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ORIGINAL ARTICLE

Systematic biases in DORIS-derived geocenter time series related to solar radiation pressure mis-modeling

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Abstract As any satellite geodesy technique, DORIS can monitor geocenter variations associated to mass changes within the Earth–Atmosphere–Continental hydrosphere–Oceans system. However, especially for the Z-component, corresponding to a translation of the Earth along its rotation axis, the estimated geocenter is usually affected by large systematic errors of unknown cause. By reprocessing old DORIS data, and by analyzing single satellite solutions in the frequency domain, we show that some of these errors are satellite-dependent and related to the current DORIS orbit determination strategy. In particular, a better handling of solar pressure radiation effects on SPOT-2 and TOPEX satellites is proposed which removes a large part of such artifacts. By empirically multiplying the current solar pressure model with a single coefficient (1.03 for TOPEX/Poseidon after 1993.57, and 0.96 before; and 1.08 for SPOT-2) estimated over a long time period, we can improve the measurement noise of the Z-geocenter component from 47.5 to 30.4 mm for the RMS and from 35 to 6 mm for the amplitude of the annual signal. However, the estimated SRP coefficient for SPOT-2 presents greater temporal variability, indicating that a new, dedicated solar radiation pressure model is still needed for precise geodetic applications. In addition, for the TOPEX satellite, a clear discontinuity of unknown cause is also detected on July 27, 1993.

Keywords DORIS · Geocenter variations · Systematic errors · Solar radiation pressure

1 Introduction

In classical mechanics, the Earth system, composed of the solid Earth, the atmosphere, the oceans and the continental

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hydrosphere, is considered as a point mass, describing a complex orbit due to its gravitational interaction with the Sun, the Moon and the other planets. Actually, only the center of mass of the Earth system properly describes the prescribed orbit, and the different parts of the system move around this center. In this study, we focus on one particular part of those motions, i.e. the motion of the center of the geodetic station network around the center of mass of the whole Earth system. Ideally, the center of the network is a realization of the center of the solid Earth, although the uneven geographic station distribution, as well as imperfect knowledge of station positions, limits the accuracy of such a realization. On the other hand, the center of mass of the whole system is realized as the orbit center of all the artificial satellites.

In this study, we will adopt the geodesist's point of view, i.e. the center of the network will be considered as fixed, and we will discuss the motion of the center of mass with respect to that fixed point. Of course, in reality, neither the center of the network nor the center of mass of the system is fixed in space, but this precision is not directly relevant for our study.

For a rigid solid Earth, we can consider that a translation of the center of the network is equivalent to a translation of the center of mass of the solid Earth. The actual Earth is not exactly rigid, and the center of mass motion is corrected using Love numbers accounting for the effect of the deformation. If the center of the network moves with respect to the center of mass of the whole system, it has to be associated with a translation of the non-solid part of the Earth, in the opposite direction. The translation of the center of mass is thus always linked to the dynamics of the external fluid layers, and can be estimated using general circulation models of the atmosphere, the oceans and the hydrology.

Such estimations have been done by several authors (see for instance Dong et al. 1997; Crétaux et al. 2002; Moore and Wang 2003), and the results are roughly consistent. The signal is strongly dominated by the seasonal signal. The atmosphere signal is at the 1 mm level for the annual and semi-annual signal (mostly in the X and Y direction). The ocean signal is mainly due to the tides, and also reaches 1 mm for the seasonal period, mostly in the equatorial component. The signal coming from the non-tidal ocean circulation is one order of magnitude smaller. The continental hydrology can reach a few millimeters in the Z component. Crétaux et al. (2002) also analyzed excitation of the geocenter motion outside of the annual period, and found evidence of an interannual signal in the Z component with peak-to-peak amplitude of 1 mm.

When estimating the systematic errors from the amplitude of the Z geocenter motion, it is necessary to remove these effects prior to any analysis.

In 2003, the International DORIS Service (IDS) was created (Tavernier et al. 2005). Among its goals is to coordinate the different DORIS analysis groups all over the world and to provide the scientific community with open access to several DORIS-derived products (Tavernier et al. 2006; Willis et al. 2006): time series of station coordinates, orbits and geocenter variations. For example, several geocenter time series are available at the NASA/CDDIS in the US (ftp://cddis.gsfc.nasa.gov/pub/doris/products/geoc), and at the IGN data center in France (ftp://doris.ensg.ign.fr/pub/doris/products/geoc).

