GEOPHYSICAL PARAMETERS FROM THE ANALYSIS OF LASER RANGING TO STARLETTE

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FINAL RESEARCH TECHNICAL REPORT

SUMMARY

Results of geodynamic research from analysis of satellite laser ranging data to Starlette conducted under NASA Crustal Dynamics Project Grant No. NAG5-757 are summarized in this report. The time period of the investigation covers from March 15, 1986, through December 31, 1991. As a result of the Starlette research, a comprehensive 16-year Starlette data set spanning the time period from March 17, 1975, through December 31, 1990, has been produced. This data set represents the longest geophysical time series from any geodetic satellite and is invaluable for research in long-term geodynamics. A low degree and order ocean tide solution determined from Starlette has good overall agreement with other satellite and oceanographic tide solutions. The observed lunar deceleration is -24.7 ± 0.6 arcsecond/century^2, which agrees well with other studies. The estimated value of $\dot{J}_2$ is $(-2.5 \pm 0.3) \times 10^{-11}$ yr^{-1}, assuming there are no variations in higher degree zonals and that the 18.6-year tide is fixed at an equilibrium value. The yearly fluctuations in the values for S_a and S_{sa} tides determined by the 16-year Starlette data are found to be associated with changes in the Earth's second degree zonal harmonic caused primarily by meteorological excitation. The mean values for the amplitude of S_a and S_{sa} variations in J_2 are 32.3×10^{-11} and 19.5×10^{-11}, respectively; while the rms about the mean values are 4.1×10^{-11} and 6.3×10^{-11}, respectively. The annual δJ_2 is in good agreement with the value obtained from the combined effects of air mass redistribution without the oceanic inverted-barometer effects and hydrological change. The annual δJ_3 values have much larger disagreements. Approximately 90% of the observed annual variation from Starlette is attributed to the meteorological mass redistribution occurring near the Earth's surface.

STARLETTE MEASUREMENTS AND ORBIT COMPUTATION

The Starlette SLR observations used in this investigation were collected from 73 globally distributed stations during the period from March 17, 1975, through December 31, 1990, which represents a continuous tracking measurement of almost 16 years. The data were compressed into 450,339 normal point observations, where the normal point bin size was 20 seconds. After data editing, a total of 26,343 acceptable passes formed the Starlette SLR data base were used for the orbit determination and geodynamic research for this investigation. A maximum of 2,516 passes were obtained during 1986, and a minimum of 845 passes were obtained during 1983. The average precision of the laser measurements for all the tracking stations during the period of the Main MERIT Campaign (September 1983–October 1984) was 8 cm, with several stations providing data with a precision of better than 5 cm. The more recent best stations have 1-cm precision and an average of 5-cm precision for the overall network. The preparation of this carefully edited 16-year Starlette laser range normal point data base (1975–92) represents one of the accomplishments resulting from this investigation. The analysis of Starlette data used individual and continuous one-year orbital arcs for 16 years. 16 one-year orbits were computed using the TEG-2 gravity field and the ocean tide model for selected tide and geopotential coefficients, along with other dynamical parameters [*Cheng et al.*, 1991]. These parameters include selected ocean tide coefficients, yearly values for S_a and S_{sa}, orbital, drag and solar radiation parameters. The laser range residual rms, after the solution, was reduced to an average of 34 cm for the 16-year batch of SLR data. The decrease in laser range residual from 120 cm for 1975 to 18 cm for 1987 can be mostly attributed to improvements in the precision of laser tracking hardware. The increased range residual rms in 1981 and during 1988 to 1990 is correlated with higher solar activity and its influence on the atmospheric density.

