Hydrographic datum and GNSS heighting in the SW Java Sea, Indonesia: Comparison between observed and models of Sea Surface

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Abstract. There have been developments of GNSS heighting in hydrography. These are motivated by the need for improving the efficacy of hydrographic operations, through omission of shore-based tidal surveys and post-processed datum reduction of depth soundings. However, this will demand presence of hydrographic separation model (HSM) that defines the vertical relationship of any tidal datum used in hydrography to ellipsoid. In addition to that, a reliable technique for real-time positioning is also required. At the same time, the overall accuracy the use of the entire system (i.e. height datum, vertical positioning) must be identified. This paper discusses the prospect of using models of sea surface for the construction and operation of HSM for the SW Java Sea, Indonesia. The discussion is based on two models of sea surface: the analytically constructed sea surfaces (i.e. HAT, MSL, LAT) according to data from TPXO.7 missions and models of sea surface database published by the Indonesian Agency for Geospatial Information. In order to verify the operability of such models, observation of geodetic heights of instantaneous sea levels across an approximately 13.5 Nm sailing tracks between Pramuka (Seribu Islands) and Ancol (Jakarta) is made. It is evident that the work presented here results in deviation level in the order of several tens of centimetres. This provides reasonably quantified contribution to the error budget against the standard of depth accuracy for data presented on nautical charts as of Zone of Confidence A and hence confirm the prospect of using existing surface models and vertical positioning respectively for the construction and operation of HSM in the domain in question.

1. Introduction
In hydrography, chart datum describes the zero-depth derived from the lowest tidal level of an observation epoch, with Lowest Astronomical Tide (LAT) being the internationally recommended [1,2]. In this presented paper, the term ‘hydrographic tide’ is proposed to assemble various expressions representing the reference plane (at a particular level of water) used to define depths on charts. It is known that various methods have been applied to determine such a hydrographic datum. These extend over the simplest and straightforward calculation, for instance the summation of four primary tidal constituents [3], to the most sophisticated hydrodynamics simulation verified by in-situ water level
gauging and global sea surface observation [4,5,6]. It should be noted that for the purpose of public use, particularly for the marine navigation in the shipping industry, the presentation of hydrographic datum shall be formally issued by the hydrographic authority of the respective national territory. In this instance, the term “chart datum” (CD) must be used, instead of hydrographic datum. Hence, CD refers to the official information of zero-depth applied on published nautical charts. In Indonesia, the authorized agency responsible for establishing CD is the Naval Centre for Hydrography and Oceanography. Conventionally, CD is used on printed nautical chart and presented as a certain vertical level below the Mean Sea Level (MSL) termed as $Z_0$. Uniform CD is usually applied throughout the area covered by the chart. Consequently, the determination of CD will contribute to the depth accuracy shown on the chart as it is used in removing tides in depth sounding. For electronic navigation, the accuracy of depths presented on a nautical chart is based on the zone of confidence (ZOC). ZOC A1 and A2 categories identify depth accuracy of respectively up to 0.5 m + 1% of the charted depth and up to 1 m + 2% of the charted depth [7].

With the advance of network of water-level gauging across the near shore zone and along with additional offshore gauging buoys, as well as considering data contributed by the global sea surface observation (i.e. altimetry satellite) it is nowadays feasible to construct a non-uniform and seamless hydrographic datum for a given ocean waters [8]. Such a datum is embedded to the so-called hydrographic separation model (HSM) [9], which defines the vertical relation between height references, particularly tidal levels (i.e. MSL, LAT) to ellipsoid, i.e. World Geodetic System 1984 (WGS84). Examples of fully operational HSM are Vertical Offshore Reference Frame (VORF) administered by the UK Hydrographic Office [4] and Hydrographic Vertical Separation Surfaces (HyVSEPs) established by the Canadian Hydrographic Service [10]. HSM offers advantageous benefits as it omits the need for shore-based tide gauges correction in hydrographic survey, provides seamless CD surface interpolation between water level station including its extrapolation to the offshore zone (hence eliminates reliance to offshore tidal observation), and integrate land-ocean height reference for use in the coastal zones [11,12]. Examples of existing HSM, such as VORF and HyVSEP, exhibit vertical accuracy of within or better than 0.1 m [4,10]. Such vertical accuracy opens opportunities to enable various improvements in marine navigation, offshore construction, and coastal management [13]. Still, the operation of HSM requires several essential elements with vertical positioning (on kinematics mode) being one of the most critical. The contribution of vertical positioning to the error budget is quite meaningful as the observed GNSS height is interfered by the attitude of the marine vehicle [14]. Therefore assessment of HSM accuracy also requires consideration on the vertical positioning in use.

