ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
СОФИЯ

Том Volume 51 2018 Брой Issue 9

ANNUAL OF THE UNIVERSITY OF ARCHITECTURE, CIVIL ENGINEERING AND GEODESY
SOFIA

Получена: 22.12.2017 г.
Приета: 28.05.2018 г.

RADIATION PRESSURE, ALONG-TRACK ACCELERATION AND GRAVITY VARIATIONS FROM LAGEOS 1 AND LAGEOS 2 SLR DATA PROCESSING FOR THE PERIOD 1984.3 – 2012.0

Y. Chapanov[1], I. Georgiev[2]

Keywords: *SLR, gravity coefficients, time series analysis, solar activity*

ABSTRACT

The laser ranging data of geodynamic satellites Lageos 1 from the period April 1984 – December 2011 and Lageos 2 from the period January 1993 – December 2011 are processed and analyzed by program SLRP (Satellite Laser Ranging Processor), version 4.2, developed in the National Institute of Geophysics, Geodesy and Geography (NIGGG). The estimated unknowns are 46180, and 740 of them are global parameters. They are coordinates of 113 stations; velocities of 98 of them; Love and Shida numbers; geogravity constant GM, selected set of gravity coefficients and part of oceanic tides. The other parameters are monthly estimates for the state vector of the satellite motion, range biases and the clock correction of tracking stations. The coefficients of the solar radiation pressure and the along-track acceleration are estimated per each half month. The polar motion coordinates and Universal Time are estimated daily. Some of the important time series of radiation pressure, along-track acceleration, zonal gravity coefficients and geogravity constant are presented. The time variations of these parameters are determined by harmonic analysis, based on the Partial Fourier Approximation. Some of these variations with periods below 10 years have good agreement with the corresponding cycles of solar indices.

[1] Yavor Chapanov, Prof., DSc, NIGGG, BAS, Sofia 1113, Acad. G. Bonchev St., Bl. 3,
e-mail: yavor.chapanov@gmail.com
[2] Ivan Georgiev, Prof., DSc, NIGGG, BAS, Sofia 1113, Acad. G. Bonchev St., Bl. 3,
e-mail: ivan@bas.bg

1. Introduction

The SLRP orbital dynamic and estimation software developed in the Bulgarian Academy of Sciences [1 ÷ 3] gives great opportunities to investigate the shape, size and dynamics of the Earth and its interaction with the atmosphere and oceans. The Satellite Laser Ranging (SLR) is the most accurate present-day space technique for determination of the absolute geocentric coordinates of the tracking sites and their motion with respect to the geocenter; determination of the Earth's gravity time variations; absolute vertical motions monitoring, which in turn gives an opportunity to estimate long period climate changes – post-glacial rebound. The observatories equipped with laser ranging systems are an integral part of the international set of observation sites including VLBI (Very Long Baseline Interferometry), GPS (Global Positioning System), GLONASS (Global Navigation Satellite System), and DORIS (Doppler Orbit determination and Radio positioning Integrated on Satellite).

2. SLR Data and Estimated Parameters

The present global solution is obtained by analyzing the data of satellite Lageos 1 laser ranging covering the period April 1984 – December 2000, and Lageos 2 satellite for the period January 1993 – December 2011. The observations acquired before 1984 (Lageos 1) are not included in the processing because of their low quality, sparseness and presence of periods with no observations at all. The total number of observations used is 2292315, 2265568 of them are three-minute normal points, and 29 747 are single shots.

