DORIS campaigns at Dome Concordia, Antarctica in 1993 and 1999-2000

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Résumé – Deux campagnes d'observations DORIS ont été menées à Dôme Concordia, Antarctique, en novembre-décembre1993 et décembre 1999 - janvier 2000 par le LGGE/CNRS. La première a permis d'obtenir les coordonnées absolues précises du point et le rattachement à l'ITRF du site européen EPICA de carottage de glace profond implanté depuis. Elle a aussi permis le rattachement d'un réseau de mesures de déformations par GPS. Durant la seconde campagne, le premier point a été observé ainsi qu'un nouveau faisant partie du réseau GPS. L'ensemble des données DORIS est en cours de traitement au LEGOS/GRGS avec le logiciel GINS/DYNAMO et incluant GRIM5, le champ de gravité de la Terre récemment calculé.
Le site de forage a été choisi au sommet du dôme parce que la vitesse d'écoulement horizontal de la glace y est, théoriquement, négligeable. L'accumulation de glace n'a donc pas été pertubée. La comparaison des coordonnées déterminées à 6 années d'intervalle fournira la vitesse absolue de la glace en surface. Cette information sera utilisée pour l'interprétation du carottage.
Cet objectif est ambitieux et d'autres déterminations paraissent indispensables pour renforcer la série temporelle. Une proposition a été soumise à l'Expérience Pilote DORIS pour renouveler ces observations. Les techniques spatiales, s'appuyant sur l'altimètre ou le radar à synthèse d'ouverture sont particulièrement intéressées par les résultats DORIS à Dôme Concordia, site idéal de calibration des instruments radar.

Abstract - The first goal of geodetic measurements carried out at Dome Concordia is to provide absolute surface velocities which will be used to interpret the deep ice core drilling. Two geodetic DORIS campaigns have been implemented at Dome Concordia by the LGGE/CNRS. The first campaign lasted from 25 November to 6 December 1993, the second lasted from 8 December 1999 to 4 January 2000. In 1993, DORIS gave accurate ITRF absolute coordinates of a reference point near the EPICA ice coring site. They were used to tie a GPS strain network. During the 1999-2000 campaign, two points were observed, the previous point and a new one simultaneously with two beacons. All data will be processed with the GINS/DYNAMO software at the LEGOS/GRGS with the most recent GRIM5 earth's gravity field.
Comparison of geodetic results over 6 years will give 3D absolute ice flow velocity close to the drilling point. The summit of the Dome has been selected to be the coring site because the horizontal displacements are expected to be the

lowest. This should make the geochronological interpretation of the ice core data easier than for previous cores like the Vostok one. Estimation of the height variations is important to verify the balanced between ice flow and snow accumulation.
However, the aim is very ambitious considering the only two determinations and the complexity of geodetic observations on ice. Carrying on DORIS measurements at Dome Concordia appears to be of great interest. GPS monitoring has already been performed in 1995 and 1999 and will be repeated. Moreover, Dome Concordia will become a space radar ice reference site. A DORIS contribution to calibrate ERS interferometry and altimetry is under investigation. Carrying on DORIS measurements at Dome C every year appears to be of great interest. A proposal for future campaigns has been proposed to the DORIS Pilot project. Past and future data will be delivered to IERS and accessible via IGN or CDDIS data base.

1. INTRODUCTION

Deep ice core has been carried out in 1975 at a site called Dome C and snow accumulation has been studied (Lorius et al. 1979, Petit et al. 1982) but this site was about 60 km far from the top of the dome (Dome Concordia).
Since 1996, a deep drilling project EPICA (European Project for Ice Coring in Antarctica) has been performed at the top of the dome. This position is optimal to minimize horizontal slopes and to guaranty regular ice layers due to snow accumulation. ate fluctuations easier to date Slow ice-flow makes ice core samples easier to date. The geodetic measurements shown in this paper should provide data about surface velocities. These data will be introduced into ice flow numerical model which will enable to date ice samples in depth. In addition to the ice-core drilling, several techniques have been implemented to improve the understanding of the ice flow at a regional or global scale. The surface topography has been computed with the ERS-1 satellite radar altimeter (Rémy et al., 1999) and kinematic GPS survey (Ceffalo et al., 1996). The ice thickness has been obtained with an airborne radio echo sounding survey (Tabacco et al, 1998). An ice surface relative movement over 69 days has been deduced from ERS-1 & 2 satellite SAR interferometry (Legresy et al., 2000) and GPS survey (Capra et al., 2000). DORIS measurements in 1993 and 1999-2000 give ITRF absolute geodetic reference for both positions and velocities of the site.

