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DORIS-DIODE / Jason-1, ENVISAT, SPOT5 : Real-Time on-board Orbit Determination in Space

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Abstract

Three satellites equipped with new DORIS receivers (Jason-1, ENVISAT and SPOT5) have been successfully launched between Dec. 2001 and May 2002. All of them host a navigation function, called DIODE.

Like the DORIS receiver, and the overall system, the three new DIODE versions in space have been dramatically improved with respect to the "SPOT4 design".

- *Accuracy of the on-board orbit has been highly improved.*
- *A self-initialisation of the navigation function (and of the whole receiver) has been added and qualified in space.*
- *A self-programming mode has been designed, and has been permanently active on-board Jason-1 and SPOT5.*
- *A precise Time-Tagging function has been added, based on DIODE synchronisation results.*

Detailed description of these new functions, and analysis of their on-board results will be presented. For the three satellites, the requirements are met, and no failure has occured since the end of the in-flight qualification phase.

Next customers of DORIS/DIODE will be CRYOSAT, Jason-2 and Pléiades : they have expressed new requirements, leading us to add new functions to DIODE : those evolutions will be detailed in the paper.

- ⇨ *On-board CRYOSAT, DIODE real-time positions will be used within the AOCS.*
- ⇨ *For Pléiades, the on-board time will be estimated using DORIS-DIODE time-tagging. In the meantime, like SPOT4 and SPOT5, the images will keep on being rectified, on ground, using DIODE positions.*
- ⇨ *On-board Jason-2, new improvements will lead to a 5 centimeters accuracy on the radial component, allowing real-time processing of the altimetric data.*

The « first generation » TOPEX-Poseidon mission has shown that DORIS was a precise and operational system for satellite localisation. SPOT5, ENVISAT and Jason-1 prove that it is automated and extremely reliable. The next generation will show that DORIS is even easier to use. Its Navigator allows real-time use of the data… and simplification of the Ground Control Center.

The authors would like to thank Mrs J. Puillet, and the whole Altimetry Department at CNES, for their precious contributions to this paper.

1. Introduction : DORIS first generation and TOPEX-Poseidon

DORIS first generation has been used from 1990 until now to perform very precise orbit determination with a few centimeters accuracy : first on SPOT2 as a probatory experiment, then on TOPEX-Poseidon for operational altimetry, and on SPOT4 for image positioning.

The whole TOPEX-Poseidon mission is a complete success (12 cm accuracy orbits expected, 2-3 cm actually performed) which has lead to important scientific progress in ocean understanding. DORIS has significantly contributed to this success, and all its initial specifications are largely met. But there is another point.

Since the beginnings, even during the conception phase, a parallel work has been conducted, to answer a complementary question : « *with such a system available, what could be done in order to extend it, and make it even better* ? ». This question has been examined together with CNES R&T teams, the project users (altimetry and image processing), the development team, and the operators.

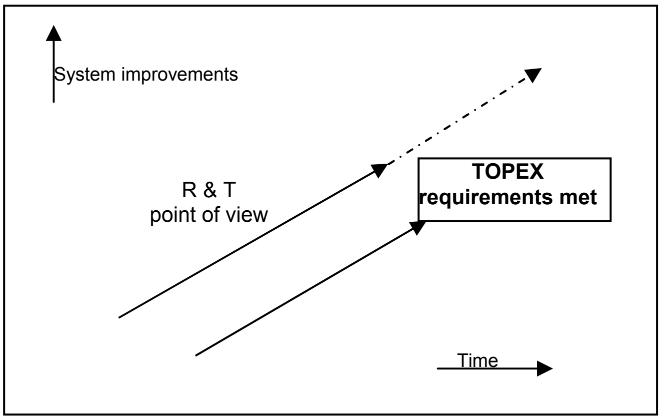

Fig. 1 : parallel points of view help to define future evolutions

For instance, DIODE initial conception was worked out in close cooperation with the SPOT4 project (our first user). It was later completed with new functions, to meet the requirements of ENVISAT, Jason-1, SPOT5, Pléiades, CRYOSAT, and particularly Skybridge.

For DORIS, this parallel work has been permanent for 15 years : it is the reason why DORIS has evolved from generation to generation, toward a more complete and accurate system, able to fulfill many satellite systems needs.