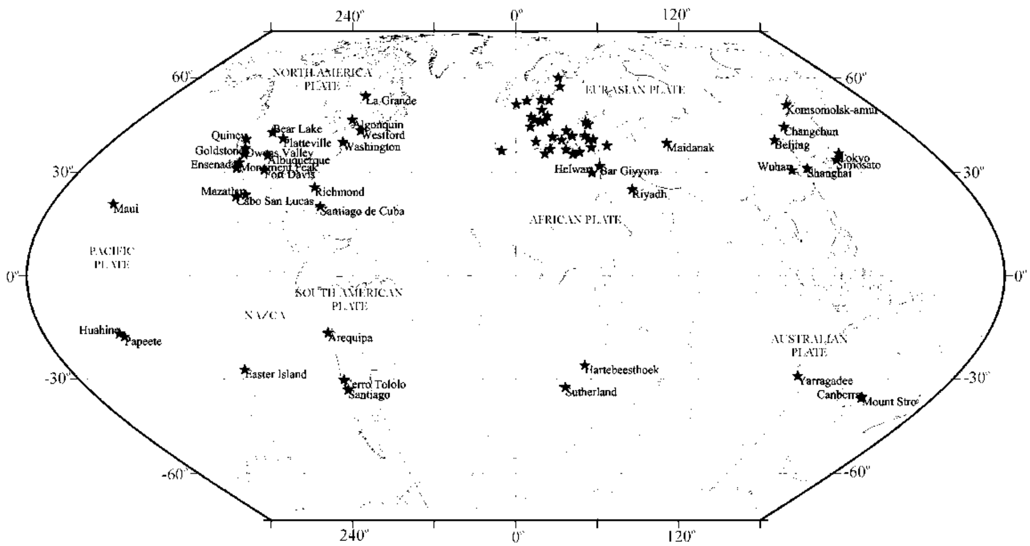

Figure 1. The set of SLR tracking stations

Since 1993 the monthly normal point number varies between 5 and 14 thousands. The observations are made from 94 laser sites with global coverage: 48 of them lie on the Eurasian plate, 22 – on the North American plate, 5 – on the South American plate, 6 – on the African plate, 4 – on the Australian plate, 7 – on the Pacific plate, 1 – on the Nazca plate and 1 on the Anatolian plate (Fig. 1). The permanent stations are 37 and the mobile – 57.

The 740 global parameters are coordinates of 109 stations; velocities of 61 stations; Love and Shida numbers; geogravitation constant GM, 3 coefficients for the zonal harmonics C_{20}, C_{30}, C_{40} and 14 coefficients – from C_{21}, S_{21} to C_{42}, S_{42}, for the tesseral and sectoral harmonics of the Earth's gravitation field; the coefficients of the oceanic tides referring to the diurnal waves Q1, O1, P1, K1, the semi-diurnal waves N2, M2, S2, K2 and the long-period waves SSa, MM, MF.

The monthly parameters are determined using the global solution. The estimates of the monthly parameters are as follows: for each satellite – six parameters for the initial conditions of movement, two parameters for each of the solar radiation pressure coefficients and the empirical force per each half month. The monthly parameters related with the tracking stations are the range biases and the clock correction, these unknowns being fixed for the station 7939. The rest of the eliminated at the second step unknowns are the pole coordinates x_p, y_p and the difference UT1-UTC for every day. The indefinite satellite RA node is solved by fixing UT1-UTC to a priori value for one of the last days of the respective month with more than 100 observations.

The total number of the unknown parameters during the data processing for the satellites Lageos 1 in the period 1984 – 2011 and Lageos 2 in the period 1993 – 2011 is 46180, 740 of them being global parameters.

3. Time Series Solution

The RMS of the global solution is 7.9 cm. When forming the monthly matrices, 182110 of the observations are rejected, which is 8% of all observations. Solving the monthly normal matrices we have "monthly" estimates for the parameters, the so-called monthly solutions, and estimates for the orbital fit. The monthly orbital fit is an illustration about the observations quality in time and the adequacy of the dynamical and geometrical models used. Fig. 2 shows the monthly number of observations and monthly orbital fit to the satellite orbits for the period 1984.3 – 2012.0. The monthly number of Lageos 1 observations before 1993 is between 2000 and 9000 with a mean value of about 5000.

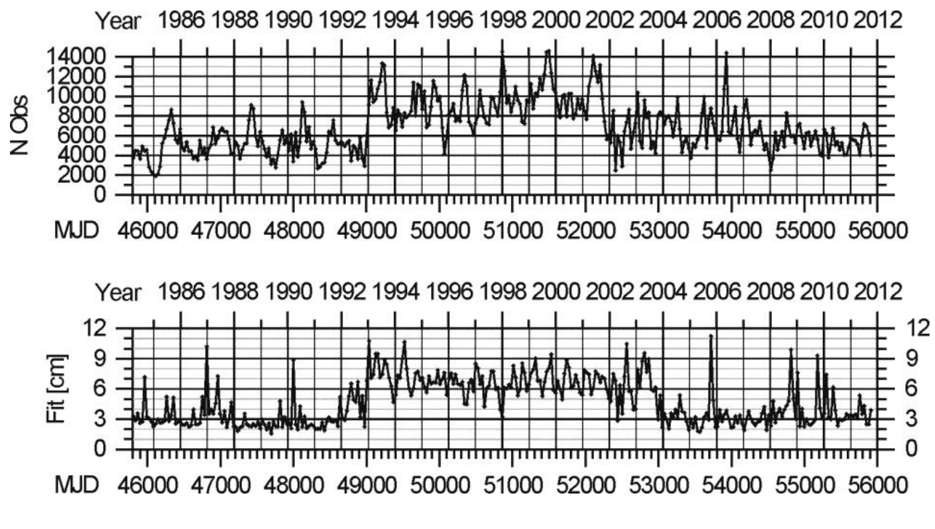

Figure 2. Monthly number of observations (N_{obs}) and orbital fit to the satellite orbits

After the launch of the second Lageos in 1993 till 2002, the number of observations increases above 6000, the RMS fit to the satellite orbit grows up with more than 3 cm, due to more adequate parameter estimation by observations from 2 satellites. After 2002 the number of Lageos observations dramatically reduces due to new strategic concepts of NASA about space research. Formally, this leads to significant improve of the accuracy level, and some problems of the solution stability.

