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Geocentre motion measured with DORIS and SLR, and predicted by geophysical models

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Abstract Geocentre motion signals measured by satellite geodesy and those predicted from the observed mass redistribution in the ocean, atmosphere and terrestrial waters over 1993.1–2003.0 are analysed and compared under two viewpoints: the amplitudes and phases of the seasonal components, and the spectral signature of the non-seasonal components. The geodetic signals partly match the geophysical variations in the seasonal band, with possible remaining annual and semi-annual errors in both techniques, at the millimetre level in the equatorial plane for Satellite laser ranging (SLR) and Doppler Orbitography and radiopositioning integrated on Satellite (DORIS), and at the centimetre level in T_z (Z-axis translation) for DORIS. Unlike SLR, the DORIS annual signatures in all three geocentre components have strongly varying amplitudes after 1996. The amplitude of the annual geophysical signal in T_y is slowly growing with time. All three geophysical fluids contribute to this effect. The magnitude of the geophysically derived long-term geocentre motion is of the same magnitude in the T_x, T_y and T_z directions, with a 0.5–1.0 mm Allan standard deviation for the 1-year sampling time, while the geodetic values are 2 mm in the equatorial plane for both SLR and DORIS, 4 mm for SLR and 9 mm for DORIS in the T_z direction. The mismatch of the geodetic signal with the geophysical one in the inter-annual band is suggested to be due partly to excessive geodetic noise and partly to underestimated geophysical signal.

Keywords Reference frames · Geocentre · Geophysical fluids · DORIS · SLR

1 Introduction

Motions of the Earth's centre of mass (geocentre) are ascribed to time-varying mass distribution in fluid layers of the Earth: atmosphere, oceans and continental waters. The observation and modelling of these changes give access to a geometrical description of geocentre motion. On the other hand, the motion of the geocentre with respect to a terrestrial reference frame (TRF) attached to the crust can be described by time-series of the coordinates of the origin of the individual data sets derived from satellite laser ranging (SLR), Doppler orbitography and radiopositioning integrated on satellite (DORIS) or global positioning system (GPS) relative to a conventional origin.

From the geodesist's point of view, the accuracy of the geocentre motion estimates is a way to asses the global consistency of geodetic-satellite data analysis. From the

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geophysicist's point of view, the challenge is the comprehensiveness and physical relevance of the modelling of the fluid layers. The comparison of the two types of measurements is expected to bring insight on remaining errors in either or both fields of research.

The International Earth Rotation and Reference System Service (IERS) conducted in 1997–1998 an Analysis Campaign (Ray 1999) to better understand the magnitude of geocentre motions and the ability of space geodesy to detect them. The conclusions were that, while a tidal model could be recommended to correct the diurnal and semi-diurnal motions, the geodetic measurements of the seasonal and longer term motions were still subject to analysis errors. On the other hand, the geophysically inferred geocentre motions appeared to be model dependent and not complete at all frequencies.

Meanwhile, a number of encouraging studies showed that it is possible to reconcile the geodetic measurements with the geophysically inferred motions, e.g. Dong et al. (1997, 2003) with 1993–2002 GPS data, Chen et al. (1999) with 1992–1997 SLR data, Bouillé et al. (2000) and Crétaux et al. (2002) with 1993–1998 DORIS (on TOPEX/Poseidon only) and SLR data, in particular in the seasonal band. These studies mostly intercompare the geophysically derived geocentre motion prediction and use the geodetic data as external evidence. They provide strong evidence that most of the observed geocentre motion can be ascribed to the atmospheric, oceanic and terrestrial fluid mass motions.

Summarizing the annual component results of several previously published articles, Dong et al. (2003) conclude that SLR best matches the geophysical expectation in both amplitude and phase, and that DORIS results are close to the SLR ones except for the amplitude in the T_y (Y-axis) direction. Determining the seasonal geocentre motion from GPS data, they find a satisfactory agreement with the SLR results in the equatorial plane, and sizeable disagreement in amplitude and phase in the T_z axial direction. Seasonal geocentre motion derived by Wu et al. (2002, 2003) from crustal displacements measured by continuous GPS using a method proposed by Blewitt et al. (2001) is in good agreement with the SLR results.

Since this paper is on the performance of the DORIS system, we decided to concentrate on the three long time-series of geocentre coordinates available in the framework of the International DORIS Service (IDS), and spanning more than 10 years (1994–2005). As opposed to the above-mentioned DORIS solutions, these series are based on several satellites in addition to TOPEX/Poseidon. Thanks to the SPOT and ENVISAT missions, at least three satellites are available since 1994, and five since 2002, for global geodetic applications. In order to keep track of the SLR reference, we used a geocentre series derived by two of us (P. Berio, D. Coulot) over the same time interval from the observations of LAGEOS-I and -II.

The purpose of this paper is to investigate, on the one hand, the matching in the seasonal and non-seasonal parts of the spectrum of geodetic data with each other, and on the other hand, the matching of geodetic data with a model derived from the analysis of the global motions of geophysical fluids. The investigation of the agreements and disagreements should help us to qualify the ability of satellite geodesy to detect motions induced by the global geophysical fluids, as well as to learn more about remaining errors in the geodetic and geophysical data analysis.

The geodetic and geophysical data sets used are described in Sect. 2 and discussed in Sect. 3. The seasonal and interseasonal parts of the signal are investigated in Sects. 4 and 5, respectively.

2 Geodetic and geophysical data

2.1 Geodetic data

The definition of the geocentre is a topic of crucial importance in the Earth deformation theory as well as in the definition and maintenance of the International Terrestrial Reference Frame (ITRF). Two concepts are relevant to our study (Blewitt 2003; Dong et al. 2003): the centre of mass (CM) of the total Earth system, the natural reference for orbit dynamical modelling, and the centre of surface figure (CF), the origin of a TRF derived from the analysis of global space geodetic data, e.g. ITRF2000 (Altamimi et al. 2002).

