Acta Geodyn. Geomater., Vol. 7, No. 1 (157), 49–60, 2010

DORIS AT GOP: FROM PILOT TESTING CAMPAIGN TO FULLY OPERATIONAL ANALYSIS CENTER

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(*Received* November 2009*, accepted* March 2010)

ABSTRACT

In cooperation with AIUB (Astronomical Institute University of Berne), GOP (Geodetic Observatory Pecný) and IGN (Institut Géographique National), DORIS data analysis capabilities were implemented into the development version 5.0 of the Bernese GPS Software. The DORIS observables are reformulated that they are similar to GNSS carrier phase observations as much as possible allowing the use of the same observation models and algorithms as for GNSS carrier phase data analysis with only minor modifications. Evolution of DORIS data analysis using Bernese GPS Software is presented from the pilot campaign (September 2004) to the automatic processing of multi-year data time-series. The station and pole coordinates were estimated within the free-network approach and the long time-series of weekly estimated parameters are presented (1993.0-2009.0) and analyzed. The RMS of the estimated polar coordinates significantly decreased after 2002, when the second generation of DORIS satellites was launched. A significant improvement has been achieved by processing the data from the new satellites (SPOT-5 and Envisat) launched in 2002. The RMS in 2003-2009.0 shows the decreasing trend and reached values close to 0.4 mas in both coordinates (2007-2008). Behavior of the terrestrial reference frame scale was quite stable with a few exceptions. Analysis of the major scale shift at the end of 2004 revealed the SPOT-5 and Envisat satellites as the source of the problem. On the other hand, the termination of the TOPEX/Poseidon DORIS data processing at the end of 2004 did not influence significantly the overall scale level. Another goal of the paper is a detail analysis of relations between the value of the observation residuals and the length of the observation time-interval. A simple empirical model considering the observation noise as a sum of the constant and time-dependent terms is applied and discussed. A significant DORIS-GNSS ZTD bias as well as station height bias have been detected in the case of the SPOT-5 data for South America stations Santiago, Cachoiera Paulista, and Arequipa. These stations are located in the area of the South Atlantic Anomaly (SAA).

KEYWORDS: DORIS, DORIS data analysis, IDS, South Atlantic Anomaly

1. INTRODUCTION

Geodetic interest in DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) resides in its reasonably dense and homogeneous tracking network that includes large number of collocations with other space-geodetic techniques (Fagard, 2006). That is why the International DORIS Service (IDS; Tavernier et al., 2006) was officially created by the International Association of Geodesy (IAG) in 2003. Several Analysis Centers contribute to IDS using different software packages (e.g. Willis et al., 2005; Soudarin and Crétaux, 2004). With the aim to make a new software package available and to stimulate further use of DORIS within the geodetic scientific community, the Institut Géographique National (IGN) approached the Astronomical Institute University of Berne (AIUB) with an idea to implement DORIS analysis capabilities into the Bernese GPS Software version 5.0 (Dach et al., 2007). Additional momentum on the developments was gained when the Geodetic Observatory Pecný (GOP) started to participate in the ongoing work in 2003 with the interest to establish an Analysis Center. Today, after a long evolution, the DORIS-capable development version of the Bernese GPS Software exists, allowing estimation of the parameters relevant for this satellite-geodetic technique. The quality of the data processing has been proven by a long data time-series analysis (1993.0-2009.0) and GOP became an official Analysis Center (AC) of IDS in 2007.

Long time-series of the station coordinates and the polar coordinates, derived from the free-network solution, have been estimated by several ACs. Although the input data are the same, the results are far from being identical due to a different approaches, models and used software platforms. Solutions of every AC are thus specific. The first part of the presented GOP DORIS data analysis deals with results of a pilot campaign. Four weeks of data had been processed to confirm the quality of DORIS data analysis using the Bernese GPS oftware (Štěpánek et al., 2006). The second part concentrates on the later developed processing automation and the long time-series of data processing (Štěpánek et al., 2009). The main estimated parameters of the free-network multi-satellite weekly solutions have been analyzed. The most important estimates are the station coordinates and their transformation parameters with respect to the International Terrestrial Reference Frame ITRF2005 (Altamimi et al., 2007), the pole coordinates and their precision with emphasis on the periodicity in their behavior. The results are discussed with regard to the results of other ACs (Willis et al., 2005; Soudarin and Crétaux, 2006) and the overall IDS combination.

The aforementioned analysis is a typical output of each AC, while the following topics are the GOP–specific investigations. Correlations between the value of the observation residuals and the length of the observation time-interval were analyzed. A simple empirical model considering the observation noise as a sum of the constant and integration time dependent terms was applied and discussed. The estimated troposphere total zenith delays (ZTD) were compared to the corresponding values from GNSS (IGS PPP products). The origin of the differences as well as their systematic behavior and dependency on several factors are discussed.

The last part is devoted to the discovered effect named here the SPOT-5 anomaly, which corresponds to the abnormalities of the station heights and other parameters, estimated from the SPOT-5 observations. The possibility of relation to the well known phenomenon of South Atlantic Anomaly is discussed.

2. IMPLEMENTATION OF DORIS INTO THE BERNESE GPS SOFTWARE

The Bernese GPS Software (Dach et al., 2007) is one of the large GNSS data analysis tools for geodetic applications. It is currently in use at more than 200 universities and research institutions worldwide for a large number of applications, including global GNSS data analysis, deformation monitoring in local and regional networks and monitoring of station-specific troposphere parameters. The Bernese GPS oftware currently supports GPS/GLONASS as well as SLR tracking data analysis and developments for the upcoming Galileo system are in progress.

The implementation strategy of the additional tracking technique DORIS was to reduce modifications of the structure of the software and of the processing algorithms to a minimum in order to take maximum profit of the models and algorithms already available for GNSS data analysis. Models describing site displacements and deterministic orbit models can obviously be directly reused. Because DORIS is, as GNSS, a microwave technique, also observation models, e.g. troposphere models or relativistic propagation models, can be used for both techniques in a similar way. This was realized by implementing the classical DORIS Doppler (i.e. the range difference) measurement as two phase measurements, the first at the start, the second at the stop of the DORIS measurement time interval (typically 7, 9 or 10 seconds). Consider the DORIS range rate measurement V as, e.g., available in data files downloaded from the Crustal Dynamics Data Information System (CDDIS) data archive

$$V = \left(c / f_b\right) \cdot \left(\left(f_b - f_s\right) - D / T\right) \tag{1}$$

where f_b and f_s are the beacon and satellite frequency, respectively, D is the cycle count number, T the count integration time interval, and c the velocity of light. The range difference in the count interval may then be written as

$$\Delta = VT = \rho\left(t + T\right) - \rho\left(t\right), \tag{2}$$

where ρ is the range including corrections for tropospheric delay, ionospheric phase shift, clock offsets, phase center offset, etc., and t is the start epoch of the count interval. GPS-like carrier phase 'measurements' may then be defined as

$$\begin{aligned} \varphi\left(t\right) &= \rho\left(t\right) + A \\ \varphi\left(t + T\right) &= \rho\left(t + T\right) + A \end{aligned} \tag{3}$$

with an arbitrary constant A that may, in analogy to GNSS, be called 'ambiguity'.

