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SOFTWARE ARTICLE

LTide - Matlab/Octave software tool for temporal and spatial analysis of tidal gravity acceleration effects according to Longman formulas

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Abstract

Tides have largest impact on gravity measurements compared to all other environmental effects. They are a direct result of the gravitational forces of the planetary bodies, mainly the Moon and the Sun. The magnitude of tidal effects depends on the relative position of planetary bodies around the Earth and can be computed from the astronomical ephemeris. In this paper, LTide software is presented, a lightweight application for computation of the tidal gravity acceleration effects according to Longman formulas. The software solves a problem of laborious calculations and simplifies the analysis of gravity data over any time period and any surveyed area worldwide. The code is open-sourced, platform independent, written in Matlab/Octave programming language. It has graphical user interface which offers several options for import, export and visualization of the results. The software is meant to be an easy-to-use tool for geoscientists and other users in processing relative gravity measurements and tempo-spatial analysis of tidal gravity effects.

Keywords Tidal gravity acceleration effects · Gravity · Longman formulas · Relative gravimetry

Introduction

The Earth is a dynamic non-uniform body shaped by joint impact of its own gravitational force and centrifugal force caused by the rotation around the axis. Gravitational force affects the Earth's surface keeping the oceans uniformly distributed over the surface.

The Earth is 'breathing' due to gravitational forces of other celestial bodies (Cartwright 2000). Gravitational force of other celestial bodies on Earth, such as Moon and Sun, is apparent in time-dependent variations of the Earth water masses, called Earth tides. Tides are not purely water effect, they are perceptible also on the Earth's continental surface and therefore can be divided on two parts: body tides and ocean tides. Deformations of the solid Earth are body tides, while tidal variations of the sea level are known as ocean tides. Tides have effect on vertical movements of Earth's topographic surface, gravitational acceleration and deflections of vertical (Cartwright 2000). Changes of topographic surface caused by body tides can reach up to 10 cm in vertical direction in tidal bulges (Hughes and Bingham 2008). In terms of the changes in gravity due to tides, its effect may be as large as $3\cdot 10^{-6}$ ms^{-2} (0.3 mGal= 300 μGal= 3000 ηms^{-2}) (Gupta 2011), which is the largest effect on gravity measurements of all other environmental effects (Schubert 2015). In addition, ocean tides cause deformation by their loading which lead to additional variations of the observed gravity values. The residuals from both effects can be filtered from gravity measurements by using another gravimeter as a base-station (Torge 1989). Effect of the ocean tides is one of the largest uncertainties in precise gravimetric measurements and may be modeled up to some degree by using ocean tide loading models (see, Lyard et al. 2006; Carrère et al. 2013; Rieser et al. 2012).

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Some widely used relative gravimeters, such as Scintrex CG-5, have integrated Earth Tide Correction (ETC) in the instrument's software for computation of tidal effect based on Longman's formulas (Longman 1959; Scintrex 2006). ETC is applied after the last station has been measured. The limitation of the ETC computation directly in gravimeter is that the ETC values can only be extracted for measured stations, and not for other locations or time. Furthermore, users do not have complete control over the input parameters used in automatic computation, such as gravimetric factor. Still, many users apply ETC directly from the gravimeter software (Repanić 2017; Medved et al. 2018; Repanić and Kuhar 2018).

Several authors published formulas for computation of the tidal effects, including Doodson (1921), Schureman (1941), Pettit (1954), Longman (1959), Munk and Cartwright (1966), and Cartwright and Tayler (1971), and Merriam (1992). Since Longman formulas are widely and commonly used, we have created a software tool called LTide (**L**ongman **Tide**) which completely replaces and automatizes the procedure with additional functionalities that enhance the input, export and computation possibilities according to user needs.

Tidal effect on gravity

Gravitational acceleration is both a spatial and a temporal variable. Global mean value of gravitational acceleration g on the Earth's surface is approximately 9.8 ms^{-2}, but its value varies from ∼9.78 ms^{-2} at the equator to ∼9.83 ms^{-2} at the poles. This change in the gravity acceleration of around 0.5% over the Earth's surface is due to the flattened shape of the Earth where polar radius is ∼21 km shorter than the equatorial radius, and also due to the centrifugal force, which is strongest at the equator, and weakest on the poles (Childers 2009).

