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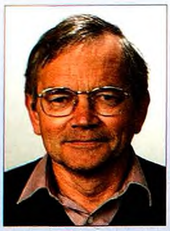

Height References in Hydrography

By Bernard Simon, Civil Engineer at SHOM

Abstract

Geoid, ellipsoid, land levelling, mean sea level, lowest astronomical tide, are reference levels used by hydrographers. From survey to chart production, hydrography operational techniques, require precise levelling of chart datum with reference to one of these levels. This presupposes in one hand, precise definitions and, in the other, a critical assessment of consistency with general reference level requirements: stability, accessibility, precision.

Résumé

Géoïde, ellipsoïde, nivellement terrestre, niveau moyen de la mer, niveau des plus basses mers astronomiques, sont autant de références utilisées en hydrographie. Les techniques mises en œuvre lors des travaux hydrographiques, depuis les levés jusqu'à la construction confection des cartes marines, nécessitent la cotation du zéro hydrographique par rapport à l'une ou l'autre de ces références. Cela suppose d'une part des définitions précises, d'autre part une évaluation critique des critères de conformité relatifs à toute référence, à savoir: stabilité, accessibilité, précision.

Resumen

El geoide, el elipsoide, la nivelación terrestre, el nivel medio del mar, la bajamar astronómica más baja, son niveles de referencia utilizados en hidrografía. Desde el levantamiento a la producción de cartas, las técnicas operativas utilizadas durante las tareas hidrográficas requieren la nivelación precisa del dátum de cartas con la referencia a uno de estos niveles. Esto presupone, por un lado, definiciones precisas y, por el otro, una evaluación crítica de la coherencia con los requerimientos del nivel de referencia en general: estabilidad, accesibilidad y precisión.

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The selection and positioning of vertical references as well as their relative dimensioning constitute fundamental issues in hydrography.

These issues are not recent, but new technologies, mainly linked to satellite observations and the evolution of computer means deeply change the way to approach them.

The GPS/Glonass/Galileo positioning systems, the development of spatial altimetry, the recognition by the entire geodetic community of a unique international reference frame, the ITRF, the determination of the global Earth gravity field with a constantly improving spatial resolution, as well as the development of increasingly performing hydrodynamic models, lead to consider new reference systems.

However, the traditional systems still exist, and it must therefore be possible to determine each measurement in relation to the other reference systems.

The reduction of hydrographic soundings consists in referring the depths measured with a sounder to an arbitrary but precisely defined level, that can be related to the reference level of nautical charts, called hydrographic zero, with sufficient accuracy for navigation needs. This operation consists in solving two problems:

- measuring the hydrographic zero, in a known reference frame, according to the geographical position,
- measuring, with respect to this reference, the sea level which varies both with the geographical position and the sounding time.

These problems are largely independent (even if the heights are obtained from the same measurements and same processing operations – in particular, the traditional and spatial methods are both based on the tide analysis and prediction) and can be solved by means of different techniques.

1 Definitions

The fundamental principles of sounding reduction are elementary but may lead to erroneous or confusing interpretations due to the inaccurate meaning given to some terms. In particular, since various height references are used, they must be accurately defined for easy differentiation.

Besides, as spatial techniques provide measurements which are different from conventional measurements, rigorous references and reduction processes must be defined.

I.1 Hydrographic zero characteristics

The hydrographic zero, reference shared by the nautical charts and the tide tables, has two fundamental characteristics:

- it is defined as a function of tide gauge criteria and aims at achieving the best possible navigational safety: it corresponds to an assessment of the lowest observable astronomical tide level, according to the IHO recommendations (International Hydrographic Organisation),
- it is measured in a terrestrial reference frame, either (traditionally) with respect to a stable benchmark located nearby an on-shore tide gauge, or (from now on) with respect to a reference surface, so as to ensure its long-term conservation and thus make it possible to use, with consistency, the surveys performed at different periods. This surface must be referred to an international reference frame such as the ITRF (International Terrestrial Reference Frame).

Close to coastal tide stations, these two problems are solved through the analysis of observations and by being able to measure the latter with respect to benchmarks located near the tide gauges, which are themselves measured in terrestrial levelling networks.

Offshore, it is necessary to use tide models, which must be assessed according to their aptitude to provide, for the hydrographic zero, results meeting quality criteria required for any reference frame, i.e.: accuracy, accessibility, stability, precision.

I.2 Lowel astronomical tides level

The hydrographic zero must correspond, according to the IHO recommendation (International Hydrographic Organisation), inasmuch as possible with the level of the lowest astronomical tides. The term «*astronomical*» *means that this level has not been* directly observed, but rather calculated from the tide generating force due to the gravitational actions of the Moon and the Sun. However, this 'astronomical' tide is generally calculated from the harmonic formula, based on harmonic constants obtained from the analysis of previous observations.

Two difficulties appear.
First, the calculation accuracy may vary greatly according to the quality and duration of the previous available observations, the correction (or not) of the meteorological and oceanographic effects, the calculation methods and means, the type and amplitude of the tide.

Secondly, during the process of observations, level variations generated by other phenomena (not astronomical, but meteorological and oceanographic for example), together with a sea level variation tendency over centuries add on to this astronomical tide. As a result, its calculation based on observations made at different periods would give different results and therefore this calculation would be spoilt by uncertainty.

Let us remember that the notion of the lowest tide level is, on the one hand intrinsically approximate and, on the other hand, closely linked to the notions of mean sea level to be dealt with hereunder. As it does not meet accuracy and stability criteria, the lowest tide level cannot, strictly speaking, constitute an exact height reference for hydrography; but once calculated, it can be used to locate the hydrographic zero which will then be «approximately» at the level of the lowest astronomical tides.

