Status of DORIS stations in Antarctica for precise geodesy

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Abstract. Polar regions and especially Antarctica are nowadays recognised as mainly controlling the Mean Sea Level (MSL) to which in turn, climate is closely related. It is consequently important to know and monitor the geodynamical behaviour of these regions. The displacement (or velocity) of reference sites helps to constrain the models of prediction of ice sheet evolution. Several precise spatial techniques using satellites observe displacements of reference sites; the most common of which is GPS. In Antarctica, besides the quite numerous GPS stations, four DORIS stations are permanently operating: Belgrano, Rothera, Syowa, Terre Adélie. In addition to the permanent DORIS stations, episodic campaigns took place at DomeC / Concordia and on Sorsdal and Lambert glaciers. In this paper, we first collect general information concerning the stations and the campaigns (location, start of measurements, etc). We then present the results of observations of the permanent stations (vertical and horizontal velocities) keeping in mind that we are primarily interested here in the vertical component, which is the most uncertain component. In particular, we use several ITRFs (from the early ITRF97 to ITRF2000) to see their impact on the derived velocities in Antarctica. Then we discuss the solutions (when available) obtained by different analysis centres for all DORIS stations, emphasising differences and attempting to explain them. Finally, we compare at these stations, the results of DORIS observations to the solutions from other geodetic techniques (GPS, VLBI) and to the results of repeated absolute gravity measurements (when available).

Keywords. Antarctica, Gravity, DORIS, GPS, VLBI, Syowa, Terre Adélie

1 Introduction

Antarctica is a vast land of about 14 million km^2 of which 98% are covered by an ice cap. The ice volume changes in time; recent studies (Weller, 1998) shows that observations in the polar regions are critical to validate climate models which still present large uncertainties. The present-day thawing of ice is one of the reasons of the vertical displacement of a point at the surface of the ice (elastic rebound); horizontal displacements also occur since the thawing is more important at the border of the continent, leading to a flux of ice from inland towards the coast. Because of thawing due to major warming of Antarctica over the past fifty years (Turner et al., 2005), there is an uplift of Mean Sea Level (MSL) due to the increasing amount of water (Cazenave and Nerem, 2004). In fact, things are more complicated because of the moving bedrock. The most important causes of vertical of the Antarctic continent is the Post Glacial rebound (PGR) and the effect of the present Isostatic Adjustment (GIA). The PGR is the visco-elastic response to the deglaciation, which occurred 11,000 years ago by the end of the last ice age (Peltier, 1996). The GIA is the elastic response of the surface to the present deglaciation. The vertical displacement at the surface can be monitored in direct and indirect ways. Direct way is the straightforward observation of the surface; this is the geometrical observation of the surface through classical geodetic techniques such as levelling or determination of the station position using satellites. The indirect way refers to gravity measurements, which is physical geodesy, depending both on the redistribution of masses and on the distance of the station from the Earth's centre. This means that if we assume no change in masses, any variation of gravity will imply a vertical displacement of the site.

2 Geodetic observations in Antarctica

a. DORIS observations in Antarctica

DORIS stands for **D**oppler **O**rbitography by **R**adiopositioning **I**ntegrated on **S**atellite; it provides the position of beacons located all over the world, through the observation of the Doppler shift of a signal received by a constellation of up to 6 satellites orbiting around the Earth (Tavernier et al., 2005, http://ids.cls.fr), namely: the altimetric satellites TOPEX/POSEIDON (only until November 2004), Jason-1 and ENVISAT and the remote sensing satellites SPOT-2, SPOT-4, SPOT-5 and SPOT-3 (only until November 1996). About 55 stations are geographically quite well-distributed on the Earth surface. There are however only four permanent DORIS stations in Antarctica (Figure 1): Terre Adélie installed since February 1987, Rothera since November 1991, Syowa since February 1993 and Belgrano that has been in operation for a few months only, from March 2004 to May 2004 and for which observations should resume in summer 2005. In addition to the permanent stations, episodic DORIS campaigns took place at Concordia/DômeC (Vincent et al., 2000) and Sordsal and Lambert Glaciers (Govind and Valette, 2004).

