ON-BOARD ORBIT COMPUTATION WITH DORIS-DIODE : FROM EXPERIMENT TO OPERATIONAL USE

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ABSTRACT *- DIODE (Doris Immediate On-board orbit DEtermination) is a series of on-board orbit determination software, which process one way up-link Doppler measurements performed by a DORIS receiver on a satellite. The DIODE software are now embedded within the DORIS receivers, and they provide orbit and time determination to the outside user as well as technical parameters to adjust the tracking loop within the instrument.*

The first issue of the DIODE family is flying on-board of the French Earth observation satellite SPOT4, which was launched on March 26th, 1998. Three years of excellent results have earned operational status to that experimental software. On SPOT4 the accuracy and reliability of the DORIS measurements made it possible to obtain a real-time orbit with an availability and reliability better than 99.5% (five days of non-nominal behavior over three years). The accuracy is of a few meters. This demonstrated reliability is an important step towards satellite autonomy, which is a key component of space formations and automated Earth observation satellites.

The second instance of the family will operate on-board of Jason-1, with more efficient and more accurate algorithms. A similar version will run on ENVISAT. For Jason-1, the expected accuracy is around 10 cm RMS on the radial component, and 1-meter RMS in 3D. This real-time orbit will be used on the ground to produce Operational Science Data Record which are generated and distributed within 3 hours to operational oceanography centers throughout the world.

In addition, with the new Failure Detection and Incident Recovery (FDIR) enhancements that were implemented in the software, the expected availability of the Jason-1 version is now very close to 100%.

The paper will review the SPOT4 results, will present the improvements introduced in the Jason-1 version, and will probably cover the very first flight results of both Jason-1 and ENVISAT. Plans for future improvements will also be presented.

KEYWORDS – DORIS, DIODE, on-board, real-time, orbit, demonstrated, availability, reliability, accuracy, autonomy.

1. INTRODUCTION

DIODE (Doris Immediate On-board orbit DEtermination) is a series of on-board orbit determination software integrated in the DORIS receivers. This project has been initiated by the CNES in 1991, after a conclusive feasability study from 1988 to 1990. Its mission was to add, inside the SPOT4 DORIS receiver, a new real-time orbit determination function, then to flight-demonstrate the reliability of the concept, and to analyse the different benefits that satellite systems could take advantage of, with such a « navigator » operating on-board.

After the very first conception, which has been done together with SPOT4 (our first user), DIODE has then been completed with new functionalities, to meet the requirements of ENVISAT1, Jason-1, SPOT5, Pléiades, CRYOSAT. Moreover, during its mission analysis phase, Skybridge has been a special challenge for DIODE, suggesting several deep evolutions in the system. Ref. [3] develops a discussion about the needs of different satellite missions, and the DORIS/DIODE answer.

Several issues have occured, with different accuracies, different functionalities and different complexities : they will be presented here as different members of a family. The most recently validated one is the « second generation miniaturised » issue (Jason-1, SPOT5), and this presentation will be based upon it : in order to avoid repetitions, only this version will be analysed in details. The other issues will be presented by their differences with respect to this reference.

After a brief summary of DORIS main characteristics and performances, we present here the common shapes of the DIODE family, then the particularities of the present and next-to-come members.

2. THE DORIS SYSTEM – OVERVIEW

2.1.Main features

The DORIS (Doppler Orbitography and Radiopositionning Integrated from Space) system [Réf. 3] has been developped jointly by CNES, IGN (Institut Géographique National), and GRGS (Groupe de Recherche en Géodésie Spatiale). It is based upon in a 53 beacons network, developped by CEIS, SOREP and SMP companies.

Fig.1 : the DORIS permanent beacon network

The beacons permanently emit in an omnidirectionnal way on two frequencies, 2036.25 et 401.25 MHz. Two particular beacons, one in TOULOUSE, the other one in KOUROU, are slaved to atomic clocks, themselves tied with the International Atomic Time (TAI) : called « Master Beacons », they constitute the time and frequency reference of the system.

DORIS on-board payload contains a bifrequency receiver, capable of very precise locking on the beacons' ascending signals. The on-board reference for time and frequency is an ultra-stable oscillator (USO). Every ten seconds, the receiver precisely measures the frequency (or the phase) of each channel signal, and the date of reception of the synchronisation signal transmitted by the beacons.

With this worlwide network, the present coverage is excellent, and measurements are made more than 65% of the time on SPOT2 and SPOT4, at an altitude of 800 km. For TOPEX higher orbit (1330 km), visibility circles are larger, and measurements are done on 80% of the orbit. Computation of these measurements, at the Doris Orbitographic Service (D.O.S.), allows elaboration of a few centimeters orbit, which is used by oceanographers to process altimetric data.

2.2.Enhancements of the system

New features have recently been added in the DORIS system : the "broadcast" uploads will be elaborated daily by the Control Center, and forwarded by the Master Beacons. They will display informations about position, time and frequency of the DORIS beacons. This will allow several on-board receivers on different satellites to acquire precise and fresh information about the current status of the network, without any human intervention : the autonomy of the receivers will be dramatically improved this way.