2. DORIS CAMPAIGNS DESCRIPTION

The two DORIS campaigns at Dome Concordia were led by LGGE/CNRS. DORIS equipment rentals and service for data acquisition and ground positioning calculations were provided by CLS (Valette et al., 1998), a subsidiary of CNES, the French Space Agency. The equipment is composed of an automatic beacon, its two frequency emitting antennas -2 GHz and 400 MHz, the last is for the ionospheric correction- and a power supply. To save energy, the beacon only transmits during satellite passes. During the last campaign, a new generation of beacon much more lightweight and portable was used.
Figure 1 maps Dome Concordia and Doris permanent stations all around the Antarctica continent. These stations are Dumont-D'Urville (IERS dome number 91501), Syowa (66006) and Rothera (66007). Surface topography is also shown.

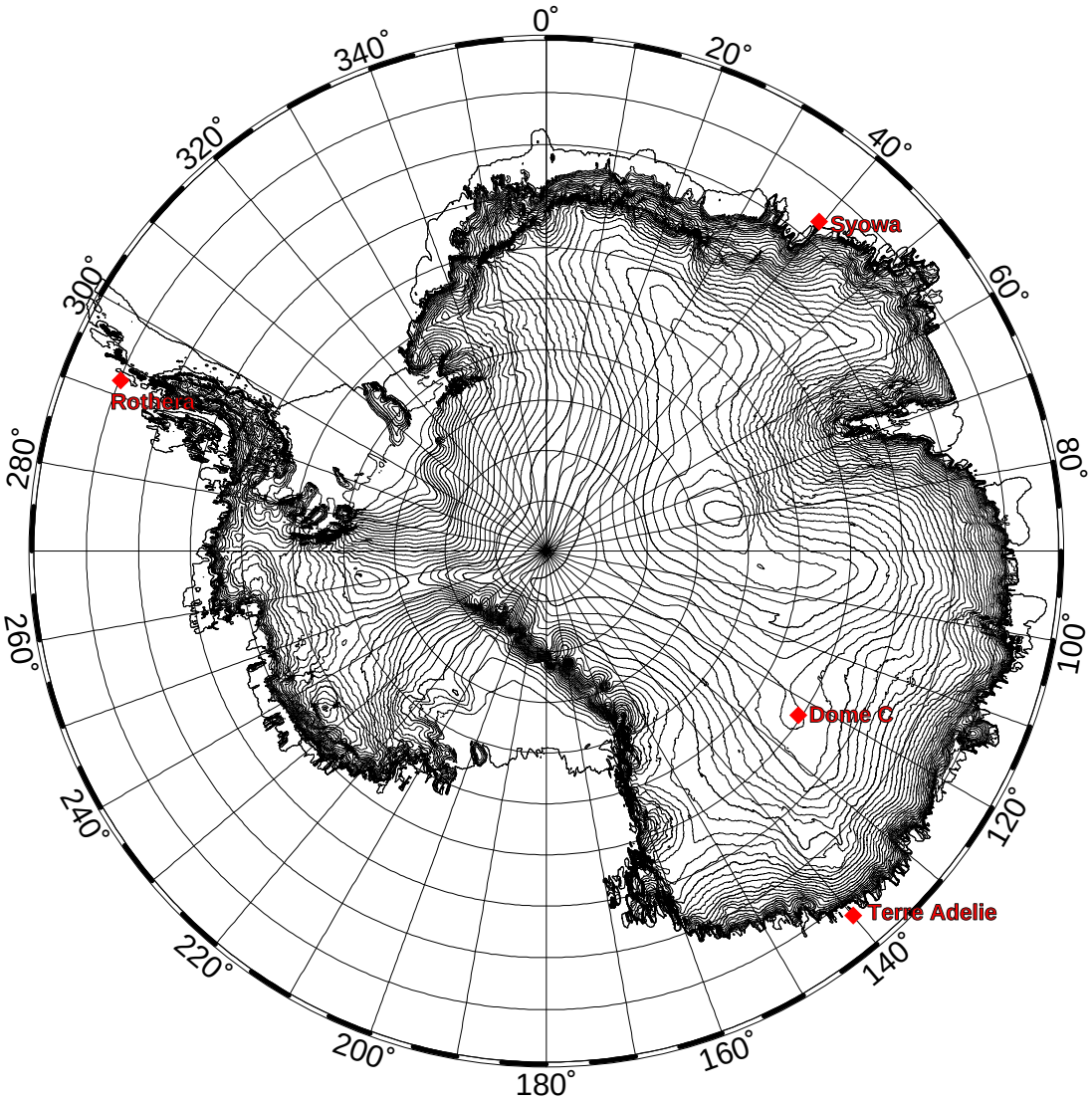
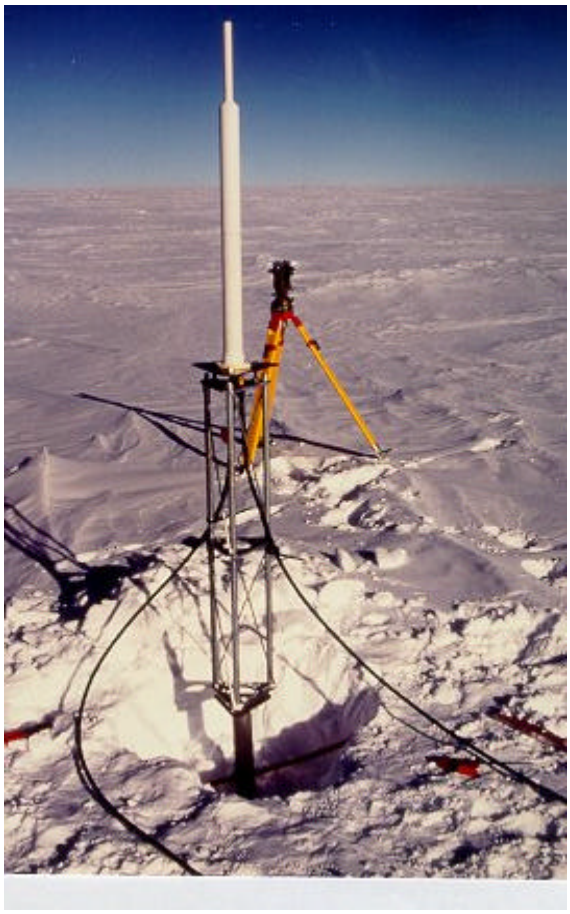


