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in 2004. Results showed very small improvement for station coordinates and confirmed that DORIS scale could match ITRF2000 scale by modifying the vector between the center of mass of the satellite and the phase center of the on-board antenna with a constant radial offset. We do not recommend the adoption of any empirical DORIS satellite phase center offsets at this point

DORIS satellite phase center determination and consequences on the derived scale of the Terrestrial Reference Frame

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Abstract

We analyzed one year of DORIS data to estimate daily corrections to the mean locations of the satellite antenna phase centers. For each DORIS satellite, we looked for possible biases, discontinuities, trends or annual signals. All SPOT satellites show very similar patterns, which are characterized by a significant constant bias of about 20 mm in the cross-track direction as well as a clear annual signal of 5 mm amplitude. All DORIS satellites show a consistent systematic radial offset of 10 to 20 mm (equivalent to 1.5 to 3.0 ppb in the Terrestrial Reference Frame) when using ITRF2000. However, this bias mostly disappears with the adoption of ITRF2005P. A discontinuity appears in DORIS radial antenna phase center offset of the ENVISAT satellite on October 12, 2004, at the time of a flight software switch. GPS phase center offsets were also computed for Jason and TOPEX/Poseidon and compared to the corresponding DORIS estimates. Significant differences were found between DORIS and GPS estimations. Finally, we applied these estimated DORIS satellite antenna phase center offsets to derive weekly time series of station coordinates in 2004. Results showed very small improvement for station coordinates and confirmed that DORIS scale could match ITRF2000 scale by modifying the vector between the center of mass of the satellite and the phase center of the on-board antenna with a constant radial offset. We do not recommend the adoption of any empirical DORIS satellite phase center offsets at this point.

1. Introduction

DORIS (Doppler Orbit Determination and Radiopositioning on Satellite) is a French tracking system initially designed for precise tracking of low-earth orbiting satellites (Willis et al., in press,a). It is an uplink Doppler system with a dense tracking network (Fagard, in press), allowing almost continuous observation for satellites above 800 km altitude. Recently, following the example of the International GNSS Service (IGS) (Beutler et al., 2002), an International DORIS Service (IDS) was created (Tavernier et al., in press).

The current accuracies of space geodetic products are usually altered by many systematic errors. Within the GPS community, several studies have been conducted to estimate antenna corrections in order to decrease possible systematic errors. These corrections can be expressed in terms of mean phase-center offsets for both ground and satellite antennas (e.g., Mader and Czopek, 2002). A more comprehensive approach is to use antenna phase-center variations (PCV) models, which provide estimates of the PCV

as a function of elevation and azimuth, seen by the antenna ground station or by the satellite antenna (Rothacher, 2001; Schmidt and Rothacher, 2003; Haines et al., 2005). Similar investigations have not been carried out yet on a systematic basis for DORIS. Willis et al. (2005b), however, did estimate DORIS satellite antenna maps that described corrections to the Doppler measurements as a function of elevation and azimuth.

Recent studies (Willis et al., in press, b) indicate that the scale of the Terrestrial Reference Frame (TRF) derived solely from DORIS (equivalent to a constant error in height of all DORIS station coordinates) is biased by a few parts per billion (ppb) with respect to the scale of ITRF2000 (Altamimi et al., 2002). By estimating the radial offset between the center of mass (CM) of the satellite and the center of phase of the DORIS antenna, this systematic scale error could be significantly reduced or eliminated. It should be noted that the success of this approach depends to a large extent on the accuracy of the modeled location of the CM in the body-fixed s/c frame. A time-dependent model for the migration of the center of mass of the SPOT satellites (as fuel is consumed) is not presently available. Such information is provided for all other DORIS satellites (TOPEX/Poseidon, Jason and ENVISAT) but not for the SPOT, for which only a constant value of this vector is provided by CNES (French Space Agency) to the IDS users.

The goals of this paper are: to estimate for all DORIS satellites empirical phase center offsets in the three directions (body-fixed frame); to compare these results with similar results obtained from GPS data when available (TOPEX/Poseidon and Jason); and finally, to test if reprocessing with these empirical offsets provides some improvement, either in terms of Terrestrial Reference Frame (geocenter and scale) or in terms of station coordinate precision.

1. Description of the method

We chose to analyze data from one full year of DORIS data in order to get reliable results. We selected the year 2004, as it is the last year for DORIS/TOPEX data. Represented in this year are data from as many as 6 satellites (Table 1). Of all possible DORIS satellites, only SPOT-3 was not studied because data are only available from 1996 to 1998.

(Table 1)

DORIS orbit solutions were computed on a daily basis independently for each satellite. Station coordinates were fixed to our latest cumulative solution IGN04D02 (Willis et al., 2005a). This solution is based on more than 12 years of DORIS data and provides a precise position and velocity for each tracking station. The frame was a posteriori aligned to ITRF2000 (Altamimi et al., 2002) using a conformal 14-parameter transformation. When fixing station coordinates to a standard frame such as ITRF2000, it is advisable to use an internal solution, such as IGN04D02, established using more data, adding the most recent stations as well. This approach also accounts for the station-related problems that were not known at the time of computation of the ITRF2000 (Willis and Ries, 2005).

The DORIS data were processed with the GIPSY/OASIS II software, using the latest analysis strategy and the latest models, including a recent GRACE-derived gravity field GGM01C (Tapley et al., 2004) up to degree and order 120 as it provided a significant improvement in DORIS station positioning accuracy as measured externally by GPS (Willis and Heflin, 2004).

2. Estimating DORIS phase center offsets

2.1 SPOT results

Figure 1 displays an example of such results in the case of all three SPOT satellites for the radial component (pointing opposite to the Earth).

(Figure 1)

Figure 1 shows that all SPOT satellite estimates present a common systematic bias of about 15 mm in the zenith direction (away from the Earth). All results are also affected by a clear annual signal of about 5 mm amplitude: 5.5 mm for SPOT-2, 4.3 mm for SPOT-4 and 5.4 for SPOT-5. The exact causes of these temporal variations are still unknown. In our opinion, they could be related to mis-modeling in the solar pressure or albedo acceleration or to remaining errors in tropospheric or ionospheric corrections.

However, the explanation of the bias itself is consistent with the fact that the IGN/JPL (Institut Geographique National/Jet Propulsion Laboratory) station coordinates solutions all suffer from a constant bias of about -2.5 ppb, equivalent to -16 mm in station height, relative to ITRF2000 (Willis et al.; in press, b). Our own solution is consistent with the DORIS measurements and to the systematic error present in our analysis. When we force the station coordinates to be aligned on ITRF2000 (being pushed up in the direction of the satellite), we need to compensate this error in our computation. As the position of the center of mass will remain the same (the semi-major axis remains the same, as the time definition is not changed, through the 3rd Kepler's law), one way to compensate these errors, is to push the satellite antenna upward, so that the distances (through the Doppler measurements) remain the same. We should then estimate a positive vector offset (from satellite center of mass to the antenna phase center), in the radial component (opposite to the Earth).

We extended this study by estimating this antenna phase center offset, only in the case of the SPOT-2 satellite, using the preliminary ITRF2005P solution (Altamimi et al., 2005) instead of the older ITRF2000.

(Figure 2)

It can be seen in Figure 2 that the estimated radial offset is quite different when fixing station coordinates to ITRF2000 or to ITRF2005P (a preliminary version of ITRF2005 that was distributed to small validation group for test purposes in May 2006). The offset estimated using ITRF2005P coordinates gets closer to zero: the mean value over 2004 is 19 mm for ITRF2000 and only 10 mm for ITRF2005P. This is consistent with the fact the DORIS TRF scale of our IGN/JPL station coordinates solutions is more

consistent with ITRF2005P (-0.7 ppb) than with ITRF2000 (-2.5 ppb). If the ITRFs scales based on VLBI and Laser results can show these large differences on the DORIS sub-network, it seems rather risky to estimate such a radial offset using a specific ITRF. First, the derived DORIS TRF scale would lose all physical meaning. Secondly, the DORIS solutions would only be compatible with the current ITRF (used to derived these satellite antenna offsets) but not with the future ITRFs.