In practice, the geocentre motion relative to some reference position can be determined using satellite observations from the Earth's crust. By the virtue of the dynamical method used in the analysis, a set of station coordinates derived from satellite observations realizes a TRF whose origin is located at the Earth's centre of mass at the mean epoch of measurements. This principle may be used in two ways: (1) by estimating the degree-one terms of the spherical harmonic expansion C_{11}, S_{11}, C_{10} of the gravity field at repeated epochs, e.g. every week, using a unique TRF; (2) by estimating time-series of sets of station coordinates, also called TRFs, in a free-network approach, with fixed values of the gravity field coefficients, and then referring the time-series of TRFs to some fixed TRF.

Time-series of translation parameters of the individual TRFs relative to ITRF2000, T_x, T_y and T_z, are produced in this unification process. They describe the motion of CM with respect to CF. The two approaches are equivalent. The C_{11}, S_{11} and C_{10} coefficients are proportional to T_x, T_y and T_z, respectively. The multiplying factor is $1.732 a_e C_{00}$, where a_e is the major semi-axis associated with the gravitational model (Greff et al. 2005). The geodetic solutions available for this study were obtained by the second method.

The time-series analysed in this study are listed in Table 1, using the IDS three-character acronyms in the case of DORIS. More detail on the IDS and its observing programme is given by Tavernier et al. (2005, 2006). The DORIS series are based on tracking by the SPOT2, SPOT3, SPOT4 and SPOT5 remote sensing satellites, and the TOPEX/Poseidon and ENVISAT altimetry satellites. The SPOT2 and TOPEX/Poseidon satellites provide the major part of tracking data.

Table 1 Time-series of TRF origin/geocentre coordinates

Series	Data span	Interval	Reference/description
DORIS			
IGN-JPL	1993.0–2005.6	Weekly	ign03wd01.geoc.dsc ([a])
INASAN	1992.8–2004.6	Weekly	ina05wd02.geoc.dsc ([a])
LEGOS-CLS	1993.0–2005.1	Monthly	lca.stcd.dsc ([a])
SLR			
OCA	1993.0–2005.0	Weekly	Coulot (2005)
Geophysical			
Atmosphere	1979.0–2003.0	Monthly	Kistler et al. (2001) (NCEP)
Oceans	1993.0–2003.0	10 Daily	Stammer et al. (2002) (ECCO)
Terrestrial	1985.0–2004.3	Monthly	Milly and Shmakin (2002) (LAD)

[a]Files available online at ftp://cddis.gsfc.nasa.gov/doris/products/geoc

The orbit arc-lengths are 1 day for IGN–JPL (Institut Géographique National–Jet Propulsion Laboratory) and INASAN (Institute of Astronomy Russian Academy of Sciences) data, and 3.5 days for LEGOS–CLS (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales–Collecte Localisation Satellites) data. The IGN–JPL (Willis et al. 2005) and INASAN series were obtained using the GIPSY/OASIS-II software (Heflin et al. 1992) and similar analysis strategies. The DORIS LEGOS–CLS series (Soudarin et al. 1999) was obtained using the GINS/DYNAMO software developed by the French Groupe de Recherches de Géodésie Spatiale (GRGS). The DORIS analysis schemes are described in the online IDS files listed in Table 1. The LEGOS–CLS DORIS solution was derived by the same team as the Bouillé et al. (2000) and Crétaux et al. (2002) solutions. The SLR solution was derived from LAGEOS-I and -II tracking data by the GEMINI department of the Observatoire de la Côte d'Azur (OCA), using the GINS/DYNAMO software. The computed orbit arc-length is 7 days. The analysis method is described by Coulot (2005).

In all cases, the series of coordinates of the TRF origin were derived by their authors. They may indeed include possible systematic errors arising from problems in various areas, like the data themselves, data processing, or projection of the results into ITRF2000.

2.2 Geophysical data

The geophysical fluids that cause changes of position of the geocentre are studied here separately for the atmosphere, oceans and continental waters. The series of geocentre coordinates are derived from global models describing the time-evolution of mass redistribution in these three fluid layers. They are listed in Table 1.

The degree-one terms, C_{11}, S_{11} and C_{10}, are extracted from spherical harmonic expansions of the gravitational potentials of the global fluids.

The selected models are the revised NCEP (National Centers for Environment Prediction, USA) series for the atmosphere (Kistler et al. 2001), ECCO (Estimating the Circulation and Climate of the Ocean) for the oceans (Stammer et al. 2002) and LAD (Land Dynamics) for the terrestrial waters (Milly and Shmakin 2002). These models were established in parallel, considering some interactions such as the NCEP atmospheric pressure over the oceans. However, a difficulty arises when using them for predicting geocentre motion, as they may not ensure mass conservation, individually or taken together. The effect from incoherent mass balance is neglected here.

Other assumptions may be considered. As an example, Clarke et al. (2005) tested the effect of constraining total mass conservation by allowing mass changes in the oceans through tidal response to the total load. This theory results in amplifying the expected annual component of the geocentre motion by a factor of 1.43, 1.13 and 1.28 in T_x, T_y and T_z, respectively, with negligible phase shifts.

3 Data accuracy and precision

In addition to their different origins, the generation of the two types of data used in this work is largely different. On the one hand, the geophysical evaluations are derived from a four-dimensional analytical modelling of gridded geophysical atmospheric, oceanic and continental water data, which are global model outputs from numerical analysis including assimilated observations. Their accuracy is dependent on the comprehensiveness of the observation systems and the relevance of the modelling.

On the other hand, the geodetic evaluations are derived from discontinuous satellite observations performed by station networks that sample the Earth in an imperfect manner. The continuity of the solutions is possible thanks to the permanent character of the geodetic network and to the modelling of the orbit considering gravitational and non-gravitational forces. Their accuracy is dependent on a number of analysis models. The possible systematic errors that may affect the accuracy of the data, as well as the precision and scatter of the times-series of both types are studied in in the following sections.

3.1 Geodetic data

3.1.1 Systematic errors

The geodetic geocentre data accuracy may be affected in different frequency bands by a number of parameters, linked to the satellite orbit configurations and to the way the observations are modelled and analysed.

