Establishment of chart datum and vertical datum transformation for hydrography in the Chinese Great Wall Bay, Antarctic Peninsula

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Abstract

The Great Wall Bay has become an important investigation area due to the establishment of the Chinese Antarctic Great Wall scientific research station. Establishing a seamless chart datum and its transformation model with other vertical data is the key to unifying sea–land measurement in vertical references. In view of this, two transformation models are constructed using two different realizations of the geodetic height of the mean sea surface (MSS), coupled to a seamless chart datum model of Lowest Astronomical Tide (LAT). One transformation model (Solution1) forms MSS height by summing modeled values of the EGM2008 geoid and averaged absolute dynamic topography from January 2017 – April 2018 via gridded satellite altimetry products. The other transformation model (Solution 2) utilizes the DTU15 gridded MSS geodetic height product, derived of multi-mission satellite altimetry from 1993-2015. The LAT seamless chart datum model utilizes tidal constituents derived from the Atlantic Ocean 2008 model. The experiment area is located −62.350° to −62.100° S and −59.050° to −58.600° W, which includes the entire Great Wall Bay, and the accuracy of Solution 1 and Solution 2 have been assessed to be 12.0 cm and 11.2 cm according to the error propagation law. Then, Compared with the field observation result by pressure tidal gauge in the Great Wall Bay, the Solution 1 and 2 exist differences of 127.6 cm and 42.2 cm, respectively. This shows that Solution 2 is much

better than Solution 1, although it is still far exceeding the accuracy evaluation of the solutions. The reasons for this comes down to the lengths of time of realized MSSs and poor accuracy of satellite altimetry in the coastal waters.

Keywords: Seamless Chart datum; Vertical datum Transformation; DTU15; Mean Sea topography; Tidal Field Observation; Great Wall Bay

Introduction

The Great Wall Station is the first scientific expedition station established by China in the Antarctic. It is located at the Fildes Peninsula to the west of King George Island in South Shetland Islands of the Antarctic and bordered by the Great Wall Bay (a small bay in the Maxwell Bay) to the east. The Great Wall Bay is wide and deep and easily accessible. Since the establishment of the expedition station, several investigation activities, such as geological exploration, topographic measurement, precision leveling, station building elevation control, settlement monitoring, and vertical crustal movement monitoring, have been performed at various scales (Xu 1989), and 1:500 topographic mapping has been conducted several times in the Great Wall station area. Moreover, a high-precision 3D map of the Great Wall station was obtained via tilting photogrammetry in 2016. With the increase in investment for scientific research and the need for station expansion, the Chinese expedition initiated bathymetry on Great Wall Bay (Ma et al. 2010). However, accurate bathymetric results are only achievable when it is performed alongside tidal level observation, chart datum calculation, and water level correction. Aside from this method being regarded somewhat inefficient, the observed tidal level data for calculating chart datum should be long enough, otherwise results in an inaccurate chart datum and wrong depth information. In addition, the results from topographic surveys and bathymetry in the station area have been difficult to unify due to their varying vertical references. Therefore, the establishment of an accurate and seamless chart datum and conversion model that can be unified with other vertical references, such as the WGS 84 reference ellipsoid, can reduce costs and improve bathymetry precision, thus laying the foundation for the integration of data derived from land and sea interfaces (Adams 2003, 2005; El-Rabbany 2003; El-Rabbany and Adams 2004; Zhang et al. 2005).

With the advent of GPS technology and the increasing accuracy of observations, many organizations and communities have attempted to link the zero point of tide gauge with the reference ellipsoid through GPS survey on the tide gauge benchmark, such as the work conducted by the

Canadian Hydrographic Service in the 1990s (O'Reilly et al. 1996; Robin et al. 2016). Isolating chart datum from the reference ellipsoid has helped create separation surfaces, and it is also known as SEPs (Lefaivre et al. 2010; Maltais 2002). The National Oceanic and Atmospheric Administration National Geodetic Survey implemented the VDatum Project to convert various vertical references, including tidal, orthometric vertical, and ellipsoidal references, in the United States (Parker 2002; Parker et al. 2003). The United Kingdom Hydrographic Office's Vertical Offshore Reference Frame Project also established a conversion model by using several vertical data in the offshore (Iliffe et al. 2007; Iliffe et al. 2013). In addition, a vertical datum conversion approach that facilitated the creation of seamless elevation datasets across the Australian littoral zone was developed, and an ellipsoid-based conversion approach was adopted (Keysers et al. 2015; Martin and Broadbent 2004; Todd et al. 2004). The hydrography branch of International Federation of Surveyors (FIG Commission 4) also proposed a work plan in 2002, aiming to develop a seamless vertical reference frame for use in hydrography and marine navigation.