One observable (Eq.1) is then transformed into two phase measurements and one ambiguity, thus leaving the degrees of freedom of the problem unchanged. By forming the difference (Eq.2), the constant A is eliminated. The two 'observations' obtained from a single DORIS observation can be analyzed in exactly the same way as GNSS carrier phase observations: For both the start and stop epochs of the count interval, the observation equations are evaluated in the same way as for GNSS (except for the beacon frequency offset parameters that are present, and the different situation compared to GNSS as the signal is emitted by the ground station and received by the satellite). To make the analogy with GNSS carrier phase data analysis perfect, an ambiguity parameter is set up for each start epoch of the count interval and pre-eliminated again after processing of the 'observation' referring to the stop epoch of the same interval.

This procedure with setting up and pre-elimination of artificial ambiguity parameters looks weird and complicated. It allows us, however, to integrate DORIS data processing to the largest possible extent into available GNSS phase carrier data analysis algorithms, where handling of ambiguity parameters is a necessity. The corresponding algorithms are already implemented in each GNSS data analysis software. In addition, the procedure may be extended in a natural way to the analysis of DORIS carrier phase observations that even more closely resembles the GNSS data analysis.

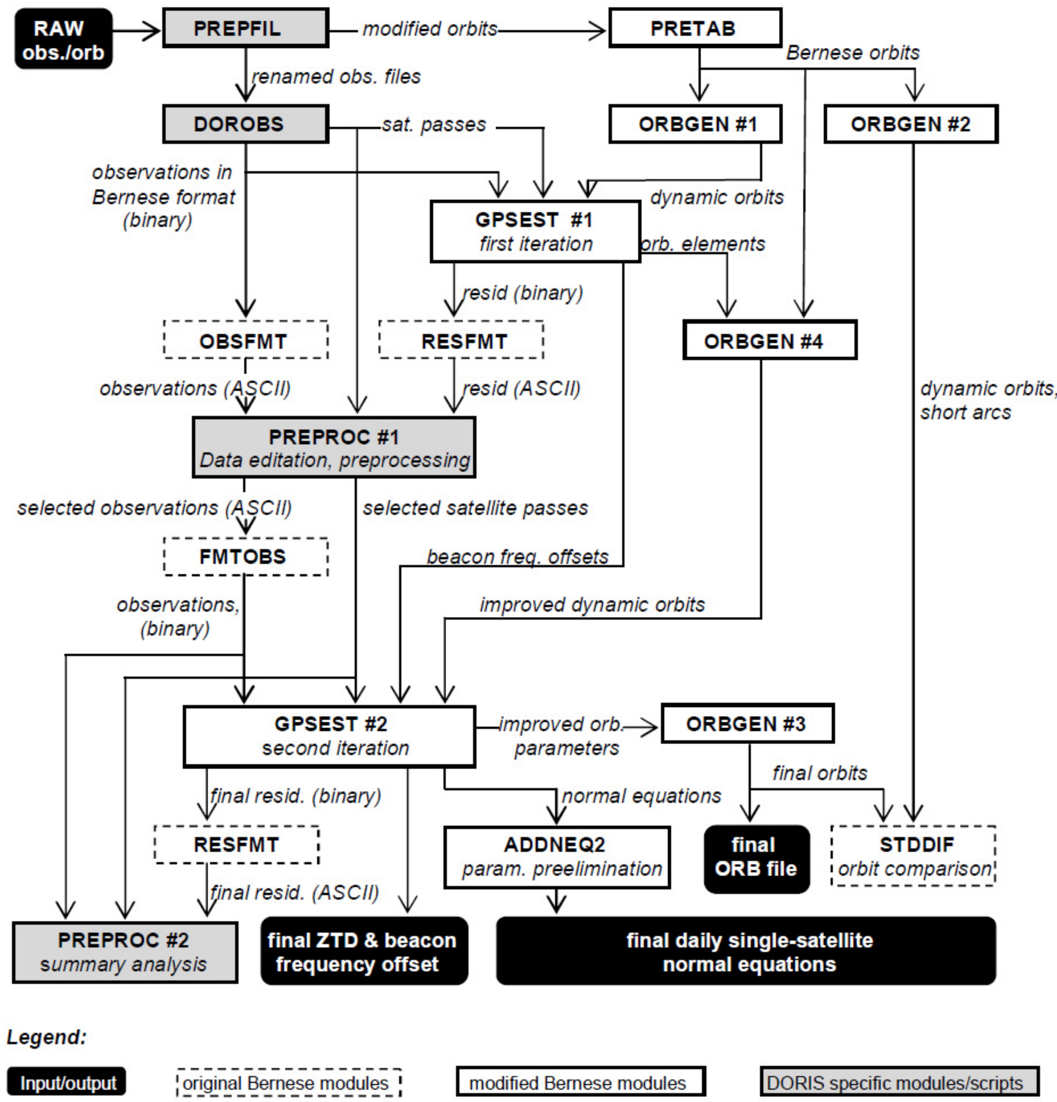

Fig. 1 Single-satellite daily processing diagram.

The procedure was implemented by writing an interface program that converts DORIS observations, as available from CDDIS, into ionosphere-corrected single-frequency 'observations' at the start and stop of the count interval and storing them in a Bernese-formatted phase observation file. Each observation referring to a start epoch is labeled with a cycle slip flag. This flag then forces the analysis program to pre-eliminate the ambiguity attached to the previous count interval on the same beacon-satellite link (if present) and to introduce a new ambiguity.