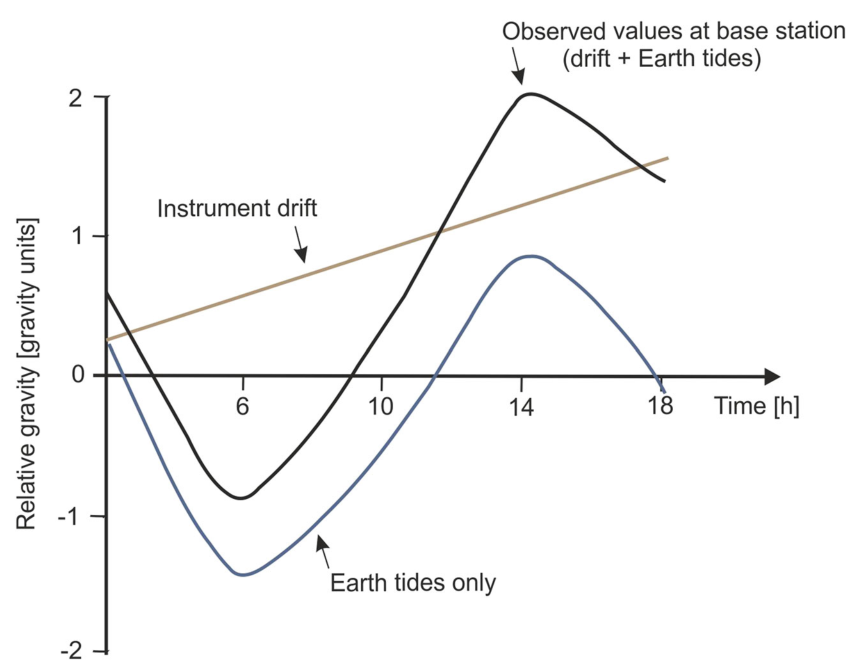
The gravitational field of the Earth is measured by gravimeters, instruments with accelerometers which measure downward gravity acceleration caused by the masses and anomalies between the observation point and geocenter. The physical deformations on the Earth's surface are caused by the transportation of the Earth's masses beneath the surface, which are reflecting on the oscillations of gravity. Depending of the scale of these geological features, measured gravity can vary in range from a few hundred mGal due to ocean ridges or mountain chains, to tenth of a mGal for a subsurface ground water motion (Childers 2009).

Sensitivity of modern gravimeters enables detection of variations in gravity acceleration with a resolution of up to 1 μGal (= $10^{-8} ms^{-2}$= 10 ηms^{-2}). Numerical studies using Scintrex CG-5 gravimeter indicate the accuracy of 2-5 μGal (Scintrex 2019; Jacob et al. 2010).

Among other external effects, raw gravity measurements obtained by relative gravimeters contain the residual instrumental drift and tidal effect, as seen in Fig. 1. Earth tides additionally increase a change in gravity up to 0.3 mGal within a period of about 12 hours (Reynolds 1998). Instrumental drift can be modelled during the observation day and filtered in the post-processing.

The ETC is an effect on gravity at location of the point in a time of observation. It compensates for the gravity effects of the Moon and the Sun (or other planetary bodies).

Fig. 1 Tidal effect on gravity (Reynolds 1998)



Tidal accelerations can be divided into rough and refine occurrences (see, Table 1). In this research, focus is on computation of a rough tidal acceleration which occurs in two forms: Solid Earth Tides (SET) and Elastic Earth Tides (EET). SET refer to a rigid and uniform body, while EET describe elastic deformations of the Earth's body due to tidal acceleration.

Gravitational potential of the point on the Earth's surface and consequent orbital movement consists of gravitational potential at the center of the Earth due to the Moon or Sun, the rotational potential due to the rotation of the Earth about its own axis, and the tidal potential. Temporal and spatial change of the tidal potential reflects on the deformations of a solid Earth and the ocean. The average effect of the elastic deformity is taken into account by the gravimetric factor β which defines percentage for which the amplitude of gravimetric tides of the rigid Earth has been increased. Gravimetric factor is latitude dependent value and may be calculated from dimensionless quasi-constants, i.e Love's numbers, h_2 and k_2 amplitudes (Mathews et al. 1995). h_2 is the ratio of the height of the solid body tide to that of the deforming potential, while k_2 number is the ratio of the additional tidal potential, produced by the re-distribution of mass (Stacey and Davis 2008). Since the constituent tidal waves are also slightly oscillating, the gravimetric factor is not a constant value. Love's numbers (Love 1911) are used for computation of EET, while SET is computed from astronomic ephemeris multiplied with gravimetric factor β (Murphy 2001):

$$\beta = 1 + h_2 - \frac{3}{2}k_2 \qquad (1)$$

For a rigid Earth, Love's numbers are zero ($h_2 = 0, k_2 = 0$), and gravimetric factor is equal to one ($\beta = 1$). With realistic values for the Love's numbers, h_2 between 0.603 and 0.624, and k_2 between 0.298 to 0.312, gravimetric factor can vary from 1.13 to 1.17, where the value $\beta = 1.16$ is often used (see, e.g. Longman 1966; Petit and Luzum 2010; Jagoda et al. 2018).