At present, a similar vertical datum transformation model with highly accurate seamless chart datum have not been developed for the Chinese Great Wall Bay. Therefore, this study aims to establish a seamless chart datum and construct a separation Δh model between the chart datum and reference ellipsoid. Subsequently, the models' accuracy will be evaluated and analyzed according to the filed observations by tidal gauge in the Great Wall Bay.

Methodology

Fig. 1 shows several common vertical data involved in hydrographic measurements. The mean sea surface is the long-term average of gravity and dynamic oceanographic effects, upon which the seamless chart datum is applied. The mean sea surface has high and low points, and the height difference of the mean sea surface to earth's geoid is called the mean sea surface topography. The chart datum L is located below the mean sea surface and negative, and it usually adopts the lowest astronomical tide (LAT) in China and usually characterized by discrete and leap points. The reference ellipsoid is located at the bottom of the Fig.1. According to the spatial relationships among these vertical data, the separation model $\Delta h(b, l)$ can be obtained by

$$\Delta h(b,l) = H_{MSS}(b,l) + L(b,l) \quad \text{(1a)}$$

$$= N(b,l) + \delta(b,l) + L(b,l) \tag{1b}$$

where b and l represent latitude and longitude. The H_{MSS} is the geodetic height of the mean sea surface relative to the reference ellipsoid, and it can be divided into two parts, namely, geoid undulation $N(b,l)$ and mean sea surface topography $\delta(b,l)$. $L(b,l)$ represents the chart datum model. Given that it is negative, the plus sign is used in front of it. In other words, according to the mean sea surface model, the geoid model, mean sea surface topography model, and chart datum model, there are two ways to establish the separation $\triangle h$ model.

Establishment of seamless chart datum

The chart datum is usually characterized by discrete and leap points, and therefore, establishing a seamless chart datum is necessary. Tidal analysis can be effectively conducted to obtain major tidal constituents and compute the chart datum with the LAT algorithm. Subsequently, a seamless chart datum model can be established according to a specific interpolation method. However, long-term tidal observation data with sufficient spatial resolution is lacking, especially in high-latitude and extremely cold Antarctic areas. At present, highly accurate local and global ocean tidal models are available for Antarctica, such as DTU15, FES2012, and TPXO8 (Lei et al. 2017). In this case, ocean tidal models can be considered for tidal constituent extraction at each grid node based on a certain spatial resolution. Moreover, the chart datum can be calculated on the basis of the LAT algorithm as shown below (Marine surveying and mapping institute of the PLA navy, 1999).

$$L = \min[(fH)_{K1}\cos\varphi_{K1} + (fH)_{K2}\cos(2\varphi_{K1} + 2g_{K1} - 180^\circ - g_{K2}) - (R_1 + R_2 + R_3)] \tag{2}$$

Where, L is the chart datum, H and g are the harmonic constants of each tidal constituent. f is the focus factor of each constituent. The corner marks $K1$ and $K2$ represent the tidal constituent, and the formula for calculating parameters R_i (i=1,2,3) are as follows:

$$\begin{aligned}
R_1 &= \{(fH)_{M2}^2 + (fH)_{O1}^2 + 2(fH)_{M2}(fH)_{O1}\cos\tau_1\}^{1/2} \\
R_2 &= \{(fH)_{S2}^2 + (fH)_{P1}^2 + 2(fH)_{S2}(fH)_{P1}\cos\tau_2\}^{1/2} \\
R_3 &= \{(fH)_{N2}^2 + (fH)_{Q1}^2 + 2(fH)_{N2}(fH)_{Q1}\cos\tau_3\}^{1/2} \\
\tau_1 &= \varphi_{K1} + (g_{K1} + g_{O1} - g_{M2}) \\
\tau_2 &= \varphi_{K1} + (g_{K1} + g_{P1} - g_{S2}) \\
\tau_3 &= \varphi_{K1} + (g_{K1} + g_{O1} - g_{N2})
\end{aligned} \tag{3}$$

According to formula (2) and (3), it can be concluded that the L is the one variable function of φ_{K1}, whose range is from 0° to 360°. The minimum value of this function is the lowest astronomical tide

(LAT), which is relative to below the mean sea surface. After conducting the calculation of chart datum at each grid node, and then a seamless chart datum can be established by the interpolation method.