2.2 ENVISAT

All estimated phase center corrections showed some small offsets and small annual signal. Only one of the DORIS satellites also showed a clear discontinuity in the estimated radial offset. Figure 3 shows that a discontinuity can be found for ENVISAT on October 12, 2004.

(Figure 3)

It is intriguing that this discontinuity occurs at the exact time of the in-flight update of the ENVISAT DORIS software. The reason for that is still unknown, but other analysis (Doornbos and Willis, in press) using results from all ACs showed that a different signature could be found in the DORIS residuals after this software change. In this study, ENVISAT data were processed using the attitude model (instead of using the DORIS phase center correction proposed by CNES in the data files) as well as the most recent solar pressure model (Sibthorpe, 2006).

2.3 Synthesis of results

Table 2 presents a synthesis of the mean values of these phase center offsets for all satellites. For non-yawing satellite, the X represents the along-track component (in the direction of the velocity), the Y represents the cross-track component (right direction) and the R represents the radial direction (opposite to the Earth). For the other satellites (TOPEX/Poseidon and Jason), X and Y are defined in the *s/c* body frame. Due to the changes in attitude of the model, these do not have a meaningful interpretation in the velocity or cross-track direction. For Topex/Poseidon and Jason, R represents also the radial direction (opposite to the Earth).

(Table 2)

For non-yawing satellites (SPOTs and ENVISAT), the along-track offset is not observable (noted as N/A in Table 2).

All estimated radial corrections are positive in the direction opposite to the Earth so the estimation tries to put the antenna farther from the Earth. This is compatible with the fact that the DORIS IGN/JPL TRF scale is negative (-2.5 ppb) when compared to ITRF2000. When fixing DORIS station coordinates to ITRF2000 (going up), the estimation tries to find a way to put the satellite farther from the Earth, in order to keep the measurements constant (basically distances from ground stations to satellite, and in the case of DORIS difference in time of such distances). Previous analysis showed that

other DORIS Analysis Center find a different TRF scale for each satellite (Willis et al., in press, b).

The DORIS/Jason data are affected by an abnormal acceleration of the on-board clock over the South Atlantic Anomaly (SAA) due to an extreme sensitivity to radiation (Willis et al., 2004). In this investigation, we did not use the recent correction model developed by Lemoine and Capdeville (in press), but we disregarded any data from ground stations located nearby the SAA. This could probably explain the larger radial offset found for this specific satellite as the global effect is not properly addressed in a proper way. All other DORIS satellite show a common bias of about 16 mm opposite to the Earth. This is equivalent to a 2.5 ppb error in the TRF scale at this altitude.

The estimated cross-track vectors are also at the same level (under 20 mm). As discussed by Willis et al., 2006, errors in this component could dissipate in error in TZ-geocenter component with an amplification factor of 6.5 for the SPOT non-yawing sun-synchronous satellites.

3. GPS phase center offsets

3.1 Estimating GPS phase center offset for Jason and TOPEX/Poseidon

Estimation of the phase-center location has long been a standard approach for diagnosing possible scale errors in the GPS measurement system (e.g., Bertiger et al., 1994). Of the DORIS missions considered in this paper, two of them - TOPEX/Poseidon (T/P) and Jason-1 - also carried precise GPS receivers.

Haines et al. (2003) reported GPS-derived phase-center offsets for the Jason-1 mission. These results, however, were based on the prevailing GIPSY/OASIS II (GOA-II) software standards for the locations of the phase center of the transmitters on the GPS satellites. We present herein results based on our new GRACE-based transmitter phase-center variation (PCV) maps (Haines et al., 2005). For the Jason-1 antenna, we used alternatively the pre-launch anechoic PCV map (Figure 4) or a map derived empirically from in-flight data (Figure 5). While the boresite of the Jason-1 GPS antenna is canted 30° from zenith, the daily estimates depicted in the Figure are expressed in the Jason s/c body-fixed frame, with the vertical (R) component of the phase center expressed as positive in the zenith direction.

(Figures 4 and 5)

Evident in the time series (Figure 4) is a dependence on the yaw regime of the satellite, which is dictated by the variation of the β' angle (~ 117 -d period). Note that fixed-yaw periods are excluded from the time series since the X axis of the s/c aligns with the along-track component of the orbit, and the corresponding X offset cannot be distinguished from timing/orbit errors. The average offset corrections in the X, Y and Z s/c directions (with sample standard deviations) are respectively -0.4 ± 1.4 cm, -0.4 ± 2.0 cm and -1.6 ± 0.5 cm. With the exception of the Z component, the estimated location of the Jason-1 GPS phase center is within a few mm of the model. The source of the small remaining Z bias (-1.6 cm) is not presently known, but multipath reflections off the Jason s/c could certainly contribute at this level. Of course, we cannot rule out some

contribution from a scale error in the adopted reference frame (IGS derivative of ITRF2000) as manifest in the GPS spacecraft orbit and clock products used in computing the Jason-1 orbit. As expected, use of the empirical antenna map reduces this Z bias to insignificance (Figure 5). The RMS phase-center variation (LC) explained by the empirical map is ~ 1 cm, and reflects principally the combination of intrinsic antenna PCV and multipath. The aggregate effect of multipath is expected to vary with β' angle because different portions of the canted Jason antenna are sampled depending upon the yaw attitude of the spacecraft.

Published estimates of the T/P phase-center offset (Bertiger et al., 1994) were based on dual-frequency data collected early in the mission. With the routine activation of Anti-spoofing (AS) in January, 1994, the older GPS Demonstration Receiver (GPSDR) design operated on a single frequency (L1) only. Figure 6 depicts daily estimates of the T/P GPS phase-center offset (L1) for the 2004 timeframe considered in the present study. While the ionosphere delay was modeled using the approach described by Lough et al. (1998), there remain significant errors compared to the dual-frequency approach wherein the delay is fully removed to first order. Further complicating the interpretation of these results is the absence of L1 PCV maps for the GPS transmitters. (The GRACE-based maps adopted for this study were constructed from LC phase data, and the L1 phase center could depart significantly from its ionosphere-free counterpart.) Despite these caveats, the estimated T/P phase-center offsets show good stability. The estimates X and Y offset corrections are centered close to zero while the radial (R) offset averages 20 cm. The principal effect of the mismodeled ionosphere and GPS s/c L1 phase-center location is expected to be in the vertical (Z).

3. Applying DORIS phase center offsets

3.1 Method used

We recomputed DORIS weekly solutions of stations coordinates and daily Earth Orientation Parameters (EOPs) after adopting the estimated phase center corrections derived earlier (Table 2). These solutions were obtained in a real multi-satellite adjustment at the data level (Willis et al., 2003). We did not add up normal matrices from individual satellite solutions as it loses some information when some common parameters are eliminated beforehand, such as vertical tropospheric corrections and station clocks. It is very easy with the GIPSY/OASIS II software to process data with or without an additional empirical phase center correction. Only one Fortran namelist needs to be changed, insuring that DORIS data will be processed exactly in the same manner, except for this additional correction. To avoid problems related to the SAA, no DORIS/Jason data were used in the estimation, as it is currently the case for the IGN/JPL operational DORIS solutions to IDS.

3.2 Terrestrial Reference Frame parameters

We did not notice any significant differences in the estimated geocenter variation, even in the TZ-component. Results are indistinguishable. However, the TRF scale decreased as expected from a mean value of almost -2.5 ppb to almost 0.

3.3 Station coordinates

As shown in Table 3, station coordinates results improved only marginally, when compared to the DORIS cumulative solution IGN04D02 (Willis et al., 2005a).

(Table 3)

In our opinion, this shows that most of the estimated DORIS phase correction absorbs systematic errors coming from some other source. It does not seem reasonable at this point to suggest the adoption of any empirical correction of this type as it does not really seem to provide much better geodetic results.

