The Permanent Tide in Height Systems

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Abstract We describe the treatment of the permanent tide in various geodetic quantities with an emphasis on systems of gravity-related heights. We review the historical development leading to the present situation, and discuss possible scenarios for the future, especially in view of the adoption of a World Height System.

Keywords Permanent tide · Heights · Levelling · Geoid · Geopotential · Reference systems · Gravity · Sea level · Altimetry.

1 Introduction

The time-averages of the tide-generating potentials of the Sun and the Moon are not zero. At the surface of the Earth both their magnitude and their range are a few parts of 10^{-8} of the potential of the Earth: To deal with the permanent deformation they cause, there are two concepts that are available for the 3-D shape of the Earth (also called crust or topography) and three concepts for the gravity field.

- In the *non-tidal* or *tide-free* system, the permanent deformation is eliminated from the shape of the Earth. From the potential field quantities (gravity, geoid etc) both the tide-generating potential, and the deformation potential of the Earth (the indirect effect) are eliminated. This corresponds to physically removing the Sun and the Moon to infinity. Typically the permanent deformation is however treated using the same Love numbers h and k (and Shida number ℓ) as for the time-dependent tidal effects (conventional tide-free system), instead of estimates for secular (fluid) Love numbers.
- In the *mean* system, the permanent effect is not removed from the shape of the Earth. The shape therefore corresponds to the long-time average under tidal forcing. The potential field retains the potential of this average Earth, and also the time-average of the tide-generating potential (though it is not due to the masses of the Earth).
- For the potential field quantities, a "middle alternative", the *zero* system is available. It eliminates the tide-generating potential but retains its indirect effect, i.e., the potential of the permanent deformation of the Earth. Thus its partner is the mean system for 3-D shape; because of this it is often said that for the 3-D shape we have zero≡mean. In this alternative, the gravity field is generated only by the masses of the Earth (plus the centrifugal force).

The terminology above has become more or less standard since Ekman (1989). In older literature sometimes the same terms were used with different definitions.

The current IAG resolution (1983, see Tcherning 1984) requires the zero system for the gravity field and the mean system for the 3-D Earth. Current practice is to use the zero system for gravity, tide-free for 3-D positions (e.g., ITRFxx), and mixed (overwhelmingly mean) for potential differences determined with precise levelling. Geopotential models are nowadays often provided both in conventional tide-free and in zero versions.

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The permanent tide in height systems cannot be discussed separately from the permanent tide in other geodetic quantities. The purpose of this paper is to give an overview of the present situation and to discuss different scenarios for the future.

2 Basic Relations

Zadro and Marussi (1973) derived formulas for the time-averages of the lunar and solar tide-generating potential. For the present discussion we only note that rounded to 1 mm we have at the (say) GRS80 ellipsoid (Heikkinen 1978, Ekman 1982)

$$W_2/g = -0.296 \sin^2 \varphi + 0.099 \text{ [m]} \qquad (1)$$

Here W_2 is the sum of the time averages of the above mentioned potentials, g is the acceleration of gravity, and φ is the geodetic latitude.

Formulas given in the literature with more digits differ in the coefficients at the 0.1 mm level. This will be discussed elsewhere. In a century the obliquity of the ecliptic changes roughly by $1'$ which changes the coefficients in Eq. (1) by 4 parts in 10^4.

Figure 1 illustrates schematically the differences between the various tidal concepts for the geoid and for the topography (crust). The geoids are represented by the solid lines and the crusts by the dashed lines. The differences are in the flattening. Using the zero geoid as a reference we enumerate four geoids, from largest flattening to smallest, and their height relative to this reference (the solid line):

- mean geoid at $+W_2/g$
- zero geoid at 0
- conventional tide-free geoid at $-kW_2/g$, $k \approx 0.3$
- fluid tide-free geoid at $-kW_2/g$, $k \approx 0.93$

Similarly, using the mean crust (topography) as a reference, we enumerate three crusts from largest flattening to the smallest (the dashed lines):

- mean crust at 0
- conventional tide-free crust at $-hW_2/g$, $h \approx 0.6$
- fluid tide-free crust at $-hW_2/g$, $h \approx 1.93$

