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Observations of Annual Variations of the Earth's Gravitational Field Using Satellite Laser Ranging and Geophysical Models

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Abstract. We have analyzed 6 years of satellite laser ranging (SLR) data to the Lageos 1 & 2 satellites to determine the annual variation of a set of spherical harmonic coefficients of the Earth's gravity field complete to degree and order 4 (half-wavelength resolution of ~5000 km). We have compared these results to a suite of geophysical models describing annual variations of the gravity field due to changes in the distribution of mass in the atmosphere, in the ocean, and continental hydrology (soil moisture and snow). We find that spherical harmonic coefficients derived from the satellite-observations and the aggregate of these geophysical models agree to about 1 mm RMS in geoid height, and have degree correlations that generally exceed the 90% confidence limit. We found that the SLR data could distinguish between two different hydrologic models, but were unable to distinguish between competing models of atmosphere and ocean mass variation, probably due to the small magnitude of the differences in these models (and the small total magnitude of the ocean signal) at the long wavelengths that can be observed by the satellite data. The satellite results should improve considerably in 2001 with the launch of the Gravity Recovery and Climate Experiment (GRACE), which will allow the determination of the time variations of the Earth's gravity field with a spatial resolution of about 300 km.

Introduction

The measurement/modeling of temporal changes in the Earth's gravitational field is important for understanding the structure of the solid Earth as well as the geophysical processes that redistribute mass on the Earth's surface and in its interior [*Dickey et al.*, 1997]. The measurement of these variations has traditionally been accomplished using Satellite Laser Ranging (SLR) to passive Earth orbiting satellites, such as Lageos, although early in the next decade several dedicated satellite gravity missions, most importantly the Gravity Recovery and Climate Experiment (GRACE), will allow unprecedented observations of the time varying gravity field. Lageos 1, launched in 1976, is regarded as one of the most precise targets for SLR, largely because its altitude of ~5900 km is well above the Earth's atmosphere, and thus non-gravitational forces are quite small. However, estimating gravity variations using a single satellite imposes significant limitations on spatial and temporal resolution. With the launch of Lageos 2 in 1992, two precise targets at roughly the same altitude, but different inclinations (109.84° for Lageos 1, 52.63° for Lageos 2), are available for geophysical studies.

The gravity field of the Earth varies due to many different phenomena, however at seasonal periods the principal contributions are expected to be due to redistribution of water mass in the atmosphere [e.g. *Chao and Au*, 1991], the oceans [e.g. *Wahr et al.*, 1998], and on the land surface [e.g. *Chao and O'Connor*, 1988; *Rodell and Famiglietti*, 1999]. Seasonal variations of the low degree zonal gravitational coefficients observed using SLR data have shown good agreement with similar estimates computed from geophysical models [*Chao and Eanes*, 1995; *Cheng and Tapley*, 1999; *Gegout and Cazenave*, 1993; *Nerem et al.*, 1993]. In addition, seasonal variations of the position of the Earth's geocenter (the location of the crust-fixed reference frame relative to the center-of-mass) due to these phenomena [*Dong et al.*, 1996] have shown good agreement with SLR observations of the geocenter [*Chen et al.*, 1999]. Similar results have been reported for the degree 2 order 1 coefficients [*Cazenave et al.*, 1999]. To our knowledge, no one has previously attempted to observe the seasonal variations of the gravity field complete to degree 4 in spherical harmonics (21 coefficients not including degree 1 terms), although the geophysical models are certainly capable of providing such estimates for comparison [e.g. *Wahr et al.*, 1998]. Herein, we describe the analysis of the Lageos 1 & 2 SLR data for determining annual gravitational variations, the geophysical models used for comparison to the SLR results, and finally the results of the comparison.