Studying the case of GPS measurements, Penna and Stewart (2003) showed that the one sidereal day repeat orbit of the constellation and the practice of analysing the data in 24-solar-hour sessions result in aliasing mis-modelled sub-daily tidal signals into annual and semi-annual spurious station motion. Based on a simulation of global GPS observations, Stewart et al. (2005) conclude that the largest effect amounts to 45% of the input model error for the semi-annual aliased image of the S2 tide, with varying phases according to the station location. However, they did not estimate how these errors would be propagated to GPS-derived geocentre motion.

The impact of the orbit configuration on the annual and semi-annual components of the station coordinates is more favourable in the DORIS case. Tidal-terms' aliasing was of particular concern in the design of the TOPEX/Poseidon and ENVISAT altimetry missions. Parke et al. (1987) describe the constraints under which the altimetry satellite orbits are chosen to avoid coincidence of any aliased period with frequencies of particular interest in oceanic studies, including the zero-frequency and the annual or semi-annual periods.

The TOPEX/Poseidon data are subject to modelling errors of solar pressure accelerations on the satellite orbit, which are seen at the period of the node motion with respect to the direction of the Sun (117 days). Oscillations with this period are found in the station coordinates' time-series (Le Bail 2006). Aliased signals or other spurious variations in the station coordinates may propagate into the measured geocentre motion, which could in turn exhibit some of the expected peaks.

Searching the spectrum of the time-series of geocentre coordinates, both the 117-day component and its first harmonic (59 days) are found in the DORIS series, at the 5–10 mm level in T_x, T_y, and the 50 mm level in T_z. Therefore, these terms were also filtered out when annual and semi-annual corrections were applied for studying the longer term spectral characteristics of the signal.

Apart from the seasonal and aliased oscillations, the IGN–JPL T_x and T_y spectra have a couple of peaks at the 1 mm level in the 20–50-day period bands, rising above a 0.5 mm background; the T_z spectrum has an 8 mm peak at 53 days and a couple of peaks at the 5 mm level in the 15–50-day period bands, rising above a 3 mm background. The INASAN T_x spectrum has a general 1 mm level; the T_y spectrum has a 2 mm peak at 14 days, rising above a 0.8 mm background; the T_z spectrum has a 6 mm peak at 50 days, rising above a 5 mm background. The LEGOS–CLS T_x spectrum has a 1 mm peak at 75 days, rising above a 0.3 mm background; the T_y spectrum has a 0.9 mm peak at 170 days, rising above a 0.3 mm background; The T_z spectrum has a 5 mm peak at 104 days, rising above a 2 mm background.

In the case of the LAGEOS satellites, using the Penna and Stewart (2003) model, the aliasing periods are found to be 35 and 17.5 days. No significant peaks are found in the spectra of the SLR(OCA) geocentre time-series. The T_z series has a 1.6 mm peak at 14 days, rising above a 1 mm background. The background of the T_x and T_y time-series spectra is at the 0.5 mm level.

Other data analysis features may impact the derived vertical motion of the stations, which could be partly propagated as spurious geocentre motion. In the case of the GPS and DORIS radioelectric techniques, the modelling of the tropospheric zenith delay may also influence the height measurement. Technique-specific corrections may also contribute to systematic differences in height, e.g. elevation cut-off or beacon phase centre offset in the DORIS case. Willis et al. (2006) studied the sensitivity of T_z to inaccuracy of the antenna phase centre location with respect to the satellite centre of mass. They conclude that the estimation of T_z from the SPOT satellites could be biased by up to 10 mm. The SLR data analysis includes the estimation of range biases over 140-day time intervals that might affect the station coordinates, and thus the geocentre.

Atmospheric loading changes the vertical station positions with an annual signature of amplitude 1–2 mm in general, reaching 3 mm in some cases (McCarthy and Petit 2004), and sub-millimetric level in the inter-annual frequencies (Le Bail et al. 2006). This effect is corrected in the LEGOS–CLS DORIS and the SLR(OCA) analyses, but not in the IGN–JPL and INASAN ones.

The reference gravity field model or the datum definition algorithm may also influence the derived motion of the TRF origin. In the case of DORIS, Tavernier et al. (2006) give an estimation of such discrepancies, based on the results of the 2003 IDS Analysis Campaign. The effect of the change of the gravity field model on the amplitude of the annual term is at the 1 mm level in both the equatorial and axial directions. The inter-annual effect is at the 1 mm level in T_x and T_y, and at the 4 mm level in T_z. Changes in the datum definition options have similar effects of the same, except for the amplitude of the annual term in T_z, which may be affected at the 10 mm level. Willis and Heflin (2004) reached similar conclusions.

3.1.2 Precision and short-term scatter

Table 2 gives information about the quality of the data in Table 1: median formal uncertainties and high frequency scattering, measured by the standard deviation of the time-series less their annual, semi-annual, 117-day, 58.5-day periodic, and long-term trend over the 1993.1–2003.0 time-span for which both geodetic and geophysical data are available. To ease the comparison of scattering of the various series, the values obtained from the original series are propagated to the

Table 2 Statistical features of time-series of TRF origin/geocentre coordinates, where τ is the data interval, σ is the median formal uncertainty. The short-term scattering ρ is given for the original time interval τ and propagated to 30 days based on the data spectrum (see text). Unit: mm

Series	τ	T_x			T_y			T_z		
		σ	ρ		σ	ρ		σ	ρ	
	days	τ	τ	30 days	τ	τ	30 days	τ	τ	30 days
DORIS										
IGN-JPL	7	2.1	4.7	4.7	2.1	5.1	2.4	1.7	26.1	26.1
INASAN	7	2.0	6.4	6.4	2.1	6.6	3.1	2.0	27.2	27.2
LEGOS-CLS	30	0.1		3.4	0.1		2.9	0.1		17.6
SLR										
OCA	7	1.5	3.8	1.8	1.6	3.5	1.7	2.4	8.9	4.3
Geophysical										
Atmosphere	30			2.1			0.7			0.8
Ocean	10		4.0	2.3		3.1	1.8		2.6	1.5
Continental water	30			0.2			0.1			0.3
Root-sum-square				3.1			1.9			1.7

1-month interval, based on the non-seasonal spectral signatures studied in Sect. 5 (Figs. 5, 6). White noise is assumed for SLR, the oceanic contribution and the DORIS T_y; flicker noise is assumed for DORIS T_x and T_z.