Besides an earlier preprocessing problem detected in the DORIS/SPOT4 1998 data affecting the DORIS Z-geocenter results (Willis et al. 2005a) and now fully understood (Willis et al. 2006), all previous analyses of DORIS geocenter time series show that the Z-component is much noisier than the other components (Altamimi et al. 2005) and that it is affected by large seasonal effects with an amplitude of 34 mm (Meisel et al. 2005), which is almost one order of magnitude larger than the expected physical signal. Note also that systematic errors in the Z-geocenter or in the Z-component of the station coordinates can easily map on to the derived mean sea level determined through the orbit estimation (Morel and Willis 2002, 2005). Such a possibility was demonstrated by Beckley et al. (2007) when comparing orbits generated from ITRF2000 and orbits generated from ITRF2005, where the difference in geocenter TZ-rate of these two realizations of the International Terrestrial Reference System (ITRS) was -1.8 ± 0.3 mm/year (Altamimi et al. 2007).

2 Systematic errors in current DORIS-derived geocenter

We will first describe the large difference currently observed in Z-geocenter time series derived from DORIS and compare it with similar results obtained from the other satellite geodetic techniques (SLR and GPS).

Our DORIS solution is a single analysis center solution (IGN) using the GIPSY/OASIS software developed at JPL (Willis et al. 2005b). Data are processed on a daily basis (24 hours of data), using all available DORIS satellites (except Jason, for a reason that will be later explained), and then combined into weekly solutions.

In our comparison, we use a geocenter time series derived from Satellite Laser Ranging (SLR) to LAGEOS-1 and LAGEOS-2 provided by the University of Texas Center for Space Research. We went with a CSR solution because there is strong confidence in the analysis methods at CSR, with published results as far back as 1985, and the results have usually been demonstrated to be reliable. The time series of 60-day geocenter estimates was obtained using a "network shift approach" (Dong et al. 2003), in which only the translational aspect of geocenter motion is estimated. This method holds the relative coordinates fixed and ignores the deformations that can occur at each site, a valid approach if the

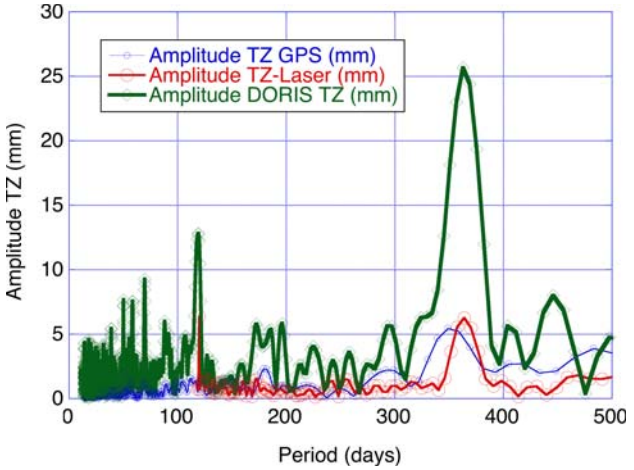

Fig. 1 Frequency analysis (periodogram) of the Z-component of the geocenter time series as derived by SLR, GPS and DORIS techniques

globally averaged deformation is relatively small. The SLR geocenter solution spans from 1993.0 to 2007.5.

For Global Positioning System (GPS), we used the combined solution computed by Natural Resources Canada's (NRCan) Geodetic Survey Division (GSD), on behalf of the International GNSS Service (IGS) (Dow et al. 2005). This combined solution is currently based on the contributions from eight Analysis Centers (AC) (COD, EMR, ESA, GFZ, JPL, MIT, NGS, SIO). A complete description of the data and the method used is provided by (Ferland et al. 2000). The GPS geocenter solutions spans from 2003.3 to 2008.0.

Figure 1 presents a frequency analysis (periodogram) of these three independent time series (SLR, GPS, DORIS) of Z-geocenter variations, after an appropriate detrending. It can easily be seen that, against the other two techniques, the DORIS results show large systematic errors. Both SLR and GPS results show a clear annual signal of around 5–6 mm. It can also be seen that the period detected from the GPS signal looks smaller than 1 year and is in fact close to 352 days. In our opinion, this could probably be related to small systematic errors in the GPS solar pressure radiation model, as detected earlier in GPS and SLR residuals (Urschl et al. 2007) at the GPS draconitic period (352 days). The period detected for SLR is exactly 365 days. For DORIS a large annual signal of about 25 mm is visible. A second narrow peak is also present at 118 days. This corresponds exactly to the draconitic period of the TOPEX satellite (beta prime frequency). After such a period, the geometric arrangement of the satellite, the Sun and the Earth is repeated. This naturally tends to amplify any error in the solar radiation pressure (SRP) correction. Note that systematic errors at the 118-day period were previously detected by several authors (Williams and Willis 2006; Feissel-Vernier et al. 2007) but never explained before this study. The 120-day signal in Fig. 1 in the SLR time series is not significant. It is just an artifact of the frequency analysis technique, as the SLR time series was provided at an interval of 60 days (GPS and DORIS time series were provided at an interval of 7 days).