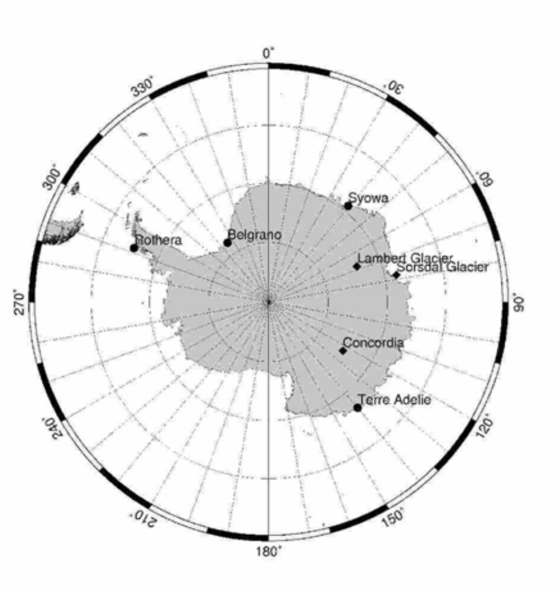

Figure 1. DORIS Antarctic stations. Full circles are for permanent stations, diamonds stand for episodic campaigns.

The DORIS data of the permanent stations are available at the NASA/CDDIS data centre through the International DORIS Service (IDS), see Tavernier et al., 2005. Table 1 shows the period of the DORIS observations available at NASA/CDDIS Data Centre after January 1993, as well as the total number of weekly solutions available.

Site	Name	Start	End	Wks
Terre Adelie	ADEA	Jan 93	Feb 02	467
	ADEB	Mar 02	Jun 05	104
Rothera	ROTA	Jan 93	Feb 05	574
	ROTB	Mar 05	Jun 05	12
Syowa	SYOB	Apr 93	Apr 98	261
	SYPB	Apr 99	Jun 05	319
Belgrano	BELB	Mar 04	May 04	7

Table 1 Summary of DORIS weekly solutions available from the IGN/JPL Analysis Centre at the NASA/CDDIS data centre (July 2005).

Table 1 shows that the DORIS system provides long-term continuous observations in Antarctica. As it is an up-link system, no data is recorded on site and the ground beacons do not rely on human intervention or data communication as for GPS. In the case of hostile environment, such as Antarctica, this is a clear advantage.
More specifically, Figure 2 shows the time series of results available at the CDDIS data centre for the IGN/JPL weekly solutions, showing some temporary interruptions for a few stations, but in general continuous observations are available during several years for the same beacon.

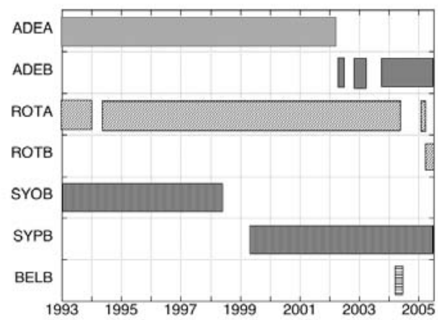

Figure 2. DORIS results for permanent Antarctic stations available at the NASA CDDIS data centre for the IGN/JPL weekly solution IGNWD04 (as July 1, 2005)

In fact, several IDS Analysis Centres (ACs) process these DORIS data and several types of solutions are available for DORIS station coordinates from these groups:
- cumulative solutions = positions and velocities at a reference epoch derived from complete data set of DORIS observations (per AC) and available in SINEX format. These solutions can be used directly for geodesy and geophysics (Soudarin et al., 1999, Cretaux et al., 1998, Willis et al., 2005). These types of DORIS results are available at ftp://cddis.gsfc.nasa.gov/pub/doris/products/sinex_global

