ORBIT AND TIME ON-BOARD COMPUTATION:
FROM THE CURRENT SPOT4 SOLUTION TO GNSS2 NEEDS

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Abstract

Using the DORIS system, CNES has developed an on-board autonomous orbit determination software, DIODE, which computes the spacecraft position in real-time. Based on a Kalman filter, it processes Doppler measurements from the ground-based beacons of the DORIS system. The first version has been flying on the SPOT4 satellite since March 1998, and successfully provides the position and the velocity with a 5 meter / 5 millimeter per second accuracy. New versions of the software improve this performance by an order of magnitude and will fly on several spacecraft: ENVISAT (ESA - 2000), Jason (CNES/NASA – 2000) and SPOT5 (CNES – 2003).

A new step for on-board navigation is to compute the clock synchronization with accuracy comparable to that of the orbit. The main applications are the GNSS2 (Global Navigation Satellite System) concepts studied at CNES, one with a LEO/GEO combination, the other based on a MEO constellation. For these systems, the on-board clocks would be ultra stable crystal oscillators (USO) or atomic rubidium clocks.

In both constellation concepts, we have chosen to compute each satellite ephemeris and synchronization on-board and in real-time, and to refresh the navigation message with these data at regular intervals. This computation uses pseudo-range and Doppler measurements collected over a dedicated ground network of navigation receivers. These measurements are then uploaded in near real-time. The goal is to contribute less than 2-3 meters in the UERE (User Equivalent Range Error) budget. This feature is therefore a critical point for the global performance of the navigation system.

For this purpose, we propose an evolution and an improvement of the current DIODE, with a coupled orbit and time estimation and taking precise pseudo-range measurements into account. A simulator of pseudo-range and Doppler measurements has been developed to analyze the performance on LEO and MEO.

In addition, this software is tested with actual GPS pseudo-range and phase data collected by ground stations of the IGS network in order to compute the orbit and synchronization of the GPS satellites as it could be done on board.

After a review of the current DIODE performances, this paper will present the principles of the proposed on-board filter. Then it will describe the results on the accuracy of the ephemeris and synchronization estimates for the GNSS2 simulations and GPS test case. We will also identify the critical points to reach this performance.

1 Genesis of the DIODE project

The DORIS system

In the mid-eighties, the French Space Agency (CNES) designed the DORIS system in order to fulfill the TOPEX-POSEIDON precise orbit determination requirements.

This system uses a worldwide network of ground beacons, which broadcast omnidirectionally on two frequencies, 2036.25 and 401.25 MHz, and which use Ultra Stable Oscillators. The number of operational beacons varies from forty to fifty. This network provides a good coverage for Low Earth Orbit: 70% at SPOT altitude (830 km, see figure 1) and 85% at TOPEX altitude (1330 km). In addition, two master beacons, one in Toulouse and one in Kourou, are tied to atomic (Cesium) clocks and connected with TAI

(International Atomic Time): they constitute the time and frequency reference of the system.

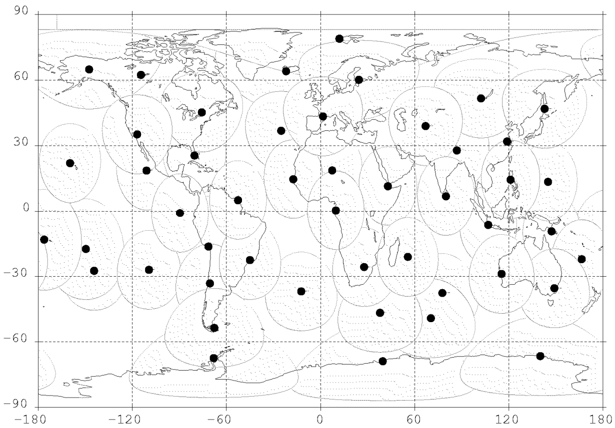

Figure 1: DORIS beacon network at 830 km

The DORIS on-board instrument, driven by an Ultra Stable Oscillator, receives the dual-frequency signals and computes their Doppler shifts and the reception time of the beacon synchronization signal every ten seconds. The overall system noise is lower than 0.3 mm/s for Doppler measurements.