In the case of the geodetic geocentre data, which are derived from least-squares analysis, the formal uncertainty is a measure of the precision of the individual values, reflecting their internal consistency for the modelling used. The SLR and DORIS formal uncertainties are close to each other, but their scattering is not always so.

Considering the equivalent 1-month interval, the scatter level in the equatorial plane is 2–5 mm for DORIS, 2 mm for SLR, and 2–3 mm for the geophysical signal. In T_z, the DORIS solutions have a 20–30 mm scattering level, to be compared with 4 mm for SLR and 2 mm for the geophysical expectation.

Part of the DORIS T_z scatter might be connected with antenna phase centre correction errors for the SPOT satellites (Willis et al. 2006). This effect would introduce internal inconsistency in the existing multisatellite solutions that would in turn enhance the time-series scatter. The scatter of the DORIS results derived by the GIPSY/OASIS II software and modelling is slightly higher than those derived by the GINS/DYNAMO sofware, which in turn are higher than those derived for SLR, also by the GINS/DYNAMO software and modelling. The higher T_z scatter in the IGN–JPL and INASAN solutions might be related to shorter orbital arcs (1 day) than that in the case of LEGOS–CLS (3 days) (P. Willis, private communication).

3.2 Geophysical data

3.2.1 Accuracy

The level of accuracy of the models used to derive the mass redistributions in the atmosphere, ocean and terrestrial waters is difficult to assess. Several authors (Chen et al. 1999; Bouillé et al. 2000; Crétaux et al. 2002) made comparisons of geocentre seasonal motion predicted from various geophysical models. The amplitude of the annual and semi-annual geocentre motion due to atmospheric and oceanic mass displacements agree with each other within 10%, but this may merely reflect the convergence of parallel treatments of observational data that are far from being comprehensive.

The models for terrestrial water degree-one effects are still quite uncertain. The predicted seasonal T_z motion is affected by the poor knowledge of water storage over Antarctica. Thanks to the recent availability of monthly time variations in the gravity field derived from the Gravity Recovery And Climate Experiment (GRACE) mission, the knowledge of regional fluid mass redistribution cycles should improve the situation.

As an example, Ramillien et al. (2005) show that the observed amplitude of the seasonal cycle of water storage in large intertropical fluvial basins may significantly disagree with the LAD model prediction, which might be reflected in the geocentre motion prediction in the equatorial plane. Meanwhile, as pointed out by Clarke et al. (2005), the modelling option for ensuring mass conservation of the set of models used may give rise to discrepancies even larger than the effect itself.

Despite the difficulties mentioned above, the seasonal component of the fluid mass redistributions is relatively well described by the global models, while the accurate modelling of smaller amplitudes inter-annual variations remains problematic.

3.2.2 Short-term scatter

Formal uncertainties are not available for the geophysical solutions, which have a more indirect connection with the original observations. The scattering of the three contributing time-series is listed in the second part of Table 2.

To help the comparison with the geodetic data scattering, the root-sum-square (RSS) of the standard deviations for the 1-month interval for the atmospheric and oceanic signals and flicker noise for the continental water contributions is also

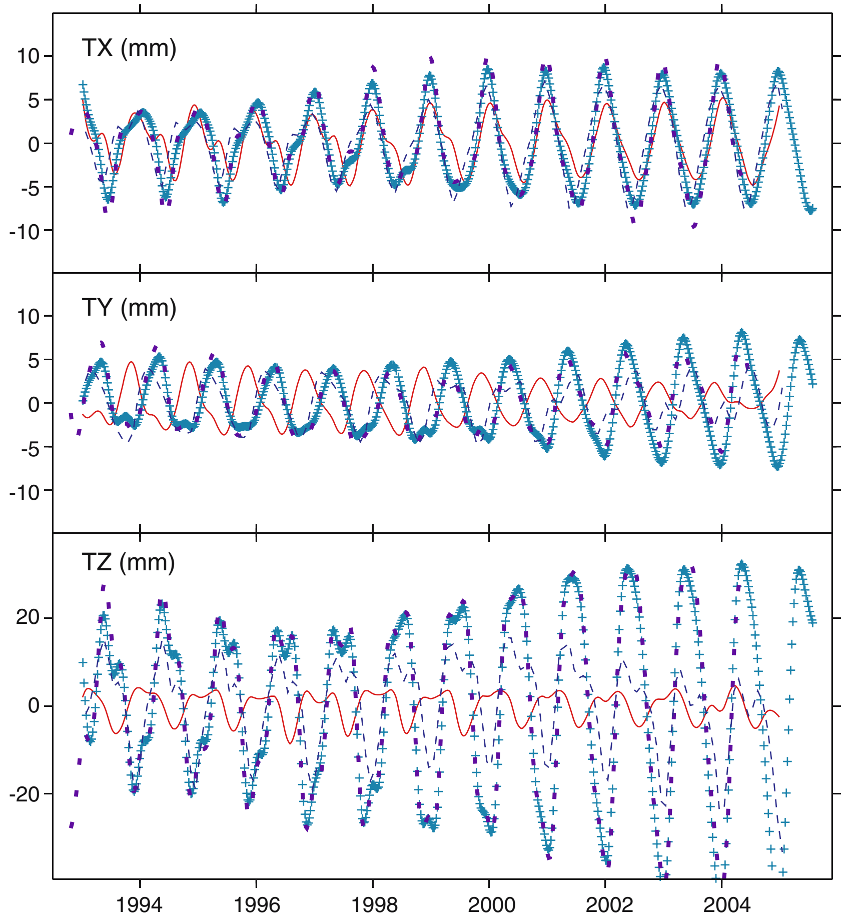

Fig. 1 Seasonal component of DORIS and SLR time-series of TRF origin. DORIS: IGN–JPL (*light blue crosses*); INASAN (*blue dots*); LEGOS–CLS (*blue dashed line*). SLR: OCA (*red solid line*). Note the different scales for T_z

listed in Table 2. The geodetic scattering level is close to the geophysical one in the equatorial plane, but much larger in the T_z direction.