Moreover, beginning with Jason-1 and SPOT5, the on-board receivers will be able to perform self-synchronization and self-initialization : the new 3.0 beacons will send the value of TAI time in their messages, and the on-board receivers will use this information to synchronize their clock. Thus, the receivers will then be able to acquire measurements, ask DIODE to process them, and perform self-programming. No human intervention will be necessary to start the operation.

The recent International Doris Service (I.D.S.) is in charge of the development and the promotion of the DORIS system : to foster the DORIS technique as a joint service to support geodetic, geophysical, and other research and operational activities, to encourage the integration of DORIS instruments on-board of future Earth orbiting satellites, and the installation of new ground DORIS beacons 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, …).

Conception of the DORIS System Simulator (DSS), a new DORIS Project facility for mission studies, has also begun.

3. DIODE : GENERAL FEATURES

The heart of the routine part of DIODE is based on a Kalman filter. It uses a numerical integration with a Runge-Kutta algorithm to propagate the state vector every ten seconds and it processes the measurements provided by the DORIS receiver to correct its state vector.

DIODE is written in Ada language, and its conception uses HOOD (Hierarchical Object Oriented Design) method. The orbitographic software has been designed by CNES, with a technical support by the COFRAMI company.

All the DORIS measurements performed on orbiting satellites are stored on-board and transmitted each day to the DORIS ground segment. We have used this large amount of data, several years of continuous Doppler measurements on SPOT2, SPOT3, TOPEX and SPOT4, to improve each version of DIODE.

Different generations of the DORIS receiver have been developped. In parallel, different generations of DIODE have been implemented. The following graph sums up this evolution, and the different members of DIODE series.

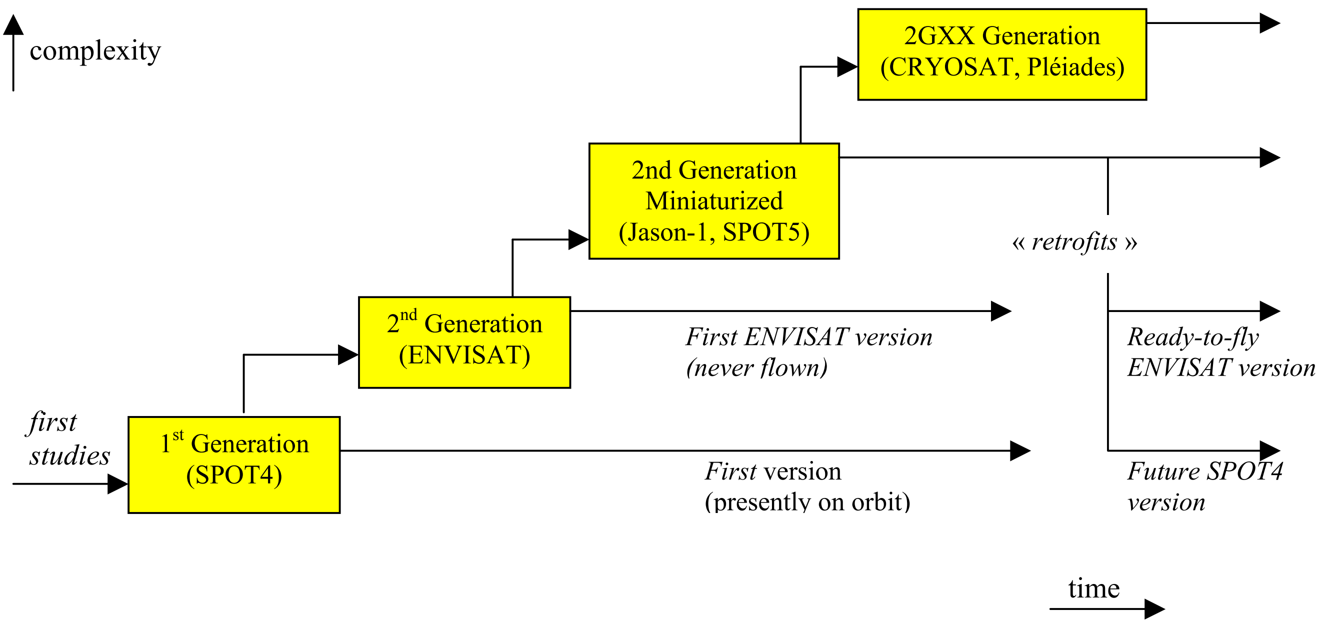

Fig.2 : DORIS and DIODE generations

From the first generation (presently operating on-board of SPOT4), has been derived the initial 2nd generation version, devoted to ENVISAT, then the 2nd generation miniaturized (to which this paper refers). From that version, two « retrofits » have been done : one for ENVISAT, which has been installed on-board of the satelite. The other « retrofit » will be for SPOT4, and it is not completed yet.

4. DIODE FIRST GENERATION

4.1.A probatory experiment, but with already used results …

The first probatory issue of DIODE (first generation) has been elaborated for SPOT4. The main purpose of the SPOT4 system, was to associate, on-board and in real time, DIODE positions and velocities to the Earth images, in order to allow immediate and precise rectification by the different ground stations throughout the world : for this purpose, the requested accuracy was 100 meters RMS and 200 meters MAX, on each component of the position.

For the previous SPOTs, image rectification was performed using extrapolated ephemeris, necessarily less precise, and periodically uploaded on-board of the satellite. Thus, DIODE allows improvement of the service, reduction of the delays and lightens the Control Center upload burden.

