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ORIGINAL ARTICLE

Impact of loading displacements on SLR-derived parameters and on the consistency between GNSS and SLR results

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Abstract Displacements of the Earth's surface caused by tidal and non-tidal loading forces are relevant in high-precision space geodesy. Some of the corrections are recommended by the international scientific community to be applied at the observation level, e.g., ocean tidal loading (OTL) and atmospheric tidal loading (ATL). Non-tidal displacement corrections are in general recommended not to be applied in the products of the International Earth Rotation and Reference Systems Service, in particular atmospheric non-tidal loading (ANTL), oceanic and hydrological non-tidal corrections. We assess and compare the impact of OTL, ATL and ANTL on SLR-derived parameters by reprocessing 12 years of SLR data considering and ignoring individual corrections. We show that loading displacements have an influence not only on station long-term stability, but also on geocenter coordinates, Earth Rotation Parameters, and satellite orbits. Applying the loading corrections reduces the amplitudes of annual signals in the time series of geocenter and station coordinates. The general improvement of the SLR station 3D coordinate repeatability when applying OTL, ATL and ANTL corrections are 19.5 %, 0.2 % and 3.3 % respectively, w.r.t. the solutions without loading corrections. ANTL corrections play a crucial role in the combination of optical (SLR) and microwave (GNSS, VLBI, DORIS) space geodetic observation techniques, because of the so-called Blue-Sky effect: SLR measurements can be carried out only under cloudless sky conditions—typically during high air pressure conditions, when the Earth's crust is deformed, whereas microwave observations are weather-independent. Thus, applying the loading corrections at the observation level improves SLR-derived products as well as the consistency with microwave-based results. We assess the Blue-Sky effect on SLR stations and the consistency improvement between GNSS and SLR solutions when ANTL corrections are included. The omission of ANTL corrections may lead to inconsistencies between SLR and GNSS solutions of up to 2.5 mm for inland stations. As a result, the estimated GNSS–SLR coordinate differences correspond better to the local ties at the co-located stations when applying ANTL corrections.

Keywords Satellite geodesy · Satellite laser ranging · Atmospheric pressure loading · Blue-Sky effect · SLR-GNSS co-locations · Local ties

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1 Introduction

Tidal and non-tidal surface loading plays a crucial role in high-precision space geodesy. Some of the corrections are recommended by the International Earth Rotation and Reference Systems Service (IERS) Conventions 2010 (Petit and Luzum 2011) to be applied at the observation level, namely ocean tidal loading (OTL) and atmospheric tidal loading (ATL). Atmospheric non-tidal loading (ANTL), non-tidal oceanic and hydrological corrections are not recommended for International Earth Rotation Service (IERS) products, because of an uncertainty of the current models or an insufficient latency of the models w.r.t. processing batch lengths and typical periods of loading effects. Moreover, not all Analysis Centers can apply non-tidal loading corrections.

1.1 Theory

The mass redistributions in oceans, in groundwater (hydrology), and in the atmosphere cause deformations of the Earth's crust. OTL deformations are induced by ocean tides, due to the gravitational attractions of Moon and Sun. Atmospheric pressure loading (APL) deformations are related to variations in the surface pressure $\Delta p(\varphi, \lambda, t)$, because the permanent deformation at the reference (mean) pressure $\Delta \overline{p}(\varphi, \lambda, t)$ is included in the station coordinates of a reference frame. APL can be considered as the sum of the ATL, expressed by the S_1 and S_2 tidal constituents, having maximum magnitude of displacements of 1.5 mm for equatorial areas, and the ANTL with variations up to 20 mm for inland stations (Böhm et al. 2009). Both oceanic and atmospheric loading displacements are calculated on the basis of Green's function $\vartheta(\cos(\beta))$ describing the deformations of the Earth crust as a function of the Legendre polynomials $\Psi(\cos(\beta))$ of angular distance β, load Love number h'_n, gravitational constant G, mean radius of the Earth R, and the mean surface gravity g:

$$\vartheta(\cos(\beta)) = \frac{GR}{g} \sum_{n=1}^{\infty} h'_n \Psi(\cos(\beta)). \quad (1)$$

The Earth surface displacement in the vertical component is calculated by an integration of the pressure variations over the area A:

$$\zeta_{up}(\varphi, \lambda, t) = \int_A \frac{\Delta p(\varphi', \lambda', t)}{g} \vartheta(\cos(\beta)) \mathrm{d}A. \quad (2)$$

(φ', λ', t) denotes the location of the surface element dA at time t. A detailed description of Earth's crust displacements induced by loading can be found, e.g., in Farrell (1972) and Blewitt (2003).

1.2 Research status

In recent years, many studies assessed the impact of loading corrections on GNSS and VLBI stations. Urschl et al. (2005) investigated the impact of OTL on GPS stations. Tregoning and van Dam (2005) and Steigenberger et al. (2009) studied the impact of ANTL corrections on GPS stations. Dach et al. (2011) compared the differences of GPS-derived parameters when applying ANTL corrections at the observation level and in post-processing. van Dam and Herring (1994); Petrov and Boy (2004); Böhm et al. (2009) studied the impact of ANTL on VLBI solutions. Tesmer et al. (2008) compared the VLBI and GPS-derived parameters and studied the consistency of different techniques when applying ANTL corrections. Only few studies evaluated the impact of ANTL on SLR solutions (Bock et al. 2005; Otsubo et al. 2004).

Bock et al. (2005) use ANTL corrections derived from regression factors between time series of local pressure and the vertical site displacements. This way of considering the impact of ANTL displacements is, however, less effective than corrections including the pressure information from the surrounding areas (Dach et al. 2011). Otsubo et al. (2004) estimate the impact of the Blue-Sky effect for selected SLR stations, using the regression factors, as well. SLR measurements can be carried out only at cloudless sky conditions—typically during high air pressure, when the Earth displacement is downward, whereas microwave observations are weather-independent. Weather dependence of the optical observations causes a systematic shift of a SLR station height, i.e., the Blue-Sky effect. Otsubo et al. (2004) study the co-located SLR-GPS stations and find the maximum impact of Blue-Sky effect of 1.3 mm for the German fundamental station in Wettzell.

The consistency between different space-geodetic techniques is of crucial importance. So far many studies on the impact of ANTL had the focus on individual technique solutions or the loading corrections were applied in the post-processing analysis (Collilieux et al. 2009). Only few studies consider the question whether ANTL corrections can improve the consistency between space geodetic techniques. In the framework of the Global Geodetic Observing System (GGOS, Plag and Pearlman 2009), the goal of the position consistency between different geodetic techniques is 1 mm (Rothacher et al. 2011). Neglecting the ANTL corrections may cause discrepancies in station positions up to several mm (the Blue-Sky effect).

In this paper, we use loading corrections at the observation level. We show the impact of loading corrections on SLR stations and SLR-derived parameters. We evaluate the magnitude of the Blue-Sky effect on SLR. Eventually, we answer the question: is the consistency between SLR and GNSS solutions improved by applying APL corrections?

2 SLR solutions

Four time series are established using observations to LAGEOS-1 and -2 for the time span 1999–2011 in order to assess the impact of atmospheric loading corrections on SLR-derived parameters. On an average 2,800 observations per 7-day solution are available. Stations with fewer than 10 observations are not considered for the weekly solutions. Our orbit modeling is similar to that used by the International Laser Ranging Service Analysis Centers (ILRS ACs): six unconstrained osculating orbital elements are estimated for each satellite together with once-per-revolution parameters for the out-of-plane and the along-track components, and a constant acceleration for the along-track direction (one set per 7-days arc) (Thaller et al. 2012a). Length-of-Day (LoD), X- and Y-pole coordinates (one set per day), station coordinates, and range biases for selected stations (one set per

Table 1 The characteristics of SLR solutions

Solution	OTL	ATL	ANTL	RMS of resid. (mm)
1	–	–	–	8.40
2	EOT11a	–	–	6.97
3	EOT11a	Ray Ponte	–	6.96
4	EOT11a	Ray Ponte	Vienna	6.89

7-days arc) are estimated, as well. As opposed to the standard ILRS solutions we also estimate geocenter coordinates (one set per 7-days arc).

No-net-rotation and No-net-translation conditions are applied for the core stations in each final weekly solution, instead of the 1-m loose constraints as in the ILRS AC solutions. Therefore, the orbit determination frame has its origin at the Earth's center-of-mass, whereas the coordinate origin is the center-of-network defined by SLR core stations. Stations with position residual differences exceeding 50 mm in the Helmert transformation are excluded from the analysis. The ILRS' SLRF2008[1] based on ITRF2008 (Altamimi et al. 2011) serves as a priori reference frame with an exception of the Russian station Altay (because of an unrealistic velocity vector for this station in the official SLRF2008 release). We also use the latest station and satellite-specific Center-of-Mass corrections from the ILRS (formerly described by Otsubo and Appleby 2003). The ILRS-recommended table of data corrections[2] containing e.g., range biases and data exclusions is used, as well. EGM2008 (Pavlis et al. 2008) serves as the global gravity field model up to degree and order 30 (Sośnica et al. 2012a). We use a static Earth gravity field and, thus, the corrections on the low degree harmonics due to the atmospheric or ocean mass redistribution are not accounted for in this study.

The impact of APL corrections is compared with the impact of OTL corrections in order to study the magnitude of different loading corrections. In Solution 1, none of the ocean and atmospheric loading corrections are applied (see Table 1). In Solution 2, we apply the OTL corrections generated on the basis of the EOT11a ocean tide model (Savcenko and Bosch 2011) with the corresponding Center of Mass Corrections (CMC) for orbit determination. The OTL EOT11a was provided by Scherneck (2012). Solution 3 in addition includes the ATL (Ray and Ponte 2003) corrections (S_1 and S_2 constituents) with the corresponding CMC. Modeling in Solution 3 is thus most consistent with the IERS Conventions 2010. In Solution 4, the ANTL corrections are additionally applied. For the Solution 4, the Vienna ANTL model based on European Centre for Medium-Range Weather Forecasts (ECMWF) was used which is given in grids with a spatial resolution of 1° and a temporal resolution of 6 h (Wijaya et al. 2011). Station displacement corrections are applied to the vertical as well as to the horizontal components.