Methodology

A software presented in this paper consists from several programming functions. Computed gravitational potential is based on eight harmonic terms (Cartwright and Tayler 1971) while the formulas for astronomical ephemeris follow from fundamental mathematical laws of spherical geometry. The position of an Earth's object in equatorial coordinate system projected on a celestial sphere is described by astronomical coordinates: right ascension and declination. The latitude of an object and the local time of observation can be then used to derive the position of an object in terrestrial coordinate system.

In continuation of this section Longman formulas for all computational steps are written and described.

Conversion of time from Gregorian to Julian calendar

Today's civil calendar is the *Gregorian* calendar, introduced by the Pope Gregory XIIII in the 16^{th} century. The calendar is a year-numbering system which starts from the Anno Domini, the traditional date of nativity. However, in astronomy, the time is expressed in a continuous number of days counted from the beginning of the Julian Period. The original Julian Period is a number of the passed consecutive days starting from the Julian Day defined at the January 1^{st}, 4713 BC at Greenwich mean noon. For example, January 1^{st} 2015 AC at 0:00 is 2,457,023.5 day according to original Julian Period. Gregorian year consists of 365 days, but as in the Julian calendar, has a leap year which is added in February.

In order to alter using large numbers, several other Julian Days, as starting epochs for Gregorian calendar, have been proposed in international associations. At assembly held in Ireland in 1955 the International Astronomical Union (IAU) had decided to define initial reference epoch as Greenwich mean noon on December 31, 1899. This is also known as *Dublin Julian Day*.

Within our software, programming function automatically converts Gregorian date to a Julian date according to formulas given in (Meeus 1998, p. 61) and (de Iaco Veris 2018, p. 158), which takes into account the leap year.

Orbital parameters

Equations for orbital parameters of the Moon and Sun are given in three main references: Schureman (1941), Bartels (1957), Longman (1959). LTide software is referring mainly to the Longman's article as the reference one, regarding

Table 1 Magnitudes of tidal effect and their corrections

phenomenon	range	effect amplitude	correction amplitude
Solid Earth Tide (SET)	decimetric	± 10-50 cm	± 30 cm[a]
Ocean Tide Loading (OTL)	centimetric	± 15-20 cm	± 10 cm[a]

[a]values from (Phillips et al. 1999)

the difference between Bartels' and Shureman's formulas as (almost) neglectable according to Dehlinger (1978). Here it should be remarked that some of the symbols used in this paper may differ with respect to cited references.

Moon's and Sun's orbital parameters

Mean longitude of the Moon in its orbit reckoned from the referred equinox is (Longman 1959, eq. 10):

$$s = 270°26'14.7'' + 1,732,564,411.2''T + 9.09''T^2 + 0.0068''T^3 \tag{2}$$

where T represents number of Julian centuries from the Dublin Julian Day:

$$T = (J_{dn} - J_0)/36525. \tag{3}$$

Mean longitude of lunar perigee is (Longman 1959, eq. 11):

$$p_m = 334°19'40.87'' + 1,4648,515.94''T - 37.24''T^2 - 0.045''T^3. \tag{4}$$

Longitude of the Moon's ascending node in its orbit reckoned from the referred equinox is (Schureman 1941, p. 162):

$$N = 259°10'57.12'' - 6,962,912.63T + 7.58''T^2 + 0.008''T^3 \tag{5}$$

Mean longitude of the Sun h (Longman 1959, eq. 12):

$$h = 2796\circ 41'48.04'' + 129,602,768.13''T + 1.089''T^2 \tag{6}$$

Hour angle of mean Sun measured westward from observation station t (Longman 1959, eq. 24):

$$t = 15(t_0 - 12) - \lambda \tag{7}$$

where t_0 is time of observation in UTC, and λ geodetic longitude of observation station on the Earth's surface.

Right ascension of meridian of observation station reckoned from A, expressed as χ_m (Longman 1959, eq. 23):

$$\chi_m = t + h - \upsilon \tag{8}$$

where longitude of intersection of celestial equator and Moon's orbit υ is $\upsilon = \sin^{-1}[\sin i \sin N / \sin I]$, with condition $-15° < \upsilon < 15°$, and I representing an inclination of Moon's orbit to equator as $\cos I = \cos\epsilon \cos i - \sin\epsilon \sin i \cos N$.