Two other payloads on-board of SPOT4 have asked for DIODE positions and velocities : POAM, a Naval Research Laboratory instrument, to point its optical terminal, and Végétation for image processing.

The size of this DIODE issue is about 2500 lines (44 Kbytes). The program is operating on a separate MIL STD 1750A-type –tiny- processor, whereas the receiver management software is written in assembly code and operates on a 8086 processor. This version has been validated in 1995.

4.2.Orbitography, conception and modelling

Of course, for this first prototype, conception and modelling are simpler than for Jason-1 issue, which is described in chapter 6. Moreover, the DORIS receiver itself is a first generation receiver, with only one U.T. (no possibility of simultaneously tracking of two beacons).

Overall design	Two separated Kalman filters : one for the orbit (UD formulation), one for the clock.

State vector of the « position » filter	
Position/velocity of the satellite	Cartesian parameters.
Earth pole coordinates	Not adjusted.
Hill acceleration	Not adjusted.
Thrust accelerations	Not adjusted.
Drag coefficient	Not adjusted.
Earth radiation	Not adjusted.

pressure coefficient	
Beacon parameters	Two biases are adjusted : one for the frequency shift of the beacons' USO, the other is a tropospheric bias, which allows the use of a very simplified troposphere model. These adjusted parameters are linked to each beacon pass.
Clock drift	Not adjusted. The on-board frequency is estimated after Doppler processing over the Master-Beacons passes.

State vector of the « datation » filter	Clock bias (difference between on-board time and TAI).

Accelerations models	
Earth potentiel	15x15 dedicated Earth Gravity Field, elaborated by GRGS.
Moon&Sun attractions	Unmodelled.
Hill empirical acceleration	Unmodelled.
Thrust accelerations	For large orbital manoeuvers, the satellite Control Center has to upload the main characteristics of the thrust (date, duration and predicted acceleration vector). These are taken into account in the force model, and DIODE is able to follow the manoeuver without any divergence problem. Residual accelerations, for instance in case of a slightly unefficient thrust, are absorbed by the filter.
Sun radiation pressure	Unmodelled.

Numerical integration	4^{th} order Runge-Kutta (Gill formulation).

Measurement model	
DORIS Doppler measurements	DORIS Doppler measurements are modelled as beacon-satellite range differences between two DORIS fixed events. They are processed by the "position" filter, and DIODE uses each pass over the Master-Beacons to adjust the frequency bias of the receiver's oscillator.
DORIS synchronization	DORIS synchronisation measurements are used by the "datation" filter to update the difference between on-board time and TAI. This difference is

measurements	then propagated with the adjusted USO frequency bias.
Ionospheric correction	The ionospheric errors are eliminated thanks to the dual-frequency combination. The large difference between the two frequency values (2036.25 and 401.25 MHz) is an advantage because the receiver frequency noise is not increased by this combination.
Tropospheric correction	Very simple model using an adjusted bias over each beacon pass.
Attitude model	None (geocentric attitude is assumed).
Beacon coordinates (re-loadable)	ITRF-97 (updated 2001) without velocities.

Initialisation	Only by upload of initial positions and velocities : at the time this version was implemented, studies for a self-initialisation subfunction had not been initiated yet.

Quality rating	Very simple (only the covariance part), on the positions only.

Products	
Positions and velocities	ITRF-97 (updated 2001).
Datation	Of course, datation of the measurements is performed as an internal subfunction of the software, but it is not provided to external users. Time-tagging of platform Tops had not been implemented yet.
Receiver programming	Not implemented yet.
Availability of the products	Every ten seconds, without possibility of interpolation.

4.3.Real in-flight results

DIODE has been switched on, on-board of SPOT4, on March 26^{th,}, 1998, and totalizes today three years and a half of flight. Detailed analysis of the on-orbit results may be examined in References [1] et [3].

First year estimations have been gathered and compared with the ZOOM precise orbit ephemeris (P.O.E.), which have an accuracy of a few centimeters on the radial component. The differences are displayed in the orbital frame, in meters.