The following paragraph sums up the general features of the current status of DORIS. After that, this text presents the 2GM generation in-flight results, then the foreseen features of the 2GXX generation and its expected results.

2. The DORIS system – current status

The DORIS system has been designed and optimised by CNES (Centre National d'études Spatiales), IGN (Institut Géographique National), and GRGS (Groupe de Recherches en Géodésie Spatiale) to perform high precision orbit determination and station positioning.

It was developped in the frame of the TOPEX-Poseidon oceanographic altimetry mission. DORIS has been operated since 1990, when the first receiver was launched as a probatory experiment on-board SPOT2. Since that time, DORIS has been opened to the scientific community with the creation of the I.D.S. :

2.1. International DORIS Service (I.D.S.)

After a four year Pilot Experiment, the IAG (International Association og Geodesy) Executive Commitee has accepted the IDS as a full IAG service in Sapporo (july 2003). The IERS (International Earth Rotation and Reference Systems Service) Directing Board is now preparing a decision to accept the IDS as a new external service.

The objectives of the IDS are :

- to provide a service to support, through DORIS data and products, geodetic, geophysical and other research and operational activities,
- to encourage the integration of DORIS instruments on-board future Earth orbiting satellites, and the installation of new ground DORIS stations with the participation of host agencies,
- to promote research and development activities in all aspects of the geodetic and geophysical DORIS technique,
- to interact with the community of users of DORIS products and to integrate DORIS into a global Earth observing system (IERS, ITRF, …).

2.2 Main technical features of the DORIS system

DORIS is an uplink radio system based on the Doppler principle. It measures relative velocity between a dense, permanent stations network, and an unlimited number of on-board packages, flying on different user satellites. Once gathered and elaborated, DORIS data may then be used :

- on-board, to perform real-time orbit determination (autonomous navigation, see chapter 2.5),
- on ground, after storage and downlink to the multi-missions orbitography and altimetry center, for very precise orbit determination, station positioning, atmosphere and earth gravity modelling, ...

System performances are summarised in chapter 2.7, while recent enhancements are described in 2.8.

2.3 The stations network

The orbit determination station network is distributed homogeneously over the Earth surface. It is managed by the DORIS Beacon Installation and Maintenance Service (SIMB), in the framework of a partnership between CNES and IGN.

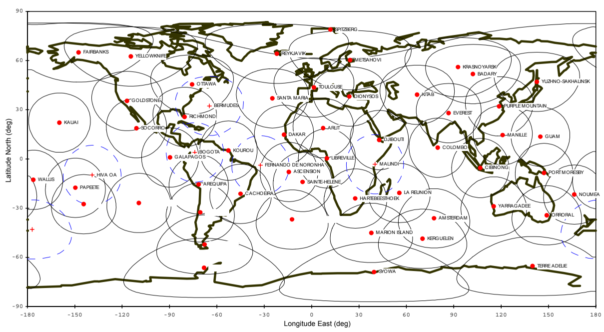

Fig. 2 : DORIS permanent stations network

The network is constituted by 56 permanent stations hosted by institutes of more than 30 different countries. More than 20 stations are colocated with other precise positioning techniques (VLBI, GPS) to allow intercalibration.

Each site is equipped with :

- 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 power supply,
- a meteorogical package providing temperature, pressure and humidity measurements, used for tropospheric correction.

These beacons emit narrow-band ultra-stable bi-frequency signals at 400 MHz and 2 GHz. They also emit auxiliary data :

- beacon identifier,

- ➪ housekeeping data,
- ➪ meteorological data,
- ➪ time-tagging reference data.

A few peculiar beacons, called "Master Beacons" (Toulouse and Kourou currently, then Hartebeesthoek in the near future), are linked to the Control Center : they can upload data to the on-board packages. They are also tied to an atomic clock, which enables synchronization of the DORIS system with international reference time (TAI).

In the next months, new sites are going to be equipped with Doris beacons, in order to reach a total number of 60 sites.

2.4 On-board packages

Each on-board package has been designed to elaborate precise Doppler measurements (between 0.3 mm/s and 0.5 mm/s), and synchronisation measurements (about one microsecond).

The DORIS on-board package includes :

- ➪ a receiver performing Doppler measurements and receiving auxiliary data from the beacons,
- ➪ a bi-frequency omni-directional antenna,
- ➪ a USO (Ultra Stable Oscillator).

