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Back to Products

ARTICLE 1

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Title

Cryosat-2: Doris Instrument and System Description and First Month Results

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CRYOSAT-2: DORIS INSTRUMENT AND SYSTEM DESCRIPTION AND FIRST MONTH RESULTS

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ABSTRACT :

Since 1990, DORIS (Dopper Orbitography and Radiopositioning Integrated from Space) has evolved from a core system initially devoted to altimetry and precise positioning to become a very complete system today, able to deliver both real-time products and very precise retrieved orbits, at the one-centimeter level.

The DORIS system is described, as it is today after more than 20 years of development and operation. The main components of the system are detailed and their external and internal connections are described. The paper briefly presents the different DORIS products which are generated and used by the scientific community in the context of the International DORIS Service.

This paper then focuses on the DORIS on-board receiver, recalling the models which have been developed for the missions including: SPOT 2, TOPEX-POSEIDON, SPOT 3, SPOT4, ENVISAT, JASON1 and finally the DGXX models which are on-board the JASON2 and CRYOSAT2 missions thereby continuously improving the performance and reducing interface data. Specific characteristics of DORIS / CryoSat-2 are also detailed.

The major components of the DGXX instrument are presented including : the RadioFrequency (RF) chain, the 3rd order phase loop, the signal processing, the antenna, the Ultra Stable Oscillator (USO).

The major instrument performance is listed and the overall interface data are provided. Then DORIS / CryoSat specifics are detailed.

Finally the paper concludes with some views concerning future missions.

KEYWORDS

DORIS, Precise Orbit Determination, Altimetry, Geodesy, Real Time Navigation, Integrity

1. INTRODUCTION

The DORIS system has been developed jointly by CNES (*Centre National d'Etudes Spatiales*), IGN (*Institut Géographique National*), and GRGS (*Groupe de Recherche de Géodésie Spatiale*) in the context of the TOPEX/POSEIDON altimetry project.

A first demonstration occurred in 1990 with SPOT2, hosting a DORIS receiver developed by Dassault Electronique. Processing of those measurements allowed a few centimeters of orbit determination and station positioning.

First developed as a contribution to scientific missions, DORIS has evolved over 20 years to become a very efficient system with a high level of integrity. Successful flights on-board different satellites have been supported : SPOT2, TOPEX/POSEIDON, SPOT3, SPOT4, Jason-1, ENVISAT, SPOT5, Jason-2 and Cryosat-2 have driven significant evolutions of the DORIS system.

The first part of this text presents the different components of the DORIS system, the second part presents the DORIS on-board instrument. The third part is devoted to CryoSat.

2. THE DORIS SYSTEM AND PRODUCTS :

The main purposes of DORIS are precise orbit determination (POD) and geodesy. The system is based on accurate measurements of the Doppler shifts on a radiofrequency signal transmitted by ground stations and received on-board different satellites, carrying DORIS receivers, when they are in view of a station. The number of carrier satellites is unlimited.

Choosing a ground-to-space uni-directional link has allowed complete automation of the beacons and very simple communication of the overall system, since measurements and real-time products are generated, time-tagged and stored on-board. For each of the carrier satellites, a unique time-scale is used to generate measurements : reference time is derived from the DORIS on-board Ultra-Stable Oscillator (USO). The behaviour of this on-board clock is verified by processing of the measurements, during the POD processes on-ground, and also on-board in real-time. This allows the linking of the DORIS on-board time and frequency to the International Time Scale (TAI).

Measurements and on-board products provided by DORIS receivers are then used for :

- ⇨ on-board use of position/velocities WRT Terrestrial Frame as a help to payload products localisation (e.g. SPOT images, Jason Near Real-Time products)
- ⇨ on-board use of position/velocities WRT Inertial Frame as a help to AOCS pointing algorithms (e.g. Pléïades, CryoSat),
- ⇨ on-board use of geodetic data as a help to altimeter acquisition and/or tracking,
- ⇨ on-board use of DORIS TAI time-tagging of on-board time,
- ⇨ ground ultra-precise Orbit Determination,
- ⇨ orbit control (on ground),
- ⇨ ground beacon positioning,
- ⇨ geophysical modelling (Earth gravity field, atmosphere, ionosphere, …)
- ⇨ integrity control of the DORIS system,
- ⇨ …

2.1 Mission Center

The signal transmitted by the stations of the DORIS network is received by the on-board DORIS receivers.

DORIS data received by the different contributor satellites, collected in rough telemetry formats, are gathered into the *Segment Sol multi-mission d'ALTimétrie, Orbitographie et localisation precise* (SSALTO, Altimetry Orbitography and positioning Multi-mission Center) ground segment located in Toulouse.

