is essential to confirm the ship's location by piloting methods at the earliest opportunity once the track is graphically established on the chart.

For example, consider a navigation system coordinate readout based on the DoD World Geodetic System 1972 (WGS 1972) and a chart oriented to an astronomic position at the observatory at Tokyo, Japan. A discrepancy in position coordinate values can then be expected in relation to chart graticule and features. The difference between WGS 1972 and chart plotted coordinates can be as great as approximately 500 meters. If the navigation system is LORAN C with an average accuracy of 460 meters, then a non-compensating resultant position-fix error could be as great as approximately 900 meters or more. In other cases, datum differences may be negligible because of the small shift involved at chart scale. Thus, it is seen that the newer sophisticated electronic navigation systems of high accuracy can lull the navigator into a false sense of security.

Definition and Methodology

As the Earth's surface is highly irregular, computation of precise positions on its surface is impossible. The surface coinciding with mean sea level is called the geoid. The geoid cannot be accurately modeled. The mathematical figure that best represents the geoid is an ellipsoid of revolution. An ellipsoid can be uniquely defined by knowing either its semimajor and semiminor axis or the semimajor axis and the flattening. Different size ellipsoids have been adopted for different areas of the Earth. The shape of the geoid for the area at the time the basic control is established is used to determine the best fitting ellipsoid.

After adopting an ellipsoid, an origin for positions on the ellipsoidal surface must be determined. This is commonly done by determining à precise position using astronomic observations which are made with an instrument with extremely sensitive level bubbles. The resulting astronomic position is adopted as the starting geodetic position. The geoid and ellipsoid are normally defined as tangent at the datum origin. Datums can originate from one precise astronomic position and astronomic azimuth. An azimuth to a second point is required to determine orientation for all other positions computed on the datum.

A datum has now been precisely defined – it has a stated ellipsoid size, an origin point, and initial azimuth. On datums originating from one precise astronomic position and azimuth, all subsequent positions must be determined by measuring angles and distances. The accuracy of positions in the network relative to the datum origin will decrease as one goes away from the origin (error propagation).

The accuracy of the network is increased by scale and azimuth control throughout the network. This involves the measurement of distances and astronomic azimuths at specified intervals. The astronomic azimuth is reduced to a geodetic azimuth by the determination of astronomic longitude and the application of the Laplace correction. In order to reduce directions and distances to the ellipsoid, deflections of the vertical and geoid heights must be determined throughout the network. This is done by the determination of astronomic positions from which astrogeodetic deflections of the vertical and a corresponding geoid profile are determined.

Deflections of the vertical can also be determined from gravity anomalies or a combination of gravimetric and astrogeodetic data. In recent years, some datums have been determined by minimizing the deflections of the vertical and geoid heights over the area of interest. The results constitute a "best fitting" datum and "best fitting" ellipsoid for the area.

Before the advent of the geodetic satellite, geodetic datums were established as outlines in the preceding paragraphs. Within the last two decades, geodetic satellites have enabled us to determine positions on the Earth's surface in an Earth-centered coordinate system. The Navy Navigation Satellite System (NNSS) is currently the most accurate navigation system and, when supplemented with additional geodesy tracking stations, provides the most accurate all-weather satellite geodesy system. NNSS consists of a set of five or six satellites in polar orbit which broadcast time and position (ephemeris) at 2-minute intervals. Each satellite contains a stable oscillator and is tracked using the Doppler principle or technique. These satellites transmit a pair of stable frequencies which can be received by a Doppler geodetic receiver on the ground. If the space positions and time of the satellite are known, the ground position of the receiver can be determined.

Two different kinds of ephemerides are determined. A predicted broadcast ephemeris is determined from data acquired at four tracking stations in the United States. The orbit parameters are injected into the satellites and updated every 12 hours. This broadcast ephemeris is determined for navigation purposes in a near-real-time environment. It can be used for geodetic or cartographic purposes if the accuracy requirements are between 5 and 10 meters. The other ephemeris determined by DMA from the NNSS is the precise ephemeris. The precise ephemeris is an after-the-fact determination from data acquired from the worldwide tracking network called TRANET which is operated by DMA. Positions determined from the precise ephemeris have an accuracy of 1.5 meters at 90 percent in each coordinate axis in the Earth-centered coordinate system. The coordinate system of the precise ephemeris can be transformed to the WGS 1972 by a scale and longitude correction. WGS 1972 can be used to relate the various local and regional datums to a single consistent worldwide system.