Dedicated to accuracy applications, bi-frequency receivers allow ionospheric correction of the measurements. The bi-channels receivers are able of simultaneous tracking of two beacons.

Software versions can be uploaded in-flight (use of EEPROM), in order to improve performances or robustness, or to correct any software anomaly.

Since the first mission, DORIS receivers have evolved, leading to different generations of the on-board instrumentation (the weights are calculated for 1 channel and without redundancy) :

1rst generation (wbut = 18 kg)	**2nd generation (wbut = 5.5 kg)**	**2nd generation miniaturised (wbut = 2.8 kg)**	**Intermediate 2GXX (wbut = 3.2 kg)**	**2GXX generation (TDB kg)**
SPOT2, SPOT3, TOPEX-Poseidon SPOT4	ENVISAT	Jason-1, SPOT5	CRYOSAT,	Jason-2, Pléiades,
1 channel no redundance	2 channels no redundance	2 channels no redundance	2 channels twinned (redundant)	8 channels twinned (redundant)

Table 1 : DORIS receivers evolution

2.5 Navigation software (DIODE)

DIODE stands for Doris Immediate on-board Orbit Determination. It is an advanced function of the DORIS receiver, that computes the position and the velocity of the satellite : a *real time on-board orbit determination* software.

DIODE was initiated by CNES in 1991, after a conclusive feasibility study from 1988 to 1990. The orbit determination software has been realised by CNES, with a technical support of the COFRAMI company.

The first issue of DIODE has already been flying on-board SPOT4 since March 1998, on an electronic card realised by Dassault Electronique and added in the DORIS receiver. After that probatory experiment, DIODE has been fully integrated in the DORIS on-board software, becoming a permanent feature.

More recent versions of DIODE are flying with ENVISAT, Jason-1 and SPOT5. The results of these flights are described in chapter 3.

Design of the following issue (CRYOSAT) has been completed, and the CRYOSAT receivers are currently undergoing validation tests.

2.6 Multi-missions orbitography and altimetry center

User projects are generally encouraged to integrate the DORIS Command/Control in their own Control Center, scientific products ground processings being performed in the SSALTO (and/or within IDS analysis centers).

SSALTO (Orbitography and Altimetry Multi-mission Center) is a facility devoted to DORIS system and to altimetry missions control and processing. Located in Toulouse, France, it is in charge of :

- ➪ station network monitoring,
- ➪ science telemetry acquisition and pre-processing,
- ➪ technological archive,
- ➪ precise orbit determination,
- ➪ station precise positioning.

IDS data centers collect measurements from the Control Center, archive and distribute them. Since DORIS was included in IERS, two user archives are in operation, one in Europe managed by IGN, the other one in the USA under NASA/CDDIS management.

2.7 System performances

Below is a summary of DORIS orbit determination performances :

	1 rst generation (1G)	2 nd generation (2G)	2 nd generation miniaturised (2GM)
Applications	SPOT2, SPOT3, TOPEX-Poseidon, SPOT4	ENVISAT	Jason-1 SPOT5
Precise Orbit	< 3 cm radial	< 3 cm radial	1-2 cm radial
Real Time Orbit	1.5m 3D (SPOT4)	20-30 cm radial, 60 cm 3D	10-20 cm radial, 50 cm 3D
Time Determination	3 µs	1.5 µs	1.5 µs (Jason-1)

Table 2 : DORIS system performances

And the station positionning results :

Data gathering duration	Accuracy (1 satellite)	Accuracy (2 satellites)
1 hour	1 m	0.5 m
1 day	20 cm	15 cm
5 days	10 cm	7 cm
26 days	3 cm	1-2 cm

Table 3 : DORIS positionning performances

Recent results using 5 satellites indicate a centimetric repeatability (see Ref. [3]). Experiments are beginning with a Grace Gravity Field (GGM01C), and should improve the accuracy once more (P. Willis, private communication, 2003).

2.8 Recent system evolutions

2.8.1. New "broadcast" uploads

These "broadcasts" are elaborated weekly by the Control Center, and forwarded by the Master Beacons to each DORIS user satellite. They display an information about time/frequency and position of the DORIS stations.

