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IMPACT OF THE DORIS PRECISE ORBIT DETERMINATION SYSTEM ON CLIMATE CHANGE STUDIES

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ABSTRACT

The goal of the paper is to demonstrate that DORIS helped opening a new era in altimetry since TOPEX/POSEIDON (T/P), and that DORIS will insure that long time series of altimeter measurements may be used in a consistent manner for the highly accurate quantification of the tiny ocean signals impacting climate change at multi-year time scales.

1. INTRODUCTION: DORIS SYSTEM DESCRIPTION

1.1. Basic principle

The DORIS system was designed and optimized to provide high precision orbit determination and beacon positioning. It was developped in the frame of the TOPEX/POSEIDON (hereafter designated by T/P) oceanographic altimetry mission. It is operational since 1990, when the SPOT2 satellite was launched with the first DORIS receiver on-board.

DORIS is an uplink radio system based on the Doppler principle. It measures relative velocity between the orbiting satellite and a dense, permanent network of orbit determination beacons.

The core of the system is the beacon network distributed homogeneously over the Earth. The bi-frequency signals at 400 MHz and 2 GHz emitted by the beacons are used by the receivers on-board the various satellites to perform Doppler measurements.

1.2. The beacon network

The DORIS permanent network includes 54 beacons (see Figure 1) hosted by institutes from more than 30 different countries. More than 20 beacons are colocated with other precise positioning techniques to allow for cross-calibration.

Each site is equipped with a beacon package including a bi-frequency 400 MHz and 2 GHz transmitter (including a USO -Ultra Stable Oscillator-), an omni-directionnal bi-frequency antenna, a battery pack to provide autonomy versus supply, a meteorological package providing temperature, pressure and humidity measurements used to correct for tropospheric effects.

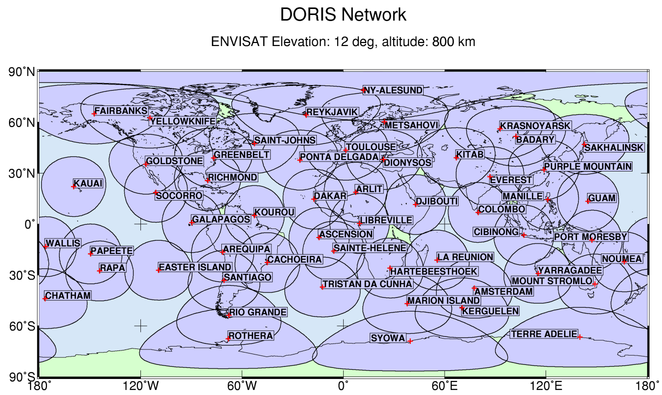

Figure 1: The DORIS ground network

The beacons emit a narrow band ultra stable signal plus auxiliary data: beacon identifier, housekeeping data, meteorological data, time tagging reference data. Presently, two Master beacons located in Toulouse and Kourou are connected to the control center to allow data upload to the on-board package and are linked to an atomic clock to allow synchronization of the DORIS system with international reference time.

The next generation of DORIS beacons (third generation) will have the ability to transmit their signals on slightly shifted frequencies with respect to the nominal system frequencies, in order to avoid the risk of « Doppler collisions » in case of the use of the DORIS system from high altitude orbits and to allow regional increase in the number of DORIS beacons.
Another major feature of these third generation beacons is that they broadcast the current complete date (year/month/day/hour/minute/seconds) in TAI scale which allows the in-flight DORIS instruments to perform their initialization process - from equipment turn-on to satellite position, velocity and time estimation - in a fully autonomous way, without any ground command or uploading.
Beacon data transmission (synchronization word, auxiliary data, uploading in case of Master Beacons) is performed according to a 10 seconds sequencing. This sequence is synchronized with respect to TAI within ± 1 seconds to guarantee a correct reception of these beacon data by the in-flight instruments.

1.3. Other aspects of the system

On-board packages, control and processing center, as well as the onboard real-time orbit computation capability offered by the DIODE software are extensively described by Costes and Jayles (2001). For the sake of clarity, we will only focus on some figures of performance that directly interest the topic of the paper.