4 Seasonal components

The largest variations in geocentre motion associated with the reorganization of the atmospheric, oceanic and continental water masses are found in the annual frequency band. They reach 1 cm peak-to-peak. In parallel, as the space-geodetic data analysis includes modelling of local effects, such as the atmospheric delays that have an annual signature, one cannot rule out the presence of residual errors in the geodetic data in the seasonal band.

The annual component and its harmonics, referred to as the seasonal component in the following, are extracted from the time-series by means of Feissel-Vernier's Crono_vue software package (http://lareg.ensg.ign.fr/IDS/software/crono_vue), which implements the Census X-11 moving-average algorithm (Shiskin et al. 1965).

Note that this algorithm isolates a cyclic component and its harmonics using a 5-year trapezoidal filter, which makes it possible to map time changes in amplitude and phase of the cyclic component that takes place in a 3–4-cycle time span.

The seasonal signatures of the geodetic geocentre signal are shown in Fig. 1. The T_x seasonal components of all four solutions are in phase with each other, with an amplitude changing in time in all four series, and smaller variations for SLR than for DORIS. The agreement is not as good in T_y, with a phase shift between SLR and DORIS and differing amplitude variations. The phase of the DORIS LEGOS-CLS signal shifts with time. T_z is large and variable in time, especially for the IGN–JPL and INASAN solutions. The SLR T_z amplitude is the smallest, but nearly twice as large as that of the equatorial directions. A semi-annual term is found in the SLR and DORIS LEGOS-CLS series in all three directions. Its amplitude is stable within 3–4 mm for all series in T_x and T_y, 5 mm in T_z for SLR and 10 mm for DORIS.

Figure 2 shows the detailed seasonal geophysical contributions to the geocentre motion (atmosphere, oceans and continental waters) over the 1993.1–2003.0 time span. The largest amplitude is in T_x (15 mm peak to peak), thanks to the close phases of the atmospheric and oceanic contributions. All three fluids have their smallest annual amplitude in the

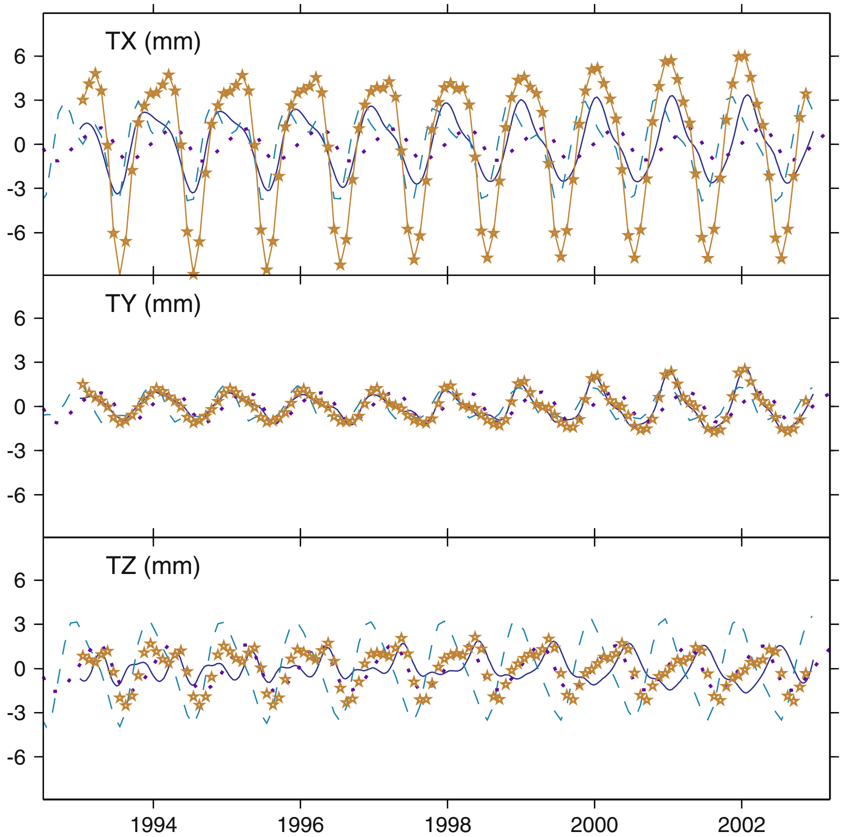

Fig. 2 Seasonal components of geocentre motion predicted from geophysical excitation. Oceans (*blue solid line*); atmosphere (*dashed light blue*); continental waters (*dotted blue*); sum of the three effects (*brown stars*). Same scale for T_x, T_y and T_z

T_y direction. T_z is dominated by the partial compensation of two large atmospheric and continental water annual terms separated by a 3-month phase shift.

Figure 3 shows the geodetic and geophysical seasonal components over the same 1993.1–2003.0 time span. For clarity, only the DORIS solution with the smallest seasonal components (LEGOS–CLS) is plotted, in parallel with the SLR and geophysical seasonal signals. The agreement of both geodetic T_x seasonal components with the geophysical one is best after 1999.0, with the exception of the already mentioned semi-annual components. The analysis of the amplitudes and phases of the annual signals shows that the uncertainty on the phases is less than 10 days. The phase inconsistencies between the geodetic and geophysical T_y annual components reach about 100 days. They can hardly be reconciled given their formal errors.

The SLR T_z is in close agreement with the geophysical expectation, with a comparable amplitude. The DORIS T_z is out of phase with the SLR and geophysical ones, and quite larger. A possible cause for this defect may be a consequence of the sensitivity of the satellite orbit to seasonal variations of the gravity field associated with the fluid mass redistribution that are not taken into account in the gravity field models used (Exertier et al. 1997).

Figure 4 summarizes the time evolution in the amplitude of the annual component in the geodetic and geophysical geocentre signals, estimated by weighted least-square analysis over the 1993–2005 time span.