Local Astronomic Datums

Before the use of the electronic navigation systems, the navigator was concerned only with celestial observations or the measurement of the range and bearings of land points. Most nautical charts were published on local datums that were also related to celestial observations; therefore, both systems (chart and navigation) were based on the same reference datum - local astronomic.

Regional Datums

As countries developed their basic control networks, more international survey ties were made. As a result, it was possible to adjust the surveys of several countries on the same datum or geodetic system. This constituted a regional or continental datum. Regional datums were usually a best fitting datum in that deflection of the vertical and geoid heights were minimized over the region. Among major regional datums are: European - 1950, Indian - 1916 and North American - 1927.

Inasmuch as the navigator used celestial observations for positioning, his results differed from the chart positions by the amount of the deflections of the vertical on the regional datum. However, as the navigator's fix was accurate to no better than 2 to 3 kilometers, no significant differences were initially evident between the chart and the navigation system. Eventually, differences between overlapping charts were detected by navigators as a result of some charts being adjusted to regional datums and others left on local datums until revision editions are programmed. Even today, numerous charts remain on local astronomic datums because it has not been practicable to convert them to the newer datums.

As already noted, horizontal datum differences between charts assumed greater importance during the period of growing use of new navigational positioning systems; for example, the LORAN A electronic positioning system which was developed in 1943. This system and others that followed transmitted or received electronic signals from sites positioned on either local astronomic or regional datums, and the resulting ship position fixes were referenced to the transmitter or receiver site datum. Unfortunately, some coordinate values could not be transformed from local astronomic to regional datums. Therefore, slight differences developed between positions developed by the electronic systems and those plotted on the charts. The differences were not positively determinable because the inaccuracy of the LORAN A was of greater magnitude than the datum difference.

When electronic positioning systems were upgraded through better electronics and improved system calibrations as provided by LORAN C, small differences between chart datums and electronic systems became readily apparent and troublesome to deal with, especially on the larger scale charts.

Mercury 1960

The Mercury 1960 Datum, developed by the U.S. Army Map Service, is recognized as the forerunner to the satellite-derived geodetic datum. It was an ambitious and successful attempt to provide a single datum to which positions on three continents (North America, Asia, and Europe) could be related. Specific formulas were developed that enabled conversion from any of the regional datums (North American, Tokyo, and European) to the Mercury 1960 Datum.

Although chart graticules were not placed on the Mercury 1960 Datum, datum transformation notes were furnished up to 1972 to provide users of emerging satellite navigation systems a reference datum closer to actual satellite-derived positions.

Mercury 1960 Center of Mass

As more satellite observations were being processed, it became obvious that the original Mercury 1960 Datum did not provide positions compatible with satellite-derived positions, because it was not based on the center of mass of the Earth. In addition, transformation formulas were only available for the three continental areas. Inasmuch as the primary objective was to provide a reference datum that could be related as closely as possible to actual satellite-derived positions, a new approach was taken. That is, actual satellite-derived positions were reduced to the Fischer 1960 ellipsoid (semimajor axis = 6378166 meters, flattening = 1/298.3). The differences between the Local or Regional datums and the satellite positions, reduced to the Fischer ellipsoid, were computed and yielded datum transformation parameters.

After the launch of the first Soviet Sputnik in 1957, the United States made a concentrated effort to place an American satellite in orbit around the Earth. When this goal was achieved in 1958, several systems with geodetic applications were soon developed. Several approaches were tested using ballistic cameras, electronic ranging, Doppler, etc. Names like SECOR, TRANET, BC-4, PC-1000 were used to designate the various systems. Using observations from these systems, plus gravity surface data and worldwide astrogeodetic data, various geodetic models were developed. Eventually, the data were weighted, recomputed, and a single model adopted by the Department of Defense.

DoD World Geodetic System 1972 (WGS 1972)

In March 1974 the Defense Mapping Agency adopted the model known as the DoD World Geodetic System 1972. This geodetic system contains the results of all previous satellite positioning systems and extensive conventional surveys and gravity surveys. After intensive study on the impact of WGS 1972 on chart productions, it was adopted by the DMA Hydrographic Center (DMAHC) as the official reference datum for all nautical charts in July 1975.

