THE STUDY OF EFFECTS OF TIME VARIATIONS IN THE EARTH'S GRAVITY FIELD ON GEODETIC SATELLITES

Reporting Period: November 1, 1997 - October 31, 1998
Investigation Period: November 1, 1997 - October 31, 1998

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November 1, 1998

SUMMARY

This final technical report summarizes research conducted under NASA's Dynamics of Solid Earth Program, Grant NAG5-6697, entitled *The Study Of Effects Of Time Variations In The Earth's Gravity Field On Geodetic Satellites*, during the current investigation time period from November 1, 1997 through October 31, 1998. The report also intends to concisely summarize results of the research work conducted under a similar investigation at the University of Texas at Austin and funded by NASA (Grant Numbers Grant NAGW-2941 and NAG5-3128) from approximately 1995 through 1998.

The temporal variations in the Earth's gravity field are the consequences of complex interactions between atmosphere, ocean, solid Earth, hydrosphere and cryosphere. The signal ranges from several hours to 18.6 years to geological time scale. The direct and indirect consequences of these variations are manifested in such phenomena as changes in the global sea level and in the global climate pattern. These signals produce observable effects on near-Earth orbiting geodetic satellites. The primary objectives of the proposed investigation include (1) the improved determination of the time-varying gravity field parameters (scale from a few hours to 18.6 year and secular) using long-term satellite laser ranging (SLR) observations to multiple geodetic satellites, and (2) the enhanced understanding of these variations with their associated meteorological and geophysical consequences.

A list of relevant presentations and publications is attached.

SEASONAL VARIATIONS

Seasonal variations arise from the solar influences on the mass transfer among the solid Earth, ocean and atmosphere, and produce detectable perturbations in satellite orbits. The spectrum coherence between the variations observed from the Lageos-1 satellite and predicted from the atmosphere mass redistribution at annual period has been studied by a number of investigators, including Dong et al. [1996]. The result from a single satellite is a linear combination of the even or the odd zonal effects. We have determined a time series of the zonal harmonics J_2, J_3, J_4 with 15 days interval over the 4 year period from 1992 to 1995 using a combination of the SLR data to Lageos-1, Lageos-2, Starlette, Ajisai and Stella [Cheng et al., 1996; 1999]. The observed annual amplitude of the even zonal variations was found to fall between those of the atmospheric mass redistribution with and without using the inverted barometer (IB) effects for the ocean response, in particular, it is closer to the IB model for J_2, to the non-IB model for J_4, the observed amplitude of the annual variations in J_3 is greater than that predicted from both IB and non-IB models [Cheng et al., 1996; 1999]. The results reveal the monthly and bimonthly correlation between the variations observed from satellites and predicted from NMC model. An important feature in these figures is that they show the ability of monitoring the Earth time-varying gravity field on time scale of a month time scale from analysis of SLR data to multi-satellite.

Orbital node residuals from Lageos 1, Starlette and Ajisai were examined using a nominal force model with and without including models in the orbit determination for the atmospheric mass and the surface water redistribution. The laser ranging residual RMS of the Lageos-1 five-year arc orbit fit is reduced by 8% for IB and no-IB model. It is shown that the long period tides (K_1 and S_1) and the even zonal rate $\dot{J}_n$ induced perturbations are dominant in the Lageos-1 orbit while the effects of the atmospheric mass excitation are relatively small. However, the RMS of one year arc orbit fit for Starlette and Ajisai can be reduced by as much as 33%. The node residuals for Starlette and Ajisai in Figure 5 and 6 are from the connection of 4 one-year-arcs, show that the meteorological effects are different for each year. Detailed comparisons indicate that the contributions of the meteorological excitations (atmospheric and ground water) to the observed annual variations are approximately 60%-90% for Starlette, and 80% -90% for Ajisai [Cheng et al, 1994; 1996; 1999]. A significant percentage of the signal remains unexplained, presumably due to deficiencies in the continental hydrological model, the mass redistribution in ocean and other excitation sources.

