DORIS-DIODE: FROM SPOT4 TO JASON 1

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ABSTRACT

A real-time orbit determination process is running permanently aboard the DORIS/SPOT4 receiver for the first time. This "navigator", called DIODE (Détermination Immédiate d'Orbite par DORIS Embarqué, Immediate Orbit Determination by Embarked DORIS), has been producing, an estimate of SPOT4's position with a 3D accuracy of a few metres, 99.6% availability, and 99.7% reliability since March 1998.
Its results are already used daily by SPOT IMAGE and VEGETATION (on the ground, for image rectification), and POAM3 (on board, for pointing an optical terminal).
On Jason 1, as well as on SPOT5 and ENVISAT, DIODE and the program managing the DORIS receiver have been combined in one program, and the direct on-board use of DIODE's « knowledge » has been greatly increased, so that new functions can be implemented (self-programming, time-tagging of platform events, self-initialisation, etc.). At the same time, DIODE's algorithms have been optimised and are now more accurate, bringing altitude determination to an accuracy of the order of 15 centimetres. Finally, with a receiver that is more resistant to radiation in the space environment, DIODE should be available almost 100% of the time
This would allow DIODE's results to be used for immediate processing of altimetry measurements as soon as they reach the ground.

1 - INTRODUCTION

Knowledge of the orbit on board and in real-time enables DIODE to provide products to the Flight software and onboard instruments, as well as ground control and data processing segments . The entire satellite system thus benefits from this new approach, by improving processing or reducing delivery time.
In seven years of discussions with future and potential users of DIODE products, the same question was asked several times: " What am I going to do with estimations of position and velocity on my satellite? ". For each new platform, new ways of using this information have been found.

Different functions providing different products are described below. Some had already been achieved during the SPOT4 mission. Others were developed later, and are waiting to fly (Jason 1, SPOT5, ENVISAT, etc.). One application (manoeuvre calibrations) has not yet been implemented . We are sure that new applications of Onboard Orbit Calculation will be found in the next few years.

2 - PRINCIPLES COMMON TO ALL VERSIONS

The DIODE (*Détermination Immédiate d'Orbite par Doris Embarqué*) project was created by the *Centre National d'Etudes Spatiales* (CNES) in 1991, after a feasibility study conducted from 1988 to 1990.

It involves exploiting onboard measurements to perform an immediate calculation of the orbit "at the source". An Onboard Orbit Calculation program called DIODE was put on the DORIS/SPOT4 receiver as an experiment.
The orbit determination program was developed at CNES with technical support from COFRAMI. All versions of DIODE are written in the Ada language, and their design is based on the HOOD (Hierarchical Object Oriented Design) method.
The standard DIODE filter has three main parts:

1 - An extrapolator, based on numerical integration (Runge-Kutta algorithm, Gill formulation) and a force model applied to the satellite. This extrapolator propagates the state vector every ten seconds.

2 - A Kalman filter that processes measurements provided by the DORIS Receiver to correct this state vector. This vector contains the position and velocity parameters of the satellite and some other pass-dependant parameters. These parameters are:

- ⇨ a frequency bias due to frequency offsets of the beacons' USO
- ⇨ the vertical component of the troposphere delay.

3 – A model of DORIS measurements, which are represented by differences in the station-satellite range between two events. Combining measurements at two frequencies eliminates ionosphere errors. The large difference between the two frequency values (2036.25 and 401.25 MHz) is an advantage because the noise of the receiver is hardly amplified by this combination.

Finally, DIODE uses phase and synchronisation measurements from each pass over the Master Beacons (Toulouse and Kourou) to adjust the frequency bias of the DORIS onboard oscillator and to estimate the difference between onboard time and TAI This difference is then propagated linearly.

3 - DIODE/SPOT4: FUNCTIONS ALREADY PROVED IN FLIGHT

The first version of DIODE has been flying on SPOT4 since 26 March 1998. It is the first onboard orbit determination tool that has produced lasting results in flight, and is still in operation today.