EARTH ROTATION PARAMETERS

He et al. [1982] and *Marsh et al.* [1985] are among the earlier studies which used Starlette SLR data to obtain solutions of Earth rotation parameters (ERP). The accuracy of those ERP solutions were estimated to about 3 or 4 times worse than the accuracy of the Lageos ERP solution. *Cheng et al.* [1985] and *Schutz et al.* [1989] performed consider covariance error analyses to understand the primary error sources affecting accurate determination of ERP using Starlette. The results showed that the accuracy of the Starlette ERP solution is limited primarily by errors in the Earth's gravity field model, in particular, errors in the first-order geopotential coefficients. The estimated accuracy for the Starlette ERP solution, thus, can be reduced about 55% by simultaneously solving for the ERP and dominant geopotential coefficients affecting the Starlette orbit [*Cheng et al.*, 1985]. A further reduction was achieved (rms of 2–3 mas for pole positions x_p and y_p with respect to Lageos) by using improved Earth gravity field models [*Schutz et al.*, 1989]. With recent advances of improved Earth gravity field models, e.g., *Tapley et al.* [1990] and in the ocean tide model for satellite orbit determination [*Casotto*, 1991], the estimated accuracy of Starlette-determined ERP parameters is approaching the 2-mas level for x_p and y_p. At the present time, the use of Starlette data for ERP determination cannot provide a strong complement to the Lageos determination, which is accurate to the sub-mas level. However, the sensitivity of Starlette to seasonal variations in the Earth's gravity field provides unique benefits in the study of the role of atmospheric mass excitation of the Earth's rotation. For example, the annual variation in the length of day (LOD) due to meteorological mass redistribution, as deduced from the Starlette-determined seasonal annual variation, has been shown to be twice as large as the effect of the solid Earth tides [*Cheng et al.*, 1990a].

OCEAN TIDE SOLUTION

A solution for 66 low degree and order prograde ocean tide coefficients for 14 tidal constituents was obtained in a simultaneous least squares solution by analyzing a four-year subset of the 16-year span of Starlette data [*Cheng et al.*, 1990b]. The solution used a one-year continuous orbit from October 1976 through October 1977 and a three-year arc from

1983 through 1985. The Starlette tide solutions were compared with hydrographic tide model (i.e., Schwiderski) and satellite solutions (e.g., TEG-2 and GEM-T2) and altimetry solution (i.e., Cartwright and Ray model). data by *Cartwright and Ray* [1991]. The comparison was performed for major constituents in the long period band ($m = 0$) the diurnal band ($m = 1$)and the semidiurnal band ($m = 2$). The comparison is also limited to low degree and order spherical harmonic expansion of the respective tide models.

The comparison of the Starlette-determined tide solution with the multi-satellite solutions (GEM-T2 and TEG-2) and the *Cartwright and Ray* tide model shows overall good agreement in the diurnal and semidiurnal bands. *Cheng et al.* [1990b] provides an evaluation of satellite determined ocean tide solutions using long-arc orbit fits for Lageos and Starlette. The study found that tide solutions determined using long arcs (i.e., one year) seem to provide better determination of long period tides than the multi-satellite tide solution (GEM-T1 solution) since typical 5-day arcs are used.

Solutions of second degree S_a and S_{sa} are shown to have overall good agreement. The third degree values of S_a from GEM-T2 and PEGM-69 multi-satellite solutions are significantly larger. The TEG-2 values, however, compare well with Starlette results. The Lageos solution of the third degree S_a has also significantly larger values which is thought to be due to influences of mismodeling of surface forces. There are large differences in the amplitude of the second and third degree M_m and M_f between the Schwiderski and satellite-determined values except for the M_m from TEG-2, the error sources are unknown at the present time.

Overall, the Starlette results compare well with other more recent solutions (Geosat, GEM-T1, GEM-T2, PEGM-69 and TEG-2 solutions). However, there are some distinct differences. For example, the second and fourth degree O_1 values from the Geosat solution [*Cartwright and Ray* model] are significantly smaller than either Starlette or other multi-satellite solutions. The second degree K_2 tide for the TEG-2 value is significantly smaller than other solutions.

In summary, the overall agreement is good among the more recent tide solutions and the Schwiderski tide model for the semidiurnal and diurnal band. Larger differences are observed among the tide solutions in the long-period band.