As new DORIS-specific parameter type, the beacon frequency offsets were implemented into the main data processing program (GPSEST) as well as into the normal equation stacking program (ADDNEQ2). Models adopting the 2003 IERS Conventions (McCarthy and Petit, 2004) for station displacements and gravitational orbit perturbations, as well as troposphere models for microwave frequencies, are already available from the GNSS implementation and can be used for DORIS without further change. For DORIS, however, pass-specific handling of beacon frequency and troposphere parameters had to be implemented since the concept does not exist for GNSS data analysis where a continuous tracking from several GNSS satellites is available. The design allows the Bernese GPS Ssoftware to process a large station network (with simultaneous observations by one satellite) as well as of several satellites in a single run.

3. PROCESSING AUTOMATION

The processing is carried out using the Bernese GPS Software (in version 5.0), and its extensions for automated processing and own scripts. The standard Bernese Processing Engine (BPE) was extended to achieve wider functionality in automated processing. The first step of the processing is a daily single-

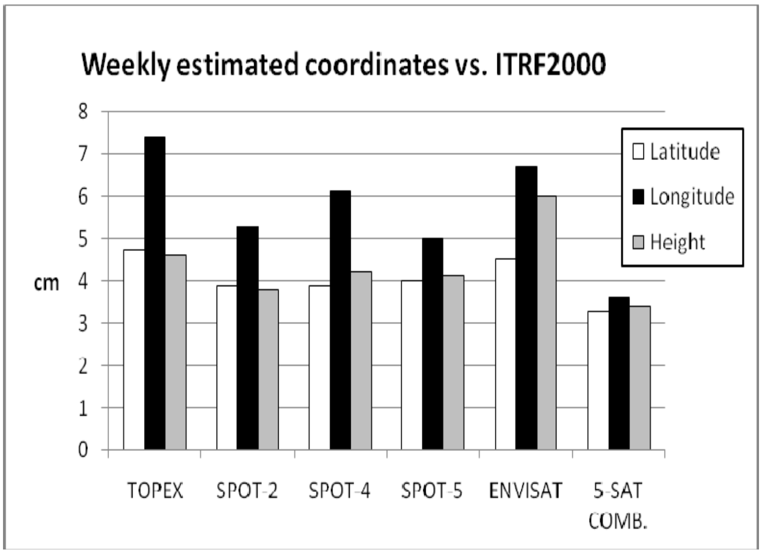

Fig. 2 Comparison of weekly coordinate estimates derived from single-satellite and multi-satellite GOP solutions with ITRF2000 coordinates (after seven-parameter Helmert transformation). Pilot testing campaign, results for single-satellite solutions and multi-satellite solution (5-SAT COMB.).

satellite solution (Fig. 1). Its output (as normal equations) is combined into a daily combination and then into weekly solutions. For the DORIS processing, various Bernese scripts had to be modified and further programs were added.

For convenient processing of longer time-series, it was necessary to develop an appropriate system of programs, covering all processing tasks (beginning by ftp download of observations and orbits and ending by an automated comparison of daily solutions in long time spans). Additionally, for the development purposes a versatile automating tool, able to process the calculation in many variants easily, was needed. An extension of BPE was therefore prepared. It contains the following scripts and modifications:

dor_get.pl. This script carries out the ftp download of observations and orbits, depending on the required epoch and satellite(s) and stores the downloaded files in the file name containing the covered observation epochs.

dor_days.pl. The script runs daily a single-satellite BPE solution for all specified epochs and satellites. The program contains particular extensions to the basic BPE functionality. Every satellite requires different setting of various parameters in the processing, especially in the orbit determination. Nine *ORBGEN* flags are set using two PCF variables $DYNPAR and $STOPAR, that are predefined in a special file for every satellite included.

dor_wk.pl. The script calculates a weekly combination that may be the single-satellite or with the specific satellite set.

dor_helm.pl. This script carries out an automated mass coordinate comparison, as well as a comparison of Earth rotation parameters (ERP).

4. PILOT TESTING CAMPAIGN

In order to validate the implementation of the new DORIS specific components implemented in the Bernese GPS Software, a number of tests with increasing complexity were performed. The complex package of the test called “Pilot testing campaign” is based on the processing of the data from September 2004. Data from all the available satellites except Jason-1 (i.e. SPOT-2,4,5, TOPEX, Envisat) were processed.

Keeping orbits and EOPs fixed, RMS obtained for monthly coordinate estimates with respect to ITRF2000 (Altamimi et al., 2002) were 2.8 cm in latitude, 2.4 cm in longitude, and 1.6 cm in height after applying a 7-parameters Helmert transformation (Štěpánek et al., 2006). In another test, orbits were determined with station coordinates fixed to their ITRF2000 values for every day of September 2004 and then compared to POE (…) orbits. The RMS differences of the estimated orbits compared to POE orbits exhibit values from 2 to 3 cm for all satellites (in the radial component).

In addition, five single-satellite and multi-satellite network solutions were compared with the ITRF2000 station coordinates after application of a seven-parameter Helmert transformation. The average values of the coordinate difference RMS for the three weekly solutions are shown in Figure 2. The RMS values in latitude range from 4 cm to 5 cm for

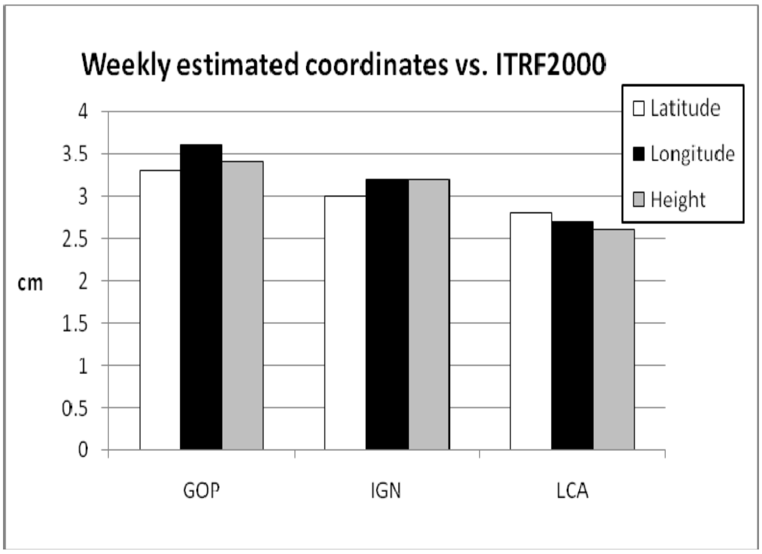

Fig. 3 Comparison of weekly multi-satellite GOP, IGN, and LCA coordinate estimates with ITRF2000 coordinates (after seven-parameter Helmert transformation). GOP pilot testing campaign and corresponding IGN and LCA solutions.