An electronic board made by Thomson-CSF DETEXIS has been added to the DORIS Receiver. The DIODE program runs on a dedicated Marconi MAS 281 processor, type MIL STD 1750A. Its size is about 2500 lines of code, and it uses about 44 Kbytes of memory space.

For this first version, the force model is limited to the Earth's gravitational potential, developed to an order of 15x15. The main characteristics are summarised in the following table:

Version	SPOT4
Date of qualification	mid-1996
Earth gravity field	15x15
Sun and Moon potential	No
Solar radiation pressure	No
Polar motion adjustment	No
1/rev corrections	No
Thrust adjustment	No
Self-programming of the DORIS receiver	No
Self-initialisation	no
Quality index	Very simple, only on positions

3.1. - FUNCTIONING OF THE NAVIGATOR ITSELF

Here are details of DIODE's performance in the characteristic areas of an Onboard Orbit Calculation program: autonomy, availability/reliability, and accuracy.

3.1.1. - autonomy

The first three months of flight of SPOT4 were dedicated to testing and validating the satellite and onboard equipment. DIODE began operating in a nominal environment in June 1998. From this date until March 1999, only FIFTEEN uploads were sent to DIODE, to take into account changes in the DORIS network (new stations), station keeping manoeuvres, and the additional second for TAI-UTC correspondence: DIODE has therefore proved to be quite autonomous.

=> Only a small number of parameters need to be sent to adjust and maintain the estimation process. Commanding DIODE is a very simple operation.

3.1.2. - availability/reliability

Since March 1998, if two DORIS upsets are excluded (the new generation processors are more resistant to radiation than those of DORIS/SPOT4), only two events have required a re-initialisation of DIODE:

- an event in July 1998, whose cause is not clear, but which could be an upset in the DIODE microprocessor, or an interrupt conflict in the onboard management software. This event put a sudden end to the supply of DIODE bulletins, which was then re-established by sending new initial conditions.
- the overly rapid re-initialisation of a beacon (KITAB) in January 2000 (beacon transmissions occurred before the USO was stabilised). This event induced a divergence in the Navigator, but did not interrupt the service: the Navigator continued to deliver positions that were off by several kilometres from the real orbit. In order to re-establish nominal functioning, it was necessary to send new initial conditions.
  This kind of incident had been identified before the flight as a possible cause of filter divergence. New instructions to beacon operators, plus improvements in 3.0 beacons and in DIODE itself (quality index improved, finer tuning, autonomous re-initialisation) should eliminate these kind of incidents .

Besides these two events, the Navigator has functioned continuously over long periods (up to twelve months) without any problems. In two years, DIODE has had only about 60 hours of unavailability, which leads to a current availability for DIODE of 99.6%. The accuracy specifications have only been exceeded for a few hours, during re-initialisation (delay before flying over a Master Beacon). The reliability is therefore also very close to 100% (99.7%).

=> After running for nearly two years, DIODE has an Average Length of Trouble Free Operation of about 9 months.

DIODE/SPOT4 was an experimental mission, designed to test the technological possibilities of an onboard Navigator. All the guaranties of absolute reliability were not taken into account, and it is not surprising that 100% availability was not obtained the first time. Nevertheless, these numbers constitute an excellent working basis, and following versions should have even better results.

3.1.3. - routine accuracy

For control purposes, the positions calculated by DIODE are memorised on board every 160 seconds, and transmitted about twice a day to the DORIS Control Centre and to DIODE's ground segment (CATODE).

The routine accuracy of DIODE has been evaluated by analysing positions transmitted from April 3, 1998 to March 26, 1999. These positions were compared to a very precise orbit, obtained on the ground by the ZOOM program. In order to observe routine behaviour, all the periods during which DIODE was not functioning nominally (orbit acquisition of SPOT4, orbital manoeuvres, Receiver test periods, etc.) were not included in the comparison.