In T_x, the SLR curve stays parallel to the geophysical one, with relative level of 0.6 (the SLR values are smaller that the geophysical ones). The high SLR amplitude at 2000.5 is due to anomalous values in January and February of that year. The geophysical fluids and SLR amplitudes show no long-term trend. The three DORIS curves have a general growing trend until 2002 with a 0.6 mm/year rate, followed by a rapid decay. As this decay takes place at the end of the series, it could not be mapped by the moving average method used to derive the seasonal components plotted in Fig. 1. The DORIS and SLR values match each other within one sigma except over 2000–2002. The DORIS curves cross the geophysical one in 1997.

In T_y, the DORIS and SLR values match each other within one sigma until 2000, and the DORIS curves diverge from each other and from SLR starting in 2002. Whereas the SLR amplitudes show no long-term trend, the geophysical fluids amplitude has a slow growing, with a 0.3 mm/year rate, trend visible in all three contributions (Fig. 2). The large geophysics value in 1996 is due to an anomalously

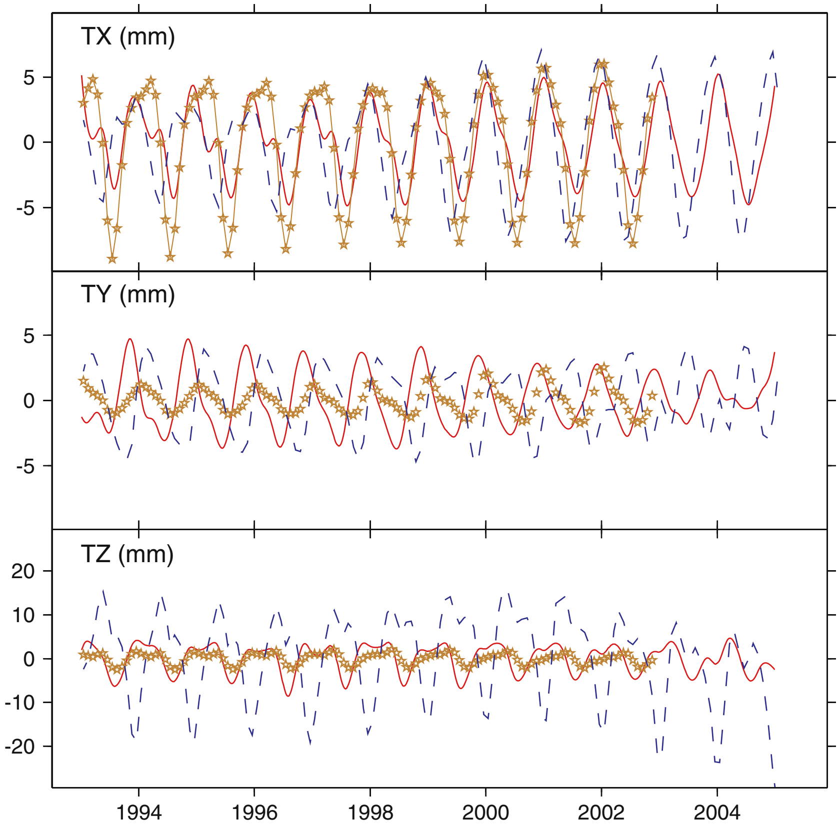

Fig. 3 Seasonal component of geocentre time-series. LEGOS–CLS (*blue dashed line*); SLR (*red solid line*); Geophysical (*brown stars*). Note the different scales for T_z

large oceanic seasonal cycle existing in the data for that year.

In T_z, the SLR curve stays significantly above the geophysical one, with no long-term trend in either curve. The LEGOS–CLS curve is quite irregular but it shows no particular long-term trend. The IGN–JPL and INASAN values have a general growing trend with a 2.5 mm/year rate until 2002, followed by a stabilization.

The above-described features of the year-to-year variations of the annual amplitude of measured and predicted geocentre motion suggest several comments. Our geophysical amplitudes match those cited by Dong et al. (2003) in T_y (2 mm), they are smaller in T_z (2 vs. 3–4 mm), and larger in T_x (6 vs 2–4 mm). Our SLR amplitudes match those cited by Dong et al. (2003) in the equatorial plane (2–4 mm), but they are larger in T_z (6 vs 3 mm). The parallel year-to-year changes in SLR and geophysical T_x annual amplitudes suggest that both data sets may map real variations.

Concerning the DORIS solutions, the difference between the two analysis softwares and strategies, at IGN–JPL and INASAN on the one hand and at LEGOS–CLS on the other hand, appear mainly in T_z after 1999, to a less extent in T_y, and not in T_x. A change in annual amplitude trends takes place in the three directions for all three Analysis Centres approximately at the beginning of the SPOT5 and ENVISAT missions in 2002.5. This seems to be a coincidence, as the amplitudes computed over the 2.5 years before and after this date stay mutually consistent within one sigma. The change is marginally significant in T_y and T_z. In T_x, considering the SLR curve, the change could also be interpreted as an anomalous DORIS value in 2002.

5 Non-seasonal components

The spectral behaviour of the geodetic and geophysical time-series is described using the Allan variance method (Allan 1966, 1987). This method allows one to characterize the statistical behaviour of the time-series (Rutman 1978), in particular for white noise (spectral density S independent of frequency f), flicker noise (S proportional to f^{-1}) and random walk noise (S proportional to f^{-2}). Note that one can simulate flicker noise in a time-series by introducing steps of random amplitudes at random dates.