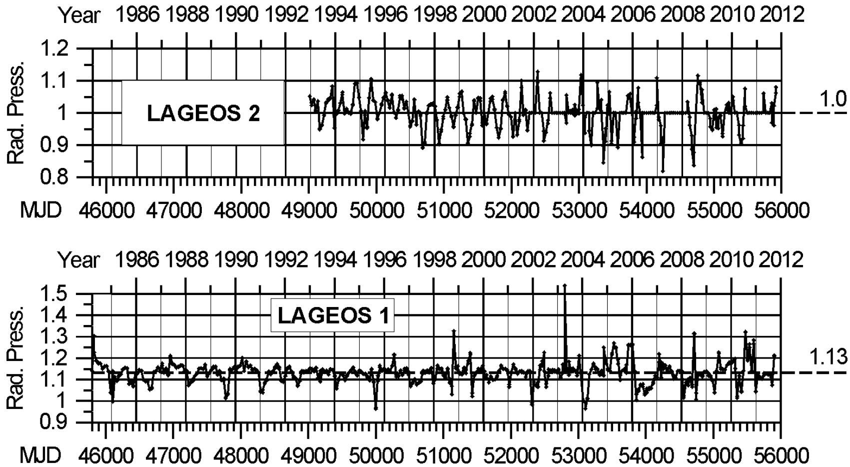

Figure 3. Lageos 1 and Lageos 2 coefficients of radiation pressure

The time series of the coefficients of radiation pressure (Fig. 3) have small deviations of about ±0.1 around its mean values. The mean radiation pressure coefficients are 1.13 for Lageos 1 and 1.0 for Lageos 2. This coefficient has more constant behavior in the case of Lageos 1 and some subdecadal modulation of the maximal deviations in the case of Lageos 2.

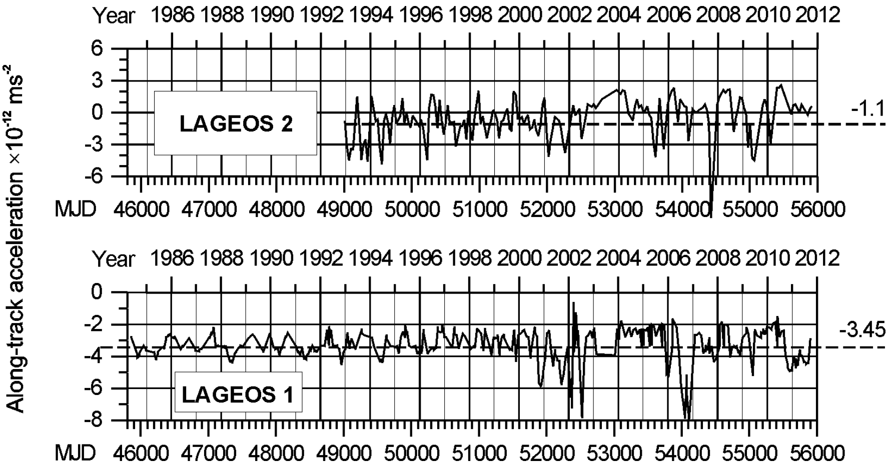

Figure 4. Lageos 1 and Lageos 2 coefficients of along-track acceleration

The LAGEOS I satellite experiences an along-track acceleration with average value – 3.34×10^{-12} ms^{-2} [4]. The primary cause of this orbital decay appears to be Yarkovsky thermal drag, which accounts for approximately 70% of the observed average drag. The rest is about equally split between neutral and charged particle drag[2] [4]. The time series from SLRP solution of along-track acceleration are rather different for Lageos 1 and Lageos 2 (Fig. 4). These coefficients have different mean values -3.45×10^{-12} ms^{-2} for Lageos 1 and -1.1×10^{-12} ms^{-2} for Lageos 2, and different systems of short term variations. Our solution exposes excellent agreement with the Rubincam's result for Lageos 1 satellite [4]. The differences of the along track acceleration coefficients are due to different individual rotation of the satellites around its centre of mass and different inclination of their orbits, too.

The periodical and secular variations of the coefficients J_2 and J_4 of the even zonal harmonics of the Earth gravitational potential are presented in Fig. 5. The time series of the combination $J_2 + 0.037\ J_4$ is estimated, because their combination significantly improves the stability of the global solution. It is possible to determine the secular changes of the earth gravity potential by estimation of the linear drift of time series of even coefficients $J_2 + 0.037J_4$ (Fig. 4), and coefficient J_3 (Fig. 5). The rate of the obtained drift of the combination $J_2 + 0.037\ J_4$ is $-1.2 \times 10^{-12}a^{-1}$ for the period 1984 – 1999; $+0.7 \times 10^{-11}a^{-1}$ for the period 1999 – 2006; and $-0.5 \times 10^{-11}a^{-1}$ for the period 2006 – 2012. The reverse of J_2 the linear drift in 1998 – 1999 is the so called "1998 anomaly" [5 ÷ 8].

