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ORIGINAL PAPER

THE EVALUATION OF TIME VARIABILITY OF TIDAL PARAMETERS *h* AND *l* USING SLR TECHNIQUE

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ABSTRACT

The estimated parameters h_2 and l_2 (Love and Shida numbers for second degree tides) are based on the analysis of the SLR data from the period 2013.1-2015.1. The solution has been computed using the LAGEOS-1 and LAGEOS-2 data. The analysis was conducted in two cases: separately and jointly for the two satellites. The results were compared with our previous work to see if there are some systematic differences and time evolution of the Love and Shida numbers. As the final adjusted values of the Love and Shida numbers were adopted parameters estimated for the common analysis based on data for LAGEOS-1 and LAGEOS-2. The new values of these parameters are equal to: $h_2 = 0.6140 \pm 0.0005$ and $l_2 = 0.0876 \pm 0.0002$.

1. INTRODUCTION

Gravitational effect of the Moon and the Sun on the Earth surface generates Earth tides which cause variations in mass distribution of the Earth. The Love *h* and Shida *l* numbers describe the Earth's response to external forces exerted by celestial bodies due to the elasticity of the Earth. The Love and Shida numbers formalism, originally developed to describe the response of a static spherical Earth to perturbing potentials of given spherical harmonic degree and order (*nm*), expresses the radial and transverse tidal displacements of the crust in terms of the Love h_n and Shida l_n numbers (Mathews et al., 1997). The parameters *h*, *l* need to be used only for degree 2 tides since the effect of latitude dependence on the already small displacements due to degrees 3 tides or higher degree are negligible (Mathews et al., 1997; Gubanov and Kurdubov, 2012). The values of the Love and Shida numbers for semidiurnal tides are chosen to be nominal for all degree-2 tides, and their values are: $h_2 = 0.6078$ and $l_2 = 0.0847$ (Petit and Luzum, 2010). For more information about the theoretical basis of the Love and Shida numbers the reader is referred to e.g. Hass and Schuh (1996), Rutkowska and Jagoda (2010a, 2010b), Krásná et al. (2013).

The first estimates of Love *h* and Shida *l* numbers from Satellite Laser Ranging (SLR) measurements were provided by Christodoulidis et al. (1985) and Wu et al. (2001), followed by Rutkowska and Jagoda (2010a, 2010b, 2012, 2015) and Jagoda and Rutkowska (2013). Determination of Love/Shida numbers using Global Positioning System (GPS) was carried out e.g. by Yuan and Chao (2012) and recent estimations from Very Long Baseline Interferometry (VLBI) were published e.g. by Petrov (2000), Gubanov and Kurdubov (2012) and Krásná et al. (2013).

Our recent studies (Rutkowska and Jagoda, 2010a, 2012) showed that SLR data can be used to estimate second degree Love and Shida numbers with high precision. In this analysis we used new SLR data to estimate tidal parameters h_2, l_2. The motivation for our paper was to compare the latest and previous results to see stability of estimated solutions if not to show some systematic differences and time evolution.

2. SLR ANALYSIS

2.1. METHODOLOGY

Satellite Laser Ranging (SLR) is a space geodetic technique used to determine various geodetic and geophysical parameters (Tapley et al., 1993), recently e.g. the station coordinates (Lejba and Schillak, 2011), Earth orientation parameters (Sośnica et al., 2014) and to study the Earth's gravity field and the ocean tide models (Sośnica et al., 2012; Sośnica, 2014).

The aim of the Satellite Laser Ranging is to measure the distance between the SLR station and the centre of the mass of the satellite equipped with retroreflectors. The Satellite Laser Ranging technique is based on measuring two way time of flight of light pulses between station and satellite with 1 picosecond granularity. The distance measured to the satellite must be corrected for the effects of the decrease in the speed of light and the difference between the curved and straight ray paths; moreover,

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Table 1 Force model used in the solution.

