Noname manuscript No.
(will be inserted by the editor)

The International Mass Loading Service

Leonid Petrov

Abstract The International Mass Loading Service computes four loadings: a) atmospheric pressure loading; b) land water storage loading; c) oceanic tidal loading; and d) non-tidal oceanic loading. The service provides to users the mass loading time series in three forms: 1) pre-computed time series for a list of 849 space geodesy stations; 2) pre-computed time series on the global $1^\circ \times 1^\circ$ grid; and 3) on-demand Internet service for a list of stations and a time range specified by the user. The loading displacements are provided for the time period from 1979.01.01 through present, updated on an hourly basis, and have latencies 8–20 hours.

1 Introduction

In December 2002 the atmospheric pressure loading service (Petrov and Boy 2004) at NASA Goddard Space Flight Center was established. This service was recently upgraded. This paper provides the outline of the current capabilities of the International Mass Loading Service.

2 The use of high resolution models for loading computation

The original atmospheric pressure loading service used the 2D NCEP Reanalysis surface pressure field (Kalnay et al. 1996) at a regular grid with a spatial resolution $2.5^\circ \times 2.5^\circ$. Modern models have much higher resolutions: for instance, the GEOS-FP model has resolution $0.3125^\circ \times 0.25^\circ$. The traditional approach for loading computation at a point with coordinate $\mathbf{r}$ involved a numerical evaluation of the integral of a convolution type (Farrell 1972):

$$\begin{aligned} \mathbf{u}_r(\mathbf{r},t) &= \iint\limits_{\Omega} L(\phi',\lambda')\,\Delta P(\mathbf{r}',t)\,G_{\mathrm{R}}(\psi)\cos\phi' d\lambda' d\phi' \\ \mathbf{u}_h(\mathbf{r},t) &= \iint\limits_{\Omega} \mathbf{q}(\mathbf{r},\mathbf{r}')\,L(\phi,\lambda)\,\Delta P(\mathbf{r}',t)\,G_{\mathrm{H}}(\psi)\cos\phi' d\lambda' d\phi', \end{aligned} \quad (1)$$

where $\Delta P(\mathbf{r}',t)$ is the pressure caused by mass redistribution, $L(\phi,\lambda)$ — is the land-sea mask, the share of land in an elementary cell, and $G(\psi)$ are the Green's functions.

L. Petrov
ADNET Systems, Inc, Falls Church, VA 22043, USA
E-mail: Leonid.Petrov@lpetrov.netw

The problem is that this algorithm has complexity $O(d^4)$, where d is the spatial grid size, i.e. it grows very rapidly with an increase of spatial resolution. It becomes impractical to use convolution for loading computation using models with a high spatial resolution. The alternative is to use the spherical harmonic transform approach. The algorithm involves the following steps:

1. forming the pressure difference with respect to the average;
2. transforming the surface pressure field to the regular grid with a higher resolution (upgridding): $2(D{+}1){+}1 \times 4(D{+}1)$ over latitude and longitude, where D is degree of the expansion;
3. multiplying the surface pressure field with the land-sea mask defined as a share of land in a cell;
4. spherical harmonic transform of degree/order D;
5. scaling the output of the spherical harmonic transform with Love numbers h'_n and l'_n of the corresponding degree n:

$$\begin{aligned} V^m_n(t) &= \frac{1}{\bar{\rho}_\oplus\, g_0} \frac{3h'_n}{2n+1} \iint\limits_{\Omega} L(\phi,\lambda)\, \varDelta P(t,\phi,\lambda)\, Y^m_n(\phi,\lambda) \cos\phi \, d\phi \, d\lambda \\ H^m_n(t) &= \frac{1}{\bar{\rho}_\oplus\, g_0} \frac{3l'_n}{2n+1} \iint\limits_{\Omega} L(\phi,\lambda)\, \varDelta P(t,\phi,\lambda)\, Y^m_n(\phi,\lambda) \cos\phi \, d\phi \, d\lambda \end{aligned} \quad , \quad (2)$$

   where $\bar{\rho}_\oplus$ is the mean Earth's density and g_0 is the equatorial gravity acceleration. The expression under the integral is the spherical harmonics $(\,)^{\,m}_{\,n}$ of the the pressure field with the land-sea mask applied.
6. inverse spherical harmonic transform:

$$\begin{aligned} D_U(\phi,\lambda) &= \sum_{i=0}^{i=m} \sum_{j=-n}^{j=n} V^i_j \, Y^{i*}_j(\phi,\lambda) \\ D_E(\phi,\lambda) &= \sum_{i=0}^{i=m} \sum_{j=-n}^{j=n} H^i_j \, \frac{\partial Y^{i*}_j(\phi,\lambda)}{\partial\lambda} \\ D_N(\phi,\lambda) &= \sum_{i=0}^{i=m} \sum_{j=-n}^{j=n} H^i_j \, \frac{\partial Y^{i*}_j(\phi,\lambda)}{\partial\phi} \end{aligned} \quad . \quad (3)$$