- time series of station coordinates = weekly or monthly station coordinates in SINEX format (per AC). These solutions can be obtained either in free-network or loose constrained solution (to be used in future geodetic combinations) or directly projected and transformed into ITRF2000 (Sillard and Boucher, 2001). These solutions correspond to a more recent way to realize the Terrestrial Reference Frame (TRF) through time series of geodetic results instead of using simplified linear model of positions and velocities (Altamimi et al., 2005). These types of DORIS results are available at ftp://cddis.gsfc.nasa.gov/pub/doris/products/sinex_series

- station coordinate differences = station coordinates expressed in ITRF2000 for weekly or monthly solutions in STCD format (STation Coordinate Difference), see Tavernier et al., 2005. This format proposes a more user-friendly presentation (tabulated in XYZ and in North/East/Vertical results) of time series results for a potentially broader community of users. These DORIS results are available at ftp://cddis.gsfc.nasa.gov/pub/doris/products/stcd

From all ACs, IGN/JPL is currently the only group to provide all types of results and to process them in timely manner (new results are posted at CDDIS every week or so). In the future, it is expected that more ACs would do the same and that also a combined DORIS would be available as well (Feissel-Vernier et al., 2005).

Figure 3 shows an example of time series available at IDS website. It can be noticed that the precision is improving in the last years.

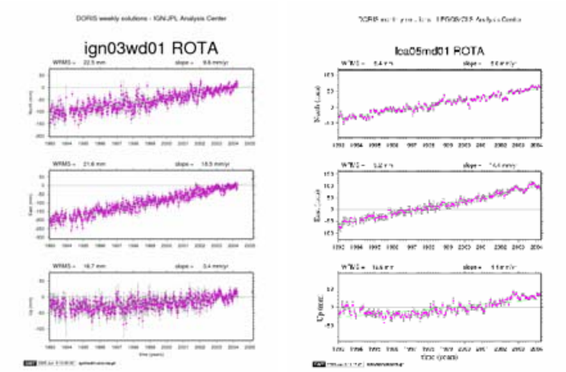

Figure 3: Doris weekly and monthly time series, at Rothera. Source IDS Web site.

On Figure 3, results from the LEGOS/CLS groups are much smoother as they are based on monthly solutions, while results from the IGN/JPL group are based on weekly solutions, hence providing more data (this could be an advantage for outlier detection). Both DORIS solutions are in good agreement. These results are regularly updated on Internet by these groups (every 3-6 month for LEGOS/CLS and every week for IGN/JPL).

It must also be noted that the precision of these DORIS geodetic results strongly depends on the number of available DORIS satellites (Willis et al., 2005), varying from 2 to 5 from 1993 to 2005. This is why the most recent results have a better precision as they use 4 or 5 satellites instead of 2 in the early 1993 solutions. We also need to point out here that unfortunately the DORIS/Jason data cannot be used for geodesy due to an extreme sensitivity to radiation affecting the satellite oscillator over the South Atlantic Anomaly (Willis et al., 2004).

b. Other positioning techniques

i. GPS

The International GPS Service (IGS), see Beutler et al., 1999, includes 7 stations in Antarctica, namely Syowa since 1999, Mawson since 1999, Davis since 1995, Casey since 1995, McMurdo since 1995, O'Higgins since 1995 and Sanae IV since 1999, of which only Syowa is equipped with DORIS beacon. There are numerous studies based on GPS observations to study the deformation, vertical and horizontal displacement in Antarctica. In addition to IGS stations, several permanent GPS receivers are settled in Antarctica. This is the case at Terre Adélie since 1998 and at Rothera since 1998. Bouin and Vigny (2000) published the results of the Terre Adélie station, which belongs to a specific network for geophysical investigations by ENS (École Normale Supérieure). In addition to these permanent stations, episodic campaigns are also organised, mostly during austral summer. Dietrich et al. (2001) analysed the GPS data for horizontal motions from campaigns organised by the Scientific Committee on Antarctic Research (SCAR) from 1992 to 1998. In addition, remote experiments are also organised during the austral summer season (Tregoning et al., 2000).