For completeness we remark that the tangential (or transverse) difference between the various crusts is not illustrated. In the north direction we have

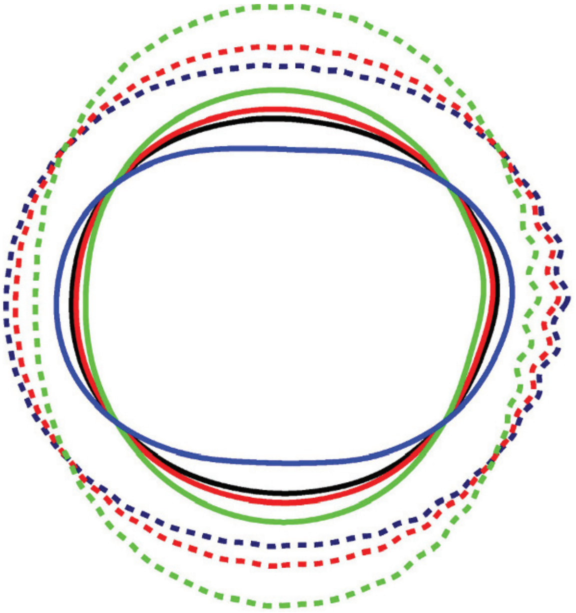

Fig. 1 Schematic illustration of different tidal concepts for the crust/topography (*dashed lines*) and the geoid (*solid lines*), as sections in a meridional plane. The crusts are from largest to smallest flattening: mean, conventional tide-free, fluid ("realistic") tide-free. The geoids are from largest to smallest flattening: mean, zero, conventional tide-free, fluid ("realistic") tide-free. The relative differences in flattening are correctly scaled while the flattening itself obviously is not. More explanations in text

- mean crust at 0
- conventional tide-free crust at $-\frac{\ell}{g}\frac{\partial W_2}{\partial \varphi}$, $\ell \approx 0.08$
- fluid tide-free crust at $-\frac{\ell}{g}\frac{\partial W_2}{\partial \varphi}$, $\ell \approx 0.22$

In the east-west direction there are no differences between the tidal systems.

The heights of various crusts above various geoids are collected in Table 1. They are taken relative to the height of the mean crust above the zero geoid. Note that in calculating numerically these heights, compatible coordinates must be used for the crust and for the geoid. E.g., if the crust is given in the ITRFxx, then the geoid surface in 3-D space must also be given in the ITRFxx, independently of whether we are using the mean, zero, or tide-free geoid.

Table 1 Crust above the geoid: all combinations of tidal concepts. They are taken relative to the height of the mean crust above the zero geoid

Geoid Crust	Mean	Tide-free
Mean	$-W_2/g$	$(-h+k)W_2/g$
Zero	0	$-hW_2/g$
Tide-free	kW_2/g	$(-h+1)W_2/g$

3 Present Situation

The current *IAG resolution* (1983) recommends the zero system for the gravity field quantities and the mean (≡zero) system for the 3-D positions.

Current practice for *3-D positioning* is tide-free. Coordinates in the International Terrestrial Reference Frame ITRFxx, and through it all modern continental and national reference coordinates (e.g., those given in the European Terrestrial Reference system ETRS89) are in the conventional tide-free system.

Current practice for *gravity* is zero-tide. It appears that all modern reference gravity values since about 1988 are in the zero-tide system.

Geopotential models (EGMs) are nowadays usually provided both in conventional tide-free and in zero-tide versions as far as the potential coefficients are concerned. The difference is only in the J_2 or C_{20} term. Note that the EGMs are to be evaluated at (conventional) tide-free coordinates (Pavlis 1998).

Regional gravimetric geoid models in the past often inherited their tidal systems implicitly from the EGM used, but nowadays are usually explicitly stated to be in the zero-tide system.