ANNUAL AND SEMIANNUAL VARIATIONS IN J_2 AND J_3

Cheng et al. [1990b] reported that the orbit node residual history for the satellite, Starlette, over a four-year time span displays a strong annual variation in which the maximum and minimum points occur in July and January, respectively. This variation was also found to have year-to-year fluctuations of more then 25% of the mean value. This annual signature is an indication of annual variation in the zonal harmonics of the Earth's gravitational potential caused by the seasonal redistribution in the air mass, ground water, and oceans. In this study, 16 one-year Starlette orbital arcs have been used to determine the seasonal variations in J_2 and J_3 [*Cheng et al.*, 1991].

Yearly amplitudes of the annual and semiannual variations in J_2 have been determined by estimating the coefficients of the second degree annual and semiannual tides, S_a and S_{sa}. The mean values are 32.3×10^{-11} and 19.5×10^{-11} for annual and semiannual contributions, respectively. The rms values about the mean are 4.1×10^{-11} and 6.1×10^{-11} for the annual and semiannual component, respectively. The ratio of the rms to the mean values represents a variability of 13% for the annual δJ_2 and 32% for semiannual δJ_2. The Starlette-determined results can be used to predict the perturbation in the orbit node for Lageos, $\delta\Omega_L$, and for Starlette, $\delta\Omega_s$. The Starlette-determined annual and semiannual variations for the second degree zonal harmonics are compared to GEM-T2, TEG-2 and GRIM4 solutions. These values can also be compared with the values of δJ_2 computed from global surface pressure data without the oceanic inverted-barometer effects (non-IB) [*Chao and Au*, 1991], and using global surface water data [*Chao and O'Connor*, 1988]. during the period from 1977 to 1986 [*Eanes et al.*, 1987]. The contributions of the long-period oceanic tides to the temporal variation in the Earth zonal harmonics, such as in J_2, is evaluated from the equilibrium tide spherical harmonic coefficients [*Cheng et al.*, 1991].

Only variations in the second and third degree zonal harmonics have been included in the satellite solutions. However, the satellite solution obtained using multi-satellite tracking data sets collected over time spans of several years have provided a significant improvement for the separation of low degree and order gravitational coefficients. Thus, the satellite-determined second and third degree annual and semiannual tide parameters represent a dominant contribution from meteorological effects. The multi-satellite solutions are compared with Chao and Au's results for δJ_2 and δJ_3. The mean values of annual and semiannual variations in J_2 determined from a 16-year set of Starlette data is in agreement with the solution obtained using multi-satellite analysis, as the uncertainties for the satellite solution is estimated to be approximately 20%–30%. The satellite-derived value for δJ_2 represents the combined effects from ocean tide, air mass redistribution and hydrological change. The Starlette-observed annual variation in δJ_2 is in general agreement with the values of δJ_2 obtained by *Chao and Au* [1991] from an analysis of geophysical data assuming an atmospheric variation without the oceanic inverted-barometer effects (non IB), combined with the hydrological influence. The contribution to δJ_2 due to the annual ocean tide variation is less than 10%. On other hand, the satellite determined semiannual variation δJ_2 is dominated by the ocean tide. Assuming that the annual and semiannual ocean tide follow the equilibrium theory, the combined effects of atmosphere and hydrological excitation is around 15% of the satellite-observed semiannual variation, δJ_2.

The annual variation in the Lageos orbit node, predicted from the Starlette observed δJ_2, and other multi-satellite derived δJ_2, and from the combination of air mass and hydrological effects is in good agreement with the results from the 10-year Lageos orbit analysis. The semiannual variation in the Lageos orbit node predicted from the satellite-determined δJ_2 is in agreement with the Lageos observed values. However, the atmospheric and hydrologically derived semiannual variations are significantly smaller than the Lageos and Starlette solutions. The annual and semiannual variations in the Starlette orbit node residuals were not in good agreement with the predicted values from analysis of atmospheric data [*Chao and Au*, 1991]. A single geophysical process, either air mass non-IB, or hydrological excitation, cannot explain the perturbation observed by Starlette, only the combination of atmospheric non-IB and hydrological effects on the Starlette orbit shows agreement with the Starlette observed or the multi-satellite predicted annual variation. Because of its lower altitude, Starlette is more sensitive to gravitational forces than Lageos. The error of 1 cm in the amplitude of the annual variation in J_2 will produce residuals of 92.6 mas in the Starlette orbit node. Hence, the Starlette orbit can provide a critical constraint on the model for the mass movement, which causes the temporal variation in the Earth's gravity field.

