DORIS FOR BEGINNERS

(VERSION 10102016)

ABREVIATIONS

AOCS	Attitude and Orbit Control System
BDR	Redunded DORIS Box
CNES	Centre National d'Etudes Spatiales. The French Space Agency
DIODE	DORIS Immediate Orbit Determination Embedded- Software DORIS Navigation
DORIS	Doppler Orbitography and Radio Positioning Integrated by satellite
IDS	International Doris Service
IERS	International Earth Rotation Service
ITRF	International Terrestrial Reference Frame
SSALTO	Multi-Mission Ground Segment for Altimetry precise positionning and Orbitography, (CNES)
TAI	International Atomic Time
USO	Ultra-stable Oscillator

CONTENTS

Man walks upright: his horizon widens and he observes the planet.
Man climbs mountains: a new step, so what now?
Man launches satellites and he observes the planet.

Michel Lefebvre, October 2004

1. WHAT DOES 'DORIS' STAND FOR?

DORIS stands for Doppler Orbitography and Radiopositioning Integrated by Satellite. It is a satellite position determination system that was developed jointly by CNES (the French Space Agency), IGN (the French National Geographic Institute) and GRGS (the Space Geodesy Research Group).

2. WHAT IS DORIS MADE UP OF?

The 'DORIS System' is mainly composed of:

- a **network of some fifty stations** evenly distributed around the world (see below, Fig. 2.). These stations are very accurately geolocated and they emit the DORIS signal, which is picked up by carrier satellites.

- the **DORIS signal,** which is continually emitted by the stations and propagates through the atmosphere and then through the ionosphere. It is a two-part signal, composed of the Standard Beacons' Emission on the one hand, and Broadcast Uploads (only emitted by Reference Stations) on the other hand.

- a set of **satellites** carrying **DORIS receivers**. Each space-based receiver takes orbitography measurements using the signal emitted by the stations. The measurements are then used to compute the trajectory of the carrier satellite.

  A distinction can be made between **client** satellites (which only use DORIS measurements and data), and **contributing** satellites, which send their measurements and information back towards the SSALTO ground segment.

- a SSALTO ground segment, in charge of gathering DORIS data, which it uses to check the condition of the whole system (station network, on-board receivers, ground segment) and develops DORIS output and altimetry products.

DORIS products are then supplied to the scientific community on the Internet, via the International DORIS Service (IDS), in charge of relations with users.