The differences between the estimates from DIODE and the Reference are shown here in the Local Orbital Reference Frame, in metres:

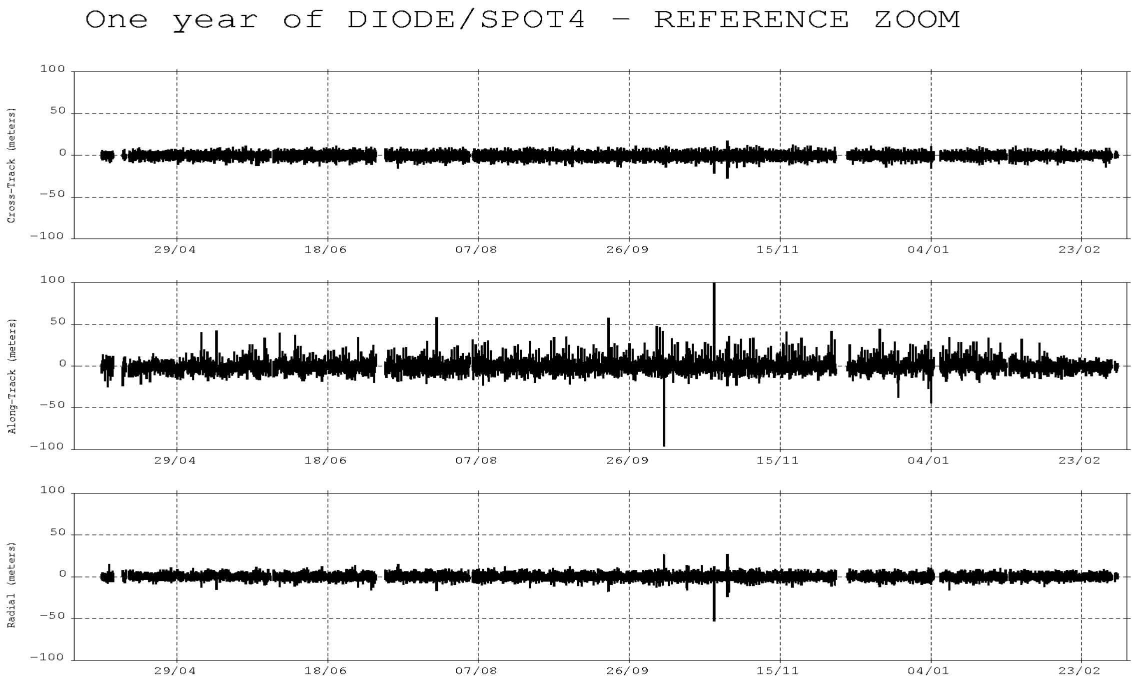

Fig. 1: one year of DIODE / SPOT4

The largest differences involve the tangential component, with peaks between 100 and 165 metres. This occurs when there is a long period without measurements (between 45 minutes and one hour), when the satellite is not in view of any ground beacon. In this case, the Kalman filter simply propagates the state vector and the error increases, in particular along track.

The lack of points on the plot is usually due to loss of ground data, with the exception of the first "gap" at the beginning of July, 1998, which was due to the first incident mentioned in 3.1.2. In the first part of the plot, the estimates become more accurate: two or three additional DORIS stations led to a spectacular reduction in extrapolation phases.

The comparison statistics are as follows:

	Minimum (m)	Maximum (m)	Average(m)	RMS (m)
Radial	-55.95	30.16	-0.12	2.73
Tangential	-110.93	165.21	0.07	4.45
Normal	-27.31	17.27	-0.15	3.04

The three-dimensional error is close to 6 metres.

=> Accuracy of a few metres has already been obtained onboard SPOT4.