It is the intention of this presented paper to examine the existing sea surface models entailing Mean Sea Surface (MSS) and LAT to be utilized in the near future for the creation of HSM for the SW Java Sea, as well as to investigate how positioning devices quantifies the vertical separation from such surfaces. The examination is based on the comparison of the models and field observations. Two models of sea surface are considered here:

- Highest Astronomical Tide (HAT) - Mean Sea Surface (MSS) - LAT database from the Geospatial Information Agency of Indonesia (Badan Informasi Geospasial - BIG), hereinafter termed as BIG; and
- HAT-MSS-LAT database derived from TOPEX/Poseidon crossover solution (TPXO.7) global ocean tide model [11], hereinafter termed as TPXO.

Field observations of instantaneous sea level are made according to three different GNSS devices:

- Hemisphere;
- Trimble; and
- Veripos.
An earlier work on the comparison of GNSS heighting and model of MSS is carried out in the same domain of investigation [14]. As reported by [14], the model of MSS combines geoid undulation (N) and mean dynamics ocean topography (MDOT). The comparison indicates that there is constant residual (i.e. deviation) between actual sea level and model of sea surface, i.e. MSS. The deviation is in the order of sub-decimetre for augmented GNSS device and sub-meter for the real-time precise point positioning one. With the comparison presented in the paper, we expect to quantify the accuracy of the models and propose advice if different sea surface models (i.e. BIG, TPXO, rather than that used in reference [14]) have the prospect for the development HSM.

2. Material and method

2.1. Conceptual framework

Conventionally, the study and presentation of various heights of sea surface and tidal phase refer to a shore-based water level gauge. The vertical separation of LAT from MSS (i.e. \( Z_0 \)) is calculated in an individual gauging station of water level (Figure 1). In this instance, HSM may define the vertical relation between MSS and WGS84 ellipsoid. Since \( Z_0 \) is known by interpolation of LATs between gauging stations, the height of LAT above WGS84 ellipsoid could be obtained from:

\[
h_{LAT} = h_{MSS} - Z_0
\]

with \( h_{LAT} \) = height of LAT from WGS84 ellipsoid, \( h_{MSS} \) = height of MSS from WGS84 ellipsoid, and \( Z_0 \) = vertical separation of LAT from MSS. Geodetic height system indicates that the height of MSS from WGS84 ellipsoid can be obtained by integrating earth gravity model and mean dynamic ocean topography (MDOT) [15]:

\[
MSS = N + MDOT
\]

with \( N \) = geoid undulation and \( MDOT \) = mean dynamic ocean topography. Equation 1 and 2 shall satisfy the requirement for a construction of HSM. When the HSM is to be operated, a vertical positioning system must be in use to define the actual height of instantaneous sea level, i.e. \( h_{SL}(t) \). With the presence of HSM (i.e. Equation 2), the vicinity of actual height of instantaneous sea level from the MSS will be:

\[
k(t) = h_{SL}(t) - MSS
\]

with \( k(t) \) = the vicinity of actual height of instantaneous sea level from the MSS.

![Figure 1](image_url)

**Figure 1.** Height system and its relevance to selected definitions of *in-situ* sea surface observed in the field and documented on nautical chart; Hydrographic Separation Model (HSM) shall define ellipsoid height of the Lowest Astronomical Tide (LAT) and vertical positioning technique shall provide instantaneous height of seal level \( (h_{SL}(t)) \).

2.2. Research design

In this work, we intend to elaborate the agreement between the actual heights of instantaneous sea level from the MSS by means of their comparison. The comparison of heights is done by subtracting the observed sea level (as sequenced by the time tag) by the corresponding height of MSS at the position of
the GNSS device along the survey track and on the same time tag. For the sake of conformity between $k(t)$ and its expected deviation in the field test, it is more convenience to rewrite equation 3 as:

$$
\Delta h(t) = h_{SL}(t) - MSS
$$

with $\Delta h$ = deviation of the observed sea level with respect to the model, $h_{SL}$ = sea level height observed from GNSS device, MSS = mean sea surface and $t$ = time. The MSS is obtained from the models of sea surface, i.e. BIG, TPXO. In order to quantify the comparison, we look into the statistical description of the average deviation in terms of its mean value. In addition to that, the trend and pattern of the deviations is assessed, by means of regression and spectral transformation, respectively. From these, we expect to quantify the agreement of the models to the observation and the characteristics of such an agreement. Figure 2 illustrates the path of the sail, where the track of survey is made. The track of survey is made along the half-way to Ancol (Jakarta) from Pramuka (Seribu Islands) on the 25th of March, 2018. The approximate length of the survey track is 25 km or equal to about 13.5 Nm. The record of GNSS positioning data (including height) considered in this presented paper is between 12:36 and 13:55 (UTC+7) or about one hour and 19 minutes, during ebb phase close to the low tide. The low tide is at about 15:04.