The first generation instrument is on-board SPOT2 (launched in 1990), TOPEX-POSEIDON (1992), SPOT3 (1993, lost in 1996) and SPOT4 (1998).

The second generation instrument will fly on ENVISAT (2000). This instrument performs more accurate measurements and can track two beacons simultaneously.

The third generation instrument is as accurate but much lighter. It will fly on Jason (2000) and SPOT5 (2001).

All SPOT satellites are on the same orbit: 98.7° inclination (sun-synchronous), 830 km altitude.

TOPEX and Jason will have the same orbit: 66° inclination and 1330 km altitude.

The DIODE project

After a conclusive feasibility study from 1988 to 1990, CNES decided to create the DIODE project in 1991. The purpose was to develop an on-board software, which uses the precise Doppler measurements from DORIS in order to compute a real-time orbit.

The first version is flying on-board the imaging spacecraft SPOT4 which was successfully launched in March 1998. As far as we know, it is the first on-board real-time orbit determination software, which is continuously producing operational in flight results with commercial applications.

The real-time orbit is sent with the image data to the Spot Image receiving stations, so the ground segment interfaces and operations are simplified. The SPOT4 performance requirements are to reach a position precision better than 200 meters maximum and 100 meters RMS. Recently, POAM3 (NASA) and VEGETATION (European Union), which are SPOT4 passengers, have shown deep interest for DIODE on-board real-time orbit estimation.

For the second and third generation DORIS instruments, DIODE is fully integrated in the receiver software.

2 DIODE description

DIODE is written in Ada language using the HOOD (Hierarchical Object Oriented Design) for its conception. It runs on a separate MIL STD 1750a-type processor for the SPOT4 version, and will run directly on the DORIS receiver processor (MIL STD 31750a-type) for the following versions.

The size of DIODE software varies from 2500 to 7500 lines depending on the version.

DIODE is based on a Kalman filter. It uses numeric integration with a Runge-Kutta algorithm to propagate the state vector every ten seconds and it processes the Doppler measurements provided by the DORIS receiver to correct this state vector.

For the SPOT4 version, the propagation model is only a 15x15 Earth gravity field. For the more recent versions, we take into account:

- 40x40 Earth gravity field,
- lunar-solar interaction with a simplified ephemeris model,
- solar radiation pressure, with a more developed geometric model for the latest DIODE versions,
- empirical adjusted accelerations.

A significant effort has been made to optimize the calculation of the 40x40 gravity field acceleration in order to reduce the on-board computation time.

The state vector of the Kalman filter contains the position-velocity vector of the satellite and also some other adjusted parameters linked to each beacon pass. These parameters are:

- a frequency bias due to the frequency shift of the beacons' USO,
- a tropospheric coefficient, which allows a very simplified troposphere model to be used.

On the most recent versions, pole coordinates and empirical accelerations are also adjusted. This evolution is the main reason for the improvement of the orbit determination precision.

The DORIS Doppler measurements are modeled as beacon-satellite range differences between two DORIS fixed events. The ionospheric errors are eliminated thanks to the dual-frequency combination. The big 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.

DIODE uses each pass over the master beacons (Toulouse and Kourou) to adjust the frequency bias of the DORIS oscillator, and to update the difference between on-board time and TAI. This difference is then propagated with the adjusted USO frequency bias.

For orbital maneuvers, the control center of the satellite has to load the main characteristics of the thrust (date, duration and acceleration vector). So, DIODE is able to follow the maneuver without any divergence problem.

DIODE has also other features associated with the orbit determination.

In routine mode, DIODE uses its orbit determination to inform the DORIS receiver at each ten second step, about the next visible beacon and its expected Doppler shift. So DIODE can program in real-time the DORIS receiver which can therefore narrow its bandwidth around the expected frequency. This feature will be used for the first time on the ENVISAT version of DORIS.

An algorithm of self-initialization for low altitude and near circular orbits has been developed and will be used for the first time on the ENVISAT version of DORIS. Without any orbital information, the DORIS receiver can perform some measurements by just listening around a given mean frequency. DIODE needs at least four beacon passes to estimate a rough state-vector by a least-square method. Then, the Kalman filter is initialized with this initial state vector and converges quite quickly.