1.4. System performances

We will come back to orbit performances in future sections. However, it appeared fruitful to already provide some elements at this stage of the paper so that the reader may refer to them easily.

	1 rst generation (1G)	**2 nd generation (2G)**	**2 nd generation miniaturized (2GM)**
Space mission	Spot-2, Spot-3, TOPEX-POSEIDON Spot-4	Envisat-1	Jason-1 Spot-5
Precise Orbit	< 3 cm / radial (observed)	< 3 cm / radial (specification)	< 3 cm / radial (specification)
Real Time Orbit	5m / 3 axes (Spot-4) (observed)	1m / 3 axes (specification)	30 cm / radial 1m / others (specification)
Time Determination	3 µs (observed)	3 µs (specification)	3 µs (specification)

Table 1 : DORIS system performances (depending on the generation of the system)

Beacon positionning is very important within the evaluation of the DORIS system. A 1 to 2 cm accuracy may be reached in terms of beacon positioning using DORIS data from 2 carrier satellites. These performances may even be improved by using DORIS data from more carrier satellites. Another measurement of positioning performances is the retrieval of vertical velocities of the natural displacement of DORIS beacons through time. The figure below has been produced by Soudarin et al. (1999) and demonstrates the ability of the DORIS system in accurately retrieving the tiny trends in the vertical displacement of beacons located on the tectonic plates. This is a very important result in the framework of the survey of the geodetic reference frame to which altimeter measurements are referred to (see discussion in the next sections).

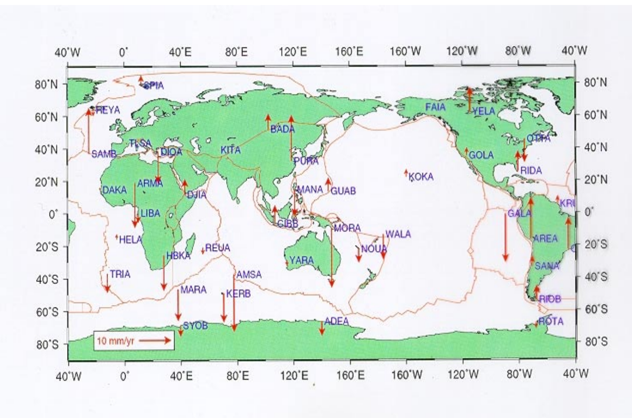

Figure 2 : Vertical displacements of DORIS beacons as the witnesses of vertical motions of tectonic plates

1.5. New system features

New concepts will be experimented very soon with the Jason-1 mission, to be fully operating for CRYOSAT, Pléiades, Jason-2, … These are :

- Autonomous initialization and synchronization
- New "broadcast" uploads
- Doris Beacon Simulator

These features are described in details in Costes and Jayles (2001).

Also, the organization of an International DORIS Service is presently under way and will allow the international development and promotion of the DORIS system in the science community as well as towards the users involved in applications.

2 - SPACE ALTIMETRY FOR OCEANOGRAPHY

2.1 - A revolution occured during the last 40 years

1950 - 1965: oceanographers find that the ocean is turbulent, and that the eddy energy has the same order of magnitude as the energy of the mean major currents;

1960 - 1980: scientists become more and more aware that phenomena such as the El Niño ones have at least a basin scale extension. The TOGA programme takes this into account and the deployment of a large network of in situ intruments in the Pacific ocean is performed. However, attempts for forecasting the ocean behaviour still remains non conclusive.