Right ascension of meridian of observation station reckoned from the vernal equinox is expressed as χ_s (Longman 1959, eq. 28):

$$\chi_s = t + h \tag{9}$$

Zenith angles

Eccentricity of the Earth's orbit e_s is (Schureman 1941, p. 162):

$$e_s = 0.01675104'' - 0.00004180''T - 0.000000126''T^2 \tag{10}$$

Geocentric distance of point P to the center of the Earth r is given as Lecar et al. (1959):

$$r = C \cdot a + H \tag{11}$$

with H being mean sea level height given in centimeters, and C is:

$$C^2 = \frac{1}{1 + e^2 \sin^2 \varphi} \tag{12}$$

Mean distance between centers of the Earth and Moon d_m is expressed as (Longman 1959, eq. 29):

$$\frac{1}{d_m} = \frac{1}{c_m} + a_m e \cos(s - p_m) + a_m e^2 \cos 2(s - p_m) + \frac{15}{8} a_m m e_m \cos(s - 2h + p_m) + a_m^2 \cos 2(s - h) \tag{13}$$

where $c_m = 3.844 \cdot 10^8$ m is a mean distance between centers of the Earth and Moon, e_m is the eccentricity of Moon's orbit equal to 0.054900489 and a_m auxiliary value that can be computed as (Longman 1959, eq. 31):

$$a_m = \frac{1}{c_m(1 - e_m^2)} \tag{14}$$

Mean distance between centers of the Earth and Sun d_s (Longman 1959, eq. 30) is:

$$\frac{1}{d_s} = \frac{1}{c_s} + a_s e \cos(h - p_s) \tag{15}$$

where c_s is a mean distance between centers of the Earth and Sun equal to $149.6 \cdot 10^9$ m, e is eccentricity of Earth's orbit and a_s auxiliary value computed as (Longman 1959, eq. 32):

$$a_s = \frac{1}{c_s(1 - e^2)} \tag{16}$$

while mean longitude of solar perigee p_s is given as (Longman 1959, eq. 31):

$$p_s = 281°13'15.00'' + 6189.03T + 1.63T^2 + 0.012T^3 \tag{17}$$

Longitude of the Moon l_m (Schureman 1941, p. 19):

$$l_m = s_m - \xi + \left[2e_m \sin(s_m - p_m) + \frac{5}{4} {e_m}^2 \sin(2(s_m - p_m)) + \frac{15}{4} m e_m \sin(s_m - 2h + p_m) + \frac{11}{8} m^2 \sin(2(s_m - h_s))\right] \tag{18}$$

Zenith angle of the Moon Z_m (Longman 1959, eq. 7):

$$\cos Z_m = \sin\varphi \sin I \sin\lambda_m + \cos\varphi \left[\cos^2\frac{I}{2}\cos(l_m - \chi_m) + \sin^2\frac{I}{2}\cos(l_m + \chi_m)\right] \tag{19}$$

Zenith angle of the Sun Z_s (Longman 1959, eq. 8):

$$\cos Z_s = \sin\varphi \sin\epsilon \sin\lambda_s + \cos\varphi \left[\cos^2\frac{\epsilon}{2}\cos(l_s - \chi_s) + \sin^2\frac{\epsilon}{2}\cos(l_s + \chi_s)\right] \tag{20}$$

Earth tide effect (ETE)

Earth Tide Effect is a sum of Moon's and Sun's gravity effects (Longman 1959, eq. 5):

$$\delta g_{ETE} = g_m + g_s \tag{21}$$

where Moon's Tidal Effect g_m is equal to (Longman 1959, eq. 1):

$$g_m = \frac{GM_m r}{d_m^3}(3\cos Z_m - 1) + \frac{3}{2}\frac{GM_m r^2}{d_m^4}(5\cos Z_m^3 - 3\cos Z_m) \tag{22}$$

and Sun's tidal effect is equal to (Longman 1959, eq. 3):

$$g_s = \frac{GM_s r}{d_s^3}(3\cos Z_s - 1) \tag{23}$$

LTide software

Software files

Developed software can run as a standalone application on any personal computer, or as a Matlab/Octave script. It is executed by running the main script *LTide.m*. Supplementary scripts have to be in the working folder: *Longman.m* - as central function for computation of gravity tidal effects, and *LTide.fig* - file which defines the design of the graphical user interface.

Design and implementation

LTide's graphical user interface (GUI) is intuitive and user-friendly (Fig. 3). User can choose between two input options, as shown in Fig. 2: a) point-wise, requiring user input of station coordinates (geodetic latitude and longitude φ, λ in degrees, and height above mean sea level H_{MSL} in meters), date in [dd-MM-yyyy] format, observation local time in [hh:mm:ss] format, and b) list of points, where stations are imported from the input file. If list of points is browsed, file needs to be properly formatted, where one line stands for one computation point at specific computation epoch which has to contain values for geodetic coordinates, date and observation time. The format sample of the list of points as input option is given in the software's folder.

Additionally, user can select local time zone of observations as it is essential that the Coordinated Universal Time (UTC) difference is properly treated. If the (positive/negative) sign is not entered properly or the value is incorrect due to the daylight saving time, the results will not be computed correctly.

Although the default reference epoch is set to conventionally accepted Dublin Julian date, the user can modify the reference time epoch on which measurements are referred to by manually entering the arbitrary reference epoch.