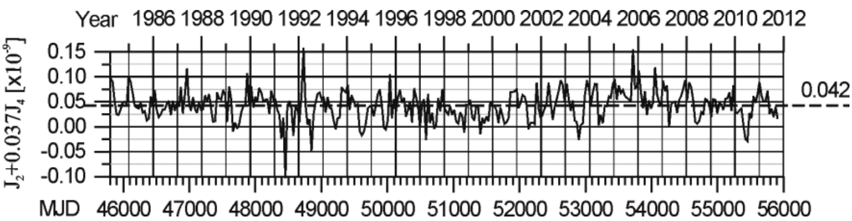

Figure 5. Variations of monthly corrections of geogravity coefficients $J_2 + 0.037J_4$

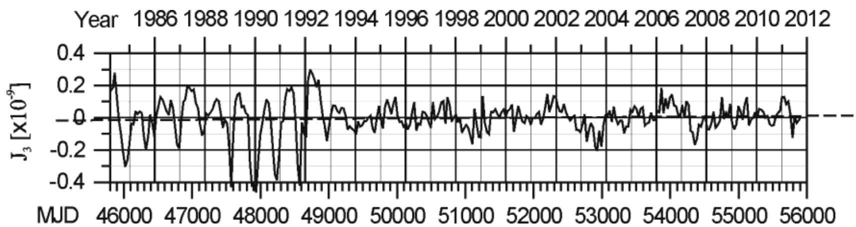

Figure 6. Variations of monthly corrections of geogravity coefficient J_3

The secular rate of J_3 coefficient is $+0.9 \times 10^{-12}a^{-1}$ for the whole period and $+0.8 \times 10^{-12}a^{-1}$ after 1993 (Fig. 6). The SLR tracking to Lageos satellites provided the most accurate determination of the Earth's gravitational coefficient (GM) [9]. The accurate determination of the GM parameter is vital for the definition of the absolute scale of the geocentric reference frame. GM is currently known to 2 ppb (parts per billion) which correspond to about 1 cm in scale uncertainty for tracking stations [9]. Our global estimate for the GM parameter is very close to its a priori value equal to 398600.44 km^3s^{-2} and has rms of the same magnitude – 1 ppb. The mean change of the monthly corrections of GM is shown in Fig. 7. The secular drift of the GM time series is presented by the linear trend of the data, whose inclination is equal to -3.0×10^{-6} $(km^3s^{-2})a^{-1}$. According this trend, we may calculate the relative secular decrease of the gravity constant $(dG/dt)/G = -7.6 \times 10^{-12}\ a^{-1}$, which agrees with some theoretically values within the interval $4 \cdot 10^{-13} \div 2 \cdot 10^{-11} a^{-1}$ [10]. These results are similar to the estimated values in [11] by means of Lageos 1 and 2 observations prior to the end of 2000.

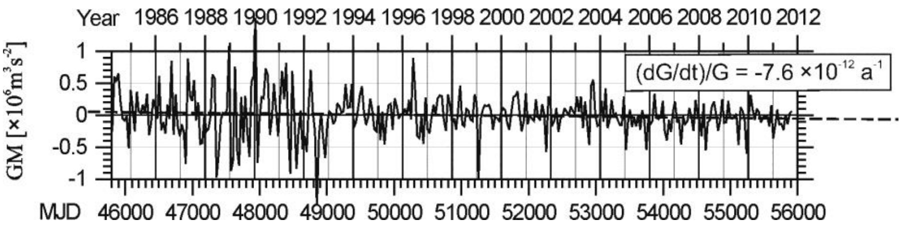

Figure 7. Variations of monthly corrections of geogravity coefficient GM

4. FFT Spectra

The amplitude spectra of radiation pressure and along-track acceleration of satellite Lageos 1 and Lageos 2, gravity coefficients J_2+0.037 J_4, J_3 and GM are calculated by the Fast Fourier Transform FFT (Fig. 8). The spectra of gravity coefficients expose significant annual oscillations. The J3 variations are dominating by two significant oscillations with periods 2.5 and 4.5 years. The coefficient J_2+0.037 J_4 has several minor peaks with periods below 6 years. The geogravity coefficient GM has a significant peak with a period between 3 and 4 years. Any GM oscillations should be interpreted as systematic, because the gravity constant G is supposed to have very small secular variations and no periodical oscillations.