Type of model	Description
Gravity field model	EGM2008 up to degree and order 30 (Pavlis et al., 2012)
Tidal forces	Solid Earth tide model, Earth pole tidal model and Ocean pole tide model applied - IERS Conventions 2010 (Petit and Luzum, 2010), Atmospheric tidal loading (Ray and Ponte, 2003), Ocean tides - FES2004 (Lyard et al., 2006)
Satellite center of mass correction	25.1 cm, derived by ILRS (Pearlman et al., 2002)
Subdaily pole model	IERS2000 (Kołaczek et al., 2000)
Troposphere delay	Mendes-Pavlis (Mendes and Pavlis, 2004)
Third-body	Earth's, Moon, Sun, Venus, Mars, Jupiter, ephemeris JPL DE405 (Folkner et al., 1994)
Reference frame	ITRF2008 (Altamimi et al., 2011)
Nutation model	IAU2000 (Petit and Luzum, 2010)
Solar radiation pressure	$C_R = 1.13$
Earth orientation parameters	C04 series from IERS, consistent with ITRF2008 (Bizouard and Gambis, 2014)
Relativity	Light time propagation correction and Schwarzschild orbit perturbation according to IERS Conventions 2010 (Petit and Luzum, 2010)

it must take into account the distance from the retroreflector to the mass centre of the satellite (Schillak, 2004), impact of satellite motion, Earth rotation and relativistic effects. In order to tie up the measured distance to the reference point at the station the calibration measurements are performed (measurements to a ground target placed at the accurately known basal distance to the station reference point). The difference between the distance measured in the calibration and the basal distance is the calibration correction (Schillak, 2004). The laser observation equation for the *i*-th laser measurement of a distance to the satellite mass centre is:

$$\frac{(\Delta t_i - \Delta c)C}{2} + \Delta a_i + \Delta m_c + \Delta r_{rc} + \\ + \Delta s_p + \Delta e_r - \Delta r_{bi} - \varepsilon_i - r_{c,i} = 0 ,$$

where: Δt_i is the two way time interval of flight of light pulses between station and satellite for the *i*-th measurement, Δc is calibration correction, C is the speed of light, Δa_i and Δm_c are tropospheric delay for the *i*-th measurement (due to the twice passage of the light pulse through the atmosphere) and correction for the centre of the satellite mass (25.1 cm for LAGEOS satellites) respectively, Δr_{bi} is the range bias of the observation, Δr_{rc} is the relativistic range correction, Δs_p and Δe_r are impact of satellite motion and Earth rotation respectively, ε_i is random error for the *i*-th measurement and $r_{c,i}$ is distance calculated for the *i*-th measurement.

Currently, the international SLR working network consists of about 40 stations. Only a limited number of stations attain highest quality of observations. Based on accuracy and number of measurements, we selected 17 stations (no.: 7080, 7090, 7838, 7839, 7105, 7110, 7501, 7840, 7237, 7941, 8834, 1893, 7406, 1868, 7821, 7841, 7825) with coordinates of the highest quality on the 1-2 mm level for each Cartesian component in ITRF2008 (Altamimi et al., 2011). Additionally, considering the geometry of the solution, we tried to select the stations in such a way that they would be evenly located on the globe. In general, localization of laser stations is not uniform; there are remarkably fewer in the southern hemisphere, which affects the solution's geometry. The stations 7090, 7501 and 7825 are situated in the southern hemisphere, hence they significantly improve the solution's geometry. For similar reasons the stations 1893, 7821 and 7838 were included. The first one is the farthest east European station, the next two ones are located in Asia where the number of stations is quite smaller than in Europe. These stations improve the network's configuration uniformity.

We used the GEODYN II NASA/Goddard Space Flight Center software written by Washington Analytical Center (McCarthy et al., 1993) to analyze LAGEOS-1 and LAGEOS-2 observations from 2013.1 to 2015.1. Measurements were divided into 1 month orbital arcs. The interval of two observation years is sufficient for determining of tidal parameters, as proved before in Rutkowska and Jagoda (2010b, 2012). The software package GEODYN follows the currently recommended model of forces according to the IERS Conventions 2010 (Petit and Luzum, 2010). The applied models of forces are presented in Table 1.