1978: The SEASAT satellite, although it lives only 3 months, brings the proof that accurate measurements may be performed thanks to space instruments. First results confirm that the ocean is varying in a very wide spectrum. A few scientists understand that oceanography will perform a decisive step forward. For instance, let' s cite Munk and Wunsch (1982):
"To understand the ocean, its dynamics, its role in climate, weather and other ocean-atmosphere phenomena, we must observe it on a basin wide scale with adequate time and space resolution. No such observation system yet exists. In the past few years, a number of technical developments have taken place that might permit the establishment by the 1990's of an operational system approaching these requirements. We focus here on two major components of such an hypothetical system: ocean acoustic tomography and satellite observations of sea-surface topography and of

wind stress; these, combined with other types of observations and with a sensible designed modelling effort might provide an ocean observing system at a not unreasonable cost. This would lead to significant progress in ocean physics and dynamics, and one could contemplate real time forecasting for ship routing, military purposes, fisheries, weather and climate".

1982 - 1985: a group of researchers defines the WOCE programme. The main goal is to extend the ocean knowledge at a global scale. From the very beginning, the WOCE Scientific Steering Committee members agree on the central role of space observations, especially altimetry. In the 1-st issue of the WOCE Newsletter, F. Bretherton (1985) declares: "The global perspective provided by satellite altimetry lies at the heart of WOCE".

2.2 - The development of ocean altimetry

Beginning with Skylab, GEOS3 and SEASAT, the development of altimetry has been steady and the benefits outstanding. There has been a quasi-continuous series of missions, starting with GEOSAT (1985), and then ERS-1/2 (1991 and 1995), and TOPEX-POSEIDON (hereafter designated by T/P) (1992). These will continue from 2001 with Jason-1 and ENVISAT that are scheduled for launch in the second half of 2001.

Following Ratier (1999), let’s take an example concerning the impact of ocean altimetry on climate science. The most relevant parameter to climate is sea-surface height, which, at this point in time can only be measured on global scale by altimeter systems. The increasing performances of the altimetric systems have cut the error budget on sea-surface height by several orders of magnitude, down to the centimetre level. The consequent reduction in the correlated part of the error now means that large-scale ocean circulation patterns can be extracted. Similarly, based on accurate sensor calibration and improved understanding of measurement physics, the global mean sea level anomalies can be monitored and compare well with measurements from sea gauges. On the user side, an integrated approach, using in situ data and modelling, has resulted in cross-benefits, along the same lines that have been achieved by meteorological Weather Prediction systems. For example, the assimilation of highly accurate T/P data has highlighted shortcomings of ocean models in their ability to handle salinity, and analysis of the data has also led to scientists revisiting the theory of Rossby wave propagation.

3 - THE ALTIMETER SYSTEM: THE ORBIT AT THE HEART OF THE OBSERVATION

3.1 – Altimetry : A system

The altimetric system has 3 components:

a. The range measurement by the radar instrument: this measurement is varying as a function of time.

b. the second component is correlated with the movement of the satellite: this is the orbit.

c. the last component is the sea-surface height which varies in space and time. These variations are the superimposition of 2 types of signals:

* geophysical signals, essentially due to density anomalies inside the Earth,

* oceanographic signals due to tides and so many aspects of the ocean circulation.

The objective of altimetric missions is to analyze the 2 types of signals by assimilating the measurements as quantitative constraints in models.

3.2 - The orbit is the heart of the system

It is clear to all of us that the sea-surface height is simply the difference between the satellite height and the altimetric range.

Concerning the range, let us recall that radar altimeters on board satellites permanently transmit electromagnetic waves to the Earth, and receive the echo reflected from the sea-surface. This echo is analysed to derive a precise measurement of the round-trip time between the satellite and the sea-surface. The time measurement, scaled by the speed of light, yields a range measurement. Classically, by averaging the estimates over one second, this produces a very accurate measurement of the satellite-to-ocean range.
However, as electromagnetic waves travel through the atmosphere, they can be decelerated by water vapour or by ionisation. Once these phenomena are corrected for, the final range is estimated within 2 cm.

The ultimate aim being to measure sea-surface height relative to a terrestrial reference frame, this requires independent measurements of the satellite orbital trajectory, i.e. exact latitude, longitude and altitude coordinates.