SECULAR VARIATIONS

Significant progress has been achieved in determining the temporal variations of the Earth's gravity field in the research work conducted under NASA Grant NAGW-2941, NAG5-3128 and this investigation. Our investigation has resulted in the most accurate solution to date involving $\dot{J}_n$ (n = 2, 3, 4, 5, and 6) and the 18.6 year lunar tide using long-term satellite laser ranging data to several geodetic satellites [Cheng et al., 1996; 1998]. The solutions for $\dot{J}_n$ have provided an improved constraint on the study the Earth's rheology and mass balance of polar ice. The satellite derived 18.6 year lunar tide provided a significant contribution to the study of the Earth's mantle anelasticity [Zhu et al., 1995; Eanes et al, 1996]. Comparison of the satellite derived seasonal variations with the results from mass redistribution in the atmosphere and surface water has shown the ability to monitor the temporal variations of the Earth's gravity field using multiple geodetic satellites [Cheng et al, 1996; 1999]. Detailed comparison indicates that the current models of the meteorological mass redistribution of atmosphere and ground-water can not fully explain the observed variations at seasonal, annual and interannual time scales [Cheng et al., 1994; Chao and Eanes, 1995; Dong et al, 1995]. The higher degree $\dot{J}_n$ are required for a realistic

constraint and possible resolution of the discrepancy in the satellite derived $\dot{J}_3$ and that predicted from the ICE model [Cheng et al., 1996]. A dedicated effort is still required to improve the satellite results and the modeling of geophysical process within the Earth-ocean-atmosphere system, particular the mass balance of the polar ice sheets.

The secular changes in the Earth's gravity field, particularly, the rates of the low degree zonal harmonics, are believed to be the results of the solid Earth's low mantle viscous response to the postglacial rebounds, and to the present-day glacial melting. A number of solutions for $\dot{J}_n$ with deferent degree n using multi-satellite SLR data were reported in recent years as shown in Table 1. A solution for $\dot{J}_n$ (n = 2, 3, 4, and 5) from analysis of SLR data to 6 geodetic satellites was reported in 1993 [Cheng et al., 1993]. Improved solutions of $\dot{J}_n$ up to degree 6 was obtained recently from combination analysis of SLR data to 8 geodetic satellites with the longest data span over 20 years, from 1975 to 1995 [Cheng et al., 1996; 1998].

Table 1. Comparison of the Satellite Derived $\dot{J}_n$ ($10^{-11}/yr$)					
$\dot{J}_2$	$\dot{J}_3$	$\dot{J}_4$	$\dot{J}_5$	$\dot{J}_6$	Study
- 2.7±0.4	- 1.3±0.5	- 1.4±1.0	2.1±0.6	0.3±0.7	Cheng et al. [1996]
- 2.6±0.3	1.6±0.4	0.2±1.5			Nerem et al. [1996]
- 3.0±0.5	- 1.7±0.1	- 0.8±1.5			Cazenave et al. [1995]
- 2.6±0.5	- 1.2±0.5	- 1.1±1.0	2.3±0.6		Cheng et al. [1993]

The even zonal rates are generally consistent with that predicted from post-glacial rebound models. However, there is a discrepancy between the geodetic satellite solution and the ICE model predicted $\dot{J}_3$ [Cheng et al., 1996; Cheng et al., 1998]. The satellite derived odd degree zonal rates represent integrated signals associated with the mass transport between the polar areas. The differences among satellite solutions are due to the use of different models, techniques and data sets. The proposed investigation is to eliminate the discrepancy by improving both the satellite solution and the geophysical models for interpretation. For satellite observations of the odd degree zonal rate, the suspected aliasing effects from the non-gravitational effects on the Lageos orbit, the so-call Lageos anomaly, will need to be further studied. The different techniques for determining the zonal rates will be examined to ensure consistency of the results using the same satellite data sets.