Our earlier papers on determination of the Love/Shida numbers from the laser measurements presented the method of orbit computation using GEODYN II software and method of determination h_2 and l_2 parameters (Rutkowska and Jagoda, 2010a, 2010b; Jagoda and Rutkowska, 2016). Therefore they are omitted in this paper.

2.2. LOVE AND SHIDA NUMBERS SOLUTION FOR THE SECOND DEGREE TIDES

The Love/Shida numbers for the second degree tides (h_2 and l_2) were determined on the basis of the laser observations of LAGEOS-1 and LAGEOS-2 satellites obtained from Crustal Dynamics Data Information System (CDDIS) in the form of two-minute normal points. The fixed stations with coordinates in ITRF2008 were used for orbital arcs determination for both LAGEOS satellites. A 24-month period of observations of LAGEOS-1 and LAGEOS-2 satellites was divided into 24 1-month arcs with half day overlaps between the successive arcs. RMS-of-fit residuals of all the 24 month arcs equal to 14 mm on average.

The cycle of the Love/Shida numbers determination was carried out in two steps: at first, the observations burdened with significant errors were eliminated. This procedure ensures that all good results are taken into account even at a large range bias of the station (Kuźmicz-Cieślak et. al., 2000). At the second step, the Love/Shida numbers were calculated from the refined data, estimated the satellite state vector, as well as 5 parameters of empirical accelerations with 7-day interval.

The sequential method was adopted for Love/Shida numbers estimation. In the first phase, h_2 and l_2 parameters were adjusted for two orbital arcs. In subsequent steps, arcs 3 and the next were included one after the other. At each step, the parameters were adjusted once again (see Tables 2 and 3). As the final adjusted values of the Love/Shida numbers were adopted parameters estimated for the 24 orbital arcs. The h_2 and l_2 parameters were determined in common solution.

At first, to verify the correctness of the obtained results parameters h_2, l_2 were determined separately from observations of satellites LAGEOS-1 and LAGEOS-2. The estimated values for the degree two Love and Shida numbers are very similar to LAGEOS-1 and LAGEOS-2, and their values are 0.6144 ± 0.0007 and 0.0881 ± 0.0004 for LAGEOS-1 and 0.6148 ± 0.0007 and 0.0879 ± 0.0004 for LAGEOS-2, respectively. There is a visible convergence of results obtained for both satellites – the differences in values of the h_2 and l_2 are 0.0004 and 0.0002 respectively, which means they are not greater than the formal errors of the adjusted values h_2 and l_2 (±0.0007 and ±0.0004, respectively).

After confirming the convergence of the individual solutions, the subsequent step was to determine the combined values: LAGEOS-1 data + LAGEOS-2 data. As the final adjusted values of the Love and Shida numbers were adopted parameters estimated for 24 arcs in the common analysis based on data for LAGEOS-1 and LAGEOS-2. The results of this analysis are shown in Figures 1 and 2 for h_2 and l_2 and listed in Tables 2 and 3, respectively.

Table 2 Values of h_2 parameter obtained from the SLR data of LAGEOS-1 and LAGEOS-2.

