20 years of evolution for the DORIS permanent network:

from its initial deployment to its renovation

Hervé FAGARD[1]

[1] *Institut Géographique National, Service de Géodésie et Nivellement*

94165 Saint-Mandé CEDEX, France.

Fax : + 33 1 43 98 84 50, phone: + 33 1 43 98 81 48, e-mail : herve.fagard@ign.fr

Abstract

The ground network is one of the major components of the DORIS system. Its deployment, managed by the French national mapping agency (IGN, *Institut Géographique National*), started in 1986 at a sustained pace that allowed it to reach 32 stations upon the launch of the first DORIS-equipped satellite (SPOT-2) in 1990. For the first generation of transmitting antennas, the installation procedures were adapted to the decimetre performance objective for the DORIS system. During the second era of the deployment of an even denser network, the antenna support layouts gradually evolved towards a better quality, thus improving the long-term stability of the antenna reference point, and a new antenna model allowed a more accurate survey. As the positioning accuracy of the DORIS system improved, it was necessary to review the antenna stability for the whole network. A first stability estimation, using criteria like antenna model and support design, was followed by a major renovation effort which started in 2000 and is now almost complete. In six years, through the renovation or installation of 43 stations and the implementation of new installation procedures to meet more stringent stability requirements, significant improvement in network quality was achieved. Later a more analytical approach, taking into account the characteristics of each element that support the antenna, has been taken to assess the potential stability of all DORIS occupations. IGN is also in charge of its operational maintenance, an intensive activity on account of the significant failure rate of the successive generations of equipment. Nevertheless, thanks to its unique density and homogeneity, DORIS has maintained a very good coverage rate of the satellite orbits. Through 38 well-distributed current co-locations with the Global Positioning System, Satellite Laser Ranging and Very Long Baseline Interferometry techniques in its current 56-station network, DORIS contributes significantly to the realisation of the International Terrestrial Reference System. DORIS stations in areas where no other space geodesy technique is available provide a significant contribution to the study of plate tectonics. Many stations co-located with tide gauges contribute to the monitoring of sea level changes. Although it has several advantages over similar techniques, there is still room for improvement in the DORIS network.

Keywords: DORIS, tracking network, geodesy, reference frames, co-location

1. Introduction : historical background

DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) is an uplink Doppler system using two frequencies (401.25 MHz and 2036.25 MHz). It consists of a worldwide network of transmitting stations on the ground, receiving instruments onboard several low orbiting satellites, and a control and data collection centre (Jayles et al. submitted). Its major applications are precise orbit determination and ground station positioning.

The realisation of the DORIS system was decided jointly in the early 1980s by the French space agency (CNES: *Centre National d'Études Spatiales*), the French national mapping agency (IGN: *Institut Géographique National*) and a research group in the field of space geodesy (GRGS: *Groupe de Recherche de Géodésie Spatiale*). Because of its experience installing geodetic networks, IGN was responsible for the deployment of the ground network and for the determination and publication of the stations coordinates (Willis et al. 2005). For more than twenty years, the geodetic department of IGN (SGN: *Service de Géodésie et Nivellement*) has negotiated agreements with host agencies, installed the equipment, carried out the geodetic survey of the antennas, and kept the DORIS stations in working condition. The DORIS system has evolved through international collaboration, from the DORIS Pilot Experiment (Tavernier et al. 2002) to the International DORIS Service (IDS) (Tavernier et al. 2005).

An essential requirement for the precise computation of the DORIS satellite orbits was to ensure an almost constant visibility of at least one ground station by the on-board receiver. In order to meet such a requirement for the SPOT-2 satellite (832km altitude), it was estimated that the network should include approximately 50 stations, as evenly distributed as possible all over the globe. On the other hand, to be able to express the orbit in a geocentric terrestrial reference system, the coordinates of a sufficient number of well-distributed stations had to be available in the same system.