ii. VLBI

There are 2 VLBI stations in Antarctica: Syowa (11 m antenna) and O'Higgins (9 m antenna) in the Antarctic Peninsula; DORIS is collocated at Syowa. Fukuzaki et al. (2005) analysed VLBI experiments connecting Syowa to 3 stations in Antarctica, Australia and Africa. They present the results for velocities for Syowa station, comparing to GPS determinations as well as to earlier DORIS determinations.

c. Physical geodesy in Antarctica

Contrary to previous techniques of precise positioning, the measurements of absolute gravity at a given station are episodic. They typically last a few days, averaging the result of thousands of drops of a reflecting body free-falling in the vacuum chamber of the gravimeter. The measurements are ideally repeated every couple of years, which is quite a tough job in these countries. The gravity changes (if any) are then interpreted as changes in mass redistribution and/or changes in height of the station. The 23 Absolute Gravimetry (AG) measurements in Antarctica, obtained at 12 stations are listed and analysed by Amalvict et al., 2005. Among them, the 2 DORIS stations are Terre Adélie and Syowa. The latter is the only DORIS station with repeated AG measurements: 7 measurements between 1992 and 2004.

3 Models and predictions

Changes in MSL and Ice Mass in Antarctica are key parameters in what is referred to as 'Global Change'. Numerous models are attempting to depict and consequently predict the observations of displacements and velocities. The models are depending on physical parameters, which can be inferred from observations: viscosity, timing of glaciation and deglaciation.

The PGR, resulting of the deglaciation more than 10 000 years ago, involves a long period of time. The rheology of the Earth is then visco-elastic. On the contrary the GIA, which is the response of the Earth surface to the present-day deglaciation does not involve time; it has an elastic behaviour. Consequently, the observations are the sum of these phenomena (and of several others) and models have to help separating the phenomena.

Among the models, we can mention Peltier, 1996, James and Ivins, 1998, Nakada et al.; 2000 these models, relying on different glaciation and deglaciation models predict vertical displacement (and sometimes gravity changes). A rapid overview of this problem, in Antarctica, is given in Amalvict et al., 2005

The value of the ratio dg/dh derived from observations of both changes in gravity and changes in height can help in constraining the physical parameters of rebound models (Wahr et al., 1995).

4 Results and discussion

We focus on vertical velocities though their determination is generally slightly less precise than the horizontal components; this is indeed the component which is involved in PGR and GIA described in models of §3. Moreover, this is also the component that is derived from the variations of gravity.

- DORIS analysis

We have analyzed here DORIS station velocities derived by different groups, using different approaches (Table 2).

First we have considered the latest ITRF solutions: ITRF96 (Sillard et al., 1998), ITRF97 (Boucher et al., 1998) and ITRF2000 (Altamimi et al., 2002). They all provide positions and velocities based on a global adjustment of several DORIS individual solutions as well as other individual solutions from other techniques (VLBI, SLR and GPS) and geodetic local ties properly weighted. Continuous improvement in the adjustment method has been done between these three realizations as well as in the pre-processing (data screening). In the future, a new ITRF2004 should be available combining time series of results instead of cumulative solutions (positions and velocities at a reference epoch) as proposed by Altamimi et al., 2005.

Solution	Source	Type	Last data
ITRF96	IERS	X/V	Jul 97
ITRF97	IERS	X/V	Dec 97
ITRF2000	IERS	X/V	Mar 99
IGN03D02	IGN/JPL	X/V	Dec 03
IGN04D02	IGN/JPL	X/V	Sep 04
IGN05D02P	IGN/JPL	X/V	Jun 05
STCD_IGN	IGN/JPL	week	Jun 05
STCD_LCA	LEGOS/CLS	month	Jan 05

Table 2 DORIS results analyzed to derive vertical velocities for DORIS stations in Antarctica (June 2005).