3.3 – Mission requirements for oceanography and terms of precision

When designing an observing system, one has first to know or imagine the signals that are in the scope of the observation. This exercise was of course done with T/P, and the a posteriori analysis of T/P results now helps us to define the requirements for future missions. Again, focusing on the ocean, it is clear that the ocean signal has a wide spectrum both in space and time. Let us recall some typical figures :

- Mesoscale eddy features, with a typical amplitude of the order of 5 to 20 cm, a spatial scale of the order of 100 to 300 km, and an associated temporal scale from a few days up to months or years.
- Large scale regional features, with a typical amplitude of 20 cm and a spatial scale of 5000 km
- The major west boundary currents, such as the Gulf Stream, with typical signals of the order of 1 meter associated with rapid variations,
- Seasonal signals of the order of 10 to 15 cm, varying mainly on an hemisphere basis,
- Interannual signals such as the El Nino phenomenon (see Figure 3), with a typical amplitude of 20 cm and time scales from several weeks to months,
- Very long time scale variations of the mean sea-level with order of magnitudes of 2 mm/year .

Recalling such figures is not neutral. Indeed, this reveals that specifying RMS error figures for all components of an altimetric system is of course far from being sufficient to characterize the system (this is of course true more generally for all ocean observing systems). At the contrary, what is needed is a spectral description of errors.
The variety of figures as a function of time-space characteristics also explains the success of previous altimetric systems. Indeed, on the one hand, GEOS3, SEASAT, GEOSAT demonstrated that satellite orbit error has been the bane of oceanographers who analyze altimetry data with quantitative objectives. Nonetheless, on the other hand, to overcome this difficulty, altimeter users imagined various error reduction methods that proved to be very efficient, in particular for ocean mesocale purpose. However, when focussing on long wavelengths of the ocean spectrum, then, even the most sophisticated orbit error reduction methods are not entirely satisfactory, as they simultaneously remove any type of long wavelength errors and signals.

When looking at an accurate estimation of the long wavelength ocean signals impacting the climate of the Earth, we should stress that achieving the observation of these signals with a 10% accuracy is one decisive step. From such a statement, it appears that 3 figures should now come to our mind as objectives of precision. These are :

- 1 centimeter (amplitude), 1 month (time scale), and 1 ocean basin (spatial scale).

From these three figures, and from the return on investment that has been possible from the careful analysis of GEOSAT, ERS-1/2 and T/P data by many major scientists, it appears that, at the required level of accuracy, strategies for artificially reducing orbit errors will never replace the production of very precise orbits. The launch of T/P, whose system definition was optimized for the quantification of large scale ocean signals, inaugurated a new era. And in that frame, DORIS played a major role.

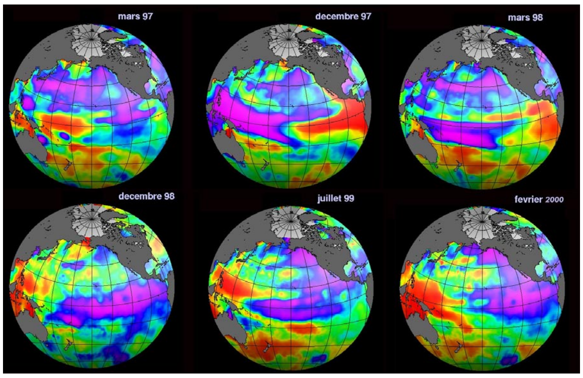

Figure 3: The El Nino/La Nina 1997-2000 events as seen by altimetry.

4 – PRECISE ORBIT DETERMINATION (POD) : A CREDIT TO DORIS ONBOARD T/P

4.1 – Breaking a barrier

The determination of the spacecraft's radial position has been one of the main limitations for using data from the altimetric systems orbiting before TOPEX/POSEIDON was launched. Nevertheless, as stated previously, scientists have been very clever at developing strategies to remove the orbit error from altimeter data but at the expense of losing valid long-wavelength oceanographic signals.

The decisive step forward to be credited to T/P has been to break the 15 to 20 centimeter barrier. What does this mean? This means that the altimeter mission objectives should not be reached without the measurements as they are proposed (in terms of accuracy of all the components of the system). This also means that the measurements are significant to constrain models, which is the final aim.