SLR Data Analysis

We summarize here the method used to analyze the SLR observations to determine the temporal gravitational variations; a more detailed description can be found in *Eanes* [1995]. We analyzed 6 years of Lageos 1 and 2 SLR observations (11/92-11/98) while adjusting 12-day estimates of the spherical harmonic gravitational coefficients complete to degree and order 4, range biases for each tracking station, the geocenter vector, and daily estimates of satellite state (epoch state at the beginning of each day) and polar motion. This is accomplished by analyzing the SLR observation residuals from a long-arc analysis of the Lageos 1 and 2, as discussed in *Eanes* [1995]. The temporal variations in the even zonals are computed from a linear combination of the observed residual node rates of Lageos 1/2 as:

$$\begin{aligned} J_2 &= -0.00621\delta\dot{\Omega}_1 \sin I_1 - 0.02038\delta\dot{\Omega}_2 \sin I_2 \\ J_4 &= 0.08576\delta\dot{\Omega}_1 \sin I_1 + 0.05501\delta\dot{\Omega}_2 \sin I_2 \end{aligned} \tag{1}$$

where the coefficients are orbit element-dependent constants that can be determined from Kaula's theory [*Kaula*, 1966], and I_1/I_2 are the orbit inclinations of Lageos 1/2. Thus, the even zonal coefficients are determined solely from the long period perturbations to the orbit. The variations in J_3 and the non-zonal coefficients are determined directly from the SLR observations, where the partial derivatives of the range with respect to the coefficients are computed from Kaula's theory:

$$\begin{aligned} \frac{\partial \rho}{\partial C_{lm}} &= \frac{\partial \rho}{\partial a_\alpha}\frac{\partial a_\alpha}{\partial C_{lm}} \\ \frac{\partial a_\alpha}{\partial C_{lm}} &= \sum_{pq}\left(\frac{\partial a_\alpha}{\partial C_{lm}}\right)_{pq} \end{aligned} \tag{2}$$

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where a_α are the orbital elements, and the summation is performed over all p and q that are significant, but not including secular and long period terms. Thus, J_3 is determined solely from short-period perturbations (minimizing the influence of the "Lageos Anomaly" [*Metris et al.*, 1997]), and the even degree non-zonal coefficients are primarily determined from the m-daily perturbations in the inclination, ascending node, and along-track. The SLR residual RMS for all 6 years of data is about 8 mm. The background models employed are similar to the 1996 IERS Conventions [*McCarthy*, 1996]. The most important deficiency is the omission of the effect of anelasticity on rotational deformation, which will introduce small signals into our $C_{2,1}$ and $S_{2,1}$ estimates at the annual and Chandler Wobble periods; however these signals are much smaller than those arising from mass redistribution.

This procedure was used to generate 12-day resolution time series for each of the gravitational coefficients to degree and order 4. The amplitude and phase of the annual variation of the coefficients was determined via a weighted (using the error estimates for each 12-day solution) least squares fit to the 6 year time series for each coefficient. The SLR tracking data we used in this study can not possibly estimate/separate all the coefficients of a 4 x 4 gravity field, mainly because of geographic gaps in the distribution of the data. Therefore, there are regions of the Earth where the annual variation of the gravity field is poorly determined, thus causing the estimated spherical harmonic coefficients to be highly correlated – for the most part their absolute values have little meaning. However, maps of the annual variation of the gravity field do have meaning because there are large areas of the Earth where the annual variations are adequately resolved. Nevertheless, for completeness, we provide the amplitude/phase of the coefficients in Table 1, although they should be interpreted with caution because of the aforementioned caveat.

Geophysical Models Employed

We have employed a variety of different geophysical models in our study, although it was not the objective of this study to test every available model, just a representative subset. The spherical harmonic coefficients for each model were computed using the gridded mass variations from each of the models. A description of each of the models follows.

Table 1. Amplitude/Phase Annual Variation of the Normalized Spherical Harmonic Coefficients Estimated Using the Lageos SLR Observations.

n	m	C_{nm} Amp (x 10^{-10})	C_{nm}Phase (deg)	S_{nm}Amp (x 10^{-10})	S_{nm}Phase (deg)
2	0	1.06	54.8		
2	1	0.27	16.5	0.42	7.6
2	2	0.14	184.1	0.94	326.0
3	0	1.38	196.9		
3	1	0.30	5.6	0.40	17.6
3	2	0.81	160.1	0.38	63.0
3	3	0.49	324.4	1.14	46.0
4	0	0.26	181.5		
4	1	0.99	96.4	0.21	244.2
4	2	0.39	176.3	0.84	58.1
4	3	0.39	92.8	0.24	109.3
4	4	0.75	283.3	0.27	101.4

The phase convention is $\cos(\omega t - \phi)$, where t is time past Jan 1, ω is the annual frequency, and ϕ is the phase.