It could be worthwhile for IDS to launch an evaluation study, asking each DORIS AC to derive similar results, using their own software and analysis strategy. In our opinion, this could help us distinguish between technique-related and software-related systematic errors.

4. Conclusions

In conclusion, we estimated mean values of phase center variations for all DORIS antennas as well as for all GPS antennas on satellites also carrying DORIS receivers (T/P and Jason). All estimated DORIS phase center corrections possess a systematic bias of about 15 mm in direction opposite to the Earth when fixing stations coordinates to IGN04D02 terrestrial reference frame, aligned to ITRF2000. This bias almost totally disappears when fixing DORIS station coordinates to the preliminary ITRF2005P solution.

SPOT satellite show small cross-track phase center bias (under 20 mm), creating potential errors in the TZ-geocenter component. They also present small annual signals that are probably related to current weaknesses in the orbit determination models or estimation strategies.

ENVISAT estimated radial phase center offset possesses a clear discontinuity on October 12, 2004 (flight software update) requiring further investigation.

Results obtained for GPS and DORIS estimated phase center offsets are different for common satellites (T/P and Jason). However, we also demonstrated that the estimated values depend strongly on the reference frame used in the case of DORIS and in the PCV model adopted for GPS.

Geodetic results derived from DORIS data reprocessing using the previously estimated phase center correction show very little improvement in weekly station coordinates. How it could be interesting to continue this study and estimate discontinuities in the center of mass of the satellite toward the center of phase of the DORIS antenna for each SPOT satellite after each satellite maneuver, as these information are currently not available from CNES for these satellites. Estimated geocenter variations were totally the same while the TRF scale could be found to significantly decrease from -2.5 ppb to -0.7 ppb.

At this point, we do not recommend the adoption of these corrections for DORIS but we recommend that the other IDS analysis centers could do a similar study to verify if

the estimated corrections have a physical meaning or are just systematic errors relative to analysis software and data processing techniques.

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Figure captions

Figure 1: Daily estimation of SPOT satellites radial phase offset using DORIS data in 2004.

Figure 2: Daily estimation of SPOT2 radial phase center offset using either ITRF2000 or ITRF2005P reference frame in 2004.

Figure 3: Daily estimation of ENVISAT satellite radial phase center offset using DORIS data in 2004. Changes in flight software occurred on October 12, 2004.

Figure 4: Estimated GPS antenna phase center offsets for the Jason satellite, using phase center variation model derived from anechoic measurements (pre-launch data) from 2004.

Figure 5: Estimated GPS antenna phase center offsets for the Jason satellite, using phase center variation model derived from maps developed with in-flight data from 2004.

Figure 6: Estimated GPS antenna phase center offsets for the TOPEX/Poseidon satellite, using phase center variation model derived from anechoic measurements (pre-launch data) from 2004.

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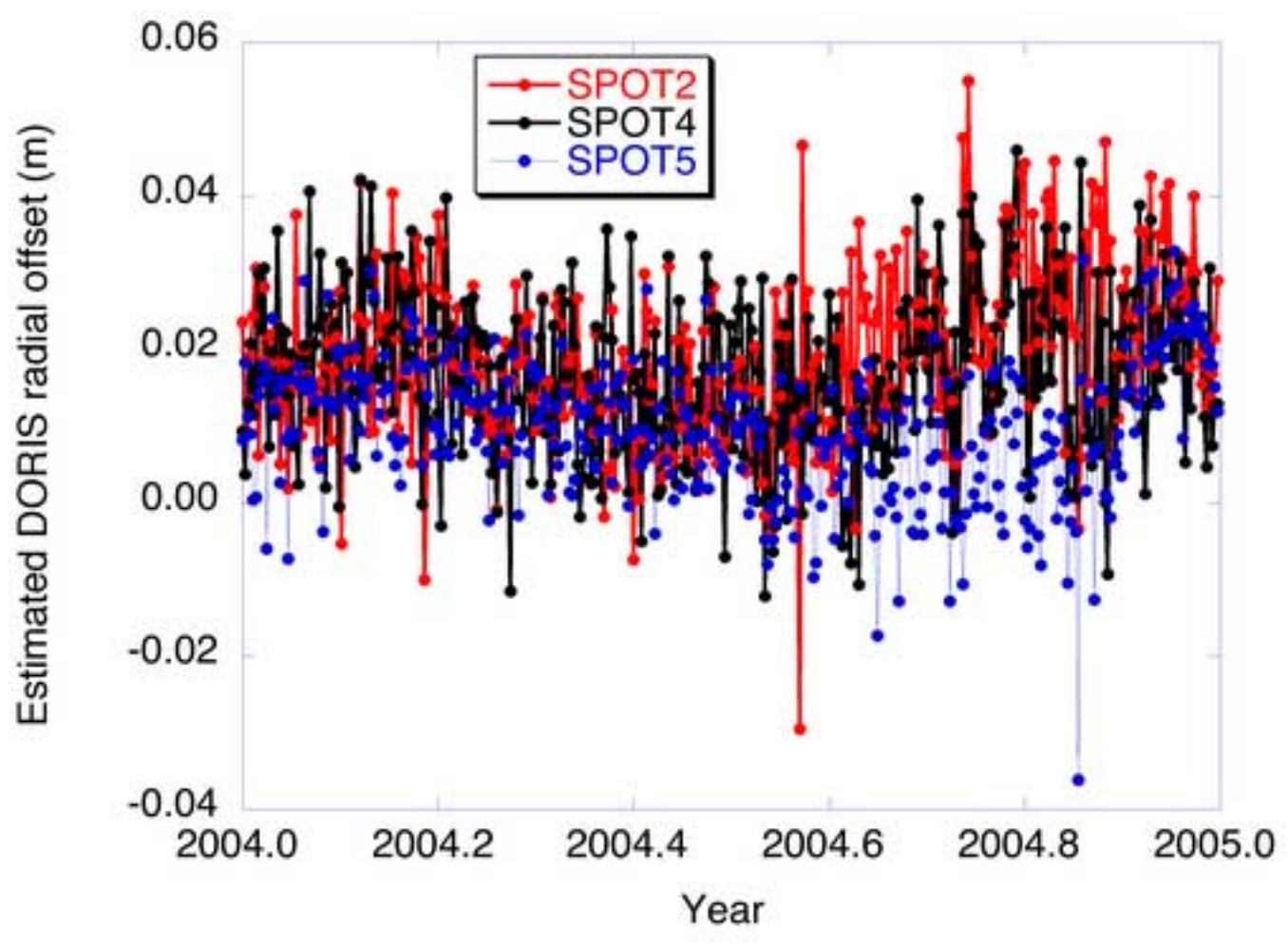