3.1.4. - tracking manoeuvres

The behaviour of DIODE during orbital manoeuvre periods has also been examined carefully. The largest manoeuvre that it tracked was on March 31, 1998. It involved raising the semi-major axis by performing two thrusts half an orbit apart. The total amplitude was 8 kilometres (about 4 metres per second). DIODE had been given predicted values for the thrusts, and processed them correctly, with residual errors of about 28 metres on the semi-major axis and about 2. 10-4 degrees in the direction normal to the trajectory.

The differences with respect to the ZOOM Reference are represented in metres, in the Local Orbital Reference Frame (normal, tangential and radial directions).

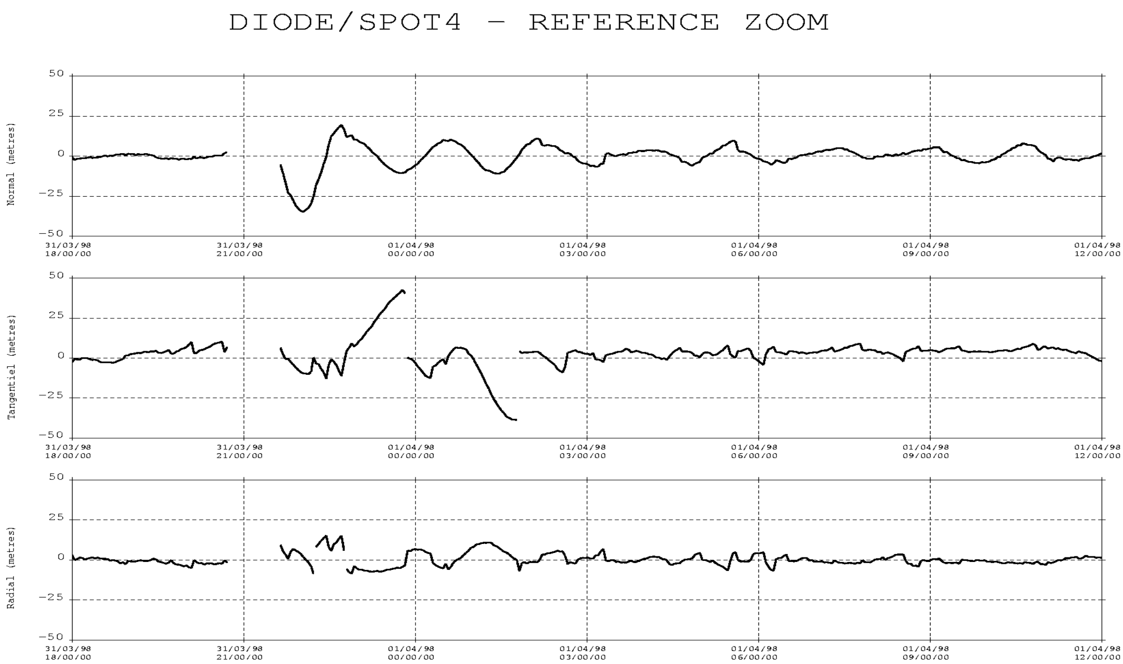

Fig. 2: the behaviour of DIODE during manoeuvre periods

On this plot, the estimation process was quite stable before the manoeuvre. Between the two thrusts, no reference orbit was available (but DIODE kept functioning correctly). After the manoeuvre, the estimations oscillated for three or four orbits, while the filter little by little absorbed the unmodelled part of the acceleration.

=> Even during large manoeuvres, the Navigator can estimate the position with a maximum error of about 50 metres.

3.2. - USE OF REAL TIME ORBIT DETERMINATION ON THE GROUND

Positions and velocities are routinely estimated onboard by DIODE and sent to the ground via satellite telemetry. This allows for immediate and accurate pre-processing of SPOT4 images by various stations in the SPOT IMAGE network.

Since March 1998, even though DIODE/SPOT4 is experimental, almost all the SPOT4 images have been rectified using the positions calculated by DIODE.

SPOT4 images need an accuracy of about 100 metres RMS on the determination of the satellite's position. DIODE has provided SPOT4 with estimates with an accuracy of a few metres for nearly two years.