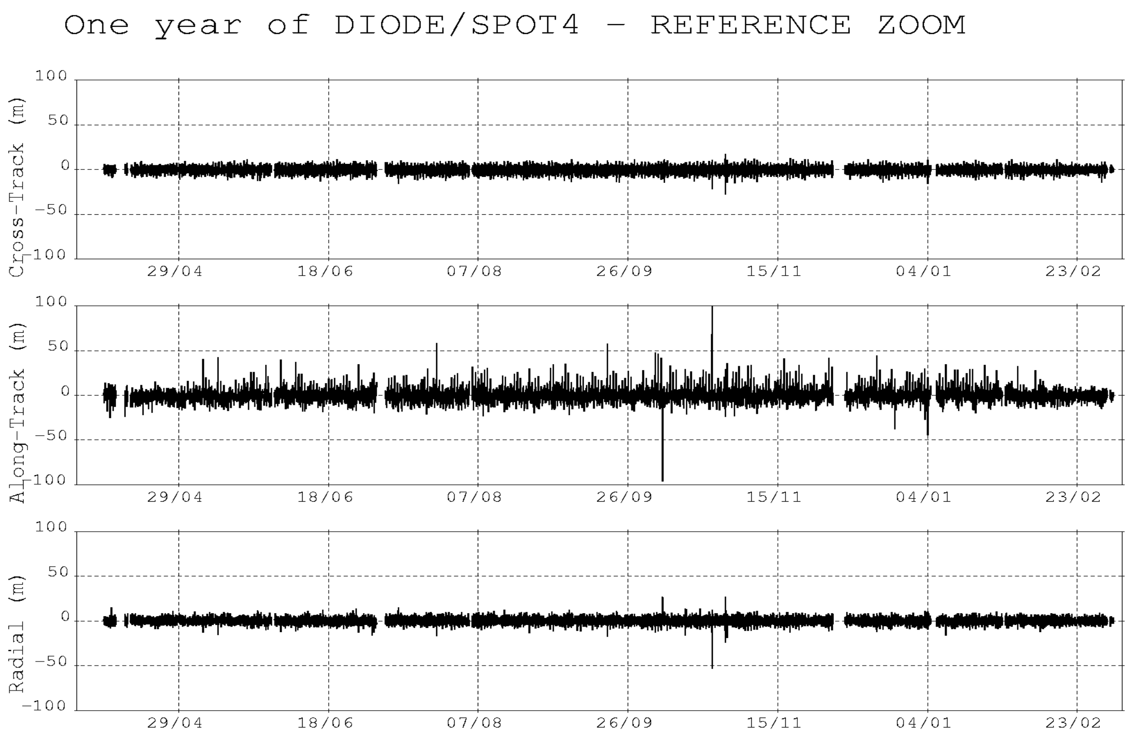

Fig.3 : DIODE/SPOT4 flight results

Periods of large manœuvres, … have been removed from this graph, in order to analyse only the routine accuracy. The largest peaks have all been analysed (see Ref [1]), and are mainly due to beacon failures at this time, provoking longer than usual extrapolations : at the end of the period, a few beacons have been installed to fix the holes, and those peaks disappear.

The main conclusions are summarized hereafter :

Accuracy : SPOT4 specifications were « 100 m RMS and 200 m MAX on each component of the position ». The observed accuracy is around 5 meters RMS in 3D, from the beginning until now.

Autonomy : a few uploads per year have been necessary to update the on-board data of this version of DIODE (coordinates of new beacons in the network, amplitude of manœuvers, TAI-UTC leap). For instance, between March 1998 and June 1999, only 15 data uploads have been sent. This is already a pretty good autonomy for such a probatory experiment, but it will be improved once again in the next issues, especially with the availability of broadcasts.

Availability : During the first year, the software has properly worked 363 days over 365, what represents an availability of 99,5 %. This ratio has roughly been confirmed during second and third years. Five restarts only have been necessary since the first activation of DIODE, three of them being due to a non-DIODE cause (DORIS receiver re-initialization for instance). The other two incidents have led to system evolutions, and software improvements integrated in the following versions.

Robustness : DIODE has handled an 8 kilometers semi-major axis raising manœuver, with errors less than 50 meters.

Utility : Since March 1998, almost every SPOT4 image has been rectified with DIODE results. Since June 1999, Végétation, a SPOT4 payload instrument, also uses DIODE. POAM3 (a Naval Research Laboratory instrument) uses DIODE positions several times a day to point its optical terminal.

4.4. Conclusions

DIODE first generation has been the first on-board orbit determination system, to provide long time results. Its main goal is achieved : on-board orbit determination is today flight-demonstrated.

The DIODE/SPOT4 on-board probatory experiment keeps on operating and giving results, now as a full operationnal function. The statistics of availability and robustness will give valuable indications for the conception of the next missions. Two conclusions should be pointed out :

- today, an on-board determination function has proved to be reliable enough, to be used in a reinforced way by the system (especially by the AOCS). Ref [3] gives the detail of different benefits of such a function.
- exceptionnally unavailable results may occur (let's say, about once a year). The way to handle this depends on the criticity of the satellite mission : scientific or commercial programs, for instance, would not have the same answers.

For DIODE himself, three years and a half of operationnal use, have suggested different enhancements, that have already been integrated in the following versions :

- Accuracy has been increased by the use of more compact algorithms, and addition of new models,
- Autonomy, by reduction of the data uploads (broadcasts, automatic reinitialization, …),
- Availability by introduction of a few Failure Detection and Incident Recovery algorithms.

Finally, all the improvements made on DIODE between the first SPOT4 and the Jason-1 issues, have lead to the idea of a new DIODE/SPOT4 version. This one is presently under integration : the microcomputer on-board of DORIS/SPOT4 is only a small MAS 281 (MIL-1750A type), and the amount of memory is limited. If it is feasible (and not too expencive), this new version could be uploaded on-board of SPOT4, providing an enhanced accuracy even on this satellite. Since March 2001, we have already been activatig this version on-ground, with SPOT2 measurements. The mean observed accuracy is 1.3 meters RMS (3D), and 60 centimeters RMS on the radial component.

5. DIODE SECOND GENERATION

During the early studies for DORIS second generation receivers, the interest for DIODE was already strong enough, to embed it as a standard function of the new receivers. This point, and other requirements, has lead to a new design of the receivers. The software has been linked with the receiver management software (realized by Thales Airborne Systems), both parts being this time developped with Ada and Hood techniques. The unique microprocessor for the second generation is a Gec Plessey 31750A. And last but not least, the DORIS receivers are from now on capable of simultaneous tracking of two beacons.