Operational Datum

An operational datum is a datum to which the latest geodetic control positions are related. Operational datums are frequently updated as new land and satellite surveys are conducted. Whenever the operational datum is tied to either a regional or world datum, one of them may become the operational datum.

Preferred Datum

The preferred datum is the datum projected to be the best for an area, even though the current geodetic control positions are not related to it. The WGS 1972 datum is the only preferred datum for DMA nautical charts.

NAVIGATION SYSTEM DATUMS

Celestial. – All celestial observations are considered to be on local astronomic datum.

Radio Beacons. – These are plotted on the chart which may be on either local, regional, or worldwide datum. Notice to Mariners positions for radio beacons must be plotted with extreme care when the datum is not listed, as the position could be related to any datum. If positions of unknown datum must be plotted by the navigator on a chart, a circle should be drawn around the plotted position with the radius of the circle being the maximum known datum difference for the area.

LORAN A. – Transmitter positions have been published on local, regional, Mercury 1960, and WGS 1972 datums. For lack of a tie-in, local datum sites could not be shifted to the Mercury 1960 and WGS 1972 datums; however, the majority of LORAN A charts are either on Mercury 1960 or WGS 1972.

LORAN C. – All transmitter positions have been shifted to WGS 1972; however, positions were published previously on all of the other major datums. The majority of LORAN C charts are either on Mercury 1960 or WGS 1972.

OMEGA. – All transmitter positions are on the WGS 1972 datum, and all charts for this system can be considered to be on the WGS 1972 datum because of their scales being generally between 1:300,000 and 1:2 million.

NNSS. – If one uses the broadcast ephemeris, the resulting positions will be in an Earth-centered coordinate system. This Earth-centered coordinate system is *not* WGS 1972, but is related to WGS 1972 by the following approximate shifts in position :

Latitude : 0.00″
Longitude : 0.26″
Ellipsoid Height : − 5.27 meters.

The shifts given above are added to a position obtained from the broadcast ephemeris, assuming the broadcast solution is given on the WGS 72 ellipsoid, to obtain WGS 1972. Some manufacturers of Doppler receivers provide transformations from WGS 1972 to local or regional datums on the assumption that broadcast ephemeris positions are on WGS 1972. This is not the case since the shifts given above must first be applied to obtain WGS 1972. Caution should be used in applying any datum shift constants, as they are subject to periodic updating when additional and usually more accurate data are obtained. If a charting agency uses updated datum transformation constants to position electronic lattice on its charts and navigators use older values, then errors in the datum shifts will result.

NAUTICAL CHART HORIZONTAL ACCURACY MEASUREMENTS

Nautical charts are supposed to meet certain horizontal accuracy limits, based on the intended use for each chart, although it is not always possible to do so because of the absence of identifiable ground control on the charts or chart sources. For surface navigation on such chart types as Harbor, Approach, Coastal, and General, the criteria are that "90 percent of all well-defined planimetric features, except those unavoidably displaced by symbol exaggeration, are located within 2 mm (0.08 inch) of their geographic position with reference to a prescribed datum". For example, a feature on a 1:2 500 chart is required to be within 5 meters; whereas, a 1:600 000 chart must be within 1 200 meters. Many charts produced prior to 1974 have not been evaluated for accuracy and are unlikely to fall within the above accuracy standard. However, if a datum shift note has been applied to the U.S. chart, it has been evaluated for horizontal accuracy and can be considered to be within the prescribed limits.

NAVIGATION SYSTEM ACCURACY

Several factors must be considered when determining navigation system accuracy. Celestial systems are affected by the observer's experience and ability, timing errors, number of observations, stars observed, and geometry involved, to list a few. Radio beacons used for range and bearing or intersection are affected by the size of the angle of intersection, beacon distance, signal power, and atmospheric conditions. Electronic navigation systems are affected by the knowledge of the propagation of electronic radiation, ionospheric disturbances, geometry of line crossings, instrument errors, and resolution. The preceding list of factors is by no means all inclusive as each system is affected by many other smaller conditions. Yet each system can be considered as having a nominal accuracy based on average conditions.