4.2 – The weight of DORIS in the JGM gravity fields

T/P has been a very good opportunity for improving the modelling of the Earth gravity field. Indeed, among other factors of error, the misknowledge of the gravity field was identified as the major contributor to the orbit error. Nerem et al . (1994) and Tapley et al. (1994a) respectively developed the JGM-2 and JGM-3 gravity fields, the issues of which were considered as 2 major steps in the improvement of the T/P orbit error budget. Among other improvements, it is remarkable that the JGM-2 and JGM-3 gravity fields rely on a pretty much enhanced set of tracking data; looking at the total amount of tracking data involved, it appears that the percentage of DORIS data from SPOT2 and mainly T/P is fairly high : and it is fair to say that the JGM models would not have reached the same level of precision without the contribution of DORIS.

4.3 – Assessing the T/P orbit performance

When talking about T/P, it should be recalled that four independent tracking systems were embarked : the DORIS system, a laser retroreflector array, a GPS demonstration receiver and the TDRSS system. This is of extreme importance. Indeed, it may now be stated explicitely that the complementarity of the 3 « DORIS + laser + GPS » systems has been extremely useful at : 1. computing the orbit in different ways, 2. evaluating its accuracy, and 3. identifying the time and space characteristics of the orbit error.

From the beginning of the mission and still now, a basic dynamic orbit determination methodology has been used to compute Precise Orbit Ephemeris from the DORIS and the laser data. And because it appeared that this approach was dependent upon and inherently limited by detailed modeling of the complete set of forces acting on the T/P satellite, the development of a reduced dynamic technique permitted the reduction of the residual dynamic force modelling error. Such a technique was also used by the teams computing T/P orbits using essentially the data from the GPS demonstration receiver. Marshall et al. (1995) give an excellent overview of the temporal and spatial characteristics of T/P radial orbit error, through the analysis of laser tracking residuals and orbit comparisons with independent generated trajectories (essentially 1 year of T/P orbits computed with GPS data). Even if there is some difficulty to measure the absolute orbit accuracy, it is now well accepted that the T/P orbits are accurate at the level of 2 to 3 centimeters (Tapley et al. 1994b ; Nouel et al., 1994), which has made unnecessary the orbit removal techniques when analyzing T/P data. The precise orbit ephemeris routinely computed using DORIS and laser data are found on the T/P GDRs distributed by the US PO.DAAC and the French AVISO.

5 - DORIS: A GEODETIC CONTRIBUTOR TO CLIMATE CHANGE STUDIES

5.1 - The sea-level change index

Within the climate change research framework, the rate of present-day global sea-level change is a crucial topic. Traditional measurement techniques rely on tide gauges, a small number of which has been measuring sea level changes on an effective manner for a few decades. From the analysis of edited tide gauge collections of measurements, several authors already issued a 1.5 mm/yr figure for the rate of sea-level change. Telling if such a figure is fully representative of the global Earth is difficult as the geographic distribution of reliable tide gauges is not regular and somewhat sparse. Also, separating the contributions of all potential causes: thermal expansion of the oceans, water transfer from continental glaciers, ice sheets, others, is still more challenging but will of course not be the subject of the following sections. More important in the frame of geodesy is to concentrate on the way classical tide gauges and its space symmetric that is space altimetry have to be used for a proper estimation of global sea-level change. In such a framework, it is very important to determine and monitor/maintain a terrestrial reference frame along time, DORIS being well suited to be a predominant contributor to such a reference frame.

5.2 – T/P altimetry and Sea-level Change

An important consideration in the success of the T/P mission is the ability to define and maintain the terrestrial reference frame throughout the duration of the mission. This was indeed extremely important as one of the objectives of the mission was explicitely to help in performing decadal studies of ocean surface change.

