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NLOADF: A program for computing ocean-tide loading

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Abstract. The loading of the Earth by the ocean tides produces several kinds of signals which can be measured by geodetic technique. In order to compute these most accurately, a combination of global and local models of the ocean tides may be needed. The program NLOADF convolves the Green functions for loading with ocean tide models using a station-centered grid with fixed dimensions, making it easy to combine different ocean models without overlap in the convolution. The program computes all the quantities of interest (gravity, displacement, tilt, and strain) and includes the case where measurements are made beneath the surface of the ocean.

Introduction

That measurements of the tides of the solid earth are disturbed by the loading of the Earth by the ocean tides has been known for most of this century; the first effective computations of these loads were made in the 1970s, when reasonable models of the global ocean tides became available. In the last few years, and especially in the last two, there has been a great increase in the number of global tidal models available from which to compute such loads. At the same time, the increasing precision of space-geodetic measurements has provided new interest in computing these loads, since they are clearly detectable in measurements of displacements (for which they are, in general, a source of "noise"). The purpose of the program described in this note is to provide a package for computing such loads that is both relatively straightforward to use for geodetic applications and also general enough to be able to combine results for global and local tidal models. Since, for sites near a coast, the local tides may contribute much of the load, it can be important to include detailed representations of these tides, which may not be accurately included in a global model.

Methodology

For any quantity of interest, the ocean load tide L is given by an integral

$$L(\theta',\lambda') = \int_0^{2\pi}\int_0^{\pi} \rho H(\theta,\lambda) G_L(\Delta) S_L(\alpha) a^2 \sin\theta \, d\theta \, d\lambda \qquad (1)$$

where Δ is the distance, and α is the azimuth, of the point with geographical coordinates (θ,λ) relative to the place of observation, which is at (θ',λ'). The tidal height at (θ,λ) is H (zero on land); for an individual tidal constituent, H (and L) is complex-valued. The ocean water density is ρ, and a is the radius of the Earth (assumed spherical). The functions G_L and S_L together express the response; G_L is the mass-loading Green function, while S_L is the combination of trigonometric functions needed when we are computing a vector or tensor load (such as horizontal displacement, tilt, or strain). G_L depends in part on the Earth model used; the Green functions included with the program are those found by *Farrell* [1972], although others can be used.

The integral (1) is a convolution and thus may be performed in two ways. One, most convenient if L is desired over the whole Earth, is to find the spherical harmonics of H and G, multiply these, and back-transform to get L, analogously to using the Fourier transform for convolution of time series [*Ray and Sanchez*, 1989; *Mitrovica et al.*, 1994]. Unfortunately, this approach has not been shown to be suitable for all the quantities that may need to be computed (such as strain), and it does not make it easy to combine tidal models.

The other method available is the older one of computing (1) directly (for a given value of (θ',λ')) as a sum over small regions; because G has (for most quantities) a singularity for $\Delta = 0$, this demands that these regions be smaller near the station. This program follows *Goad* [1980] in using regions that form a grid centered on the station. We may then write (1) as

$$L = \int_0^{\pi} \rho a^2 H(\Delta,\alpha) G_L(\Delta) \sin\Delta \int_0^{2\pi} S_L(\alpha) \, d\alpha \, d\Delta \qquad (2)$$

and note that the multiplication by $\sin\Delta$ lowers the degree of singularity by one. Now define the ijth region by $\Delta_i<\Delta<\Delta_{i+1}$ and $\alpha_{ji}<\alpha<\alpha_{j,i+1}$, and let H_{ij} be H at the center of the region. Finally, define

$$G_i = a^2 \int_{\Delta_i}^{\Delta_{i+1}} G_L(\Delta) \sin\Delta \, d\Delta \qquad\qquad S_{ij} = \int_{\alpha_{ji}}^{\alpha_{j,i+1}} S_L(\alpha) \, d\alpha$$

Then, assuming H is constant and equal to H_{ij} over each region, the integral becomes the sum

$$L = \rho \sum_{i=1}^{N} \sum_{j=1}^{M_i} H_{ij} S_{ij} G_i$$

where N is the number of intervals in Δ and M_i the number of intervals in α for distance Δ_i.

Once we have chosen the Δ_i, we need compute the G_i only once; because these have been integrated, the only quantity whose variation over a region should concern us is H, and we therefore need to make the cell sizes such that H may be taken to be constant. It is therefore appropriate to make the regions about the same size as those used in the ocean tide model. However, just doing this overlooks an important source of

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discontinuity in H: the presence of land. The spacing of cells in most global models means that the coastline representation is not very detailed. The program therefore uses smaller regions near the station, deriving the presence of land from a detailed land-sea grid (resolution of 0.94 arc min, or about 1.7 km at the equator) derived from the coastline database of *Wessel and Smith* [1996]. When this grid indicates water but the tidal model has land, the nearest values from the model are extrapolated if possible.

In order to combine global and local models, the program reads a file of points that describe a polygonal area (designed by the user): all regions within this area can then be automatically excluded (for use with the global model) or included (for use with the local model). Since the grid of regions used is fixed for any station, this assures that there will be no overlaps in the sum, even if the models themselves overlap.

For gravity and tilt the Green function G_L includes a part from the direct attraction of the load; the size of this is affected, especially for gravity, by the height of the station above (or below) the load (that is, sea level). In this program, suitable approximations are used for this part of G_L to ensure accurate results even when there is a load at zero distance, something rarely true on land but always true for sea bottom gravity or tilt measurements, which have been proposed for precise seafloor geodesy.

Verification, Accuracy, and Availability

The loads computed at several places for the Schwiderski ocean models have been compared against those found using other programs, especially those of *Goad* [1980] for gravity, the GOTIC program of *Sato and Hanada* [1984] for strain, and the results of *Scherneck* [1983] for displacement. In most cases the results agree to within better than 5% (often to within 2%); the discrepancies are probably caused by differences in the grids used, especially in the representation of the coastline. The total accuracy of the predicted loads will of course also depend on the accuracy of the ocean-tide models, which varies with location [*Le Provost et al.*, 1995]. While the Green functions of *Farrell* [1972] are for a relatively old Earth model, the differences between tides computed from these and from newer Earth models are not more than a few percent [*Scherneck*, 1990].

NLOADF is written in FORTRAN 77 (with one subroutine in C); the only nonstandard system call required is one to read the command-line arguments. This call is available in most versions of UNIX. The distribution includes the program, along with supplementary documentation, the new global models TPXO.2 [*Egbert et al.*, 1994], CSR 3.0 (R. J. Eanes, personal communication, 1995), and FES 95.2 (C. Le Provost, personal communication, 1995), the Schwiderski models, several regional models, several Green function files, and additional programs for manipulating the output of NLOADF and for computing tides in the time domain by interpolating from the values for several constituents (described by *Agnew* [1996]). Currently, the distribution is available by anonymous FTP from directory /pub/spotl at bilby.ucsd.edu; it has also been deposited with the NASA Crustal Dynamics Data Information System at the Goddard Spaceflight Center (Greenbelt, Maryland) and with the International Center for Earth Tides at the Observatoire Royal de Belgique (Brussels, Belgium).

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