I.3 Mean sea level, nominal mean sea level, Mean Sea Surface (MSS)

The term 'Mean Sea Level' (MSL) is ambiguous. Intuitively, it refers to a value assumed to be constant. However, it is fundamentally variable since it depends on the period for which it has been calculated. If it is truly a mean value, it is obtained with the following formula where t_1 and t_N are the dates of beginning and end of observations and $h(t_n)$ the sea level height measured at time t_n, the origin of height measurements being fixed and the time interval between the measurements being generally constant and small with respect to the interval between the successive low tides and high tides.

$$NM_{t_1}^{t_N} = \frac{1}{N}\sum_{n=1}^{n=N} h(t_n)$$

In practice, in documents relative to tides, the term 'mean sea level' does not apply to the strict mean value of the levels observed, but to the result of a digital filtering (whose mean value is only a specific case). According to common practice, the 'Instantaneous Mean Sea Level' (IMSL) is the result of an operation consisting in subtracting the astronomical tide from the heights measured.

$\mathrm{IMSL}(t) = (\text{height observed at time } t) - \Sigma A_i \cos(q_i t - \alpha_i)$

According to this definition, and for statistic purposes, the instantaneous mean sea level can be considered as a random variable which would represent the height of the free surface in the absence of periodical oscillations caused by astronomical effects. The mean value of the IMSL gives a result which is more accurate than the simple average of heights since it minimises the disturbances of the periodical components, which are low in any case over long periods; therefore the Mean Sea Level (MSL) over long periods is generally calculated from the IMSL. The difficulty results from the fact that, whatever the time frame, even long (a few years), this random variable is not stationary because the mean value depends on the sample considered. The following figure, in which the rise of the annual mean sea levels in Brest over two centuries is displayed, is a vivid illustration.

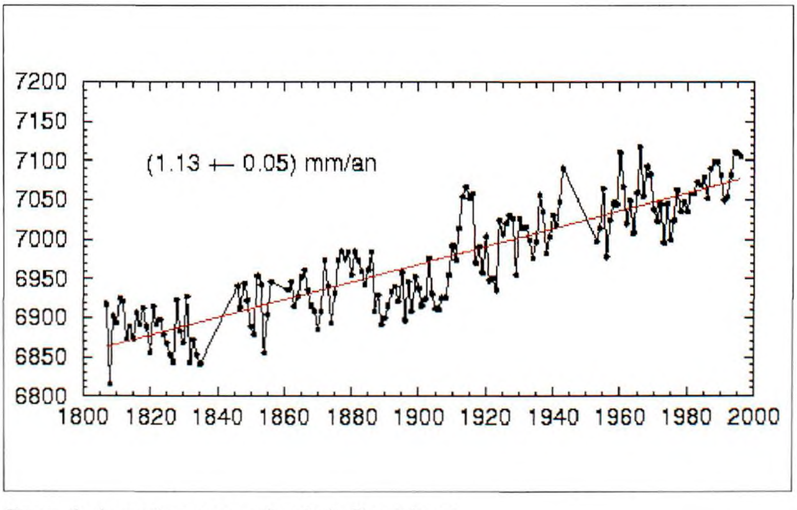

Figure 1: Annual mean sea levels in Brest (mm).

The mean sea level (which should include at least the times of beginning and end as well as the calculation method) and the instantaneous mean sea level, referred to a terrestrial reference frame, are a function of time. This variability does not make it possible to impart to either one of them the vertical reference status, since one of the fundamental criteria, stability, is not observed.

Tide predictions use the mean sea level calculated over the longest possible period, fixed with respect to the shore and to the terrestrial reference frames. This level is called 'Nominal Mean Sea Level' (NMSL). This calculation is made for long-duration (if possible several years) tide observation sites. These sites are then called reference stations.

In the application of the harmonic formula to the reduction of soundings, it is estimated that the instantaneous mean sea level and the nominal mean sea level, and thus all other mean sea levels, define parallel surfaces, but whereas the height of the instantaneous mean sea level is a function of time, the height of the nominal mean sea level referred to a terrestrial reference is constant.

The Mean Sea Surface (MSS), calculated by means of satellite altimetric measurements, will be frequently mentioned hereunder. The ellipsoidal height of the sea surface is averaged at each point of the ground track, after different corrections intended, in particular, to eliminate the astronomical tide. After interpolation to fill the zones which are not covered between the ground tracks, the result is presented in the form of an average surface, representative of the mean sea level at each point (with the resolution allowed by the spacings between the satellite ground tracks) during the observation time.

Currently, we do not know how to measure by satellite the MSS close to coasts, and the resolution is only a few tens of kilometres, thus limiting its use in hydrography.

I.4 Geoid

A geoid is an equipotential surface of the Earth gravity field.

Ashore, a geoid is determined by geometric levelling and by also using gravimetry measurements; the tide gauge levelling benchmarks are, if possible, referred to a geoid, in practice, the terrestrial levelling reference surface, called here the 'terrestrial levelling geoid'.

At sea, the same geoid can be extended by means of gravimetric measurements. A major argument to use a geoid as a reference for the tide is the fact that the vertical reference of mathematical models used to simulate the ocean dynamics is a gravity field equipotential line. At all points, the local vertical is perpendicular to the geoid. A very common error consists in mistaking it with the MSS. These two surfaces must be distinguished because the MSS is, with respect to the geoid, affected by 'meteorological and oceanographic' phenomena. These phenomena include the general ocean circulation (at a latitude of 45°, a current of 1m/s over a width of 10km creates a height difference of 10cm perpendicularly to the current), the average distribution of densities, the atmospheric pressure gradients and the non-linear effects of tide propagation in shallow water zones. Between them, the non-linear effects generate, for example in the English Channel, differences which can reach about ten centimetres.