Considering the high latitude Antarctic region, the real-time tidal observation data is very precious and rare, and it is difficult to meet the spatial resolution required for the establishment of seamless chart datum. In view of this, the ocean tide model is considered for constructing the seamless chart datum. According to the experimental area, the appropriate ocean tide model will be selected, and extracted the tidal harmonic constants of each constituent, and then the datum value of each grid can be calculated according to the LAT model. Finally, the seamless chart datum can be established.

Construction of the separation model

In Formula (1b), the geoid undulation $N(b,l)$ can be derived from the official EGM2008 geoid model released by the EGM Development Team of the US National Geospatial Intelligence Agency, and it can be used to compute geoid undulation values with respect to WGS 84 (Pavlis et al. 2012). By calculating $N(b,l)$ at each grid node, a geoid model covering the Great Wall Bay can be established via Bi-Quadratic interpolation.

Because the satellite altimetry has the advantage of a wide range, therefore, the acquisition of mean sea surface topography $\delta(b,l)$ can consider using the relevant satellite altimetry products. For instance, the Copernicus Marine Environment Monitoring Service provides products with parametric settings for global or local, orbital or intersecting, time period, temperature, salt, wind speed, flow direction, sea surface height above geoid, and other data. In this study, a corresponding satellite altimetry product is selected to establish the mean sea surface topography model for Great Wall Bay.

After obtaining the seamless chart datum and the geoid and mean sea surface topography model, the Solution 1 separation surface between chart datum and ellipsoid reference is established according to Formula (1b). However, although the formula is simple to calculate, an important practical issue needs to be addressed. In particular, with regard to model spatial resolution, the three models for superimposition have different spatial resolutions, and therefore, resampling is needed.

In addition, the separation model can also be established by the mean sea surface model and chart datum, as shown in formula (1a). For instance, The Danish Technical University (DTU) MSS is the global mean sea surface model which includes data from multiple altimetry missions (T/P, Jason-1, ERS-2, T/P interleaved mission, GFO, ERS-1 GM, Geosat GM, Envisat, and ICESat) and covers the period 1993-2015. This model contains multiple versions DTUXX, where XX refers to versions 10, 13 or 15. Among them, the DTU15MSS (See Fig.2) is the latest release with the high resolution, and the major new advance leading up to release of this DTU15MSS is the use of an improved 4 years Cryosat-2 LRM, SAR and SAR-In data record, which has been proven to be major steps forward for altimetric MSS determination in Arctic and Antarctic ocean area (Andersen et al. 2016; Skourup et al. 2017; Stenseng et al. 2015). Based on this, DTU15MSS and established seamless chart datum are used for constructing the Solution 2 model.

Experimental Results and Discussion

Transformation model establishment

The Great Wall station is located at the southern tip of King George Island in the South Shetland Islands of Southwest Antarctica, and its geographic coordinates are 62°12'59" S and 58°57'52" W. The selected experimental area is the one around the Great Wall station with a scope of 62.350° to 62.100° S latitude and 59.050° to 58.600° W longitude, which covers the whole Great Wall Bay (See Fig.3).

According to the experiment area, the Atlantic Ocean 2008 model, released by Oregon State University with a resolution of 1/12° covering the entire King George Island and its surrounding sea areas, is selected. The data assimilated include 531 cycles of Topex/Poseidon + Jason data, 114 cycles of Topex tandem data (in shallow water), and 108 cycles of ERS data (in shallow water and above 66 °N). The tidal constituents of M_2, S_2, N_2, K_2, K_1, O_1, P_1, and Q_1 are extracted by using the OSU Tidal Prediction software. Then, a seamless chart datum model is established via minimum curvature interpolation, as shown in Fig.4. LAT varies between −1.4 and −1.2 m and depicts a lower-south to higher-north trend. The contour line is nearly parallel to the latitude line.

According to the EGM2008 model, the geoid covering the Great Wall Bay can be computed via Bi-Quadratic interpolation, and its spatial resolution is the same as that of the chart datum (See Fig.5). However, the geoid undulation values change from 21 to 22 (i.e., lower-north to higher-south trend), and the change in contour lines are more complex than that of the chart datum.