The best example is provided by the ability of T/P to allow the first measurement of interannual variations of the global mean sea level with a precision better than 1 mm/yr: Nerem et al., 1997, Cazenave et al., 1999, for instance. Using more than 7 years of T/P measurements, Cazenave et al. (personal communication) report a 2.0 +/- 0.2 mm/yr global mean sea-level rise. Such a figure includes corrections for various factors such as the identified drift of the T/P microwave radiometer. Other sources of error have been neglected up to now and should surely be taken into account to reach the few tenths of mm accuracy that is desired to make a large step in our knowledge of mean sea level change. Among the potential error sources are those issued from geodetic aspects of the altimetry system.

5.3 – Geodetic contribution of DORIS to the terrestrial reference frame

One remarkable feature of altimetry is that the observation is performed at a global scale in a center of mass-fixed reference frame. The positions of the stations tracking the satellite define the orbit reference frame, and consequently, the ability to precisely determine their locations within a coordinate system whose origin is located at the Earth's center of mass is of considerable importance. It is widely agreed that the international network of satellite laser ranging systems is an important contributor to T/P reference frame definition. The permanent orbitography network of DORIS beacons is the other major contributor. Indeed, since T/P launch, the knowledge of the coordinates of the ground beacons has greatly improved, which allowed to introduce the DORIS system in the IERS reference frame computations, and then to reprocess T/P orbits in a consolidated geodetic reference frame.

As already mentioned, the T/P POD efforts have been continuous and exceptional since launch and have helped to reach the better than 3 cm accuracy rms that is generally agreed.
Among various orbit error sources, uncertainty in the position of the tracking stations is now one which is looked at very cautiously. For instance, it was evidenced that, for long term sea-level change studies that involve tiny figures of the order of 1 mm/yr, managing the evolution of the reference frame through time by taking into account station horizontal velocities in the orbit computation process is of crucial importance.
Once again, the term of the error we have just discussed above is not of very high importance for much of the ocean applications. However, because the goal of altimetry is now to contribute to a continuous ocean observing system on a long term basis, then it becomes extremely important to manage the evolution of the terrestrial reference frame.
Notice that the impact of vertical velocities of tracking stations is not yet so well estimated. In addition to absolute positions and horizontal velocities of DORIS beacons, Cretaux et al. (1998) also computed the vertical velocities of DORIS stations, based on the analysis of 4 years of DORIS data from 3 satellites. It appears that uncertainties are still at the level of 1 mm/yr. Use of the 2nd generation of DORIS instruments onboard SPOT4, Jason and ENVISAT will allow to continue the DORIS station motion analysis, with an even better accuracy, since the instrumental noise of the DORIS receiver will be of the 0.1 mm/yr order of magnitude to be compared with the 0.3 mm/yr noise for T/P like receivers. T/P orbits taking into account both the horizontal and the vertical motions of the DORIS beacons should now be computed to look for a potential trend between sea-levels computed in the 2 cases (A. Cazenave, personal communication); then the rate of sea-level change from T/P may be updated as well as the associated error budget.
Last, one other subject of study should also be the stability of the reference frame in which sea-levels are computed. It is known that geocenter variations are related to the adopted reference system, and in particular to its origin. Sea-surface heights are related to the Earth's center of mass since the satellite orbit is defined in an inertial reference frame which center is the center of mass of the Earth. In practice, tracking data involved in the orbit computation are collected by stations that are distributed at the Earth surface, which define an earth fixed reference frame which origin is the center of figure. Hence motions of the center of figure relative to the center of mass should be taken into account in the global mean sea-level problem.

5.4 - Tide gauges are the required complement to space altimetry

It has to be emphasized that the tide gauge / altimetry comparison process that has been initiated with great success by G. Mitchum (1998) is now generally accepted as a vital contribution to the assessment of the quality of any altimetry system. Fixing tide gauges geodetically is now recognized of very high priority. Indeed, it is well known that in addition to the irregular geographical distribution of high quality tide gauges over the world, another difficulty in getting a reliable estimate of sea-level change from such a technique is to accurately separate the absolute part of sea-level change from vertical land movements such as post glacial rebound, seismic and tectonic deformations. Results by Cazenave et al. (1999) using data from tide gauge stations equipped with DORIS beacons show extremely convincing features in terms of decorrelation of land movements in tide gauge measurements, and a very fruitful comparison to altimetry analysis. Such a work of comparing tide gauge data equipped with DORIS beacons to altimeter measurements will be continued in the frame of the Jason-1 and ENVISAT missions by A. Cazenave's team. And the results should be better and better with series of more than 10 year long coupled tide gauge/DORIS stations.