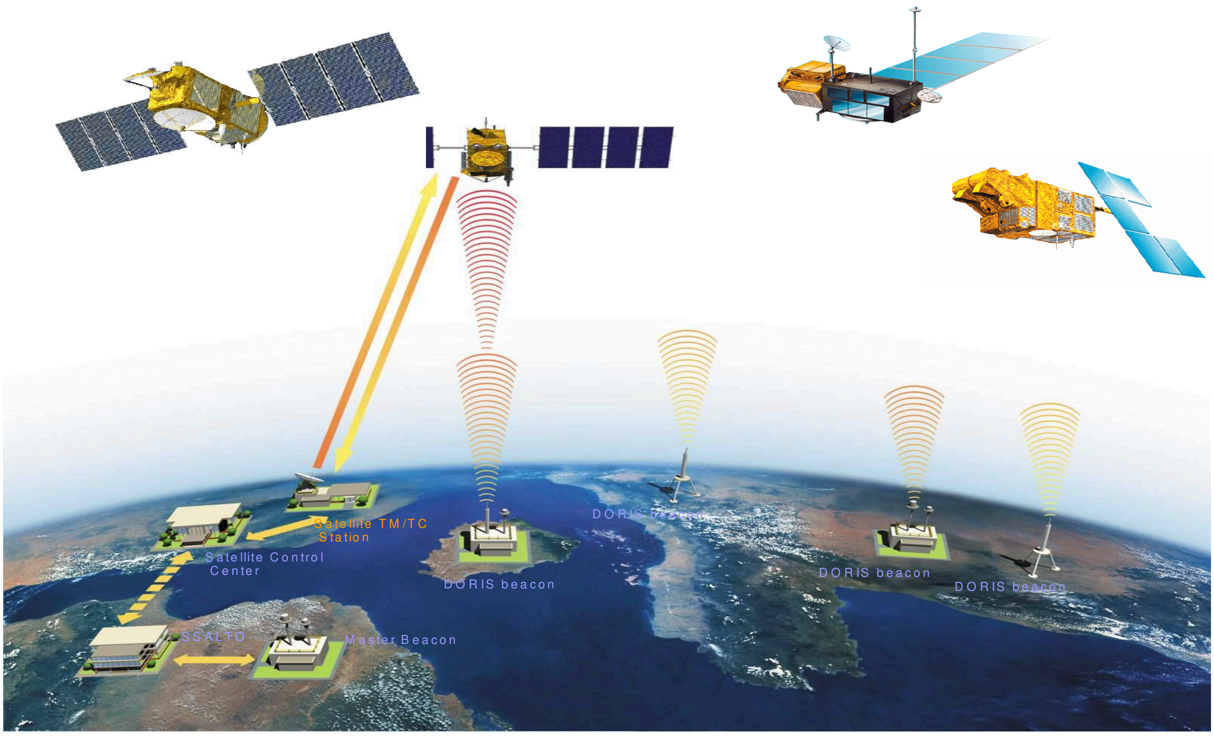


Figure 1: The DORIS system

Figure 2: The DORIS network in 2011 (56 stations)

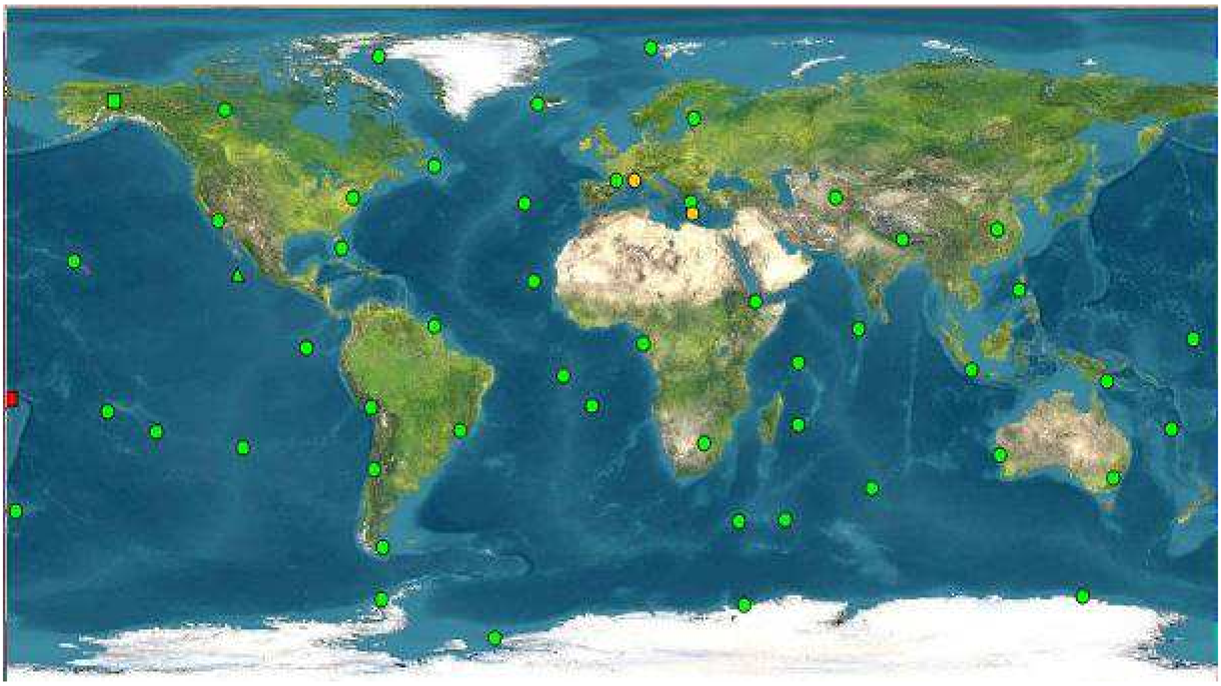


Figure 3: Active stations on a day in October, 2008

3. THE DORIS SIGNAL

The DORIS signal is continually emitted by the beacons, then propagates through the atmosphere and ionosphere, ultimately to be picked up by each of the space-based receivers. The signal is composed of two different kinds of upload:

- **The Standard Beacon Emission** is carried by two frequencies (401.25 MHz and 2036.25 MHz), on which the in-flight receivers measure the Doppler effect. Using these two frequencies enables combination and elimination of the ionospheric delay which is imperfectly modelled.

  Via the antenna, each on-board instrument receives the sum of different signals from various stations (all those currently visible), and demodulates this composite signal, splitting each beacon's data for each one of its seven Processing Units.