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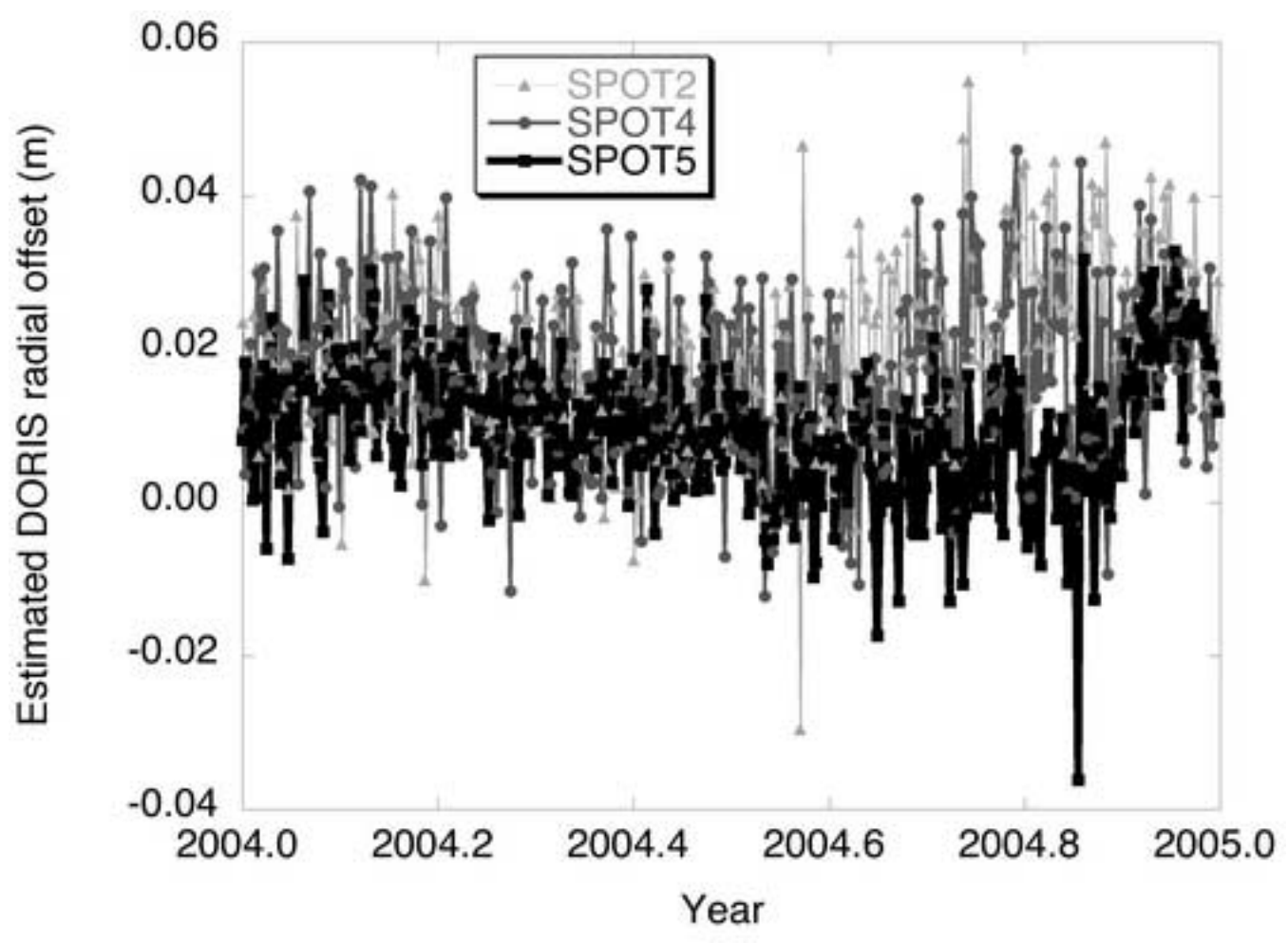


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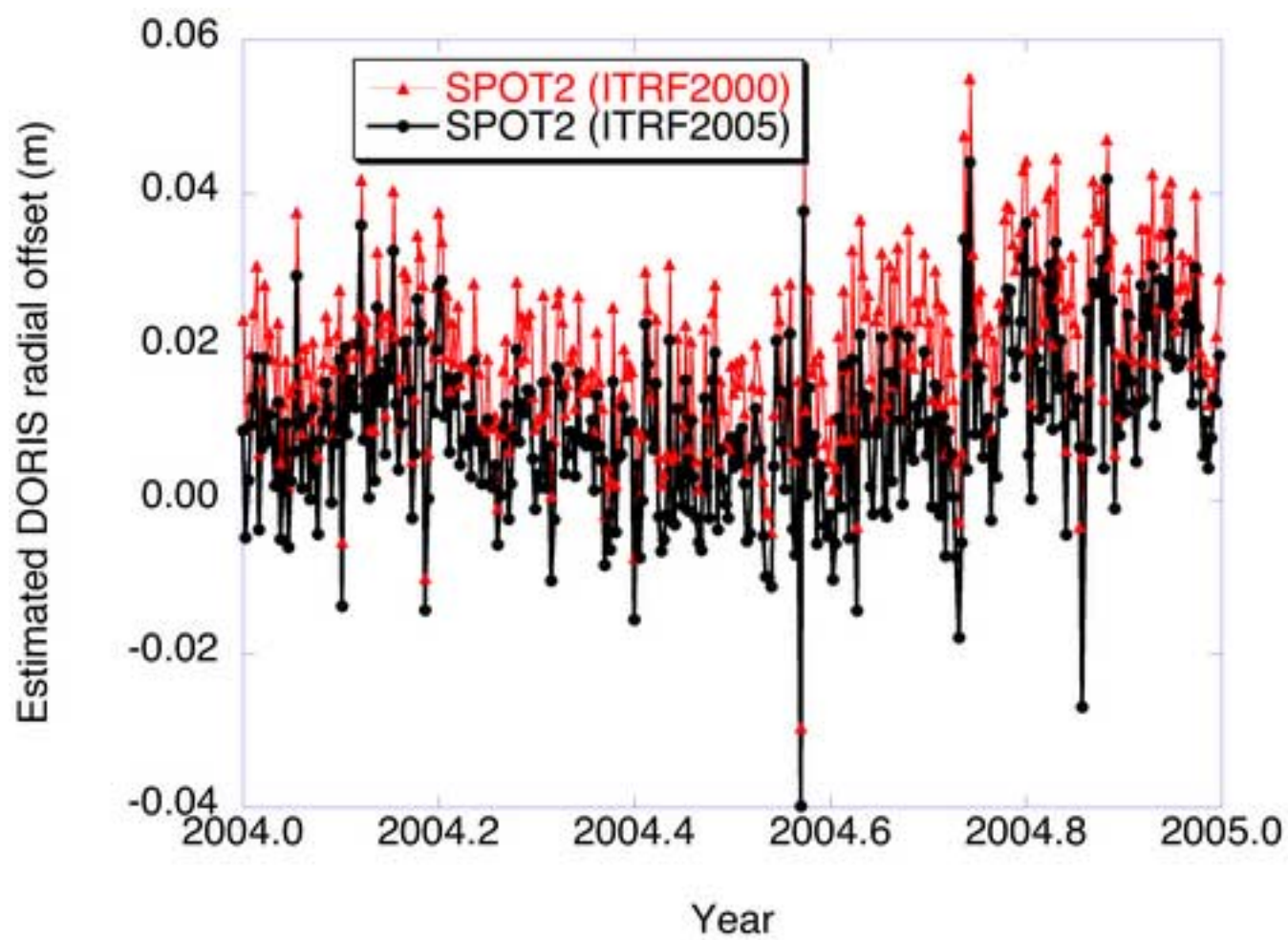