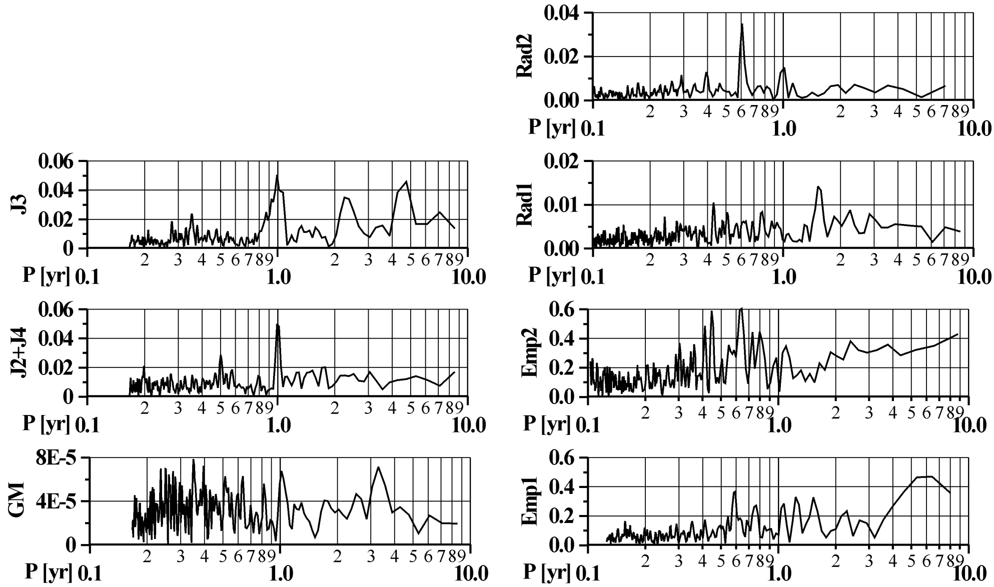

Figure 8. Amplitude spectra of monthly values of rradiation pressure of satellite Lageos 1 and Lageos 2 (Rad1 and Rad2), along-track acceleration (Emp1 and Emp2) and gravity coefficients (J_2+0.037 J_4, J_3 and GM)

The Earth mass M is variable due to incoming meteorites and outgoing atmosphere ions, but these variations are very small and it is not possible to be estimated by the SLR technique. The Lageos 2 time series are relatively short and their spectra have significant noise with periods below 1 year. The radiation pressure of Lageos 1 has significant peaks with periods 1 – 3 years, while the coefficient of radiation pressure is dominating by periodicity between 5 and 7 years.

