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DORIS system: The new age

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Abstract

The boarding of the first DGXX DORIS instrument on Jason-2 mission gives us the opportunity to present the improvements that have been implemented on the DORIS system. The goal of this paper is to present information about the new capacities of the DORIS system and to give the current status of its components. An overview of the DORIS system, the International DORIS Service and the Jason-2 satellite mission are first presented. Then the new characteristics of the on-board instrument are detailed. The capacity to track up to seven ground beacons simultaneously dramatically increases the number of measurements performed: a factor of three increase over Jason-1 is observed at the altitude of 1330 km. It also increases the diversity of directions of observation and allows low elevation measurements from 0°. The new phase measurements capability allows now phase processing. The instability of the Jason-1 USOs (Ultra-Stable Oven-controlled quartz oscillator) while crossing the South Atlantic Anomaly has been solved by decreasing the sensitivity to radiation by a factor of 10. New features of the on-board software enhance the coastal and inland water altimetry and increase the robustness of the data. The new software also improves the real time orbit accuracy for operational altimetry. The improvements introduced concurrently on the ground segment have also significantly enhanced capability. The new RINEX exchange formats provide simultaneous phase and pseudo-range measurements. The maintenance of the DORIS Beacons Network and the work done by the DORIS Signal Integrity monitoring team lead to an increased availability of the Network from 75% to 90% and so to a more homogenous orbit coverage.

All these improvements including the lessons learned during the past 20 years of operations have pushed the DORIS system forward to a New Age.

Keywords: DORIS; DIODE; DGXX receiver; RINEX; Phase measurements; Real time orbit

1. Introduction and background

DORIS (Doppler Orbitography and Radio-positioning Integrated by Satellite) is a tracking system developed in the early 80s by the French "Centre National d'Etudes Spatiales" (CNES) in collaboration with the "Institut Geographique National" (IGN) and the "Groupe de Recherche de Géodésie Spatiale" (GRGS). It was originally designed to perform very precise orbit determination of low-Earth orbiting satellites, in support of the oceanic altimetry mission on-board the TOPEX/Poseidon satellite operated from 1992 to late 2005. In order to demonstrate the capacity of the DORIS system to fulfill the mission, the first DORIS on-board equipment was launched on the SPOT-2 Earth observation satellite, in February 1990. This first demonstrator operated through the satellite lifetime ending in August 2009 and provided amounts of quality data used for many applications. Others DORIS instruments are presently flying aboard SPOT-4 and SPOT-5, Jason-1 and Jason-2 (Ocean Surface Topography and operational altimetry mission), and Envisat (environment monitoring mission). DORIS instruments will be embarked on future missions including Cryosat-2[1] (ice monitoring mission), Pleiades (High Resolution Earth observation satellites), AltiKa (Ka band altimetry), HY2 (Chinese ocean observation satellites), Sentinel3 (ocean and medium-resolution land mission for Global Monitoring Environment and

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[1] Cryosat-2 was launched on April 8th 2010.

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Security operational services satellites), and Jason-3, and are also planned for SWOT (large swath altimetry) and others Earth observation satellites.

DORIS is an uplink Doppler radio system (Jayles et al., 2006). Roughly every 10 s the on-board receiver accurately measures the Doppler shift of radio-frequencies signals continuously transmitted from ground beacons at two frequencies: at 2.03625 GHz for precise Doppler measurement and at 401.25 MHz for correction of the propagation delay trough the ionosphere. The two channels are also used for time-tagging measurements and auxiliary data transmission. The selection of an uplink-only system allows fully automated operation of the beacons and easy communication links for the overall system, data being centralized through the satellite and its ground segment to the DORIS data processing centre included in CNES altimetry, positioning and orbit processing multi-mission centre (French Acronym: SSALTO) located in Toulouse. The orbit determination beacons are deployed on a well distributed, dense worldwide network. Installation and maintenance of the network is performed by IGN. The time reference for the system is provided by the time beacons which are connected to atomic clocks. Time parameters and beacon coordinates are continuously and automatically transmitted to DORIS instruments via the master beacons.

The measurements are processed on ground in the SSALTO. DORIS system operations, including beacon network operations, and data processing are part of the CNES altimetry and precise positioning service (French Acronym: SALP) project undertakings. This also includes the DORIS beacon network operation. The measurements are also processed by the DIODE (DORIS on-board Immediate Orbit Determination) navigation function imbedded in the DORIS on-board software to provide real time satellite positions (Jayles and Costes, 2004).

In addition to orbit determination, DORIS observations are also used for geodesy, geophysics, Earth rotation or atmospheric sciences (Willis et al., 2006). The increasing number of applications led in 2003 to the creation of the International DORIS Service (Tavernier et al., 2006). The IDS is part of the Global Geodetic Observation System (GGOS) within the International Association of Geodesy (IAG).

The Ocean Surface Topography Mission (OSTM)/Jason-2 has two objectives: the operational one is to provide near-real time high-precision altimetry data for integration into ocean forecasting models and other products. The scientific one is to extend the precise surface topography time series started with TOPEX/Poseidon in 1993 (Lambin et al., submitted for publication). The Jason-2 satellite was successfully launched on June 20th 2008. It carries a dual-frequency altimeter, a 3-frequency microwave radiometer and three precise positioning systems.

Taking the opportunity of the first flight of a DORIS instrument from the DGXX series on-board Jason-2, the goal of this paper is to describe the improvements implemented in the DORIS system and to give the current status of its components. The new characteristics of the on-board instrument are detailed first, including the capacity to track up to seven ground beacons simultaneously, the new phase measurements allowing now phase processing and the decreased sensitivity to radiation of the USO (Ultra-Stable Oven-controlled quartz oscillator). The new features of the on-board software enhance coastal zones monitoring, inland water access and operational altimetry. Improvements added to the ground segment include: the new Receiver Independent Exchange formats (RINEX), the improved maintenance of the Beacons Network and enhancements done to the DORIS Signal Integrity monitoring system.

2. On-board instrument improvements

The new generation of DORIS instruments called "DGXX" (see Fig. 1) is now flying on Jason-2. The main difference from the previous generation flying on-board Jason-1 and SPOT-5 are (1) the "all in one box" concept containing two receivers and two USOs in cold redundancy. In order to improve the reliability, one receiver and one USO are operating while the others remain not powered. When one equipment is out of order the other is operated. (2) An automatic radio-frequency switch to drive the signal received by the antenna to the operating receiver. The weight of the receiver divided by the number of tracking channels is decreased by a factor of 2.5 compared with 2nd generation miniaturized receivers (SPOT-5, Jason-1) and a factor of 15 compared with 1st generation receivers (Jayles et al., 2006). Beside previous generations, the number of boxes to be mounted on the satellite to built a redounded instrument has been dramatically decreased from 6 (2 receivers, 2 USOs, 1 Switch, 1 magnetic shielding) to 1. This makes the accommodation on-board the satellite simpler and reduces the integration cost. The power consumption has slightly increased from 18 W for the 1st generation up to 25 W for current DGXX receivers due to the increase in processing capability. The others improvements are detailed in the following sections.