5.5 - Towards an integrated « Tide gauge + GPS + DORIS + altimetry + laser » sea-level monitoring system

Observation of the ocean is now thought by oceanographers in terms of a global and « integrated » system. What does this mean ? Essentially, this refers to the fact that there is now a general agreement that space techniques will not replace in situ techniques. At the opposite, it is now well understood that complementarity in terms of characteristics of the observation techniques, sampling, precision and accuracy, must be exploited in a maximum way to provide the optimum observing system.

For the sea-level change problem, the same kind of idea may be appropriate. Indeed, since a few years, the GPS and DORIS geodetic techniques have been used extensively together with altimetry and tide gauges to estimate the rate of change of sea-level. It should be recognized that, until now, the international community has put a large effort on collocating GPS stations with tide gauge sites, for instance in the frame of the GLOSS network (at the time of this paper, 31 GLOSS sites are equipped with permanent PGS receivers). It is clear that this latter technique is accurate and has appeared to many people as the ideal solution, as the GPS ground network may be extended in a quasi illimited manner. However, as it has revealed already true in all previous problems of accurate geodesy, there is a large amount of experience showing that relying on one technique only is not very cautious at all. Indeed, it is often of much interest and always necessary to identify all biases, drifts, etc. that could be attributed to a technique or a system. Then, once again, the author would strongly encourage the sea-level community in thinking at the enhancement of the DORIS ground network by multiplying the collocation of DORIS beacons with tide gauges and with/without GPS stations. It is important to note that the author does not tell that DORIS should replace any other geodetic technique at tide gauge sites. At the opposite, the author wishes to argue that the upgraded versions of the DORIS system, for instance through the multiple channel capability, now offer the very true possibility to take part in an efficient integrated « tide gauge + GPS + DORIS + altimetry» sea-level system. And losing one of this four techniques should probably be a large drawback : indeed, it would endanger the characterization of errors that need to accompany any estimate of the rate of change of the sea-level. In that frame, proposals like the one by Crétaux et al. (2000) are the starting point for defining the future DORIS contribution to an integrated sea-level system.

At last, the laser system should not be forgotten in such a system: it is indeed vital for calibration and orbitography of altimetry mission in the event one of the nominal tracking system fails.

6. ALTIMETRY AND DORIS FOR CONTINENTAL ICE MONITORING

The polar ice caps have a very significant role in the study of climate, since they are at the same time, a paleoclimatic archive and a climatic index. Antarctica extends over 14 millions km², and has an average ice thickness of 2200 m. It represents 90% of the terrestrial ice and, if melted, would lead to an equivalent sea level rise of up to 70 m. The Greenland ice sheet is smaller and represents only 9% of the terrestrial ice. To understand, model or predict the ice sheet evolution, one requires to acquire an insight on the climatic and dynamic processes which control them using observations. The size of these lands, the difficulties of access, the weather conditions, make in situ measurements difficult and very sparse, so that radar observation is an important tool. Among the parameters that can be derived from space, the topography of the surface is probably one of the most important. The ERS-1 satellite, launched in 1991, allowed, for the first time, the mapping of the surface topography over 80% of the Antarctica ice sheet (F. Remy et al, 1999 and Figure 4) and the whole of Greenland.