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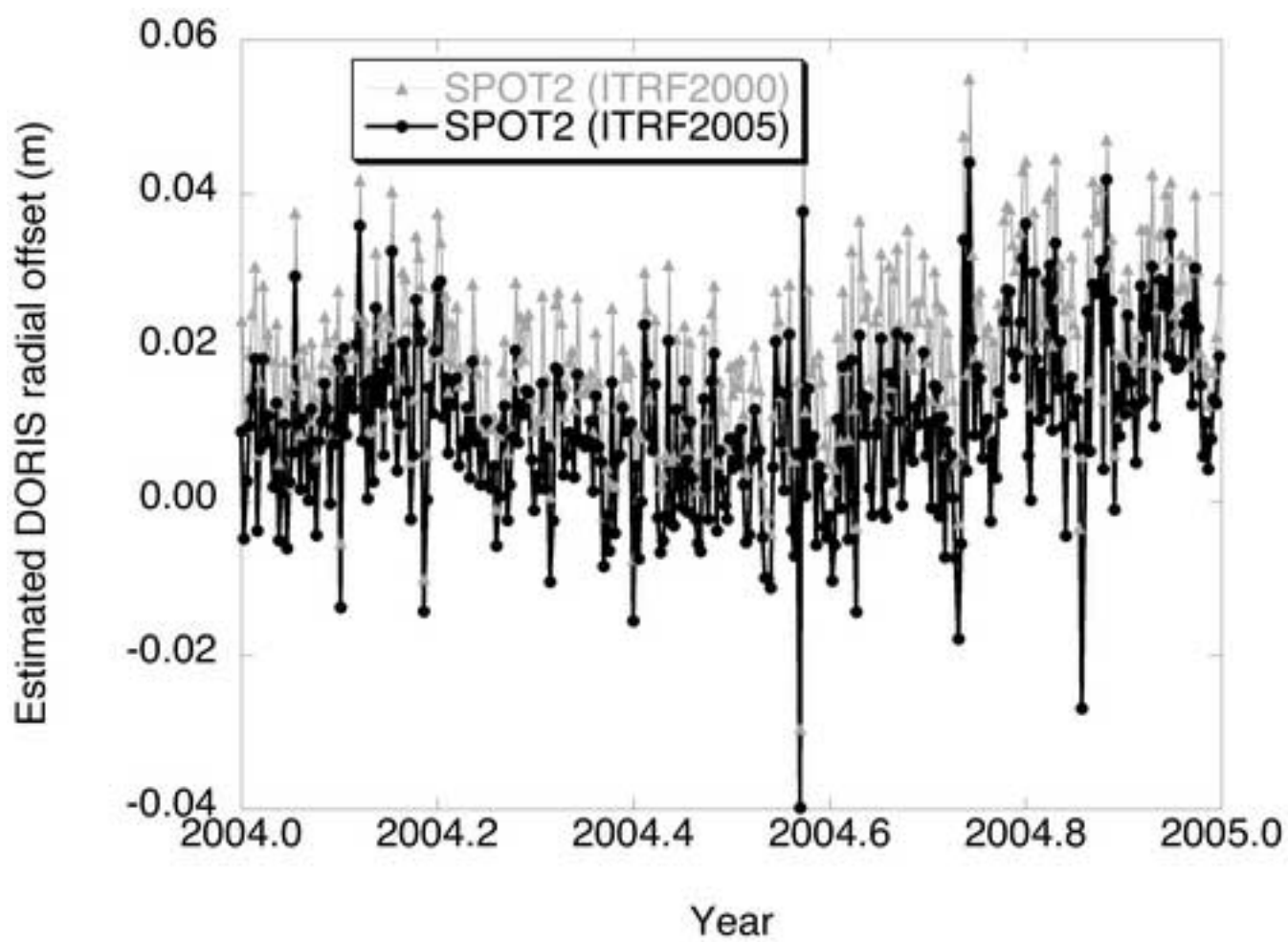


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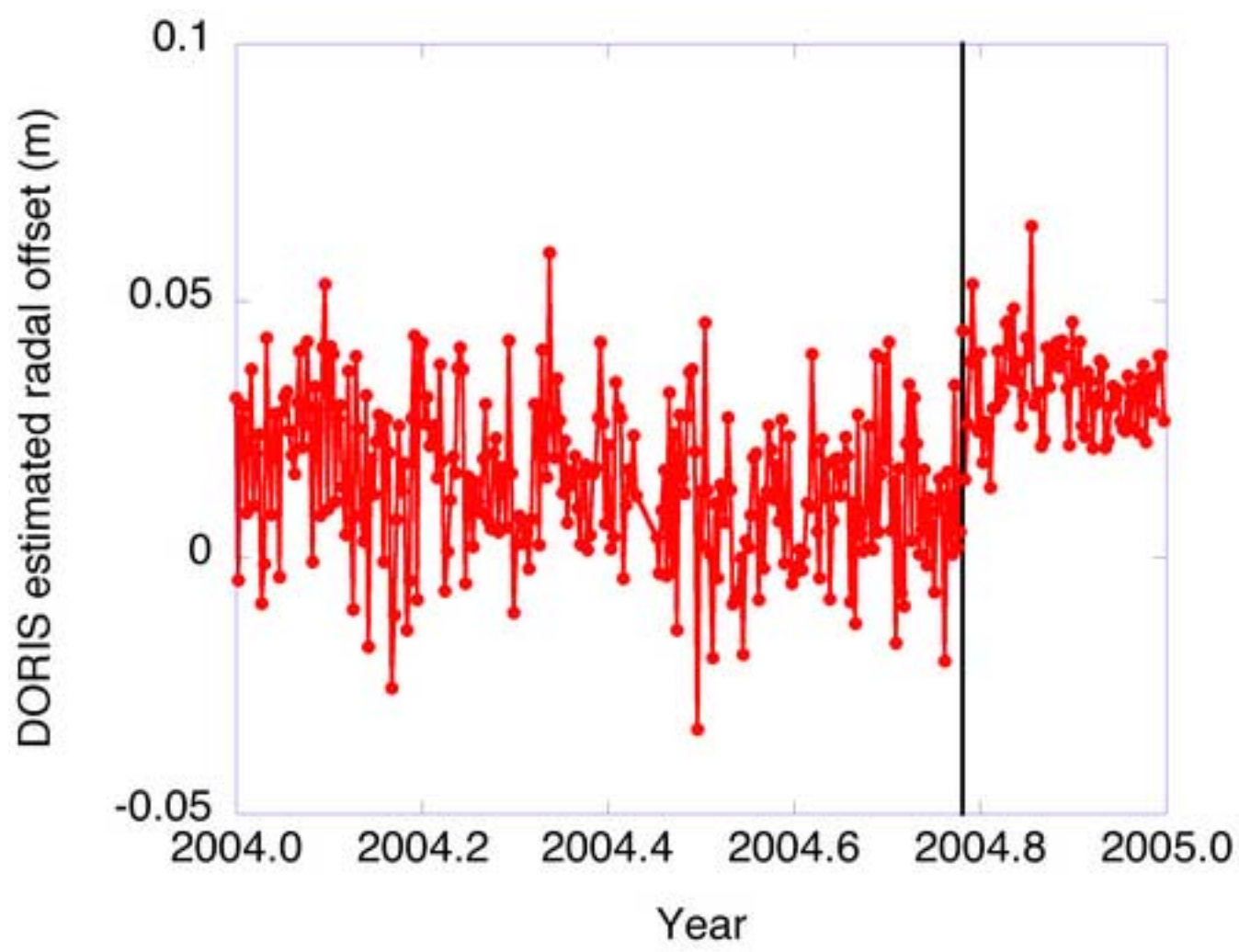


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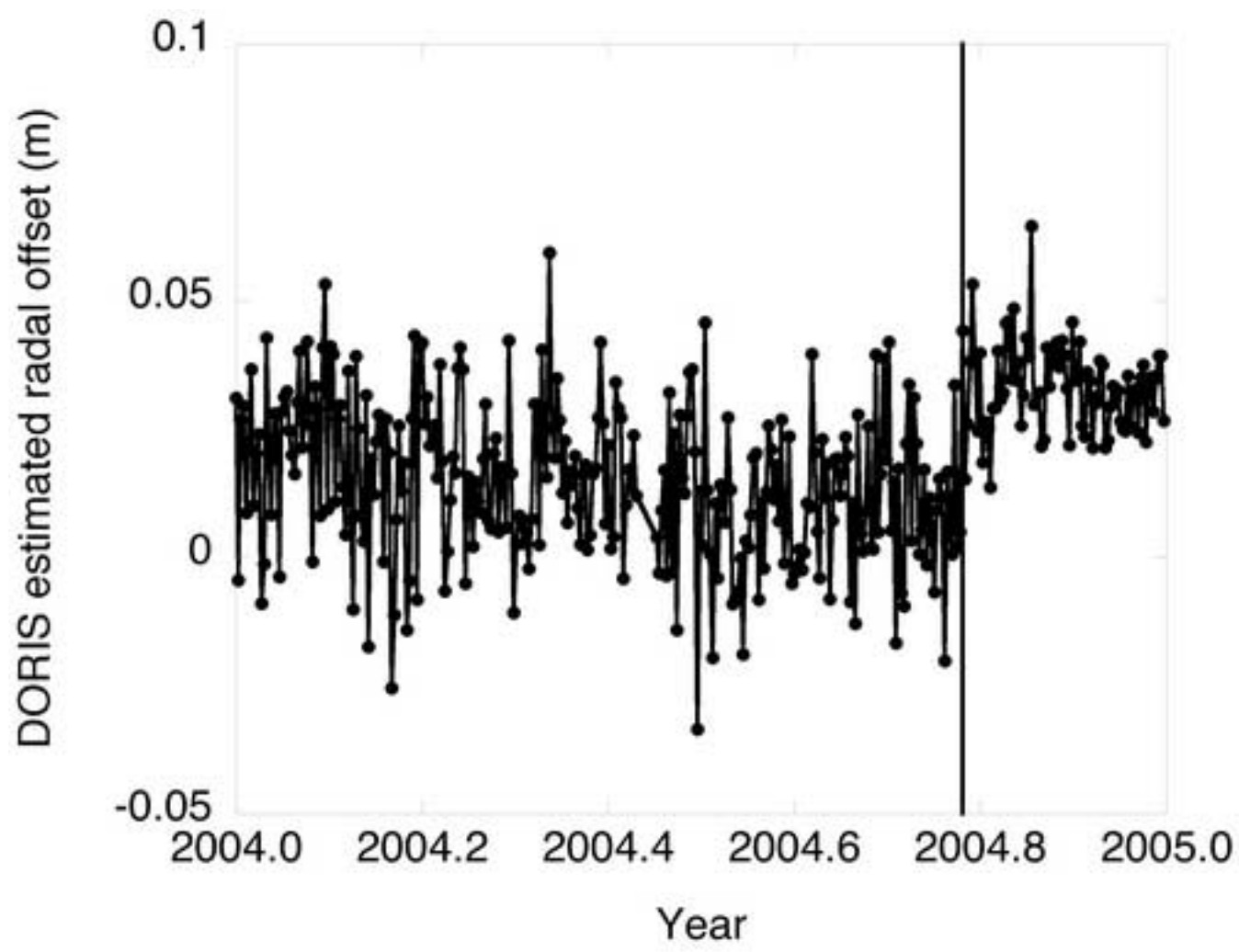