Fig. 1a. The "BDR" (Redounded DORIS Box). Weight: 16.5 kg; overall size 400 × 370 × 180 mm. Power supply: 22–37 V DC; typical cons: 25 W Telemetry and Command interface: MIL-STD-1553 CCSDS packet terminal protocol.

Fig. 1b. The DORIS on-board antenna. Weight: 2 kg; overall size: high 420 × f160 mm.

2.1. Seven processing units

Each receiver is now able to track up to seven beacons simultaneously (instead of two for the previous generation). At the Jason altitude (1330 km), most of the time, four beacons are simultaneously visible (see Fig. 2a). The geographical distribution is given in Fig. 3. It shows that the seven processing units (usually called by the French acronym UT) are fully used in North Atlantic and South Indian Ocean. On the other hand, this picture also shows that the DORIS Network could be enhanced in Asia and the Pacific regions. Simulations performed at a lower altitude such as SPOT or Envisat (800 km), show that a maximum of five processing units would be necessary to acquire data from the current configuration of permanent DORIS stations (see Fig. 2b). However, the use of DGXX type receivers at this altitude or lower such as 730 km for the Cryosat-2 satellite, will still increase the number of observations from the permanent network. Furthermore, it will provide additional tracking capacities for temporary stations proposed in the context of the International DORIS Service.

Jason-2, with seven UT, collects more than twice the data collected by Jason-1 (32,000 observation/day for Jason-2 versus 14,000 for Jason-1; see Fig. 4). Low elevation measurements are now accessible below the Jason-1 limitation of 12°. This limitation on Jason-1 (with only two UT's) was necessary to decrease the number of conflicts between co visible stations and so, to optimise the continuity and the distribution of the passes. It is no longer necessary on Jason-2 with seven UT's. Low elevation measurements may be now collected without any concurrence with higher elevation measurements. Although it is too early to say if these low elevation measurements which include large troposphere effects will benefit to orbit processing or geodetic applications, this capacity of DGXX receivers offers the opportunity to test the concept and develop better techniques to address troposphere issues. Furthermore, these low elevation measurements are essential to improve the robustness and availability of satellite critical navigation data (see Section 2.4.3). Extra data also permits a more reduced-dynamic strategy for orbit determination (Barotto and Berthias, 1996).

The beacons to be tracked are selected via the expected received frequency. Usually all the beacons transmit at the same frequency and are discriminated by the Doppler effect. In case of potential Doppler conflict between different beacons, the transmitted frequency of the beacons may be shifted. Under the current operating mode on-board Jason-2, the beacon tracked for UT 1 trough UT 6 are selected by the on-board software. The received frequency is predicted taking into account Doppler effect and eventual beacon frequency bias. This is done for stations whose identification and coordinates have been uploaded on-board (permanent DORIS Network). Observations start as soon as elevation reaches 5°. For UT 7: the beacons to be tracked are selected by Spectrum Analysis as soon as they are visible over the noise floor. This mode allows tracking of temporary stations (IDS) whose coordinates are not known. This mode also permits to perform very low elevation (0°–5°) measurements on stations that are tracked by the others UT's above 5°. The Jason-2 DORIS

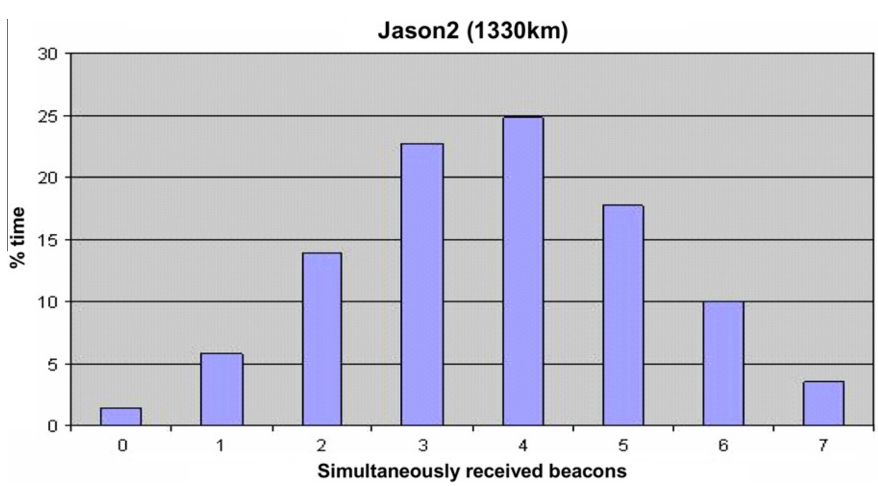

Fig. 2a. DORIS beacons simultaneously visible from Jason altitude (1330 km). This histogram represents real data performed on-board Jason-2 during commissioning phase.

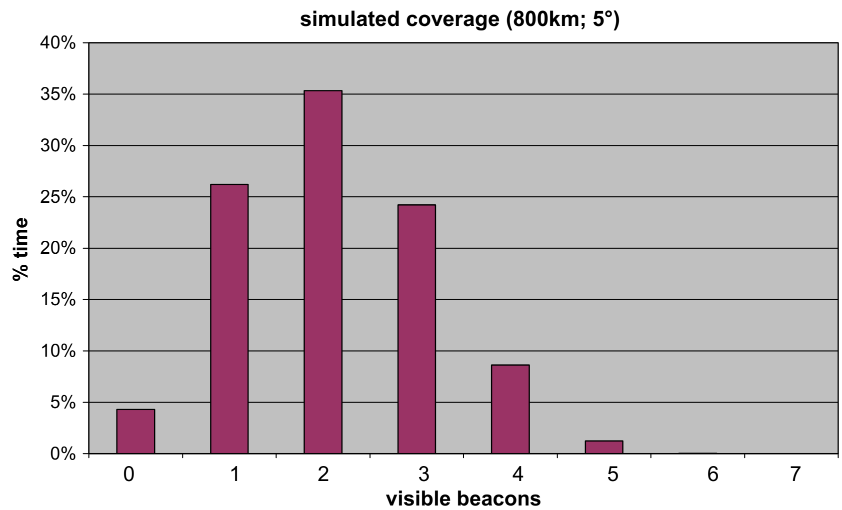

Fig. 2b. DORIS beacons simultaneously visible from 800 km altitude. This histogram is simulated assuming beacons are visible from 5° elevation.