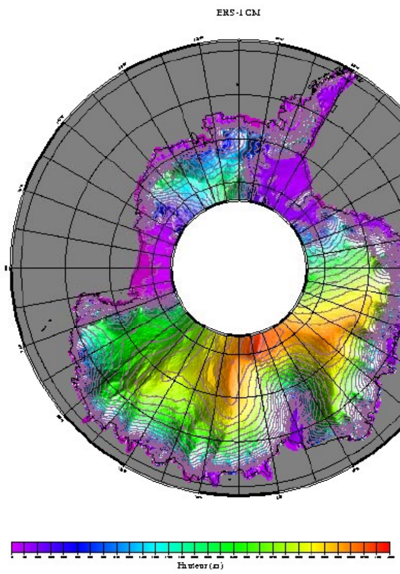

Figure 4 : Topography of Antarctica derived from ERS-1 altimeter measurements (courtesy, F. Remy, LEGOS)

From a climatic point of view, the monitoring of the elevation changes allows to constrain balance and volume variations. Indeed, the shape of the ice sheet is controlled by the equilibrium between snow fall and ice flow. Each year, the equivalent of respectively 6 mm and 1.5 mm of sea level is precipitated over Antarctic and Greenland ice sheets before being calved or melted. Thus, even a slight imbalance between both terms could significantly contribute to ice volume change and thus to sea level change. The difficulty for modeling mass balance is due to the numerous processes acting on both the atmospheric and dynamic components and to the large time scale difference in the response of both components to climate change.

A few attempts to use radar altimetry to measure ice sheet imbalance have been performed. Greenland is found to react to current climate warming: the central part grows while the coastal areas decreases, due to an increase in both the accumulation rate and the surface melting. In term of sea level change, the global effect is probably negligible. The Antarctica is also found to be in slight imbalance. The topographic height of area above the bedrock valley is found to decrease with respect to others. This seems to be the signature of the delayed response of the Holocene warming.

To illustrate the above considerations with figures, let us cite the 0.9 +/- 0.5 cm/year figure computed by Wingham et al. (1998) for the falling of the average elevation of the Antarctic ice sheet interior from 1992 to 1996, and the estimate of –0.06 +/- 0.08 of the mean mass accumulation rate for the mass imbalance of the Antarctic interior this century.

In 2001, ESA will launch ENVISAT whose altimeter will ensure the continuity of the ERS series, with a dual-frequency altimeter that will allow to better estimate long term change in elevation. Onboard ENVISAT, the DORIS system will be a major contributor in the continental ice mission, through its excellent performance in orbitography and by placing data in a well monitored geodetic reference frame, which will be of much use on a long term basis given the small figures of topographic variations that are involved. From 2004, ESA will fly the CRYOSAT mission allowing the accurate observation of sea-ice and continental ice to improve our knowledge of the cryosphere with the goal of using new space data in the frame of climate studies. This will be done using an improved altimeter instrument with new working modes (namely, a SAR-like and an interferometric mode) associated with the DORIS system to account for all geodetic issues. This reinforces again the role of DORIS in ocean and ice observations from space using radar altimetry, in a long term perspective.

7 - CONCLUSION

From its probatory status onboard SPOT 2, the DORIS system has evolved to become a major contributor in oceanographic and geodetic science and applications. Continuous performance improvements of the onboard and ground instruments, improvement of the onboard (DIODE real time navigation system as a proved system onboard SPOT4) and ground system capabilities, intend to install the DORIS system as a major permanent actor in geodesy and altimetry. The fact is that the DORIS system is now the core of many altimeter missions: T/P, but also the coming Jason-1, ENVISAT and CRYOSAT missions.

The T/P experience has strongly proved that, for interdecadal ocean surface change studies, there is a crucial importance in knowing and monitoring very well the terrestrial reference system in which orbit computation is performed. The continuous maintenance and development of the DORIS system, as well as the exploitation of the data by several groups worldwide, will make feasible such a task.

Ultimately as far as sea-level studies are concerned, it is now proved that DORIS is a quite well suited companion to tide gauges to allow investigators continue their sea-level work as well as for the calibration of new altimeter systems. The definition of an « integrated » sea-level system including tide gauges, GPS, DORIS and altimetry should be the task of the sea-level community : the future International DORIS Service should bring a major contribution in that.

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