In *satellite altimetry* of the oceans, the Geophysical Data Records (GDRs) by the operating agencies typically provide the range from the satellite to the instantaneous sea surface, the height of the satellite above a reference ellipsoid, tidal corrections that do not remove the permanent tide, and geoid heights of an EGM in the mean tidal system, relative to the field of the reference ellipsoid (see e.g., AVISO/Altimetry 1996). Calculations with the quantities in the GDR thus give the height of the sea surface relative to a mean geoid, as recommended by Rapp et al. (1991). *Models of mean sea surface*, constructed from multi-mission altimetry data, refer the surface either to an ellipsoid, or to an EGM geoid in the mean tidal system, though the tidal system of the geoid is not always explicitly stated in the papers.

National height systems are overwhelmingly in the mean-tide system, i.e. mean crust over the mean geoid. This has usually not been by design: if no "luni-solar correction" is applied to precise levelling, then the mean system emerges automatically. The luni-solar correction when applied has almost invariably (and unwittingly) resulted in a conventional tide-free system (tide-free crust over tide-free geoid). Zero-tide systems (mean crust over zero geoid) are very recent: RH 2000 adopted in Sweden in 2005 (Ågren and Svensson 2007) and the N2000 adopted in Finland in 2007 (Saaranen et al. 2007).

Regarding *continental and global height systems*, the European Vertical Reference System (EVRS2000; Ihde and Augath 2001) is zero-tide by definition, but due to the mixed systems (mostly mean, some non-tidal) of the national observations going into the United European Levelling Network UELN-95/98, the current realization EVRF2000 is mixed. The Conventional Vertical Reference System (CVRS) proposed by the IAG ICP1.2 "Vertical Reference Frame" is zero-tide (Ihde et al. 2007). See also Heck (1993, 2004).

During the adoption of the new height systems, there has been no renewed debate about the advantages and disadvantages of the different tidal systems. The attitude has been mostly "we do as the IAG recommends". The current recommendations are the IAG resolutions adopted at the XVIII General Assembly of the IUGG in Hamburg in 1983 and they are as follows (see Tcherning 1984):

> Resolution No. 9
>
> The International Association of Geodesy
>
> *recognizing* the high level of accuracy of both absolute and relative gravity measurements recently attained
>
> *considering* the necessity to adopt standard corrections to gravity observation in order to allow intercomparisons between measurements at different epochs of time
>
> *recommends*
>
> 1. that the tidal correction applied to the gravity observations follow the final recommendations of the Standard Earth Tide Committee as presented at the XVIII IUGG General Assembly [the Committee recommended zero tidal gravity (Rapp 1983), note added by the authors]
>
> Resolution No. 16
>
> The International Association of Geodesy
>
> *recognizing* the need for the uniform treatment of tidal corrections for various geodetic quantities such as gravity and station positions, and
>
> *considering* the reports of the Standard Earth Tide Committee and S.S.G. 2.55, Predictive Methods for Space Techniques, presented at the XVIII General Assembly,
>
> *recommends* that:
>
> 3. the indirect effect due to the permanent yielding of the Earth be not removed.

4 Historical Development

For understanding the present situation it is useful to review the development that lead us here.

Tidal corrections were introduced to improve the precision of geodetic measurements. In many cases their implications for the reference systems and reference frames dawned on geodesists much later. There is no "automatic split" of a tidal correction into a time-variable and permanent part, e.g. when simple tidal corrections are calculated on the basis of ephemerides. Then the permanent part must be evaluated separately and restored by design. Therefore at the first stage of tidal corrections, the conventional tide-free systems were the almost inevitable outcome.

4.1 Precise Levelling

Tidal corrections appeared in the 1940s. The early paper by Jensen (1949) pointed out the significance of the time-independent part and introduced the concepts of mean geoid and tide-free geoid (he called the latter "zero" geoid).

However, the levellers doing the "luni-solar correction" usually did not distinguish between the permanent and the time-independent part. This led to the conventional tide-free system. Most countries did not make any correction at all and ended with the mean tidal system.

4.2 Acceleration of Gravity

Tidal corrections to gravity measurements became important when the accuracy of spring gravimeters improved in the 1950s. The corrections led to nontidal gravity.