Number of arcs	**h_2 value** LAGEOS-1 + + LAGEOS-2 2013.1-2015.1 SLR data	**h_2 value** LAGEOS-1 + +LAGEOS-2 2005.1-2007.1 SLR data (Rutkowska and Jagoda, 2010b)
arc 1-2	0.6128 ± 0.0030	0.6113 ± 0.0038
arc 1-3	0.6190 ± 0.0025	0.6182 ± 0.0030
arc 1-4	0.6200 ± 0.0021	0.6175 ± 0.0025
arc 1-5	0.6170 ± 0.0019	0.6614 ± 0.0021
arc 1-6	0.6154 ± 0.0015	0.6006 ± 0.0016
arc 1-7	0.6163 ± 0.0014	0.5986 ± 0.0015
arc 1-8	0.6147 ± 0.0012	0.5987 ± 0.0013
arc 1-9	0.6140 ± 0.0011	0.6084 ± 0.0011
arc 1-10	0.6148 ± 0.0010	0.6048 ± 0.0010
arc 1-11	0.6159 ± 0.0009	0.6072 ± 0.0010
arc 1-12	0.6150 ± 0.0009	0.6076 ± 0.0009
arc 1-13	0.6148 ± 0.0008	0.6097 ± 0.0009
arc 1-14	0.6145 ± 0.0008	0.6120 ± 0.0008
arc 1-15	0.6140 ± 0.0007	0.6106 ± 0.0008
arc 1-16	0.6143 ± 0.0007	0.6107 ± 0.0008
arc 1-17	0.6147 ± 0.0007	0.6144 ± 0.0007
arc 1-18	0.6144 ± 0.0006	0.6152 ± 0.0007
arc 1-19	0.6148 ± 0.0006	0.6143 ± 0.0007
arc 1-20	0.6147 ± 0.0006	0.6135 ± 0.0006
arc 1-21	0.6144 ± 0.0006	0.6148 ± 0.0006
arc 1-22	0.6142 ± 0.0005	0.6139 ± 0.0006
arc 1-23	0.6140 ± 0.0005	0.6147 ± 0.0006
arc 1-24	**0.6140 ± 0.0005**	**0.6146 ± 0.0006**

Table 3 Values of l_2 parameter obtained from the SLR data of LAGEOS-1 and LAGEOS-2.

Number of arcs	**l_2 value** LAGEOS-1+ +LAGEOS-2 2013.1-2015.1 SLR data	**l_2 value** LAGEOS-1+ +LAGEOS-2 2005.1-2007.1 SLR data (Rutkowska and Jagoda, 2010b)
arc 1-2	0.0869 ± 0.0009	0.0706 ± 0.0011
arc 1-3	0.0831 ± 0.0009	0.0698 ± 0.0010
arc 1-4	0.0815 ± 0.0008	0.0722 ± 0.0008
arc 1-5	0.0826 ± 0.0006	0.0614 ± 0.0007
arc 1-6	0.0811 ± 0.0006	0.0760 ± 0.0006
arc 1-7	0.0824 ± 0.0005	0.0764 ± 0.0005
arc 1-8	0.0833 ± 0.0005	0.0823 ± 0.0005
arc 1-9	0.0844 ± 0.0004	0.0833 ± 0.0005
arc 1-10	0.0852 ± 0.0004	0.0843 ± 0.0004
arc 1-11	0.0860 ± 0.0004	0.0844 ± 0.0004
arc 1-12	0.0876 ± 0.0004	0.0862 ± 0.0004
arc 1-13	0.0880 ± 0.0003	0.0872 ± 0.0004
arc 1-14	0.0879 ± 0.0003	0.0873 ± 0.0003
arc 1-15	0.0875 ± 0.0003	0.0870 ± 0.0003
arc 1-16	0.0880 ± 0.0003	0.0871 ± 0.0003
arc 1-17	0.0883 ± 0.0003	0.0887 ± 0.0003
arc 1-18	0.0880 ± 0.0003	0.0889 ± 0.0003
arc 1-19	0.0878 ± 0.0002	0.0892 ± 0.0003
arc 1-20	0.0880 ± 0.0002	0.0888 ± 0.0003
arc 1-21	0.0879 ± 0.0002	0.0884 ± 0.0003
arc 1-22	0.0876 ± 0.0002	0.0885 ± 0.0003
arc 1-23	0.0876 ± 0.0002	0.0884 ± 0.0003
arc 1-24	**0.0876 ± 0.0002**	**0.0883 ± 0.0003**

The first column of each table contains the number of orbital arcs used to determination of the Love/Shida numbers. Columns 2 and 3 list obtained results of the Love and Shida numbers in our current and former (Rutkowska and Jagoda, 2010b) analysis.