Fig. 1: Map of the antarctic continent with isoline every 100m,
Doris stations are indicated.

Installation

DORIS antenna is supported by a metallic mast screwed on the top of a stake (photo). The stake of 2 m long is buried on the snow. To make sure that the stake doesn't subside because of density difference with the snow and move jointly with it, horizontal sticks were added.

The beacons are not designed to operate when temperature is under –20° C while typical value is from –25°C to -45°C in December. The beacon and its ultrastable oscillator (on separated box with the first equipment generation used in 1993), were set up in a shelter. The beacon should be programmed with parameters supplied by the DORIS processing center operated by CLS at Toulouse, France (Loaec et al., 1998). They include identification number, transmission sequence and the satellites to be used. Each measurement last 10 seconds. The beacon internal clock is tuned to the International Atomic Time. After setting up, the beacon is functioning automatically and operations are routinely checked from Toulouse, France.



DORIS antenna at Dome Concordia

1993 campaign

One of the objectives of the 1993 franco-italian expedition at Dome Concordia (Concordia Project) was geodetic. The DORIS system has been used at the point located (75° 09'S; 123° 06' E). In 1993, this site was supposed to be at the top of the dome (but the map was inaccurate); in fact, the further topographic surveys have shown that this point is 9 km far from the summit on which the drilling point has been carried out. Nevertheless, the ice flow velocity should be low. This point is the center of a strain network with a few kilometers extension (25 km). DORIS measurements have been made during 10 days from 11/26/1993 to 12/5/1993 at the point referenced 66009 DOME C. The beacon transmitted 3 times per minute. The sun-synchronous SPOT 2 satellite has been used. Because of its polar orbit with inclination of 98°, it is visible from 8 to 10 times per day at the latitude of Dome Concordia. Each one lasts from 4 to 10 minutes considering a cutoff angle of 12° over the horizon.