This algorithm is equivalent to eqn (1) when $D \longrightarrow \infty$, but it has complexity $O(d^3)$. It outperforms the convolution algorithm when $D > 30$. Numerical tests showed that in order to have errors in loading computation everywhere on the Earth less than 0.15 mm, degree/order 1023 is sufficient.

3 Mass redistribution models

Three numerical weather models developed at the NASA Global Modeling and Assimilation Office (GMAO) are used for loading computation:

- MERRA (Modern-Era Retrospective analysis for Research and Applications) (Rienecker, et al. 2011). Resolution: $0.67° \times 0.5° \times 72$ layers $\times 6^h$, runs from 1979.01.01 through present, latency 20^d–60^d. This model is frozen and it is considered the most stable.
- GEOS-FP (Global Earth Observing System Forward Processing) (Molod et al. 2012). Resolution: $0.3125° \times 0.25° \times 72$ layers $\times 3^h$, runs from 2011.09.01 through present, latency 6^h–15^h. This is the operational model, updated approximately once a year.
- GEOS-FPIT (Global Earth Observing System Forward Processing Instrumental Team) (Rienecker, et al. 2008). Resolution: $0.625° \times 0.5° \times 72$ layers $\times 3^h$, runs from 2000.01.01 through present, latency 6^h–25^h. In terms in stability this model is intermediate between MERRA and GEOS-FP, but it has a low latency.

The surface pressure is computed from a 3D model. This process involves several steps. Firstly, each column of the output at the native, *irregular*, terrain-following grid is interpolated to the column at a new regular grid that is formally extrapolated down to -1000 m and up to 90,000 m. Then the atmospheric pressure at a given epoch is expanded into the tensor product of B-splines over the entire Earth. Using the expansion coefficients, the pressure on the surface at resolution D1023 ($0.088° \times 0.088°$) is computed. The height of the surface is derived from $30'' \times 30''$ GTOPO30 model[1] by averaging over cells of the D1023 grid. Using the expansion coefficients, the atmospheric pressure on that surface is computed.

Three land water storage models are used for loading computation:

- GLDAS NOAH025 (Global Land Data Assimilation System) (Rodell et al. 2004). Resolution: $0.25° \times 0.25° \times 3^h$, runs from 2000.01.24 through present, latency 35^d–70^d.
- MERRA TWLAND (Reichle et al. 2011). Resolution: $0.67° \times 0.5° \times 6^h$, runs from 1979.01.01 through present, latency 35^d–60^d. This model is considered the most stable.
- GEOS-FPIT TWLAND. Resolution: $0.625° \times 0.5° \times 1^h$, runs from 2000.01.01 through present, latency 6^h–25^h. It was found that hourly time resolution is excessive for loading computation. The resolution was reduced to 3 hours.

Upgridding involves refining the pressure field according to the fine land-sea mask. If a cell at the new $0.088° \times 0.088°$ grid falls in the area that was ocean in the old grid, the pressure of the water equivalent of soil moisture and/or snow cover is computed by interpolation from surrounding cells that are land in the original grid with applying Gaussian smoothing.

Non-tidal ocean loading is computed from the Ocean Model for Circulation and Tides (OMCT) (Thomas 2002). The original resolution of the model is $1° \times 1° \times 6^h$, latency: 10^d–60^d.

Two models of ocean tidal loading are used: the GOT4.8 (Ray 2013) and FES2012 (Carrere et al. 2012). They are upgridded to degree/order 2047 in a

[1] https://lta.cr.usgs.gov/GTOPO30

Table 1 Estimates of admittance factors for Up, East, and North components for three different loading models from the global least squares solution using geodetic VLBI data.