SSALTO, within the project SALP (Service d'Altimétrie et de Localisation Précises), archives the data of each contributor satellite, checks the different DORIS receiver's performance and checks the overall DORIS system health. This is how these satellites contribute to the DORIS health control.

Finally, SSALTO generates the DORIS orbits and processed measurements, that are then forwarded to users, either together with altimetry products, or in the context of the International DORIS Service (IDS).

SSALTO may also generate commands and uploads for the satellites (parameter modification, new version of an on-board software), or for the network (broadcasts that will be transmitted by the "Master" beacons).

2.2 DORIS BEACONS NETWORK

The DORIS signal is transmitted towards space by the DORIS station network. The DORIS network is composed of about 60 permanent beacons, hosted by institutes of more than 30 different nations.

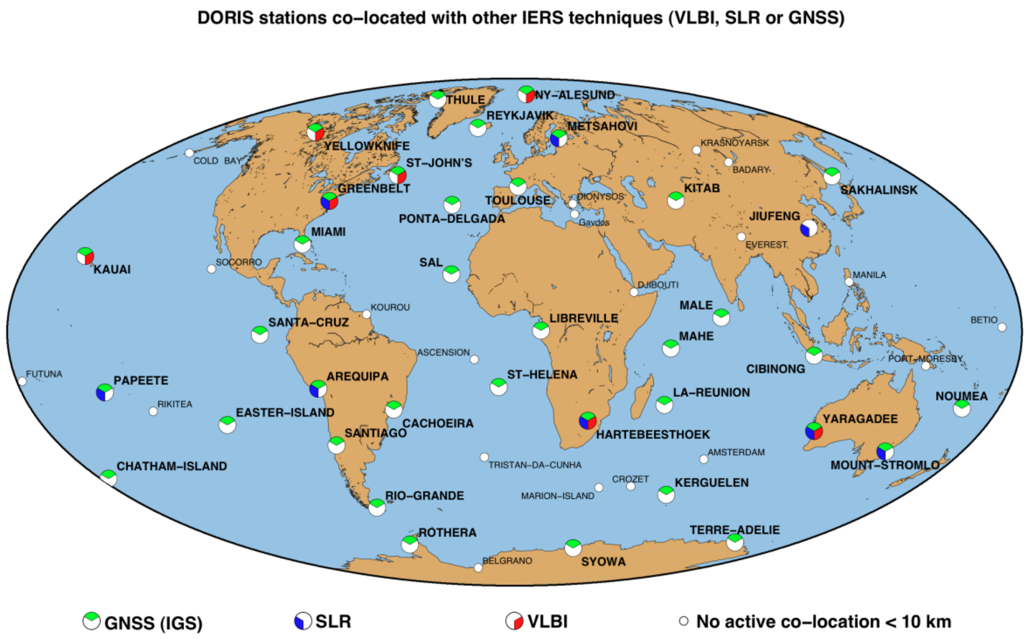

Figure. 1 – DORIS beacon network and IERS co-locations, January 2011

Figure. 2 – DORIS beacon antenna in Papeete

The beacons transmit the radiofrequency DORIS signals, composed of two modulated carriers. Two frequencies are used : 2.03625 GHz for precise measurement of the Doppler effect, and 401.25 MHz for ionospheric effect compensation.

Every station includes :

- a dual-frequency 400 MHz and 2 GHz transmitter with output power between 4 to 15 Watts depending on the channel or the beacon type or configuration,
- a USO delivering the reference frequency with a specified stability less than $5\ 10^{-13}$, over periods from 10 to 100 seconds.
- an omni-directional dual-frequency antenna,
- a battery pack, to provide autonomy versus power supply,

Several Time-Beacons (currently six) are tied to atomic clocks, whose delays are estimated and monitored with respect to TAI (International atomic time).

2.3 DORIS PRODUCTS :

DORIS has been contributing to the determination of the International Terrestrial Reference Frame (ITRF) of the International Earth Rotation and Reference System Service (IERS) since 1994 and since then its accuracy has always been improved. Measurements are retrieved by the different IDS Analysis Centers, to generate high-level scientific results or products, such as those described below.

2.3.1 DORIS ORBITS

The DORIS precise orbit ephemeris (POE) product is especially useful to scientific projects, as they help in the science processing of the satellite data. This has been the case of the CNES/NASA projects (TOPEX/POSEIDON for thirteen years and Jason-1 and 2 to-date) and of the ENVISAT and CryoSat ESA missions for their altimetry measurements. DORIS is the operational technique used for these orbits whose accuracy is estimated between 1 and 3 centimeters. When available, SLR or GPS data are used together with DORIS data to take advantage of these different techniques and provide the most accurate and validated products.