  To identify the beacon (which will be necessary for processing the measurement), emitted frequencies are modulated by a message containing the beacon number and some information on its internal state.

  Jamming between stations is rare: it sometimes occurs when the signal emitted by two different stations reaches the receiver with comparable frequencies, and with similar strength. Temporarily, a few measurements can be corrupted, before the receiver is able to distinguish stations.

- **Broadcast Uploads** are only emitted by Uploading Stations (one of the functions of the Reference Stations). These uploads contain the list of the active stations in the DORIS Network, and information necessary for the flight software to accurately determine time and process measurements.

All this information is used by every in-flight receiver to establish a set of orbitography measurements, which will then be processed by one of system's Orbitography Software Applications, either on board (DIODE), or on the ground.

4. WHAT DOES DORIS PRODUCE?

The precise processing of orbitography measurements enables SSALTO to create DORIS products, in particular 'Precise Orbit Ephemerides', which give the accurate location of satellites in the International Terrestrial Reference Frame (ITRF).

Be it on board or on the ground, 'orbit' products are created by comparing DORIS orbitography measurements and satellite movement models.

As in oceanography, meteorology and other disciplines alike, the 'orbit restitution' process uses an assimilation technique: this results in a very precise trajectory by drawing out the best data from the confrontation of measurements and models.

There are two kinds of DORIS measurement: Doppler measurements and synchronisation (or pseudo-distance) measurements.

5. WHAT IS A DOPPLER MEASUREMENT?

When a beacon emits an oscillatory signal with a known frequency fe, this signal is received by the satellite with a slightly different frequency, $fr = fe\ (1 - v / c)$, a function of the 'radial' velocity, i.e. the relative velocity v between the beacon and the satellite (in this formula, c is the speed of light). This is the Doppler effect, and it not only affects trains and ambulances, but also satellites.

DORIS uses this effect on oscillatory signals (with two frequencies 2036.25 and 401.25 MHz, modulated to identify the broadcasting beacon). Every ten seconds, the on-board DORIS receiver performs 'radial' velocity measurements of the satellite with respect to the stations.

The position of the satellite can then be determined by assimilating these measurements in a satellite movement model. If both the measurement and the model are precise, the resulting information on the position will be accurate. This is the case for DORIS, which was designed to be accurate to the nearest millimetre.

6. WHAT IS A SYNCHRONISATION MEASUREMENT?

The Doppler measurements are generated on board each satellite (in the DORIS receiver). They are time-tagged by the internal clock of the DORIS receiver. To assimilate these measurements into a satellite trajectory model, it is necessary to position them on a ground time scale. It is thus necessary to know how to establish the relation between the space-based clock and a ground time scale: International atomic time (TAI).

This ground time scale is established using a number of ultra-precise clocks in various laboratories (including the Caesium clock from the Time-Frequency Laboratory at CNES).

To establish the relation between beacon time and on-board time, we locate a particular bit from the beacon message: its arrival on board is time-tagged precisely by the on-board clock. As its emission date is known for sure (in the beacon's time), the time lag between the on-board clock and each of the stations can be deduced, every 10 seconds.

Since every beacon has its own time, this would of course be useless unless we 'tie up the loose ends': some DORIS stations (the Time Reference Beacons) are tied to a ground clock the time of which is known for sure with respect to the TAI.

Processing the synchronisation measurements made on the Time Reference Beacons establishes the on-board satellite clock time for each DORIS satellite. The Doppler measurements can then be processed to finally deduce the trajectory.

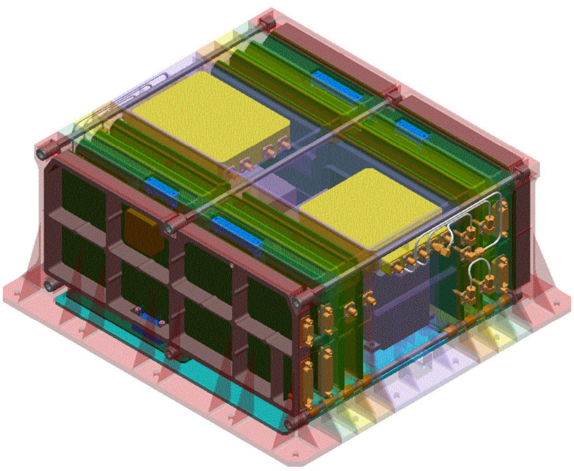
7. HOW IS THE RECEIVER MADE?