1999-2000 campaign

During this new expedition of the Concordia Project, the previous DORIS site has been visited again. The antenna was installed on the same vertical but not exactly with the same support. The antenna height had changed. Thus, a new point has been defined, the IERS reference is 66013 DOME 1 C. The measurements have been performed for 25 days, from 12/08/1999 to 1/2/2000, furnishing three measurements per minute. Another site referenced as 66014 DOME 2 C was observed. It is 15 km far from the first site and nearly at the same distance from the drilling rig.
The DORIS measurements have been performed for 18 days from 12/14/1999 to 1/1/2000. The beacon transmitted two measurements per minute alternatively with the beacon to prevent from inter-beacon interferences. At both sites, SPOT 2 and SPOT 4 satellites were used. Table 1 details data collection.

Data acquisition and control

Within a few hours following the beacon transmission, data are downlinked by the satellite to the receiving stations at Aussaguel, France or Kiruna, Sweeden. They are immediately delivered at the DORIS operational processing center. Any anomaly on the fields can thus be rapidly resolved. Routine satellite orbits and beacon locations are calculated within 48 hours with a 10 cm accuracy. This step contributes for the elimination of rough data and for the system performance reliability control.

DORIS Site	1993	1999-2000	
	SPOT 2	SPOT 2	SPOT 4
66009	85 pass./	-	-
66013 DOME 1 C	-	251 pass./ 6563 mes.	247 pass./ 6601 mes.
66014 DOME 2 C	-	167 pass./ 2948 mes.	164 pass./ 2951 mes.

Table 1 : DORIS data acquisition at Dome Concordia.
(pass. and mes., respectively for the numbers of validate satellite passes and Doppler measurement)

All DORIS pre-processed data from the two campaigns will soon be delivered to IERS and available via IGN and CDDIS data base in the RINEX International Exchange Format. All DORIS Information is communicated by way of IGN DORIS mails service (daemon@ensg.ign.fr).

3. DATA PROCESSING

Accurate geodetic parameters have been calculated at the GRGS/CLS data analysis center for IERS and DORIS Pilot Experiment, the future International DORIS Service (Soudarin et al, 2000). The software used is Gins/Dynamo developed by GRGS. It realizes the integration of the satellite motion equations and a least squares adjustment of DORIS data. The geodetical or geodynamical estimated parameters are the satellite orbits, the station positions and velocities and the earth polar motion. Some empirical parameters are also estimated to balance the model imperfections for atmospheric drag, solar pressure radiation effect on the satellite orbits and for the tropospheric propagation delay

on the measurements. The ionospheric propagation delay is efficiently corrected with the 400 MHz frequency auxiliary to the 2 GHz main frequency. A frequency bias per satellite pass is calculated for every beacon oscillator.
Dome Concordia DORIS data have been processed with the last software improvements. They include the most up-to-date GRIM5 earth gravity field model and two atmospheric effects. One is gravitational and affects the satellite orbit and the other is a loading effect on each station due to the air column pressure and its variations (Biancale et al, 1999). For the SPOT satellites, normal equations are basically formed with one day orbital arcs. Solutions for the station positions may be obtained over any time scale by addition of normal equations and inversion. Positions for the whole network are systematically determined on a monthly basis. Solutions are expressed in DORIS reference system. They are transformed to ITRF97 with a classical 7-parameters Helmert transformation including the origin translation, the axes rotation and a scale factor.

4. EXPECTED DORIS RESULTS

Processing DORIS data acquired in 1999 with the most recent models above mentioned is still under work. The chapter here after presents the results that have already been obtained for the cinematics of Antarctica tectonic plate and those expected specially with the 1993 and 1999-2000 DORIS campaigns at Dome Concordia.

4.1 Antarctic tectonic plate motions

Based on for years (1993-1996) of DORIS data issued from about 50 permanent stations and three satellites in orbit, Spot 2, Spot 3 and Topex-Poseidon, the present-day tectonic plate motion has been yielded (Crétaux et al., 1998). Results for the Antarctic plate are summarized in tables 2 and 3.
They have been deduced from five stations. Three are on the continent, Syowa, Rothera and Terre Adélie (Dumont D'Urville), and two are on the austral islands : Kerguelen, Amsterdam. Comparisons of horizontal velocities and absolute plate rotation with NNR-Nuvel-1 model (Argus and Gordon, 1991) or GPS determination (Larson et al., 1997) are in a good agreement. Horizontal motion deduced from DORIS results at Dome Concordia is of –9.4 mm/y in latitude and of 0.4 mm/y in longitude. It corresponds to a reference point displacement of 56 mm in latitude south-oriented and of 2.4 mm in longitude east-oriented between the two campaigns over a 6 year interval.
Calculations in work will refine these determinations mainly thanks to the DORIS data from 1997 until now.