Atmospheric Mass

Surface atmospheric pressure is a direct indicator of the amount of atmospheric mass above a given site, thus atmospheric pressure can be used to determine the temporal variations of the gravity field caused by the atmosphere [*Chao and Au*, 1991]. We analyzed atmospheric pressure grids from the European Center for Medium-range Weather Forecasts (ECMWF) and the National Center for Environmental Prediction (NCEP) Reanalysis Project [*Kalnay et al.*, 1996]. An inverted barometer correction was applied to these models, effectively removing their contribution over the oceans. These models assimilate a variety of meteorological measurements in order to adjust the dynamical equations describing the evolution of the atmosphere in time. At seasonal frequencies, large differences between the NCEP and ECMWF models can be observed in regions where there is a sparcity of meteorological data, such as in Antarctica. However, these differences occur at shorter wavelengths than can be resolved by the degree 4 spherical harmonic expansion used here, and thus for this study the two models are essentially identical. For this reason, we have adopted the ECMWF results (see *Wahr et al.* [1998] for maps of this model).

Ocean Mass

We have studied seasonal gravitational variations caused by ocean mass redistribution using two distinctly different approaches. In the first, spherical harmonic coefficients computed from the output of a numerical ocean model were provided to us by *Wahr et al.* [1998]. The model employed is the Parallel Ocean Program (POP) developed by *Dukowicz and Smith* [1994]. Details of the computation of spherical harmonic geopotential coefficients from the output of this model can be found in *Wahr et al.* [1998]. In the second approach, we computed similar quantities using global (±66° latitude) maps of sea level observed by TOPEX/POSEIDON [*Tapley et al.*, 1994] after correcting for steric effects using monthly compilations of hydrographic data from *Levitus et al.* [1994]. This analysis is described in *Chen et al.* [1999]. The contribution of ocean mass redistribution relative to those of the atmosphere and continental water mass is seemingly small based on these analyses. Maps of the annual variations of the geoid due to ocean mass redistribution as computed from the POP model are presented in *Wahr et al.* [1998].

Continental Water Mass

For the contribution of continental water mass variations we considered two different models, one computed by *Wahr et al.* [1998], and another computed by ourselves. In the former, a global gridded soil moisture and snow mass data set generated by NCEP [*Huang et al.*, 1996] was used to compute the annual variation of the gravity field. *Wahr et al.* [1998] describe the details of these computations. We also used the monthly gridded soil moisture and snow depth fields from the NCEP 40-year reanalysis model [*Kalnay et al.*, 1996], referred to as the NCEP-NCAR Data Assimilation System (CDAS-1). The analysis of this data set to produce seasonal gravitational variations is described by *Chen et al.* [1998; 1999]. Neither model analysis includes water storage variations below 2 m depth or over the Antarctic continent, which could be a significant error source. In addition, the CDAS-1 model does not assimilate precipitation and surface