Considering the location of the Great Wall Bay and the required parameter information, global ocean-gridded L4 sea surface heights and derived NRT (Near real time) variables are selected as the products from the Copernicus Marine Environment Monitoring Service. The spatial resolution is 0.25°×0.25°, and coordinate reference system is WGS84. The product variables (i.e., absolute dynamic topography and geostrophic currents) are processed by the DUACS (Data Unification and Altimeter Combination System) Multi-mission Altimeter Data Processing System, which serves as the main operational oceanography and climate forecasting center in Europe and other countries. The system also offers near-real time data processing of altimeter missions of Jason-3, Sentinel-3A, HY-2A, Cryosat-2, Jason-2, Jason-1, T/P, ENVISAT, GFO, and ERS1/2. Subsequently, optimal interpolation is performed by merging all data from flying satellites to compute the gridded SLA (Sea Level Anomalies) and ADT (Absolute Dynamic Topography). The temporal coverage of this product is from January 2017 to April 2018. During computation, the sea surface height above the geoid of each day is extracted, and the average value is taken as the mean sea surface topography. Similarly, the mean sea surface topography is computed at each grid node, and then the model covering the whole Great Wall Bay is constructed by minimum curvature interpolation (Fig.6 (a)). It can be seen that the mean sea surface topography is relatively gentle and varies between −1.30 and −1.15 m. The contour lines are also nearly parallel to one another. The satellite altimetry product not only gives the sea surface height above the geoid but also the error of height of each node in each time epoch. We also calculated the average error for each node from January 2017 to April 2018, and then draw the following Fig.6 (b) by minimum curvature interpolation. As it can be seen, the mean error of the sea surface height is relatively small, basically within 2cm, even in coastal waters. Although this result looks pretty good, note that it is just an appearance of the interpolation, which can easily lead to illusion. Actually, it is known that the accuracy of satellite altimetry in coastal area is much worse than that in the deep ocean, due to the complex reflected waveforms from lands and seas, and the low accuracy of geophysical correction (Deng 2004). In addition, the spatial resolution of sea surface height provided by CMEMS is only 0.25 degrees, which leads to the fact that there are not many sea surface topography points in the experiment area. Although the accuracy of these points is still good, so after interpolation, the accuracy of the coastal regions also "looks" good, which should be paid attention. Therefore, this accuracy, especially in coastal areas, is just for reference only.

After establishing the seamless chart datum and the geoid and mean sea surface topography models, the separation Δh model between chart datum and WGS84 ellipsoid is established according to Formula (1b). Resampling is needed to derive the same grid points for the three models. The geoid and the chart datum are interpolated at the same grid nodes as the mean sea surface topography before these three models are merged. Consequently, the separation $\triangle h$ at each grid node is calculated and fitted into a surface via minimum curvature interpolation (Fig.7).

As shown in Fig.7, the gradient of separation surface is large in the Drake Passage, and the distributions of contours are extremely close to one another. Meanwhile, the variation trend of separation in the Great Wall Bay is relatively smooth. Although the Great Wall Bay area is small, the variation of the separation value still exceeds 10 cm, which cannot be ignored in the elevation conversion. Thus far, the Solution 1 transformation model has been established.

Similarly, according to the DTU15MSS model (1′×1′), the geodetic height of mean sea surface and the error information around Great Wall Bay have also been extracted, as shown in the following Fig.8. It can be seen that the error of DTU15 MSS around Great Wall Bay is small magnitude and has a good precision. When close to the continent, the error slowly increases. Compared with the mean sea surface topography model, the DTU15 MSS not only has the same accuracy, but also has a higher space resolution (1′×1′ vs 0.25°×0.25°). However, like the sea surface topography provided by CMEMS, DTU15 actually has the similar problem, the poor accuracy in the coastal regions. Due to the interpolation, the coastal error information shown in Fig. 8(b) may not show a true accuracy.

Combined with the above MSS model, and according to the previous established seamless chart datum, the Solution 2 separation surface model can be obtained according to equation (1a), and it is shown in the Fig.9. It can be found that the characteristic of the contour are similar to those of DTU15 MSS, however, it is quite different from the separation model established via Solution 1. The difference is not only reflected in the value of separation, but also in the trend of contour orientation.