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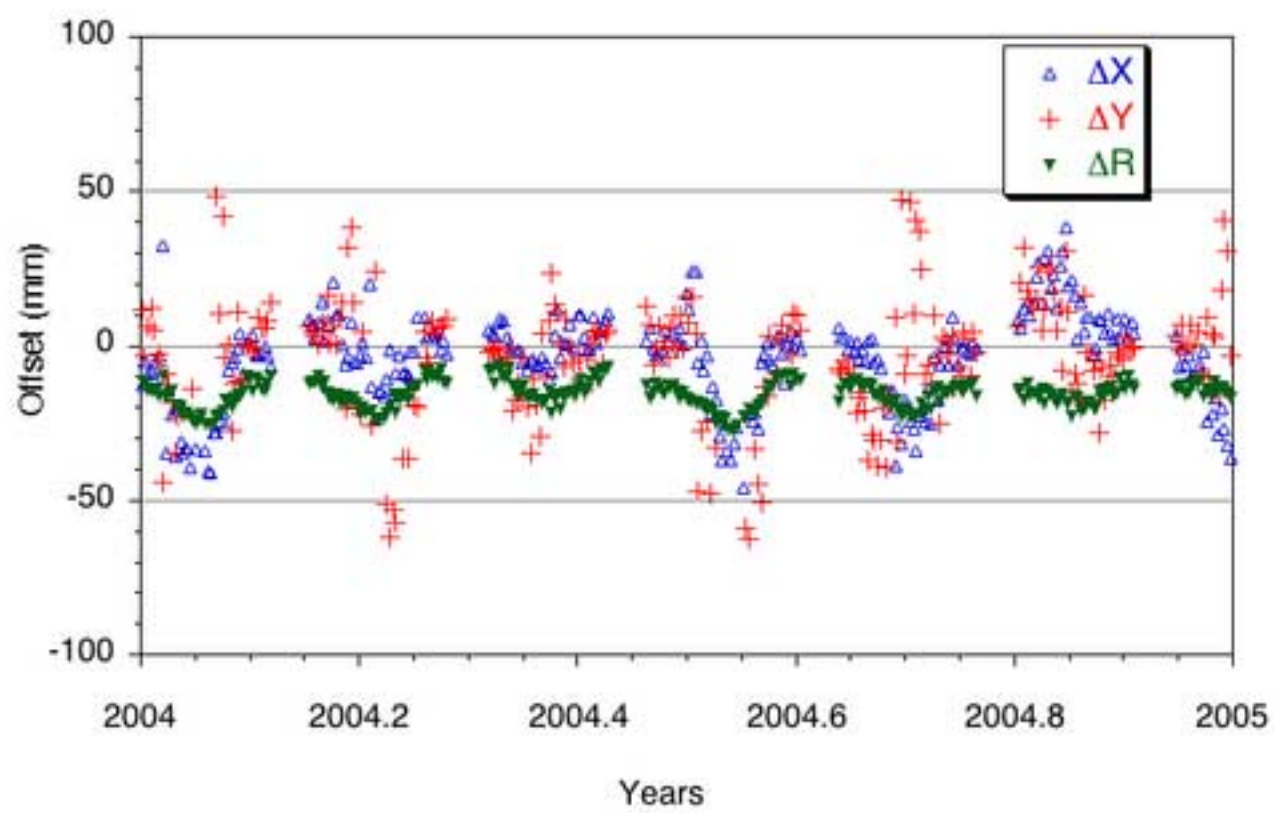


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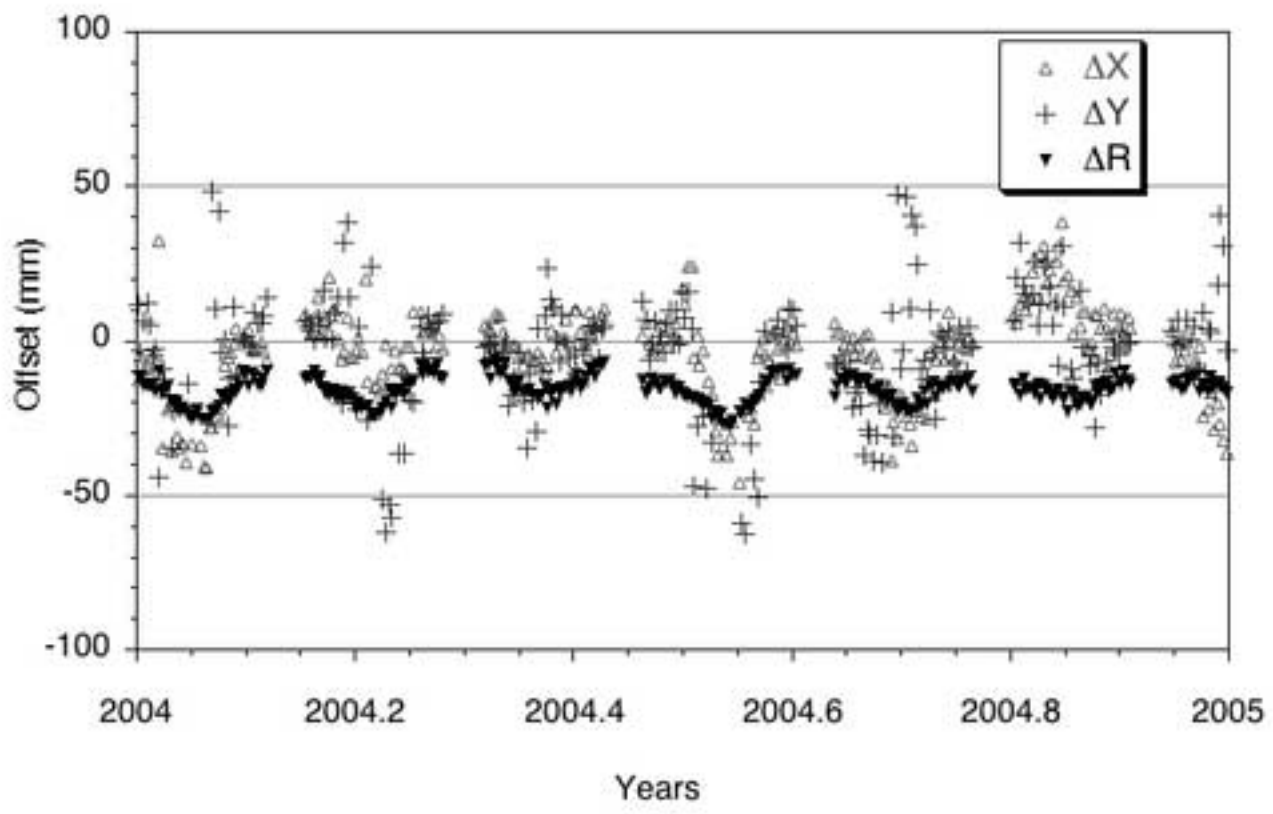