Φ_p (deg)	λ_p (deg)	Ω_p (deg/Myr)
65.3 (6.7)	-114.2 (10.9)	0.24 (0.04)

Table 2 : DORIS absolute plate rotation vector in Antarctica (Crétaux et al., 1998)
standard deviations are in parentheses

Site	Velocity and Error (in mm/yr)			
	North	East	σN	σE
MarionIsland	6.5	3.0	0.7	1.3
Syowa	7.7	-6.0	0.5	0.6
Rothera	8.0	21.9	0.5	0.6
Kerguelen	7.1	8.3	1.1	2.0
Terre Adelie	-10.9	-1.0	0.4	0.6

Table 3 : Horizontal velocities for DORIS permanent stations in Antarctica. (Crétaux et al, 1998)

1.2 Expected geodetic results at Dome Concordia

absolute positions and their variations

3D absolute coordinates of DORIS antenna will be obtained for each data set. They will be transformed to the most recent ITRF and brought back to the reference mark on each stake. They will tie the polar base to ITRS world reference system, in particular the regional GPS monitoring deformation network installed in 1995 then surveyed in 1998 and 1999-2000 by ENEA team (Capra et al., 2000).
At the main DORIS point referenced as 66009 in 1993 and 66013 in 1999-2000, position changes will indicate, after subtraction of the horizontal plate motion, the amplitude and direction of the surface ice flow at the dome top. A vertical uplift of ±1-3 mm/yr (Conrad and Hager, 1995; James and Ivins, 1995; Wahr et al., 1995, Lemeur, 1996) due to ice load change and post-glacial rebound may be taken into account but without significative effect.
The velocity is expected to be null at the top but since recently even the order of magnitude remains unknown. The use of the SAR interferometry technique with ERS data (Legrésy et al., 2000) concludes to a maximum of surface velocity at the ice sheet top of about 3 cm/yr. But neither Insar nor GPS furnish absolute velocities but relative velocities.

baselines determinations and their variations

DORIS vector changes from Dome Concordia to Terre Adélie, Syowa and Rothera the nearest permanent stations will be examined. In spite of the quite long baselines, from 1200 km up to 4000 km, the displacement at Dome Concordia should be seen in the polygon deformation over a 6 year interval.

5. CONTRIBUTION TO ICE CORE ANALYSIS

One of the main problems relative to ice core is the datation of ice samples in depth. The deep ice samples are dated with numerical ice flow model. As well as data about surface topography, ice thicknesses or snow accumulation, the horizontal velocities are needed to the ice flow models used to interpret the deep drilling core. They will enable to calibrate or check the numerical models.
The next figure shows a model of horizontal surface ice flux resulting from the equilibrium between the snow accumulation on the ice cap (vertical flux) and the ice flow.