Model Accuracy Evaluation and Discussion

Model accuracy is a highly important index in model evaluation. From the viewpoint of transformation modeling, error sources are mainly caused by inaccurate mean sea surface model, geoid EGM2008, ocean tidal model, and satellite altimetry product information. Findings on EGM2008 model development and evaluation have shown that the RMS value of the commission error is 5.8 cm in ocean areas with latitudes lower than 66°, whereas the modeling error in other ocean areas is 6.1 cm (Pavlis et al. 2012). The latitude of Great Wall Bay is located below the 66°

S, so the accuracy of geoid model there could be considered as 5.8cm by referring to this paper. However, it should be noted that the commission error is the mean value, which does not really reflect the true accuracy of the experimental area. Therefore, we only maintain a reference attitude to the results when evaluating the accuracy of the Solutions, and the real check still needs the field observation data to conduct.

As a local tidal model, the Atlantic Ocean 2008 model is derived essentially from the global tidal ocean model TPXO7.1. Therefore, we assume that these two tidal models have similar accuracies. On this basis, the accuracy of TPXO7.1 is studied. Tab.1 lists the RMS (Root-Mean-Square) and RSS (Root-Sum-Square) values of several different global ocean tidal models for the Antarctic Peninsula (Lei et al. 2017). In the table, *Num* denotes the number of tide stations that have contributed to the comparative results of the ocean tidal model.

The results of the other six models are relatively close to one another with RSS values of approximately 10cm, except that of the HAMTIDE12 model. Although TPXO8.0 and TPXO7.0 slightly differ, the accuracies are essentially close to each other. Therefore, the chart datum accuracy can be assessed according to the accuracy of each tidal constitute of the TPXO8 model. Given the complexity and non-linear of the LAT algorithm, we adopt an approximate principle to evaluate the precision of LAT. According to formula 2, each cosine part is taken its maximum value of 1, which can be simplified as follows:

$$L = \min[R_{K1} + R_{K2} - (R_{M2} + R_{O1} + R_{S2} + R_{P1} + R_{N2} + R_{Q1})] \quad (4)$$

Where R equals fH, and each focus factor f is taken as unity and known. In this way, the complex formula (2) has been converted into a simple linear expression. Meanwhile, according to the accuracy of each tidal constituent in Tab.1 and the law of error propagation, the accuracy of LAT can be evaluated to be about 10.4cm.

It can be seen from Fig.6(b) that the accuracy of each grid node is not consistent, in this experiment, we adopt the maximum error of 1.7cm for these grid nodes as the accuracy of mean surface topography in Great Wall Bay. Then, on the basis of the error propagation law, the accuracy of the separation surface model integrated by EGM2008, mean sea surface topography and seamless chart datum is estimated to be 12.0 cm.

Similarly, Fig.8 (b) gave the error information of mean sea surface model around Great Wall Bay, and we also took the maximum error 4.2 cm as the mean sea surface error of the whole water area. Then combined with the established seamless chart datum in Fig.3, the accuracy of separation model has been estimated to be 11.2 cm according to the error propagation law. Therefore, it can be seen that the precision estimations of the separation models obtained by two different methods are equivalent. However, it is also important to note that due to the accuracy or error used for evaluating the Solutions may not represent the true accuracy information, such as the error of satellite altimetry products, EGM2008. Therefore, this two evaluation values are just only for reference significance. The validation based on the field observation should be the better one.

In 2012, the Chinese Antarctic Center of Surveying and Mapping of the Wuhan University set up a pressure tidal gauge in the Great Wall Bay for tide observation, analysis and forecast, sea level change research and etc. After that, the GPS leveling had been carried out, and obtained the geodetic height of zero point of pressure tidal gauge. The principle of zero calibration is shown in Fig.10.

A geodetic control point has been set up on the dock of Great Wall bay, and through the GPS static joint observation of this point and other known points in the Great Wall station area, the accurate geodetic elevation of the control point on the dock was obtained. Then, a water gauge is attached to the side of the dock to conduct simultaneous tide observations by comparing the observation of pressure tidal gauge. The height difference of these two tidal level sequences represents the height difference of two tidal gauge zero points. While, the height difference between the zero point of water gauge and the control point on the dock can be determined by triangulation, from which the geodetic height of the water gauge at zero point can be obtained. Subsequently, the geodetic height of the pressure tidal gauge can be determined according to the height difference of two tidal gauge zero points. At last, the geodetic height of the tidal level is recorded by referring to the geodetic height of pressure tidal gauge zero point, which can be expressed as

$$H_P = H_{Ben} - h_2 - (h_1 - h_3), \tag{5}$$

where H_P is the geodetic height of pressure tidal gauge zero point, H_{Ben} is the geodetic height of the control point on the dock, h_2 is the height difference between the control point and the water gauge at zero point, and h_1 and h_3 are the tidal heights recorded by the pressure tide gauge and the water gauge, respectively.