Atm GEOS-FPIT UP	0.963	±	0.023
Atm GEOS-FPIT EA	0.609	±	0.049
Atm GEOS-FPIT NO	1.027	±	0.041
Lws GEOS-FPIT UP	0.955	±	0.016
Lws GEOS-FPIT EA	0.804	±	0.029
Lws GEOS-FPIT NO	0.886	±	0.024
Lws NOAH025 UP	1.220	±	0.013
Lws NOAH025 EA	0.660	±	0.030
Lws NOAH025 NO	0.826	±	0.033

similar way as it was done for land water storage, except reversal of land and sea cells.

4 Processing pipeline

The two servers of the International Mass Loading Service that work independently check every hour whether new data appeared. If the new data appeared, they are downloaded, decoded, up-gridded, and the surface pressure anomaly at the D1023 grid is computed by subtracting a model that includes the mean surface pressure value, sine and cosine amplitudes of pressure variations in a range of frequencies in the diurnal, semi-diurnal, ter-diurnal and four-diurnal bands. Then the spherical harmonic transform of degree/order 1023 of the pressure field anomaly is computed and scaled by Love numbers of the corresponding order. The coefficients V_n^m and H_n^m in eqn (2) are stored. They are used for loading computations in three ways:

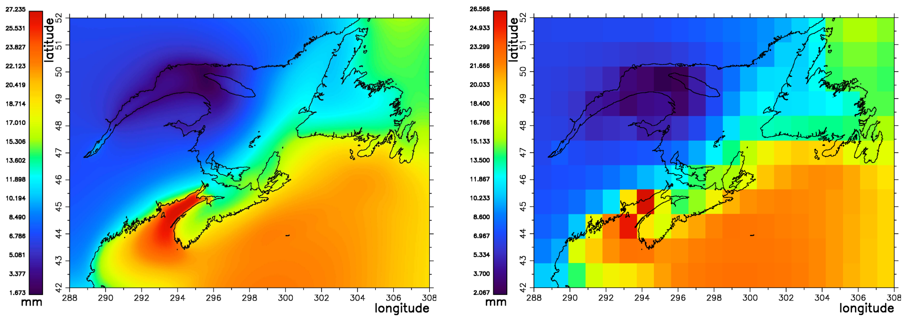
1. Computing loading at the D89 grid ($1^\circ \times 1^\circ$). This is done in the following way: the spherical harmonic transform of degree/order D1023 is padded with zeroes to degree/order D1079. The coefficients V_n^m, H_n^m are underwent the inverse spherical harmonic transform and produce the loading field in local Up, East, and North direction at the D1079 grid ($1/12^\circ \times 1/12^\circ$). Every 12th element of the intermediate D1079 grid is written in the output file.
2. Computing loading for a set of 849 commonly used GNSS, SLR, DORIS, and VLBI stations.
3. Computing loading on-demand for the set of stations supplied by the user. A user fills the Web form where he or she specifies the model, the range of dates and the list of stations with their Cartesian coordinates. When the loading computation is finished, a user can retrieve the files with results.

The loading displacements are computed using the Love numbers defined in the coordinate system with the origin at the center of mass of the total Earth: the solid Earth and the fluid under consideration. For some applications displacements with respect to the center of mass of the solid Earth are desirable. The International Mass Loading Service computes the differential loading displacements between these two systems. When this differential displacement is added to the displacement with respect to the center of the total mass, the sum is the displacement with respect to the center of mass of the solid Earth.

5 Validation

VLBI observations for the period of 2001.01.01 – 2014.07.01 were used for loading validation. The same technique was applied as we used for loading validation in Petrov and Boy (2004): the global admittance factors were estimated from the data together with estimation of site positions, velocities, the Earth orientation parameters, source coordinates and nuisance parameters such as clock functions and atmosphere path delays in zenith direction (see Table 1). The partial derivative for admittance factors was the contribution of the loading displacement into path delay. If the model is perfect, the admittance factor will approach to unity.