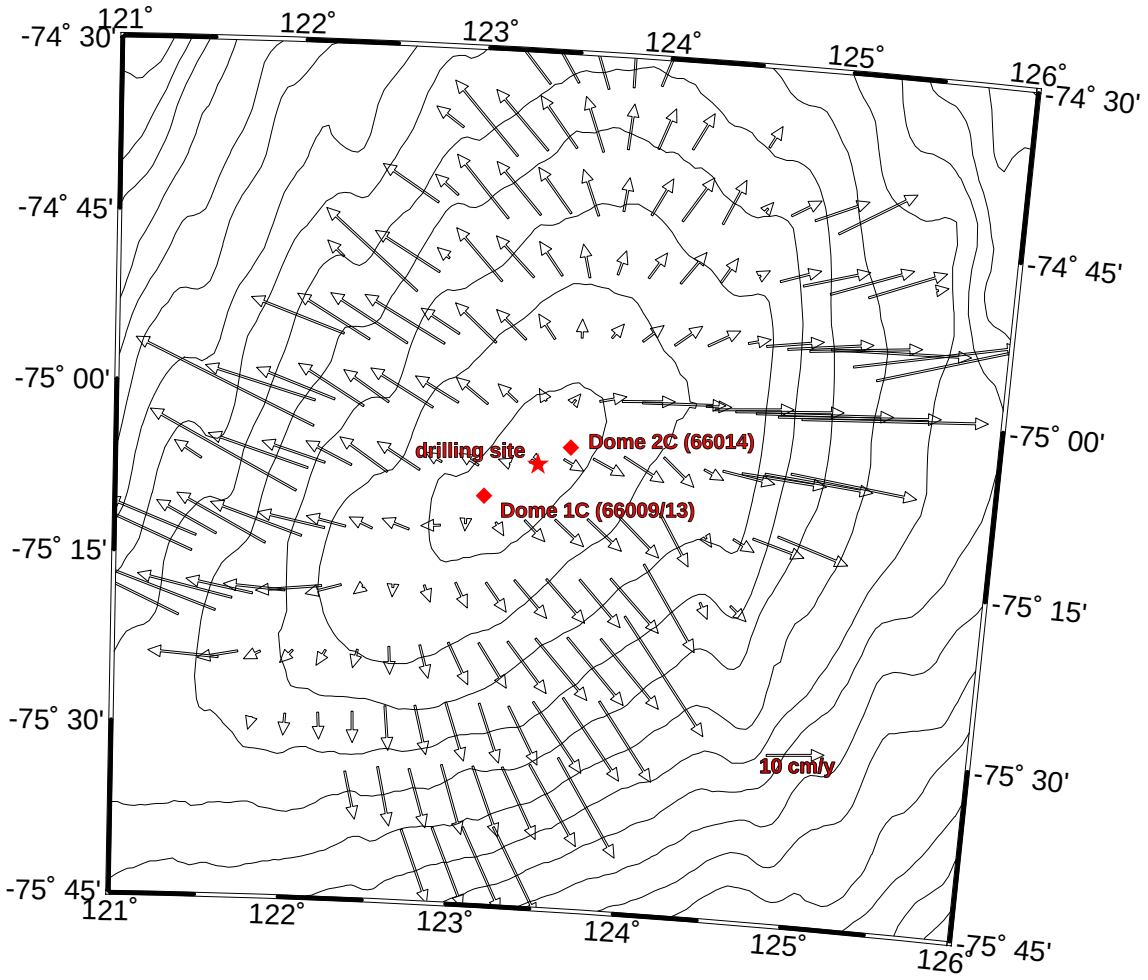


Fig. 2 :
Horizontal velocity field model at Dome Concordia in balance with snow accumulation (Legrésy et al., 2000) and altimetric topography with 5 m isolines (Rémy et al. 1999).
The ice core drilling site is at the top of the dome. DORIS sites are also indicated.

6. CONTRIBUTION TO GLACIOLOGICAL REMOTE SENSING OBSERVATIONS

The two techniques mentioned here are based on space radars. One is the SAR interferometry, a very efficient tool to map surface velocity and study ice dynamics. At Dome Concordia, an interferogram was formed with two geometrically identical ERS satellite passes at a 69 day interval (Legrésy et al., 2000). It yields an ice surface velocity fields in the surroundings of the drilling point which is characteristic of each pixel displacement in the direction of the SAR line of sight. It is encouraging to see that relative motion at the top of the dome is negligible and in any case under 3 cm/yr. To go further, an absolute velocity reference is needed and DORIS will furnish it.

The other very powerful satellite radar space technique for ice remote sensing is the altimeter. Altimeter onboard ERS satellite maps ice topography in Antarctica over large scale regions with a 10 cm accuracy, that was not accessible up to now (F. Rémy et al., 1999).This technique needs an in-situ height reference specially for calibration of radar altimetric time series. Also the radar signal penetrates the snow depending on its structure and on meteorologically induced surface conditions. DORIS answers to this need and also helps for essential in-situ periodic snow accumulation measurements (Vincent et al., 2000).

7. CONCLUSION

DORIS observations at Dome Concordia in 1993 and 1999-2000 are still under processing. They should confirm that no significant absolute horizontal displacement is occurring at the EPICA drilling site. A permanent DORIS occupation of the site such as in the Antarctic continental boarder regions (stations of Dumont D'Urville, Syowa and Rothera) would be ideal for 3D surface deformation monitoring. Unfortunately, the base only operates during austral summer. A proposal for periodic DORIS campaigns at Dome Concordia has been submitted to the DORIS Pilot Experiment, a build-up step of the future International DORIS Service (Tavernier et al., 2000).
This proposal also joins the requirements of the altimeter and SAR satellite remote sensing techniques for an in-situ calibration site at Dome Concordia. With the perspectives of ERS2, ENVISAT, ICESAT and CRYOSAT missions, the radar techniques combined with DORIS and GPS geodetic techniques will be fully used for ice dynamics studies at both regional and continental scales in Antarctica. They will also contribute to verify the ice mass balance between ice flow from the continent to the sea and snow accumulation.