The final adjusted values h_2 and l_2 given in Tables 2 and 3 amount to 0.6140 ± 0.0005 and 0.0876 ± 0.0002, respectively. The discrepancies between the h_2 and l_2 values obtained in Rutkowska and Jagoda (2010b) and this analysis are very small and amount to -0.0006 or 0.1 % for h_2 and -0.0007 or 0.8 % for l_2 also the formal errors of the adjusted values h_2 or l_2 are similar to our previous determination (Rutkowska and Jagoda, 2010b). Both in our previous and present work we have adopted the same strategy of data processing, we used observations of the same satellites from the time interval of the same length but we applied updated force models according to the recommendations given in IERS TN 36 (Petit and Luzum, 2010), e.g. gravity field model, tidal model, troposphere delay model. Some observatory stations included in the previous analysis (Rutkowska and Jagoda, 2010b) had ceased their activity which forced inclusion of other stations for this work to ensure a correct geometry of the solution (e.g. the stations number 7020, 7034 and 7052). Also, the coordinates of all stations have been provided in a more up-to-date ITRF2008 reference system. All of these may have had some influence on the values of h_2 and l_2 obtained as well as formal errors.

The adjusted parameters h_2, l_2 and formal errors of h_2, l_2 determination achieve stability at about 19 month time intervals (solution for 19 1-month orbital arcs), as observed in Figures 1 and 2. The nominal values from Petit and Luzum (2010) are represented in these figures as the solid black line, while Love and Shida numbers from our solution are shown in black diamonds. The black circles show the results of our former analysis (Rutkowska and Jagoda, 2010b). The discrepancies between estimated Love number h_2 and Shida number l_2 in our solution and nominal values given in Petit and Luzum (2010) are on the level of 1 % for h_2 and of 3 % for l_2.

The latest determination of h_2 and l_2 parameters is the one performed by Krásná et al. (2013) from VLBI data. In 2013 they obtained h_2 value equaling 0.6072 ± 0.0003 and l_2 value equaling 0.0843 ± 0.0000. The discrepancies between our and Krásná' s et al. (2013) solutions are amount to 0.0068 or 1 % for h_2 and 0.0033 or 4 % for l_2. The influence of used the different kind of data, a priori models and localization of stations as well as regional properties of the Earth's crust in the observation site in our and Krásná's et al. (2013) solutions on the estimation of h_2 and l_2 may constitute the source of the discrepancies. It is needed to mention that, the SLR network is not uniformly distributed. A greater share of the best stations which observe with high accuracy is located in Europe and the US, with only a few ones located in the southern hemisphere of the Earth. The network of VLBI stations is more uniformly distributed. Love and Shida numbers are truly global parameters and as such their solutions are dependent on the location of the stations.

3. CONCLUSIONS

The analysis of the Love/Shida numbers presented in this paper was performed on the basis of results of the geodetic satellites LAGEOS-1 and LAGEOS-2 observations. The estimated value of the second degree Love number h_2 is 0.6140 ± 0.0005, which differs by 0.0062 from its nominal value. The estimated value of the Shida number l_2 is 0.0876 ± 0.0002 with a difference of 0.0029 from its nominal value. The discrepancy may be due to the fact that nominal values of h_2 and l_2 parameters recommended by the International Earth Rotation and Reference System Service Conventions (Petit and Luzum, 2010) are consistent with the theoretical calculations by Mathews et al. (1997), whereas our estimation is empirical one, based on SLR observations conducted by stations closely connected with the observation sites, thus they are impacted by regional properties of the Earth's crust. Moreover, the estimated values may be impacted by the effect of range bias of the station (constant shift between the calculated and measured distance to the satellite). The analysis of the range bias problem was discussed by Rutkowska (1999). It can be assumed that application of observations conducted by other stations could influence the obtained values of the Love/Shida numbers. It needs to be confirmed in further analysis.