The receiver is an electronic device (called '*Boîtier DORIS Redondé*': BDR) screwed onto one of the walls of the satellite. Its current dimensions are 390 x 370 x170 mm, weighing 18 kg, with power consumption of 20 to 30W. In cold redundancy, the device contains:

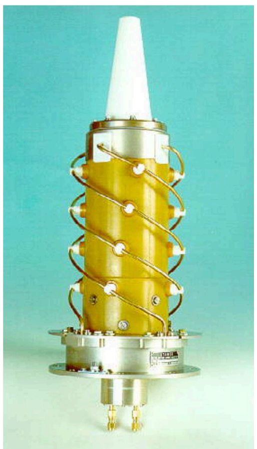
- two Ultra-Stable Oscillators (USO), used both as time generators (clock) and as frequency generators,
- a number of electronic boards equipped with resistors, memory units, capacitors and processors.

The electric power is supplied by the carrier satellite (the platform, generally via its solar array). The signals emitted by stations are picked up by the on-board DORIS Antenna (see below) and transmitted to the BDR by cables connected to the antenna's socket.

The output data are sent to the central computer (the satellite's 'brain'), which uses them in the satellite Attitude and Orbit Control System (AOCS), stores them in its mass memory and transmits to the ground via telemetry stations.



The DORIS Receiver: '*Boîtier DORIS Redondé*'



The DORIS dual-frequency antenna

8. HOW DOES THE RECEIVER WORK?

A DORIS receiver spends its first minutes in orbit as follows: as soon as it is switched on by the spacecraft, the receiver starts up in acquisition mode, acquiring the DORIS signal from the ground stations. During every pass over a station, the receiver alters its time schedule to best pick up the message emitted by the beacon every 10 seconds: the receiver is attuned.

One of the fundamental characteristics of a DORIS receiver is this time-scheduling on a 10-second cycle called 'Top Tdi' which is generated from its on-board clock (an Ultra-Stable Oscillator). The first goal is to properly synchronise this cycle with respect to the ground segment.

Acquisition of the common date and time (to the nearest 10 seconds): The first beacon successfully tracked by the receiver will give the time (to the nearest 10 seconds). The beacon message in fact includes the number of the sequence, i.e. the number of 10-second intervals elapsed since 1 January 2000, 0 hours (origin of the 'DORIS calendar'). This number is correct if the beacon is working properly (to the nearest 10 seconds). DORIS is a synchronised system, i.e. it requires its clocks to be correctly synchronised (let's say that the tens of seconds must be correct).

Synchronisation: It is not necessary, for the large majority of beacons in the network, to be synchronised with greater accuracy: a few seconds is enough. It would be difficult to require finer synchronisation for 50 beacons, some of them in rather isolated places, like Antarctica.

In order to tune its synchronisation, the receiver now has to wait until it passes over two Time Correction Beacons: these special beacons, driven by atomic clocks, are synchronised with TAI to with a few tens of microseconds. The receiver recognises them by their code. The first Time Correction Beacon passed over enables the receiver to choose the correct synchronisation, which is then confirmed by the second, after which the receiver continues its initialisation phase.

At this step, the on-board Tdi schedule is properly synchronised (to within around 10 microseconds) with the Time Correction Beacons and the receiver 'knows' time.

From this moment, a few minutes after flying over the second Time Correction Beacon, nominal synchronisation is acquired, and the receiver triggers the second phase of its initialisation process: the DIODE navigation system, when present, is activated.

As soon as DIODE is functional (it has its own convergence process), it knows the spacecraft trajectory and it is therefore able to compute the propagation time of the signals between the beacons and the satellite. The time correspondence between the Reference Stations and on-board time-scales can now be accurately measured. The accurate determination of this correspondence enables Doppler measurements to be precisely time tagged.

Very fine synchronisation: Bearing in mind what we have already seen, DORIS synchronisation measurements could allow even finer synchronisation (since DORIS receivers can handle propagation delays), to about the nearest microsecond. This possibility (enslaving the on-board time to the TAI, to within a few microseconds) is of no real use to DORIS today, and so is not performed by current DORIS receivers.

9. WHAT IS DIODE?

DIODE, when present, is a program embedded in the on-board DORIS receivers since DORIS / SPOT4, which processes DORIS measurements 'at the source', as soon as they are performed by the receiver. From this information, DIODE deduces an estimation of the carrier satellite position in real time every ten seconds (plus different by-products, in particular TAI time). DIODE provides a service to the spacecraft, by continually indicating its position (to within a few centimetres for some missions), and TAI time (to within a few microseconds).