Broadcasts uploads allow several on-board receivers on different satellites to acquire a precise and up-to-date information about the current status of the network, without any human intervention : the autonomy of the receivers has been strongly improved this way.

2.8.2. New "frequency shifted" beacons

The new Third Generation Beacons may be shifted in frequency, in order to minimise their interaction with other DORIS beacons in close vicinity. This will allow us to densify the network in the future, without being limited by Doppler collisions.

2.8.3. Autonomous initialisation and synchronisation of the receivers

Beginning with Jason-1 and SPOT5, the on-board receivers are able to perform self-synchronisation and self-initialisation : the new 3G beacons are emitting the value of TAI time in their data, and the on-board receivers use this information to synchronise their clocks. Thus, these receivers are then able to acquire measurements, ask DIODE to process them, and perform self-programming. Human intervention is no longer necessary to start the operation.

2.8.4. System check and control

The role of this ground tool, is to check the way the system operates, by acquiring data coming from different satellites and the whole stations network. Functions, statistics and graphs are performed to check that every beacon is properly operating.

2.8.5. Doris Beacon dynamic Simulator

The DORIS Beacon Simulator (DBS) is a new ground test tool integrated in a new set of test bench used during AIT phase. It is the core of the DORIS System Simulator, a new DORIS Project facility for mission studies.

Its role is to generate the RF signals, transmitted by two beacons, representative of the real signals received by the DORIS on-board instrument. It is then possible to provide the receiver with these RF signals, as if it was in orbit.

Development and qualification of the DBS has been achieved this year, with a technical support of the DACTEM and COFRAMI companies.

The DBS has already been used with ground versions of ENVISAT and Jason-1 receivers, and is currently being used for the validation of the CRYOSAT flight receivers.

3. DORIS 2GM generation (Jason-1-SPOT5)

A large part of what follows here is also applicable to ENVISAT (2nd generation).

With DORIS 2GM, many features that were flight-demonstrated in the first generation, have been reinforced and made more reliable. New functionalities have also been flight-demonstrated.

3.1 Reliability improvements for already flight-demonstrated features

The new receivers are more compact, lighter (5.6 kg), and more efficient as they are able to track two beacons at the same time.

DORIS hardware and software sensitivity to radiations has been improved : until now, there has been no mission interruption related with a SEU on SPOT5 and Jason-1.

After its first probatory status, DIODE has been fully integrated on-board, and its products (position, velocity and datation) are permanently used by our customers (SPOT5 image processings, SPOT5 Control Center, Jason-1 near real time altimetric products (OSDR), Jason-1 altimeter measurements time-tagging, …).

DIODE accuracy and performances have been validated and improved by a permanent ground processing of SPOT2, SPOT4 and TOPEX-Poseidon measurements.

DIODE’s capacity to pass through the manoeuvers has been reinforced, and no navigation interruption after manoeuvers has occured on Jason-1 until now (but one on SPOT5 during the huge orbit acquisition manoeuvers).

3.2 New tools have been flight demonstrated

Time Determination is now available for the platform, with a 1-2 microseconds accuracy : DORIS may be used as an on-board clock by its user satellites.

The on-board receivers are now able to perform self-initialisation without any ground help (time acquisition, self-synchronisation, position determination and activation of the routine navigation) (see 2.8.3).

DORIS self-programming mode is today the nominal way to track the stations : every ten seconds, DIODE predicts the next visible beacons, operates an optimal choice between the different possibilities, and provides this programmation to the DORIS receiver. This automation has relieved the Control Center of the burden of sending every day the beacon programmation to each satellite.

Failure Detection and Recovery is now used : DIODE is able to detect its own divergence and to try to recover on its own. If it fails, the receiver is able to switch into a more robust « waiting » mode.

Broadcast uploads are operational and provide Jason-1 and SPOT5 receivers with a very precise time/frequency status of the station network.

3.3 In-flight results

Availability : DORIS/DIODE has been properly operating for more than **one year** now on-board SPOT5 : no anomaly since the end of the assessment phase. On –board Jason-1, we have had more than **15 months** without interruption (except a volontary interruption to upload a new issue of the software) : **on both missions, the availability of positions, velocities, and time is 100%.**

Autonomy : in routine phase, a few uploads per year are necessary to update DIODE data (mainly the expected manœuvers characteristics) : for Jason-1, between January 2002 and August 2003, only 10 data uploads have been sent.