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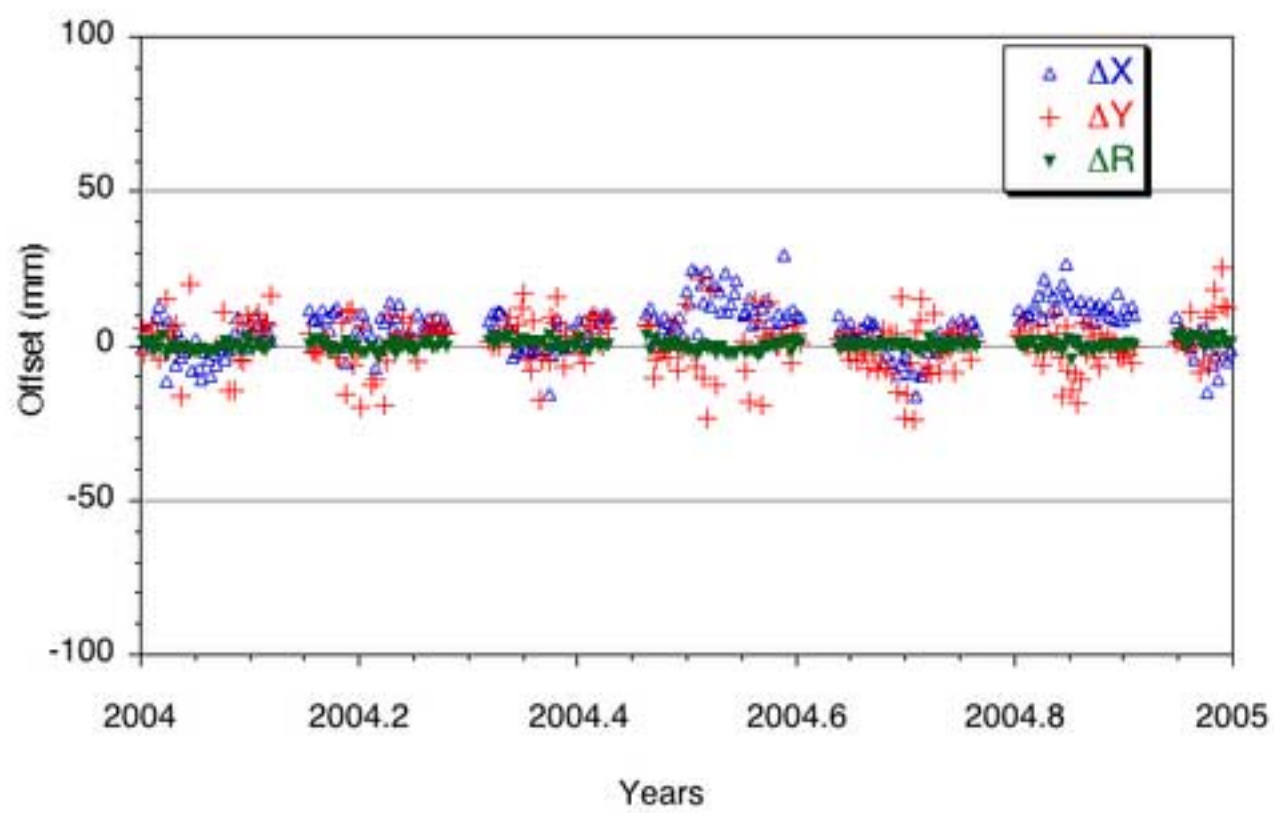


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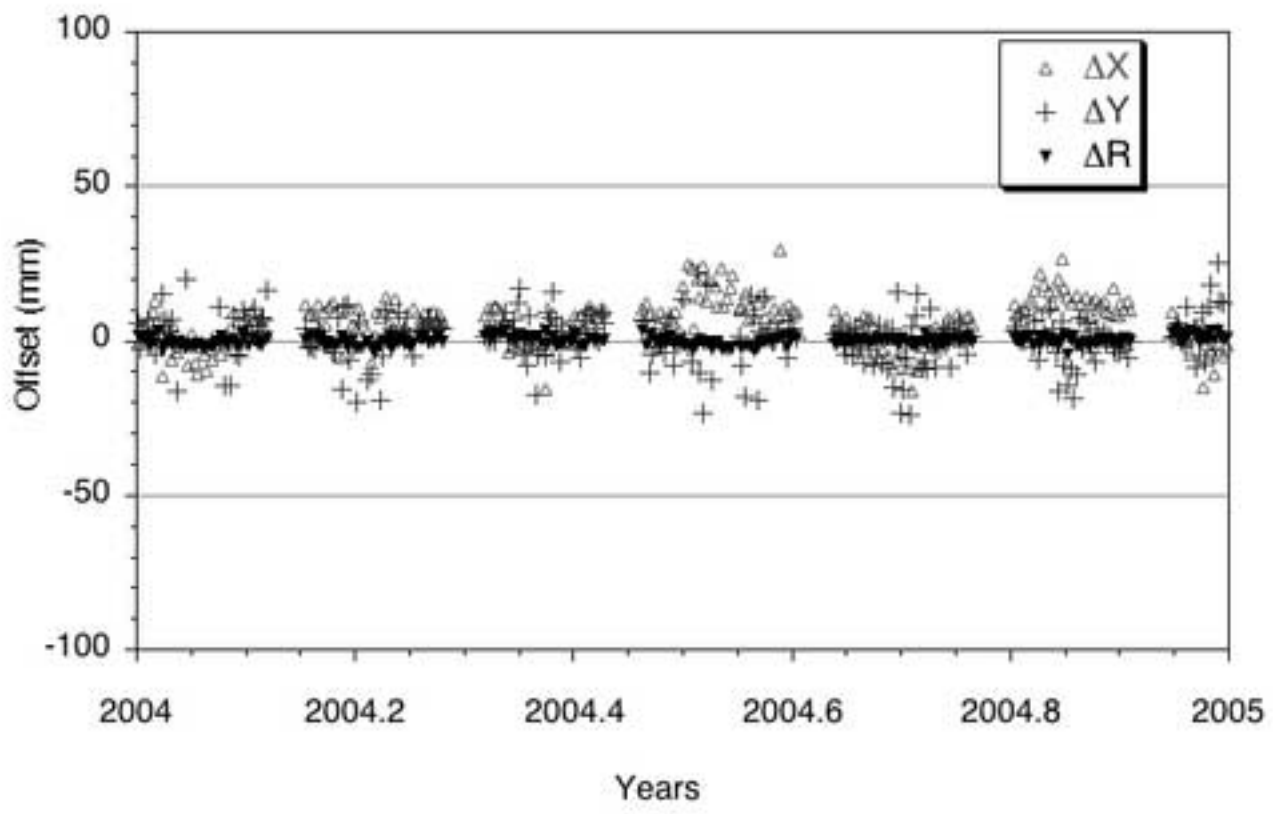