single-satellite solutions while it is only 3.3 cm for the multi-satellite solution. Slightly worse but comparable RMS values have been obtained for the longitude, where the single-satellite solution RMS ranges from 5 to 7.5 cm and the multi-satellite RMS is 3.6 cm. RMS for the height differences is also similar, from 4 cm to 6 cm and 3.4 cm, respectively. In general, lower RMS values of the single-satellite solutions have been obtained for the SPOT satellites than for TOPEX/Poseidon or Envisat. The coordinate results were compared with the corresponding weekly solutions of IGN and LCA (CNES/CLS, formerly LEGOS/CLS) analysis centers. The difference from ITRF2000, the differences between the solutions and the site coordinate repeatability RMS were used to qualify the comparisons. All differences and also the repeatability were determined after application of a seven-parameter Helmert transformation. Mutual comparisons of the solutions are presented in Figure 3. The RMS values demonstrate comparable precision of all of the solutions. In latitude and height they are similar for all three solution differences. Only the RMS differences in longitude are slightly higher when our results are compared with the other centers than those obtained from the comparison between the results of IGN and LCA. More detail results of this campaign are presented in Štěpánek et al. (2006).

5. FREE NETWORK SOLUTION GOP31

The processing of long data time-series is based on a two-step approach. The first step represents the independent single-satellite analysis of each daily session. The CDDIS DORIS data (Berthias, 2003) are used as input and the system of normal equations is created as the main output. Some parameters, i.e., zenith troposphere delays (ZTD), beacon frequency offsets and orbital parameters, are estimated only at this processing level and then eliminated from the normal equations system, while station coordinates and Earth rotation parameters are retained. Each satellite is processed separately at this step. The second step of the processing is based on the combination of daily single-satellite normal matrices creating in this way multi-satellite solutions, typically for each GPS week. The daily normal equation matrices represent the input, the corresponding cumulative matrix, the SINEX file including the system of normal equations, station coordinates, and the Earth rotation parameters are the main output.

A free-network processing strategy was used to create the weekly solution labeled as GOP31 (Štěpánek et al., 2009). The DORIS extension of ITRF2005 called DPOD2005, version 1.4 (Willis et al., 2009) coordinates were used as a priori with constraints of 10 m RMS. Loose constraints of 500 mas were applied for polar coordinates with respect to the C04 IERS parameters (Bizouard and Gambis, 2009). The values at noon and daily rates were estimated without continuity constraints, in contrast to previous results (Pilot campaign), where a piecewise-linear modeling was applied (Štěpánek et al., 2006). The frequency offsets as well as the troposphere zenith delays were estimated per satellite pass. Daily orbit arcs were modeled with six Keplerian elements as well as with six empirical parameters (2 constant and 4 once-per-revolution accelerations in the direction to the Sun and along the solar panel axis) with loose constraints (1×10^{-6} ms^{-2}).

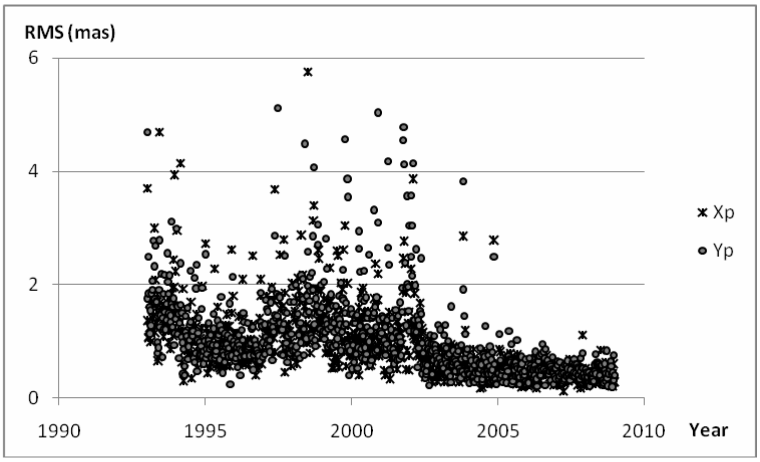

Fig. 4 RMS of estimated X- and Y-pole with respect to IERS C04 model, weekly values.

Atmosphere drag was eliminated by estimating stochastic parameters (velocity changes according to Beutler et al. (1994)) in the radial direction. The constraints on the stochastic parameters and the intervals were adapted such that the RMS difference of the estimated orbits with respect to LCA precise orbits (Soudarin and Crétaux, 2004) was minimized. Optimum intervals and constraints were 15 minutes and 6×10^{-5} ms^{-2}, respectively.

All available satellites were processed, i.e., TOPEX/Poseidon, SPOT-2,3,4,5, Envisat, with exception of Jason-1, which was only included in the 2002 solutions. For the Jason-1 data, the SAA corrections were applied (Lemoine and Capdeville 2006). The list of the most important external models and standards is available at official the IDS data center CDDIS (ftp://cddisa.gsfc.nasa.gov/doris/products/sinex_series/gopwd/gopwd31.snx.dsc).

6. LONG TIME-SERIES OF ESTIMATED PARAMETERS

The pole estimates (1993.0-2009.0) were compared with the IERS C04 pole time-series at the level of the daily noon values, while estimated rates were not used for the comparison. Since the pole parameters were estimated in the framework of a free-network, not transformed and not-projected solution, the comparison with IERS C04 model values was based on the RMS difference after mean removal. However, this approach could generate more optimistic results than the comparison after transformation to the reference frame (ITRF or other), as presented in Gambis (2006). Figure 4 shows the differences between the estimated polar coordinates Xp, Yp and IERS C04. The improvement in precision after 2002, when a new generation of DORIS satellites was launched and when the renovation of the DORIS network started (Fagard, 2006), is obvious. The resulting RMS is lower in the period 1995-1996 (below 1 mas in both Xp and Yp) than in 1996-2001, which emphasizes the strong impact of SPOT-3 (observed until 1996) on the quality of the pole parameter estimates. A significant improvement has been achieved by processing the data from the new satellites (SPOT-5 and Envisat), launched in 2002 and some improvement is also probably related to the renovation of the DORIS ground network. The RMS in 2003-2008 shows the decreasing trend and reached values close to 0.4 mas in both coordinates (2007-2008).