5. Influence of Solar Harmonics

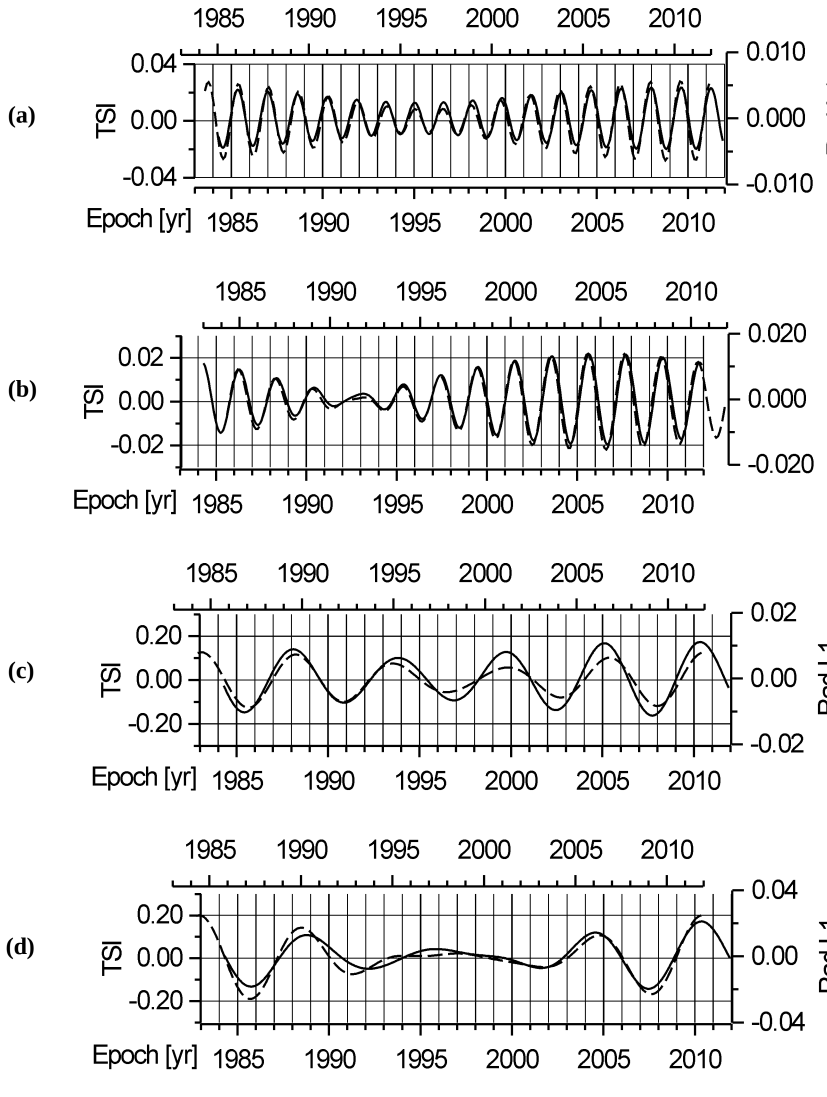

Figure 9. Influence of TSI (in [W/m^2], dashed lines) on radiation pressure coefficient of Lageos 1 (solid lines) with periods 1.6-1.7yr (a); 1.9-2.1yr (b); 4.6-5.5yr (c); and 4.6-6.9yr (d)

The solar influence on satellite radiation pressure, along-track acceleration and gravity variations is determined by the method generally described in [12]. The solar activity affects terrestrial systems by means of direct radiation, charged particles of the solar wind, and the solar magnetic field. The solar wind directly affects Earth magnetic field, ionosphere and atmosphere. The variations of solar magnetic field modulate solar wind and cosmic rays in the frame of the solar system. The cosmic rays near Earth are modulated by Earth magnetic field variations, too. The solar activity variations are presented by several numerical indices. The most popular of them are indices of sunspots, Wolf's numbers and Total Solar Irradiance TSI. The Wolf's numbers represent the variations of solar wind and TSI. It is possible to calculate a new index of North-South (N-S) solar asymmetry, based on sunspot numbers S_n and S_s over the North and South solar hemisphere by the expression $S_a=(S_n-S_s)/(S_s+S_n)$. The N-S solar asymmetry represents variations of the solar magnetic field. The time series of TSI, Wolf's numbers and N-S solar asymmetry have different spectra, so their influences on terrestrial cycles may vary in frequency, amplitude and phase.

(a)

(b)

(c)

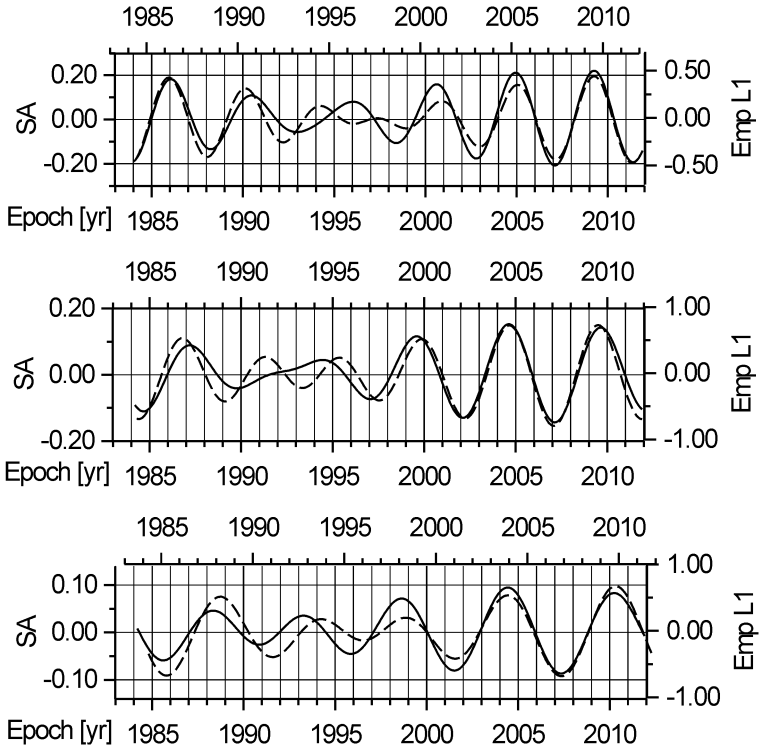

Figure 10. Influence of N-S solar asymmetry (dashed lines) on empirical acceleration of Lageos 1 (solid lines) with periods 3.9-4.5yr (a); 4.6-5.5yr (b); and 5.5-6.8yr (c)

The variations from a given band are determined by superposition of two neighbor harmonics of the Partial Fourier Approximation, described in [12]. The resulting time series are given in Fig. 9 ÷ Fig. 13. It is remarkable that the TSI harmonics affect radiation pressure coefficient (Fig. 9) by the direct influence of the solar light, while the coefficient of empirical force is affected by the changes of solar magnetic field, represented by N-S solar asymmetry harmonics (Fig. 10). The harmonics of solar magnetic field affect the variations of gravity coefficients $J_2+0.037\,J_4$, too (Fig. 11). The J_3 variations have a good agreement with the harmonics of the Wolf's numbers and TSI (Fig. 12). The most powerful 3-year oscillation of geogravity coefficient GM is connected with the corresponding harmonics of N-S solar asymmetry. The origin of these oscillations is probably some unmodeled perturbations of Earth-satellite system, connected with the solar magnetic field, cosmic rays and corresponding atmosphere and surface changes.