Several receiver self-initialisations were successfully performed, during Jason-1 and SPOT5 assessment phases. A few DIODE self-initialisations occured (and succeeded) on-board ENVISAT.

Robustness : DIODE has handled several very large manœuvers, with errors lower than 50 meters (SPOT4 orbit acquisition 8 kilometers semi-major axis raising manœuver, several SPOT4 inclination control manoeuvers, SPOT5 orbit acquisition 13 kilometers semi-major axis raising manœuver, …).

Position in-flight results : Figure 3 shows the results achieved with three months of Jason-1 real measurements: DIODE estimations are compared with the ZOOM precise orbit ephemeris (P.O.E.), which have an accuracy better than 3 centimeters on the radial component. The differences are shown in the orbital frame, in meters.

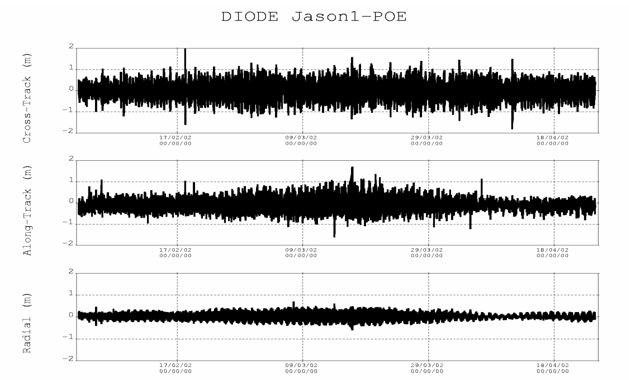

Fig. 3 : position real in-flight results

Radial RMS oscillates between 8 and 25 centimeters. The accuracy specified by altimetric users is 30 cm RMS on the radial component, and 1 meter RMS in 3-D.

In fact, these results are dominated by a numerical degradation of the calculations (due to the 31750 microcomputer) which leads to a radial RMS error of about 13cm !

On the workstation used for the software development, DIODE has been operated for more than three years, on-ground, using DORIS/TOPEX and Jason-1 measurements. Below are the results obtained with the 10-days cycle 316 of TOPEX : DIODE estimations are compared with the ZOOM precise orbit ephemeris (P.O.E.) :

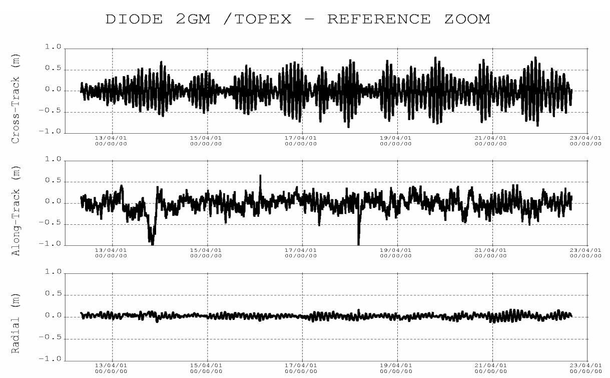

Fig. 4 : DIODE 2GM / TOPEX positions accuracy

The statistics of this comparison are given in Table 4 :

	MAXIMUM	MEAN	R.M.S.
Radial (m)	0.191600	0.026413	0.056897
Tangentiel (m)	1.098805	-0.014242	0.183014
Normal (m)	0.868090	-0.008175	0.289291
Distance (m)	1.107651	0.301818	0.347016
Vit rdle (m/s)	0.001001	0.000018	0.000160
Vit tgtle (m/s)	0.000152	0.000002	0.000044
Vit nrmle (m/s)	0.000744	-0.000002	0.000262
Norme vit (m/s)	0.001042	0.000267	0.000310

Table 4 : DIODE 2GM / TOPEX positions accuracy statistics

Notice the 5.6 cms RMS on the radial component, and the maximum value lower than 20 cm (during ten days). A 2.6 cms mean value can be observed, which has been improved in the following issues.

Also notice the 35 cms RMS in 3D.