The estimated weekly station coordinates were compared with DPOD2005 version 1.4, an extension of ITRF2005, applying a Helmert 7-parameter transformation. Figure 5 shows the behavior of the translation parameters. The X- and Y-translation parameters are varying between -20 and +20 mm, while the variation in the Z-translation is 2-3 times higher. This is typical for solutions of all the IDS Analysis Centers (e.g. Valette et al., 2009). We observe that the Z-translation values show a pronounced maximum around the year 2002 while the Y-translation shows a somewhat less expressed minimum in the same time period. These extremes are probably directly related to the period of maximal solar activity (see e.g. Cole, 1973). Using spectral analysis, semiannual and annual periodical variations were found in the X and Y translations with a dominant semiannual period. In the Z-translation, the annual periodicity is dominating significant periodic variations at simiannual and 118 days peroid. The behavior of the X and Y spectrum is specific for the GOP solution and is different from the most of the other Analysis Centers, where the annual periodicity dominates for all the translation parameters (Valette et al., 2009; Soudarin and Crétaux, 2004; Willis et al., 2005). The 118-day period was detected by a majority of the analysis centers.

The scale, presented in Figure 6, shows a stable behavior in comparison to other analysis centers (Valette et al., 2009). From the beginning of 2005, the

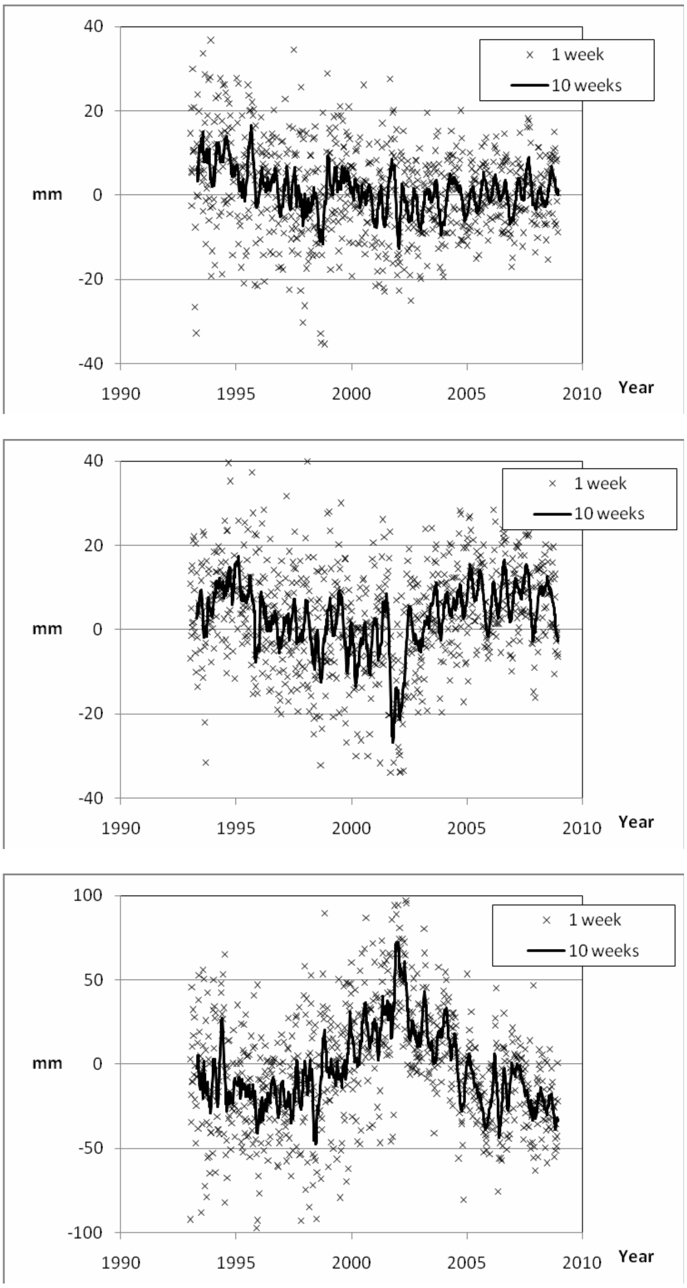

Fig. 5 Translation parameters between estimated network (sol. GOP31) and DPOD2005. Tx (top), Ty (middle), Tz (bottom). According to Štěpánek et al. (2009).

scale values are varying between 0 and -1.6 ppb (0 and -10 mm in height at the Earth's surface). The scale behavior changes in 2002 and at the end of 2004 are interesting enough to be analyzed. In 2002, SPOT-5 and Envisat were launched and this important improvement of the satellite constellation probably explains the scale change. At the end of 2004, two important factors were changed: First, CNES operating software of Envisat was updated (Doornbos and Willis, 2007), and second, TOPEX/Poseidon stopped the production of DORIS data. Missing TOPEX/Poseidon observations seem not to have a significant impact on the scale change, since scale estimations with and without TOPEX/Poseidon leads to similar values (Štěpánek et al., 2009).

All single-satellite solutions were created and analyzed in order to find the source of the scale change (Fig. 7). It is difficult to find a significant change using SPOT-2 and SPOT-4 results, since the single-satellite solutions of the first DORIS satellite generation are not very stable. A significant change of the Envisat-derived scale is visible in week 1292, which corresponds to the above mentioned change in

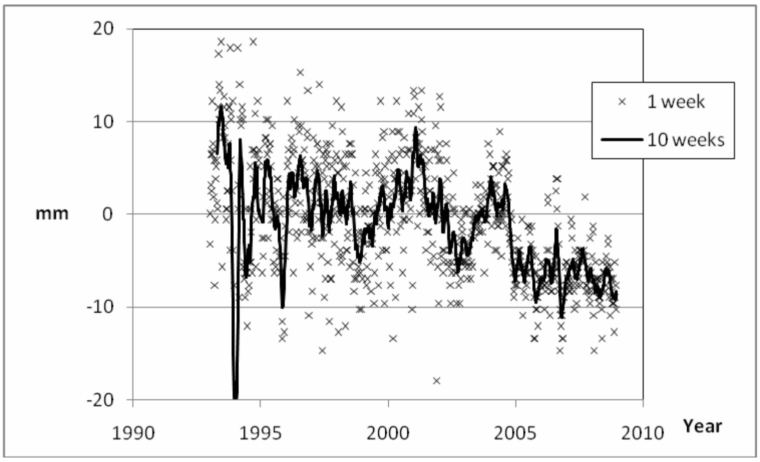

Fig. 6 Scale between estimated network (sol. GOP31) and DPOD2005. According to Štěpánek et al. (2009).