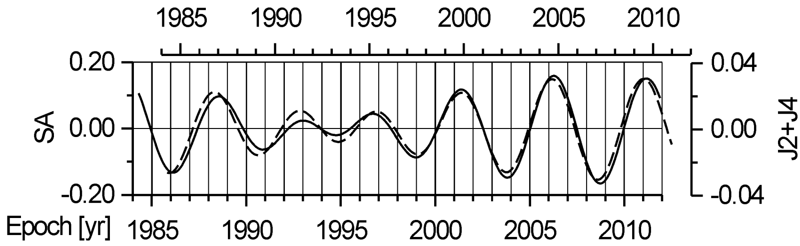

Figure 11. Influence of N-S solar asymmetry (dashed lines) on variations of coefficients J_2+0.037 J_4 (solid lines) with periods between 4.6yr and 5.5yr

(a)

(b)

(c)

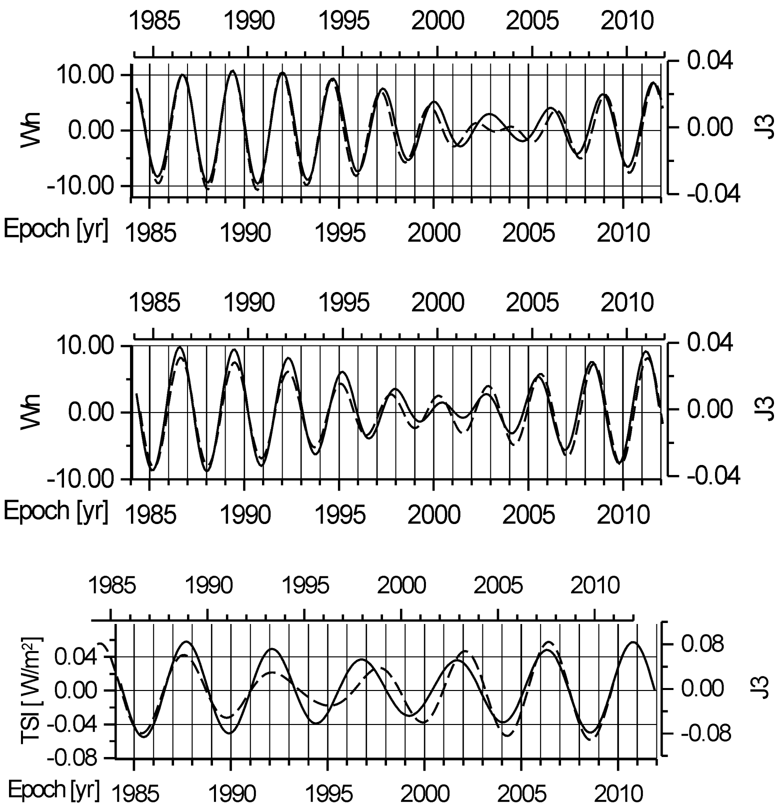

Figure 12. Influence of W_n (dashed lines) on variations of coefficient J_3 (solid line) with periods 2.5yr - 2.8yr (a) and 2.8yr – 3.0yr (b). Influence of TSI (dashed lines) on J_3 variations (solid line) with periods 3.9yr - 4.5yr (c)

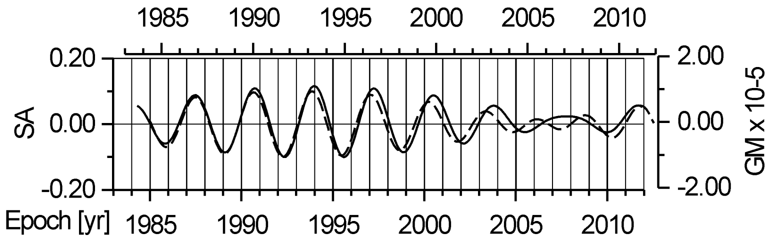

Figure 13. Systematic effect of N-S solar asymmetry (dashed lines) on variations of coefficient GM (solid lines) with periods 3.0yr – 3.4yr

6. Conclusions

The processing of Lageos 1 and Lageos 2 laser ranging data by the program SLRP version 4.2 yields 27-year time series of various global and local geodynamical parameters and improves the values of some important geogravity coefficients. These parameters are necessary to investigate dynamics of the Earth.

The secular changes of the earth gravity potential coefficients are estimated by the linear drift of the combination of even coefficients $J_2 + 0.037J_4$, and of the change of the coefficient J_3. The rates of the combination $J_2 + 0.037\ J_4$ are: $-1.2 \times 10^{-12}a^{-1}$ for the period 1984 – 1999; $+0.7 \times 10^{-11}a^{-1}$ for the period 1999 – 2006; and $-0.5 \times 10^{-11}a^{-1}$ for the period 2006 – 2012.