Rapid products are also generated with a few days delay for quick-look processing. Agreement with the POEs is a few centimeters on the satellite altitude (the radial component).

DORIS real-time products are also available when the delay is very short (a few hours), as is the case for Jason-1 and Jason-2 operational products. The accuracy achieved in real-time on the radial component of the Jason-2 orbit is approximately 3 cm RMS.

2.3.2 DORIS PROCESSED MEASUREMENTS

Associated with the precise orbit products, the DORIS processed measurements are made available to the scientific community via the IDS. The current format is Receiver Independent (RINEX)

2.3.3 POSITIONING PRODUCTS (TIME SERIES OF STATION AND POLE COORDINATES)

These products are generated by IDS Analysis Centers, and time-series are delivered to the scientific community.

2.3.4 OTHER CONSIDERED PRODUCTS

DORIS ionospheric data is not a routine product yet, but comparisons with GPS-derived results have already been made, showing good correlation. A project is underway to study to use DORIS ionospheric product as an additional source for International GPS Service (IGS) maps comparison and validation.

Comparisons have been made between DORIS and other systems tropospherical corrections, showing that DORIS produces a very interesting accuracy on this effect and should be more widely used.

DORIS is also very interesting for geocenter determination, which is a recent scientific subject. Accuracy of the geocenter determination (through the station coordinates time-series) is directly tied to the quality and the internal coherence of the Reference System.

3. DORIS INSTRUMENT

3.1 GENERAL CHARACTERISTICS :

The signals emitted by different beacons in view are received simultaneously on-board the satellite by a dual frequency omni-directionnal antenna (provided by Cobham, Dourdan).

The DORIS instrument, developed by Thales Systèmes Aéroportés (TSA, Elancourt), receives the signals through two RF chains (amplifiers, filters, mixers) at 401.25 MHz and 2036.25 MHz.

For the signal acquisition and precise tracking, the receiver includes a seven channel processing system. Each channel handles a single beacon signal, and includes a third order phase lock loop, which provides an excellent phase tracking, along with a minimal phase lag in case of rapid Doppler frequency changes.

The DORIS receiver performs Doppler measurements, i.e. phase and delta phase measurements (variation of phase between two measurements). When expressed in radial velocity, the delta phase measurements are designed to have a noise lower than 0.3 mm/sec.
All the receiver operations (clocks and local oscillators) are derived from the internal 10 MHz USO which provides the overall instrument phase and frequency stability. The on board USO is provided by the RAKON Company in Argenteuil.

Auxiliary data from the beacon (the beacon message) is also received. Those messages allow a time-tagging measurement which is performed by measuring the on-board date of the reception of a specific event (the raising edge of the first zero in the synchronisation message). This time-tagging measurement has an accuracy of a few microseconds.

The DORIS on-board package includes :

- two redundant processing chains performing Doppler measurements and receiving auxiliary data from the beacons,

- a fixed dual-frequency omni-directional antenna,

a USO delivering the reference frequency with a specified stability less than $5\ 10^{-13}$ over periods from 10 to 100 seconds.

In order to improve performance or robustness, software is stored twice in 2 redundant banks of Electrically Erasable Programmable Read-Only Memories (EEPROM). Software versions can be uploaded in-flight without any mission interruption drastically decreasing the criticality of this operation.

3.2 FROM FIRST GENERATION TO DGXX :

Since the first mission, DORIS receivers have evolved, leading to different generations of the on-board instrumentation. The capacity to track beacons simultaneously has also been increased :

- One beacon for the first generation instruments (SPOT2, TOPEX/POSEIDON, SPOT3, SPOT4)

- Two beacons for second generation instrument (ENVISAT, SPOT5, JASON1)

- Up to seven beacons for DGXX receivers (JASON2, ALTIKA, CRYOSAT2, PLEIADES,..)

This increases the number of measurements passes and their geometrical diversity, decreases or avoids the tracking conflicts for beacons in co-visibility and allows lower elevation measurements.

Figure 3 - DORIS DGXX receiver and the on-board antenna

DGXX generation receivers also perform accurate and complete phase, delta-phase and time-tagging measurements.
The interface has also been optimised : 18 kg, 24 Watts, 390*370*165 mm for the redundant DGXX configuration including two USOs which are now packaged inside the receiver.