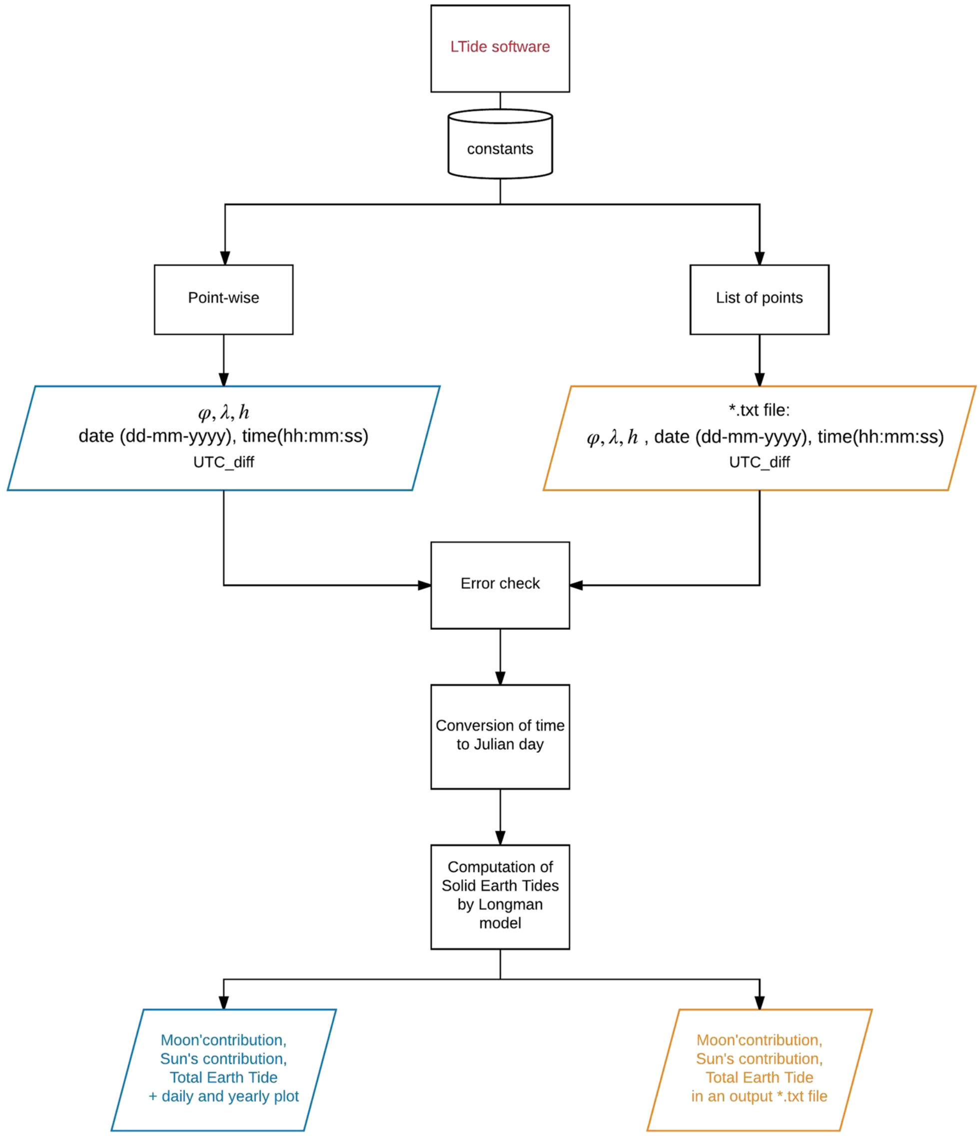
After all input parameters and points are defined correctly, LTide starts computations by pressing the button *Compute*. With the initialization of the computation, software perform a preliminary error checking and screening in the background to eliminate wrong formats of the input variables or overstepping the defined ranges for input values. If the software detects omitted input field or other error it interactively shows the message box highlighting the type of the input error issue and mandatory returning user to the input step. If the error check passes regularly, a program proceeds to the conversion of time from Gregorian date to Julian day, and runs LTide main computational script (*Longman.m*) where tidal gravity effects are computed (Fig. 3).

At the end of the program execution, the message box pops out towards the path of the output file. The software provides results in three ways: 1) numerical output in GUI, 2) numerical output in **.mat* and **.txt* files, 3) graphical output for the visualization of daily and year tidal effects. In point-wise computations output file contains the step-by-step computation parameters, whereas for list of points computations output file contains values of Moon and Sun's tidal effects, as well as total Earth tidal effect δg_{ETE}, given in mGal, as shown in Fig. 4.