Fig. 1 Mass loading caused by the M_2 ocean tide near Newfoundland island computed with two resolutions: $0.01° \times 0.01°$ grid (*Left*) and $1.0° \times 1.0°$ grid (*Right*)

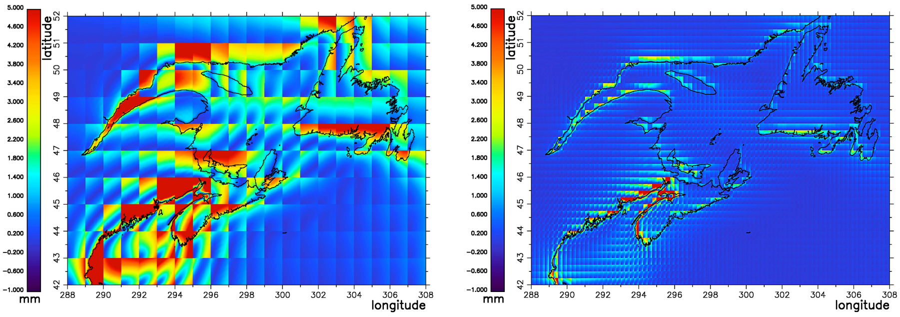


6 Using the International Mass Loading Service

The gridded loading displacements are useful for visualization of the loading field and for computation of integrals over the area. However, a user should be aware that the field of loading displacement near the coastal area is not smooth. Therefore, using gridded loading for data reduction by interpolation the displacement field to the position of a given station may cause significant errors. This problem is illustrated in Figures 1–2 for a case of ocean loading near Newfoundland. The M_2 ocean loading displacement has the vertical amplitude ~ 30 mm, but interpolation errors exceed 30% within 100 km of the coastal area when the $1.0° \times 1.0°$ grid is used. The errors are in excess of 30% within 30 km from the coast when the $0.25° \times 0.25°$ grid is used. They fall below 1 mm only when the grid with a resolution $0.05° \times 0.05°$ or finer is used.

Gridded loading at $1° \times 1°$ or $0.25° \times 0.25°$ resolutions **should never be used** for data reduction. The International Mass Loading Service computes loadings for 849 fundamental GNSS, DORIS, SLR, and VLBI stations directly without the use of interpolation. Loading displacements for other stations are computed using Web on-demand interface.

Fig. 2 The difference of mass loading caused by the M_2 ocean tide computed with two resolutions: $1.0° \times 1.0°$ grid versus $0.01° \times 0.01°$ grid (*Left*) and $0.25° \times 0.25°$ grid versus $0.01° \times 0.01°$ grid (*Left*) and



7 Summary

At present, the International Mass Loading Service offers to the geodetic community computation of 3D displacements caused by the atmospheric pressure loading, land water storage loading, tidal and non-tidal ocean loading, free of charge, 24/7 with a latency from 8 hours (atmospheric and land water storage loading) to 30 days (non-tidal loading). The URL of the primary server is `http://massloading.net`, the URL of the secondary server is `http://alt.massloading.net`. The loading displacement were validated against the dataset of global VLBI observations for 2001–2014.

This project was supported by NASA Earth Surface and Interior program, grant NNX12AQ29G.

References

Carrere L, Lyard F, Cancet M, Guillot A, Roblou L (2012) FES2012: A new global tidal model taking taking advantage of nearly 20 years of altimetry, Proceedings of meeting "20 Years of Altimetry", Venice.

Farrell, WE (1972) Deformation of the Earth by Surface Loads, Rev. Geophys. and Spac. Phys., vol. 10(3), 751–797

Kalnay EM et al. (1996) Bull. Amer. Meteorol. Soc., 77, 437–471

Molod A, Takacs L, Suarez M, Bacmeister J, Song I-S, Eichmann A (2012) The GEOS-5 Atmospheric General Circulation Model: Mean Climate and Development from MERRA to Fortuna, NASA/TM–2012, 104606, vol. 28

Petrov L, Boy J-P (2004) Study of the atmospheric pressure loading signal in VLBI observations, JGR, 10.1029/2003JB002500, vol. 109, No. B03405.

Ray R (2013) Precise comparisons of bottom-pressure and altimetric ocean tides, JGR, 118, 4570–4584, doi:10.1002/jgrc.20336

Reichle RH, Koster RD, De Lannoy GJM, Forman BA, Liu Q, Mahanama SPP, Touré A (2011) J. Climate, 24, 6322–6338

Rienecker MM, et al. (2008) The GEOS Data Assimilation System — Documentation of Versions 5.0.1, 5.1.0, and 5.2.0, NASA/TM–2008–104606

Rienecker MM, et al. (2011) J. Climate, 24, 3624–3648

Rodell MP, et al (2004) The Global Land Data Assimilation System, Bull. Amer. Meteor. Soc., 85(3): 381–394

Thomas M (2002) Ozeanisch induzierte Erdrotationsschwankungen, PhD