BIBLIOGRAPHY

Argus D.F. and R.G. Gordon. No-net rotation model of current plate velocities incorporating plate motion model NUVEL-1.Geophys. Res. Lett. 18, 2039-2042, 1991.

Biancale R., G. Balmino, J.M. Lemoine, J.C. Marty, F. Barlier, Y. Boudon, P. Exertier, O. Laurain, P. Gegout, P. Schwintzer, C. Reigber, A. Bode, T. Gruber, Z. Kang, F.-H. Massmann, H. Meixner, J.-C. Raimondo, S. Zhu. GRIM5-S1/C1 earth gravity field model. Science Working Team meeting, Nice, nov. 1999

Capra A., S. Gandolfi, F. Mancini, C. Vincent, L. Vittuari. GPS and DORIS measurements for Dome Concordia absolute referentiation. EGS, Nice, France, 25-29 April, 2000.

Ceffalo R., I. Tabacco and G. Manzoni : Processing of kinematic GPS trajectographies at Dome Concordia (Antarctica) and altimetry interpretations. Reports on survey and geodesy, 25 pp., Bologna, Distart Ed Nautilus, 1996.

Conrad C.P. and B.H. Hager. The elastic response of the earth to interannual variations in Antarctic precipitation. G.R.L. 22, 23, 3183-3186, 1995.

Crétaux J.F., L. Soudarin, A. Cazenave, and F. Bouillé. Present-day plate tectonic plate motions and crustal deformations from the Doris Space system,
J. Geophys. Res., 113, 30167-30181, 1998.

James T.S. and E.R. Ivins. Present-day Antarctic ice mass changes and crustal motion. G.R.L. 22,8, 973-976, 1995.

Larson K.M. , J. Freymueller, and S. Philipsen. Global plate velocities from the Global positioning System,.J. Geophys. Res., 102, 9961-9981, 1997.

Legrésy B., E. Rignot and I. Tabacco. Constraining ice dynamics at Dome C, Antarctica using remotely sensed datasets. G.R.L. Submitted, 2000.

Lemeur E. : Spécificité de l'isostasie en contexte glaciaires. Présentation et application d'un modèle de réponse terrestre. Thèse de doctorat de l'Université Joseph Fourier - Grenoble I, 1996

Loaec M.N., B. Nhun fat and JJ. Valette. One day operation of the DORIS ground system segment. DORIS Days, Toulouse, France, 27-29 April, 1998.

Lorius C., L. Mervilat, J. Jouzel and . Pourchet. A 30,000 year isotope climatic record from Antarctica ice, Nature, 280 (5724), 644-648, 1979.

Petit J.R., J. Jouzel, M. Pourchet and L. Merlivat. A detailed study of snow accumulation and stable isotope content in Dome C (Antarvtica), J. Geophys. Res., 87, 4301-4308, May 20, 1982.

F. Rémy, P. Schaeffer and B. Legrésy. Ice flow physical processes derived from the ERS-1 high resolution map of the Antarctica and Greenland ice sheets. Geoph. J. Int. 139. 645-656, 1999.

Rémy F.and I.E. Tabacco. Basal erosion network near the EPICA ice core site (dome C, Antarctica). G.R.L. 27, 3, 405-408, 2000.

Soudarin S., J.J. Valette, J.F. Crétaux, A. Cazenave. Participation of LEGOS-GRGS and CLS as an Analysis Center in the future IDS. DORIS Days, Toulouse, France, 2-3 Mai, 2000.

Tabacco: I.E., A. Passerini, F. Corbelli and M. Gorman. Determination of the surface and bed topography at dome C, East Antarctica, J. of Glaciol. , 44, 185-191, 1998. .

Tavernier G. Current status of the DORIS pilot experiment.DORIS Days, Toulouse, France, 2-3 Mai, 2000. .

Valette J.J. DORIS operational location performance.DORIS Days, Toulouse, France, 27-29, April, 1998.

Vincent C. 1999-2000 snow accumulation observations at Dome Concordia, Antarctica, Personal communication, 2000.

Wahr J., H. DaZhong and A. Trupin. Predictions of vertical uplifte caused by changing polar ice volumes on a viscoelastic earth. G.R.L. 22, 8, 977-980, 1995.