NAVIGATION SYSTEM EFFECT ON DATUMS

As previously discussed, the increased accuracy of navigation systems is uncovering heretofore unknown errors in charts. Some chart users, when plotting a course using celestial observations, would draw an error circle of 3 kilometers around navigational dangers. This error range was larger than almost all datum differences encountered, therefore, no problem was indicated. However, using LORAN C of the NNSS with accuracies to within 463 and 160 meters, respectively, depending on operating conditions, a navigator can now plot error circles smaller than the normal datum shift. The effect of the datum shift on the error circle can be viewed as shifting the entire error circle in the direction of the datum difference. Electronic navigation systems can be referenced to any datum; therefore, the navigator must be aware of the reference datum for each navigation system used.

BASIC CHART DATUM PROBLEM

A basic problem of nautical charts and their datum differences is that the latter cannot be reconciled until all the charts covering the same area pass through a corrective production cycle. Additionally, datums are developed by field surveys, whereas charts are compiled from many different source materials which include surveys and other published maps and charts that need datum adjustments.

As noted earlier, prior to the calibration of LORAN C and use of NNSS navigation system accuracy was usually less than nautical chart accuracy. However, the present navigation systems make it feasible to position a ship to within 160 meters depending on operating conditions. If nautical charts are not properly corrected for datum differences, users will not realize the true accuracy of which the navigation systems are capable. More important, if a navigator employs a variety of navigation tools – each referenced to a different datum – his position fixes will vary considerably unless they are shifted to one datum. Several positioning problems may be encountered due to datum differences; however, without being aware of them the navigator might assume incorrectly that errors were due to oversteering, faulty navigation, or poorly compiled charts.

CHART DATUM TRANSFORMATION

Significance for Plotting

The application of a datum conversion from one datum to another, for example, local to regional or local to WGS 1972, causes a direct shift of all positions on the chart in relation to its graticule. Therefore, the use of datum conversions is necessary whenever the magnitude of the datum shift can be plotted on the chart. The well-known standard for manual plotting ability is 0.10 mm. Therefore, any datum shift that amounts to more than 0.10 mm should be applied. For example, a 1:2 500 chart should have any datum shift over 0.3 meter (ground) applied; whereas, a 1:600 000 chart requires that any datum shift above 76 meters (ground) be applied. If datum shifts are not applied, the shift can be viewed as an additional positioning error on the chart.

Notes

Since January 1968, various versions of datum transformation notes have appeared on DMA nautical charts. The initial notes provided information to draw new graticules on the chart. Included with the note was an example of shifting the charted position to the other datum (fig. 1). These initial notes provided for transformation from chart to local, local to regional, local to Mercury 1960, or regional to Mercury 1960 datum. The rationale for this type of note is that if a mariner is plotting continuous fixes, it would be easier to shift the graticule than to shift each fix. The example of shifting a charted position to the new datum was given as a check on the graticule shift. During the period, no chart graticules were changed to either the Mercury 1960 or world datum. The majority of the

MERCURY DATUM

To place this chart on Mercury Datum, shift all parallels .... seconds (north, south) and all meridians .... seconds (east,west).

PREFERRED DATUM ADJUSTMENT

To place this chart on the European Datum, shift all parallels 3 seconds (south) and all meridians 10 seconds (east). In effect, this shift changes the coordinate values of charted features as follows:

St. Stephens Church –

Charted Position	16 25'46"N	11 32'40"E
Correction	– 3"	+ 10"
European Datum	16 25'43"N	11 32'50"E

FIG. 1. – Sample graticule shift note.

(1) Chart is on the preferred datum.

SAMPLE NOTE

WORLD GEODETIC SYSTEM DATUM ADJUSTMENT.
To place this chart on WGS 1972 Datum, shift all parallels 11.5 seconds south and all meridians 9.8 seconds east.

(2) Chart not on the preferred datum.

SAMPLE NOTE

World Geodetic System 1972 Datum.
To place this chart on WGS 1972 Datum, shift all parallels .... seconds (north, south) and all meridians .... seconds (east, west).
WGS 1972 Datum correction unrelated to *(Preferred Datum)* adjustment.

FIG. 2. – Sample graticule shift notes (WGS 1972 Datum).

notes corrected charts by placing them on either a known local datum or a regional datum.