Time determination in-flight results : Figure 5 shows the results of a comparison between DIODE and the GPS 1 PPS, of the correspondence between on-board time and ground TAI time :

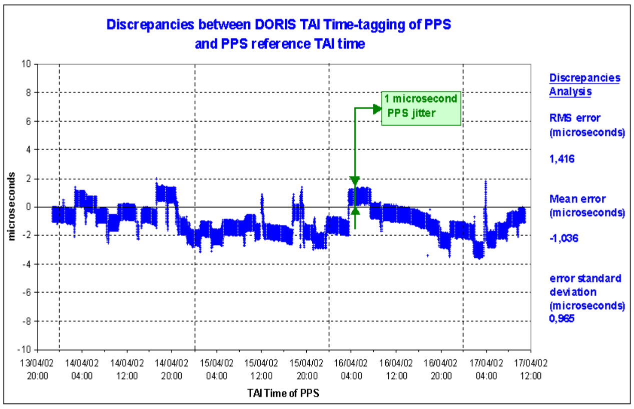

Fig. 5 : Time determination real in-flight results

On this graph, 30 passes over the Master-Beacons have lead to periods of synchronisation adjustment. In between, a prediction is elaborated, using the on-board estimation of the USO frequency. The agreement is within 1.4 microseconds.

3.4 For the users :

We have already detailed (see Ref. [2]), the advantages that our « customer » satellites take of DORIS/DIODE results : accurate position, velocity, and time (with quality indexes !), are available on-board in real-time, ready to be used either by the satellite AOCS, or by the payload.

Since March 1998, almost every SPOT4 and SPOT5 image has been rectified using DORIS/DIODE results. Since June 1999, VEGETATION, a SPOT4 payload instrument, also uses DIODE. POAM (a US Naval Research Laboratory instrument) uses DORIS/DIODE positions to point its optical terminal.

On-Board Time determination is used on SPOT5, to elaborate image time-tagging. Since the receiver is the same as Jason-1, the accuracy is very probably coherent with Fig 5. DIODE position estimations are also used in the Control Center, and participate to SPOT5 orbit control.

On-Board Jason-1, DORIS/DIODE results are used for two purposes : first, the position/velocity are used in the near real time products (OSDR) to locate the altimeter measurements.Second point, the altimetrer measurements are time-tagged by use of DORIS/DIODE synchronisation results.

On-Board ENVISAT, navigation results are used for the delivery of payload products.

For every customer project, moreover, DIODE results are carefully examined by system engineers, in order to check and control the whole DORIS system status.

4. DORIS 2GXX generation (CRYOSAT, Jason-2, Pléiades)

Our next users will be CRYOSAT, Jason-2 and Pléiades : a new 2GXX generation is being developed, with important enhancements in the whole DORIS system.

4.1 Reliability improvements for already flight-demonstrated features

The self-programming function is already very reliable : we have added a Doppler quality index, that will help the DORIS receiver to narrow its phase thresholds over well-known stations.

Self-Initialisation of the receivers : delays have been adjusted, and two different stations are now needed. This in order to be robust against erroneous beacon transmission.

Failure Detection and Recovery has been reinforced, by addition of divergence detection on the time determination filter : as it was already true for the position/velocity filter, if the synchronisation measurements processing begins to get degraded, DIODE is now able to ‘reset’ its covariances and reconverge on its own.

DORIS station network has been reinforced by installing new 3G beacons, more reliable and performing more precise measurements. A third Master Beacon is currently being installed in Hartebeesthoek (South Africa). This will allow faster convergence of the initialisation phases, and more robust synchronisation of the system during routine phases.

Control of the network has been reinforced this year, by using a new System Survey Software, checking everyday how many measurements are made by each beacon. Status of each station is carefully examined every Monday in GECO operational meetings.

DORIS/DIODE control has been simplified, by reducing the number of commands. Tuning of the on-board filters, accuracy assessment and expertise are performed by the DORIS system team.

DIODE Navigation accuracy has been improved once again (new reference system, 60x60 Grim5 earth gravitation field, earth tides, advanced measurement modelling…).

4.2 New tools are going to be flight demonstrated

A new J2000 inertial bulletin will be elaborated, in order to help AOCS in its operations. The specified accuracy is 100 meters, but we expect a few meters accuracy on board CRYOSAT.

A new ‘altimetric bulletin’ will provide users with geodetic informations about the position of the satellite : latitude, longitude, and altitude wrt the geoid.