Honkasalo (1964) found that tide-free gravity does not represent the time-average of the acceleration of the free fall. He introduced a correction ("Honkasalo correction") to remedy this, i.e., to obtain mean tidal gravity. The correction was applied in the International Gravity Standardization Net IGSN71 (Morelli et al. 1974) which is thus in the mean tidal system.

Then Heikkinen (1979) pointed out that the permanent tide-generating force is due to masses external to the geoid. If it is retained in the free air gravity anomalies, the direct application of Stokes' formula will lead to erroneous results.

This viewpoint (the importance of the simple application of Stokes' formula without ad hoc corrections) has subsequently been taken for granted by most writers on the subject. Thus almost all authors who have advanced the adoption of mean-tidal gravity have simultaneously proposed the adoption of a normal gravity field containing the mean tide, such that the mean-tide contribution will be eliminated from free-air anomalies. How such a normal field is implemented is shown e.g. by Vermeer and Poutanen (1997). On the other hand, Yurkina et al. (1986) demonstrate that Stokes' formula can be modified to allow the input of gravity anomalies containing the mean tide.

The discussion that was started by Heikkinen's (1979) paper led to the first IAG resolutions on the subject, adopted at the XVII General Assembly of the IUGG in Canberra (1979). The IAG in its Resolution No. 15 (see Mueller, 1980).

> *resolves* that the tidal effect be removed completely from all geodetic observations, without restoring the permanent deformation, and that, consequently, the so-called Honkasalo correction should not be applied to observed gravity.

This (conventional) tide-free system was considered the simplest way to solve the problem caused by the Honkasalo correction to Stokes' formula, by obtaining an anomalous potential that is harmonic outside the masses of the Earth. Instructions how to eliminate the Honkasalo correction from the IGSN71 values were subsequently published by the International Gravity Bureau's Working Group for World Gravity Standards (Uotila 1980).

The problems of the tide-free system were discussed by Ekman (1979, 1981) and Groten (1980) who independently proposed zero tidal gravity. The IAG then revised its position and in 1983 recommended the zero system (see Chap. 3). It is note-worthy that the Standard Earth Tide Committee (Rapp 1983) did not discuss the merits of the zero-tide system, only how to implement it technically. The zero system was quickly adopted for absolute gravity measurements through the IAGBN processing standards (Boedecker 1988). Subsequently, all absolute gravity work and all new national gravity systems are in the zero system.

4.3 Positioning

The tide-free approach seems to have entered the 3-D reference frames more or less by accident (not by design), through the processing programs of the observations (VLBI, SLR, GPS). That apparently happened despite the recommendations of the IERS processing standards (McCarthy 1992, 1996; McCarthy and Petit 2004) for the mean ($\equiv$ zero) system. The situation was pointed out by Poutanen et al. (1995). In fact, attempts were made in the 1990s to go over to the mean system for the global 3-D reference frames. That however provoked strong protests from the users, as it would have abruptly changed the established coordinates of the stations by 0.1 m and more. The attempts were abandoned.

5 Some Pros and Cons of Tidal Systems

A thorough review of the advantages and disadvantages of various tidal systems was given by Ekman (1996). Here we only take up some additional points.

- *Realistic tide-free system* (fluid Love numbers). Apparently this has not been proposed by anyone. But many authors have considered that one of the main arguments against tide-free systems in general is that the secular or fluid Love numbers are not known or cannot be known well enough. Implicitly they are thus saying that if these numbers were known, a realistic tide-free system might be a desirable alternative. However, a realistic tide-free system would take us even further from the actual average Earth than the conventional tide-free system.
- *Conventional tide-free system*. For the 3-D positioning the advantage is that it is the present realization, i.e., we have continuity of coordinates. For the potential field quantities there does not seem to be any "standalone" advantages, but it would bring them in line with the 3-D positions. Such proposals have recently been made.
- *Zero system for gravity acceleration*. The deviation ($-30\ldots+60\mu$ Gal) of the time average of the acceleration of the free fall from the acceleration of gravity in the zero system has not turned out to be a disadvantage. Any user (say in metrology) who requires the free-fall value with this accuracy will probably need the instantaneous value. When the time variation is calculated; the permanent contribution can be restored at the same time.
- *Zero system for potential*. Potential differences (or gravity-related heights) are needed to describe how water flows. Potential differences in the zero system do not fulfill this task, as the water does not care where the potential comes from and settles according to potential in the mean system. Similarly, clock rates (general relativity) do not distinguish between sources of potential. This will be discussed in the next chapters.