After conducting the zero height calibration of the pressure tidal gauge, the chart datum and mean sea level can be calculated for tidal analysis. The tidal level observation at the Great Wall station has lasted for four years from 2014.03 to 2018.03, which is sufficient for tidal analysis and chart datum calculation. Therefore, the tidal harmonic analysis has been accomplished by the least square method, and then the chart datum *L* and geodetic height of mean sea level were calculated, which were -1.430m and 21.723m respectively (See Tab.2). Summing these two results in the field-observed geodetic height of chart datum at the tide gauge of 20.293 m. So far, three kinds of results about the separation value between the chart datum and the reference ellipsoid at the pressure tide gauge are obtained, and listed in Tab.2.

At this point, the estimate of each separation model can be compared. The estimated value of separation $\triangle h$ derived from Solution 1 is 19.017m, which is based on integration of geoid EGM2008, mean sea surface topography and seamless chart datum model. In comparison, the Solution 2 separation model established by DTU15 MSS and seamless chart datum model is estimated to be 19.871 at pressure tidal gauge, which is 85.4 cm different from the Solution 1 model estimate. However, the geodetic height of chart datum obtained from the field observation data is 20.293 m, which differs from Solution 1 and 2 by 127.6 cm and 42.2 cm, respectively. From this results, it can be concluded that the Solution 2 is closer to the field value, and the previous fear was also fulfilled that the accuracy estimate of the model was only of reference and can’t represent the true error in the coastal waters. In practice, the accuracy of satellite altimetry in coastal areas is much worse than that in the deep ocean. While, the validation site is exactly that kind of coastal water. Therefore, it is not difficult to understand why the results of the two Solutions differ greatly from the field measured result.

In addition, the mean sea surface involved in these three methods are different from each other. That may be another reason for accounting for the large differences. Solution 1 utilizes the SSH model derived from satellite altimetry product provided by CMEMS, with a time span from January 2017 to April 2018. The DTU15 MSS used in solution 2 is also obtained by multi-source satellite altimetry missions, but its time span is from 1993 to 2015, more than 20 years. While, the mean sea surface calculated in the field observation is about 4 years from 2014 to 2018. Therefore, it can be seen that the mean sea surface used in solution 2 is the longest, followed by the field observation, and the shortest is the mean sea surface in option 1. In theory, the mean sea surface is time-domain, and the longer the time, the more stable the corresponding mean sea surface. Based on this point of view, the mean sea surface in solution 2 is more than 20 years, which has exceeded 18.6 years of longest periodic vibration of the tide. Therefore, this mean sea surface should be the most accurate, stable and representative (Except, of course, for coastal waters.). While, the mean sea surface in solution 1 is about 1 year and 4 months long, there are still some long-term components in the mean sea level. According to the data in Tab.2, the geodetic height of mean sea level of Solution1, 2 and filed observation can be obtained, which are 20.450 m, 21.180 m and 21.723 m, respectively. From the results, it is true that the mean sea level of Solution 2 is closer to that of field observation, and this also supports the previous view. Based on this, it is more inclined to prefer the separation model in the solution 2.

At last, the International Hydrographic Organization (IHO) standards for hydrographic surveys has specific accuracy requirements for depth sounding (IHO 2008). All errors caused by tidal observations, vertical datum determination, and datum conversion, should therefore be included. Furthermore, the maximum allowable total vertical uncertainty should be below $(a^2 + b^2d^2)^{1/2}$ at 95% confidence level. In this formula, a represents that portion of the uncertainty that does not vary with depth, and b is a coefficient representing that portion of the uncertainty that varies with depth d. For IHO Order 1, the above parameters are $a = 0.5$ m and $b = 0.013$. In the experimental area, most of the water is more than 100 meters, therefore, even if the error between model estimation and field observation is large, it can still satisfied the requirements of IHO specifications. Based on this, the separation model can unify the topography survey of Great Wall Station and the water depth survey results of the nearby sea area into a vertical datum.