The annual variations obtained in GEM-T2 and GRIM4/C1 are significantly larger when compared to the TEG-2 and Starlette solutions and to the results from geophysical data analysis. It is possible that some nongravitational effect has been aliased into the solutions of GEM-T2 and GRIM-4/C1 for the third degree annual tide parameter due to effect of Lageos. The annual variation in J_3 obtained from 16 years of Starlette orbit analysis is in agreement with the results from the analysis of the effect of air mass redistribution either with or without the oceanic-inverted barometer (IB), given by *Chao and Au* [1991]. It should be pointed out that no empirical term was introduced in the Starlette solution for the determination of the third degree tide S_a. The combined effects of the air mass redistribution and hydrological influence is smaller than the Starlette-observed annual variation. The comparisons for the semiannual variation in J_3 show some agreement in amplitude, but have a large difference in phase. At this point, it seems to be difficult to draw any conclusion about the meteorological excitation in J_3. An improvement is required for both the satellite solution and geophysical data analysis.

SECULAR VARIATIONS IN THE LOW DEGREE ZONAL HARMONICS

The Starlette $\dot{J}_2$ solution (in units of $10^{-11}\ \mathrm{yr}^{-1}$) was given as a linear combination of contributions from higher degree even zonals and from errors in the 18.6-year lunar tide [*Cheng et al.*, 1989]:

$$\dot{J}_2 = -2.5 \pm 0.3 + 1.5\,\dot{J}_6 + 0.4\,\dot{J}_8 + 0.7\,\delta C_{lp} + 0.4\,\delta S_{lp}$$

where δC_{lp} and δS_{lp} are deviations in cm of the 18.6-year tide from equilibrium values.

The solution for $\dot{J}_3$ and $\dot{J}_4$ has also been obtained by analyzing three-year Starlette arcs. However, the uncertainties in this solution are questioned by more recent analysis of Starlette SLR data over the time span of 5 to 16 years. The sensitivity analysis indicates that the reported solutions of $\dot{J}_2$, $\dot{J}_3$ and $\dot{J}_4$ from analysis of Lageos or Starlette SLR data contain contributions from high degree zonal variations and the 18.6-year long-period tide. Furthermore, in addition to the contribution of the post-glacial rebound to the change in the Earth zonal harmonics, both present-day glacial discharges and the ice buildup on the Antarctic ice sheet can cause perceptible perturbations. The time series for the variation in the Earth's low degree zonal harmonics caused by atmospheric mass redistribution during the period from 1980 to 1989 displays a strong secular trend. Clearly, improvement in the solution for $\dot{J}_2$ to $\dot{J}_6$ must be obtained by analyzing a multi-satellite data set and to achieve this analysis an improved knowledge in the 18.6-year long-period ocean tide must be obtained.

THE LUNAR TIDAL DECELERATION

Tidal deceleration of the Moon's mean motion, $\dot{n}$, from the most recent satellite-determined ocean tide solutions, were compared. The averaged value is -25.2 ± 0.4 arcseconds/century^2. This value is in good agreement with the value obtained from analysis of 20 years of lunar laser ranging observations. The comparison of the lunar decelerations inferred from the oceanographic tide solution [*Schwiderski* model] with the values from satellite observation and LLR data is less satisfactory [*Cheng et al.*, 1992].

PUBLICATIONS AND CONFERENCES

The following is a list of publications and conference presentations pertinent to research activities supported partially by NASA Grant NAG5-757:

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