10. AND WHAT ABOUT ON-GROUND ORBIT RESTITUTION SOFTWARE?

Functionally they have the same purpose, but they have a little more time for their computations: for example, time to get a refined position of Earth in space thanks to the VLBI system, or time to get refined Earth atmosphere reports in order to better handle the air drag or the troposphere. Furthermore these ground programs may process large amounts of data together, so that they can easily distinguish errors related to non-permanent disturbances because, for instance, they have the data from after an event, they somehow know the future... Finally, if anything occurs, we can change their tuning parameters and reactivate them so as to obtain a more satisfactory result.

These software programs also compute the satellite trajectory, but this time down to the nearest centimetre… sometimes even less.

11. THAT'S ALL VERY WELL, BUT WHAT EXACTLY IS DORIS USED FOR?

Altimetry satellites such as Jason 1, Sentinel 3 or SWOT, are fitted out with radar altimeters measuring distance between the spacecraft and the ocean surface (to within a few centimetres). **DORIS products provide an accurate estimate of the satellite position with a similar accuracy**. It is then possible to deduce the oceanic height of the overflown points, with unrivalled precision, even in the middle of the ocean!

Processing this information (also using an assimilation technique with an ocean model), gives more insight into:

- the average sea level and how much it rises every year; an indicator of climate change,
- tides (improvement of models) and water currents,
- El Niño, this huge 'wave' of warm water, as big as the United States, which sometimes crosses the equatorial Pacific in a few months (will there be one this year?),
- the mean surface of the ocean, with its hills and valleys correlated with the bottom.

The French MERCATOR centre, a forerunner in this field, communicates this information to navigating ships, offshore platforms, for management of marine resources or marine weather forecasting. Understanding the ocean is also very important for climatology and our understanding of the Earth's ecosystem.

For other satellites (SPOT), knowing their position is necessary for processing their photographs of Earth: DORIS contributes to the production of SPOT images.

And that's not all: when the position of several satellites is known with very high accuracy, it is possible to invert the point of view and adjust the positions of the stations over a time span of several years. This fine processing allows us to observe geophysical phenomena such as plate tectonics (continental drift), or vertical movements of stations, such as Everest's rise. With similar processes, it is also possible to observe Earth's orientation in space (the direction of the instantaneous pole of rotation), or the position of the centre of Earth: the centre is subject to small movements (of less than one centimetre), which DORIS can pick up! All this information helps to define and update the International Terrestrial Reference Frame (ITRF) which is necessary for accurate observation of the phenomena affecting our planet.

Furthermore, DORIS measurements are also sensitive to Radio Frequency disturbances of the signal as it propagates through the troposphere and the ionosphere. Processing these measurement 'residues' can help to better understand and model what occurs in the different layers of our atmosphere.

12. SALP AND SSALTO…?

SALP (which stands for '*Service d'Altimetrie et de Localisation Precise'*) is a CNES project, in charge of analysing Earth observation missions in the field of Altimetry and Space Geodesy. This project drives the operational activities related to the payloads POSEIDON (altimeter) and DORIS (precise orbit and geolocation), CNES satellites (SPOT, Pléïades) as well as non-CNES satellites fitted out with a DORIS receiver (Swot, Sentinel, Cryosat2). SALP also ensures the through-life support for the ground component of DORIS, the DORIS station network, in cooperation with IGN (the National Geographic Institute).

SALP is also responsible for the production and distribution of all the altimetry and precise location data; for this, it relies on SSALTO (the Ground segment for Altimetry and Orbitography, located in Toulouse) which includes facilities for:

- the control and monitoring of the POSEIDON and DORIS payloads
- monitoring the quality of real-time DORIS / DIODE orbits calculated on board the different satellites
- the control and monitoring of the DORIS ground station network and the integrity of the signal
- telemetry acquisition and data processing
- production of accurate orbits (with contributions from other techniques) and location of DORIS stations
- the archiving and distribution of altimetry and precise location user products through two websites: http://www.aviso.oceanobs.com and http://ids-doris.org/

13. SO WHAT ABOUT IDS THEN?

IDS (International DORIS Service) is in charge of data and product delivery to scientific users. It provides support for geodesy and geophysics research activities.