In the most recent versions, the calculation of the 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. Its main advantage is that it can detect a divergence of the filter due to either measurement errors such as beacon failures, or model errors such as an unexpected orbital maneuver. So DIODE can autonomously decide to run a self-initialization.

Finally, in the most recent versions, thrust errors can be adjusted during maneuvers. This gives a position precision comparable with the routine precision even during maneuvers, to make the filter more robust to unexpected thrust errors and to better follow the long thrusts, which will occur with electrical propulsion.

Hereafter are the main characteristics of the existing DIODE version. At this date, the only flying version is SPOT4.

Table 1: evolution of DIODE characteristics

Version	SPOT4	ENVISAT	Jason
Date of qualification	mid-96	end-97	beg-99
Earth gravity field	15x15	40x40	40x40
Sun-moon potential	no	yes	yes
Solar radiation pressure	no	yes	yes (precise)
Pole adjustment	no	yes	yes
Empirical force adjustment	no	no	yes
Thrust adjustment	no	no	yes
DORIS programmation	no	yes	yes
Self-initialization	no	yes	yes
Quality rating	very simple	very simple	improved
Accuracy (3D RMS)	6 m	1 m	0.4 m

3 SPOT4 on orbit performance

For monitoring purposes, the position vector estimated by DIODE is stored on-board each 160 seconds and these data are transmitted about twice a day to the DORIS control and monitoring center. A very precise orbit determination is performed on ground and is used as a reference orbit in all the precision analyses of DIODE. So DIODE behavior has been monitored since 26 March 1998.

The first three months were devoted to satellite and equipment tests and validation. DIODE has been running in a nominal spacecraft environment since July 1998. From this date to January 1999, only one event has forced DIODE to stop during 48 hours. So the actual availability of DIODE can be estimated today at around 99%.

Moreover, during the first six months, only ten data sets have been uploaded to DIODE to take into account some changes in the DORIS beacon network and some orbital maneuvers. DIODE has proved to be very autonomous.

In order to estimate the routine accuracy of DIODE, we analyzed the data transmitted from 3 April to 4 October. All the periods where DIODE was not in a routine mode (orbital maneuvers, DORIS test mode, …) have been removed. The errors are in table and figure 2.

Table 2: DIODE-SPOT4 routine errors

	Min. (m)	Max. (m)	Mean (m)	RMS (m)
Radial	-28.58	15.57	-0.10	2.68
Along track	-28.27	62.16	0.06	4.26
Cross track	-15.78	12.88	-0.16	3.07

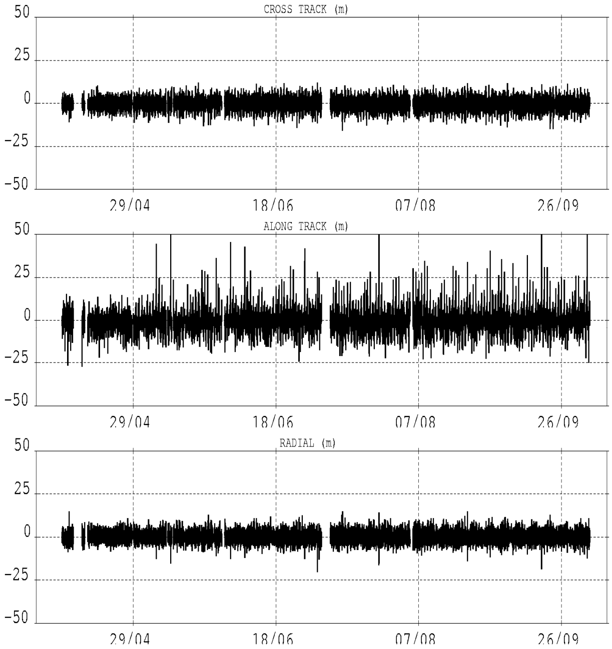

Figure 2: DIODE-SPOT4 routine errors

The 3D error is around 6 meters RMS, while the SPOT4 requirement is 100 meters RMS. We notice that the greatest errors are along track, with some peaks around 30-50 meters. This occurs during long periods without measurement when the satellite is out of visibility from the DORIS beacons. In that case, the Kalman filter propagates the state-vector and the error increases, especially along track.