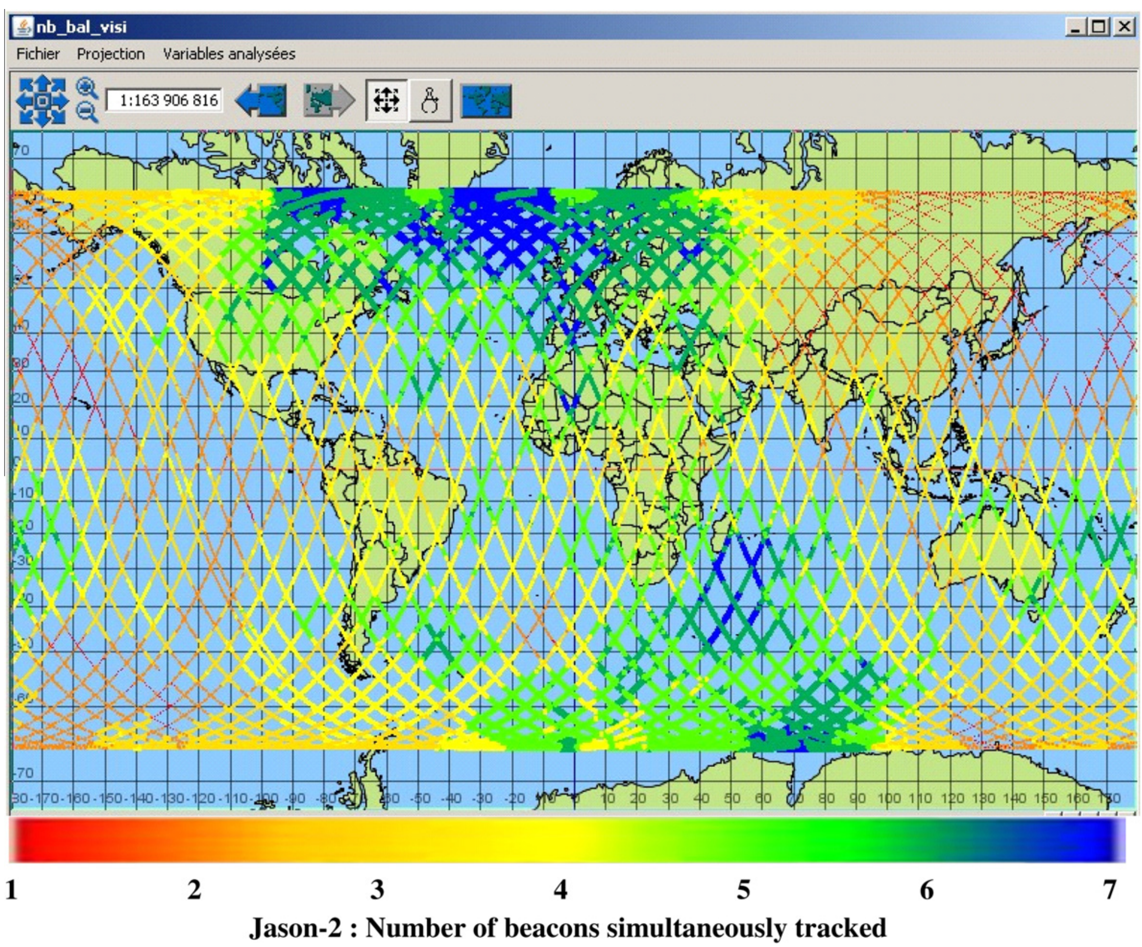

Fig. 3. Geographical distribution of the number of beacons simultaneously tracked by the DORIS receiver on-board Jason-2 (for black and white issue: size of the dots depends on number of beacons tracked). This plot has been obtained with real data collected by Jason-2 during commissioning phase.

operating mode ensures that one station should not be tracked simultaneously by two different UTs excepted in special situations (Doppler conflict, beacon temporary out of service, etc.). However, in these exceptional situations, the measurements are exactly duplicated thanks to digital processing and the duplicated measurement is discarded by ground pre-processing, so, there is no duplicated measurements in RINEX files.

The simultaneous multiple beacons tracking capability of DGXX DORIS instrument also improves the distribution of passes. This is illustrated in Fig. 5 with three stations: St-John's (Canada), Reykjavik (Iceland) and

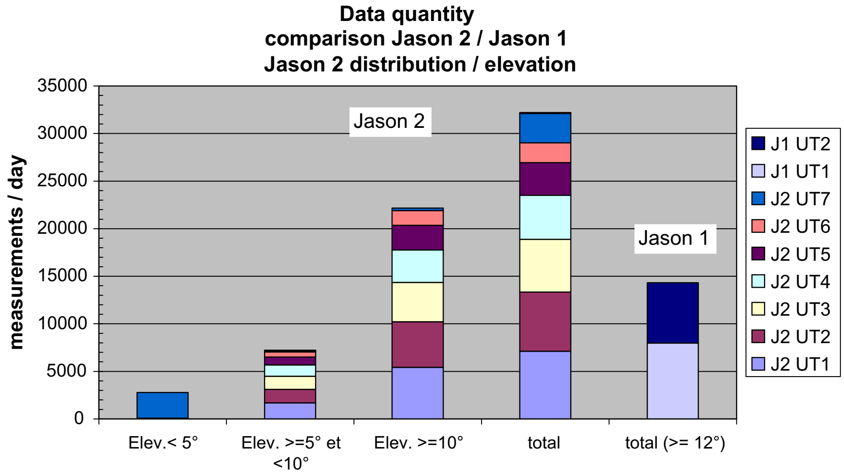

Fig. 4. Measurements per day collected by Jason-2 (1st to 4th column on the left) shared out by processing unit (4th column from left; UT1–7 from bottom to top) and allocation with respect to elevation (1st to 3rd column on the left) compared with Jason-1 (last column on the right).

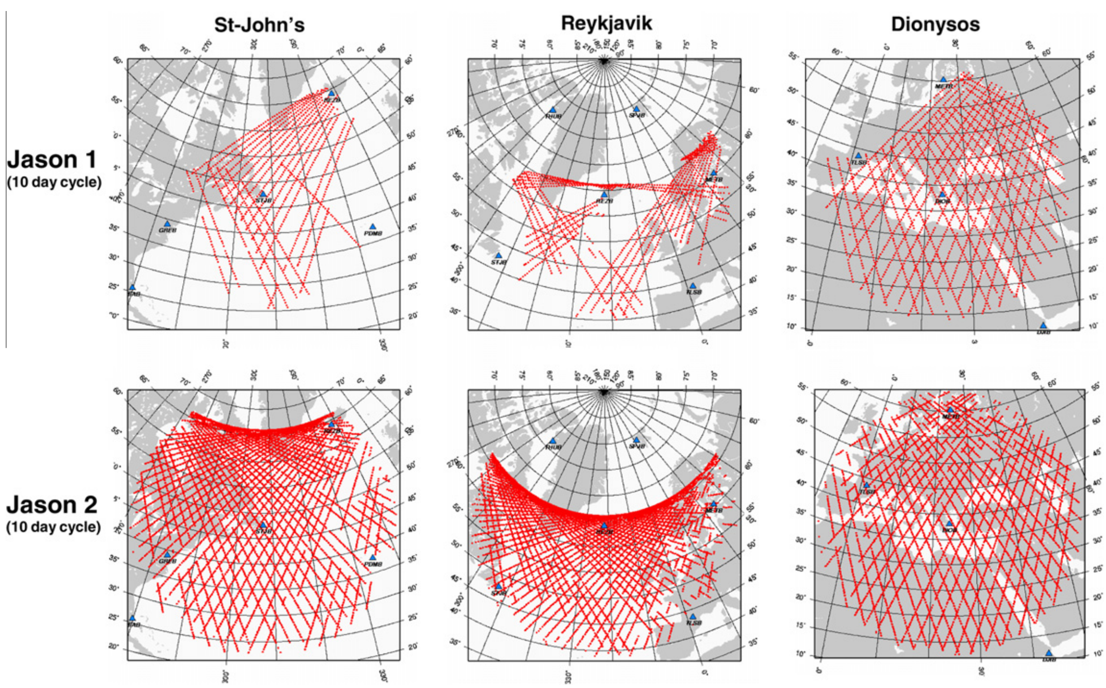

Fig. 5. Comparison of passes distribution between DORIS/Jason-1 (2 processing units) and DORIS/Jason-2 (7 processing units) on a 10 days cycle from July 27th to August 5th 2008 (*Source*: CLS).