Before DIODE, image positions were determined on the ground from ephemerides extrapolated ahead of time (thus clearly less accurate), and loaded onboard the satellite by the Control Centre. The use of DIODE thus reduces the volume of information transmitted from the ground to the satellite, while making the operation:

- quicker, since the information is available in real time,
- more efficient (the information is recent and more accurate than before),
- almost automatic, and therefore much more reliable to run.

VEGETATION has also used DIODE products to rectify its images, since June 1999.

=> The ground segment can benefit from the DORIS/DIODE results .

3.3. - USE OF THE REAL TIME ORBIT ON BOARD

The position/velocity bulletins of the satellite are also sent, via the Central Flight Software of the platform, to onboard users: POAM3 (a SPOT passenger operated by the Naval Research Laboratory, which measures the density of ozone and water vapour as a function of altitude) has used DIODE's estimates to point its optical terminal since March 1998.

=> The platform and passengers can benefit from the DORIS/DIODE results .

4 - FUNCTIONS DEMONSTRATED ON THE GROUND AND READY TO FLY ON ENVISAT, JASON-1 AND SPOT5

The next versions will fly on ENVISAT (second generation), Jason 1 and SPOT5 (miniaturised second generation): DIODE has been adopted and directly integrated into the processor of the DORIS receivers (type MIL STD 31750A) of the second generation and the miniaturised second-generation.

These versions take into account:

- the Earth's gravitational field to an order of 40x40 (a significant effort was made to optimise the calculation of the acceleration of the 40x40 field, in order to limit onboard calculation time),
- Sun and Moon attraction with a simplified ephemerides model,
- Solar radiation pressure, using a box and wing model for the spacecraft,
- Empirical, adjustable, one per revolution accelerations, to absorb residual errors.

Version	Jason 1
Qualification date	mid-1999
Earth's gravity field	40x40
Sun Moon potential	Yes
Solar Radiation Pressure	yes (box and wing)
Polar Motion Adjustment	Yes
1/rev corrections	Yes
Thrust Adjustment	Yes
Self-programming of the DORIS receiver	Yes
Self-initialisation	Yes
Quality Index	Improved, for positions and for times

The size of the program is about 7500 lines of code, which takes about 75 Kbytes of memory.

All the DORIS measurements performed on the various satellites in orbit are stored onboard and transmitted to the DORIS ground segment every day. We have exploited this large database (several years of measurements on SPOT2, SPOT3, TOPEX and now SPOT4) to improve each version of DIODE.

4.1. - FUNCTIONS OF THE NAVIGATOR ITSELF

4.1.1. - self-initialisation

Without orbital information, the DORIS receiver can perform measurements by simply scanning around an average frequency.

As the largest consumer of DORIS measurements, DIODE is thus capable of estimating the satellite's position by itself , without needing initial conditions sent by the ground ("lost in space" scenario). The only difficulty is the non-linear behaviour of the equations of motion, and this is resolved by using two separate filters which process the measurements from four passages.

These two filters are based on two different models: the first is crude, but converges rapidly, while the second is more accurate. The resulting orbit (generally with accuracy of a few metres) is then provided to the standard filter for the final convergence. Right now, the method implemented is limited to low altitude circular orbits.

This function has been intensively tested on the ground on measurements from TOPEX. The time needed to deliver a first estimate to the standard filter is always less than one orbit (1h40), and on average it is about half an orbit. In fact, this time is directly related to the time needed to acquire four successive passes.

=> The Control Centre no longer needs to send approximate initial conditions to start the adjustment process.

In addition, DIODE now can trigger a self-initialisation by itself, even before the ground is able to react to an anomaly (see paragraph 4.4).

4.1.2. - improved routine accuracy

DIODE/Jason 1 has been implemented on the ground for over a year, with the measurements from TOPEX. The statistics and the differences shown here were during TOPEX cycle No. 232:

The differences from the ZOOM Reference orbit are shown in metres, in the Local Orbital Reference Frame (normal, tangential and radial directions).