The processor has been changed : next generations will use a Sparc ERC 32 microcomputer, and we have already checked that the numerical degradation described in 3.3 has disappeared.

Qualification of the on-board receivers will be pronounced by testing them with the DORIS Beacon Simulator. This equipment allows a more complete and precise qualification than before, and this work has already begun for CRYOSAT.

4.3 Expected results

As we have been used to doing for several years, the future DIODE flight version has been validated on-ground, using real DORIS measurements gathered from the different satellites : here are the results on a TOPEX two-days arc (August 2001).

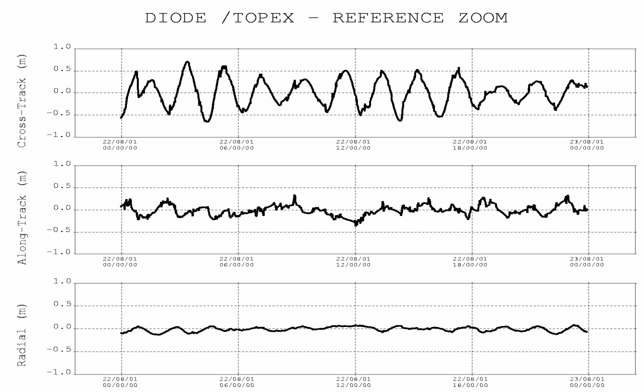

Fig. 6 : DIODE next issue : TOPEX positions accuracy

The statistics of this comparison are given in Table 5 :

	MAXIMUM	MEAN	R.M.S.
Radial (m)	0.128637	-0.007453	0.048899
Tangentiel (m)	0.368314	-0.008722	0.116062
Normal (m)	0.714313	-0.010742	0.300972
Distance (m)	0.724247	0.292357	0.326260
Vit rdle (m/s)	0.000354	0.000009	0.000100
Vit tgtle (m/s)	-0.000183	0.000002	0.000045

Vit nrmle (m/s)	0.000725	0.000023	0.000284
Norme vit (m/s)	0.000737	0.000264	0.000304

Table 5 : DIODE next issue : TOPEX positions accuracy statistics

Please compare with Table 4 to appreciate the improvements.

As on-board Jason-1 and SPOT5, we expect a 100% disponibility and availability of the products.

4.4 For the users

Users will be provided with two types of additional results :

DORIS/DIODE will elaborate J2000 bulletins, for the spacecraft AOCS.

Geodetic coordinates of the satellite will also be elaborated, to be used by altimeters (Jason-2, AltiKa). This new product will allow in the future, immediate convergence of the altimeter tracking loops : the expected altitude will directly be programmed by the DORIS receiver, with a few meters accuracy !…

4.5 Still under study

A few evolutions have been kept for the following 2GXX receivers (Jason-2, Pléiades) :

First, the number of channels (UT) will be increased from 2 to 8, in order to perform more measurements, to be more precise, and more robust wrt beacon transmissions…

A new « spectral analysis mode » will be implemented in the receivers, allowing more efficient detection of recently emitting stations, or of external emitters. This mode, more robust than our current « waiting mode », will be especially useful in the initialisation phases.

A new input is being added, so that Attitude Quaternions may be taken into account by the navigation function. This will allow better modelling of the surface forces, and better information on the Center of Phase – Center of Mass vector.

The J2000 bulletins will be completed with their own Quality Index : this has not been possible on CRYOSAT, as the Data Packets were already defined… This J2000 Quality Index will be a combination of the terrestrial quality index, and of the newness of the UT1-UTC information, uploaded weekly in the broadcasts.

5. CONCLUSION

The « first generation » TOPEX-Poseidon mission has shown that DORIS was a precise and operational system for satellite localisation.

SPOT5, ENVISAT and Jason-1 prove that it is automated and extremely reliable.

The next generation will show that DORIS is really very easy to use (switch on and let it do). The number of receiver control commands has been reduced, and many on-board features have been automated. DIODE Navigator provides now a wider set of products, which may be used by the satellite AOCS, the payload equipment or the Control Center, opening the door to important simplifications in the whole customer system.

IDS gives now an excellent international framework, installing DORIS as an international system, with the participation of many IDS analysis centers all around the world.

And, for future evolutions, parallel work is still going on !…

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