Dionysos (Greece). The comparison with Jason-1 measurements collected over these beacons clearly shows the dramatic increase of symmetrical passes and passes density.

Furthermore, this increased capacity may accommodate more "IDS beacons" proposed by the International DORIS Service members for specific positioning purposes.

2.2. Phase measurements

Several modifications have been implemented for measurements performed by DORIS DGXX receivers:

2.2.1. Synchronization of phase measurements on both channels 400 MHz and 2 GHz

There is a differential internal delay between the 400 MHz channel and the 2 GHz channel in the receiver. On DORIS DGXX receivers this difference is compensated, thus phase measurements reflect the phase status of both signals simultaneously received at the antenna phase centre. This permits a simple and proper ionosphere correction calculation. Previously this computation was difficult due to the different epochs of the 400 MHz and 2 GHz phase measurements.

2.2.2. Synchronization of pseudo-range measurements with phase measurements

DORIS measurements are performed every 10 s. These 10 s sequences are based on the on-board time driven by the USO and roughly synchronized on International Atomic Time (TAI). Previous generation receivers perform the pseudo-range measurement upon arrival of the modulated synchronization word included in the beacon message, that is to say approximately at the middle of the 10 s sequence. The phase measurement in these earlier vintage systems is performed at the beginning of the sequence. This leads to different epochs for phase measurement and pseudo-range measurement. DGXX receivers still perform the pseudo-range measurement (PR3) upon arrival of the synchronization word, however, they simultaneously perform an additional phase measurement (Phi3). The pseudo-range value (PR0) corresponding to the epoch of the phase measurement (Phi0) performed at the beginning of the sequence is then obtained by subtracting the difference of phase measurements [Phi3–Phi0] from the initial pseudo-range measurement (PR3). This computation is done while generating the DORIS RINEX files to provide pseudo-range data re-synchronized with phase measurements. Note that pseudo-range measurements are only used for time-tagging purpose as they have an accuracy of about 1 km (few microseconds) while phase measurements have an accuracy of a few degrees (few millimetres).

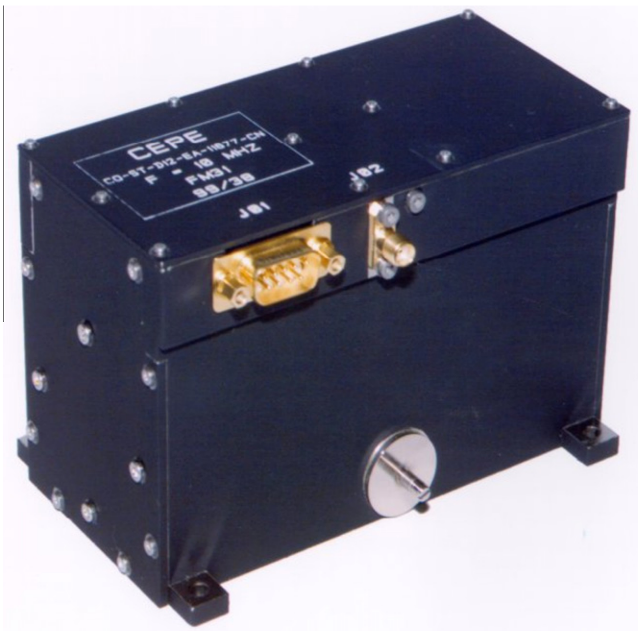

Fig. 6. DORIS oven controlled ultra stable quartz oscillator.

2.2.3. Non-ambiguous phase measurements

Two non-ambiguous phase measurements are now available for each sequence. The first phase measurement

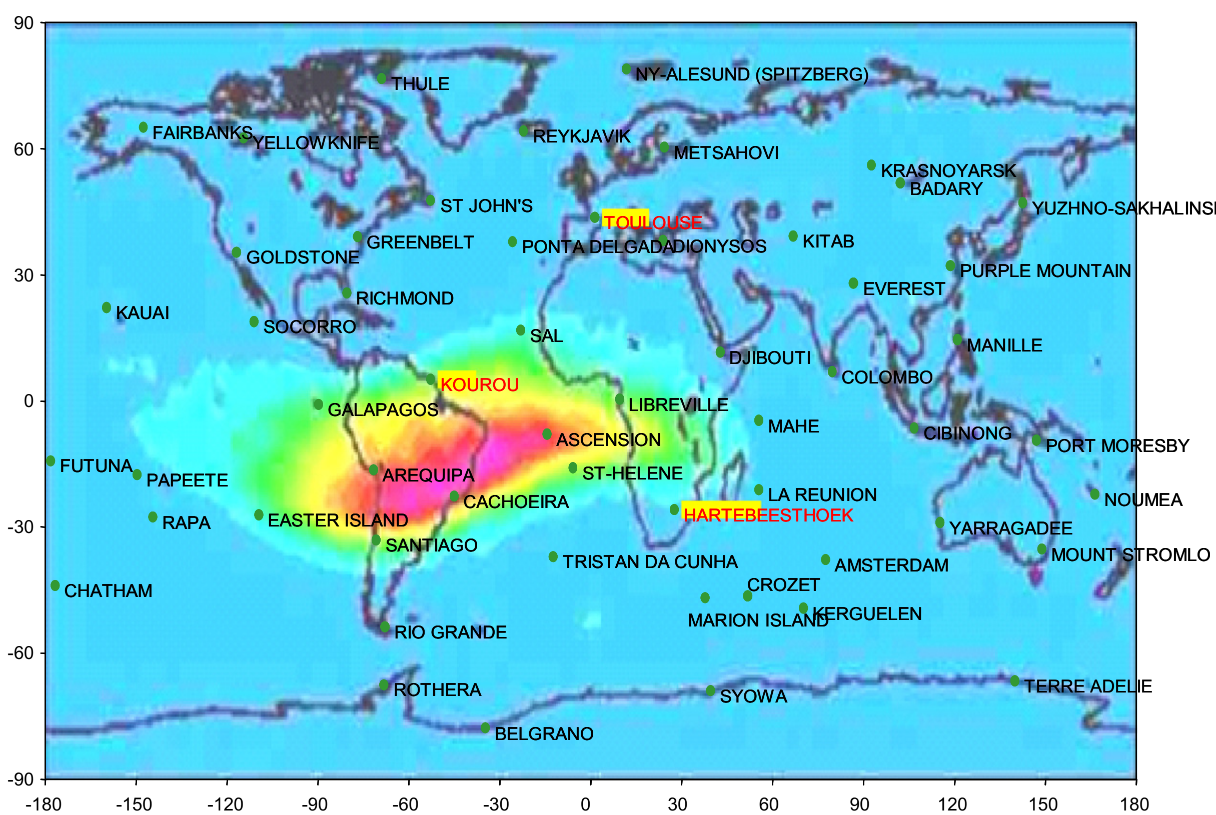

Fig. 7. Density of trapped protons of high energy in South Atlantic Anomaly; higher density in red (or dark grey in B&W iss.); lower density in blue (or light grey in B&W iss.). *Source*: Lemoine and Capdeville (2006). (For interpretation of color mentioned in this figure the reader is referred to the web version of the article.)