CENTER FOR MASS VARIATIONS OF THE EARTH'S SYSTEM

The dynamic equation governing the gravitational acceleration of a satellite is described with respect to a frame with its origin located at the center of mass of the planet (the solid Earth-atmosphere-ocean-cryosphere), or geocenter. The space geodetic observations (SLR, DORIS and GPS) are attached to the solid Earth and move with respect to the geocenter due to the redistribution of mass within the Earth system. The space geodetic observation can therefore be used to monitor the motion of the terrestrial frame rigidly attached to the stations with respect to geocenter, or equivalently the variations of the degree 1 spherical harmonics of the Earth's gravitational field, which provides a global

constraint on the mass redistribution within the Earth/ocean/atmosphere system. The geocenter variations will also affect the absolute sea surface height measurements. Because the geometric distribution of polar ice sheets, which are closer to the Earth's rotation axis, the contributions from mass load variations of the polar ice sheets to the Earth rotation and the polar motion will be relatively small, but its contribution to geocenter variation could be significant. The observed geocenter time-series could be a tool to constrain the variations in the ice sheet thickness and snow cover in polar regions. The observed geocenter motion exhibits apparent annual and semi-annual variations with an amplitude of 2-3 mm for x and y component, 6-7 mm for z component, as well as interannual variations [Eanes et al, 1995]. We have characterized and contributed to the potential causes of the geocenter variations [Dong et al., 1995].

VARIATIONS IN THE NON-ZONAL HARMONIC COEFFICIENTS

Global mass redistribution within the Earth system changes the Earth's gravity field at all time and space scales. In addition to measuring the secular and seasonal variations in zonal harmonic coefficients and the geocenter variations, we will study the variations in the other harmonic coefficients of the time-varying gravity field. For example, the observations of ΔC_{21} and ΔS_{21} can be used to constrain the mean equatorial rotation of the core with respect to the mantle. The possible secular variation in C_{22} and S_{22} may describe the feature of the drift of the mass anomalies near the core-mantle boundary, which correlates with the secular change of the geomagnetic field. In principle, a satellite at lower altitude can sense these changes in the Earth's gravity field. The variations in the non-zonal spherical harmonics of the higher order $(m > 1)$ are associated with relatively small scale or regional mass transport in different scale, and result in small amplitude with high frequency oscillations in the satellite orbit, and are difficult to determine. With improving satellite orbit accuracy, those small signals in the satellite orbit could be detectable from analysis of the multiple type space geodetic measurements from multi-satellite. A time series of a 4x4 gravity field with 15-day interval has been determined using combination of SLR data from 5 geodetic satellite over a 4 years period [Cheng et al., 1999]. The time series for ΔC_{21}, ΔS_{21}, ΔC_{31} and ΔS_{31} indicated that all of the estimated non-zonal geopotential coefficients vary in the region of $\pm 5 \times 10^{-10}$, which are beyond the uncertainty of the JGM-3 gravity model, and with a rate of $\pm 3 \times 10^{-12}$/yr for the first order coefficients (degree < 5). The periodic variations were removed by adjusting the global diurnal and semi-diurnal tidal parameters. The accuracy of this time series is limited by the spatial and temporal distribution of the SLR data.

TIDES AND MANTLE ANELASTICITY OF THE EARTH

Improvements in modeling the diurnal and semi-diurnal ocean tides with an accuracy at the few centimeter level in the deep ocean from analysis of T/P altimetry [Shum et al., 1996] provide an opportunity to separate the signals of the non-ocean tides from satellite determined tidal parameters, such as radiation tides S_1 and S_2 .

The response of the Earth system at the long period tidal frequency is subject to a considerable dispersive effect due to the Earth's anelasticity. In addition, the largest impediment to extracting the secular signals in the satellite orbit is due to the 18.6 year lunar tide. Accurate determination of the long period tides, including the M_f, M_m, 9.3-year and 18.6-year lunar tide parameters, is demanded to improve our understanding of the frequency dependence of the anelastic processes and the dissipation of the tidal energy in the Earth system. Currently, the signals for $\dot{J}_2$ and the 8.6-year tide become separable from analysis of multi-satellite SLR data covering a 20 year time span. The results for the 18.6-year tide are in good agreement with that predicted from analestic effects [Zhu et al., 1995; Cheng et al., 1996]. The tidal signal at the 9.3 year period is small, and detecting this tidal

signal from analysis of long term SLR data has been an important result for the study of the anelasticity of the Earth.