Currently a new DGXX-S generation receiver is being designed for Sentinel-3 and Jason-3 missions.

3.3 NAVIGATION FUNCTION :

First introduced on SPOT-4, the on-board DORIS instrument embeds the DIODE (DORIS Immediate on-board Orbit Determination) software package which processes the beacon signals in order to provide real-time estimates of the orbital state vector. The estimated accuracy of these real-time values are :

• < 1 m (RMS) 3-axis position;

• < a few centimeters (RMS) radial component.

This service, sometimes called the DORIS *Navigator*, is used by the on-board systems for satellite navigation, and it is also provided in the telemetry so that good quality orbital parameters will be available before the POD can be produced.

The DIODE orbit determination software has been developed by CNES, with technical support by the AKKA Company. The first issue of DIODE has been flying on-board SPOT4 since March 1998, on an electronic card produced by Dassault Electronique and added as a passenger in the DORIS receiver. After this demonstration experiment, DIODE has been fully integrated in the DORIS on-board software, becoming a permanent feature.

Enhanced versions of DIODE are flying with ENVISAT, Jason-1 and SPOT5, allowing advanced automation of the receivers ; positions and velocities are produced with an accuracy better than 1 m RMS in 3D WRT the International Terrestrial Reference Frame and an availability close to 100%.

On-board processing pseudo-range measurements also allow comparisons to be made between on-board time and International Atomic Time (TAI) with an accuracy of a few microseconds.

On-board CryoSat-2, a J2000 estimate of position/velocity is delivered to the AOCS (see below).

On-board Jason-2 and AltiKa, a new DORIS-DIODE product has been implemented : Geodesic reports giving the altitude WRT a reference Geoid in order to help the altimeter tracking, to make available altimeter data over coastal and continental waters.

4. CRYOSAT-2 AND DORIS

4.1 ON-BOARD USE OF DORIS :

On-board CryoSat-2, DORIS is also used as a whole component of the satellite :

- The TAI time reference, provided by DORIS, is used as the central time reference on board CryoSat. The accuracy with which DORIS is able to provide the on board reference time is around 1 microsecond with respect to TAI.
- For the CryoSat mission, inertial J2000 on-board position and velocity (DORIS-DIODE new product) are now used by the Attitude and Orbit Control System (AOCS). This informs Cryosat-2 about its position, in an autonomous way. It is the first time that DORIS/DIODE estimations are used on-board in a satellite AOCS, thus contributing to satellite autonomy and the reduction of operations.
- A final on-board service offered by DORIS is the provision of the reference frequency to the SIRAL instrument, which does not have its own ultra-stable oscillator. The frequency of the DORIS oscillator is continuously monitored as part

of the POD service, and this measurement is taken into account in the processing of the altimeter data.

4.2 FIRST MONTHS RESULTS :

CryoSat-2 was launched on April 8, 2010 from Baikonour (Kazakhstan). DORIS was set on during the second day (Saturday, 14h). After a short convergence phase, DORIS has always been efficient since that time and has given the following overall results :

- POE ground orbits (DORIS+SLR) are estimated to have an accuracy of 1-2 cm RMS on the Radial component.
- The real-time orbit offers better than 99.98% availability and its results are compliant with specifications : between 7 and 9 centimeters RMS on the Radial component, while the expected accuracy was 30 cm.
- A failure caused by an unlikely event in the YellowKnife beacon, has led to a self-re-initialisation and a 1 hour unavailability of CryoSat-2 on-board products (not for the other DORIS missions).
- A new version of on-board software, correcting this failure handling, has been validated and is ready to be uploaded.
- Performance should be much better when improved thermo-optical properties of the satellite surfaces are delivered and taken into account.

5. CONCLUSION

Performance and operation of the DORIS system as well as other techniques for space geodesy (SLR, VLBI, GPS) have regularly progressed to meet the more and more demanding needs of the scientific community in oceanography, geodesy or geophysics. These different techniques have different characteristics making them complementary.

DORIS has reached a high level of integrity, which leads to an excellent overall availability of its different products. With DORIS/SPOT2, SPOT3, SPOT4, ENVISAT, TOPEX/Poséidon, SPOT5, Jason-1, JASON-2, ENVISAT and Cryosat-2, the DORIS system has today cumulated the equivalent of more than 50 satellite-years on-orbit.

On-board CryoSat-2, real-time J2000 estimates and time-tagging functions are fully operational and used by the satellite AOCS and system. This first demonstration opens the door to future on-board uses of DORIS system, allowing an improved autonomy of the satellites, among which Pléïades.