is performed at the beginning of the 10-s sequence, except for the first sequence of a pass or in case of signal temporary lost. The second phase measurement is performed 3 s later in on-board time. Non-ambiguous phase measurements allow direct phase processing (Mercier and Cerri, 2010) instead of, or in complement with, "Doppler" processing using the phase increments between the beginning and the end of the sequence. These Non-ambiguous phase measurements may also open the way to DORIS antenna maps for phase correction of the type computed for Doppler measurements (Willis et al., 2005).

At last, the new DORIS phase measurement, should give now the possibility to derive instantaneous TEC measurements without any software modification in standard GPS-oriented software packages for ionosphere monitoring (tomography, scintillation). This may provide additional interesting information to the IGS data derived from GPS system (Mannucci et al., 1998; Hernandez-Pajares et al., 2009). The altitude distribution of the DORIS DGXX receivers: 700 km (Cryosat-2), 800 km (Saral-AltiKa), 900 km (HY2) and 1300 km (Jason-2) may also provide information about the upper part of the ionosphere.

2.3. Hardened Ultra Stable Oscillators

The heart of the DORIS receiver is a USO (see Fig. 6). The accuracy of the phase measurements performed by the DORIS receiver strongly depends on USO frequency stability. Both DORIS USOs aboard on Jason-1 have shown an unforeseen radiation sensitivity whose effects are mainly visible when it crosses the South Atlantic Anomaly (SAA; see Fig. 7). This sensitivity was revealed by observing abnormal motion of the stations located in SAA area. The satellite clock acceleration tending to attract the station only when the satellite is in the SAA, an asymmetric behaviour between the ascending and descending passes was observed (Willis et al., 2003). The outcome was a complex transfer function depending upon the flux, the cumulated dose received and a memory effect (Willis et al., 2004; Cibiel et al., 2006). The orbit determination mission was saved thanks to low weighting and/or appropriate modelling (Lemoine and Capdeville, 2006). For geodesy applications, Jason-1 data cannot be used without using this correction (Willis et al., 2006). Although some groups are using these data with the correction provided by Lemoine and Capdeville there is still some degradation in the geodetic results.

The DORIS DGXX USOs have been hardened though pre-irradiation of the quartz resonator. The sensitivity of these USOs to radiation measured on the ground was reduced by a factor of ten from relative frequency variation of some $10\,E^{-11}$ per rad for non-hardened USOs to some $10\,E^{-12}$ per rad when the hardening process had been applied (Sengenes, 2006). The behaviour of the first hardened USO on Jason-2 was checked during commissioning phase. The result compared to Jason-1 is shown in Fig. 8 where the on-board frequency is derived from frequency bias estimation over time beacons in the orbit determination processing. The effect of the radiation is not detectable on Jason-2. The daily variation of the frequency of about $10\,E^{-10}$ peak-to-peak is no longer visible. The stability of the new USO provides a better quality Medium Orbit Ephemeris (MOE) for Jason-2. MOE is the orbit derived from combining data from DORIS and SLR, provided for intermediate altimetry products with 2 days latency and an accuracy of less than 2 cm (Olivier et al., 2009) while POE is the three techniques (DORIS, GPS, SLR) combined orbit taking into account external data such as earth rotation parameters or solar activity, available after a latency of 6 weeks, fully validated and having an accuracy better than 1 cm (Cerri et al., 2009, 2010). The improved frequency stability the better distribution of the passes and the increased amount of available data per station should make DORIS/Jason-2 an excellent tool for geodetic positioning.

2.4. On-board software improvements

2.4.1. Management software

The robustness of the on-board software in charge of instrument management (synchronization acquisition and maintenance, instrument and measurements modes, memories, etc.) has been improved to autonomously address different situations aboard the satellites such as erroneous data transmitted by the beacons, single or multiple event upsets in memory, etc. This is done to reduce data loss. First generation receivers were subject to Single Event Function Interruption (SEFI) leading to weekly losses of data once every 3 or 4 month on the average. The DGXX series, like second generation DORIS instruments (Envisat, Jason-1, SPOT-5), are equipped with microprocessors which are not subject to these kinds of incidents.

2.4.2. Navigation data in terrestrial frame

The DORIS receiver provides real time ephemeris every 10 s formatted in X, Y, Z components in a terrestrial frame aligned on station coordinates provided by DPOD2005 (Willis et al., 2009). This set is an extension of ITRF2005 (Altamimi et al., 2007), but it provides all DORIS station coordinates and velocities. This "X, Y, Z" format (called "ITRF" in technical documentation), is used for Near Real Time Altimetry Products location. A new format of terrestrial navigation data called "geodetic" is now available on Jason-2. This navigation packet contains the altitude with respect to a specified surface (ellipsoid or geoid), the altitude variation rate, longitude and latitude coordinates, orbit cycle number and on-orbit position. These data are used by the Poseidon3 altimeter to drive two new acquisition and tracking modes (Lombard et al., 2008). The first one is similar to the traditional closed loop tracking mode of the altimeter but the acquisition of the backscattered altimeter signal is now helped by the geodetic navigation data provided by DORIS. The acquisition delay while the altimeter is passing from land to water is reduced allowing altimeter measurements in coastal zones which were previously lost. The second mode called "open loop" associates