The secular drift of the coefficient J_3 determined by the observations of Lageos 1 and Lageos 2 satellites is $+0.9 \times 10^{-12}a^{-1}$ for the whole period and $+0.8 \times 10^{-12}a^{-1}$ after 1993.

The rate of the secular change of the product GM between the gravity constant G and the Earth's mass M is -3.0×10^{-6} $(km^3s^{-2})a^{-1}$. According to this trend, the relative secular decrease of the gravity constant (dG/dt)/G is $-\ 7.6 \times 10^{-12}\ a^{-1}$, which is below the upper theoretical boundary of the secular drift of the gravity constant G.

The large time span of the satellite laser ranging since 1983 allows to obtain long time series. They give us opportunity to provide analysis and comparisons with the time series of solar activity.

The shapes of solar cycles are rather different from sinusoidal form, and this is the reason to generate a lot of subdecadal and decadal harmonics. The Total Solar Irradiance (TSI), Wolf's Numbers (Wn) and North-South (N-S) solar asymmetry expose different spectral peaks, amplitude modulation and phases from these bands. These solar time series represent thermal heating over the Earth, solar wind (space weather) and solar magnetic field variations. The subdecadal cycles of N-S solar asymmetry strongly affect corresponding cycles of the empirical force and combination of gravity coefficients $J_2 + 0.037J_4$. These cycles also produce some systematic variations of the time series of gravity coefficient GM. The subdecadal oscillations of radiation pressure coefficient are affected by the Total Solar Irradiance TSI. The subdecadal variations of gravity coefficient J_3 are connected with the Wolf's numbers and TSI. Some common oscillations of satellite coefficients and solar indices have small time lag below 1.5yr.

REFERENCES

1. *Chapanov, Y., Georgiev, I.* Data Structure in the Processing of Satellite Laser Ranging by the Program SLRP 4.1, Proc. Int. Symp. “Space Information-Technologies, Acquisition, Processing and Effective Application”, 7-8 Nov. 2002, Sofia, 2002, 240-247.

2. *Georgiev, I., Y. Chapanov*. Analysis of Laser Ranging Data to the Geodynamic Satellites Lageos 1 and Lageos 2 for the Period 1984 – 2000, BGJ, 28, 2002, 43-57.

3. *Georgiev, I., S. Shanov, J. Chapanov*. A Contribution in the Estimation of Tectonic Plate Motion from the CLG99 SLR Solution, Geologica Balcanica, 30, 3-4, 2001, 89-100.

4. *Rubincam, D. P.* The LAGEOS Along-Track Acceleration: a review, in Relativistic Gravitational Experiments in Space, edited by M. Demianski and C. W. F. Everitt, World Sci., River Edge, N. J. pp 195-210, 1993.

5. *Chao, B. F., A. Y. Au, J.-P. Boy, and C. M. Cox*. Time-Variable Gravity Signal of an Anomalous Redistribution of Water Mass in the Extra-Tropic Pacific During 1998–2002, Geochem. Geophys. Geosyst., 4 (11), 1096, 2003, doi:10.1029/2003GC000589.

6. *Cheng, M., and B. D. Tapley*. Variations in the Earth ’s Oblateness During the Past 28 Years, J. Geophys. Res., 109, B09402, 2004, doi:10.1029/2004JB003028.

7. *Cox, C., B. F. Chao*. Detection of Large-Scale Mass Redistribution in the Terrestrial System Since 1998, Science, 297, 2002, pp 831.

8. *Dickey, J. O., et al.* Recent Earth Oblateness Variations: Unraveling Climate and Postglacial Rebound Effects, Science, 298, 1975–1977, 2002, doi:10.1126/science.1077777.

9. *Beutler, G., R. Eanes, J. Engeln, T. Herring, W. Melbourne, M. Pearlman, J. Rundle, I. Shapiro, J. Wahr, C. Wunsch*, SLR Review Committee Report (1997). Prepared by the SLR Review Committee, April 1997, http://ilrs.gsfc.nasa.gov/slrreport.html.

10. *Weinberg, S.* Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity, John Wiley and Sons, New York, 1972, 659–674.

11. *Chapanov, Y., I. Georgiev*. Secular Drifts of the Low Degree Zonal Coefficients Obtained from Satellite Laser Ranging to the Geodynamic Satellites Lageos 1 and Lageos 2, BGJ, 28, 2002, 58-68.

12. *Chapanov Y., Ron C., Vondrák J.*: Decadal Cycles of Earth Rotation, Mean Sea Level and Climate, Excited by Solar Activity. Acta Geodyn.Geomater., 14, No. 2 (186), 241–250, 2017. DOI: 10.13168/AGG.2017.0007.