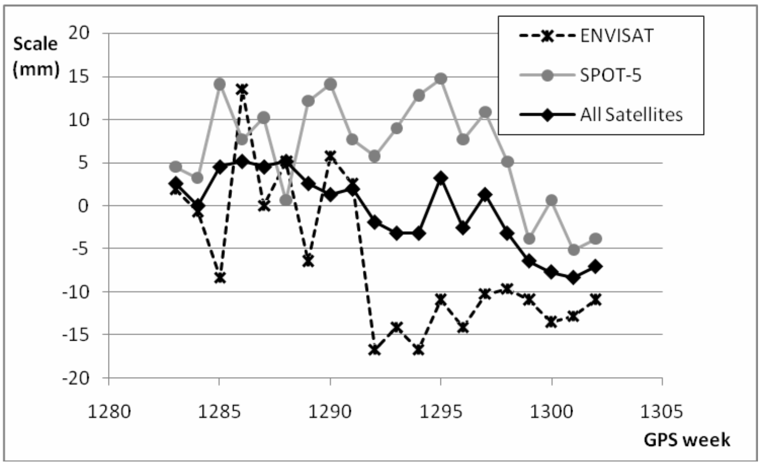

Fig. 7 Scale (weekly values) between estimated network and DPOD2005, single-satellite solutions for SPOT-5 and ENVISAT and multi-satellite solution GOP31. GPS weeks 1283-1302 correspond to the period from August 9th to December 25th of 2004. According to Štěpánek et al. (2009).

the operational software at CNES and is supported by results published in Willis et al. (2007). In that time the chained observation mode started to be dominant for Envisat and the number of observations increased because more measurements at low-elevation were processed. The impact of these Envisat changes on the multi-satellite solution scale is important but does not completely explain the behavior of the scale at the end of 2004. The Envisat scale decreased by about 11-13 mm, while the effect on the combined scale was only about half of the approximately 1 cm total change in 2004. The rest is probably caused by the SPOT-5 scale change around GPS weeks 1298-1299, which has not a simple explanation like the effect of Envisat.

7. ADDITIONAL EXPERIMENTS

This section is devoted to the results of advanced data analyses. In contrary to the previous section, describing the basic analyses made by most of the IDS analysis centers, the results presented here concern the GOP-specific investigations. More detailed descriptions and discussions are presented in Štěpánek et al. (2009).

7.1. RESIDUAL ANALYSIS

DORIS residuals are usually presented as range-rate residuals (in mm/s) (e.g. Doornbos and Willis, 2007; Willis et al., 2005), but they can be expressed as phase count residuals (mm) as well. The basic relation between the range-rate and the count residuals is simple: the range-rate residual multiplied by the

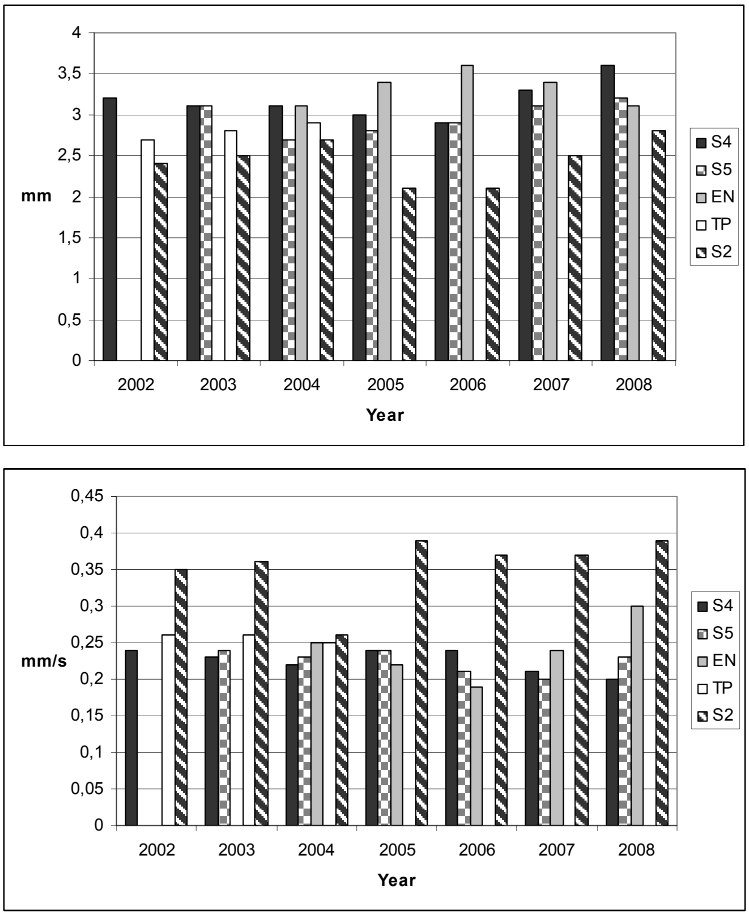

Fig. 8 Constant (upper) and integration time dependent (lower) part of the observation standard deviation derived from post fit residual RMS (for each satellite and the year). According to Štěpánek et al. (2009).

length of the observation time interval is equal to the count residual. The situation is more complicated due to the frequently switched chained/unchained observation mode. Observations with different time intervals are usually acquired (and processed) together. It is thus desirable to analyze the residuals of both types of observations separately, i.e., to distinguish the mixed "short" 7 s or 9 s observation intervals (unchained mode) and the "long" 10 s observation intervals (chained mode), or at least to pay attention to their ratio. Note that if observations with different time intervals are processed together, there is a difference between the minimization of the sum of squared range-rate residuals and the minimization of the sum of squared count residuals. In the GOP solution, the sum of squared count residuals is minimized. All results described in this chapter are derived from the daily GOP single-satellite solutions with adjusted orbits, station coordinates, ZTD and beacon frequency offsets but with fixed ERP.

A profound and detailed comparison of the "short" and "long" measurement accuracy based on the analysis of post-fit residuals is difficult, since both types of observations are processed together. The amount of the short observation intervals is usually too low to be processed separately. The presented approach can thus give only an approximate estimation of the relation between the measurement precision and the length of the observation interval.