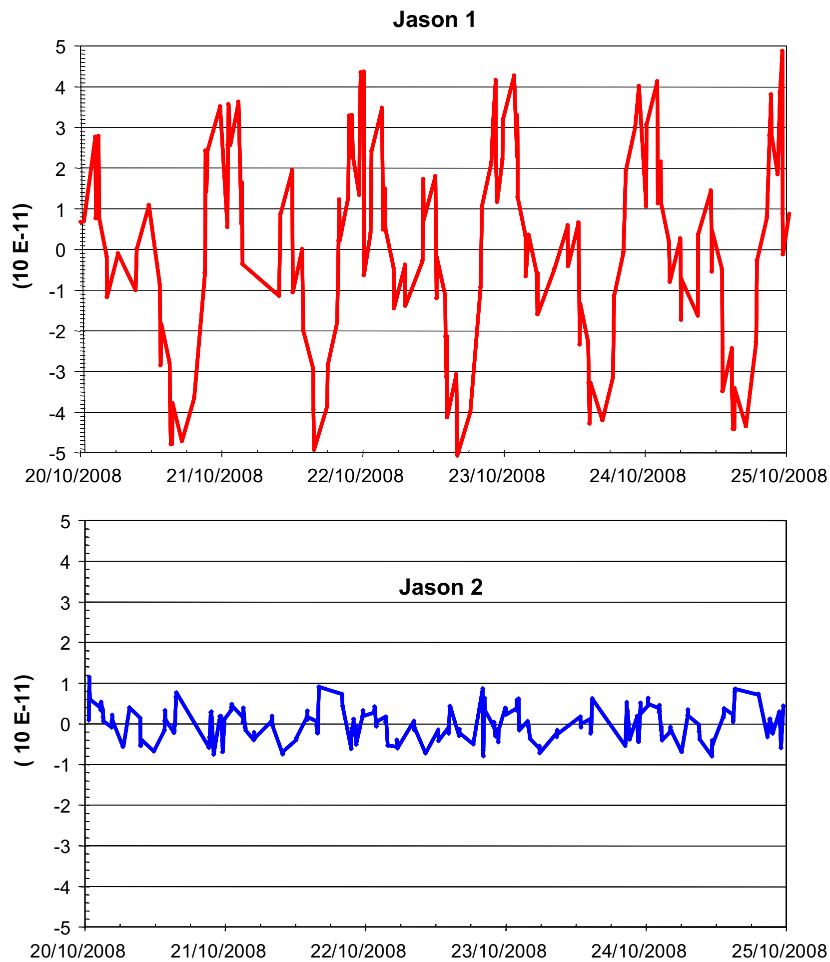

Fig. 8. Behaviour in orbit of hardened USO on-board Jason-2 in comparison with not hardened one on-board Jason-1. The long term trend has been removed on the both plots showing the relative frequency variation ($\Delta F/Fo$). The residual noise ~10 E^{-11} is mainly due to frequency estimation process.

the data provided by DORIS with an uploaded Digital Elevation Model. The altimeter loop is forced to track the signal in the designated window. This allows access to new zones of interest such as inland water and eventually off nadir targets assuming an appropriate DEM is used. This new mode is particularly efficient in case of water surface located in regions of strong relief such as Norway fjords (see Fig. 10). This new capacity should make land hydrology studies easier (Birkett et al., 2008).

These different modes are illustrated in Fig. 9. Only the two new modes (b and c) are currently used on Jason-2. This new navigation packet is also down linked to ground segment for validation purpose.

2.4.3. Navigation data in inertial frame

A third navigation packet provides the satellite position and velocity with respect to J2000 Inertial Reference Frame every 10 s. This packet will be used in the Attitude and Orbit Control System (AOCS) on Cryosat-2 (ESA ice mission satellite) and Pleiades (High Resolution Earth Observation satellites). This navigation data is critical for the satellite mission. This implies a large robustness and availability of the navigation function. The DGXX receiver takes up this challenge thanks to improvements described in Section 2.4.1. Furthermore, the DGXX receiver capability to provide low elevation measurements reduces the initial convergence delay of the navigation function. It also reduces its re-convergence delay after a manoeuvre. For this purpose, the troposphere effect is not an issue as the low elevation data required are used mainly from the contents of the beacon message and not from the accuracy of the measure. In fact, low elevation data provide availability and robustness while higher elevation data provide accurate navigation.

2.4.4. Navigation accuracy

Thanks to the capacity of the new processor (ERC32), the DIODE navigation function of the DORIS instrument has been upgraded leading to better than 10 cm accuracy of on-board delivered ephemeris and better quality Jason-2 near-real time products (Jayles et al., 2010).

2.4.5. Navigation autonomous integrity monitoring

As with previous receivers, all the DORIS DGXX navigation data (in terrestrial or inertial reference frame, time-tagging) are provided with a quality index which is the

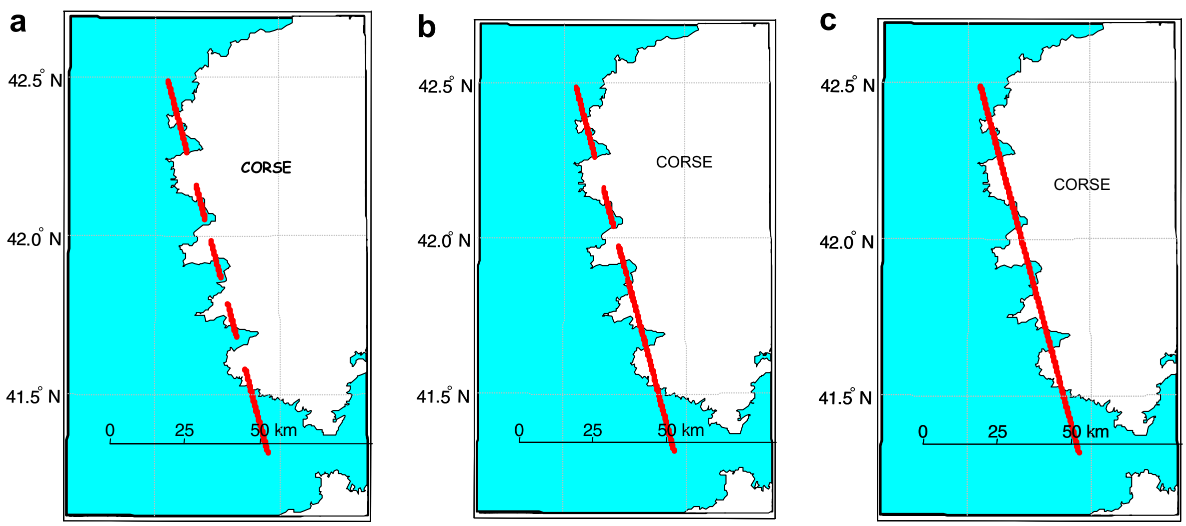

Fig. 9. Altimeter different modes. (a) Autonomous acquisition and tracking; this mode is the traditional one used on-board Jason-1; measurements on coasts are lost due to acquisition delay; few measurements are performed on Land. (b) Acquisition helped by DORIS/DIODE and autonomous tracking; gain in acquisition delay >1 s (~7 km); this mode allows to access to coastal zones. (c) Acquisition and tracking helped by DORIS/DIODE; this mode allows to access to water surfaces in strong relief, to focus on zones of interest selected in the DEM and to access to off Nadir targets (appropriate tailoring of DEM). *Source*: Lombard et al. (2008).