3 Systematic errors in single-satellite DORIS-derived geocenter

Nevertheless, the DORIS time series is by nature very inhomogeneous due to the evolution with time of its satellite constellation. SPOT-2 and TOPEX data are present during the whole considered period (1993.0–2007.0), while SPOT-3 data is only available from 1994.1 to 1996.8. Other satellites (SPOT-4, ENVISAT and SPOT-5) are more recent. A complete description of the entire DORIS data set available at the IDS data center can be found in Willis et al. (2007a).

If we assume that the systematic errors in the DORIS-derived geocenter are caused by mis-modeling errors in the satellite orbit determination, it makes sense to separate the complete DORIS time series into specific periods demarcated by their component satellites. Table 1 presents a list of the periods that we selected for this study.

Note that the IGN analysis center does not use any DORIS data from the Jason satellite, as these data are affected by a large error related to the extreme and unexpected sensitivity of the on-board receiver to radiation over the South Atlantic Anomaly (Willis et al. 2004). A correction model was developed by CNES (Lemoine and Capdeville 2006) but is still in a testing phase for other software packages. However, early results using the GIPSY/OASIS software show that if this correction is used for orbit determination, it does not provide any significant improvement for geodetic positioning, especially around the SAA region. A detailed study is underway within several IDS Analysis Centers.

For each period provided in Table 1, we extracted the geocenter time series as a subset of the complete time series. Figure 2 presents a periodogram for each of these subsets. It can now be seen that periods having larger TOPEX contribution (thinner lines) generate a larger systematic effect at the 118-day period. When only two satellites are available in the DORIS constellation (TOPEX and SPOT-2) (case A), the amplitude of the systematic error is close to 30 mm, exceeding by far the real geocenter signal. Conversely, the most recent period, in which TOPEX data are not available (DORIS receiver died on November 1, 2004), does not show any significant effect at the 118-day period.

On the other hand, periods including more SPOT data show a larger annual signal (up to 30 mm). This annual signal is at a minimum in the early DORIS data when only TOPEX and SPOT-2 are present. It can also be seen in Fig. 2 that the peak at 118 days is more pronounced (narrower) than the peak at 1 year for reasons that will be explained below.

Table 1 Time evolution of the DORIS satellite constellation

Series	Number of satellites	Duration (years)	Observation data span	Satellites
A	2	3.2	1993.00–1994.09 1996.85–1999.03	SPOT-2 + T/P
B	3	2.7	1994.09–1996.85	SPOT-2+ T/P + SPOT-3
C	3	3.4	1999.03–2002.44	SPOT-2 + T/P + SPOT-4
D	5	2.4	2002.44–2004.84	SPOT-2 + T/P + SPOT-4 + SPOT-5 + ENVISAT
E	4	3.2	2004.84–2008.00	SPOT-2 + SPOT-4 + SPOT-5 + ENVISAT

Sub-series having exactly the same DORIS satellites

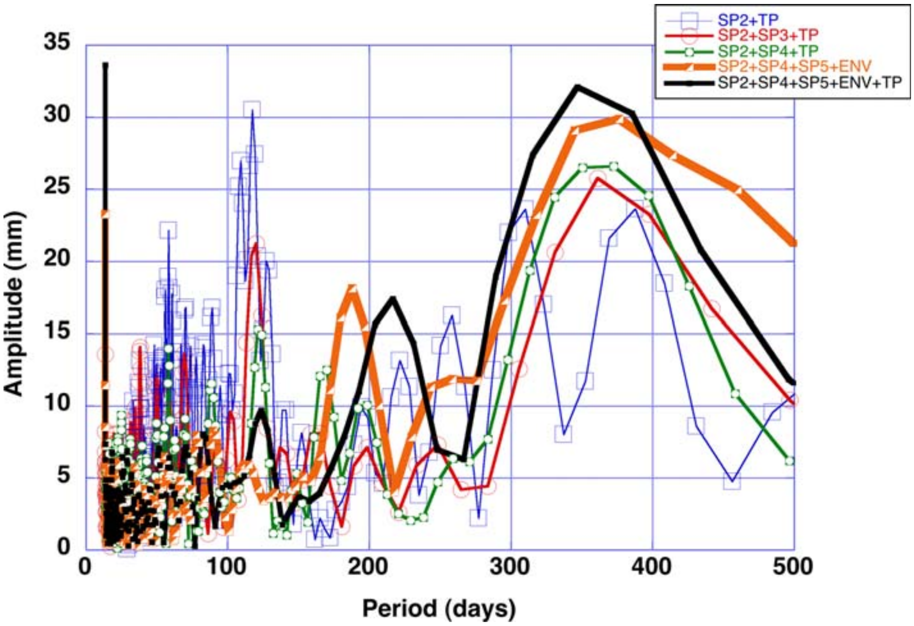

Fig. 2 Frequency analysis (periodogram) of the Z-component of the geocenter time series of the DORIS different sub-series using the same DORIS satellite constellation, as described in Table 1. *Lines* are thinner when TOPEX contribution is larger

As 118 days is the draconitic period of the TOPEX satellite, and the draconitic period of the sun-synchronous SPOT satellites is 1 year, we will test the reasonable assumption that these systematic errors are related to mis-modeling in the solar pressure models of these satellites.