6 Considerations for the Future

A frequently evoked principle in geodetic theory and practice is the "consistency of all geodetic quantities". It is actually used in two different meanings:

- (1) Beauty of theory; in the current context it usually boils down to the requirement that Stokes' formula should be applicable without adhoc corrections
- (2) Simplicity for the user: simple relations between the commonly used geodetic quantities (in the present context, say normal heights, height anomalies, ellipsoidal heights) should hold without the user needing to worry about their tidal systems

In view of the different tidal systems of quantities currently in practical use, it seems that (2) which might be perhaps termed "the age of innocence" is not at present achievable whatever we do with the tidal system of the heights.

As noted by Groten (2000), different applications may in fact require different tidal systems. Some of the major uses of a World Height System (WHS) are expected to be in the ocean sciences and in hydrographic mapping. If/when geodesists adopt a WHS in the zero-tide system, a parallel system in the mean-tide system (or alternatively a set of adhoc corrections) would need to be maintained for oceanography. E.g., to start presenting the global mean sea surface (say, from altimetry) relative to a zero geoid could be misleading and lead to confusion.

Similar considerations could hold for clocks (frequency standards). This is taken up briefly in the next chapter.

7 Clocks and the Permanent Tide

According to general relativity, the frequency of clocks depends on potential by

$$\frac{df}{f} = -\frac{dW}{c^2} \tag{2}$$

where f is frequency, W potential, and c velocity of light. Thus $dW = -1\,\mathrm{m}^2\mathrm{s}^{-2}$, which corresponds e.g. to a height change of $+0.1\,\mathrm{m}$ causes a relative frequency change $df/f = 1.1 \times 10^{-17}$. Clock frequency has been proposed as a method of determining potential differences (Bjerhammar 1975, 1985; Vermeer 1983). Bjerhammar (1985) even points at the possibility of defining the geoid as a surface of constant clock rate.

Clock stability of the order of 10^{-17} has recently been demonstrated and 10^{-18} is claimed to be within sight. Now, the permanent tide-generating potential W_2 influences f as the clocks do not care where the potential comes from. Thus the mean tidal system for potential is relevant for clocks.

The W_2 corresponds to about 3×10^{-17} in df/f. If the zero tide system for potential is adopted, then the "reference frequency" of a stationary clock will different from its frequency averaged over time (i.e., tides) in exactly the same way as gravity in the current zero system is different from the time-average of the acceleration of the free fall. This has not been a problem for gravity; could it be a problem for clocks? This is obviously not merely a technical question but goes right into the heart of the definition and realization of Terrestrial Time.

8 Discussion

A very large number of 3-D reference coordinates both for scientific and practical applications are currently given in a conventional tide-free system. Similarly the zero tidal system is well established in gravimetry. Thus it seems that a uniformity of the tidal systems in geodetic practice cannot be attained on a short term, whichever tidal system is chosen for gravity-related heights.

A world height system (WHS) when implemented will probably be adopted for practical applications that we only in part can foresee now. If/when geodesists adopt a WHS that is zero-tide, it appears that a parallel system in mean-tide system (or ad-hoc corrections) would need to be maintained at least for oceanography and perhaps in the future for clock rates. Can we at this stage identify any other WHS user group that would rather use mean-tide heights (potentials) than zero-tide heights? Similarly, are there any users outside of geodesy who emphatically require zero-tide heights?

Depending on the answers to the previous questions, would it be reasonable for the geodesists to insist that their zero-tide WHS be the principal system in practical applications and the mean-tide WHS a shadow system (or a set of ad-hoc corrections)? Geodesists inputting data to boundary value problems would obviously need first to do transformations to their quantities (gravity anomalies etc.) if they are computed in a mean-tide WHS. Would this be only an aesthetic problem? These questions need to be debated in the work towards the adoption of a world height system.

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