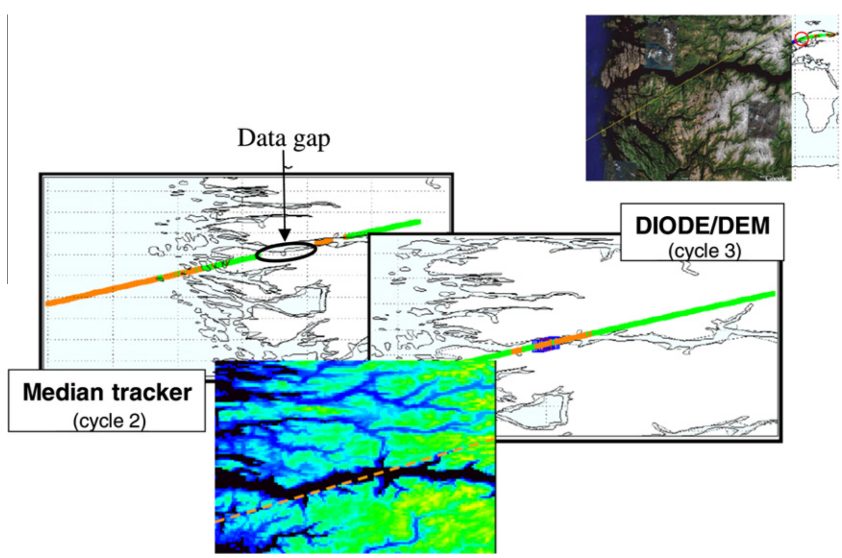

Fig. 10. Example of coastal zone altimetry in Norway fjords. During cycle 2 the Poseidon3 altimeter on-board Jason-2 was in autonomous tracking mode; there is no available data over the surface of the water in the fjord (left map). During cycle 3, the altimeter was in DORIS/DIODE helped tracking using a Digital Elevation Model; the altimeter is continuously tracking and the altimetry data over the fjord are available (right map). *Source*: Lombard et al. (2008).

maximum estimated error. For instance, a navigation quality index set to 1 m means that the accuracy of the position of the satellite provided in the bulletin is strictly better than 1 m in distance. This capacity is mainly useful for operational functions such as AOCS or Payload products operational localization (remote sensing satellites, operational altimetry) which need this quality of real time data. In DGXX receivers, the quality indexes have been tuned to optimize the availability and integrity of data by taking into account ground simulations and lessons learned from flying DORIS receivers.

2.5. Accurate internal delay measurement

In previous generation instruments, the internal delay affecting the Doppler or phase measurements was estimated and not measured, leading to a possible bias of 4 or 8 μs in the time-tagging of the Doppler measurements (Willis et al., 2005; Zelensky et al., 2006). This may cause an along track error of 3 or 6 cm. Using the seven processing units in the current instrument, it is now possible to measure accurately (error < 100 ns) on the ground the internal delay of the receiver. The new measurement method is based on seven simultaneous phase measurements performed on a composite radio-frequency signal containing seven consistent frequencies. This accurate internal delay is taken into account in the epoch of the measurements provided in DORIS RINEX files. So, any time-tagging or along track bias should no longer be seen on DORIS orbits derived from DORIS DGXX series instrument. Proper time-tagging could be tested using SLR as control point or as reference orbit (see Zelensky et al., 2006).

3. Ground segments improvements

3.1. RINEX format

Previously, the distribution of DORIS measurements was delayed due to data processing for orbit determination. The DORIS measurements are now available daily in a RINEX format which contains the phase and pseudo-range measurements and auxiliary data helpful for processing. These DORIS new exchange formats are comparable to the ones widely used in the GPS community (Gurtner et al., 1989).

The epoch of the measurements is given in On Board Time (OBT). The time tagged event is always the signal arrival at the antenna phase centre. The measurements may be time tagged in TAI scale in two ways:

– By processing the pseudo-range measurements on identified time beacons with information about the time scales of the time beacons given in the header.
– By using the OBT offset field as following: Epoch (TAI) = Epoch (OBT) + OBT offset. This time correspondence is currently achieved with accuracy at the microsecond level.

Available received power on both channels (400 MHz and 2 GHz) may be used for data weighting purpose. On-board clock (USO) frequency is also available as per on-board software (DIODE) estimation with accuracy of about 10 E^{-11}. The two sets of phase measurements called "Phi0" and "Phi1" are available corresponding to two different epochs as presented in the on-board instrument section above. The DORIS RINEX Format is shown in Fig. 11. Documentation on RINEX files is available on International DORIS Service web site: ftp://ftp.ids-doris.org/pub/ids/data/RINEX_DORIS.pdf.

3.2. DORIS ground network

The DORIS ground network is permanently being upgraded (Fagard, 2006, 2008). Currently, 95% of the stations are equipped with third generation beacons (see Fig. 12). Compared to the previous generation, these beacons have additional features: data transmission on both channels for more security, transmission of non-ambiguous date for on-board receiver date maintenance, possible transmission on shifted frequencies to avoid Doppler collision when located close to others DORIS beacons. With these new capabilities, third generation beacons are contributing to increase availability of DORIS data. Antenna supports have been rebuilt in order to improve the stability and reduce the eventual masking and multi-path effects (see Fig. 13). In order to decrease data outages, the availability of stable sources of power is now strongly considered for station placement and renovation. The permanent network currently contains 57 beacons. Six of them are now driven by atomic clocks. These particular beacons are listed in

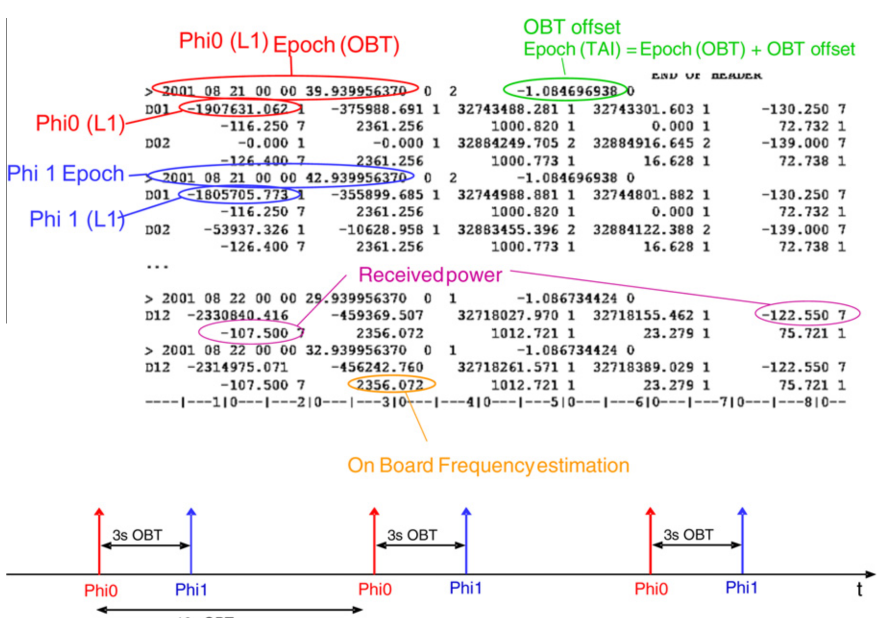

Fig. 11. DORIS RINEX files format. Phi0 and Phi1 are the non-ambiguous phase measurements performed respectively at the beginning of the 10 s sequence and 3 s later. L1: stands for 2 GHz signal; OBT: stands for on-board time based on on-board USO. OBT offset is the quantity to be added to OBT epoch to convert it in an epoch expressed in International Atomic Time. The received power is in dBm. The relative on-board frequency bias is expressed in 10 E^{-11}.