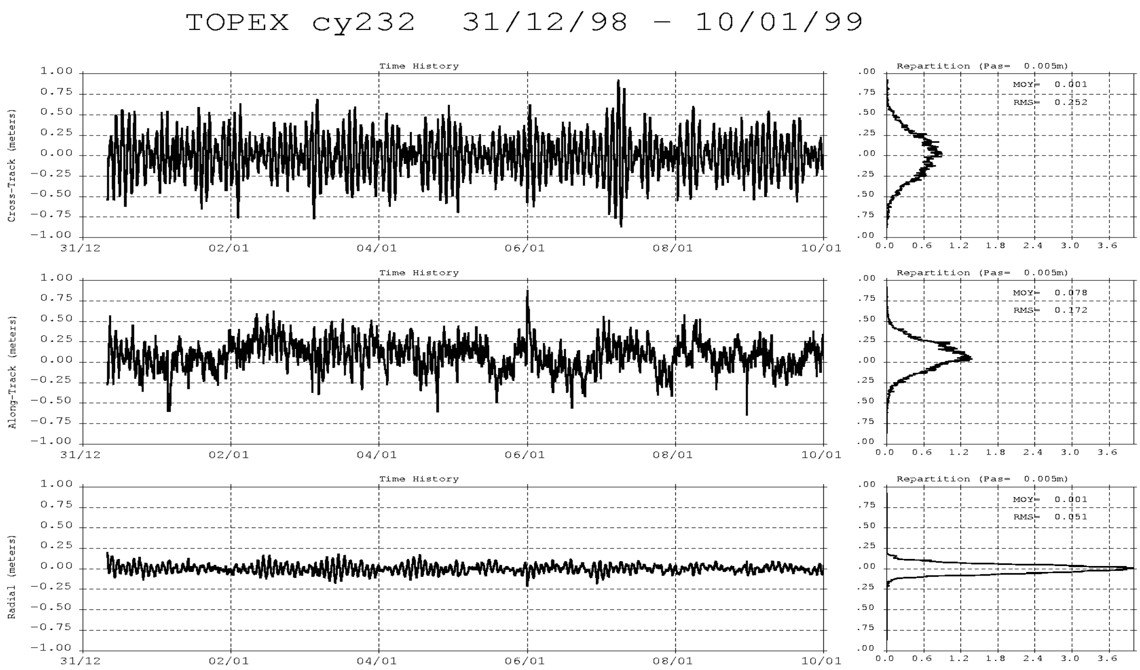

Fig.3: accuracy obtained on the ground with DIODE / Jason 1

The three-dimensional error is of the order of 30 centimetres RMS. Note in particular the statistics on the radial component: about 5 centimetres of error RMS, with a maximal value of 20 centimetres.

	Minimum (m)	Maximum (m)	Average(m)	RMS (m)
Radial	-0.214	0.206	0.001	0.051
Tangential	-0.650	0.881	0.078	0.172
Normal	-0.869	0.922	0.001	0.253

It is important to note that these results were obtained on a 64-bit workstation, which was used to develop DIODE. With the onboard processor (type 31750), a numerical degradation of the results leads to a RMS accuracy of about 13 centimetres on the radial component! We are of course trying to reduce this phenomenon. .

To reach this level of accuracy, all the filter's parameters had to be adjusted coherently. This is a difficult problem because of the number of parameters, and the fact that they are strongly correlated. A compromise is sometimes necessary between the accuracy in the converged mode and the robustness to noisy measurements or beacon incidents. If necessary, the filter adjustments can always be modified on board by uploading.