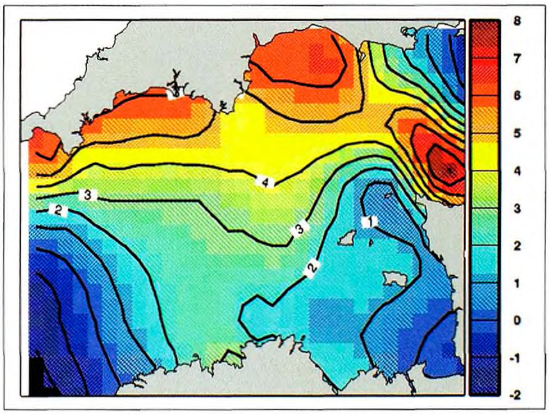

Figure 2: Influence of non-linear effects of the tide on the difference between the MSS and the geoid (expressed in cm) (calculated by SHOM with the model used for sounding reduction).

The geoid to be used as initial surface for the simulation models is also different from the terrestrial levelling geoid: the geoid at sea is an equipotential of the gravity field which would roughly correspond to the surface of a homogenous ocean at rest with a density equal to the average density of the ocean at the initial time, submitted to an atmosphere also homogenous and at rest. It will be called the 'marine geoid'. The marine geoid is quite similar, in its practical determination, to the terrestrial levelling geoid, which is usually set on the mean sea level, but possibly measured a long time ago and at a distant point. However, it does not coincide with the latter (if only due to the evolution of the sea level over centuries) and the differences, which cannot be currently measured with accuracy, could reach several tens of centimetres, which is not acceptable for hydrography and for the study of ocean circulation.

It is possible, using the harmonic formula, to measure the lowest astronomical tides level, and therefore the hydrographic zero, with respect to the mean sea level over the period considered. The variations of harmonic constants as a function of mean sea level variations can be disregarded in practice, as well as in models. This is a fundamental property for the determination of the hydrographic zero and for the reduction of soundings using the so-called traditional method, because it nearly clears all doubts on the mean sea level measurement.

A complete digital model should make it possible to measure the hydrographic zero with respect to the marine geoid, which is the vertical reference of the model. But in practice, this is nearly impossible because it implies performing a simulation over several years and accounting for external meteorological conditions and oceanographic effects mentioned above (except for tide non-linear effects which are easily accounted for by the models). Besides, the relative differences of the mean sea level and geoid are not well known at the open borders of the models, forbidding the simulation of induced residual circulations and the corresponding height variations.

To apply such a modelling on large areas using the marine geoid as reference requires that the latter be determined accurately in a terrestrial (or spatial) reference frame and all MSS variations with respect to the marine geoid be known with accuracy (cm). There is still a long way before such knowledge is acquired, but progress is being made owing to spatial techniques (including gravimetry) and to modelling.

I.5 Ellipsoid and ITRF

A reference ellipsoid is a 'convenient' mathematical surface to define a geodetic system from the relative positions of points located on the surface of the Earth. The stability of this reference frame, as well as that of any other geodetic reference frame, depends on the number and geographical distribution of the points used to define it as well as the diversity of techniques used to locate them. The interest of the ellipsoid is that it constitutes a convenient reference, mainly for some spatial techniques, and in particular in altimetry. According to the UGGI and AIG recommendations in 1991, the International Terrestrial Reference System (ITRS), achieved with the International Terrestrial Reference Frame (ITRF) should be used for all applications requiring an accuracy greater than the metre. Although the WGS84 (the GPS reference system) is more popular, this recommendation is still valid because the ITRS is based on a very dense geographical coverage including hundreds of points, versus only about twenty for the WGS84, and using different techniques (VLBI, SLR, GPS, DORIS), versus a single one for the WGS84 (GPS). In practice, the two systems have quite similar designs, but the ITRS is, on the design level, independent of the technique and any new successful technique can be integrated. In particular, the future evolutions and the development of new positioning systems (Galileo, etc.) must not be disregarded. Another argument (if needed) is that the ITRS is maintained and improved by the international community and therefore does not depend on any organisation or country but rather on an international scientific association, the AIG (International Association of Geodesy), which confers it its scientific quality label.

I.6 Ground marks and levelling

In stations, the hydrographic zero and the nominal mean sea level are materialised by their heights with respect to levelling benchmarks. These benchmarks are located near the tide gauge and are sufficiently numerous and spaced out so that they cannot be damaged simultaneously, for example during works in port. Their positions are calculated with respect to each other by geometrical levelling, and if possible, referred to the general levelling. It should be emphasised that the hydrographic zero is not defined by its height in the general levelling. The zero height should not be altered by successive levelling operations which might give different results, not only because of the evolution of measuring techniques, but also because of possible terrestrial vertical movements of tectonic or seismic origin. Let us mention, in this connection, that ocean loading due to the tide itself can generate vertical movements (periodical –as the tide) of the benchmarks (referred, for example, to the geoid) which may exceed 20 cm; these movements are of little significance locally for hydrography as they are part of a general movement of the basement already accounted for in observations and models. But, in certain zones, it will be necessary to consider them to maintain centimetric accuracy when spatial techniques are used.

II Accuracy

The notion of accuracy includes two aspects. In fact, the accuracy resulting from the degree of conformity with the definition (lowest tides) must be distinguished from the measurement accuracy in a benchmark.