3 Impact of loading corrections on SLR-derived parameters

All loading corrections are applied at the observation level, because this type of corrections provides the best repeatability of station coordinates for other geodetic techniques, e.g., for GNSS (Dach et al. 2011) and VLBI (Böhm et al. 2009). As opposed to microwave data analyses, no troposphere parameters have to be estimated in SLR analyses, because the troposphere delay for optical measurements is one order of magnitude smaller due to the shorter wavelength. The troposphere zenith path delay and the corresponding mapping function according to Mendes and Pavlis (2004) are well established for laser observations, allowing us to model the impact of the troposphere delay at the 1-mm level for observations above 20°. Moreover, the stability of the vertical components of the best performing SLR stations (about 3 mm) is better than for GNSS stations (about 4 mm), because in SLR the direct laser ranges are measured, whereas in the GNSS solutions double differences of microwave observations are considered. The largest variations of the loading corrections are in the vertical direction. Therefore, SLR provides a unique tool for validating the impact of loading displacements. The development version of Bernese GNSS Software 5.1 (Dach et al. 2007) is used for SLR and GNSS solutions.

Figures 1 and 2 show the maximum vertical site displacements due to OTL and ATL, respectively, computed from the EOT11a ocean tide model and the S_1–S_2 constituents of ATL model from Ray and Ponte (2003), by summing up the

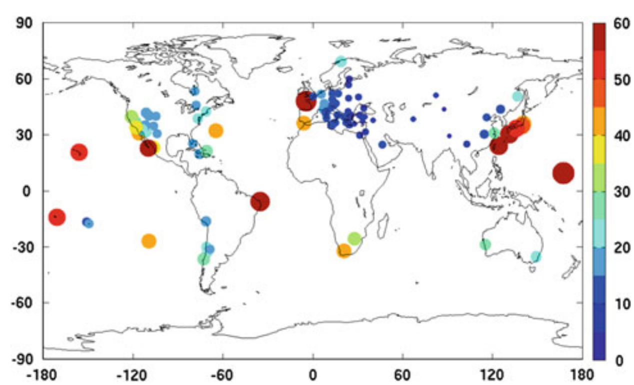

Fig. 1 Summed amplitudes of OTL vertical corrections for SLR stations (units: mm). The area of the *circles* is proportional to the magnitude of the OTL corrections

[1] ftp://cddis.gsfc.nasa.gov/pub/slr/products/resource/SLRF2008_110913.txt.

[2] http://ilrs.dgfi.badw.de/data_handling/ILRS_Data_Handling_File.snx.

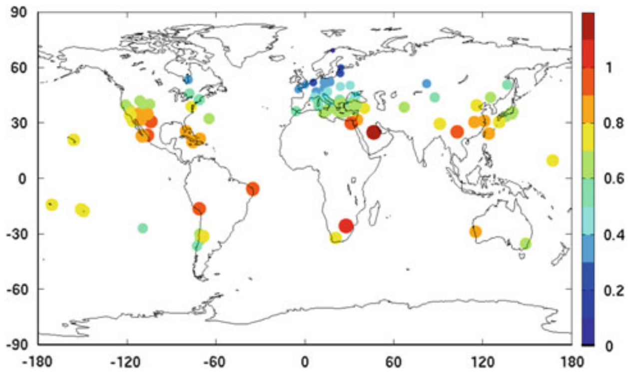

Fig. 2 Summed amplitudes of ATL vertical corrections for SLR stations (units: mm). The area of the *circles* is proportional to the magnitude of the APL corrections

vertical amplitudes of the main constituents for each SLR station. The resulting vertical site displacements induced by OTL are of the order of 15 mm in continental regions and they may reach up to 60 mm at the coasts. The magnitudes of vertical ATL corrections are 0.4 mm for SLR stations in high latitudes, and reach up to 1.5 mm for stations close to the equator. The impact of OTL is, thus, approximately 40 times larger than ATL. In reality, taking into account different phase relationships, the maximum site displacements induced by OTL are smaller, because adding up the amplitudes of the constituents results in an overestimate of the effect (Yi et al. 2000; Urschl et al. 2005).

Figure 3 shows the variation of the ANTL vertical corrections for the SLR stations in the 12-year period. The ANTL corrections are small for coastal stations (1 mm) and large for inland stations (up to 6 mm in central Asia). In global GNSS networks there are many inland stations strongly affected by the ANTL effect with the maximum APL effect reaching 10 mm (Dach et al. 2011). Most of the SLR stations are located close to the ocean, where the influence of APL is compensated by the inverse barometer effect. Currently, there are

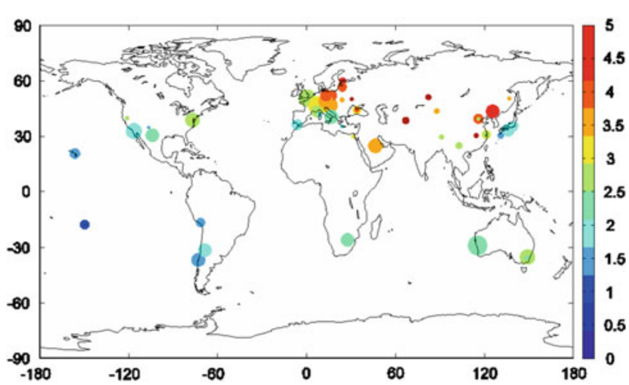

Fig. 3 Standard deviation of the ANTL corrections over 12 years for the vertical component (units: mm). The area of the *circles* is proportional to the number of SLR observations

no inland SLR stations in North and South America and the observations collected by SLR stations in Central and North Asia are rather sparse (with insufficient number of observations in winter time). The horizontal ANTL corrections (not shown here) are approximately a factor of five smaller than for the vertical component. A rather sparse SLR network and the uneven distribution of observations may cause the so-called network effect, because an ignored ANTL effect shifts the complete network in conjunction with horizontal deformations. For the SLR network, the effect is similar to the VLBI network (Böhm et al. 2009).

3.1 RMS of residuals

The mean value of the RMS of observation residuals per 7-day arc of both LAGEOS satellites is shown in Table 1. The omission of OTL displacement corrections (Solution 1) obviously leads to solutions of inferior quality and large RMS of residuals. The impact of ATL on the RMS is small, as expected by the small corrections for the SLR stations. Solution 4 (including OTL, ATL and ANTL) has the smallest RMS of observation residuals, indicating a small positive impact of atmospheric loading corrections on SLR solutions. The differences between the RMS of observation residuals indicate that ATL and even ANTL corrections might be ignored without a significant degradation of the RMS of observation residuals.

3.2 SLR station coordinates

Figure 4 shows the annual and semiannual signals and the mean offsets for the horizontal and vertical components of SLR station Riyadh (Saudi Arabia), an example of a well-performing inland station. The annual and semiannual signals and the mean offset w.r.t. SLRF2008 are fitted to the 12-year series of 7-day coordinate solutions using the least squares method. The estimated amplitude of the annual signal for the vertical component is 4.8, 4.4, 4.4, and 1.6 mm for Solutions 1, 2, 3, and 4, respectively. The amplitude of the semiannual signal is reduced from 2.0 mm in Solution 1 to 0.7 mm in Solution 4. There are minor improvements in the horizontal components (see Fig. 4) as expected from small horizontal a priori corrections. As the background models in Solution 2 are very close to the models underlying SLRF2008, the mean offset of station coordinates is minimum for this solution (−0.7 mm for vertical component). Using different parameterizations and including ATL and ANTL corrections leads to a small increase of the mean offset (−1.0 mm for vertical component). ANTL corrections do, however, clearly reduce the amplitude of the annual signal in the vertical component for this station. They should be, therefore, included in future ITRF computations (as also proposed by Collilieux et al. 2009).

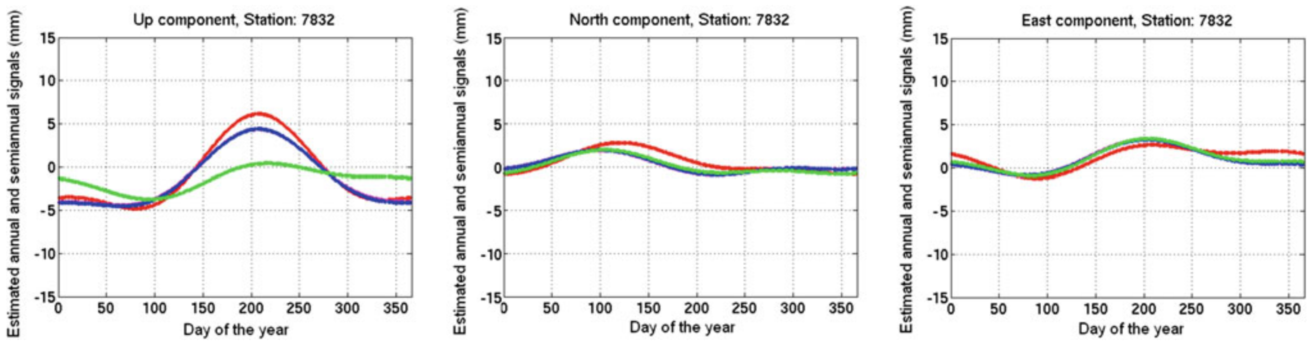

Fig. 4 Annual and semiannual signals and mean offsets w.r.t. SLRF2008 for horizontal and vertical components of the 12-year LAGEOS solution for SLR station Riyadh (Saudi Arabia). *Red lines* Solution 1, *magenta lines* Solution 2 (mostly covered by blue lines), *blue lines* Solution 3, *green lines* Solution 4

Figure 5 illustrates the estimated annual and semiannual signals of the station vertical components for SLR stations observing minimum for 3 years. The general reduction of the amplitude of the annual signal for the vertical component of all SLR sites due to OTL is 20–30 % and due to ANTL 10 % w.r.t. the corresponding solutions without corrections. Even though loading displacement corrections have the largest effect on the vertical station component, there is also a non-negligible improvement of stability of the horizontal components. In the North component, for stations providing at least 25 weekly solutions during the 12-year period, the estimated annual amplitudes are 2.6, 2.4, 2.3, and 2.1 mm for Solutions 1, 2, 3, and 4, respectively, whereas in the East component the annual amplitudes are 2.5, 2.0, 2.0, 1.7 mm, corresponding to an amplitude reduction of 25 % due to OTL and 15 % due to ANTL, whereas ATL has no significant impact on the horizontal component. The larger improvement in the East component than in the North component due to ANTL was expected, because many of the SLR sites are located at North-South coast lines, where an East-West ANTL effect is dominating.

As expected, the loading displacement corrections reduce the the amplitudes of annual and semiannual signals of SLR station coordinates, in particular in the vertical component (see Fig. 5). ANTL corrections reduce the amplitudes for inland stations (e.g., from 19.3 to 11.3 mm for Altay in Russia, from 4.8 to 1.6 mm for Riyadh in Saudi Arabia, from 5.2 to 3.5 mm for Beijing in China), whereas the impact of OTL corrections is mainly visible for coastal stations. The impact of ATL corrections is barely recognizable. Small differences between the annual amplitudes of station coordinate time series in Solutions 2 and 3 occur only for Tahiti in French Polynesia (amounting 0.5 mm). Land hydrology and oceanic non-tidal loading effects are neglected in this study. They may, however, be out-of-phase w.r.t. the atmospheric contribution, which is why the analysis of the annual amplitude when applying ANTL is not solely conclusive.