Fig. 12. Picture showing the 3rd generation DORIS beacon with the power supply unit (at the bottom) and the electronic unit containing the USO and the RF transmitter (on the top).

Fig. 13. View of the DORIS antenna of the Crozet Island, French Southern Indian Ocean territories (T.A.A.F.). The concrete pillar anchored in the rock ensures a perfect stability of the reference point. (*Source*: IPEV, Bricaud, C.).

Table 1 with their current identification acronym, clock type, date of installation of first beacon on the site, date of first use as a master or time station.

Time beacon are beacons whose time scale is known with respect to TAI scale by time bias, frequency bias and frequency drift parameters. The time scale of the time beacon are predictable up to 10 days with accuracy better than 500 ns. A master beacon is a time beacon synchronized on the TAI scale with an accuracy better than plus or minus 50 ms and able to transmit auxiliary data to the on-board instruments (DORIS Network coordinates and time parameters). These beacons are all driven by an atomic clock and may be used for time-tagging purpose. Nevertheless the short term stability over 10 s and the mid-term stability over a pass (1000 s) are the same as for standard beacons (few $10\,E^{-13}$). With the use of time

Table 1
List of time and master stations in the DORIS Network.

Station name and country	Current ID	Current function	Clock type	Installed since	Current function since
Toulouse France	TLSB	Master	USO slaved to cesium	August 3rd 1989	August 3rd 1989
Kourou French Guyana	KRVB	Master	USO slaved to cesium	December 5th 1986	June 25th 1992
Hartebeestoek South Africa	HBMB	Master	USO slaved to cesium	March 10th 1988	September 12th 2005
Papeete French Polynesia, South Pacific	PAUB	Master	USO slaved to cesium	July 27th 1995	November 19th 2009
Yellowknife Canada	YEMB	Time	H. maser	June 6th 1989	May 16th 2007
Terre Adelie Antarctica French base	ADFB	Time	H. passive maser	February 5th 1987	January 21st 2010

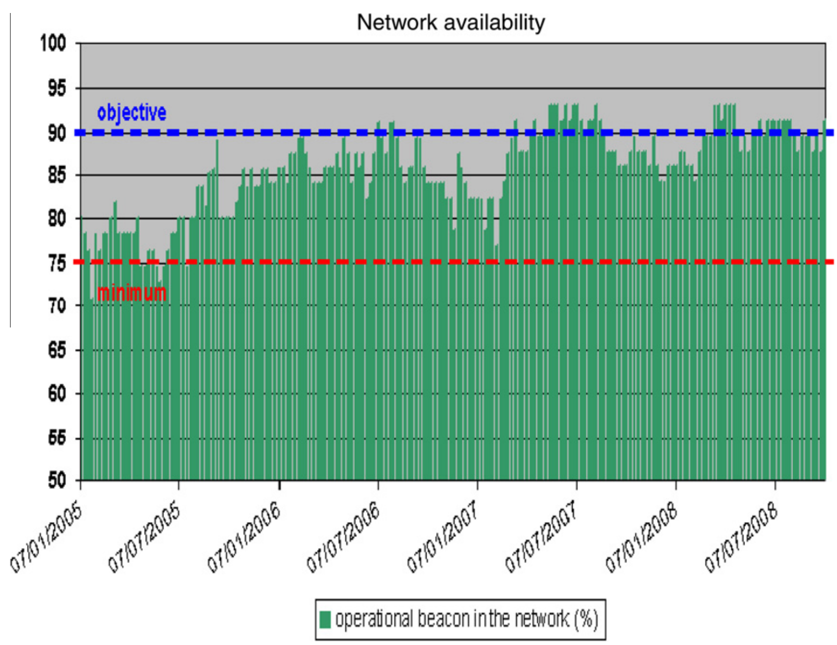

Fig. 14. Availability of the DORIS Network increasing since the DIT has been set up early 2005.

beacons, the co-visibility between stations for the same DORIS instruments and the same DORIS station observed by different satellites, new processing methods may be tested for global solutions of clocks behaviour. By estimating fewer parameters and giving more information to the models, these methods may present some gain in terms of accuracy (Willis et al., 2003).

3.3. Signal integrity monitoring

The "DORIS Integrity" Team (DIT) was set up in late 2004-early 2005 to permanently monitor the DORIS signal transmitted in space by the beacons in order to prevent or correct any malfunction, before it has a significant impact on the performances of the system (Jayles et al., 2006).

This permanent monitoring is achieved by systematic analysis of:

- Radio-frequency levels received by all contributing instruments in operations and comparison with theoretical expected levels.
- Orbit or positioning processing residuals.
- On-board and beacons USOs frequencies estimated by ground processing software.
- Time-tagging performance on-board Jason-1 and Jason-2.
- Navigation quality indexes.
- Software reports of DGXX instruments.

The positive impact of the activity of the DIT is evident on the availability of the DORIS Stations Network (see Fig. 14). The minimum station participation required for successful system operation is 75% of the beacons being active. Through careful and systematic monitoring, trends are detected, beacon malfunction are anticipated and corrective action is often initiated before a failure, thereby increasing network availability up to the objective of 90%. For instance the permanent monitoring of the signal transmitted by the Kauai station (Hawaii, USA) revealed that a metallic tower has been placed in the antenna field of view. The upper part of the tower was removed to resume the quality of the observations over this station (Yaya and Tourain, 2010).

4. Conclusion

With seven processing units, the new DORIS DGXX receiver is well adapted to track all the stations in the current DORIS Network from usual altitudes (500–2000 km). It also provides enough capacity for additional beacon tracked in the context of IDS experiments. The DORIS

DGXX receiver performs a complete set of phase, phase increments and pseudo-range measurements that are accurately time tagged and synchronized allowing different processing methods, and potential improvements. The sensitivity to radiation while crossing the South Atlantic Anomaly discovered on-board Jason-1 is now solved and should not degrade the geodetic applications for Jason-2 and other future satellites. A complete set of navigation data are provided allowing multiple applications such as operational navigation with respect to a terrestrial frame for the payload or with respect to an inertial frame for the spacecraft. The altitude with respect to the geoid surface is also helpful for altimeter control. No further evolution is currently planed for DORIS receivers, so, future altimetry or Earth observation missions will use DORIS receivers of the DGXX series.

The adoption of RINEX formats allows a daily distribution of data and makes the processing easier for the users.

Finally, the efforts to maintain upgrade and monitor the DORIS stations network, make it more available, reliable and accurate for the benefit of all the DORIS applications.

All the improvements realized on the DORIS system, presented above, are the result of work done in different workshops and groups (Operations Coordination, Orbit calibration and validation activities, DORIS Performance, DORIS Prospective), the feedback of the users via the International DORIS Service and the lessons learned through 20 years of operations and more than 60 years of equivalent single-satellite cumulated life in orbit. The major aim is to provide to the users an operational system which is accurate and stable for the long term. Taking into account current developments, the DORIS system should be operational for the next couple of decades.

After 20 years of operations, the DORIS system has reached the age of maturity.

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