The discrepancy between the estimated h_2 and l_2 values, and the nominal ones can also be linked to satellite orbit errors, in a way discussed by Ray (2013), e.g. errors in the tide model adopted for the dynamical modeling can lead to tidally coherent errors in the orbit. Estimated Love/Shida numbers are sensitive to errors of 1 mm (Ray, 2013), so the SLR estimates of h_2 and l_2 may be affected. This is implied by a large coincidence of the theoretical values with Krásná's et al. (2013) estimation, VLBI is immune to such errors, the SLR and others satellite techniques would not be. Greater than Krásná's et al. (2013) discrepancy was obtained by the authors estimating the Love/Shida numbers from other satellite techniques, e.g. Ray et al. (1995), Ray (2013) from altimetry, Wu et al. (2001) from SLR, thus they can be impacted by satellite orbit errors. But, the ever increasing precision of the satellite techniques allows accessing the theoretically computed numbers of the models and providing their validation from observations.

The results presented in Tables 2 and 3 do not show time evolution of the Love and Shida number values and any systematic differences between our previous and current estimates. The discrepancies between the h_2 and l_2 values obtained from SLR observations performed during the period 2005.1-2007.1 (Rutkowska and Jagoda, 2010b) and 2013.1-2015.1 amount of 0.0006 or 0.1 % for h_2 and 0.0007 or 0.8 % for l_2. The differences do not exceed criterion 3 x formal errors (MPE) of the h_2, l_2 determination.

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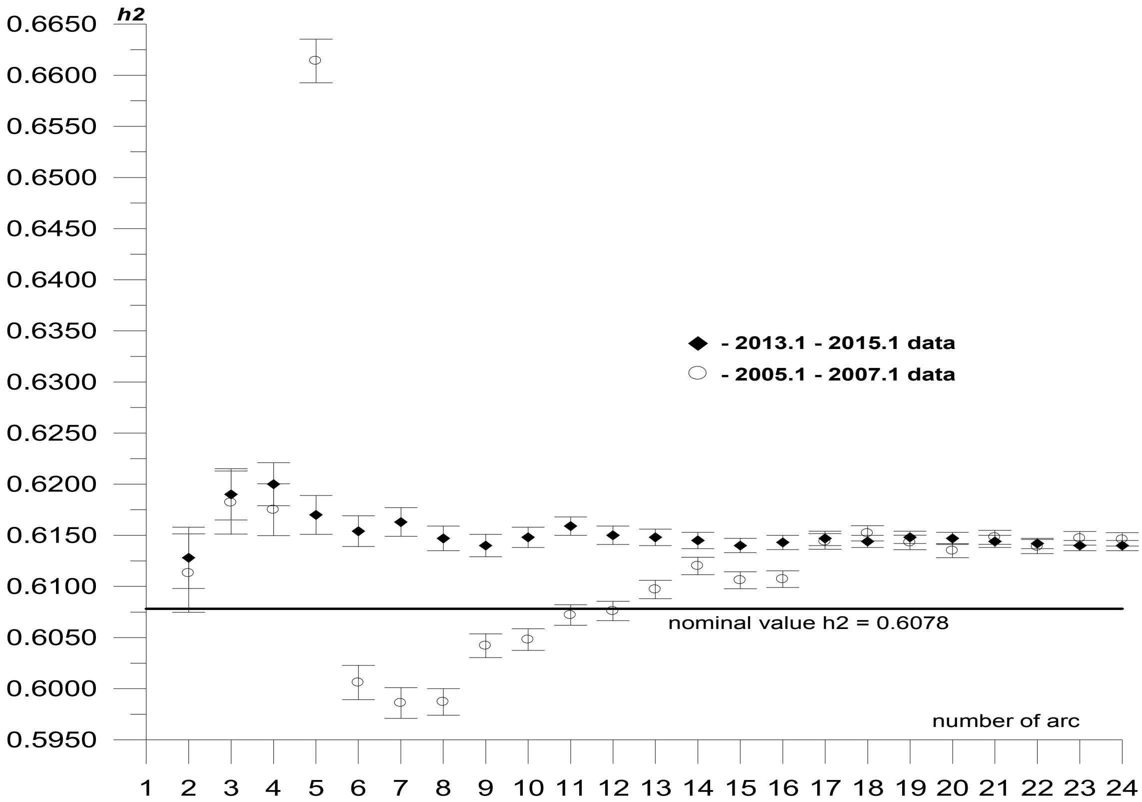