MASS REDISTRIBUTION OF THE OCEAN

The oceans occupy about 70% of the Earth's surface area, and the change of the oceanic mass balance will certainly play an important role in the temporal variations of the Earth's gravity field. The availability of satellite altimetry missions in this decade (ERS-1, TOPEX/POSEIDON, ERS-2, GFO-1, Envisat, and Jason-1) presents an opportunity to establish a more accurate observation system for global sea level measurements with 1 mm/yr accuracy or better [Shum et al., 1995]. A variety of ocean signals can be detectable, such as the oceanic contribution to the variation in the Earth's gravity field and rotation due to the changing mass balance in the ocean. Fig. 15 shows the secular trend over T/P altimeter data span, which can used to potentially measure mass variation of the oceans [Shum, et al., 1996]. We have developed techniques to study the mass component of the sea surface variations by removing the effects of the inverted barometer and thermal expansion and other geophysical and oceanic circulation signals from the observed sea level changes. A clear seasonal signal in the low degree zonal spherical harmonic coefficients of the sea surface height variations from analysis of five years T/P altimeter data [Chen et al., 1998a; 1998b].

ICE SHEET MASS BALANCE

Recent IPCC studies of global sea level change have concluded that the average rate of rise during the last century has been 1-2 mm/yr. The uncertainty about the mass balance of the World's ice sheets and glaciers contributes significantly to sea level change. Analysis of 5 years of ERS-1 and ERS-2 altimeter measurements has indicated that the interior of the Antarctic Ice Sheet is melting less than 1 cm/yr from 1992-1996 [Wingham et al., 1998]. The accurate time series of the mass balance of Antarctica and Greenland from analysis of ERS-1 and ERS-2 altimeter data, and from ICESAT, the secular rates of the Earth's zonal harmonics, and the time-varying gravity measurements from the advanced gravity mapping mission, GRACE, can potentially provide a definitive measurement of mass balance of the ice sheets.

PATENT/INVENTIONS REPORT

There is no patent/invention to report.

RELEVANT PUBLICATIONS AND PRESENTATIONS

Relevant publications and presentations are listed as follows.

Chen, J., C. Wilson, B. Tapley, C. Shum, Oceanic mass variation from satellite altimetry and geodynamic applications, PORSEC 98, Qingdao, China, July 28-31, 1998a.

Chen, J., C. Shum, C. Wilson, D. Chambers, and B. Tapley, Seasonal sea level change from TOPEX/POSEIDON observation and thermal observation, submitted to Jl. Of Geodesy, 1998b.

Cheng, M. K., C. K. Shum, and B. D. Tapley, Global constraint on the model of mass transport within the Earth system using multi-satellite SLR data, Proc. IUGG General Assembly, Boulder, CO, July 1995.

Cheng, M. K., C. K. Shum, and B. D. Tapley, Global constraint on the modeling of mass transport within the Earth system from long-term SLR observations, Proc. International Union of Geophysics and Geodesy XII General Assembly, Boulder, Co., July 1995.

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Cheng, M., C. Shum and B. Tapley, Determination of long-term changes in the Earths gravity field from satellite laser ranging observations, J. Geophys. Res., 102(B10), 22,377-22,390, 1997.

Cheng, M. K., Studying the temporal variations of the Earth's gravity field using DORIS data, presented at DORIS day meeting, Toulouse, France, April 27-29, 1998.

Cheng, M. K., H. J. Rim, and B. D. Tapley, Contribution of the spaceborne GPS data to determination of the Earth's gravity field and its temporal variations, presented at the Fall AGU meeting, December 1998.

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Cheng, M. K., C. K. Shum, R. J. Eanes, B. E. Schutz, and B. D. Tapley, Long-period perturbation in Starlette orbit and tide solution, J. Geophys. Res., 95(B6), 8723-8736, June 10, 1990.

Cheng, M. K., R. J. Eanes, C. K. Shum, B. E. Schutz and B. D. Tapley, Temporal variations in low degree zonal harmonics from Starlette orbit analysis, Geophys. Res., Lett., 16(5), 393-396, May 1989.

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Shum, C., Determination of Earth's static and time-varying gravity field, National Astronomical Observatory, Mizusawa, Japan, February 24, 1998.

Shum, C., Understanding Earth's system dynamics using satellite geodesy, Department of Geophysics, Graduate School of Science, Kyoto University, Kyoto, Japan, February, 1998.

Wingham, D., A. Ridout, R. Scharroo, R. Arthern, and C. Shum, Antarctic Elevation Change 1992-1996, Science, September, 1998.