The approximate computation of the post fit residual RMS of the chained and unchained observations σ_c, σ_u (eq. 4)

$$\sigma_u = \sqrt{\frac{\sum e^2}{n_u}\frac{n}{n-u}}, \qquad \sigma_c = \sqrt{\frac{\sum e^2}{n_c}\frac{n}{n-u}} \tag{4}$$

was used to compare the residuals of both types of the measurement, where e are post-fit residuals referring to unchained or chained observations, n is the total number of observations, n_u the number of unchained observations, n_c the number of chained observations, and u the total number of estimated parameters. The fact, that the short (unchained) observations have higher range-rate residuals but lower count residuals than the long ones (chained), makes it clear that the measurement noise partly depends on the length of the observation time interval. We may, as a simple approximation, explain the accuracy of the count measurements as the result of a combination of two uncorrelated processes, where the first one is independent and the second one dependent on the count interval. More specifically, we may write the variance of the count measurements in the form (eq. 5)

$$\sigma^2 = \sigma_1^2 + \left(T\,\sigma_2\right)^2 \tag{5}$$

where σ_1 is related to the phase measurement noise while σ_2 relates to the frequency dependent noise and T is the count interval. We may thus write (eq. 6)

$$\sigma_u^2 = \sigma_1^2 + T_u^2\,\sigma_2^2\,, \qquad \sigma_c^2 = \sigma_1^2 + T_c^2\,\sigma_2^2 \tag{6}$$

where T_u (T_c) is the time interval of the unchained (chained) observation. We may then use the post-fit residual RMS computed using eq. 1 as the estimate of the observation standard deviation for the short and long observation intervals. The system of the two equations (eq.6) can then be solved for the two noise components σ_1 and σ_2. The values obtained by this procedure for the time period 2002-2008 are similar for all satellites except for SPOT-2. The unchained observations of SPOT-2 are based on a 9 s time interval, while unchained observations of the other satellites have 7 s time intervals. The standard deviation σ_2 ranges between 0.225 and 0.257 mm/s for all satellites except for SPOT-2, where σ_2 is 0.307 mm/s. On the other hand, σ_1 is lower in the case of SPOT-2 (2.57 mm) than for the other satellites (2.77-3.16 mm). Figure 8 shows the corresponding average values for each year of the analyzed time interval. The estimated relations between constant and time-dependent term are very similar, except for SPOT-2. The analyzed residuals were derived from daily free-network solutions.

There are more possible reasons for the differences between SPOT-2 and the other satellites. The description of the observation variance by eq. (5) may be too simplistic. Also, the different strategy used for SPOT-2 observations (9 s unchained interval instead of 7 s) may relate with another differences that are not easily visible from the data analysis, e.g., differences in the choice between the chained and unchained mode. All this factors could affect the SPOT-2 computation of σ_1 and σ_2 strongly, since the equation system (eq. 6) is numerically rather unstable for 9 s unchained and 10 s chained observation time intervals.

It is worth to remember that the comparison of the chained and unchained residuals is complicated by the fact, that the switch between the chained and unchained mode is not random, but depends on the strategy chosen by the satellite operator (CNES; Tavernier et al., 2006). Despite these complications, the above described approach offers relevant information, eventually leading to a better understanding of the observation noise and to an alternative way on how to analyze the post-fit observation residuals.

7.2. SPOT-5 ANOMALY

The analysis of single-satellite solutions revealed a SPOT-5 specific abnormality, called here the ‘SPOT-5 anomaly’. The estimated station heights and other related parameters derived from SPOT-5 single-satellite solutions are significantly biased. Figure 9 shows the differences between the weekly estimated station coordinates, using the SPOT-5 single-satellite solution and the combined solution GOP31. The highest bias was found in the station heights, where the differences between both solutions reached the highest values for South America stations Cachoeira Paulista (-105 mm), Arequipa (-42 mm) and Santiago (-36 mm). The horizontal positions show the largest absolute differences (from 30 to 45 mm) for the same stations and also for Kourou. Corresponding differences were detected also in the comparison between estimated ZTD (Zenith Troposphere delay) and GNSS ZTD (IGS PPP product, Byun and Bar-Server (2009)). Detailed results are discussed in Štěpánek et al. (2009). The geographical location of the SPOT-5 anomaly is related to the phenomenon known as South Atlantic Anomaly (SAA) (Willis et al. 2004), based on the geometry of the Van Allen radiation belts (e.g. Naugle and Kniffen, 1961). The Van Allen radiation belts are symmetric with the Earth's magnetic axis, which is tilted with respect to the Earth's rotational axis by an angle of ~11 degrees. Because of this tilt, the inner Van Allen belt is closest to the Earth's surface over the south Atlantic ocean, and farthest from the Earth's surface over the north Pacific ocean.

The above described analysis should not be considered as a final proof of the significant effect of the South Atlantic Anomaly (SAA) on SPOT-5 data, but SAA should be taken in account as a probable explanation of the SPOT-5 anomaly. Information about important DORIS data corruption by the SAA effect were not published in the past except for Jason-1 (Willis et al., 2004), but some recent multi-satellite ZTD DORIS-GPS comparisons (without Jason-1) at IGN (Bock et al., 2009) indicates significant SAA related effects as well. The impact is not as big as the SPOT-5 anomaly described here, since only the multi-satellite combination results are presented. The fact that such an effect could exist but has never been detected by any analysis group during the last years looks surprising. On the other hand, there are several arguments supporting the hypothesis of the SAA effect on SPOT-5. The general assumption, that lower altitude satellites (SPOTs, Envisat) are not affected because the SAA effect is too weak at these altitudes, is not completely certain. Some satellite missions (ROSAT, NASA Terra Spacecraft, NOAA POEs) were studying and mapping the SAA effect at the same or even lower altitude (e.g. Huston and Pfitzer, 1998). The SAA effect is clearly less significant at lower atlitude, but Jason-1 data are in fact much more corrupted than those of SPOT-5. The maximal vertical station bias found with SPOT-5 is around one decimeter while the Jason-1 vertical bias reaches