The definition of the hydrographic zero includes an arbitrary side, which allows a certain freedom as shown by the diversity of definitions still in use. Adopting the lowest tide level is mainly an advantage. It allows the navigator to determine from which sounding on the chart it will be necessary to account for the tide, but the accuracy of the hydrographic zero determination with respect to the lowest tide level is not a fundamental criterion: the fact that soundings are referred 'approximately' to the lowest tide level, as it is very often mentioned on the nautical charts, will be considered as acceptable.

The second aspect of the notion of accuracy concerns the reference system for the hydrographic zero. Once adopted, it must be measured in a stable and accessible reference frame. This operation is very important, because, as the hydrographic zero must acquire the status of vertical reference, its main quality must be stability. For coastal observation stations, height measurement with respect to benchmarks must be performed with utmost care, to prevent variations due to successive levelling operations. An accuracy of approximately one millimetre, which is authorised without major difficulties by standard levelling operations, must be obtained. Of course, this accuracy is useless for maritime navigation, but it is fundamental when assessing the stability of benchmarks and when conducting studies relating, among others, to the sea level evolution.

III Accessibility

Away from coastal observation stations, the main problem to be solved is the accessibility of the vertical reference.

III.1 Traditional method

During hydrographic soundings performed in a conventional manner, the two surfaces directly accessible are the surface and the bottom. The bottom can be used, but in a very marginal way, to locate the height of the hydrographic zero close to a tide gauge whose levelling benchmarks have disappeared. In practice, for traditional surveys, the only accessible reference is the surface, which has obviously the drawback of being unstable. Therefore, only a provisional reference status can be allocated to it.

The conventional procedure used is based on the concordance method (see Chapter VII-1) which models the correspondence between the tides of two close points by linear regressions. It can also be perceived as a geometric levelling obtained via the sea level in order to refer the water heights to the only benchmarks known which are generally installed on the coast close to the tide gauges. In fact, the aim is to locate the hydrographic zero with respect to the sea surface, at the location and time of measurement, using harmonic constants resulting from a tide model and offset considered as constant in space between the nominal mean sea level and the instantaneous mean sea level. An improved procedure, but virtually not used because soundings are made during calm weather, would consist in using a model incorporating the meteorological effects. Accuracy would also be enhanced when moving away from the reference station. For example, the mean instantaneous current created by wind can generate significant surface slopes (one cm for 10km is frequent; Refer to § 1.4). A similar reasoning can be made for density variations, which could be significant, in particular at river mouths.

Modelling[1] makes it possible to calculate, on the one hand an instantaneous astronomical tide

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[1] The SHOM currently (2005) uses the TELEMAC model described in:
Jean-Michel Hervouet (2003), Free surface flows hydrodynamics (Digital modelling with the finite elements method), ENPC presses, ISBN: 2-85978-379-2, 336p.

height at the sounding point, referred to the mean sea level and

$$A_S(X,Y,t)=\sum_i A_{si}\cos\left[q_i t-\alpha_{si}(X,Y)\right]$$

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on the other hand, the height of the nominal mean sea level $N_S(X,Y)$ with respect to the lowest tide level. This height being a constant at a given point, it has been calculated from a cartography of the lowest tide level referred to the mean sea level, obtained by digital modelling. The figure hereafter gives an example.

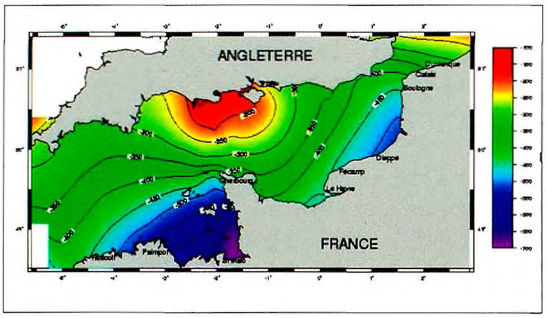

Figure 3: Lowest tide level referred to mean sea level:- $N_S(X,Y)$ (calculated by SHOM with the model used for the reduction of sounding).

The height of the astronomical tide with respect to the lowest tide level is thus obtained at the sounding point:

$$H_{AS}(X,Y,t)=N_S(X,Y)+A_S(X,Y,t)$$

To obtain the sea surface height with respect to the hydrographic zero, this value must be corrected to account for the 'positive/negative height variations' due to meteorological and oceanographic effects[2], and for a possible difference between the hydrographic zero and the lowest tide level at the closest reference station. This last correction is designed to prevent discontinuities in the sounding values plotted on the charts, when moving away from the reference station to the open sea.

Given δh_R, the value of the positive/negative height variations at the reference station. It is the difference between the tide observed and the predicted tide; it is also, because of the process used to calculate the instantaneous mean sea level, the difference between the latter and the nominal mean sea level. This difference, as mentioned before, is *assumed to be constant in space. This correction* is therefore applied at the sounding point and symbolised by δh.

Given δZ_R the height, referred to the hydrographic zero, of the lowest tide level at the reference station. A non-nil value is generally the consequence of an old and possibly inaccurate determination and of the evolution of the mean sea level over centuries. A current practice consists in determining $\delta Z_S(X,Y)$, the hydrographic height of the lowest tide level at the sounding point, with a height concordance; or the same result can be obtained by posing $\dfrac{\delta Z_S(X,Y)}{\delta Z_R}=\dfrac{N_S(X,Y)}{N_R}$

where N_R is the nominal mean sea level referred to the lowest tide level at the reference station (in fact it is the opposite value that is determined).