There are big differences in SLR station stability and quality of data within the ILRS network. SLR normal points—the basic SLR pseudo-observables used for analyses—significantly differ in quality between the stations. Moreover, some of the SLR stations carry out observations on a regular basis, whereas others deliver data occasionally (Sośnica et al. 2012b). Therefore, in Table 2 three groups of SLR stations are considered.

Figure 6 shows the mean 3D repeatability of SLR stations with at least 150 weekly solutions and Table 2 summarizes the mean station repeatability. The general improvement of repeatability for the best performing SLR stations is 3.3 % due to ANTL, 19.5 % due to OTL, and only 0.2 % due to ATL. The overall repeatability improvement due to ANTL for SLR stations is considerably smaller than that found for GNSS stations: 20 % (Dach et al. 2011). This fact may be associated with the uneven distribution of SLR sites and with the location of most of the well performing SLR sites close to an ocean. Moreover, the aforementioned large differences in the technical capabilities of SLR stations are not irrelevant. The 3D repeatability of Changchung in China is 19 mm, whereas the 3D repeatability for Yarragadee, Herstmonceux, Zimmerwald, Greenbelt, and Graz is approximately 6 mm (see Fig. 6).

3.3 Geocenter coordinates

SLR solutions based on the observations of LAGEOS result in very reliable geocenter time series (Meindl et al. 2013) thanks to the stable LAGEOS orbit and the satellite characteristics, i.e., the favorable area-to-mass ratio. A reduction of the annual signal in geocenter coordinates due to ANTL is expected, because loading corrections compensate the mass redistribution inside the Earth, and thus, reduce the difference between the center of mass w.r.t. the center of figure. Figure 7 shows that ANTL reduces the amplitude of the annual signal in the X-, Y-, and Z-geocenter component by 0.2, 0.4, and 0.8 mm, respectively. The amplitude in the X-component

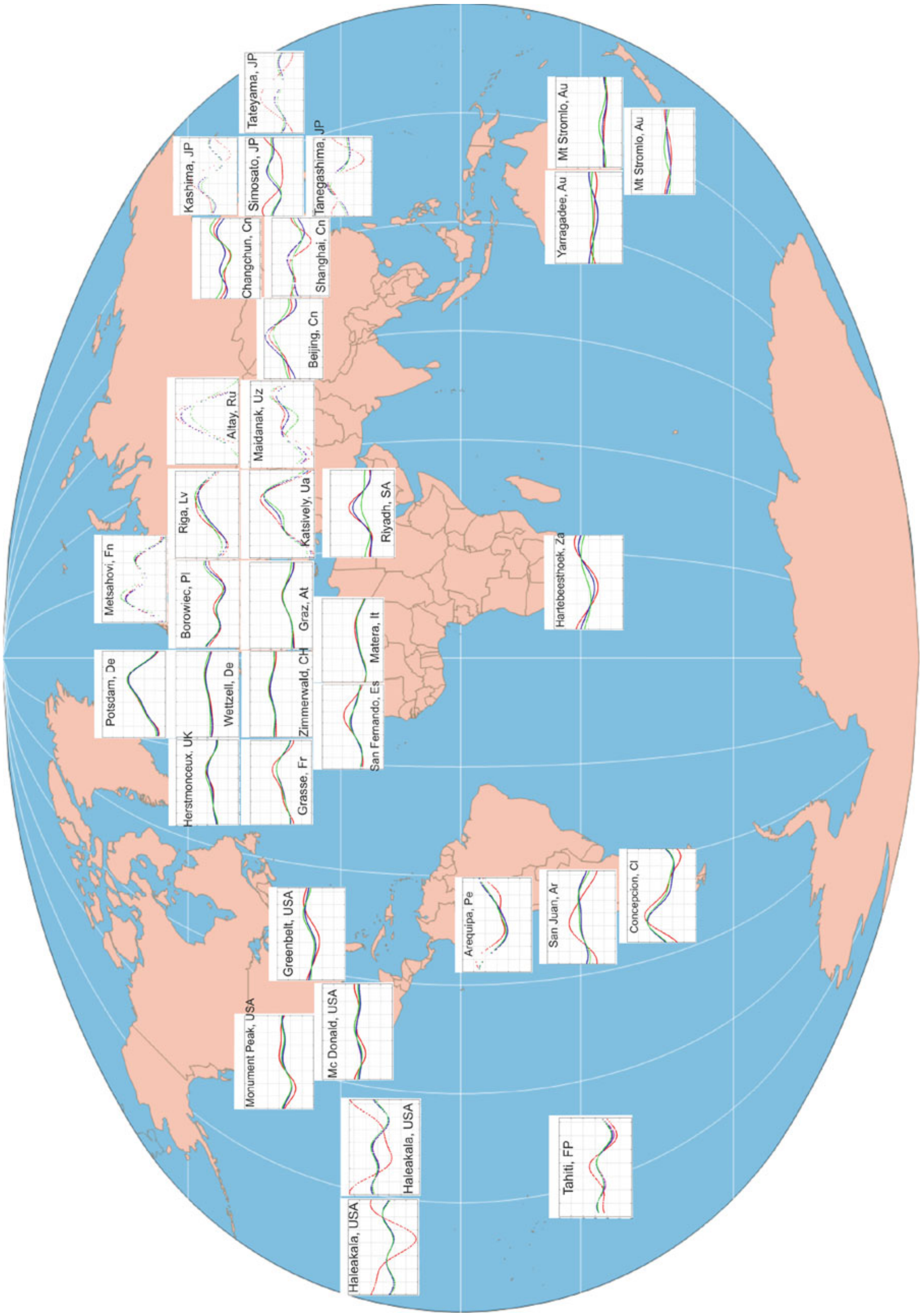

Fig. 5 Annual and semiannual signals of the vertical components of SLR station coordinates in Solution 1 (*red*), Solution 2 (*magenta*), Solution 3 (*blue*) and Solution 4 (*green*). *Solid lines* denote a continuously observing station, *dotted lines* denote a station with sparse observations. Scale of the plot is the same as in Fig. 4

Table 2 Mean 3D repeatability of SLR stations and improvement of repeatability due to different loading corrections for SLR stations with minimum 25, 150 and 400 weekly solutions

	Sol1 (mm)	Sol2 (mm)	Sol3 (mm)	Sol4 (mm)	Impr. due to OTL (%)	Impr. due to ATL (%)	Impr. due to ANTL (%)
min. 25 weeks	17.86	15.40	15.42	15.14	18.71	−0.12	2.42
min. 150 weeks	15.53	13.23	13.17	12.97	19.40	0.40	2.26
min. 400 weeks	10.74	9.09	9.07	8.85	19.53	0.21	3.28

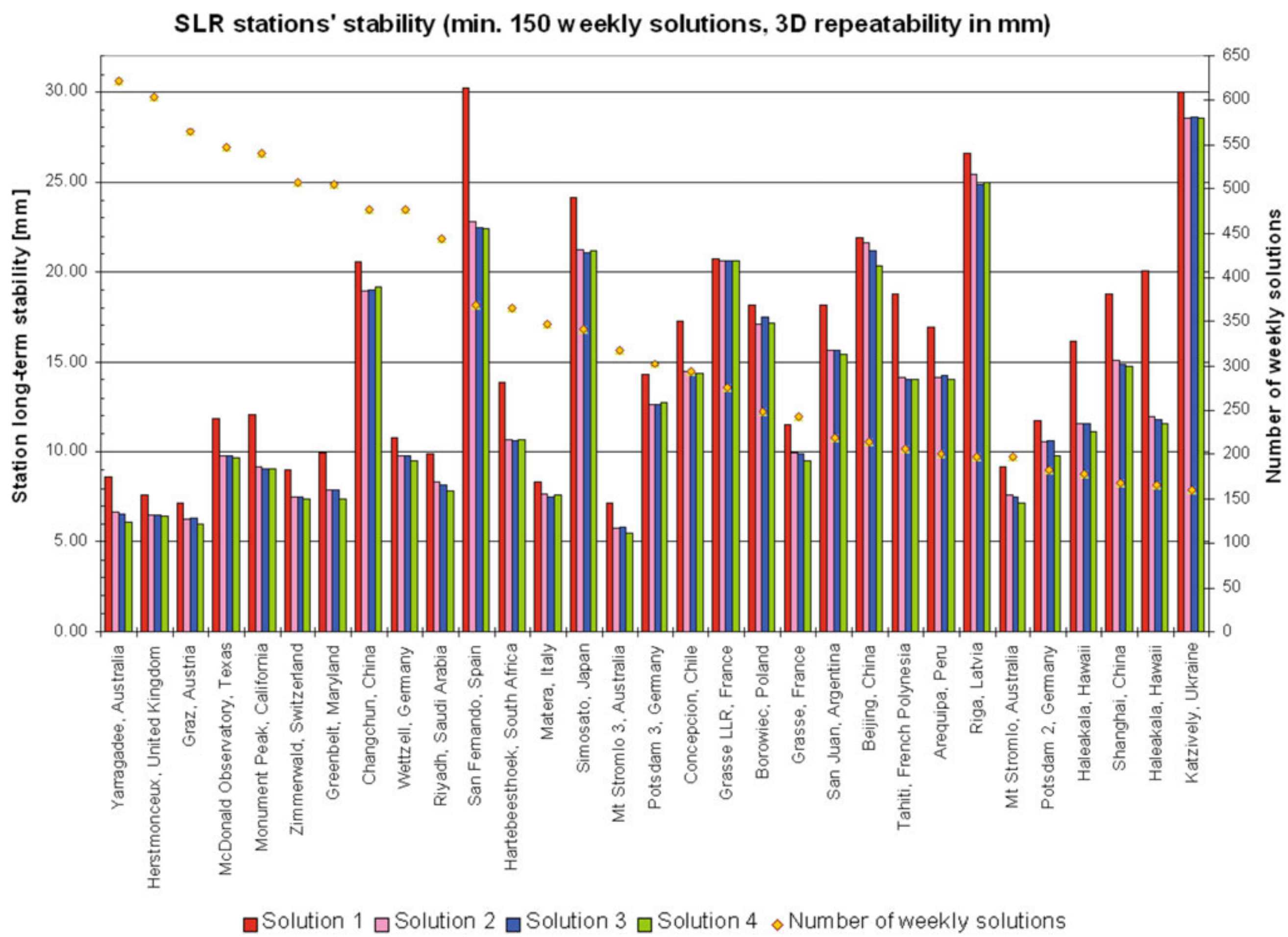

Fig. 6 3D repeatability of SLR station coordinates for SLR stations providing at least 150 weekly solutions between 1999 and 2011. Solutions with different types of loading corrections are defined in Table 1

increases from Solution 1 to 4, but the differences in all four solutions are well within the two-sigma, indicating that the differences are not significant. The theoretical impact due to ANTL on the geocenter coordinates according to Crétaux et al. (2002) is 0.4, 1.3, and 0.7 mm for X, Y, and Z, respectively. Therefore, the reduction of the amplitudes of the annual signal of the geocenter coordinates agrees very well for the Z component and is substantially smaller for the X and Y components. The differences in the X and Y components show that the loading corrections applied at the observation level have an impact on the whole SLR solution and all estimated parameters and not only on station and geocenter coordinates.