4 Estimating solar pressure coefficients per satellite

Solar radiation pressure (SRP), due to momentum exchange from solar photons impacting the spacecraft surfaces, is one out of a number of non-conservative (non-gravitational) forces that perturb the trajectories of Earth orbiting satellites. In fact, SRP is the principal driver of the non-conservative force field except for satellites at very low altitude (less than circa 600 km), where atmospheric drag may dominate.

Over the past two to three decades, two basic techniques have become commonplace when modeling SRP accelerations on a variety of satellites: (i) Empirical Model or (ii) Analytical Model.

Empirical models (Bar-Sever and Russ 1997; Springer et al. 1999) are derived by fitting “optimally parameterized” models to large quantities (several years worth) of orbit data. The choice of parameterization often involves the specification of local coordinate systems designed to offer the model the greatest likelihood of success. When modeling SRP, a primary direction for such a coordinate system might be along the line between the Sun and the satellite. Analytical models compute SRP effects a priori by considering the interaction of photons with [simplified] representations of a satellite. The two main differences between the techniques used to compute such analytical models concern: (1) how a satellite is represented (e.g. simple sphere, flat plates (Marshall and Luthcke 1992; Marshall et al. 1995), triangulated surface (Marquis and Krier 2000), geometric primitives (Antreasian 1992; Antreasian and Rosborough 1992; Fliegel et al. 1992; Ziebart 2004), and (2) how the model is implemented for purposes of orbit determination (e.g. truncated Fourier series Fliegel et al. 1992, grid file Ziebart 2004). Historically, each of these differences has represented a trade-off between accuracy and computational intensity, though it is now possible to compute both very accurate and very efficient models (Ziebart 2004).

Both approaches (i.e. (i) and (ii)) also rely, to varying extents, upon empirical estimation during orbit determination purely to soak up unmodeled radiation pressure effects. For example, a single scale factor (Cr) can be estimated to scale the underlying model, as well as functions computed on a per orbit (once-per-revolution, 1/rev) basis having the form:

$$\ddot{r}_{\mathrm{SRP}} = a\cos(\theta) + b\sin(\theta) = c\sin(\theta - \theta_0) \qquad (1)$$

where θ may take a value such as the argument of latitude, while a, and b (resp. c, and θ_0) are coefficients of the model.

It has long been suspected that “science data” such as long wavelength ocean topography features, estimated during orbit determination, will alias into these soak up parameters (Marshall and Luthcke 1994; Springer et al. 1999). Now, it has been shown directly that having an SRP scale factor different from unity by only 7% can cause problems with orbit centering along the terrestrial Z direction (i.e. Earth’s spin axis) on the order of 10 mm (Haines et al. 2004), and results in aliasing into estimated drag coefficients (Ziebart et al. 2005). Therefore, the best approach is to use the most accurate [radiation pressure] models in order that reliance on soak up parameters is reduced.

In our current DORIS data processing, a standard SRP model was used, an SRP coefficient was estimated daily to cope with mis-modeling in the dynamic model and 1/rev empirical accelerations were estimated daily. However, recent studies have shown that these 1/rev parameters also have a tendency to soak up all types of systematic error and could be correlated with Z-geocenter (Willis et al. 2006) or could create mis-centering of the orbits.

We then tried to estimate an empirical coefficient (Cr) to map the solar pressure models. This empirical parameter is only valid with the specific macro model used. Table 2 provides a detailed description of the SPOT2 macro model that we used in this study. Currently, only corrections in the visible spectrum are done for the GIPSY/OASIS software package. No infrared corrections or thermal model are currently applied. Furthermore, it must also be noted that the solar array does not point directly towards the Sun, as the angle between the X-axis of the satellite body (pitch) and the solar array has a fixed value, depending on the SPOT satellite (5 degrees for SPOT-2).

A TOPEX/Poseidon 8-surface macro-model was initially constructed by estimating the reflectivity and thermal properties of each surface from pre-launch micro-model acceleration data (Marshall et al. 1992; Luthcke and Marshall 1992). It was returned several times using SLR/DORIS tracking data (Marshall et al. 1995). Table 3 displays the current macro-model used in the GIPSY/OASIS software package. As shown in Tables 2 and 3, the sum of the specular, diffuse and absorbed reflectivity is still exactly equal to 1.0, however, some negative non-physical values clearly show that the TOPEX model was tuned and not derived from a priori physical properties of the satellite materials, as available before launch.