As two years had passed since the first generation's validation, many improvements had been done and integrated in this issue, in particular the products have been completed : synchronization results would be from now on provided to the platform, the DORIS receiver programming mode and DIODE self-initialization capability have been integrated. DIODE concept has progressed in its integration in the satellites.

The first ENVISAT1 version has been qualified mid-97. Two years later, several other improvements had been done to produce the Jason-1 issue (Hill accelerations, thrust adjustment, drag coefficient, …). Finally, a « retrofit » for ENVISAT of this last version has been done and qualified mid-2000.

Unfortunately, real ENVISAT1 results are not available yet. Anyway, the accuracy on ENVISAT1 should roughly be the same as for the SPOT4 « retrofit », slightly better because measurements are more frequent and more accurate : around 1.0 meter RMS (3D), and 50 centimeters RMS on the radial component.

6. DIODE SECOND GENERATION MINIATURIZED

6.1.Main features

DIODE last validated version will be sent on-board of Jason-1, and will also fly with SPOT5. The DORIS receiver have changed their technique : phase measurements will be performed from now on, instead of Doppler measurements. The DORIS receiver himself is also able to perform self-initialisation, broadcasts upload will be used for demonstration
For DIODE, the very last enhancements are integrated, and accuracy has been once again improved (phase measurements, beacon velocities, …).

The real-time orbit will be used on ground to produce Operational Science Data Record which will be generated and distributed within 3 hours to operational oceanography centers throughout the world.

This version has reached ground qualification in mid-2000.

6.2.Orbitography, conception and modelling

Hereafter are described the algorithms of DIODE/Jason-1.

Overall design	Unchanged.

State vector of the « position » filter	
Position/velocity of the satellite	Cartesian parameters.
Earth pole coordinates	Adjusted.
Hill acceleration	Adjusted (orbit period, normal component).
Thrust accelerations	Adjusted (in the local frame)
Drag coefficient	Adjusted (for lower orbits – this won't be used on Jason-1).
Earth radiation pressure coefficient	Not adjusted.
Beacon parameters	Unchanged.
Clock drift	Not adjusted.

State vector of the « datation » filter	Unchanged.

Accelerations models	

Earth potentiel	May be tuned, up to 40x40. The model is JGM3, and a significant effort has been made to optimize the calculation of the Earth attraction acceleration, in order to spare on-board computation time.
Moon&Sun attractions	Yes (with a simplified ephemeris model).
Hill empirical acceleration	Yes (orbit period).
Thrust accelerations	In this version, thrust errors can be adjusted during manoeuvers. This gives a position precision comparable with the routine precision even during manoeuvers, to make the filter more robust to unexpected thrust errors. This will also allow better follow up of long thrusts, which may occur with electrical propulsion.
Sun radiation pressure	Yes (with a box and wings model).

Numerical integration	Unchanged.

Measurement model	
DORIS phase difference measurements	DORIS phase difference measurements are modelled as beacon-satellite range differences between two DORIS fixed events.
DORIS synchronization measurements	Unchanged.
Ionospheric correction	Unchanged.
Tropospheric correction	Unchanged.
Attitude model	Yes (SPOTs Geocentric, Jason-1 Yaw-steering mode).
Beacon coordinates (re-loadable)	ITRF-97 (updated 2001) with beacon velocities.

Initialisation	The self-initialisation algorithm developped for DIODE needs four beacon passes to estimate an initial state-vector by a least-square method. Two different filters, the first very one being rough, and the second one having a more precise modelling. Then, an initial state vector is estimated and forwarded to the routine filter for further convergence. This algorithm is dedicated to low altitudes and near circular orbits. Usual initialisation by uploading an initial state vector is still possible.

Quality rating	The elaboration of an orbit quality rating has been improved. This calculation now takes into account the covariance matrix of the filter, the correction vector at each step and other measurement indicators. This quality rating gives an order of magnitude of the estimated position error to the users of the products. Another advantage is to allow detection of a divergence of the filter due to either measurement errors such as beacon failures, or model errors such as an unexpected orbital manoeuver. Thus, if the ground has authorised it, DIODE is able to autonomously decide to run a self-initialization. A similar quality rating is elaborated for datation products.

Products	
Positions and velocities	ITRF-97 (updated 2001).
Datation	Platform tops are dated in TAI time. A quality assessment has been added to this product.
Receiver programming	In routine mode, DIODE will use its orbit determination to inform the DORIS receiver at each ten second step, about the next visible beacon and its expected Doppler shift. An optimal choice is made in case of multiple visibilities. So DIODE will program in real-time the DORIS receiver, which can therefore narrow its bandwidth around the expected frequency.
Availability of the products	Every ten seconds, with a possibility of interpolation of the positions/velocities around current time.

6.3.Expected in-flight results

Because of a delay in Jason-1 launch, we have not the opportunity to present real on-board results. What follow here are the expected performances, obtained on-ground with real TOPEX measurements : this issue has been operated for almost three years this way.

During this ground experiment, only one incident occured, caused by abnormal re-initialization of a beacon. This has lead our « ground navigator » to re-initialize, what he did himself alone : two hours later, the routine mode was already back.