The behavior of DIODE during orbital maneuvers has also been tested. The largest maneuver occurred on 31 March. It was a semi-major axis raising in two thrusts separated by a half-orbit. The global amplitude was 8 kilometers (around 4 meters per second). DIODE was informed of the expected thrusts, and it correctly followed them, as we can see on figure 3. The achieved thrusts were different from the commanded ones by about 28 meters on the semi-major axis and around 2.10^{-4} deg cross track.

After the maneuver, the estimated position has some oscillations during five hours, but never greater than 60 meters. We were not able to calculate the orbit errors between the two thrusts because the precise reference orbit was not generated on this arc, but we think that the error has the same behavior between the two thrusts as after the second thrust. This estimation is precise enough to use DIODE as a first real-time estimation of the maneuver.

Since the end of the orbit raising phase, three station keeping maneuvers occurred and have been very accurately followed by DIODE. But their amplitudes were smaller, around 50 m semi-major axis raising (0.025 m/s).

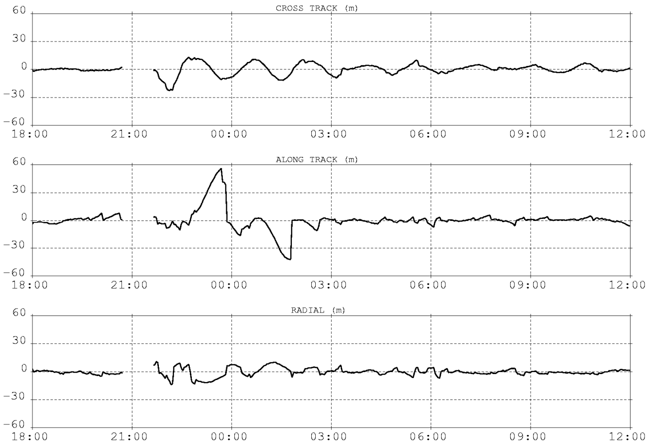

Figure 3: DIODE-SPOT4 errors after a maneuver

4 Performance of the more recent DIODE version

All the DORIS measurements are also stored on-board and transmitted each day to the DORIS ground segment. We use this large amount of data (several years of continuous Doppler measurements on SPOT2, SPOT3, TOPEX and SPOT4) to test the more recent DIODE versions (ENVISAT and Jason).

The Jason version of DIODE (the most recent) has been tested on TOPEX measurements because Jason will have the same orbit and the same attitude as TOPEX. The statistics and the errors presented on figure 4 and table 3 have been obtained on the 10-day cycle 148 of TOPEX. We must note that this DIODE version has been validated on the workstation used for the software development, but not yet on the actual processor (expected date: March 1999). So we can not exclude a small numeric degradation of these results in flight.

Table 3: DIODE-Jason routine errors

	Min. (m)	Max. (m)	Mean (m)	RMS (m)
Radial	-0.170	0.180	-0.008	0.042
Along track	-0.469	0.501	-0.032	0.136
Cross track	-0.935	0.943	-0.001	0.301

The 3D error is about 33 centimeters RMS. Notice the very small error in the radial axis: 4 cm RMS and only 20 cm maximum! This error is nearly comparable to the accuracy of the reference orbit.

To reach this level, we must tune all the parameters of the Kalman filter consistently. It was a hard task because of the number of parameters and because they are highly correlated with each other. A compromise has to be made between the accuracy in converged modes and the robustness to some noisy measurements or to beacon failures.