From Fig. 7 we state that ATL corrections may even slightly increase the amplitudes of annual signals, but the obtained differences are not significant. Amplitudes of the semiannual signals are of the order of 0.2 mm only (not shown) for all solutions and all components. Thus, the differences between the solutions are marginal.

Table 3 shows the comparisons of the estimated annual and semiannual signals of the geocenter coordinates with other LAGEOS solutions (Gourine 2012; Altamimi et al. 2011; Angermann et al. 2002; Chen et al. 1999; Moore and Wang 2003). There is a good agreement at Solution 4 and the other solutions for the X and Y components with differences not exceeding 0.7 mm (with the exception of the values derived

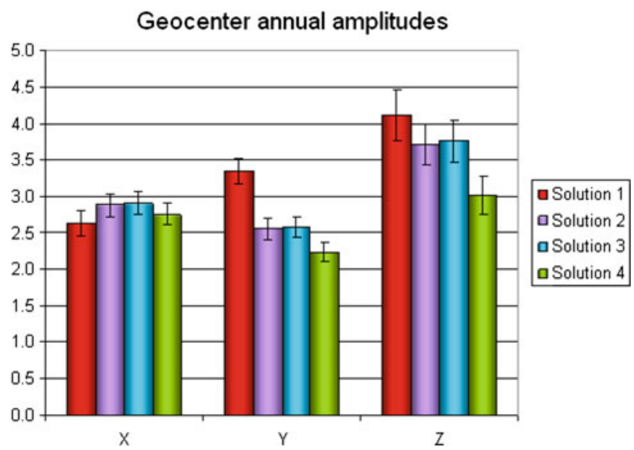

Fig. 7 Amplitudes of annual signals in geocenter coordinates with one-sigma *error bars* (in mm)

by Moore and Wang 2003). In the *Z* component there is a big disparity between individual solutions, ranging between 2.3 and 5.5 mm. However, in all solutions different time-spans are considered, which may be a contributing factor to the differences in the *Z* component. The estimates of the amplitudes of semiannual signals in the geocenter coordinates are below 1 mm for all solutions. In general, the amplitudes of the annual and semiannual signals of the geocenter coordinates from Solution 4 have very small amplitudes and they are in good agreement with the other solutions.

Figure 8 shows the differences of the *Z* component estimates of the geocenter due to OTL, ATL, and ANTL. ANTL corrections are strongly related to the seasons: in winter the omission of ANTL corrections causes positive differences in the Northern hemisphere, whereas in the summer the differences are negative. Almost all SLR stations with big impact of ANTL signal are in the Northern hemisphere. Therefore, the observed variations in the *Z* coordinates of the geocenter are related to the compensation of seasonal high and low air pressure variations in the Northern hemisphere, because of the different land-to-ocean ratio for both hemispheres. Apart from that, all SLR stations in the Southern hemisphere are coastal stations with very small impact of ANTL. The variations of the *Z* coordinate of the geocenter are different in different years, e.g., in 2010 and 2009 the effect is hardly noticeable, due to anomalous pressure variations, as compared to, e.g., 2008 and 2005 (see Fig. 8). For *X* and *Y* similar signals with smaller amplitudes (not shown here) are obtained.

The OTL corrections do not generate an annual signal (see Fig. 8). The resolution of 7 days does not allow us to recognize high frequency tidal corrections. The impact of ATL corrections is smaller than OTL and ANTL, but with different periods. A Fourier analysis of the differences between Solution 2 and Solution 3 shows two dominating periods of 222 days and 560 days, corresponding to the draconitic years of LAGEOS-2, and -1, respectively, indicating possible modeling problems related to the solar radiation pressure (Meindl et al. 2013).

3.4 Impact of loading correction on Earth Rotation Parameters (ERPs)

Table 4 shows the differences of mean offsets of estimated ERP and weighted RMS w.r.t. the a priori IERS-08-C04 series (Bizouard and Gambis 2012). The differences of mean offsets caused by ATL and ANTL are rather small, i.e., approximately 1 μas for the pole coordinates and 1 μs for LoD. The mean offsets and the weighted RMS w.r.t. the IERS-08-C04 series do not allow us to decide which solution is the best one, because the C04 series are based on solutions without ANTL corrections applied.

Figure 9 shows the differences between estimated time series of ERP in different solutions. The impact of ANTL on the *X* and *Y* coordinates of the pole is systematic with a dominating annual signal. The amplitude of the annual signals due

Table 3 Amplitudes of annual and semiannual signals of geocenter coordinates based on SLR observations of LAGEOS-1 and -2

	X		Y		Z	
	Value (mm)	Formal error (mm)	Value (mm)	Formal error (mm)	Value (mm)	Formal error (mm)
Annual signal						
This study, Solution 4	2.75	0.15	2.22	0.12	3.01	0.27
Gourine (2012)	2.9	0.8	2.3	0.5	2.3	0.6
Altamimi et al. (2011)	2.6	0.1	3.1	0.1	5.5	0.3
Chen et al. (1999)	2.38	NP	2.00	NP	4.10	NP
Angermann et al. (2002)	2.8	NP	3.0	NP	5.1	NP
Moore and Wang (2003)	3.5	0.6	4.3	0.6	4.6	0.6
Semiannual signal						
This study, Solution 4	0.27	0.16	0.17	0.13	0.22	0.26
Chen et al. (1999)	0.75	NP	0.89	NP	0.50	NP

NP not Provided

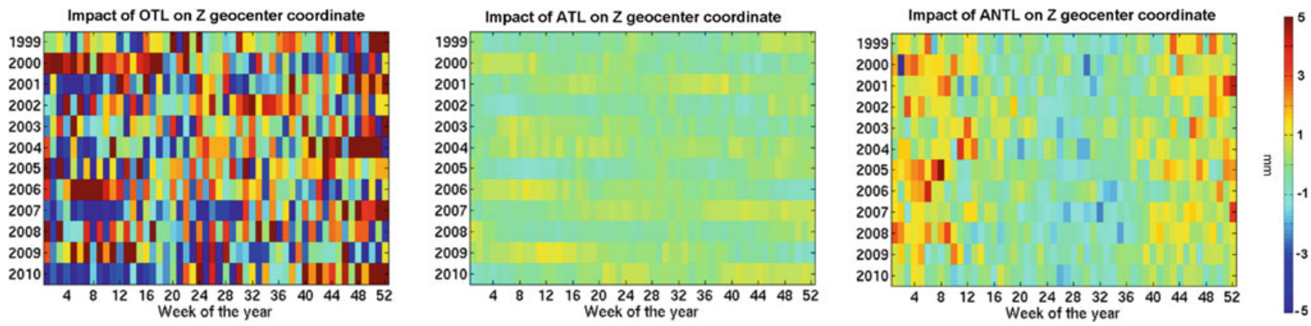

Fig. 8 Differences in the *Z* coordinates of the geocenter derived from different solutions (Solution 1–Solution 2, Solution 2–Solution 3, Solution 3–Solution 4, from *left* to *right*)

Table 4 ERPs derived from SLR solutions (comparison w.r.t. IERS-08-C04 series)

	Mean bias			Weighted RMS		
	X pole (µas)	*Y* pole (µas)	LoD (µs)	*X* pole (µas)	*Y* pole (µas)	LoD (µs)
Solution 1	42	−2	−2.1	205	210	40
Solution 2	38	−2	−1.4	179	180	37
Solution 3	37	−2	−1.3	179	180	37
Solution 4	36	−2	−1.2	180	178	36

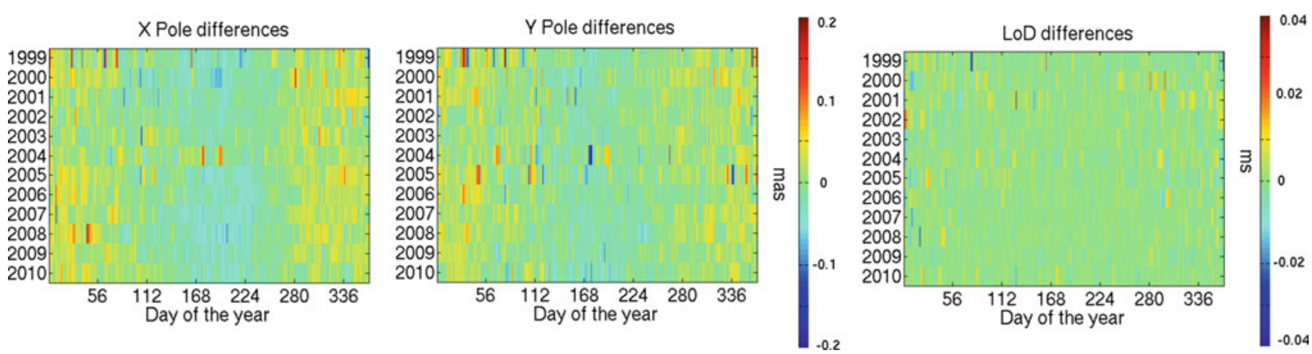

Fig. 9 Differences of daily *X* pole and *Y* pole coordinates and LoD between Solution 3 and Solution 4 (the effect due to ANTL)

to ANTL corrections on the *X* and *Y* pole coordinates are 45 and 42 µas, respectively, thus not negligible for ERP estimation. The mean biases w.r.t. the IERS-08-C04 series remain the same for the *Y* coordinate of the pole and almost the same for *X* coordinate of the pole (see Table 4). The impact of ATL and ANTL on LoD is negligible. Differences of the estimated ERPs due to OTL are the largest: 250 µas in pole coordinates and 43 µs in LoD. A Fourier transform of ERP differences shows many significant periods corresponding to the typical periods of tidal waves (14, 15 days), draconitic years of LAGEOS satellites (222, 111, 560 days), and an annual signal (365 days).