With the complete algorithms described above, the accuracy has been highly improved. Hereafter are the results obtained on one day of TOPEX real measurements : DIODE estimations are compared with the ZOOM precise orbit ephemeris (P.O.E.), which have an accuracy of 3 centimeters on the radial component. Here again, the differences are shown in the orbital frame, in meters.

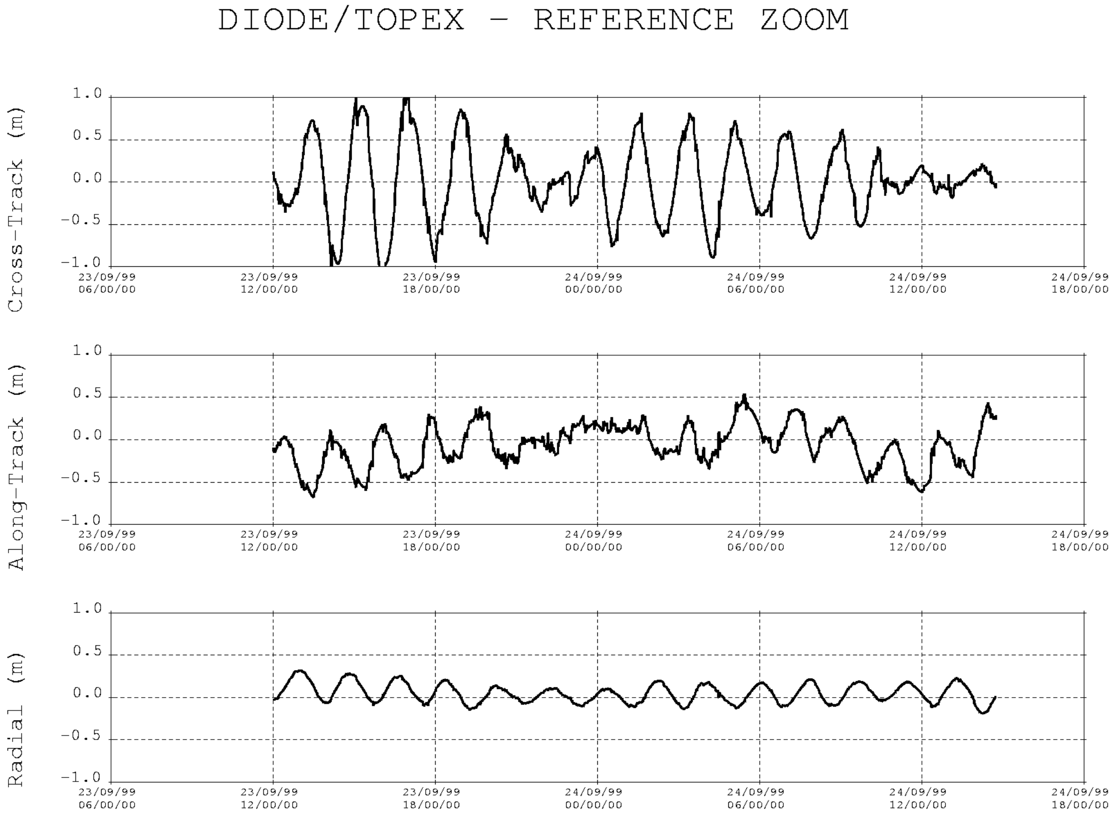

Fig.4 : DIODE/Jason-1 positions accuracy

The cross-track component is the most difficult to restitute, with those range and range-rate measurements.

Radial and along-track errors are anti-correlated (because of Kepler's law). The oscillation is basically due to a numerical degradation of the calculations on the DORIS GEC Plessey 31750A, with the TLD compiler used there. On the workstation used for the software development, mean radial RMS is around 5 centimeters. After long investigations, we have failed in our attempts to identify and correct this effect. The next versions will use another processor.

The statistics of this comparison are :

	MAXIMUM	MEAN	STANDARD DEVIATION
Radial (m)	0.317678	0.047948	0.111382
Tangentiel (m)	0.681144	-0.064112	0.250718
Normal (m)	1.275026	0.005417	0.448138
Distance (m)	1.282861	0.467221	0.253449
Vit rdle (m/s)	0.000511	0.000064	0.000205
Vit tgtle (m/s)	0.000215	0.000006	0.000089
Vit nrmle (m/s)	0.001185	0.000005	0.000427
Norme vit (m/s)	0.001218	0.000428	0.000232

Thus, on Jason-1, we expect a radial RMS around 14 centimeters. The accuracy specified by altimetric users is 30 cm RMS on the radial component, and 1 meter RMS in 3-D.

Time determination is also elaborated, and provided to the platform. Hereafter are the results of a comparison between DIODE and ZOOM, of the correspondance between on-board time and ground TAI time.