As a first step, we simultaneously estimated the Cr parameter along with all the station coordinates and 1/rev orbit parameters. The estimated SRP coefficient was very noisy

Table 2 SPOT-2 macro model as available from CNES at ftp://ftp.cls.fr/pub/ids/satellites/macromodels/sp2mod.pdf

Surfaces	$X+$	$X-$	$Y+$	$Y-$	$Z+$	$Z-$	SA+	SA−
Area (m^2)	6.69	6.69	6.51	6.51	3.515	3.515	19.5	19.5
Specular reflectivity (unitless)	0.54	0.54	0.54	0.54	0.54	0.54	0.16	0.16
Diffuse reflectivity (unitless)	0.07	0.07	0.07	0.07	0.07	0.07	0.16	0.16
Absorbed reflectivity (unitless)	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39

$X+$ is the axis of the pitch angle (satellite main direction), $Y+$ is the axis of the roll angle (in opposite direction of the velocity), $Z+$ is the axis of the yaw angle (toward the Earth), SA+ is the normal to the Solar Array pointing in direction of the Sun. The above values correspond to the visible spectrum. Values for Infra Red are also for the CNES macro model but were not used in this study. The original value proposed by CNES for diffuse reflectivity was 0.7. However, we assumed that this was a typo in the documentation and we used 0.07, (maintaining the sum of the three reflectivities to physically being 1.0)

Table 3 TOPEX macro model

Surfaces	$X+$	$X-$	$Y+$	$Y-$	$Z+$	$Z-$	SA+	SA−
Area (m^2)	4.294	4.294	8.374	8.374	7.957	7.957	25.5	25.5
Specular reflectivity (unitless)	0.201	0.295	0.886	0.782	0.652	0.859	0.139	0.217
Diffuse reflectivity (unitless)	0.375	0.386	0.302	1.029	0.390	0.363	0.220	0.660
Absorbed reflectivity (unitless)	0.424	0.319	−0.188	−0.811	−0.042	−0.222	0.641	0.123

$X+$ is the along-track direction (toward velocity), $Y+$ is the cross-track direction, $Z+$ is the axis of the yaw angle (toward the Earth), SA+ is the normal to the Solar Array pointing in direction of the Sun (formal errors of Cr were typically at the 0.15 level, for 1 day). In a second step (this study), we fixed the 1/rev parameters to 0, in order to estimate a truly dynamic orbit, and estimated only station positions and a single SRP coefficient. In this case, the formal errors were typically around 0.01 (1 day), showing the large correlation between these two types of parameters: SRP Cr and 1/rev coefficients.

For test purposes, we decided in a second step to reanalyze the daily SRP coefficient using the same estimation strategy, but fixing all station coordinates to their ITRF2005 values (Altamimi et al. 2007). Results were indistinguishable from those where the station coordinates were also estimated. However, we prefer to show here results in free-network mode (estimating orbit and all station positions simultaneously), as our results will then be truly independent of any ITRF realization. This is important to ensure the physical meaning of our DORIS-geocenter results and not to “force” them to be as close as possible to the latest ITRF realization. We try to avoid propagation of errors in past ITRFs to future ITRFs.

In order to track systematic errors in precise orbit determination (POD), we will now compute geocenter time series from a single-DORIS solution. Figure 3 shows results for TOPEX over the years spanning the period 1993–2004. A clear discontinuity can be seen in July 27, 1993. Discussion with CNES showed that on this specific day, the TOPEX DORIS receiver changed its method of measurement. However, there is no clear reason why such a change should create a systematic effect in the DORIS data and this question is still under investigation. A similar problem was previously found for ENVISAT when a flight software change unexpectedly created a discontinuity in the derived radial error offset (vector between the center of mass of the satellite and the phase center of the antenna in the direction of the Earth) (Doornbos and Willis 2007; Willis et al. 2007b).

A similar study was conducted for SPOT2 and the results are very different. Figure 4 shows a clear annual signal in the case of SPOT-2. In our opinion, the TOPEX solar pressure model is already quite good and estimating only one additional coefficient should probably be sufficient. As SPOT satellites are not used for altimetry, no specific attempt was made in the past to derive an accurate SRP model. The box-and-wing model that we are using is certainly not of the same quality as the one derived for altimetry mission satellites, such as TOPEX, Jason and ENVISAT. In these conditions, estimating only one additional parameter may not be sufficient and the annual signal that we see in Fig. 4 can be interpreted as being due to a lack of accuracy in the current SPOT-2 SRP model. The larger variations observed around 2001–2002 could certainly be attributed to its being the maximum amplitude of the solar cycle (11 years).

Table 4 summarizes our results for TOPEX and SPOT-2 over the whole period (1993.0–2007.0). The mean of the daily formal errors corresponds to a mean value over the whole period and provides an average of daily formal errors. The standard deviation in the last column represents the precision of this Cr parameter, estimated using all data, and a posteriori reweighted in a least square sense. It provides a realistic estimate of the accuracy of this parameter as estimated from data over the full period. In the case of TOPEX, because of the discontinuity detected from Fig. 3, we present two different estimates (before and after the discontinuity). Note that the first value for TOPEX is very close to the value derived at JPL using only early GPS data and a similar technique (0.97).