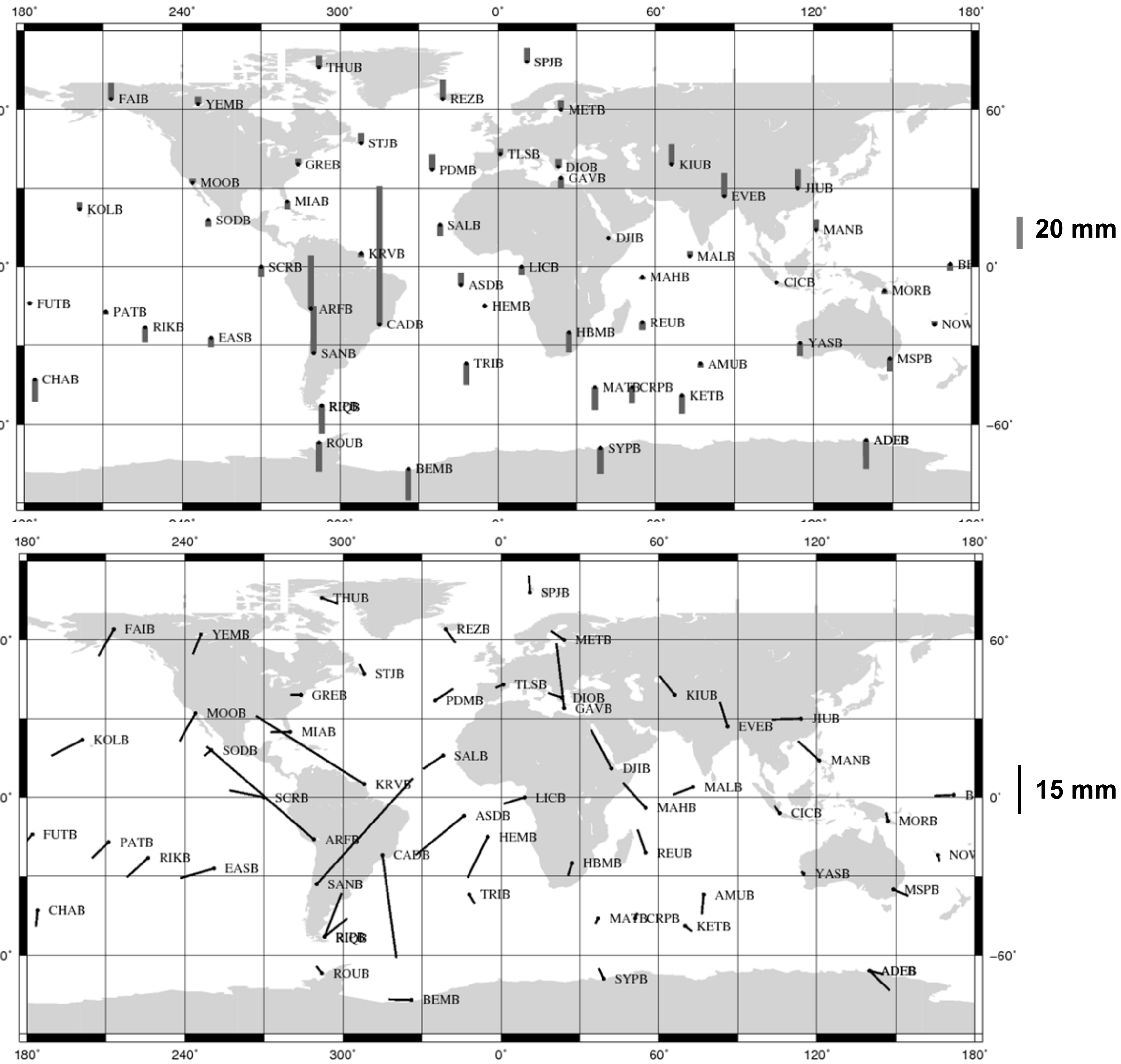

Fig. 9 Bias of the weekly coordinates between SPOT-5 single-satellite solution and multi-satellite solution GOP31. Data from year 2008. vertical (top), horizontal (bottom). According to Štěpánek et al. (2009).

a meter level (Willis et al., 2004) in extreme cases. Such a huge corruption, as seen on Jason-1 data, would have been detected by all the analysis groups. The much smaller effect on SPOT-5 data, even if it is far from being negligible, could escape detection in multi-satellite solutions, as single-satellite weekly or monthly positions are not a standard output of most DORIS analyses. The specific geographical distribution of the SPOT-5 anomaly makes it difficult to formulate alternative hypotheses for the origin of the SPOT-5 anomaly. The SAA is thus the most probable explanation. Last but not least, SPOT-5 is equipped with the same generation of onboard DORIS instruments as Jason-1 (2^{nd} miniaturized generation), contrary to the other satellites. The SPOT-5 on-board oscillator could be sensitive to SAA as well.

8. CONCLUSIONS

We demonstrated an alternative approach for DORIS tracking data analysis that is very close to GNSS carrier phase tracking data analysis. With an implementation into a development version of the Bernese GPS Software, it is possible to analyze tracking data as available at CDDIS and to estimate the essential DORIS-specific parameters, while using observation models and models for station displacements, troposphere, and orbits identical to GNSS. Weekly free-network multi-satellite solutions (1993.0-2009.0) were processed and analyzed. The scale between the GOP31 solution and ITRF 2005 was stable with two exceptions. The change of scale in 2002 probably reflects the changes in the DORIS satellite constellation. This is not the case of the dramatic change of scale in 2004, where the detailed analysis proved that it is not caused by the change of the satellite constellation (end of TOPEX/Poseidon data production). One part of the effect can be explained by changes in the Envisat operational software, while the other part is related to a non-specific change in the SPOT-5 single-satellite scale.

The pole estimates were compared with the IERS C04 pole time-series at the level of the daily noon values and a very high impact has been achieved by processing the data coming from the second generation satellites (SPOT-5 and Envisat), launched in 2002. The RMS with respect to IERS C04 model is around 0.4 mas for the last two processed years.

The post-fit observation residuals were analyzed with respect to the length of the observation time interval. A simple empirical model of observation error was applied that describes the observation noise as a combination of two uncorrelated processes, where the first one (σ_1) is independent, the second one (σ_2) dependent on the measurement count interval. The standard deviation σ_2 gained value between 0.225 and 0.257 mm/s for all satellites except SPOT-2, where σ_2 was 0.307 mm/s. On the other hand, σ_1 was lower in the case of SPOT-2 (2.57 mm) than for the rest of the satellites (2.77-3.16 mm). Note that the difference in the length between the short and long SPOT-2 observations is only 1 second (3 seconds for the other satellites) and the numerical stability of σ_1, σ_2 solution is then reduced.

The station height differences between the SPOT-5 single satellite solution and the combined solution (SPOT-4, SPOT-2, Envisat) achieved the highest value for stations Cachoeira Paulista (-105 mm), Arequipa (-42 mm) and Santiago (-36 mm). The presented analyses do not completely prove that SPOT-5 is affected by the South Atlantic Anomaly, but the geographical distribution of the SPOT-5 anomaly is very similar. SAA is thus the most reasonable explanation

ACKNOWLEDGMENTS

The presented work was supported by grant LC506 “Center for Earth Dynamic Research” and by grant GACR 205/08/P601 “DORIS observations time-series analysis“.

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