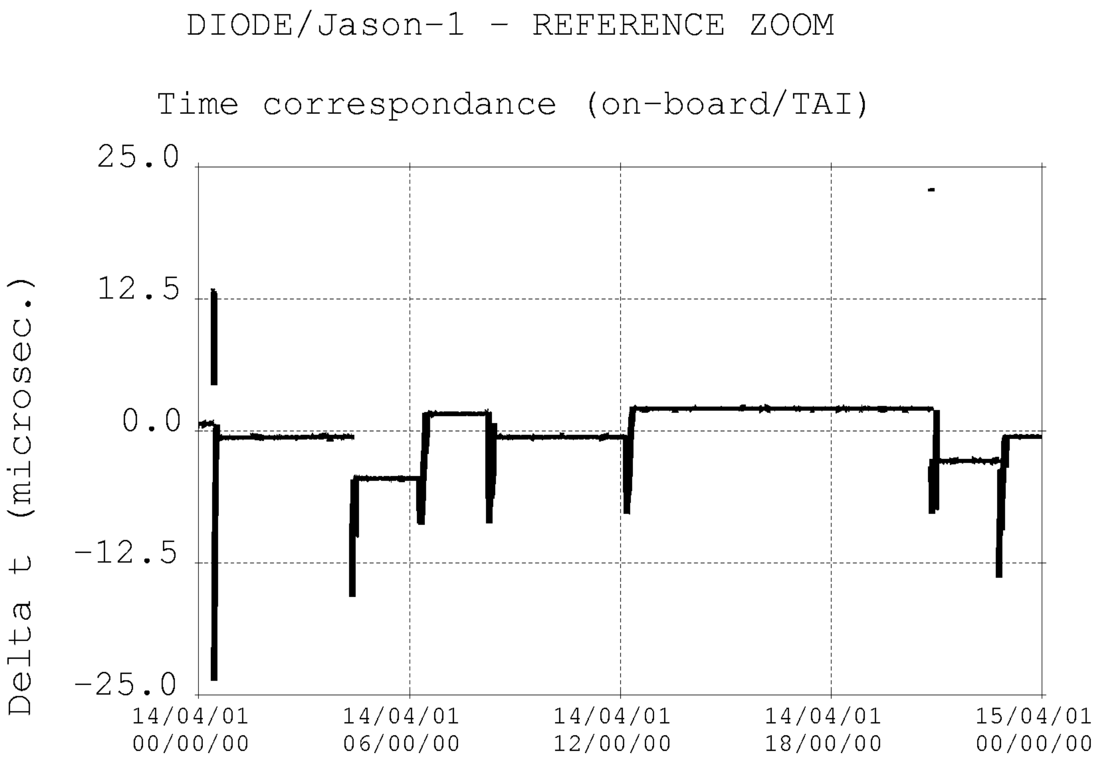

Fig.5 : DIODE/Jason-1 time determination accuracy

On this graph, seven passes over the Master-Beacons have lead to seven periods of synchronisation adjustment. The rest of the time, a prediction is elaborated, using the on-board estimation of the USO frequency.

Agreement between DIODE and ZOOM is of a few microseconds :

	MAXIMUM	MEAN	R.M.S.
Deltat (microsec)	23.66300	0.999830	2.476932

The DORIS receiver may be used as an on-board clock, providing a few microseconds time determination to the spacecraft.

6.4. Conclusions

After analysis of DIODE/SPOT4 events over three years and a half, several improvements have been integrated in DIODE. All the problems encountered in the first generation have been fixed : on Jason-1, the expected availability should be very close to 100 %.

7. FUTURE IMPROVEMENTS : THE 2GXX GENERATION

7.1.Orbitographic conception

This next-to-come version is currently under development. CRYOSAT should be the first satellite to fly with this issue on-board. At this time, the main improvement is the selection of a Sparc ERC 32 microcomputer : our Jason-1 numerical degradation should disappear with this 64 bits processor, very close to the software development workstation processor.

A very preliminary version has been completed recently, and is undergoing complete validation : first on the workstation, to verify its orbitographic performances; and then on the target computer, to check its on-board capabilities.

We have integrated a new Doppler quality rating, in order to improve our efficiency in adjusting the receiver tracking loop.

A new Failure Detection and Incident Recovery strategy has been implemented, allowing the « navigator » to restart himself alone, even in case of divergence or fatal error. Autonomy should be significantly better this way.

Integration of a new dedicated version of Grim5 60x60, elaborated by the G.R.G.S., is under progress.

7.2.Results on real TOPEX measurements

As we have always used to do, this preliminary version has been put in daily operation, on-ground, fed by TOPEX measurements. Hereafter are displayed the results of a three day comparison with the Precise Orbit Ephemeris :