The TOPEX/Poseidon mission is also equipped with laser retroreflectors. To validate results from Table 4, and to demonstrate that 1.03 is a better rescaling value than 1.00, we have recomputed TOPEX orbits with the GEODYN software package using both values. GEODYN models are described

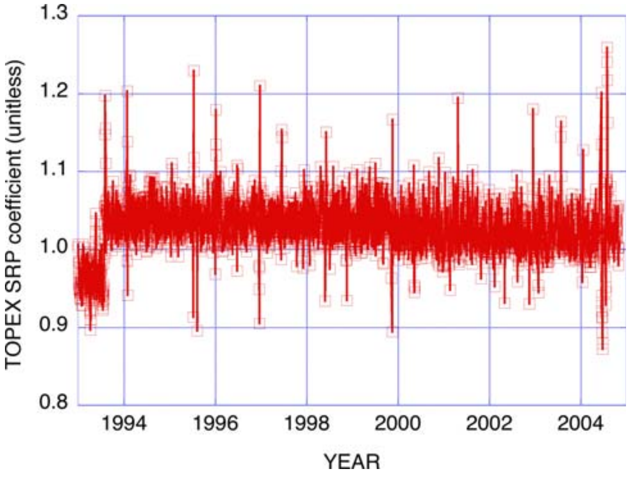

Fig. 3 Daily estimation of TOPEX solar radiation pressure (SRP) coefficient. Empirical 1/rev coefficients were fixed to 0

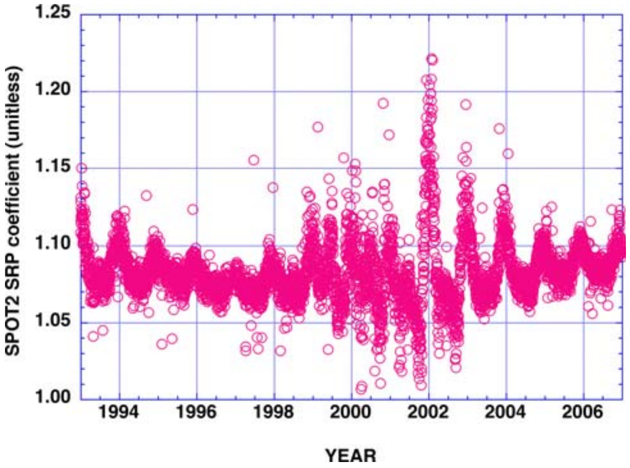

Fig. 4 Daily estimation of SPOT-2 solar radiation pressure (SRP) coefficient. Empirical 1/rev coefficients were fixed to 0

Table 4 Statistics of TOPEX and SPOT-2 solar radiation pressure coefficients estimated daily (1993.0–2007.0)

Satellite	Period used (years)	Average SRP coefficient (unitless)	Mean of daily formal errors (unitless)	Standard deviation (re-weighted over the whole period) (unitless)
TOPEX	1993.00–1993.57	0.962	0.007	0.0015
TOPEX	1993.57–2004.83	1.031	0.010	0.0006
SPOT-2	1993.00–2007.00	1.084	0.0185	0.0003

in detail in (Marshall et al. 1992). In particular, they allow a more complete correction including thermal effects on the satellite. From cycles 33 to 364, unweighted SLR residuals show a slight but significant improvement (3.53 mm for Cr = 1.03 vs. 3.57 mm for Cr = 1.00), even if orbit differences are very small (less than 1 mm). Estimated empirical accelerations are also almost undistinguishable at the 1–2 nm/s^2 level.

5 Fixing the SRP coefficient for single satellite solutions: TOPEX and SPOT-2

In a second step, we reprocessed the DORIS single-satellite data using the SRP coefficients provided in Table 4, i.e. the SRP coefficient was fixed to a known value instead of estimating it daily (as currently done in the IGN solutions submitted to IDS).

In order to assess the sensitivity of the results to the adopted value of the SRP coefficient we performed several computations, using different values. To be certain that our interpretation is correct, we recomputed the geocenter motion from TOPEX and SPOT-2 data for a large range of SRP coefficients. As we try to show a systematic effect at the 118-day period, we choose to reprocess only 1 year of data (1995) for TOPEX. In the case of SPOT-2, as we are trying to show an annual signal, we reprocessed 3 years of data (1995–1997).

Figures 5 and 6 show a frequency analysis of the Z-geocenter time series derived from the TOPEX and SPOT2 DORIS data using these different analysis strategies. Figure 5 shows an improvement in the results (i.e. 118-day signal is less important) when the SRP coefficient is fixed, even when the adopted value (1.53) is far from the value proposed in Table 4 (1.03). When the value from Table 4 (1.03) is used, the erroneous signal at 118-days almost disappears.