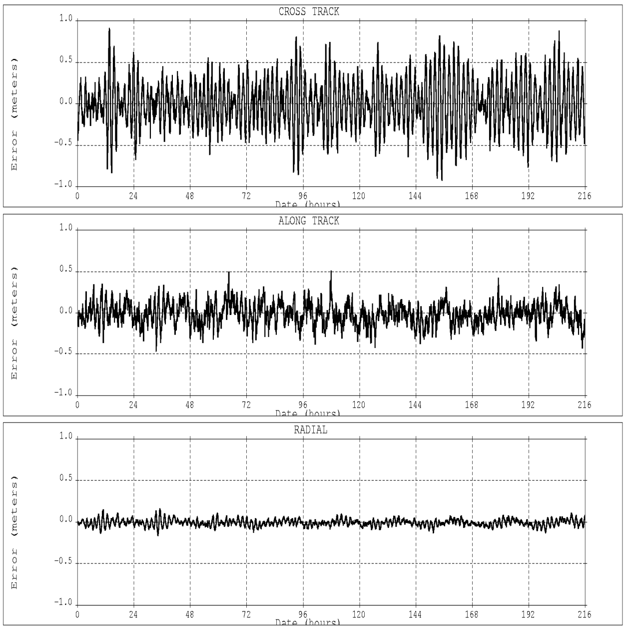

Figure 4: DIODE-Jason routine errors

Until a few months ago, the ENVISAT version of DIODE had been running on all the real TOPEX measurements for more than two years. Each ten days (duration of a TOPEX cycle), a self-initialization was performed, so that we have around 80 different tests of this function. In all cases, the time to deliver a first state vector to the Kalman filter is less than one orbit (2 hours), and is around one half an orbit (1 hour) on average. In fact, this duration is linked to the number of successive beacon passes needed for this self-initialization. The minimum number is 4 passes and it is sufficient in most cases.

5 Use of DIODE for GNSS projects

5.1 Architecture for orbit and time determination

Since 1997, CNES has studied several satellite constellation concepts for GNSS2. Like every navigation satellite system, the capability to transmit the ephemeris of the satellite and the synchronization of its clock very accurately to the users is a key point for the performance of the system. For this function, we have chosen the following architecture:

- Dual-frequency pseudo-range and carrier phase data are collected over a ground station network which is part of the GNSS2 mission segment,
- These data are uploaded in quasi real-time through a dedicated RF up-link,
- An on-board program using a Kalman filter computes these measurements to provide a precise position-velocity-time estimation.
- Then these data are used to compute the navigation message parameters.

In this architecture, all the measurements are performed in ground stations. These measurements are necessary to monitor the navigation signal for the integrity of the navigation system. Then these data are also used for orbit and clock determination.

Range is deduced from pseudo-range collected by the stations by correcting these data with the estimated station synchronization. Therefore, each station must know its own clock synchronization with a given precision, and transmit this information to the satellite with the pseudo-range measurements. This relative synchronization of the station network can be achieved for example by ground processing (e.g. time-filtering) of the same pseudo-range and phase data as those used by the on-board-filter. The precision of such a solution depends on the station clock stability to a large degree.

The on-board solution allows the navigation message to be refreshed as often as needed for the performance. Moreover, each satellite is more autonomous than with an architecture based on a centralized ground computation of the orbits and clock synchronization. It avoids operational constraints on the ephemeris and synchronization up-loading, which would have been necessary to reach a similar accuracy.

To analyze this concept, we adapted the DIODE software to make a GNSS version. We changed the measurement functions to pseudo-range and Doppler measurements performed on ground. We also improved the model of the on-board clock in the Kalman filter and we unified the orbit and time filters. So the position-velocity vector and the three parameters of the parabolic clock model are in a single state vector and are simultaneously processed.

We also developed a measurement simulator, which generates pseudo-range and phase difference measurements by taking into account:

- Troposphere and ionosphere models,
- Computation of the RF-link budget with tabulated diagrams of the station and spacecraft antennas,
- Noise of the station clocks, from either a mathematical model of the clock or a tabulated time and frequency file.
- Variations of the clock frequency and electronic propagation delays for the on-board and ground equipment.

The output data are:

- Doppler (difference of carrier phase) and pseudo-range measurements on each frequency,
- The station synchronization model, basically a time linear function. This model has to represent the estimated station synchronization at a given time, with the associated errors.

5.2 Test of DIODE on real GPS data

We have evaluated the performance of this adapted version of DIODE with real GPS data. The measurement simulator is not needed for this test.

For this purpose, we have chosen 14 stations of the International GPS Service (IGS). The criteria of selection was good clock stability. We worked with all the GPS measurements collected over these stations from 5 to 9 January 1998 (GPS week 939, days 1-5).

We have seen that the on-board filter needs the synchronization of the clocks of each station. So we determined the synchronization of the global GPS system using an IGS-like method. For this computation, we used JPL orbit solutions as input data.