Figure 4 plots the values of the standard deviation, mean and maximum error averaged on a daily basis:

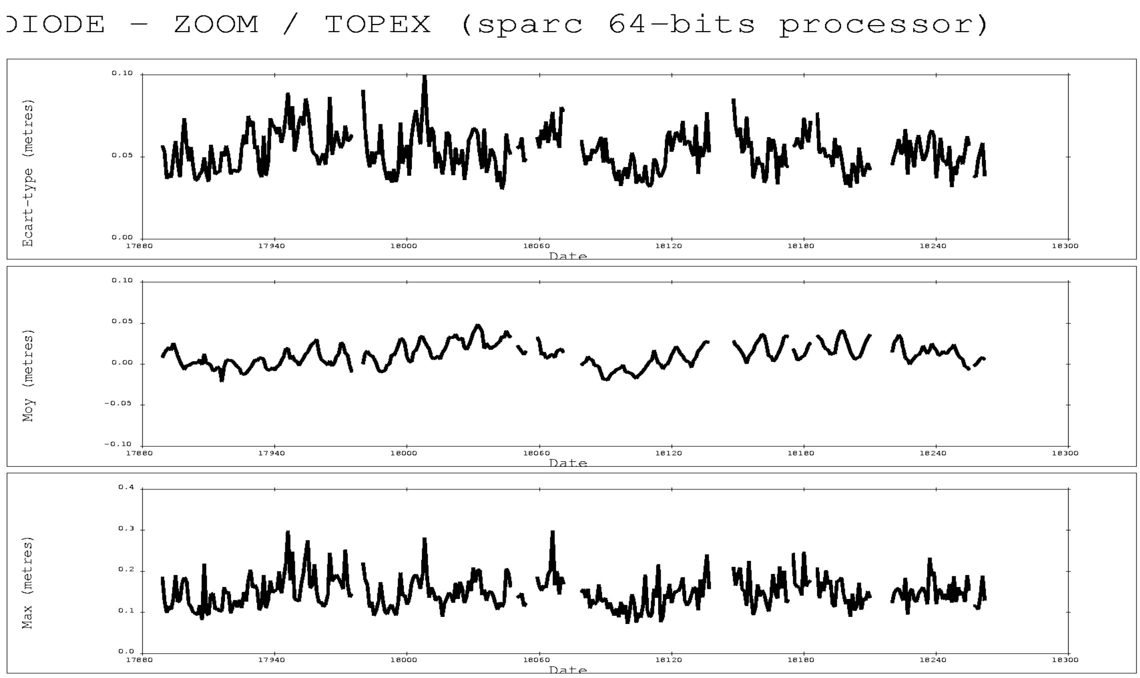

Fig. 4: average precision obtained on the ground with the DIODE / Jason 1 version

The accuracy of the reference is about 2 to 3 centimetres RMS on the radial component: DIODE is not very far from that!

=> The accuracy has been greatly improved, to respond to application requirements that are more and more refined.

The use of DIODE results on the ground will be extended with ENVISAT and Jason 1, by the use of precise positions for a "quick-look" analysis of altimeter data (mesoscale circulation, quick detection of phenomena, etc.).

=> Towards real-time surveillance of the oceans?

4.2. - DETERMINATION OF TIME

To perform its position determinations, DIODE must estimate the correspondence between the onboard clock (the USO) and a ground reference time scale (TAI, or UTC). In the second-generation receivers, this internal function can be seen by the onboard systems. A determination of the time may now be provided to the platform, allowing precise time-tagging in TAI of onboard events: DORIS will act as an onboard reference clock.

The average precision of the time determination is of the order of a few microseconds, and a quality index can detect unexpected events.

=> Each passenger, and the spacecraft's Central Flight Software, can now receive a determination of time from DORIS/DIODE that is accurate to within a few microseconds.

4.3. - SELF-PROGRAMMING

Normally, DIODE uses its estimation of the orbit to inform the DORIS receiver every ten seconds about the next visible station and its Doppler shift. The accuracy is such that these predictions can be used by the receiver itself, to self-program the next station to be received. A selection algorithm has been added, for the cases in which several beacons are visible at once.