A similar study was done in the case of SPOT-2 and showed similar results (Fig. 6). Fixing the SRP coefficient tends to reduce the erroneous annual signal detected when estimating daily values of the SRP coefficient. However, in this case, fixing to the value proposed in Table 4 (1.08) does not solve all the problems, as the SRP model itself is probably less accurate. It can be seen that the 1.08 value better minimizes the artifact at 120 days, where no geophysical signal is to be expected (Lavallée et al. 2006).

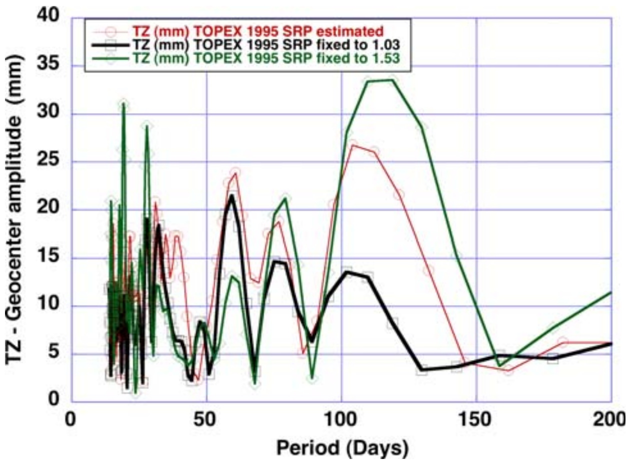

Fig. 5 Frequency analysis (periodogram) of the Z-component of the geocenter time series of several TOPEX-only DORIS solutions (estimating daily SRP coefficients or fixing it to different values)

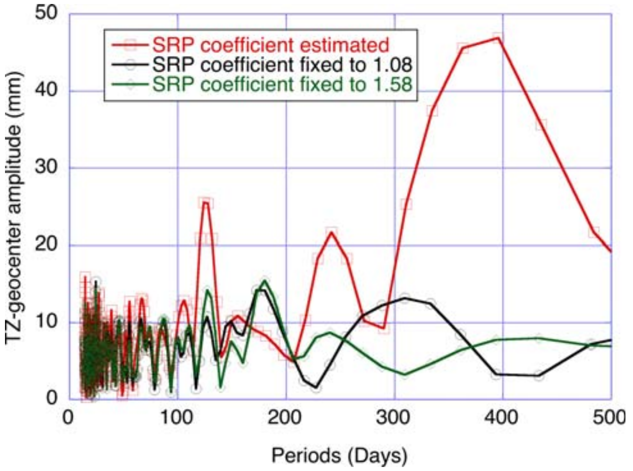

Fig. 6 Frequency analysis (periodogram) of the Z-component of the geocenter time series of several SPOT-2-only DORIS solutions (estimating daily SRP coefficients or fixing it to different values)

Evaluation of the recovered 1/rev acceleration parameters may reveal the character and magnitude of the mis-modeled satellite forces. The estimated daily 1/rev along-track accelerations over 12-years of TOPEX SLR/DORIS 10-day GGM02C–based (Tapley et al. 2005) orbit solutions were reviewed (Fig. 7), from T/P cycles 1–446 (25-SEP-1992 to 01-NOV-2004) using the complete available data set.

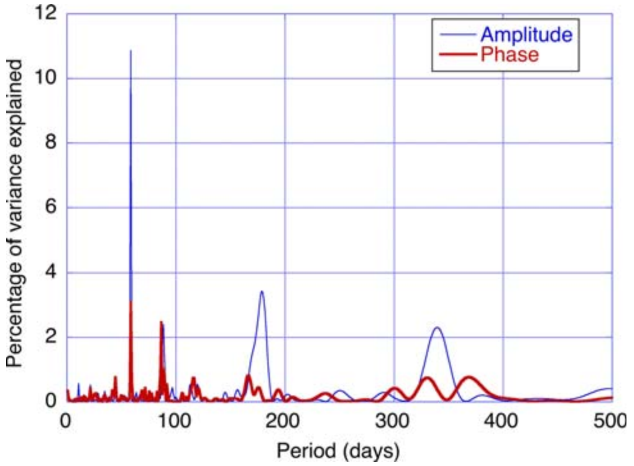

Fig. 7 Frequency analysis (periodogram) of TOPEX 1/rev empirical parameters. Cycles 1–446 (25-SEP-1992 to 01-NOV-2004). Percentage of variance explained in the along-track orbit component

Table 5 RMS of the DORIS geocenter time series when estimating or fixing the SRP coefficients

SRP coefficients	TX − RMS (mm)	TY − RMS (mm)	TZ − RMS (mm)
Estimated (standard)	8.8	7.8	47.5
Fixed (this study)	7.6	7.7	30.4

Although the acceleration amplitudes were small, averaging 0.8 nm/s^2, spectral analysis shows most power at a 59-day period. This is clearly related to the 118-day period of the beta prime angle (the angle between the orbit plane and the Sun), and indicates SRP is the largest remaining mis-modeled force acting on TOPEX when a GRACE-derived gravity field is used.