We have also considered three recent DORIS solutions from the IGN/JPL DORIS Analysis Center: IGN03D02 (Willis et al., 2005), IGN04D02 (Willis and Heflin, 2004) and a preliminary solution for IGN05D02, based on the same DORIS analysis strategy but using more DORIS data (Table 1) and also a refined pre-processing (data screening and also identification of station coordinates discontinuities as described in Willis and Ries, 2005). These three solutions are also cumulative solutions (positions/velocities) but they only take into account DORIS results from the IGN/JPL Analysis Centre as well as DORIS-DORIS geodetic local ties when a new DORIS beacon is installed in close collocation with an older DORIS instrument. Results from other techniques or from other groups were not used in this study.

As a test, we have also analyzed two new types of solutions, provided as time series of results expressed in ITRF2000 in the STCD format (STation Coordinate Differences). We have considered here the latest LEGOS/CLS (LCA) monthly solutions and the IGN/JPL (IGN) weekly solutions as they are regularly updated by these groups and available at NASA/CDDIS through the IDS (Tavernier et al., 2005). These results are available per station (there are potentially several DORIS beacons at the same site, corresponding to successive instrument occupations) and for each solution we derived a weighted slope using the available data on July 2005.

Source	acronym	V (mm/yr)	Sig V (mm/yr)
ITRF96	ADEA	-5.90	6.56
ITRF97	ADEA	0.93	4.05
ITRF2000	ADEA	-0.86	1.39
IGN03D02	ADEA/ADEB	-1.10	0.16
IGN04D02	ADEA/ADEB	0.47	0.16
IGN05D02P	ADEA/ADEB	0.63	0.15
STCD_IGN	ADEA ADEB	-0.01 8.04	0.19 0.88
STCD_LCA	ADEA ADEB	1.37 4.43	0.16 1.31

Table 3 DORIS vertical velocities estimated for Terre Adelie

In Table 3, the constant decrease of the formal errors between ITRF96, ITRF97 and ITRF2000 shows the continuous improvement made by the IERS in the global combination. A similar trend can also be seen in parallel in the three consecutive IGN/JPL solutions. However, the improvement is much smaller because it only corresponds to an increase in the considered DORIS observation data span (the DORIS analysis strategy was exactly the same). The IGN/JPL also provides much smaller formal errors than ITRF solutions. This can come from a different re-weighting of the solutions and also from current systematic errors in the different IERS techniques. Finally, the STCD approach provides less precise results because the DORIS-DORIS local tie information was not used, so all the DORIS results and information (local ties) were not used when more than one DORIS beacon exists at the DORIS site.

Source	acronym	V (mm/yr)	Sig V (mm/yr)
ITRF96	ROTA	-5.40	8.32
ITRF97	ROTA	3.54	5.29
ITRF2000	ROTA	1.27	1.95
IGN03D02	ROTA	1.95	0.14
IGN04D02	ROTA	3.71	0.13
IGN05D02P	ROTA/ROTB ROTA(*)	1.53 4.78	0.56 0.20
STCD_IGN	ROTA ROTB	3.93 -92.07	0.13 34.25
STCD_LCA	ROTA ROTB	5.25 -	0.12 -

Table 4 DORIS vertical velocities estimated for Rothera

In table 4 (Rothera) and Table 5 (Syowa) we observe the same decrease of formal errors than in Table 3. In the case of Rothera, the new beacon ROTB is too recent to provide any valudable information on the velocity using the STCD solution. However, it is also possible to use the ROTA and ROTB STCD solutions, as well as the DORIS-DORIS local tie information to provide a longer time series better suited for velocity determination. In this case, the local time precision is assumed to be at 1 mm and does not degrade the precision of this technique.