3.5 LAGEOS orbits

The direct orbit differences show that the mean impact of ATL and ANTL on LAGEOS orbits is 1.69 and 1.33 mm, respectively. The larger impact of ATL can be explained by the Center-of-Mass corrections applied along with the ATL corrections.

Through applying the full impact of the ANTL on satellite orbits with the atmosphere-induced gravity field variations, the LAGEOS orbits are improved by 3–5 % when analyzing the predicted orbits (Thaller et al. 2013, submitted manuscript). The impact of the atmosphere-induced gravity field variations on LAGEOS orbits is one of the major issues raised by Thaller et al. (2013, submitted manuscript), therefore we refer to this study for a detailed discussion.

4 Blue-Sky effect

The consistently reprocessed time series of SLR stations with appropriate handling of loading displacements allow us to assess the order of magnitude of the so-called Blue-Sky effect on SLR stations. The omission of APL may in particular lead to inconsistencies between optical (SLR) and microwave (GNSS, VLBI, DORIS) solutions. SLR observations are carried out during almost cloudless sky conditions, whereas microwave observations are weather-independent. Cloudless weather conditions are typically related to high air pressure conditions, when the Earth's crust is deformed by pressure loading. Therefore, weather dependence of the optical observations causes a systematic shift of the station heights, which is called the Blue-Sky effect. Applying APL corrections should compensate the Blue-Sky effect.

We estimated the impact of the Blue-Sky effect on SLR stations as the difference between mean loading correction applied to SLR stations, when SLR station performs the observations, and the mean correction to SLR stations for the entire time series. The value of the mean correction to SLR stations for the entire time series ought to be zero, because the impact of reference pressure should be removed from the APL model. This mean value is below 0.1 mm, indicating that the reference pressure field in the background of the APL model is sufficiently accurate. Therefore, only the mean loading correction for epochs when a SLR station is performing observations is important when assessing the Blue-Sky effect.

Table 5 summarizes the Blue-Sky effect for the selected SLR stations. The number of normal point observations is shown in Table 5, as well. The largest effect is associated with inland stations in central Asia and Eastern Europe. It is not surprising that the largest Blue-Sky effect occurs for stations with the largest magnitude of APL impact.

The impact of the Blue-Sky effect is below 1 mm for most of continuously observing SLR core stations, despite a large impact of APL. For Riyadh the mean magnitude of APL is, e.g., 3.7 mm, whereas the Blue-Sky effect is only 0.2 mm. It suggests that the Blue-Sky effect can be reduced by semi-continuous SLR observations (Sośnica et al. 2012c).

The systematic shift of SLR station height due to Blue-Sky effect has a non-negligible impact on the scale derived from SLR technique. The shift of 1 mm corresponds to the scale discrepancy of about 0.2 ppb w.r.t. the radius of the Earth. Therefore, the disagreement between the scale derived from SLR and VLBI (1.2 ppb in ITRF2008) can be partly diminished when applying APL corrections.

The impact of the Blue-Sky effect is largest for inland stations observing occasionally. The Blue-Sky effects in Golosiv in Ukraine (4.4 mm), and Wuhan in China (3.2 mm) assume the largest values. On the other hand, the aforementioned stations collected a rather small amount of data and corresponding values of the Blue-Sky effect are not very reliable. We conclude that the maximum impact of the Blue-Sky effect is approximately 2.5 mm for most of the SLR stations, but it may be larger, if the amount of observations is insufficient. Fortunately, the stations with the largest impact of Blue-Sky effect have only a small influence on a potential SLR-derived reference frame due to the limited number of normal points.

Table 5 also shows the estimates of Blue-Sky effect by Otsubo et al. (2004). It is consistent with our results, even though different methods were applied in the two studies. Otsubo et al. (2004) use regression factors and pressure observables from GNSS stations, whereas Vienna ANTL corrections are used in this study. Both approaches lead to similar results with a mean difference of only 0.2 mm. The mean Blue-Sky effect is 1.1 mm for all SLR stations and the median 0.8 mm.

Regarding the fact that some of the SLR stations are continuously improving their tracking capabilities the impact of the Blue-Sky effect becomes smaller in time for a few stations, e.g., the Blue-Sky effect was reduced for Zimmerwald, Switzerland from 1.8 mm in 1999 to 0.5 mm in 2010, for Greenbelt, Maryland from 0.9 mm in 1999 to 0.3 mm in 2010, and for Katzively, Ukraine from 3.1 mm in 1999 to 1.4 mm in 2010. The reduction of the Blue-Sky effect is especially visible for SLR stations which updated and automatized their laser systems or enabled day-time tracking capabilities. For the stations without significant tracking capability improvements the Blue-Sky effect remains at the same level or may even increase.

All error sources leading to larger discrepancies than 1 mm between space geodetic techniques should be taken into account, as the goal of GGOS for the precision of station positions is 1 mm. Table 5 shows that the Blue-Sky effect exceeds the maximum value accepted by GGOS for more than 50 % of the SLR stations. This may in particular affect mobile SLR stations. Therefore, ANTL corrections are of crucial importance for the inner consistency of SLR solutions and the consistency between different space geodetic techniques.

5 Agreement of sites co-located by GNSS and SLR

Let us now assess the impact of APL on SLR and GNSS solutions and the improvement of consistency of both techniques by comparing time series of GNSS and SLR weekly solutions. Two GNSS network solutions are estimated for the time span 2000–2011: one with APL corrections and one without APL corrections. The GNSS results are compared to the corresponding two SLR solutions. The best possible consistency between the SLR and GNSS solution can be guaranteed because in both cases the same set of models and the same software, the Bernese GNSS Software 5.1 is used. In the daily GNSS solutions (Steigenberger et al. 2011) the screened observation files are used. Satellite orbit parameters are estimated together with ERPs, station and geocenter coordinates, and troposphere parameters. Subsequently, the weekly

Table 5 Blue-Sky effect for selected SLR stations, ordered by the size of the Blue-Sky effect

SLR station	Number of normal points	Mean impact of ANTL (mm)	Blue-Sky effect (this study) (mm)	Blue-Sky Effect (Otsubo et al. 2004)(mm)
Golosiv, Ukraine	330	6.6	4.4	
Wuhan, China	1,052	4.9	3.2	
Greenbelt[a], Maryland	150	3.3	2.5	
Beijing-A, China	189	2.7	2.5	
Helwan, Egypt	223	3.2	2.4	
Orroral, Australia	3,550	3.0	2.3	
Altay, Russia	1,776	6.7	2.3	
Lhasa, China	981	2.5	2.1	
Urumqi, China	1,265	3.7	2.0	
Beijing, China	15,669	4.1	1.9	
Riga, Latvia	11,728	4.2	1.8	
Maidanak 1, Uzbekistan	3,914	4.8	1.7	
Metsahovi, Finland	3,395	4.5	1.6	
Changchun, China	52,808	4.3	1.5	
Maidanak 2, Uzbekistan	1,284	5.3	1.5	
Simeiz, Ukraine	1,039	4.1	1.4	
Lviv, Ukraine	621	3.7	1.4	
Potsdam, Germany	26,449	4.1	1.3	
Kunming, China	2,990	2.8	1.3	
Borowiec, Poland	14,898	4.0	1.2	
Zimmerwald, Switzerland	188,806	3.2	1.2	0.9
Wettzell, Germany	73,215	3.6	1.2	1.3
Komsomolsk-na-Amure, Russia	393	3.5	1.1	
Hartebeesthoek, South Africa	49,550	2.4	1.1	
Tateyama, Japan	4,884	1.7	0.9	
Mt Stromlo, Australia	82,648	2.7	0.8	
Greenbelt, Maryland	71,571	2.7	0.7	0.4
Graz, Austria	110,888	3.6	0.7	0.7
Koganei, Japan	10,771	1.9	0.7	
Herstmonceux, United Kingdom	133,739	2.7	0.6	1.0
Katzively, Ukraine	7,766	3.1	0.6	
McDonald Observatory, Texas	50,269	2.4	0.5	0.7
Monument Peak, California	105,110	1.7	0.5	
Simosato, Japan	43,722	1.8	0.5	
Yarragadee, Australia	229,063	2.2	0.4	
San Fernando, Spain	12,204	1.2	0.3	
San Juan, Argentina	47,624	1.9	0.3	
Grasse, France	30,624	2.6	0.3	
Tahiti, French Polynesia	12,204	1.2	0.3	
Riyadh, Saudi Arabia	68,631	3.7	0.2	
Concepcion, Chile	56,385	1.6	0.2	
Matera, Italy	60,380	2.5	0.2	
Haleakala, Hawaii	20,890	1.5	0.1	

[a] 7918-Inactive mobile SLR station

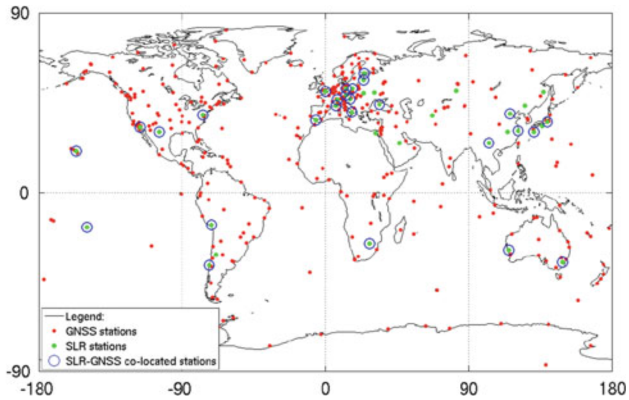

Fig. 10 SLR, GNSS and SLR-GNSS co-located stations

solutions are derived by stacking the daily normal equation systems. The station coordinate time series from weekly solutions are analyzed and validated by identifying outliers, discontinuities, and velocity changes according to Ostini (2012). The LAGEOS solutions have been already described in Sect. 2. The global distribution of SLR and GNSS stations and of GPS-SLR co-locations is shown in Fig. 10.

5.1 Analysis of GNSS–SLR co-location stability

Table 6 shows the comparison of differences in the vertical component of the selected GNSS and SLR co-located stations with long periods of observations and possible none or only a small number of discontinuities in the SLR and GNSS coordinate time series. The mean RMS of the differences of the vertical components of SLR and GNSS is 11.43 mm when APL corrections are applied, and 11.56 mm when APL corrections are omitted. A small improvement is thus seen in the GNSS–SLR co-located stations stability, but it must be distinguished between high-performing stations, e.g., Zimmerwald, Graz, and Tahiti, where the improvement is more pronounced (0.3, 0.2, 0.3 mm, respectively), and the other stations.