Figure 6 (color) - for internet only
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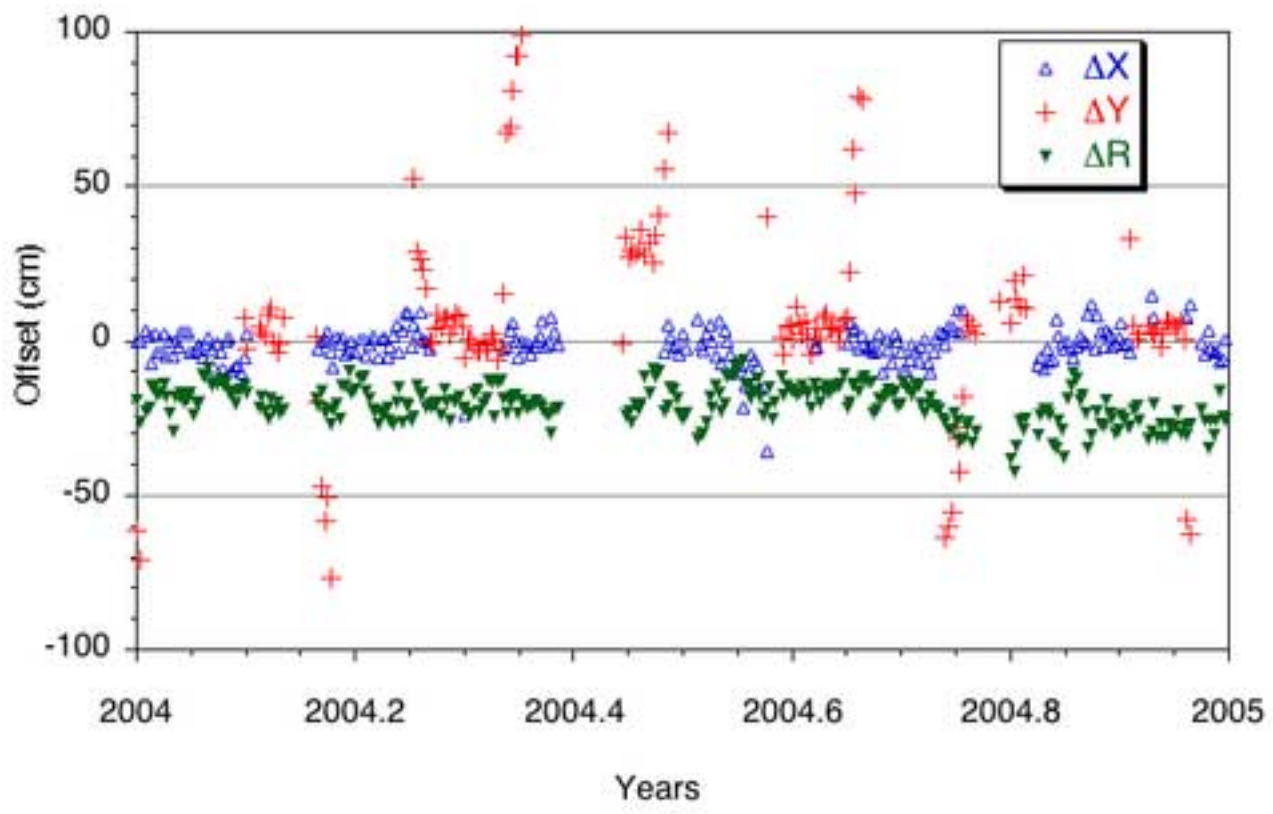


Figure 6 (black-and-white)

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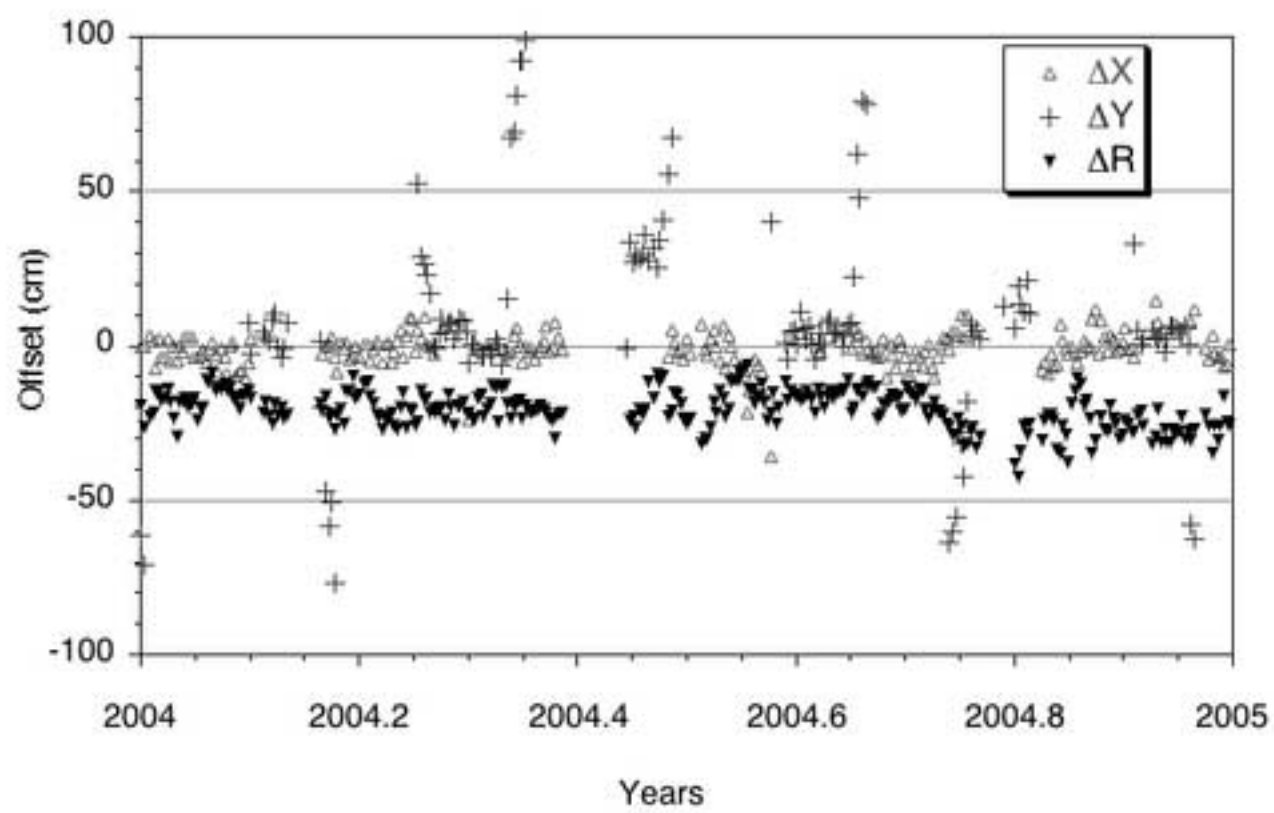


Table 1

Table 1 : List of available DORIS satellites in 2004. 1G = 1st generation, 2G = 2nd generation, 2GM = 2nd generation modified.

Satellite	Altitude (km)	Attitude	Mission	Tracking systems
ENVISAT	750	Specific model	Altimetry Environment	DORIS-2G Laser
Jason	1,330	Specific model	Altimetry	DORIS-2GM, affected by South Atlantic Anomaly (Willis et al., 2004) GPS Laser
SPOT-2	830		Remote sensing Sun- synchronous	DORIS-1G
SPOT-4	830		Remote sensing Sun- synchronous	DORIS-1G
SPOT-5	830		Remote sensing Sun- synchronous	DORIS-2GM
TOPEX/Poseidon	1,330	Specific model		DORIS-1G GPS (single- frequency) Laser

Table 2: Estimated mean values of satellite phase center offset in body fixed coordinates over 2004, using ITRF2000 reference frame.

Satellite	X (mm)	Y (mm)	R (mm)
ENVISAT	N/A	24	19
Jason	2	17	37
SPOT-2	N/A	-13	19
SPOT-4	N/A	-17	17
SPOT-5	N/A	2	10
TOPEX/Poseidon	5	-17	24

Table 3: Mean value of weekly station coordinates WRMS, using or not the estimated DORIS phase corrections for all DORIS satellites but Jason-1. In 2004.

	Standard processing	Using estimated phase center corrections
North (mm)	19.4	19.0
East (mm)	16.7	16.6
Vertical (mm)	18.5	18.4