Given $A_R(t)=\sum A_{Ri}\cos(q_i t-\alpha_{Ri})$, the height of the astronomical tide at the reference station R, referred to the nominal mean sea level and $H_M(t)$ the height measured on the tide gauge, referred to the hydrographic zero.

By adopting the notations of Figure 4, sounding reduction consists in calculating the height of the water surface $H(X,Y,t)$ at the location of sounding S by performing the following operation:

$$H(X,Y,t)=H_{AS}(X,Y,t)-\underbrace{H_M(t)-\left[A_R(t)+N_R+\delta Z_R\right]}_{\delta h}+\underbrace{\delta Z_R\frac{N_S(X,Y)}{N_R}}_{\delta Z_S(X,Y)}$$

If S is the sounder indication ('sounding'), the height Z to be plotted on the chart ('reduced sounding') is:

$$Z=S-H(X,Y,t)$$

Let us note that A_S, A_R, N_S, and N_R are referred to the Nominal Mean Sea Level (NMSL), which can then be considered as a factual reference. But it is a reference whose absolute positioning has little influence on the soundings, because the NMSL intervenes both to determine the hydrographic zero position with respect to the level of the lowest astronomical tides and to calculate the astronomical tide in R, and the offset effects in S on these values nearly cancel. In fact, if the nominal mean sea level is offset by a value ΔN, the height of the lowest astronomical tides is offset in proportion,

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[2] Within an unknown constant since the marine geoid is not known with accuracy.

δZ_R is increased proportionally and δh, measured in R, varies by -ΔN. In S, the hydrographic zero is offset by ΔN.(N_S/N_R). The offset on $H_{AS}(X,Y,t)$, thus on sounding Z (noting that δh in S and in R are equal to ΔN), is then $\Delta N(N_S - N_R)/N_R$. If the amplitudes in R and S are close, this offset may be disregarded; if these amplitudes are not close, the error remains low as long as they are not too far from the 'true' values (unknown) and as the hydrographic zero selected is close to the lowest astronomical tides; for example, for ΔN = 20 cm, which is significant (see Figure 1)[3], and for a relative variation of $(N_S - N_R)/N_R$ equal to 10%, we obtain ΔH = 2 cm, which remains acceptable.

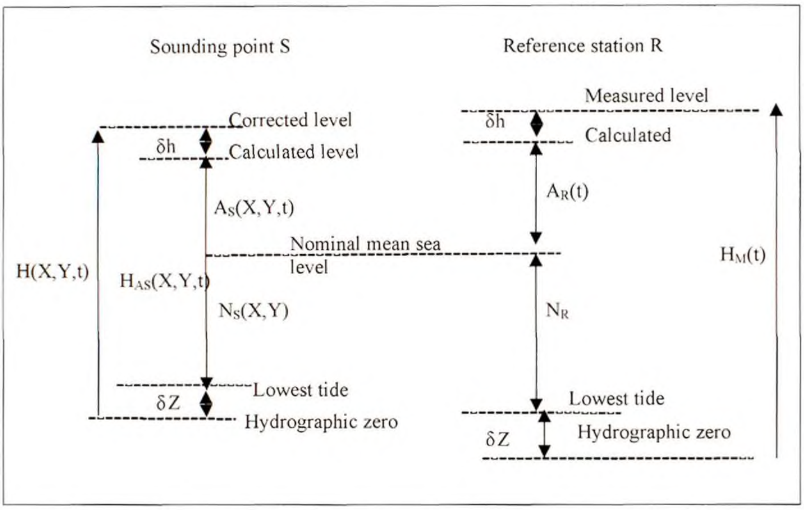

Figure 4: Sounding correction, conventional method.

A major consequence of this practice must be emphasised: a possible difference may be observed at the sounding station, resulting from the difference existing at the reference station between the hydrographic zero and the lowest tide level. If this difference is low, it may be disregarded, but any significant difference may lead to difficulties when changing the reference station. For this reason, SHOM instituted 'tidal zones' relative to the main stations of the French coasts. Another difficulty is linked to the distance to reference: a long distance may render highly unreliable the correction method of meteorological and oceanographic effects by carrying over δh.

The procedure has been improved by using pressure sensor tide gauges laid on the bottom near the sounding area. When a month's worth of tide gauge observations are available, the species concordance method makes it possible to obtain an astronomical tide accurate enough to use this measurement point at sea as the reference station. Due to its proximity, a better correction of meteorological conditions and oceanographic effects will thus be achieved. It is however necessary, beforehand, to measure the hydrographic zero at the measurement point, with respect to the instrumental zero of the immersed tide gauge.

Since the method described above makes it possible to locate the hydrographic zero with respect to the nominal mean sea level, the latter must be measured with respect to the instrumental zero. For this purpose, the approximation of parallelism is used for the different mean sea level surfaces between the reference station and the immersed tide gauge, better verified for a mean sea level calculated over a certain period of time than for an instantaneous mean sea level (but undetectable biases cannot be excluded over this period); the immersed tide gauge also allows to ensure the validity of the tide model used. Once the mean sea level instrumental height has been calculated at the immersed tide gauge during the measurement period, the correction applied to it is the difference between the mean sea level during the same period and the nominal mean sea level at the reference station.

Despite the use of immersed tide gauges, it remains necessary to observe the tide in a reference station. It does not solve the problem of tide zones, but allows a better compensation of meteorological and oceanographic effects.

III.2 Spatial techniques

Spatial techniques bring a different solution to the problem of sounding reduction.