DORIS products are: DORIS measurements, Precise Orbit Ephemerides (POE), DORIS station coordinates, Earth Reference System characteristics, ionospheric data, etc.

Just like other systems (GPS, SLR, VLBI), it was set up as a service of the IAG (International Association of Geodesy), based on the DORIS technique, to work in close cooperation with the IERS (International Earth Rotation and Reference Systems Service).

IDS is based on:

- the DORIS station network, and the DORIS system group

- the 'DORIS satellite constellation' and the control centres of these satellites that collect DORIS telemetry

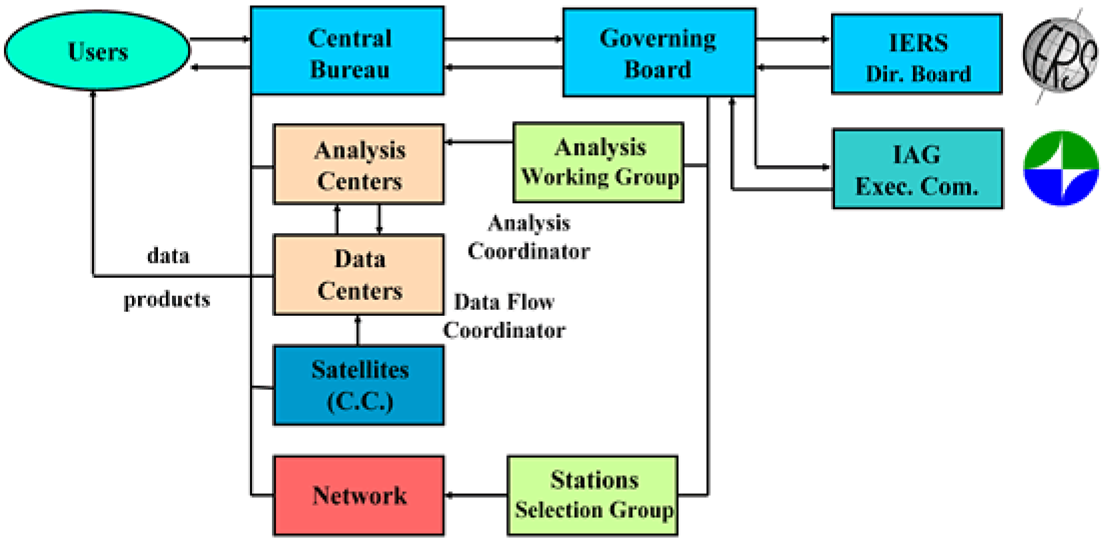
- two data centres, a server, a website for data distribution / archiving

- several analysis centres for data processing and generation of DORIS products, studies and research in geodesy / geophysics

- a governing board, that defines the guidelines / decisions of the service to users and the geodesy scientific community. A central office implements the decisions of the governing board.

- scientific users working in geodesy / geophysics using these data / products, as they participate in the research work.

A working group (AWG) periodically meets to discuss current studies conducted by the analysis centres and scientific users.



14. BUT IS DORIS TRULY AUTOMATED?

Almost. A lot of work was required even to get us to this point. Still, every day we perform detailed checks on its operation in order to upgrade it and enhance its performance, autonomy and robustness as it works to meet users' needs. This is what we call 'experience feedback'.

15. BIBLIOGRAPHY: A FEW DOCUMENTS:

Journal of Geodesy	DORIS Special Issue, vol. 80 No. 8-11, November 2006
Advance in Space Research	ISSN 0273-1177, vol. 45, issue 12, 15 June 2010
Advance in Space Research	ISSN 0273-1177, vol. 46, issue 12, 15 December 2010

16. A FEW SYSTEM DOCUMENTS:

INTERFACE SPECIFICATIONS BETWEEN THE BEACON NETWORK AND THE DORIS ON-BOARD INSTRUMENT
DORIS BROADCAST UPLOADS DEFINITION
DATING AND SYNCHRONISATION PRINCIPLES OF DORIS
SPECIFICATION OF INTERFACE BETWEEN DORIS BEACONS AND EXTERNAL CLOCKS
DORIS SYSTEM DESCRIPTION
SYSTEM REQUIREMENTS FOR MANAGEMENT OF THE DORIS STATION NETWORK
CALIBRATION PLAN
JUSTIFICATION OF THE DORIS-DIODE CONFIGURATION
CONFIGURATION OF THE IN-FLIGHT EQUIPMENT
DEFINITION OF THE SYSTEM