Finally, we adjusted a linear function of time over each selected station clock synchronization. The stability of these 14 station clocks was good enough not to need a quadratic model (the frequency drifts were so small over these five days that they can easily be neglected). This linear model is therefore representative of a real-time estimation of each station synchronization. The RMS residuals of these adjustments were all lower than 0.6 meters (2 nanoseconds). Mauna Kea station (MKEA) was chosen to be our time reference for the global synchronization determination. All the others clock synchronization parameters were calculated relative to the MKEA clock.

For this test, we considered only the GPS PRN 15 satellite, because it is the only satellite without Selective Availability in the GPS constellation at this date. Our global time determination gave us the GPS15 clock synchronization at a 30 second rate, which is the IGS measurement rate. This synchronization and the JPL orbit solution were our time-orbit reference to determine the performance of the on-board filter.

Figure 5 shows the 14 selected stations and the projection of the GPS 15 orbit.

The Kalman filter started with an initial position-velocity vector from the reference orbit, but with a 200 nanosecond synchronization error. The delay for a full convergence of the filter was around 12 hours, which is the orbit period. This is a minimum delay because an orbit determination needs at least one orbit period to be able to observe the orbital parameters. Figure 6 and table 4 show the errors on the 4.5 day period after the convergence period.

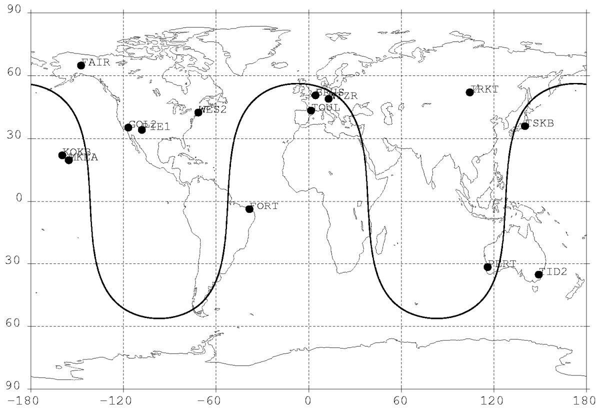

Figure 5: The station network used

There are some harmonic errors at the orbital frequency on the cross track axis and also on the along track axis. This phenomena can be explained by the irregular distribution of the measurements along the orbit. Indeed, the 14 considered stations do not cover all the GPS15 orbit. There are long time periods with one or zero simultaneous station passes in the southern hemisphere when there are often more than five simultaneous station passes in the northern hemisphere.

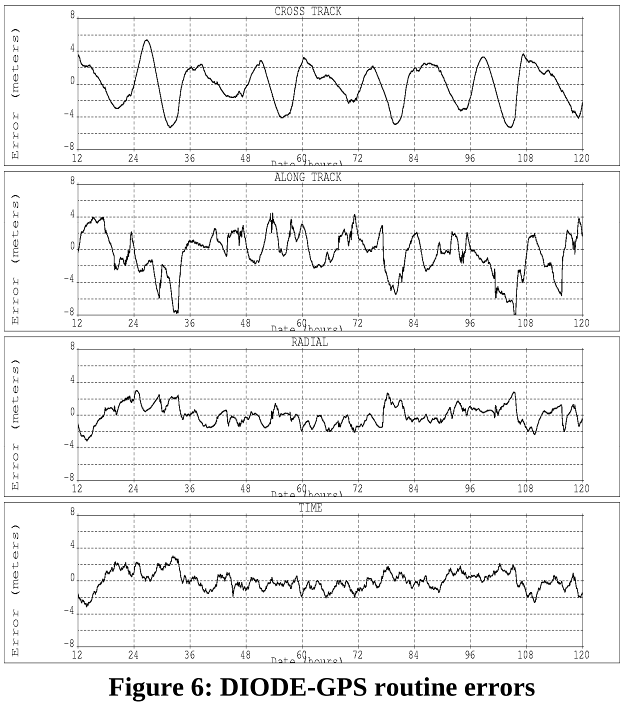

Figure 6: DIODE-GPS routine errors

In these tests, only dual-frequency pseudo-range measurements have been taken into account. All the benefits of the phase data have not been taken into account yet. At this time, we think that it is an important way to improve the performance.