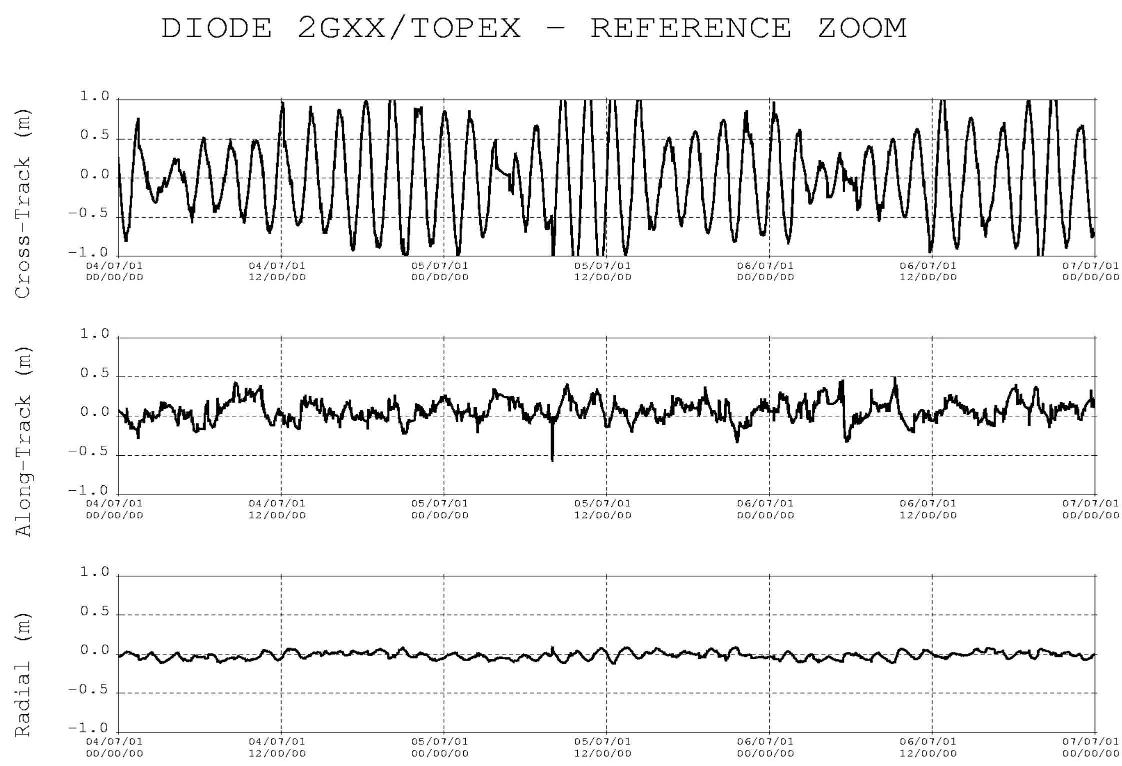

Fig.6 : DIODE/CRYOSAT position accuracy

Strong oscillations on the cross-track component should be reduced by a specific tuning : this has not been done yet.

The results presented here have been obtained on the workstation used for the software development, and not on the on-board processor. Anyway, preliminary evaluations seem to indicate that numerical degradation should not be present on the ERC32. Complete validation will occur in the next months.

The statistics of this comparison are :

	MAXIMUM	MEAN	STANDARD DEVIATION
Radial (m)	0.132102	-0.018097	0.044645
Tangentiel (m)	0.580465	0.067075	0.131132
Normal (m)	1.372985	-0.005726	0.547599
Distance (m)	1.400495	0.495331	0.280286
Vit rdle (m/s)	0.000493	-0.000061	0.000113
Vit tgtle (m/s)	0.000130	-0.000013	0.000043
Vit nrmle (m/s)	0.001293	-0.000001	0.000507
Norme vit (m/s)	0.001296	0.000455	0.000261

Notice the 4.8 cms RMS on the radial component, and the maximum value better than 14 cms (during three days). A 1.8 cms mean value can be observed, and we investigate to find the reason for this bias.

7.3. Further improvements

« Melting » of the two Kalman filters would allow to take advantage of the common parameters in the two measurement types. This point is especially interesting for MEO missions. A specific study has been lead on this topic in 2000, and experiments are still going on.

Real-time attitude information would be very useful for DIODE, in order to precisely predict the position of the center of phase of the DORIS antenna : studies have begun to acquire these data from the AOCS by a standardized interface.

The current state of DIODE algorithms reflects the specificity of our customer missions. For instance, until now, DORIS has only been used on circular low Earth orbits. Thus, several algorithm improvements have not been studied yet :

- self-initialisation algorithm for excentric orbits (the present algorithm is limited to near-circular orbits),
- adjustment of a solar radiation pressure coefficient, very important on high orbits,
- improved model for thrusts, taking into account the mass reduction (for long manœuvers),
- …

Of course, all those enhancements may be evaluated in the next years. Each new mission analysis is the opportunity to elaborate new products and new functionnalities.

8. CONCLUSION

From its probatory status on-board of SPOT2, the DORIS system has evolved to become a fully operationnal multi-mission system. Its results contribute to different geodetic and scientific applications with a significant accuracy, that should increase once again in the next years.

Jason-1, ENVISAT and SPOT5 flights will validate the current status of the system, and also probably suggest new ideas and new features for the next generation (CRYOSAT, Jason-2, Pléiades).

For DIODE, on-board orbit determination is today a reality and has been in-flight demonstrated : this concept enters now an operationnal phase, and its main ideas and principles are validated. Many satellite conceptors now integrate a « navigation » function in new platforms designs.
As an exemple, during its mission analysis phase, Skybridge has analysed DORIS/DIODE, and concluded that this system was compliant with the orbit/datation needs of the constellation (even if Skybridge has not finally adopted DORIS). At this time, several evolutions had been made to meet their requirements, and now they are integrated.
On Galileo, a similar on-board solution for orbit&time determination has been studied by the CNES, leading to the proposition of a new architecture of the system (see Ref [2]). For different reasons, this is not the baseline at the moment.

From now on, constellations, automated Earth observation systems, and satellite designers in general, should be confident that on-board orbit computation has become an operationnal facility, with a pretty good accuracy and a convincing reliability. CRYOSAT and Pléiades will be our next users. We are sure that, for those flights, DORIS and DIODE will still be in progress.

9. REFERENCES

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