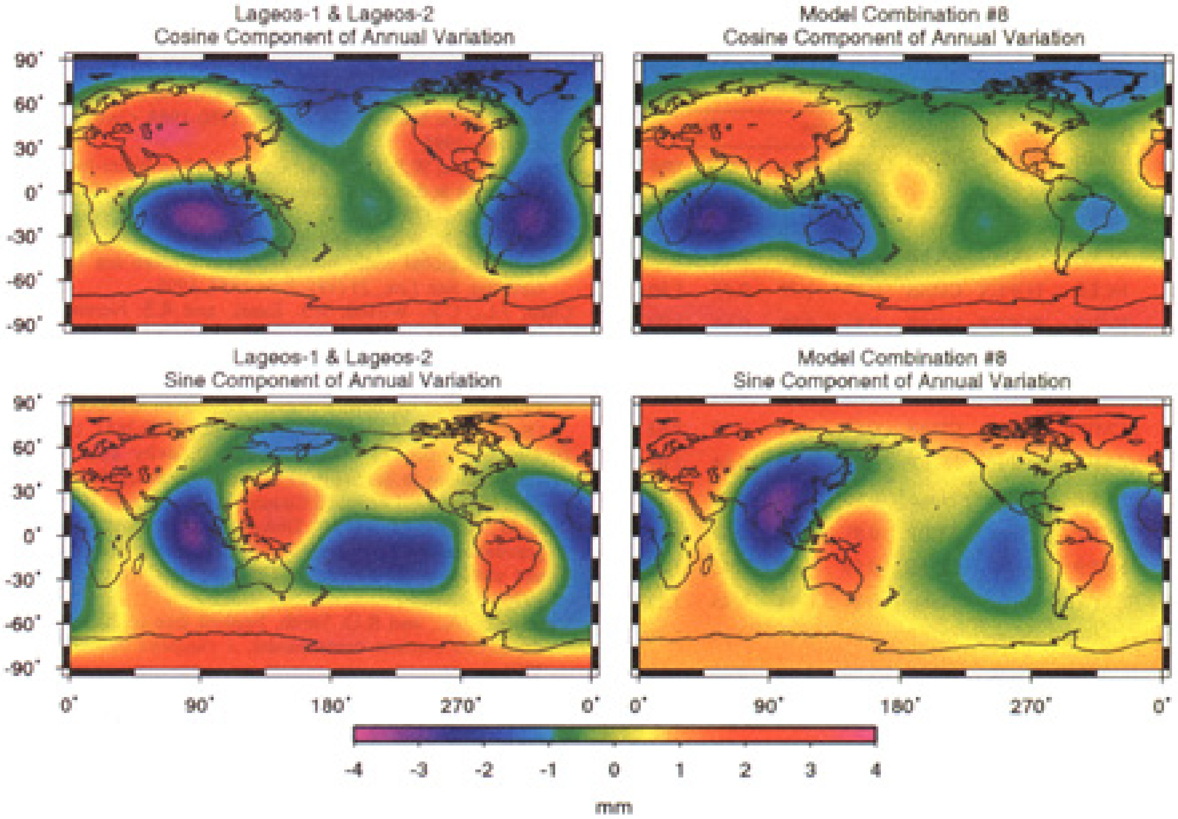

Plate 1. Maps of the cosine and sine components of the annual variation in the geoid complete to degree and order 4 in spherical harmonics, as determined from a) Lageos 1/2 SLR observations, and b) the sum of the suite of geophysical models shown in Case 8 of Table 2.

fluxes important for predicting soil moisture and snow depth. Gridded maps of the NCEP model are presented in *Wahr et al.* [1998]

Comparison of Results

For this study, we would like to use the geophysical models to validate the SLR observations of the time varying gravity field. In the future, dedicated satellite gravity missions should allow the satellite to validate and improve the geophysical models. The SLR observations of the time-varying gravity field measure the sum of all sources of mass variation in the Earth system. Thus, we need to combine the results from the geophysical models we believe are the major contributors to the seasonal variation of the gravity field, in this case the atmosphere, the ocean, and continental water. Plate 1, which is the principal result of this paper, shows the cosine and sine components of the annual variation of the geoid complete to degree 4 in spherical harmonics for both the Lageos 1 & 2 SLR observations, as well as for a particular combination of the geophysical models (in this case, the ECMWF atmosphere model, the TOPEX-derived ocean model, and the NCEP hydrologic model). Degree 1 terms (the geocenter variations) are not included in these maps, but a similar analysis for these terms is given by *Chen et al.* [1999].

Our analysis technique did not allow us to robustly estimate the errors in the Lageos solution shown in Plate 1, although we did test the sensitivity of the solution by computing estimates using temporal subsets of the full set of observations. For example, we computed solutions based on the first 2.5 years of Lageos data and compared them to the solution from the complete dataset. The general shape of the maps shown in Plate 1 was the same for each solution, although the geoid height amplitudes could vary by up to a few mm, especially over poorly tracked regions such as the Pacific Ocean. In general the differences were less than 1 mm.