Table 4 : DIODE-GPS routine errors

	Min. (m)	Max. (m)	Mean (m)	RMS (m)
Time	-3.15	3.00	0.01	1.10
Radial	-3.10	3.04	0.00	1.18
Along track	-8.92	4.48	-0.46	2.58
Cross track	-5.28	5.36	-0.14	2.41

In a navigation satellite system, these errors contribute directly to the User Range Error (URE) budget. To evaluate this contribution, we apply the following formula which is a quadratic mean between the four worst conditions of view for a terrestrial user (zero elevation from the user) and the best condition of view (zenithal elevation from the user).

$$URE^2 = (Radial - Time)^2 + 0.24^2/3\ (AlongTrack^2 + CrossTrack^2)$$

The statistics on URE over this 4.5 day interval are:

URE = 0,71 meter

Radial and time errors contribute the most to the URE budget. Moreover, URE is very sensitive to the correlation between these two terms. That explains the good performance of the filter with the URE criteria in comparison with the global performance on position and time. That is also a benefit of choosing the same measurement channels for the orbit and clock determination as for the users of the navigation system.

5.3 Test of DIODE on a GNSS2-MEO constellation

At the end of 1998, CNES and Alcatel Space Industries proposed a MEO design for GNSS2. In this solution, the on-board time/frequency reference is a rubidium clock. The orbit is very similar to that of Glonass: 19140 km altitude and 64.8° inclination. A eight Orbitography and Synchronization Station (OSS) network is dedicated to collecting the dual-frequency pseudo-range and carrier-phase measurements and transmitting them to the GNSS2 satellites (see figure 7). Each station has a very stable Cesium clock as a time and frequency reference.

A 6-day long orbit has been generated using precise numeric integration. On this orbit, pseudo-range and phase measurements have been simulated taking into account errors in accordance with the results of the Alcatel Space Industries studies (see table 5).

We have seen that DIODE needs to know the synchronization of each station to process pseudo-ranges. So we have adjusted daily linear model on the clock errors of each station and we have used this model propagated over a one day period as the station synchronization knowledge.

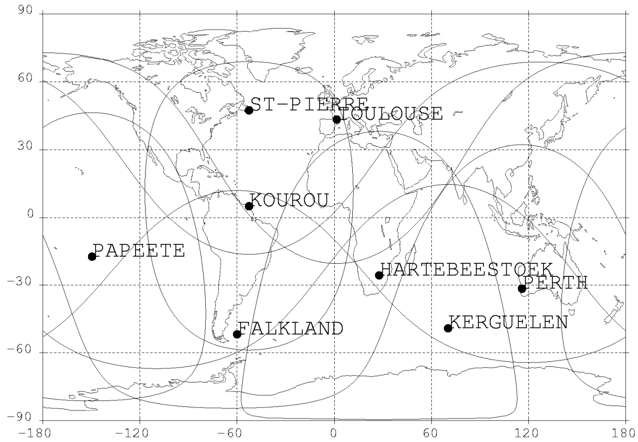

Figure 7: GNSS2-MEO OSS network

Table 5: Measurement errors

On-board clock: clock noise (Allan variance) frequency drift orbital variations (thermal)	 $5.\ 10^{-16}.\tau^{0.5}+8.5\ 10^{-12}.\tau^{-0.5}$ $1.10^{-12} + 2.\ 10^{-14}$ /day $3.\ 10^{-13}$ amplitude
Station clocks: clock noise (Allan variance) frequency drift daily variations (thermal)	 $8.5\ 10^{-12}.\tau^{-0.5}$ $1.\ 10^{-13} + 2.\ 10^{-14}$ /day $1.\ 10^{-13}$ amplitude
On-board electronic propagation delay, orbital variations: on L1 band L2-L1 differential effect	 0.3 ns amplitude 0.2 ns amplitude
On-ground electronic propagation delay, daily variations: on L1 band L2-L1 differential effect	 0.3 ns amplitude 0.2 ns amplitude
White noise on L1 and L2 pseudo-range measurements (30s phase smoothing)	0.30 m
Tropospheric delay	Calculated with each station meteorological conditions
Ionospheric delay	Removed by dual-frequency combination

After a 12-hour convergence period as in the GPS test case, DIODE errors are as shown in table 6 and figure 8. There are some error peaks, especially the last two days. These errors are explained by a long period without visibility or with only one station in visibility. This period occurs each day when the satellite is over Eastern Asia where the OSS network coverage is poor.