Figure 2. Track of GNSS observations half-way to Ancol (Jakarta) from Pramuka (Seribu Islands) 25 March 2018 over an approximate length of 25 km or roughly 13.5 Nm.

2.3. Models of Sea Surface (BIG and TPXO)

Sea surface model from BIG is accessible from its website, i.e. http://tides.big.go.id. The surface model is described as HAT, MSS, and LAT referring to WGS84 ellipsoid. BIG sea surface model is developed through coupling of altimetry satellite data and model of global current circulation [16]. In this presented paper, TPXO sea surface model used here is developed from TPXO.7 mission. It provides model of sea level oscillation due to tide according to eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long period (Mf, Mm), and three non-linear (M4, MS4, MN4) harmonic constituents [17]. The presentation of TPXO.7 data into sea surface model (i.e. HAT, MSS, LAT) is made according to a calculation using tidal harmonic equation involving 13 constituents over the course of nutation, i.e. 19 years [14]. WGS84 ellipsoid is also the reference height of the presentation of the TPXO sea surface model.
An off-line interface for extracting BIG and TPXO models of sea surface considered in this presented paper is provided by Oceanomatics™ Hydro (OH). Figure 3 shows typical display of the extractor. OH is accessible from http://oceanomatics.com/oceanomatics_hydro.rar. From OH interface, one can obtain the required surface (i.e. HAT, MSS, LAT) by keying in the relevant geodetic coordinates. OH stores sea surface database on 0.125° x 0.125° grid size. Linear interpolation is applied to facilitate query of location due to finer coordinates [18].

Figure 3. Display of Oceanomatics™ Hydro developed by [18] as an offline digital tool for extracting BIG and TPXO sea surface models; Users shall key-in the geodetic coordinates to obtain the requested surface.

2.4. Field observation
Figure 4 exhibits schematic installation (side and top views) of the GNSS antennas during the experiment. In Table 1, the measured antenna heights above the sea surface are shown. The antennas are mounted from each other within about 2 m or more lateral distances and with approximately comparable heights of within about 3 m or more with respect to the sea level.

Figure 4. Installation diagram of three GNSS antennas on board of MV “Pesona Alam” along with their lateral gap from one to another and the indication of vertical vicinity above sea surface
The GNSS devices used in the experiment presented in this paper are categorized into two different configurations: the satellite-based augmented system (Veripos) and real-time precise point positioning or RT-PPP (Hemisphere and Trimble). Further description of the GNSS devices used in the experiment can be found in [19]. For the purpose of observing instantaneous height of sea level, the three GNSS antennas are installed on the stern deck on board of the Motor Vessel (MV) “Pesona Alam”.

Table 1. Heights of GNSS antenna above sea level.

|            | Hemisphere | Trimble | Veripos |
|------------|------------|---------|---------|
|            | 3.48       | 3.22    | 3.05    |

Occasionally, the heights of GNSS antennas above sea level are also monitored during and after the cruise. However, it should be noted that the precision of the observation of height is somewhat poor due to the difficulty of accurately estimating the sea surface visually. To the extent of the archive of the experiment, it is known that final (post-sail) check on the height of GNSS antenna height is also made. In this instance, no identifiable changes of the antenna heights are recognized.

3. Results and discussion

Over the course of the sailing track, the field observation results in several thousands and several hundreds of pairs of data, i.e. 3146 data pair (at roughly 1 Hz interval) for Veripos and Hemisphere devices, 599 data pair (at roughly 0.2 Hz interval) for Trimble and Hemisphere devices. The previously mentioned duration of observation (see: Section II.B.) is actually the coinciding time-window of the three devices simultaneously. In order to comply with Equation 1, the vertical element (i.e. geodetic height) of the GNSS data and the corresponding height of MSS from the both models, i.e. BIG, TPXO, are contrasted. In Figure 5, the geodetic heights of actual sea surface observed by three different GNSS devices (i.e. Veripos, Hemisphere, Trimble) and MSS provided by BIG and TPXO models over the time along the sailing track are shown. From Figure 5, one would see that the typical geodetic height in the region is within 19 m or 19.5 m. It can be also seen from Figure 5 that there is noticeable trends of increasing geodetic heights shown by all observations and the models. Vertical offsets between the observations and the models are detected. Moreover, there is also persistent vertical offset between BIG and TPXO models. The height of TPXO model is somewhat ‘lower’ with respect to the BIG model. In Table II, a summary of statistical description of the vertical deviations between the observations and the models is shown.