Qualitatively, the comparison between the satellite-observed gravity variations and the geophysical models (which are mainly constrained by surface observations of one type or another) is quite good. We can also demonstrate this quantitatively by computing the RMS difference and the correlation of the geoid maps of the cosine and sine terms of these two estimates. For the combination of geophysical models shown, the cosine terms have an RMS difference of 1 mm and a correlation of 0.62, and the sine terms have an RMS difference of 0.9 mm and a correlation of 0.80. Because we have two models for each of the major geophysical contributions (atmosphere, ocean, hydrology), there are a variety of different combinations we might employ when comparing to the SLR results. Table 2 illustrates the performance of the geophysical models relative to the SLR results. Clearly, the SLR results compare better when the NCEP hydrologic model is employed. While using the hydrologic model does not improve the comparison with Lageos for the cosine term, the comparison for the sine term is clearly improved (smaller RMS difference and higher correlation). Indeed, the majority of power in the sine term arises from hydrologic sources. The NCEP and ECMWF pressure fields compare equally well to the SLR results. The ocean mass models are indistinguishable in the comparisons, largely because the signal is small for the long-wavelengths examined here. The larger differences between Lageos and the models in the Antarctic are likely due to deficiencies in the models, i.e., the lack of meteorological and hydrologic measurements to drive the models (the analysis of hydrologic models used here omitted Antarctica entirely).

Table 2. Comparison of the Annual Geoid Variations to Degree and Order 4 from Lageos 1/2 SLR Observations and a Suite of Geophysical Models.

Case	Atmos. Model	Ocean Model	Hydro. Model	Cosine		Sine	
				Correl.	rms (mm)	Correl.	rms (mm)
1	NCEP	POP	CDAS	0.62	1.42	0.49	1.60
2	NCEP	POP	NCEP	0.81	0.92	0.63	1.06
3	NCEP	TOPEX	CDAS	0.67	1.37	0.50	1.69
4	NCEP	TOPEX	NCEP	0.83	0.89	0.63	1.09
5	ECMWF	POP	CDAS	0.62	1.36	0.49	1.54
6	ECMWF	POP	NCEP	0.82	0.91	0.63	1.05
7	ECMWF	TOPEX	CDAS	0.67	1.31	0.50	1.63
8	ECMWF	TOPEX	NCEP	0.83	0.87	0.64	1.07
9	NCEP	None	None	0.85	0.90	0.50	1.19
10	NCEP	None	NCEP	0.81	0.92	0.59	1.12
11	NCEP	None	CDAS	0.59	1.45	0.46	1.66
12	ECMWF	None	None	0.84	0.94	0.45	1.22
13	ECMWF	None	NCEP	0.81	0.92	0.59	1.10
14	ECMWF	None	CDAS	0.58	1.42	0.46	1.60

It is not possible to compute meaningful confidence limits for the correlation of the gridded maps shown in Table 2. One can compute confidence limits if the original spherical harmonic coefficients are compared directly, but then only over each individual degree [*Eckhardt*, 1984]. We computed the degree correlations and confidence limits for one suite of geophysical models (Case 8 from Table 2). With the exception of the sine term at degree 3, where only 75% confidence was found, the confidence limits are always greater than 90%.

Conclusions

We have used Lageos 1/2 SLR observations over 1993-1998 to determine the annual variation of the Earth's gravitational field with a half-wavelength resolution of 5000 km. Maps of the observed annual geoid variation are in good agreement with similar maps computed from geophysical models of water mass redistribution in the oceans, atmosphere, and continents. Given the uneven distribution of the SLR tracking network, it is unlikely that the spatial resolution of this estimate can be greatly improved. However, with the launch of the GRACE satellite gravity mission in 2001, we expect to be able to compute monthly maps of the time varying geoid with sub-millimeter accuracy and a spatial resolution of 300 km.

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