6 Dual-satellite DORIS solutions

Based on these results, we have reprocessed all DORIS data for periods when only TOPEX and SPOT-2 are available (case A) and have compared our new results to our previous results available on the IDS Web site. Results are presented in Table 5.

As the DORIS errors in the Z-component are still large compared to the real geophysical signal, we choose here to present only the root-mean-square of the time series. Note that we do not subtract any geophysical model of the geocenter motion in Table 5, as the errors found are far larger than the expected geophysical model (1–3 mm).

Table 5 shows that a significant improvement (DORIS results are closer to zero) was obtained for the Z-geocenter time series. Note however, that if we choose to first detrend these results, assuming a possible unknown in the realization of the X, Y and Z-rate of the Terrestrial Reference Frame, these numbers are almost unchanged (46.6 mm when estimating the SRP coefficient, compared to 30.1 mm when fixing the SRP coefficient). These numbers may still seem rather large but they correspond to old DORIS data (earlier type of ground equipment) and a limited DORIS constellation of two satellites.

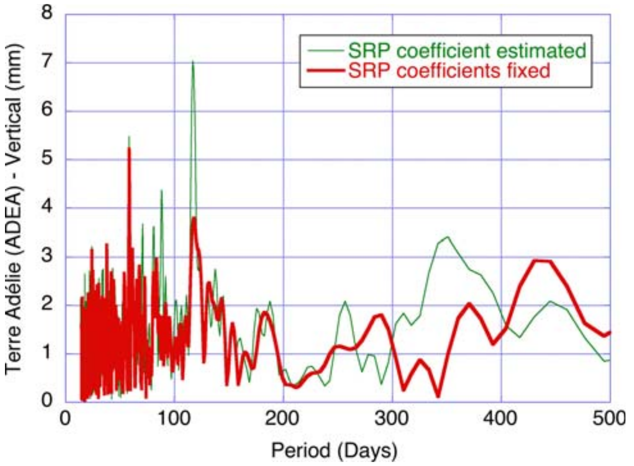

Fig. 8 Frequency analysis (periodogram) of Dumont d'Urville (Terre Adélie) DORIS station in Antarctica vertical component, estimating or fixing SRP coefficients. Only TOPEX and SPOT-2 data from 1993.0 to 1996.0

7 Investigating high latitude station altitude

Finally, as an erroneous signal of 118 days was recently observed in the Dumont d'Urville station (Amalvict et al., in press), we decided to reanalyze the 1993.0–1996.0 DORIS data, excluding the SPOT-3 satellite in order to assess if this technique also removed this problem for high latitude tracking stations. The Dumont d'Urville station in Terre Adélie is located in Antarctica, and the station height is then strongly correlated with the Z-component of the Terrestrial Reference Frame.

Figure 8 shows the results obtained for vertical component of this DORIS station, using a similar frequency analysis of these results. It can be seen that the 118-day period detected by these authors, which was not present in the GPS results, now tends to disappear using our improved processing strategy.

8 Conclusions

Large systematic errors in the Z-component of the geocenter time series are present in values coming from current

DORIS solutions. An important part of these errors (periods of 118 days and 1 year) can be attributed to non-optimal DORIS data processing. Current SRP models for the TOPEX and SPOT-2 satellites need to be multiplied by an empirical coefficient, close to 1. This study proposes the use of 1.03 for TOPEX and 1.08 for SPOT-2. DORIS data reprocessing for a single DORIS satellite or for dual DORIS satellites (TOPEX and SPOT-2) for early DORIS data from 1993 to 1996 show that a large part of these periodic errors can be avoided when fixing the SRP coefficient to the above values, instead of estimating daily values. A sensitivity study demonstrated that the geodetic results are not strongly affected by the adopted value, as long as the SRP coefficient is fixed and within a few percent of its actual value. Finally, the vertical component of high-latitude DORIS stations, such as Terre Adélie in Antarctica, may also be improved with such a data reanalysis. Previous systematic errors in DORIS results were due to mis-modeling of SRP and showed a strong correlation with 1/rev empirical coefficients. The discontinuity detected on July 27, 1993 for the TOPEX SRP coefficient is still not understood. The current SPOT-2 SRP model appears to be far less accurate than the TOPEX SRP model. A specialized SRP model based on the SPOT-2 satellite's physical properties (surface, orientation in space, reflectivity coefficient) could help improve the DORIS geodetic results further. Another possibility may also be to extend the number of estimated SRP coefficients, such as estimating an additional force (Y-bias for the solar panel) as is regularly done in GPS data processing. Finally, the technique proposed here should be extended to all available DORIS satellites and a complete reprocessing of all DORIS data should be envisioned in view of the preparation of the future ITRF realization.

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