The vertical offsets of the deviations are within several decimetres. Here, one can learn that all deviations show comparable range and uncertainty, i.e. standard deviation within 7 cm and 8 cm. The TPXO sea surface model is distant in the range of 0.28 m 0.55 m or comparable to 1.7 to 2.8 times to the BIG model. In particular, the vertical offset between the observations and the BIG sea surface model is within half-meter or less. In case of TPXO sea surface model, the observations show vertical offsets of higher than half-meter. From the field experiment presented in this paper, Trimble device combined with BIG sea surface model seems to provide the minimum mean deviation with a value of within 0.2 m. In Table III we show the assessment of trend and pattern of the deviations in form of their slope of the regressions and their identifiable dominant period. From Table III, it can be seen that there are quantity of vertical slope throughout the course of observation. This is thought to be due to the lowering of water level the tide, close to low tide. The relatively short observation, i.e. 1:19 hour, does not seem to require removal of the effect of the tide. Within such very short period, the change of water level in the domain of investigation cannot be clearly identified. As it is known that the tidal range is in the order 0.7 m, such period of observation would experience change in water level of 0.14 m during ebb or flood phase. Rather than applying complex correction methods as advised by [14], we would assume that the application of regression line to the deviations shall be sufficient in removing the effect of tide.
Table 2. Trend and pattern of the deviations

|       | Hemisphere | Trimble | Veripos |
|-------|------------|---------|---------|
| BIG   | Slope^a    | -0.1171 | 1.1995  | -0.5759 |
|       | Period^b   | 0.1896  | 0.0758  | 0.1896  |
| TPXO  | Slope^a    | -0.1865 | 1.1866  | -0.6453 |
|       | Period^b   | 0.1896  | 0.0758  | 0.1896  |

^a along track in m/s

^b in hour unit

Figure 5. Geodetic heights of actual sea surface observed by GNSS and Mean Sea Surface (MSS) provided by BIG and TPXO along the sailing track 25 March 2018.

Having removed the trend of the deviations, spectral transformation is applied to the de-trended data with 1 Hz interval of data re-sampling. From here on, we notice that the dominant period is within 0.19 hour and 0.08 hour, respectively with the corresponding relative magnitude of within 0.015 and 0.02. One should bear in mind that the spectral transformation is only able to decompose the signal of less than one hour. Nevertheless, with the applied method discussed here, one shall hence accept the fact that our field experiments confirm the measure of vertical uncertainty of GNSS heighting in the order of sub-meter. As advised by [14], the vertical uncertainty of GNSS heighting from a moving vessel is governed not only by the vertical precision of the positioning but also due to the vessel attitude. The attitude of the vessel on plumb axis is controlled by instantaneous vertical shift due to tide, sea surface roughness, and vessel behavior. The latter is reported by [14] as having a magnitude of a decimeter per day after the removal of the effect of tide and the mean of residuals. This is thought to be the effect of reducing vessel’s heave due to depleting storage of water and fuel.
4. Conclusions
In this presented paper, we have shown an activity related to the development of GNSS heighting in hydrography. The activity is facilitated by observation of geodetic heights of instantaneous sea levels across an approximately 13.5 Nm sailing tracks between Pramuka (Seribu Islands) and Ancol (Jakarta). Here, a discussion of the prospect of using models of sea surface for the construction and operation of HSM for the SW Java Sea, Indonesia has been presented. It is based on BIG and TPXO models of sea surface contrasted against data collected from field observation, by means of three different GNSS devices. It can be concluded that the existing BIG sea surface model possess the potential for development of HSM. All of the GNSS devices used here can be reasonably used in hydrographic operation. By considering error contribution from depth sounding, the contribution of deviation from the determination of hydrographic datum using BIG sea surface model in the geographic domain investigated here would satisfy the standard of depth accuracy for data presented on nautical charts as of Zone of Confidence A1 and A2.

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