First of all, the sea bottom can now be accurately

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[3] The low relative variations in nominal mean sea levels of adjacent stations with respect to the terrestrial geoid (a few centimetres) confirm that a 20cm error is very pessimistic, all the more as much of these levels have been determined over significantly different periods.

measured in a terrestrial reference frame without using the sea level and thus without a tide model of the liquid medium. This therefore constitutes an absolute and perennial measurement, which is one of the major advantages of these techniques. Today, it is not possible to perform this measurement in real time in a global reference frame (ITRS for example), but it is possible, close to a terrestrial reference station to locate oneself with accuracy with respect to this reference station.

For better accuracy, it is also necessary to account for basement movements, which may be considered as identical in an area measuring a few tens of kilometres for the earth tide, but not for the basement bending caused by ocean loading, where gradients of about one cm for 10km[4] have been observed. Unlike the traditional method where the tide model (based on coast and sea observations including both sea surface and bottom movements) also compensate for basement movements, the spatial method, even in certain limited zones, must take into account the latter to maintain the accuracy.

It is also possible to position precisely in a geodetic reference system (ellipsoid) the Mean Sea Surface (MSS) obtained by altimetry. TOPEX/ POSEIDON already yielded satisfactory results and JASON should allow further advance in this direction. Accuracy deteriorates close to coasts due to the low resolution (10km) and the inappropriate integration of shore portions in the calculation; but this problem can be solved by taking advantage of tide observations made on the coasts and correlating them to an accurate geodetic system. As for the traditional method, the hydrographic zero must also be determined, in the present reference frames which remain local (tide zones), by means of the nominal mean sea level. This is achieved by correcting the MSS from differences between the mean sea level calculated by means of the reference tide gauge during the altimetric measurement period and the nominal mean sea level, then applying the tide modelling results to position the hydrographic zero at all points of the tide zone. The MSS ellipsoidal height being known, the ellipsoidal height of the hydrographic zero can be deduced. The fundamental reference is always the hydrographic zero at the reference station.

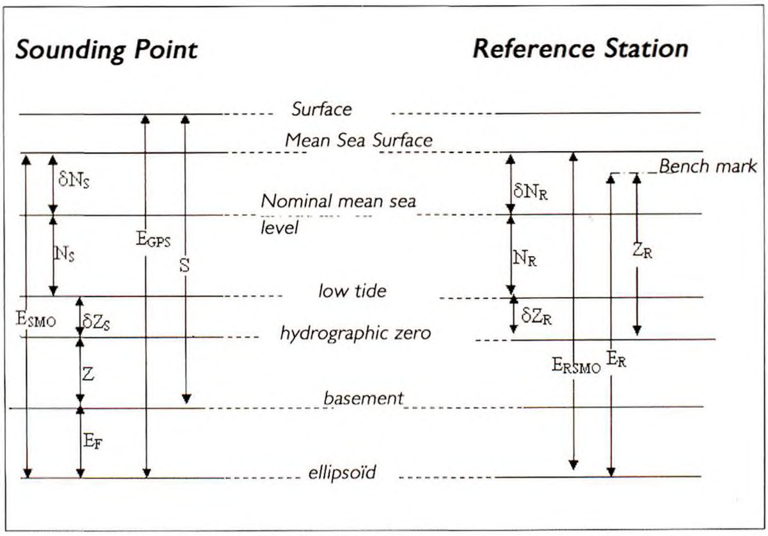

Figure 5: Sounding correction, spatial technique.

Note: for the accuracy of soundings, in the present status of knowledge, it is recommended to use a tide model set on observations integrating sea surface movements and the basement movements, as for the traditional method. It is the easiest method. To reach the maximum accuracy, it would be necessary to model all the sea surface and basement movements taking into account all the effects: astronomical tide, meteorological conditions and oceanographic conditions.

The increase in accuracy of measurements and models makes it possible to seriously envisage a continuous determination of the hydrographic zero on vast surfaces. But it is necessary to work in the existing cartographic reference frame, which is based on the tide zones. To change over to a continuous hydrographic zero, it will be necessary to go over all the charts and correct them. This will probably last for decades, as it is a major endeavor for which no hydrographic department has the resources allowing to speed up the process.

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[4] F. DUQUENNE (2001), OCEAN LOADING by - ESGT .

Let us recall the notations of Figure 5:

E_{SMO} = MSS ellipsoidal height from altimetric measurements,

δN_S = difference, at the sounding point, between the nominal mean sea level and the MSS level,

N_S = nominal mean sea level referred to the lowest tide level at the sounding point,

δZ_S = hydrographic height of the lowest tide at the sounding point,

Z = hydrographic height of the bottom at the sounding point,

E_F = ellipsoidal height of the bottom,

E_{GPS} = ellipsoidal height of the free surface measured by GPS,

S = depth measured by the sounder,

δN_R = difference, at the reference station, between the nominal mean sea level and the MSS level,

N_R = nominal mean sea level referred to the lowest tide level at the reference station,

δZ_R = hydrographic height of the lowest tides at the reference station,

E_{RSMO} = MSS ellipsoidal height at the reference station,

E_R = ellipsoidal height of the tide gauge reference mark,

Z_R = hydrographic height of the tide gauge reference mark.

The problem consists in determining E_F the bottom ellipsoidal height (it is one of the IHO recommendations), as well as Z the bottom hydrographic height. Using Figure 5, the following results are obtained easily:

$E_F = E_{GPS} - S$

$$Z = E_{SMO} - E_F - \left(\delta Z_S + N_S + \delta N_S\right)$$

E_{GPS}, S and E_{SMO} result from measurements. Figure 6 gives an example of the E_{SMO} values close to the French coastlines, obtained from TOPEX/POSEIDON altimetric measurements.