Prior to July 1972, only charts covering the three continental areas for which the Mercury 1960 Datum was developed carried Mercury 1960 Datum notes. In addition, charts of 1:100 000 to 1:250 000 were the only scales required to provide the notes. This requirement was levied in support of updating charts for use by both satellite navigation and LORAN C systems. All LORAN C sites were being updated to Mercury 1960 to alleviate the problem of the same LORAN C rate being on different datums.

From July 1972 to July 1975, Mercury-Center of Mass transformations were depicted on charts instead of the original Mercury shifts. However, the words "Center of Mass" were not added to the actual note shown on the chart. As a result, Mercury transformations could be based on either the original Mercury datum or the satellite-compatible Mercury-Center of Mass datum.

All charts of scales 1:600 000 and larger were to provide datum conversion notes to the WGS 1972 when possible (figure 2). In addition, all new compilations were produced on WGS 1972, when feasible. On charts compiled on WGS 1972, notes provided methods to shift the chart's graticule to local or regional datum. However, upon receiving inquiries from mariners on the application of datum shifts using the graticule shift notes, it became apparent that the note was being misinterpreted and caused confusion.

In May 1978, after consultation with both military and commercial mariners, a new series of notes was devised (figure 3). If the chart is compiled on the WGS 1972, the first note provides for the transformation of a navigation fix related to the operational datum to be plotted on the chart. The second note allows the mariner to plot a WGS 1972 satellite-derived position on a chart compiled on either a local or regional datum. The third note states that the chart

1. Chart constructed on WGS 1972 :

a) Depict this note when chart is constructed on WGS 1972 :

TO THE NAVIGATOR

Chart is based on WGS 1972 datum; therefore, no adjustment is necessary to position fixes determined by navigation system based on WGS 1972.

b) Depict this note to position operational datum on the chart (operational datum is either a local or regional datum) :

TO THE NAVIGATOR

Operational Datum Adjustment.

To position (operational datum name) coordinates on this chart :

Add/Subtract .... seconds to/from latitude
Add/Subtract .... seconds to/from longitude

2. Chart is not constructed on WGS 1972 :

a) Depict this note to position WGS 1972 coordinates on the chart datum when the chart can be shifted :

TO THE NAVIGATOR

World Geodetic System Datum Adjustment.

To position WGS 1972 coordinates on this chart :

Add/Subtract .... seconds to/from latitude
Add/Subtract .... seconds to/from longitude

b) Depict this note on the chart when the chart cannot be shifted to WGS 1972 :

TO THE NAVIGATOR

This chart cannot be shifted to WGS 1972 datum because of (list one of the following reasons dependent on geodetic analysis by DMA).

1. Internal inconsistencies.
2. Lack of control points.
3. Lack of datum connection to WGS 1972.

FIG. 3. – Series of new datum adjustment notes.

cannot be placed on WGS 1972. In addition, when possible, a note positioning operational datum coordinates on the chart is provided.

Formula

As mentioned previously, under *Navigation System Datums*, the application of the datum shift formula must be made with caution, as the constants required are updated periodically. The exact constants used by the geodesist are not likely to be known by either the cartographer or mariner. Presently, the Defense Mapping Agency Hydrographic/Topographic Center is using the abridged Molodensky formulas for the majority of all datum transformations.

PRESENT STATUS OF CHART DATUMS

All charts must be individually evaluated for horizontal accuracy before datum shift can be recommended. If the evaluation indicates that features on land areas contain inconsistent deviations from their respective survey-controlled positions, then a datum shift cannot be made. The evaluation includes verification of the datum on which the chart is based. Survey control points based on the operational datum are compared with charted features during the evaluation process. Occasionally, charts that are reportedly based on a particuler datum do not conform to control points on that frame of reference. In such cases, notes are provided to shift the chart datum to the operational datum.

Presently, over 40 percent of the nautical charts produced by DMAHTC at 1:600 000 scale and larger have been evaluated for horizontal accuracy. Out of 1 500 charts evaluated, over 800 can be placed on WGS 1972. The other 700 cannot be converted to WGS 1972 due to the lack of either control points depicted on the chart or a connection between the operational datum to WGS 1972. Given the present rate, it will take 2 years before all charts have been referred by correction or non-correction notes to WGS 1972.

Chart users should write to Director, Defense Mapping Agency, Hydrographic/Topographic Center, Washington, D.C. 20315 for any specific chart conversion to WGS 1972.