The DORIS receiver can thus narrow its acquisition loops around the expected frequency. This function will be used for the first time on the Jason 1 mission.

=> DORIS now asks DIODE for its program forecasts.

4.4. - IMPROVED QUALITY INDEX

Finally, the development of the quality index has been improved. In addition to the filter's covariance matrix, the calculation now takes into account the correction vector for each measurement, and the processing indicator for the latest measurements.

This quality index gives an empirical order of magnitude on the estimated position error, and should lead to better detection of orbital errors, and incidents on DORIS or the platform. It will in particular be able to detect the start of a filter divergence due either to measurement errors (beacon anomaly), or to model errors (unexpected manoeuvre). Thus, users will have more reliable information on the quality of position estimates, and will be able to take this into account in their processing.

=>DIODE will offer better detection of external perturbations and therefore the start of divergence.

In addition, if the ground segment authorises it, DIODE is capable of autonomously triggering a self-initialisation (if the quality index crosses a threshold fixed by the ground). This option will also be evaluated during the Jason 1 mission.

=>DIODE will be able to autonomously trigger its own re-initialisation.

5. - FUNCTIONS DEMONSTRATED ON THE GROUND BUT NOT YET IMPLEMENTED ON BOARD

5.1. - MANOEUVRE CALIBRATION

DIODE is capable of going through manoeuvre phases:

- without any help for small manoeuvres ($\Delta V < 5$ cm/s),
- with predicted acceleration values for larger thrusts (from 5 cm/s to several m/s): the satellite's control centre must then upload the predicted characteristic for each thrust (date and time, duration and accelerations).

In addition, if the satellite is in view of a beacon, thrust errors can now be adjusted during the manoeuvres. If the manoeuvre is covered well enough by measurements, the resulting position accuracy is comparable to the normal accuracy even in manoeuvre phase, and contributes to making the filter more robust for unplanned thrusts.

These elements make it possible to foresee a real-time diagnosis of manoeuvre performance, onboard. A post-processor could be developed to achieve real in-flight calibration, by providing the result in appropriate parameters: thrust efficiency, post-manoeuvre orbit, etc. This function was implemented on the ground in 1998, and gave results whose accuracy is encouraging.

The manoeuvre calibration could certainly prove to be useful onboard, with the final goal being real time monitoring of long manoeuvres (for platforms equipped with electric propulsion) and optimal termination of the thrusts when the target orbit is reached. This kind of function could be very interesting for large constellations (orbit acquisition, replacement of a satellite by a backup satellite, etc.).

5.2. - AUTONOMOUS ORBIT CONTROL

With DIODE/SPOT4, Orbit Determination has proved to its flight capability. By adding onboard:

- the target orbit,
- an orbit comparison algorithm,
- and an optimal manoeuvre calculation,

it will be possible to achieve real Autonomous Orbit Control (A.O.C.). Such a concept is under study at CNES, and will be tested on board the satellites STENTOR and DEMETER (but not with DORIS).

Autonomous Orbit Control will reduce the risks of human error (in particular for large constellations, where ground control is not adapted to a large number of satellites). Autonomous control seems like a natural next step, which attitude control has already taken over the past twenty years.

This "onboard" approach will also make it possible to adopt new strategies, for example, frequent thrusts to compensate for atmospheric drag, or to maintain phasing of the ground tracks of a satellite to within a few metres, etc. This type of alignment was not conceivable as long as people were in the control loop.

6. – CONCLUSION

Since 1991, DIODE has been a living project, constantly improving itself as the onboard specifications got tighter. The current results (accuracy of one meter RMS in three dimensions, and a few centimetres on the radial component) would have been difficult to predict a few years ago.

It is now up to the people responsible for platforms and satellite systems to push this new function as far as possible, to enable DIODE to go even farther. French missions will be using DIODE in the years to come (notably SPOT5), as well as the French-American mission Jason 1 and the European mission ENVISAT. Why not other missions?

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