Comparison with existing software

Several similar software packages were published in the past which offer computation of tidal gravity effects, such as: BAYTAP-G (Tamura et al. 1991), ETGTAB (Timmen and Wenzel 1995), ETERNA (Wenzel 1996), T_Tide (Pawlowicz et al. 2002), CG3TOOL (Gabalda et al. 2003), TSoft (Van Camp and VAuterin 2005), UTide (Codiga 2011), GravProcess (Cattin et al. 2015), pyGrav (Hector and Hinderer 2016), GravSur (Amarante 2012; Amarante and Trabanco 2016), GMTEarthTide (Tools 2019), S_Tide (Pan

Fig. 2 Flowchart of the LTide software tool



et al. 2018), and GSolve (McCubbine et al. 2018). Some of these tools are not available, downloadable, nor updated anymore. We have tried out a few of the available tools, the ones which use Longman formulas, and have encountered errors in some of them, which means that they could not be used as safe and reliable as expected. Apart from this, some of the tools use harmonic constituents and analysis to obtain tidal effects, such as ETERNA, but require more efforts and knowledge for running, implementation, and combination with other gravity data post-processing steps. Advantages of the LTide are its open-sourceness, platform independence and simplicity. LTide can be integrated in any other software for gravity data postprocessing and can be conveniently rewritten to any other modern programming language, such as Python or C#. It has graphical user interface and can also be used for batch computations using unlimited stations and time intervals. Values of astronomical constants given in original paper (Longman 1959, eq. 3) are replaced with updated values (Petit and Luzum 2010) which may be considered as more precisely estimated than former ones. If needed, the user can add tidal effects of any other celestial body, such as Venus or Mars (see, e.g. Amarante and Trabanco 2016, eq. 12).

Results of the computations made by LTide have been compared with control and test values at 10 stations obtained from Amarante (2012), Amarante and Trabanco (2016). Results of the comparison are summarized in Table 2. Differences between the values made by LTide and other softwares are maximally $\pm$ 2 μGal, whereas IAG given values are identical with values computed by our software for all tested stations. This confirms that the the main computation script *Longman.m* is free of any coding error.

Furthermore, in order to verify the accuracy and purposefulness of the LTide for filtering tidal gravity effects