Conclusion

In this paper, the principle and method of establishing a seamless chart datum and the transformation model between the WGS84 reference ellipsoid and seamless chart datum are presented. There are two transformation models have been established, and one is based on geoid model EGM2008, mean sea surface topography and Atlantic Ocean 2008 (AO08) model (Solution 1), the other based on DTU15 MSS and AO08 (Solution 2). Compared with the field observation result by pressure tidal gauge in Great Wall Bay, the Solution 1 and 2 exist differences of 127.6 cm and 42.2 cm, respectively, far exceeding the accuracy estimations of the Solutions. The reason for this is attributed to the length of time for determination of MSS and poor accuracy of satellite altimetry in the coastal waters.

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Data Availability Statement

- Some or all data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies (Provide full citations that include URLs or DOIs.)

DTU15 MSS
https://www.space.dtu.dk/english/Research/Scientific_data_and_models/downloaddata
Mean sea topography
http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=SEALEVEL_GLO_PHY_L4_NRT_OBSERVATIONS_008_046
Atlantic Ocean 2008
http://volkov.oce.orst.edu/tides/region.html
EGM2008
https://www.eye4software.com/hydromagic/documentation/manual/utilities/egm2008-geoid/

- Some or all data, models, or code generated or used during the study are available from the corresponding author by request. (List items).

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Pressure tide gauge data; Water gauge data; GNSS observation data; Leveling data.
http://data.hbaa.cn/ (In Chinese)

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Tab.1 RMS between the interpolated tidal signal and common tide gauges and the corresponding RSS values of eight major constituents (in cm) (Lei et al. 2017)

Tide Model	**K_1**	**K_2**	**M_2**	**N_2**	**O_1**	**P_1**	**Q_1**	**S_2**	**RSS**
Num	30	17	30	17	30	17	16	27	-
Mean amplitude	30.17	10.99	47.79	8.70	28.61	9.57	5.66	33.98	-
DTU10	5.57	1.09	3.77	2.02	4.63	2.39	1.43	4.40	9.96
EOT11a	5.64	1.09	4.03	1.99	4.59	2.27	1.37	4.51	10.08
FES2004	5.68	1.16	4.07	2.00	4.62	2.29	1.37	4.51	10.14
FES2012	5.68	1.11	4.07	2.00	4.62	2.29	1.37	4.51	10.14
GOT4.8	3.64	0.99	5.01	1.34	7.42	1.66	1.06	3.71	10.67
HAMTIDE12	7.80	6.77	27.59	5.21	6.58	4.27	3.02	18.28	36.05
TPXO8	6.36	1.33	5.26	1.89	3.39	2.07	1.77	3.96	10.40

Tab. 2 SSH, chart datum, geoid undulation, mean sea surface (DTU15 MSS) and separation $\triangle h$ model estimations. Pressure tide gauge readings from field measurements in Great Wall Bay.

Method	*L* /m (Relative to *MSL*)	*MSL* /m (Geodetic height)		Separation $\triangle h$ /m
Solution 1	Tide model estimate	Geoid Model estimate (EGM2008)	SSH Model estimate	Model estimate
	-1.338	21.648	−1.198	19.017
Solution 2	Tide model estimate	Mean sea surface model (DTU 15) estimate		Model estimate
	-1.338	21.180		19.871
Field observation	Harmonic analysis of tide observation	GPS leveling		Field measurement
	-1.430	21.723		20.293

Figure captions

Fig.1 Spatial interrelationships among Chart datum, Mean sea surface (MSS), Geoid, and Reference ellipsoid.

Fig.2 The global DTU15 mean sea surface model (Andersen et al. 2016; Stenseng et al. 2015)

Fig.3 Geographical location map of the Great Wall Station

Fig.4 Seamless chart datum model derived from Atlantic Ocean 2008 around Great Wall Bay

Fig.5 Geoid model of Great Wall Bay

Fig.6 (a) Mean sea surface height above the geoid model of Great Wall Bay; (b) Mean error of sea surface height in Great Wall Bay.

Fig.7 Separation surface model derived from geoid EGM2008, mean sea surface topography and seamless chart datum

Fig.8 (a) DTU15 MSS; (b) Error of DTU15 MSS

Fig.9 Separation surface model derived from DTU15 MSS and seamless chart datum

Fig.10 Zero calibration schematic of pressure tidal gauge in Great Wall Bay