Source	acronym	V (mm/yr)	Sig V (mm/yr)
ITRF96	SYOB	2.14	8.58
ITRF97	SYOB	5.89	5.06
ITRF2000	SYOB/SYPB	2.11	1.89
IGN03D02	SYOB/SYPB	1.81	0.25
IGN04D02	SYOB/SYPB	3.61	0.21
IGN05D02P	SYOB/SYPB	3.89	0.19
STCD_IGN	SYOB SYPB	4.04 3.50	0.49 0.28
STCD_LCA	SYOB SYPB	0.17 6.40	0.44 0.26

Table 5 DORIS vertical velocities estimated for Syowa

In the case of the Syowa stations, all DORIS estimations show a clear positive and small vertical uplift of the station.

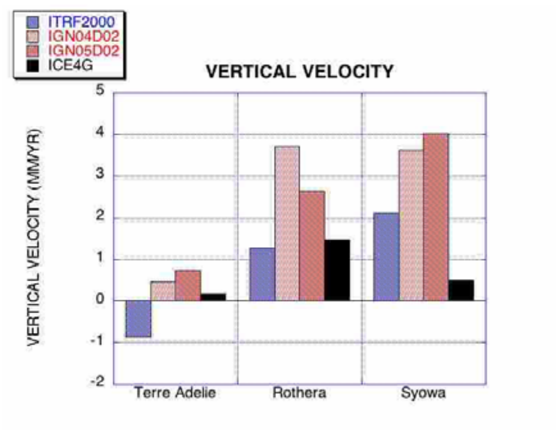

Figure 4: Vertical velocities

Figure 4 shows the vertical velocities at the 3 stations, according to different models. Figure 5 shows the same result for horizontal velocities. We notice again than ITRF2000 leads to slightly different results. The IGN/JPL cumulative solutions based on the same DORIS processing strategy provides closer results. All results differ from ICE-4G models at a few mm/yr, especially in Syowa.
Figure 5 shows the agreement between the estimated DORIS horizontal velocities and a plate

motion model GSRM 1.2, see Kreemer et al., 2003. All results are in good agreement within a couple of mm/yr. In the case of Terre Adelie, geodetic results may differ slightly from the GSRM 1.2 model.

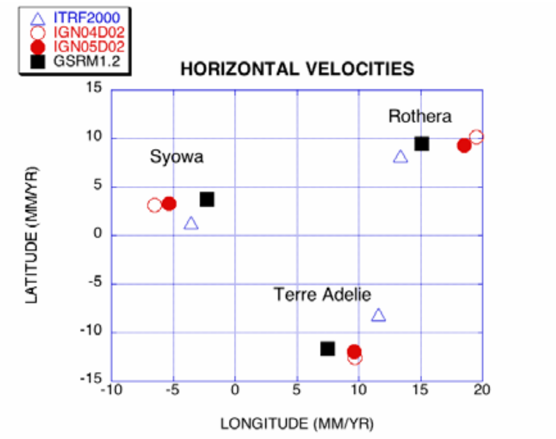

Figure 5: Horizontal velocities

In the case of the Belgrano station, the DORIS results are only based on 7 weeks of data and are currently rather useless for any geodetic or geophysical investigation (Table 6).

Source	acronym	V (mm/yr)	Sig V (mm/yr)
ITRF96	-	N/A	N/A
ITRF97	-	N/A	N/A
ITRF2000	-	N/A	N/A
IGN03D02	-	N/A	N/A
IGN04D02	BELB	-75.78	17.04
IGN05D02P	BELB	-74.20	46.38
STCD_IGN	BELB	-171.43	83.74
STCD_LCA	BELB	206.49	187.37

Table 6 DORIS vertical velocities estimated for Belgrano

The station does not even appear in the earlier DORIS TRFs. However, more recently, after an interruption of more than a year, a new station (BEMB) has been installed and should provide soon some regular data to the NASA/CDDIS IDS Data Centre. The velocity estimation should then rapidly improve as soon as the first data become available (a geodetic local is provided by IGN/SIMB between BELB and BEMB with a precision of 2 mm).