Fig. 1 The sequential solution for the Love number h_2 estimated in the combined analysis based on data for LAGEOS-1+LAGEOS-2.

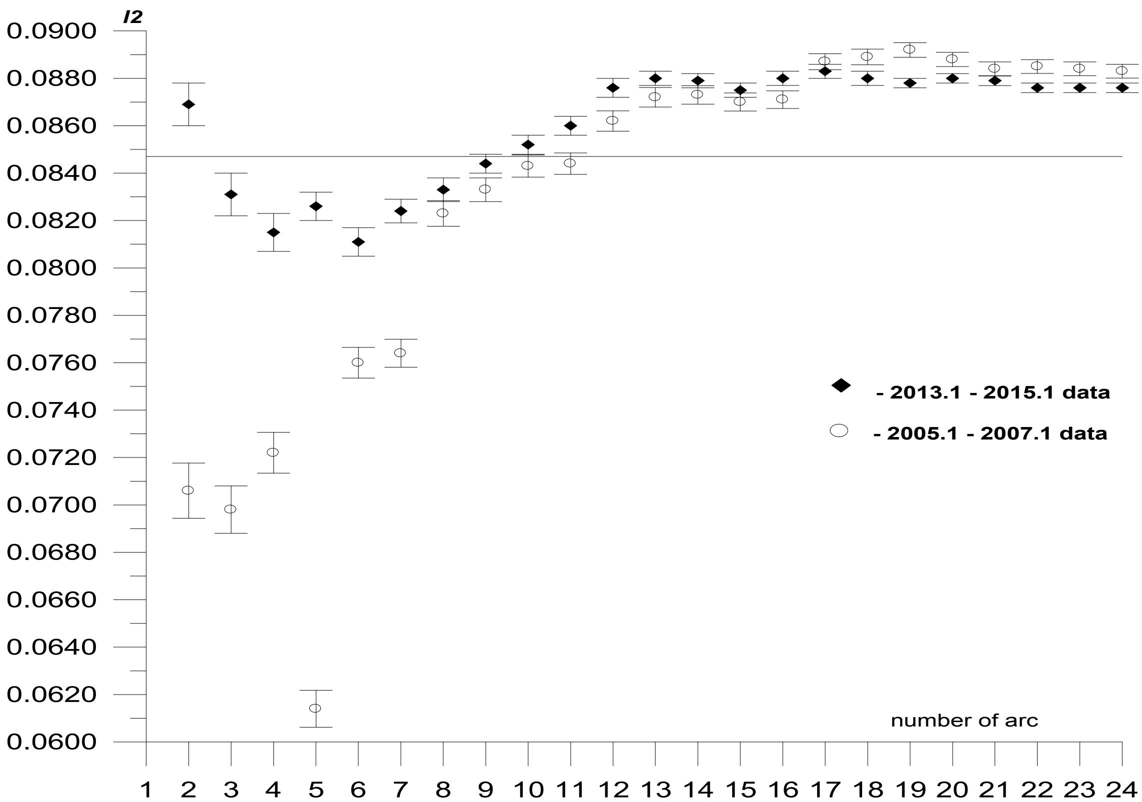

Fig. 2 The sequential solution for the Shida number l_2 estimated in the combined analysis based on data for LAGEOS-1+LAGEOS-2.

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