A convenient and rigorous way to relate the Allan variance of a signal to its error spectrum is the interpretation of the Allan graph, which gives the changes of the Allan variance for increasing values of the sampling time τ, in logarithmic scales. Slope values -1, 0 and $+1$ correspond to white noise, flicker noise and random walk noise, respectively. The presence of a cyclic variation is recognized by the superimposition of a dip when the sampling time is equal to the cycle

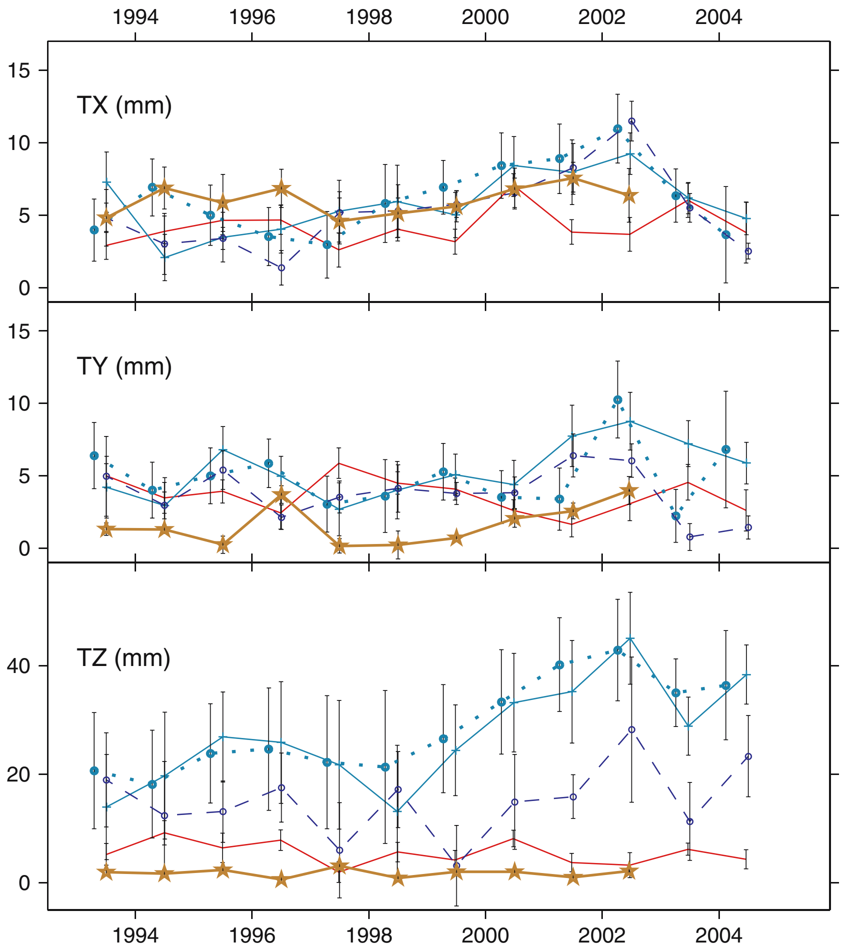

Fig. 4 Yearly amplitudes of the annual component of geocentre time-series. DORIS: IGN–JPL (*light blue solid line*); INASAN (*light blue dotted line*); LEGOS–CLS (*dark blue dashed line*). The *error bars* are one sigma. SLR: OCA (*red solid*); Geophysical: all contributions (*stars*). Note the different scales for T_z

period and a bump at about 1/2 the cycle period, with a size that depends on the signal/noise ratio of the amplitude of the cyclic component.

Figure 5 shows the spectral signatures of the three contributions to the geophysically derived geocentre motion (oceans, atmosphere and continental waters) over the 1993.1–2003.0 time span, considering on the one hand the total signal and on the other hand the signal corrected for its annual and semi-annual components derived from a least-squares analysis, to avoid the above-mentioned biasing effect.

The upper graphs of Fig. 5 are for the complete signal. The continental water spectra show a dominant annual signature in all three directions. The spectra of the three oceanic directions and of the atmospheric T_x, as well as that of the total signal show a mix of seasonal and non-seasonal excitation.

The lower graphs in Fig. 5 show the spectrum of the non-seasonal signal, after taking out the annual and semi-annual signal components. The continental water signal is negligible, whereas the oceanic and atmospheric contributions have white noise signature in the equatorial, and flicker noise in T_z for sampling times longer than a few months, suggesting that the excitation in the axial direction does not vanish in the long term.

Figure 6 shows the spectral signatures of the geodetically and geophysically derived geocentre measurements over their common 1993.1–2003.0 time span. The upper graphs in Fig. 6 are for the complete signal. The three DORIS solutions have similar signatures in the equatorial plane: the seasonal signature is embedded in a noise with a spectrum close to white noise. The SLR annual signature is more visible, also in a white noise background. T_x and T_y reach a stability of 2–3 mm for a 1-year sampling time. The spectrum of the T_z variations is quite noisier than those in the equatorial plane. The spectral power of the DORIS signal remains higher than that of the geophysical one in T_x and T_y, while the SLR spectral power matches the geophysical one. In T_z, both DORIS and SLR levels are higher than that of the geophysical one.

The lower graphs in Fig. 6 show the spectrum of the remaining signal after taking out the annual and semi-annual

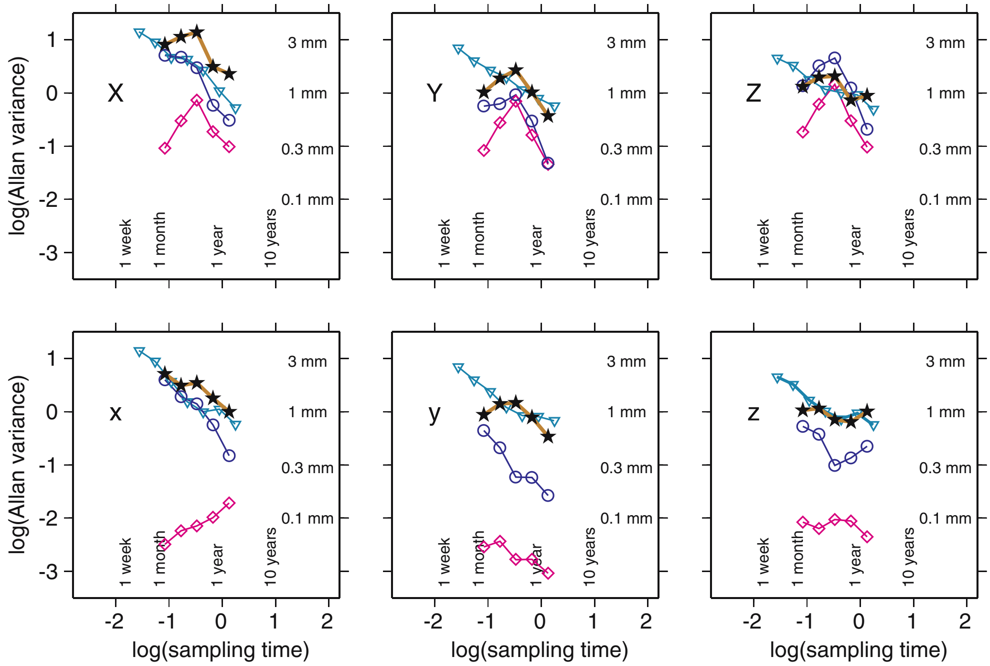

Fig. 5 Spectral signature of geocentre motion predicted from geophysical models over 1993.1–2003.0. *Top* total signal. *Bottom* signal corrected for its seasonal content. Oceans (*light blue triangles*); atmosphere (*blue open circles*); continental waters (*open diamonds*); total (*black stars*)