This method presents a major advantage: the height of the free surface in a terrestrial reference frame does not appear (even implicitly) in the previous formula; this eliminates the problems linked to tide prediction (except for the determination of the lowest tides and the basement movements when they are significant) and to meteorological and oceanographic effects.

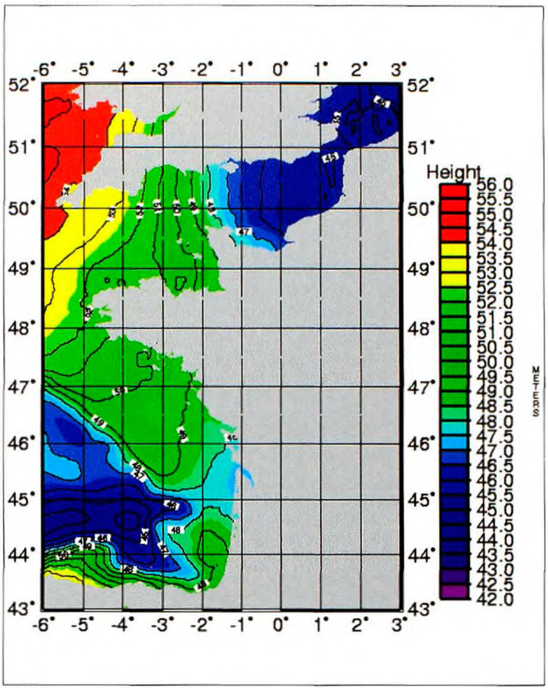

Figure 6: Ellipsoidal height of the Mean Sea Surface.

As seen in the previous chapter, δZ_S results from the following relation: $\delta Z_S = \delta Z_R \dfrac{N_S}{N_R}$

N_S and N_R are obtained with harmonic constants from tide models offshore and observations at the reference station. Figure 3 gives an illustration for the English Channel.

δN_S is the difference between the nominal mean sea level and the MSS level at the sounding point. According to the approximation of parallelism of the mean sea level surfaces, we pose $\delta N_S = \delta N_R$ where δN_R is, at the reference station, the difference between the mean sea level calculated from the observations covering the period used to define the Mean Sea Surface (MSS), and the nominal mean sea level. All the formula elements to calculate Z are thus available.

However, there remains a difficulty, due to the inaccuracy of altimetric measurements close to coasts, but the accurate geodetic measurements performed in tide observation stations may help to solve this problem by providing a possibility of interpolation. For example, due to this inaccuracy, the ellipsoidal height E_{RSMO} of the MSS at the reference station cannot result from the altimetric measurements, but the ellipsoidal height E_R of the tide gauge benchmark

can be obtained by means of geodetic measurements made on the observation station site, which makes it possible to use the following formula:
$E_{RSMO} = E_R - Z_R + \delta Z_R + N_R + \delta N_R$

IV Stability

The notion of benchmark stability requires answering the following question: Stability with respect to what? This generally depends on the problem to be solved: for hydrography, the stability criterion requires that sounding values not be challenged by successive measurements of the reference system. This particularly concerns the stability of material benchmarks whose height with respect to the hydrographic zero is determined with accuracy.

As seen previously, an excellent accuracy in the positioning of the lowest tide levels is not required, but once fixed, the height of the hydrographic zero defines the latter very accurately and permanently, except in exceptional circumstances, independently of a subsequent determination, possibly more accurate, of the lowest tide level. A perennial cartography must be established in order to avoid successive determinations. Now, with the a priori commendable intention of improving accuracy, this stability rule is often infringed.

Although it is made possible by harmonic constants, for reasons of stability, the lowest astronomical tides level should not be calculated on the occasion of new observations, but preferably, should be the result of an ongoing global cartography. However, because of a lack of confidence in the quality of models, and especially because of the feeling that this quality evolves rapidly as calculation means progress, this rule is rarely observed. Besides, the question of compatibility with neighbouring countries can be posed. Ideally, a common model should be adopted, but attempts in this direction within the 'Tidal Working Group' of the Northern Sea Hydrographic Commission, demonstrated the difficulties involved. Probably, over the short and medium terms, we will have to satisfy ourselves with a kind of adjustment at the borders of the responsibility zones.

This lowest level astronomical tide cartography is obtained with respect to the mean sea level of the model, whose height has little influence, within the limits of realistic values, on the harmonic constants (used to calculate the lowest astronomical tides level).

IV.1 Traditional methods

The nominal mean sea level has acquired, during the hydrographic zero positioning procedures according to traditional techniques, the vertical reference status. Its accessibility offshore is ensured by means of a model used to calculate its height with respect to the free surface at the sounding location and time (assuming that δh is constant in space at the sounding time).

The question of the stability of the nominal mean sea level, selected as vertical reference, is not posed in terms of height measurement accuracy with respect to the free surface (which results in an uncertainty on the reduced soundings), but in terms of relevance for selecting this reference surface to solve the problem of reduction of soundings. First, let us emphasise that, for coastal observation stations, the vertical reference is materialised by tide gauge benchmarks. This choice is pertinent because their possible vertical movements should be close to those affecting adjacent coastal zones. It is also the case for the nominal mean sea level, whose height with respect to coastal benchmarks is fixed.