From the analysis of the differences between the vertical components of SLR solutions with and without APL corrections (see Table 6) it results that the mean difference has a value of 0.35 mm. For GNSS it is only 0.13 mm, because GNSS data, as opposed to SLR data, are not affected by the Blue-Sky effect. The variations of GNSS station height differences in solutions with and without APL corrections are clearly larger (2.46 mm on average) than for SLR (1.63 mm on average), because GNSS stations observe continuously, whereas SLR observations are weather-dependent.

Unfortunately, all well-performing SLR stations co-located with GNSS show only a small impact of APL (due to their locations close to oceans). When subtracting station height differences between GNSS solutions with and without APL from the station height differences between SLR solutions with and without APL (see Table 6), the large differences between SLR and GNSS solutions appear for semi-continental stations, e.g., Riga (RIGA-1884, Latvia), Borowiec (BOR1-7811, Poland), and Potsdam (POTS-7836, Germany), amounting 0.8, 0.5, and 0.4 mm, respectively. The results for these stations indicate that the omission of APL corrections may lead to inconsistencies between SLR and GNSS solutions of up to 0.8 mm.

Figure 11 shows the amplitudes of estimated annual signals of the station heights for co-located SLR and GNSS sites. Solutions with APL and without APL corrections are presented. For some co-located stations the agreement between the GNSS- and SLR-derived amplitudes is rather poor (e.g., for Graz, McDonald and Monument Peak), implying that the amplitudes are influenced by technique-specific problems and data processing issues, and do not show any geophysical or environmental effects. On the other hand, for stations Greenbelt, Tahiti, San Fernando, and Hartebeesthoek the agreement between the amplitudes is on the sub-mm level. The amplitudes of the vertical components are usually smaller for the SLR stations (on the average 2.6 and 2.3 mm for the solutions without and with APL corrections, respectively) than for the GNSS stations (3.5 and 2.8 mm for the solutions without and with APL corrections). Smaller variations of the vertical components in SLR may be explained by

– the correlations in GNSS solutions between the vertical component and other estimated parameters, e.g., station clock corrections or troposphere delays. None of these parameters have to be estimated in the SLR solutions, making the vertical component more robust,
– in SLR solutions the strongest and best established component is the vertical component, because it is defined by direct range observations. In GNSS the solution is based on double-difference phase observations,
– in GPS the orbit modeling deficiencies are typically reflected in draconitic year periods, and thus, accumulated in the annual signal of geocenter coordinates. The draconitic years of LAGEOS-1 and -2 are different and not coincident with the annual period (560 and 222 days, respectively).

For some co-located stations the amplitude is increased by an insignificant amount when applying APL corrections (e.g., Zimmerwald), but for most stations APL reduces the amplitude. The mean amplitude reduction is slightly larger for GNSS (0.6 mm) than for SLR stations (0.4 mm), even if the same APL corrections are applied on co-located stations. Therefore, either the impact of APL in GNSS solutions is overestimated (due to correlations with other parameters) or the impact of APL in SLR is underestimated (due to discontinuous observations). In the solutions with APL the discrepancy of the estimated amplitudes in the vertical components

Table 6 Impact of APL corrections on selected co-located GNSS–SLR stations, ordered by the decreasing number of weekly co-locations

Co-location		RMS of height differences between SLR and GNSS With APL	RMS of height differences between SLR and GNSS w/o APL	Station height differences between SLR solutions with APL and w/o APL		Station height differences between GNSS solutions with APL and w/o APL	
GNSS station	SLR station			RMS	Mean	RMS	Mean
GRAZ	7839	5.2	5.4	1.8	0.2	2.8	0.0
MDO1	7080	10.2	10.3	1.4	0.2	2.3	0.2
MONP	7110	8.6	8.6	1.0	0.3	1.6	0.2
ZIMM	7810	8.8	9.1	1.4	0.4	2.4	0.1
YAR2	7090	5.8	5.9	1.5	0.4	2.6	0.2
GODE	7105	6.6	6.9	1.7	0.2	2.0	0.0
MATE	7941	7.4	7.7	1.0	−0.1	2.3	−0.1
HARB	7501	8.4	8.3	1.8	0.4	2.4	0.3
SFER	7824	19.7	19.5	1.0	0.0	1.7	0.0
CONZ	7405	16.3	16.3	0.9	0.3	2.2	0.0
GRAS	7845	12.9	12.7	1.4	0.1	1.9	−0.1
BOR1	7811	15.8	16.0	2.5	0.7	2.9	0.2
STR1	7825	5.2	5.7	1.5	0.6	3.0	0.2
BJFS	7249	19.1	19.2	3.1	0.7	3.4	0.6
THTI	7124	10.9	11.2	1.0	0.1	3.4	0.0
RIGA	1884	19.4	19.4	3.1	1.2	3.0	0.4
AREQ	7403	18.5	18.5	1.0	0.1	1.8	0.0
POTS	7836	7.0	7.3	2.3	0.5	2.5	0.1
MEAN		11.43	11.56	1.63	0.35	2.46	0.13

Units: mm

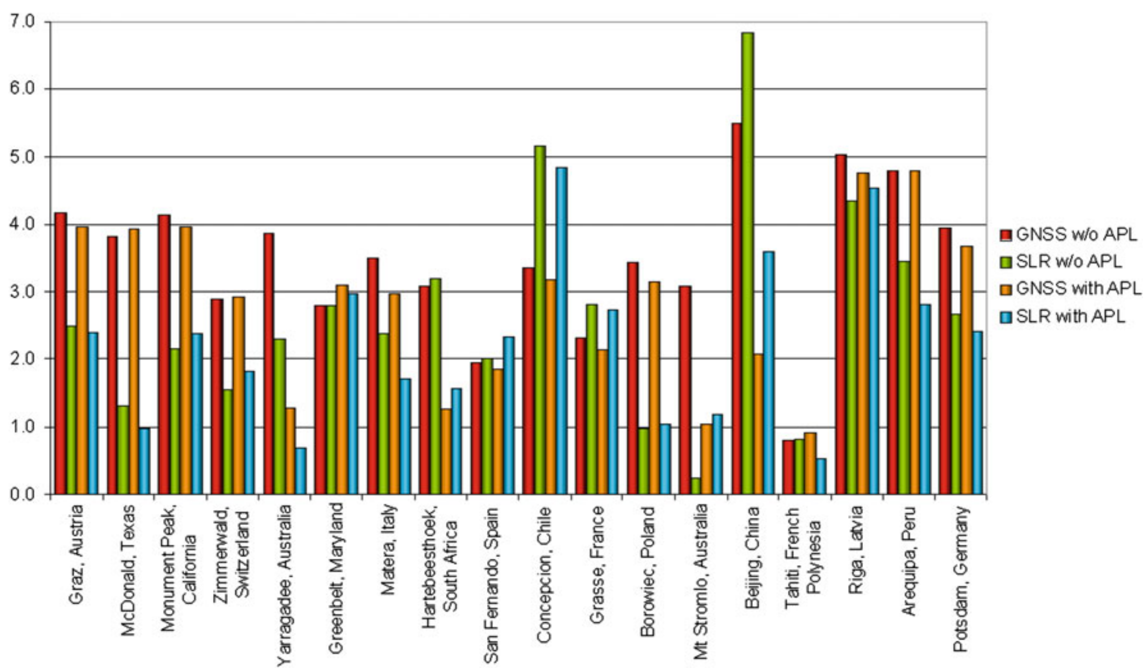

Fig. 11 Annual amplitudes of vertical components in mm for selected SLR-GNSS co-located stations for solutions with and without APL corrections

Table 7 Comparison between GNSS–SLR from local ties (used in ITRF 2008) and station coordinate differences derived from space geodetic solutions (with APL and without APL corrections)

Co-location		Local tie			3D difference of coord. between local tie and the solution	
GNSS station	SLR station	dx (m)	dy (m)	dz (m)	w/o APL (mm)	with APL (mm)
GRAZ	7839	−2.558	8.516	−1.321	12.1	11.9
MDO1	7080	22.394	8.467	23.408	9.4	9.4
MONP	7110	31.365	−5.456	20.526	9.1	9.7
ZIMM	7810	13.506	5.986	−6.420	4.2	3.8
YAR2	7090	−18.612	−12.467	−5.841	4.5	4.9
GODE	7105	54.230	97.009	93.863	4.1	3.7
MATE	7941	−29.157	−22.201	37.912	10.2	10.4
HARB	7501	−743.471	1,994.877	207.587	3.7	3.8
SFER	7824	45.041	−35.273	−89.594	97.8	97.9
GRAS	7845	−1.173	−81.348	5.620	4.8	5.0
BOR1	7811	25.767	−72.908	−0.324	9.0	8.1
STR1	7825	−38.054	4.584	58.108	12.2	11.7
BJFS	7249	16.517	−118.317	146.279	4.0	2.8
THTI	7124	−8.456	24.551	−28.299	23.8	23.8
RIGA	1884	3.401	−18.661	6.963	51.7	50.0
AREQ	7403	18.614	−0.547	21.499	3.0	2.7
POTS	7836	50.091	95.219	−40.438	3.9	4.4
Median					9.0	8.1
Mean					15.7	15.5

between GNSS and SLR solutions is reduced from 0.8 to 0.6 mm, implying a better consistency between SLR and GNSS with APL corrections.

5.2 Comparison with GNSS–SLR local ties

The differences between station coordinates derived from SLR and GNSS multi-year solutions can be compared to the local tie values used in the ITRF computations (Altamimi et al. 2011). Not all co-locations have, however, reliable local ties. Table 7 shows the comparison of the local ties used in the latest ITRF solutions with the estimated mean differences between SLR and GNSS coordinates in the solutions with and without APL. Two co-locations seem to have erroneous local ties, namely Riga and San Fernando. Most other differences do not exceed 10 mm, indicating a good agreement between estimated and measured distances. The SLR and GNSS solutions are processed independently without introducing local tie constraints on station coordinates. Therefore, the tie residuals are larger than those from the ITRF2008 analyses.

APL improves the consistency between estimated and measured ties by only 0.2 mm. But for stations with moderate APL impact the improvement is larger, e.g., from 9.0 to 8.1 mm for Borowiec, from 4.2 to 3.8 mm for Zimmerwald, and from 4.0 to 2.8 mm for Beijing. For only few stations APL has a negative impact on the agreement with the local tie (e.g., for Monument Peak), but in general, we may conclude that the agreement between SLR and GNSS station coordinates with local ties is slightly improved by applying APL.