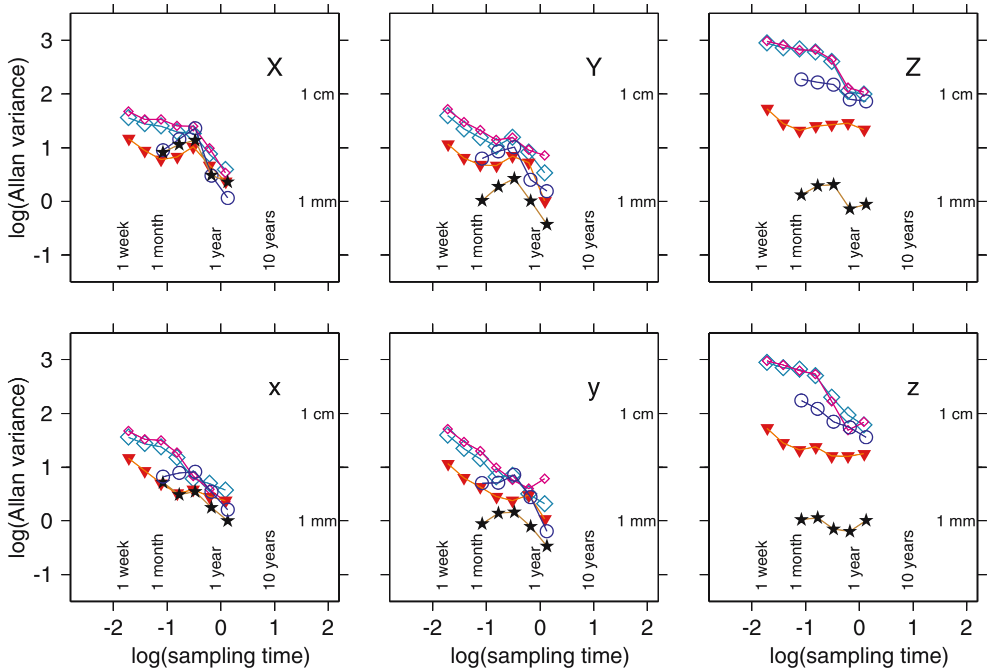

Fig. 6 Spectral signature of geocentre motion observed with DORIS, SLR and predicted from geophysical data, over 1993.1–2003.0. *Top* total signal. *Bottom* signal corrected for its seasonal content, plus 18-day and 59-day terms in the case of DORIS. IGN–JPL (*small pink diamonds*); INASAN (*light blue open diamonds*); LEGOS–CLS (*blue open circles*); SLR (*red triangles*); geophysical (*black stars*)

components, plus 117-day and 59-day terms in the DORIS series.

T_x and, to a lesser extent T_y, shows an excellent agreement of the geodetic and geophysical signals for sampling times longer than 1 month, with 1-year Allan standard deviations at the 2 mm level, and white noise signature for DORIS, SLR and geophysics. The T_z situation is different, with a flicker noise signature for the SLR and geophysical signals, and white noise for DORIS. For the 1-year sampling time, DORIS spectra are at the 9 mm level, and SLR is at the 4 mm level, to be compared with 1 mm for the geophysical data.

6 Conclusion

The comparison of geodetic and geophysical determinations of the Earth's geocentre motion gives indication about their respective accuracies. Although the results in the equatorial plane are roughly consistent with each other, there are noticeable diverging behaviours in the T_x and T_y directions, characterized by dominant ocean and land, respectively. For example, the oceanic zones have fewer observing stations and may show larger oceanic influence on the motion, and land zones have more observing stations and may show larger terrestrial water influence on the motion.

The magnitude of the long- term geophysically derived geocentre motion is of the same magnitude in the T_x, T_y and T_z directions, with a 0.5–1.0 mm Allan standard deviation for the 1-year sampling time. The DORIS- and SLR-observed geocentre motions in the equatorial plane are at a similar variance level, both having white noise in T_x and T_y, with a 2 mm Allan standard deviation for the 1-year sampling time, close to the geophysical signal level.

This is not the case in the T_z direction, with 4 and 9 mm Allan standard deviations for the 1-year sampling time for DORIS and SLR, respectively. All data types are likely to contribute to the long-term T_z discrepancies. Among the possible causes for inaccuracy, one can mention the antenna phase centre correction in the DORIS case, network geometry in the SLR case, method for referencing the series of free-network space-geodetic TRFs, global fluids mass conservation hypotheses, or missing information on inter-seasonal mass redistributions in the geophysical models. More investigations are needed to reconcile geodetic and geophysical information.

The comparison of seasonal signatures suggests that solutions from DORIS and SLR geodetic techniques still suffer from annual or semi-annual analysis errors, resulting in discrepant amplitudes and phases. The best agreement is found in the T_x direction, where the SLR and geophysical series show parallel year-to-year amplitude changes, although the SLR amplitude reaches only 60% of the geophysical one. Considering the T_y annual components in Figs. 1 and 2, a slight phase shift in the continental water contribution might reconcile the geophysical signal with the geodetic data. However, this latter point would require more investigation by comparing our results with the ones obtained using other global hydrology models.

The largest discrepancies in the annual band appear in the DORIS solutions, with some of the solutions showing variations of the amplitude of the annual component in T_x (0.6 mm/year) and T_z (2.5 mm/year) until 2002. Finding the explanation for the differences between the various data analysis strategies should allow for a general improvement in DORIS products.

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