If we calculate the URE as we did for the GPS test, we find: **URE = 1.29 meter**. This value is very sensitive to the error peaks. We estimate that a URE of about 80-

100 centimeters is reachable only with one or two more stations in Eastern Asia.

Table 6: DIODE errors for GNSS2-MEO

	Min. (m)	Max. (m)	Mean (m)	RMS (m)
Time	-5.47	3.83	-0.27	1.78
Radial	-7.97	4.02	-0.74	2.26
Along track	-12.01	25.88	1.01	4.89
Cross track	-8.12	9.23	-0.04	3.09

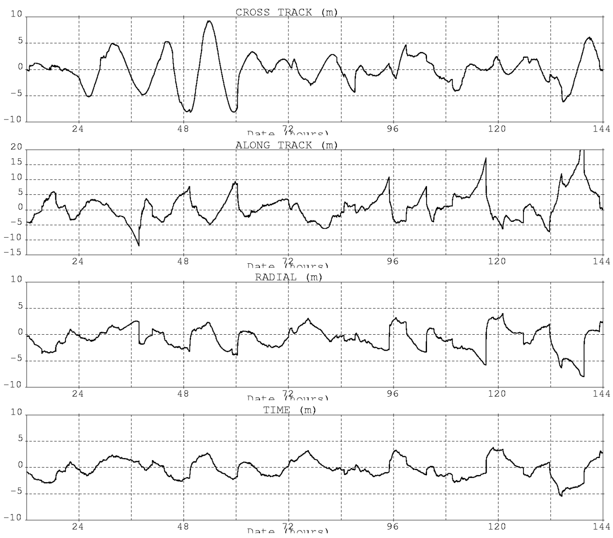

Figure 6: DIODE errors for GNSS2-MEO

5.4 Test of DIODE on a GNSS2-LEO constellation

CNES and Alcatel Space Industries also proposed a LEO/GEO design for GNSS2. In this solution, the on-board time and frequency reference for LEO satellites can be a rubidium clock as for the MEO GNSS2 design or a USO. The orbit is around 1300-1500 km altitude. It is a problem for quartz oscillators because they are far more sensitive to radiation than atomic clocks.

The performance of DIODE in this configuration is still under analysis. First results confirm that, on the contrary to the GNSS2 MEO case, the orbit and time determination are not very correlated as the station-satellite direction changes very quickly on LEO.

Of course, a denser OSS network than for GNSS2-MEO is needed in order to reach similar performances. But these stations can be separated into an orbitography network and a synchronization network.

The orbitography stations can perform only Doppler measurements, which are very useful for LEO, so they can be driven only by a USO. With around 20 stations, the expected DIODE performance is around 50 centimeters like the Jason version of DIODE.

However, the synchronization stations have to be driven by very stable atomic clocks (Cesium for instance) because they have to perform precise pseudo-range measurements. A compromise has to be made between the number of these stations and the stability of the on-board clock. We estimate that with a good on-board rubidium clock, five to ten stations are needed to reach URE performances similar to the GNSS2-MEO configuration.

6 Conclusion

On-board and real-time orbit determination has been studied at CNES for eight years thanks to DORIS system. It has been successfully running for the first time on-board SPOT4 since March 1998 with a 6-meter position accuracy and the most recent version precision is about 40 centimeters.

The main interest is the satellite autonomy. Indeed, the satellite localization is an on-board function and can be just transmitted to the ground by telemetry. Moreover, the on-board orbit knowledge can be used to autonomously determine orbital maneuver and also to perform them. Some such experiments are under way in several space projects. The satellite autonomy is very useful for all the satellite constellations which are under study or development because it allows the simplification of the ground operations for localization and for station keeping maneuvers.

A new challenge for on-board navigation is to compute the clock synchronization with an accuracy comparable to that of the orbit. Our simulations demonstrate the technical feasibility of this technique. These results are validated by application with real GPS data. The main application is the synchronization and orbit determination for navigation satellite systems like GPS, Glonass or the European GNSS2 project. The accuracy of the determination depends a lot on the stability of the on-board clocks and on the global coverage of the stations which perform the measurements on the navigation signal. The interest is still to simplify the ground operations and interfaces.

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