5.3 Geocenter coordinates

Ideally, the time series of geocenter coordinates derived from different techniques (e.g., SLR, DORIS, GNSS) should be the same. The derived time series of geocenter coordinates are, however, always affected by orbit modeling problems, correlations with other estimated parameters, and the inhomogeneity of networks. An example for discrepancies in geocenter coordinate estimates has been described in Sects. 3.3 and 3.5 Here we compare the geocenter coordinates derived from SLR and GNSS solutions with and without applying APL. In theory, the largest impact of APL corrections should be in the Y component, because the largest Earth crust deformations occur in Central Asia and Central Canada (along the meridians 90°E and 90°W). The impact of APL on the X component should be rather small, because of the domination of oceans along the meridians 0° and 180°. The deviations of the Z component may be related to the land domination in the Northern hemisphere and the ocean domination in the Southern hemisphere.

Figure 12 shows a major impact of APL on the Y geocenter coordinate and a minor impact on the X geocenter coordinate

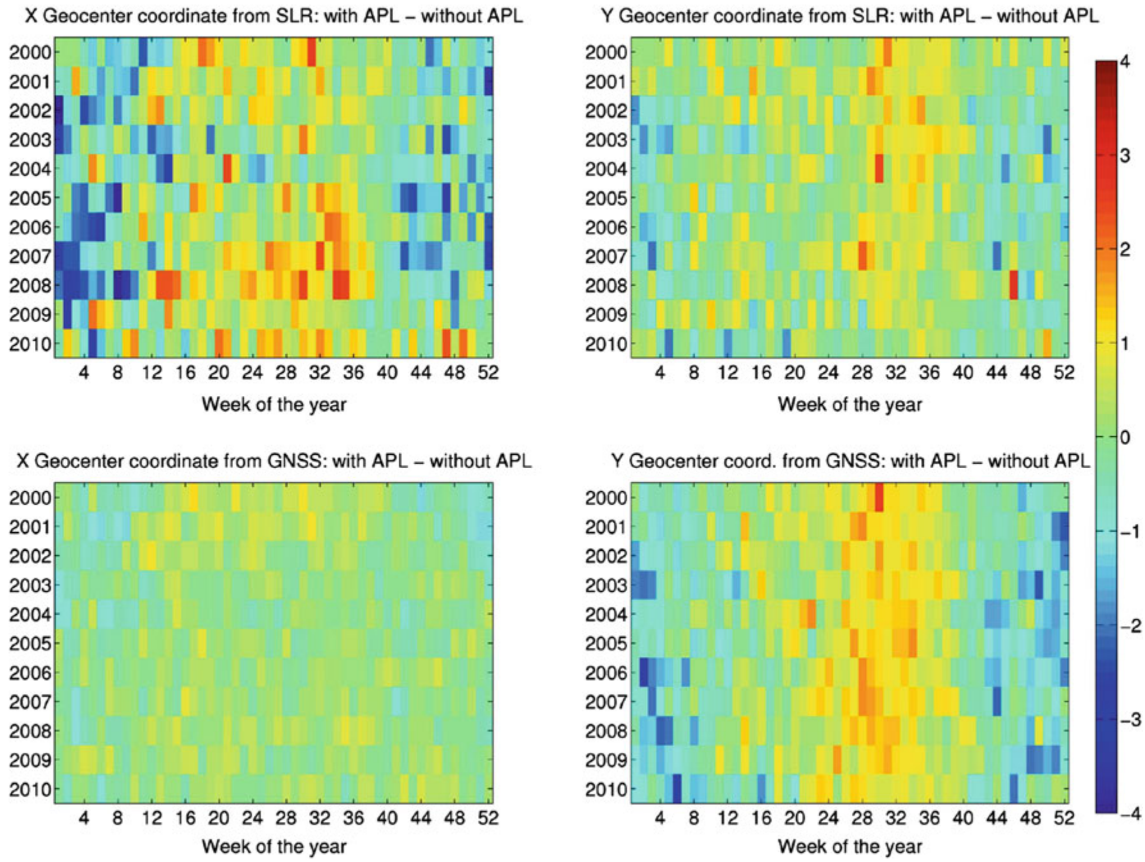

Fig. 12 Differences of geocenter coordinate estimates in SLR and GNSS solution due to APL corrections. Units: mm

in the GNSS solution. The same figure shows that a major impact on the *X* geocenter coordinate and a minor impact on the *Y* geocenter coordinate is for the SLR solution. Moreover, the estimated annual amplitudes in the GNSS solutions (1.57, 3.49, and 3.36 mm for the *X*, *Y* and *Z* components, respectively) do not agree well with SLR solutions (3.22, 2.57, and 3.93 mm for the *X*, *Y* and *Z* geocenter coordinates, respectively). This situation may be caused on one hand by the correlations between geocenter coordinates and empirical orbit parameters in GNSS solution (Thaller et al. 2012b) and on the other hand by the global distribution of SLR stations (see Fig. 10). The network of SLR stations is unbalanced with most of the high performing core stations along the *X* axis. SLR stations located along the *Y* axis are either coastal stations with minor impact of APL or low performing inland stations. The GNSS network is to a great extent well balanced with also high performing inland stations along the *Y* axis. The difference in the global distribution of SLR and GNSS stations may explain the different impact on geocenter coordinates in Fig. 12. There is also a reduction of annual amplitudes of the *X* and *Y* geocenter components in both, SLR and GNSS solutions, when applying APL, amounting 0.15, 0.38, 0.04, and 0.82 mm for the SLR *X*, SLR *Y*, GNSS *X*, and GNSS *Y* components, respectively.

Figure 13 gives some additional information regarding the impact of the a priori applied ANTL model on geocenter coordinates. To assess the effect of a priori Vienna ANTL corrections on geocenter coordinates the deformations in North, East, and Up directions were transformed to Cartesian coordinate system, by integration over the Earth surface, making use of the Eqs. 3 and 4 described by Dach et al. (2011). The total impact of ANTL model on the geocenter is shown in Fig. 13a. The impact of ANTL model on the geocenter *Y* coordinate (see Fig. 13a) is closer to the impact on the *Y* geocenter obtained from the GNSS solution than from the SLR solution (see Fig. 12). However, in both cases the magnitude of the a priori impact is larger than the obtained differences in the *Y* geocenter coordinate time series. The differences can be explained by the distribution of observing stations. Figure 13b is generated in a similar way as Fig. 13a, but the inhomogeneous distribution of SLR stations and irregular observation epochs are taken into account. Therefore, Fig. 13a shows the a priori ANTL signal as seen by the SLR network. The difference of both a priori impacts from Fig. 13a, b implies that the SLR network is far less sensitive to geocenter variations in the *Y* component, due to the uneven distribution of the stations and the sparse observations. For the *Y* component, the theoretical impact of ANTL on the

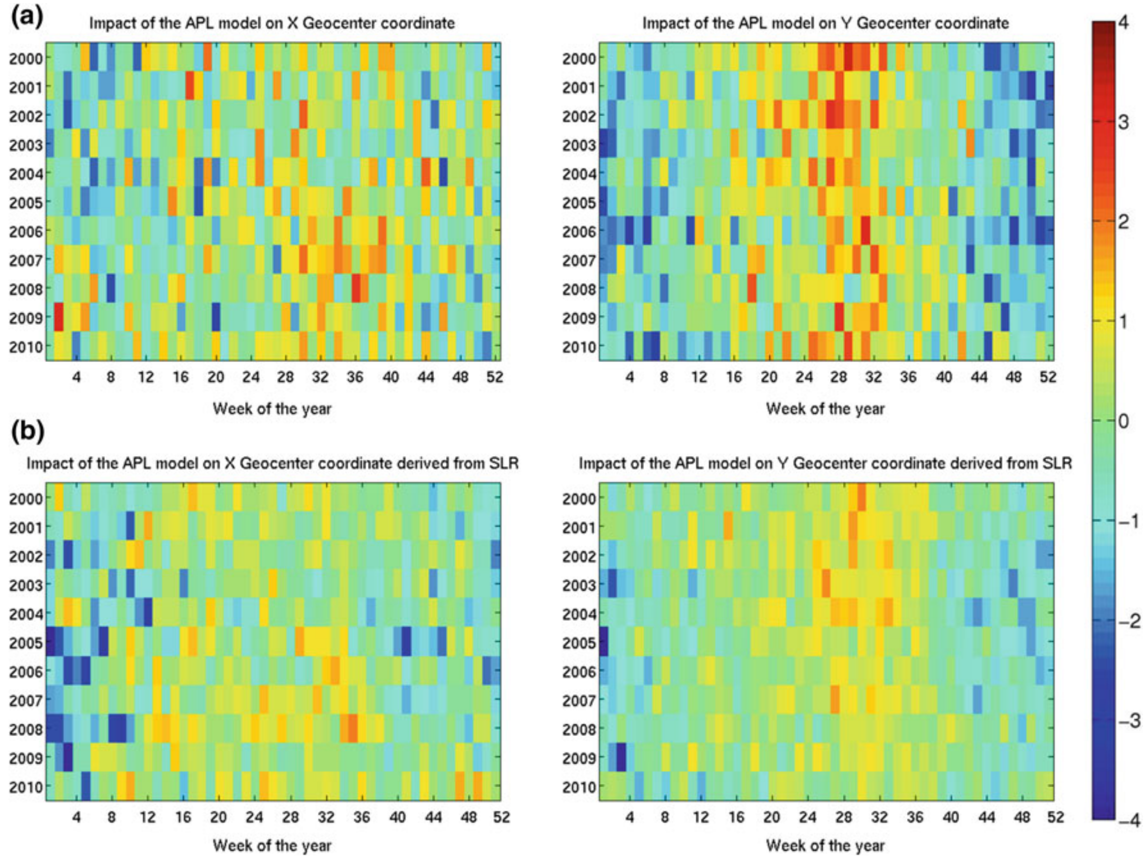

Fig. 13 The impact of Vienna ANTL corrections on *X* and *Y* geocenter coordinates; **a** the impact of the a priori grid model, **b** the impact of the model concerning the uneven distribution of SLR stations and the observation epochs. Units: mm

geocenter (Fig. 13b) is in a good agreement with the impact of ANTL corrections from the SLR solution (Fig. 12). We can conclude that for the SLR network there is a significant network effect that can affect the geocenter coordinate estimates.

The comparison between the a priori impact of the ANTL (Fig. 13a) and the resulting variations (Fig. 12) for the *X* geocenter coordinate shows that the variations in the SLR solutions are overestimated and, on the other hand, the variations in GNSS solution are underestimated. Different patterns between the results obtained from the SLR solutions and the a priori ANTL impact can be partly explained by the distribution of the SLR stations and the sparse observations (Fig. 13b), but the magnitude of the estimated *X* geocenter variations remains larger than theoretical a priori variations. The variations of the *X* geocenter coordinate obtained from the GNSS solutions suggest that the ANTL corrections might be absorbed by other parameters than station and geocenter coordinates. The GNSS network is well distributed as compared to the SLR network and the observations are continuous for most of the GNSS stations. Therefore the uneven distribution of the stations cannot solely explain the differences of the *X* geocenter between the a priori ANTL impact and the impact obtained from GNSS solution.