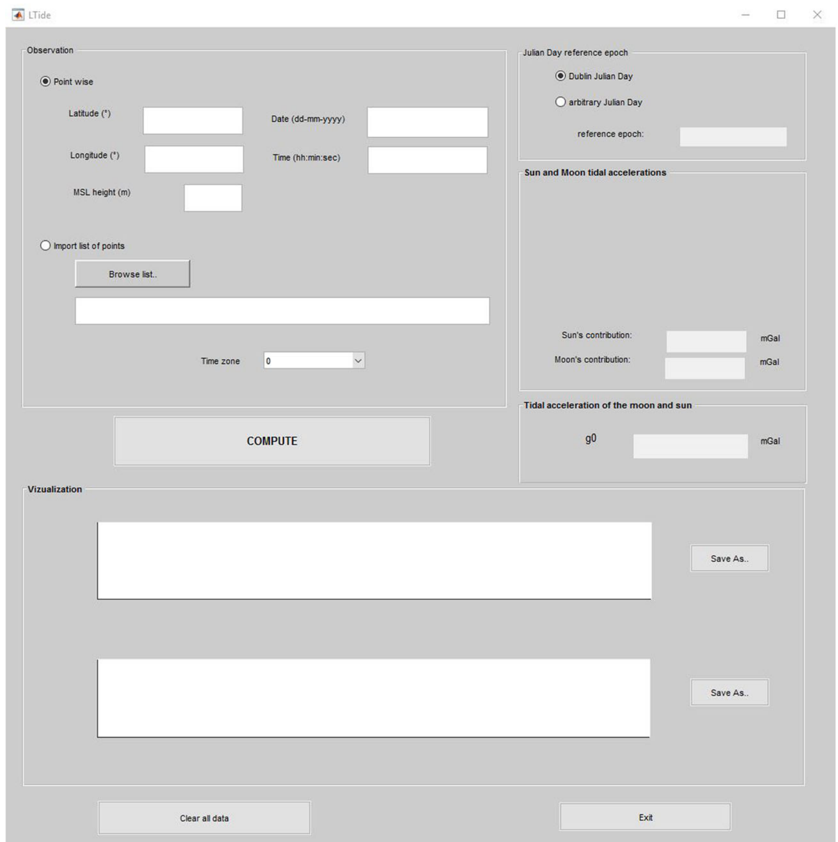


Fig. 3 Graphical user interface of LTide software tool

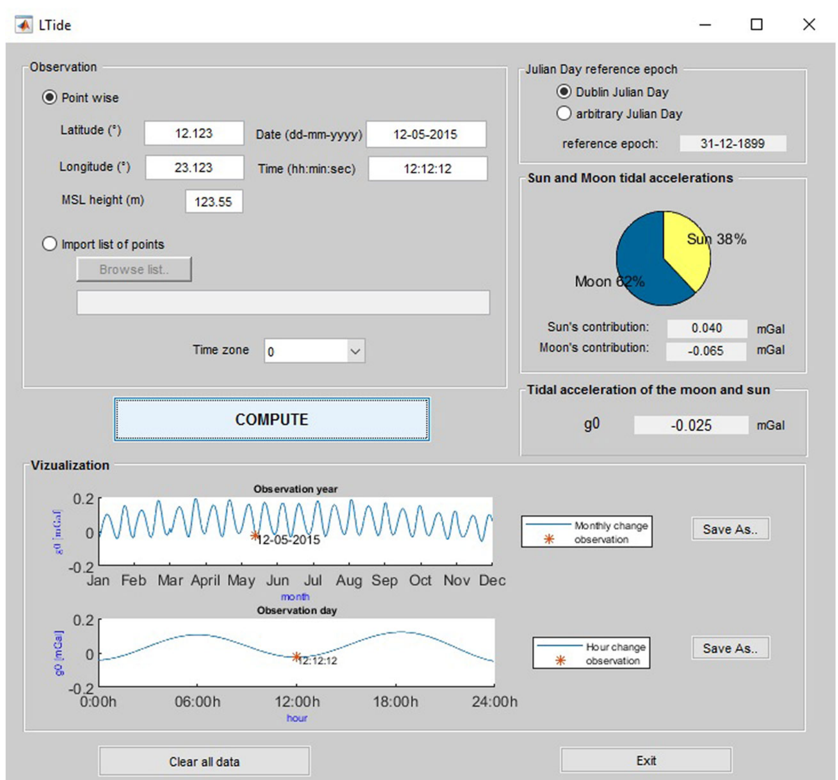


Fig. 4 Point-wise computation: input and output

Table 2 Comparison of computed gravity tidal effects δg_{ETE} by using different software

Station info			Epoch		Software				
Latitude	Longitude	Height	Date	UTC Time	GravSur	REDGRAV	GRAVSYS	IAG	LTide
−23.95	−46.3	0	18-02-11	15:20:00	0.188	0.193	0.186		0.186
40.7	−77.8	370	23-04-15	00:00:00	0.004				0.004
−22.733	−90.5	0	31-10-10	08:10:00	−0.055	−0.056		−0.054	−0.054
−22.733	90.5	0	31-10-10	08:10:00	−0.003	−0.003		−0.002	−0.002
22.733	−90.5	0	31-10-10	08:10:00	−0.007	−0.007		−0.007	−0.007
22.733	90.5	0	31-10-10	08:10:00	−0.052	−0.053		−0.051	−0.051
−22.733	−90.5	0	31-10-96	08:10:00	0.028	0.029	0.028	0.028	0.028
−22.733	90.5	0	31-10-96	08:10:00	0.120	0.123	0.119	0.119	0.119
22.733	−90.5	0	31-10-96	08:10:00	0.123	0.126	0.122	0.122	0.121
22.733	90.5	0	31-10-96	08:10:00	0.029	0.030	0.029	0.029	0.029

Units: latitude and longitude in [°], height in [m], gravity in [mGal]

from measurements, an analysis by using real gravity data is performed. First, gravity data measured by superconducting gravimeter in Conrad observatory (Germany, φ= 47.9283°, λ= 15.8598°, H= 1044.12 m) was downloaded from the data-center of the International Geodynamics and Earth Tide Service (IGETS, Geodynamics and Service 2019). The data are Level-2 and have a time-sampling of one hour (mean gravity value $g_{measured}$ for each hour obtained by averaging of minute values) covering period of one year (2013). The objective of was to compare gravity data