However, it should be noted that, due to the reduction procedures, the possible vertical movements of the tide gauge have an incidence on the vertical reference stability for distant points where the vertical movements of the terrestrial basement can differ from those of the tide gauge. This problem can only be solved correctly by taking into account the geodetic positioning of the coastal tide gauges surrounding the sounding zone and by modelling possible movements, offshore like ashore. Finally, when using immersed tide gauges, another difficulty relating to stability results from a slow evolution, undetected during the measurement period, due to the mean slope of the water surface between the sounding zone and the reference station. The future coastal modelling systems (following the research in progress) of the meteorological and oceanographic effects (coupled) should allow to quantify this slope.

Although we concentrate here on hydrographic sounding correction, we should also keep in mind the navigators' needs, as most often they only have at their disposal a tide prediction referred to the nominal mean sea level and not to the instantaneous mean sea level. The 'reverse barometer correction' recommended in the tide tables makes it possible to improve the accuracy, but it would be preferable to have the value of δh (difference between the instantaneous mean sea level and the nominal mean sea level) measured on the tide gauge, which is performed by the pilot services of some stations.

IV.2 Spatial techniques

Concerning the reference systems from spatial techniques, it has been shown hereabove, concerning the reference ellipsoids, that the stability and accuracy criteria lead to prefer the ITRS rather than the WGS 84. To position the hydrographic zero, it is still necessary to use a local nominal mean sea level (and extended via the MSS, and translated to be adjusted to the nominal mean sea level at the reference station) as long as the present tidal zones are in force. The MSS (established over a long period, 'correctly selected') when evolving towards a generalised continuous hydrographic zero reference. But the nominal mean sea level then loses its reference status, because once it has been used to position the lowest tide level in the 'ellipsoidal' reference frame, the latter acquires the hydrographic zero reference status whose ellipsoidal height can be fixed definitely. This solves the problem of the reference system stability. But the question of relevance for selecting the ellipsoidal reference system is posed, because unlike the nominal mean sea level, which is based on coastal references, the ellipsoid is independent of the vertical movements of the terrestrial benchmarks which, if they exist, may induce variations of the sounding values. The use of this technique must be accompanied, if necessary, by a geodetic monitoring of the vertical movements of the tide gauge benchmarks in the vicinity (which must be taken into account for the different measurements of the ITRS) and the modelling of basement movements.

V Conclusion, recommendations for model use

The main difficulties linked to the reduction of hydrographic soundings appear when moving away from the coastal tide stations. Recourse to tide modelling is then necessary. The main role of modelling is to locate the hydrographic zero in a reference frame linked to the Earth. This reference being fixed, other techniques can be used to determine water heights, for example the kinematic GPS (and its accurate ephemeris) or another more specific model.

Near tide gauges, the height of the hydrographic zero with respect to levelling benchmarks is seldom questioned, even after a possibly more accurate positioning of the lowest tide level. This prevents adding, to the uncertainty regarding water height (referred to terrestrial benchmarks), the uncertainty on the zero position. Offshore, according to the technique used, the nominal mean sea level or the ellipsoid constitute the fundamental references. For the same reason which leads us to fix the hydrographic zero height of coastal stations, the zero reference height with respect to these references should be fixed permanenly. In fact, the present performance of digital models leads us to pose the problem in this manner, by making it possible to locate the lowest tide level with enough accuracy to define the hydrographic zero reference. The question is then posed to know which performances are required in order for a model to be used for this purpose.

The location of the hydrographic zero depends, of course, on its definition, usually the level of the lowest astronomical tides. Two options can be envisaged:

- either the model provides the low tide levels for various spring tide situations and the lowest tide level is deduced by extrapolation,
- or the model provides harmonic constants used to calculate the most extreme lowest level.

These two solutions are not equivalent, because for the first one, the lowest tide level is referred to the model reference level, a geoid if it is a mathematical model, while for the second one, the reference is that of the harmonic formula, the mean sea level.

Note: the observation in Paragraph 1.4 to the effect that 'The variations of harmonic constants as a function of mean sea level variations can be disregarded in practice' makes it possible to do without an accurate determination of the mean sea level.

The second solution is the only practicable one currently, because it is sometimes hazardous to appeal to extrapolations, the marine geoid is not known very precisely and the meteorological and oceanographic effects are still not modelled with sufficient accuracy.

Moreover, for the reduction of soundings by means of the traditional method, the accurate position of the 'true' mean sea level is not necessary. For the spatial method, it is possible to use the absolute measurements of the MSS (problems of interpolation near the coasts, that will be appropriately solved by the modelling of meteorological and oceanographic effects while allowing a better validation of the MSS).

The experience acquired for tide modelling in the English Channel provides information on what was obtained with these techniques:

- the simulation of an annual tide period allows to calculate the harmonic constants of a standard list at each of the (approximately) 25,000 points of the model.
- these constants are corrected in order to correspond, as much as possible, with those which are already known, according to their level of confidence.
- the calculation of the lowest astronomical tides is performed using the harmonic method at each point of the model infrastructure.

This technique provides an accuracy close to 1% of the tidal range. This value order seems to be reasonable and could be adopted as a standard, correlatively to the following rule: if the lowest tide level cannot be determined with an accuracy greater than N cm (typical value: 10cm), the hydrographic zero will be lowered to a level such that, given the uncertainty on its determination, the level of the lowest astronomical tides could not be below. On the Metropolitan French coasts, the mean sea level tends to rise, thus making it possible not to apply any additional safety margin.

Biography

Civil engineer at SHOM (Service Hydrographique et Océanographique de la Marine) since 1970, in charge of acoustic sub-bottom studies, later coastal hydrodynamics. Teacher at the Ecole Nationale Supérieure d'Ingénieurs des Etudes et Techniques de l'Armement (ENSIETA) and at the Ecole Nationale Supérieure des Techniques Avancées (ENSTA).