6 Other methods of correcting for ANTL

Let us now test whether it is sufficient to take into account ANTL by applying the corrections in post-processing or using regression factors between time series of local pressure and the vertical site displacements. Regression factors may be derived, because every SLR station measures simultaneously laser ranges and meteorological data. Therefore, reliable values for air pressure are available for all SLR stations. This approach is motivated by the compatibility to previous ANTL studies for SLR. However, one has to bear in mind that the full integration using Green's function over the surrounding area of about 2,000 km is the most favorable approach (Dach et al. 2011).

6.1 ANTL corrections in post-processing

The SLR station coordinates computed with ANTL corrections at the observation level are compared with the station coordinates with ANTL corrections applied a posteriori. The resulting differences, e.g., in January 2010 amount up to 4.2, 2.4, and 2.5 mm for the North, East and height components, respectively, for the station coordinates of Altay in

Table 8 Differences between SLR station coordinates obtained from the solution by applying ANTL at the observation level and by applying ANTL in post-processing

SLR station	N	E	U	Total
1879 Altay, Russia	4.16	2.37	−2.43	5.37
7080 McDonald, Texas	−1.02	0.00	0.35	1.08
7090 Yarragadee, Austr.	0.72	0.06	0.26	0.77
7105 Greenbelt, Maryland	−0.76	−0.47	0.30	0.94
7119 Haleakala, Hawaii	−0.09	0.22	−0.05	0.24
7124 Tahiti, French Pol.	0.17	−1.12	−0.13	1.14
7237 Changchun, China	0.35	1.22	0.35	1.32
7308 Koganei, Japan	0.46	0.73	0.05	0.86
7405 Concepcion, Chile	−0.87	0.18	0.33	0.95
7824 San Fernando, Spain	−0.06	0.53	0.26	0.59
7825 Mt Stromlo, Austr.	0.17	−0.33	0.41	0.55
7840 Herstmonceux, UK	0.04	0.10	−1.06	1.07
7845 Grasse, France	−0.95	−0.49	0.12	1.08
7941 Matera, Italy	−0.08	−0.38	−0.22	0.45
Mean	0.66	0.31	0.57	0.93

Week 4 in January, 2010, Units: mm

Russia (see Table 8). When estimating seven parameters of Helmert transformation the residual differences are 3.7, 2.2, and 2.3 mm for the North, East and height component, for the same station (not shown here). The mean ANTL correction for Altay is 6.7 mm, indicating that most of the ANTL signal cannot be properly considered when applying ANTL corrections in post-processing, due to data sampling. Therefore, correcting the ANTL in post-processing seems to be insufficient and cannot account for the ANTL signal for SLR station coordinates. For 6 out of a total of 14 stations from Table 8 the total difference exceeds 1 mm. The median value for all stations is 0.93 mm.

Statistical tests lead to insignificant differences, because the a posteriori sigma of the vertical station component for Altay is 5.5 mm (whereas it is about 2.0 mm for the core stations), due to only 29 LAGEOS normal points registered by Altay. The atmospheric loading corrections are, however, at the same level or even smaller than the accuracy of the determined station coordinates. Moreover, when applying ANTL corrections in post-processing the other estimated parameters remain unchanged (e.g., LAGEOS orbits and ERPs), so the regional Earth's crust deformations, having an impact on all estimated parameters, are not taken into account appropriately. The coordinate differences between ANTL corrections applied at the observation level and in post-processing may slightly be reduced when estimating station coordinates with a higher time resolution. Unfortunately, the number of SLR observations to LAGEOS does not allow deriving reliable 1-day solutions. The problem of application of the loading corrections at the observation level or in post-processing is a fundamental question facing geodesists and geophysicists today, and therefore, needs further analysis.

6.2 Regression factors

In this approach, the corrections derived from Vienna ANTL files are compared with ANTL corrections estimated using regression factors and reference pressure values. We use the pressure readings from meteorological observation files for selected SLR core stations and estimate the ANTL corrections on a basis of regression factors from Bock et al. (2005); Otsubo et al. (2004), and the IERS Conventions 2003 (McCarthy and Petit 2004). Figure 14 shows that the regression factors can reduce the ANTL only to a very small extent, because the agreement between corrections from the Vienna ANTL files applied for the Riyadh station and corrections from regression factors estimated on the basis of different publications is unsatisfactory.

The Riyadh station shown in Fig. 14 is an example of one of the fourteen SLR core stations with the measurable impact of ANTL. The correlation coefficients between corrections from regression factors and corrections from Vienna ANTL files for selected SLR core stations are 0.12, 0.31, 0.33, and 0.38 for Riyadh, Yarragadee, McDonald, and Zimmerwald, respectively, implying that the regression factors may account only for roughly 30 % of the total ANTL signal. These results are in good agreement with other comparisons between direct ANTL corrections and corrections using regression factors (e.g., Dach et al. 2011 for GNSS solutions).

7 Summary and conclusions

The SLR solutions are very sensitive to atmospheric and ocean loading corrections. OTL corrections have the largest impact on the SLR station coordinates, geocenter coordinates, ERPs and LAGEOS orbits, but the impact of ANTL cannot be neglected either. The ATL corrections are very small and they affect only the LAGEOS orbits, mainly due to CMC. The repeatability of coordinates of coastal SLR stations is mostly improved when applying OTL corrections (up to 73 % for Tanegashima in Japan), whereas inland stations achieve a better repeatability when applying ANTL corrections (up to 12 % for Altay in Russia). The overall improvement of 3D SLR station repeatability is 19.5 %, 0.2 %, and 3.3 %, due to the OTL, ATL, and ANTL corrections, respectively, whereas the general reduction of the annual amplitudes of SLR station height is 30 %, 2 %, and 10 %, due to OTL, ATL, and ANTL corrections, respectively.

We assessed the impact of the Blue-Sky effect on all SLR stations. The effect exceeds 2.0 mm for nine SLR inland stations. For the Golosiv station in Ukraine the Blue-Sky

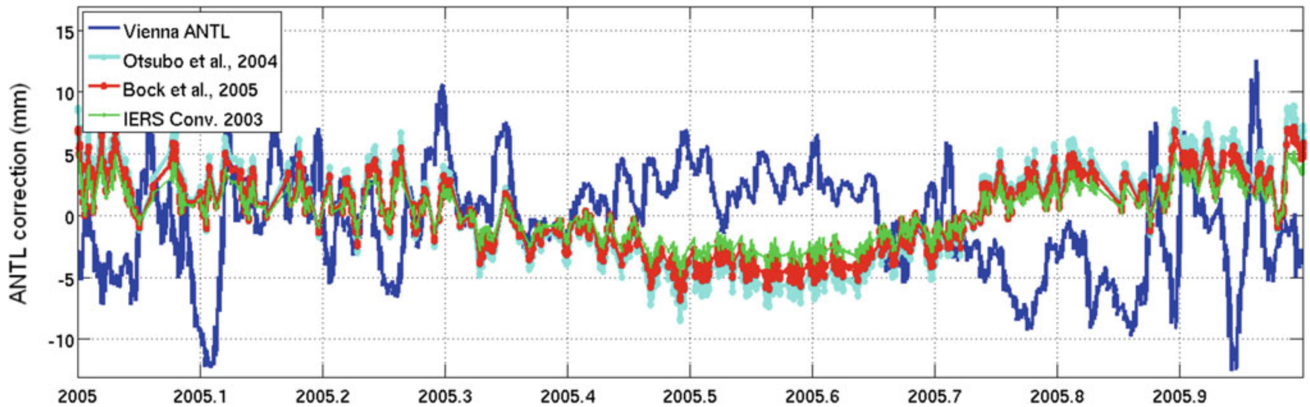

Fig. 14 ANTL corrections taken directly from the Vienna ANTL files and estimated ANTL corrections using regression factors between time series of local pressure and vertical displacements. Different reference pressures are considered. The figure shows the comparison for 2005 for the SLR station Riyadh

effect reaches even 4.4 mm, due to sparse SLR data collected by this station. The mean Blue-Sky effect is 1.1 mm for all SLR stations. Our results agree well with the Blue-Sky effect assessed for six stations by Otsubo et al. (2004). The Blue-Sky effect causes inconsistencies between SLR and microwave solutions. Applying ANTL corrections slightly improves the inner stability of SLR solutions and reduces the discrepancies between GNSS and SLR solutions. As a result, the estimated GNSS–SLR coordinate differences fit better at the 10 % level to the local ties at the co-located stations when applying APL corrections. The discrepancies in the tie residuals may also be due to technique errors, both GNSS and SLR, and perhaps in the ground survey measurements themselves. The inter-technique SLR-GNSS improvements due to APL are, however, rather small.

The annual amplitudes of geocenter coordinates are reduced due to the OTL and ANTL corrections by 0.4 and 0.7 mm for the Z component. The reduction is different in GNSS and SLR solutions, which can be caused by the global distribution of observing stations and by the unbalanced SLR network. In GNSS solutions the annual amplitude of the Y component of the geocenter is maximally reduced (0.82 mm for Y and only 0.05 mm for X component), whereas in SLR solutions the reduction of the annual amplitude of X geocenter component is somewhat larger (0.38 mm) than the reduction of the Y component (0.15 mm).

Systematic seasonal effects, such as atmospheric pressure variations in the Northern hemisphere, cannot be appropriately accounted for, when the ANTL corrections on station coordinates are omitted or only applied in post-processing analysis. In analogy to the VLBI network, the ignored loading in SLR shifts the origin away, from what should be the origin of the rotation axes. Therefore, the seasonal signal which occurs, e.g., in geocenter and in pole coordinates, can appropriately be accounted for when correcting for ANTL.

The loading corrections applied at the observation level and in post-processing lead to different results, because of an irregular distribution of the SLR measurements in time and because of the Blue-Sky effect. The differences reach 5.37 mm for the inland station Altay in Russia. Applying APL corrections in post-processing takes only the effect on the station coordinates into account. We showed in Sect. 3, however, that all parameters are affected by APL, and in Sect. 5.3 that there is a difference between the a priori impact of ANTL model on the geocenter coordinates and the resulting geocenter variations, due to the network effect and the absorption of ANTL corrections by the parameters other than geocenter coordinates. Estimated values of ERPs and satellite orbits benefit from applying APL corrections at the observation level. Eventually, applying the loading corrections in post-processing cannot fully compensate the Blue-Sky effect, because this method implies a continuous and uniform distribution of the measurements in time, which is typically not the case for SLR.

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