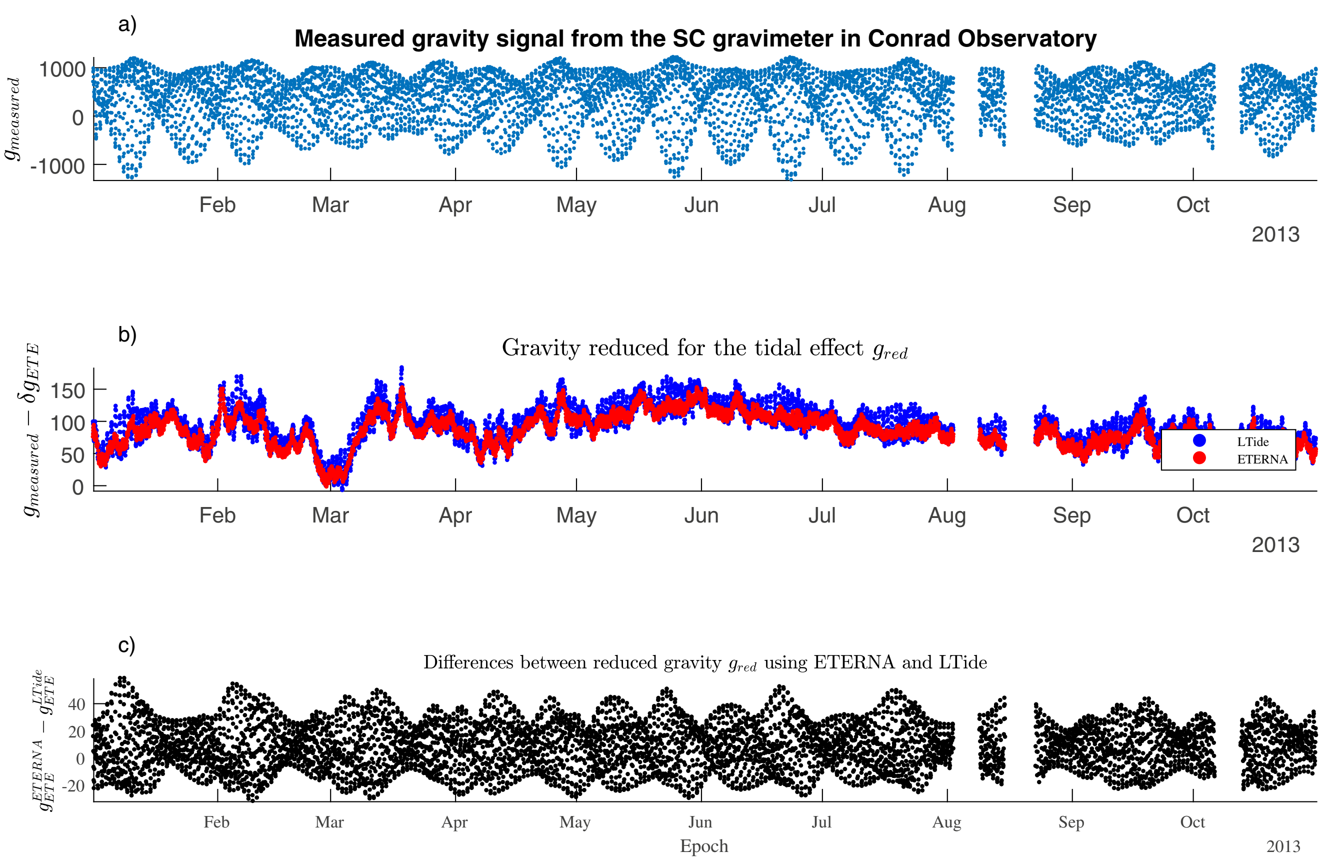


Fig. 5 Comparison of tidal effect reduction from measured gravity from SC gravimeter in Condrad observatory using LTide and ETERNA. Units for gravity and tidal effects (on y-axis): [ηms^{-2}]

reduced for tidal effects using two software - ETERNA and LTide. ETERNA is the only earth tide data processing package which models a tidal gravity effects with an accuracy better than 1 ηms^{-2} (Yu et al. 2019). In this case filtering of tidal gravity effects using ETERNA may be considered as the *reference* and *true* one. Reduced gravity data where effects are filtered using LTide g_{red}^{LTide} are considered to be tested (validated) ones.

Figure 5a shows Level-2 measured gravity signal $g_{measured}$ which has an amplitude of ± 1000 ηms^{-2}. Tidal effects were computed using the LTide and ETERNA and subtracted from the measured gravity: g_{red}=$g_{measured}$-g_{ETE}, see Fig. 5b. It can be seen that the trends and the behaviour of the both reduced signals are almost similar, although a gravity reduced using ETERNA has smaller dispersion in most of the epochs indicating its higher accuracy compared to the LTide. Both ETERNA and LTide remove harmonic characteristic from the gravity signal, which is known to be caused by tides.

Finally, the difference between reduced gravity signals using ETERNA g_{red}^{ETERNA} and LTide g_{red}^{LTide} is calculated and visualized on Fig. 5c. Results from this figure show that for the whole time span of one year the differences between reduced gravity using ETERNA and LTide do not exceed 40 ηms^{-2}. For most of the geodetic and geophysical purposes, in the context of the magnitudes and sizes of other effects and errors included in the measured gravity signal, these differences are rather small or even negligible. This justifies the purpose of using simple and more manageable routine as the LTide in processing of all relative gravity measurements, instead of the tools based on tidal potential catalogs and harmonic analysis.

Summary

Longman formulas are commonly used for computation of tidal gravity acceleration effects. This article presents the LTide software tool for computation of these effects. Article also consolidates and sums up several reviews of the formulas, briefly explains a theoretical background and describes Matlab/Octave code of created LTide software tool. The comparison with other software confirms software's accuracy and practical applicability.

Remark

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