- GPS analysis

Fukuzaki et al., 2005 obtain – 2.26 ± 0.33 mm/yr at Syowa for the vertical displacement. The daily JPL GPS results, available on-line at http://sideshow.jpl.nasa.gov/mbh/series.html provide an estimate with opposite sign 2.53 mm/yr ± 0.27. These GPS/JPL results are based on a Precise Point Positioning technique (Zumberge et al., 1997). Terre Adélie is not an IGS station; the value of the vertical velocity is 0.43 mm/an according to the TIGA analysis and – 0.56 according to M.N. Bouin's analysis (personal communication).

- VLBI analysis

Fukuzaki et al., 2005 report on VLBI measurements at Syowa from 1999 to the end of 2003. They obtain – 2.79 ± 2.01 mm/yr for the vertical component of velocity.

- AG analysis

Amalvict et al., 2005 follow the analysis of Fukuda et al. (2004) at Syowa station, leading to a change of gravity equal to – 0.3 ± 0.4 µGal/yr.

- Comparison of results from different techniques

	Syowa	Terre Adélie	Rothera
DORIS mm/yr	3.6 ± 0.2	0.63 ± 0.15	1.53 ± 0.56
GPS mm/yr	2.3 ± 0.3	0.43 ± -0.56 ±	-8.5 ± 2.0
VLBI mm/yr	4.6 ± 2.2	N/A	N/A
AG µGal/yr	-0.3 ± 0.43	N/A	N/A
Prediction	~ 0	~ 0	

Table 7 Comparison of vertical velocities at different DORIS stations. Syowa: GPS and VLBI results from Fukuzaki et al., 2005; DORIS results, IGN04D02 solution. Terre Adélie: GPS results from TIGA and MN Bouin, 2005; DORIS results, IGN04D02 solution. The value of the GPS vertical velocity at Rothera is from http://itrf.ensg.ign.fr/ITRF_solutions/2000/results/ITRF2000_SCAR.SSC.txt, is rather different from DORIS but the standard deviation makes it compatible with the DORIS results. It is highly possible that only a few GPS data were used to derive this GPS velocity (short time series). Future solutions should confirm or infirm our DORIS results.

The agreement between different positioning techniques is fairly good at Syowa; the results are consistent with both AG trend and modelled predictions. At Terre Adélie, the 2 GPS solutions can be seen as no significant displacement, which is the modelled prediction. DORIS solution for Terre Adelie is consistent with a very small displacement.

Syowa	East	North
DORIS mm/yr	-6.5 ± 0.8	3.2 ± 0.9

GPS mm/yr	-4.4 ± 0.2	-0.2 ± 0.2
VLBI mm/yr	-2.5 ± 0.6	4.0 ± 0.7

Table 8 Comparison of horizontal velocities at Syowa station; GPS and VLBI results from Fukuzaki et al., 2005; DORIS results, IGN04D02 solution.

In our opinion, the difference in periods of observations could, partly, explain the differences in results.

5 Conclusions

The present analysis of DORIS data at Antarctic stations shows the sensitivity of the solution to the models (Earth model, data sampling,…). Comparison of different positioning techniques at the same station shows a fairly good agreement for vertical velocities (typically 1-2 mm/yr in horizontal and only slightly worse in vertical). There is only one station (Syowa) with repeated Absolute Gravimetry measurements, observations are also in good agreement. DORIS prove to be a useful tool for geodetic purposes, especially as it provides long-term and continuous measurements in this hard-environment. It is also quite encouraging to see that the most recent results (since 2002) provide far better geodetic precision.
In conclusion, we should say that the number of DORIS beacons should be increased in Antarctica. There is now such a possibility as the new satellite receiver allow measurements from shifted frequency transmission from ground station, decreasing possible interferences on-board the satellite and allowing a larger number of DORIS beacons in the same region of the world.We do hope that the coming IPY (International Polar Year) will give a boost in that direction.

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