In this paper, we will relate the genesis of this unique network, and its evolution over two decades. After a general description of the site selection and installation procedure, and a description of the sites and points naming conventions, we will detail the history of the network's deployment and the three major eras of its evolution. We will describe the equipment used, focusing on the various antenna layouts that may have a significant influence on long-term stability, a growing concern as the accuracy of the DORIS data analysis results have steadily improved over the years. After listing the additional stations installed following proposals made in the framework of the IDS, we will explain how the network is maintained and give some statistics on the equipment maintenance. Then we will review the current network status: dealing with its configuration, its host agencies, user information, and an evaluation approach for antenna stability. In section 11 we will address DORIS antennas' surveying and coordinate determination including the definition of reference points, surveying procedures, and the determination of a priori geocentric coordinates. Co-locations with other space geodesy techniques and with tide gauges will then be listed. We will conclude by presenting the planned evolution of the network, after analyzing its strengths and weaknesses and comparing it with other space geodesy technique networks.

2. The steps of a DORIS station installation

2.1 Site selection criteria

The initial list of potential DORIS station locations, established around 1985, ensued mainly from the need for geocentric coordinates, the best source of which would be a co-location of the DORIS antennas with the highest accuracy space geodesy techniques available at that time: Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR). When none of these instruments were available, coordinates could be obtained through Doppler Transit or GPS (Global Positioning System) positioning, either already determined through international measurement campaigns or to be measured by IGN during the DORIS equipment installation. This was notably the case at many island locations selected to meet the density and homogeneous distribution criteria for the network, despite the lack of former measurements by space geodesy at these sites. The concern for co-locations between the DORIS stations and tide gauges appeared later, around the mid-nineties, with the growing interest for sea level change studies (Cazenave et al. 1999).

2.2 Selection of a host agency

After a site had been selected, a local agency was sought to host the station and take care of its maintenance, which would satisfy the following requirements :

- The transmitting beacon and its backup power supply needed to be in a room with moderate temperature and temperature variations and with continuous power available.
- The antenna had to be installed outside with a clear sky view above 10 degree elevation, on a structure that would allow the use of the antenna supports available at that time: guyed tower or wall side mount.
- Occasional maintenance operations would be carried out at IGN's request, including minor verifications and adjustments and return of malfunctioning equipment for repair.
- Frequencies transmitted by DORIS should not interfere with existing receivers in the same area; when this could not be avoided, a temporary interruption of the DORIS transmissions, either manual or automatic, could be accepted. The receiving systems that are likely to be affected by the DORIS signal are:
    - VLBI antennas: such interference, if it exists, may be avoided by having a physical signal obstruction between both antennas. Nevertheless there is one case (Kauai) where both antennas are inter-visible and no interference have been noted, so this issue deserves further investigation as its better understanding might open up new opportunities for DORIS-VLBI co-locations.
    - Upper atmosphere soundings carried out by most meteorological stations: some models of Vaisala receivers – which are used to receive the data transmitted by the radiosondes – are likely to be affected if the DORIS antenna and the radiosonde antenna are very close to each other (less than 30 m or so).
    - The 2 GHz antennas used by the Ariane tracking stations at Kourou, Ascension and Libreville.

In order to check that the prospective host agency would meet the above requirements, a questionnaire was sent which generally resulted in yes/no answers to a few questions, and a variable amount of details about the site layout. This has progressively evolved throughout the network's history, with a deeper and more detailed preliminary survey being conducted as the requirements for antenna stability have become more stringent (see section 7.2).

Once the planned location and host agency were found to be satisfying on the above points, the next step was to negotiate a written agreement signed by IGN and the host agency. Frequency clearance had also to be granted, which was generally handled by the host agency through an application with the relevant national radio communications authorities. Negotiation generally took several months, but some– especially in the recent years – took up to two or three years to succeed.

2.3 Installation stage

Once a host agency had been found and all the necessary authorizations granted, the installation was performed by IGN. This stage included :

- Dispatch and customs clearance of the equipment.
- Installation and starting up of the station.
- Training of the staff who would take care of the maintenance.
- Geodetic survey of the antenna's reference point, resulting in the connection to another space geodesy technique, or to the local geodetic network.

3. Identification of the DORIS site and points

Each "DORIS site" (i.e. a location hosting a DORIS station, where there may have been several successive DORIS points) is identified by its name. This name can be:

- The name of the "space geodesy site" – especially in the early days of the network deployment – which in some cases was very large (up to several dozens of km). For example, the so-called "Libreville" station is in fact located at N'Koltang, 40 km away from Libreville.
- The name of the city where the station is located, or the name of a nearby major city.
- The name of the island where the station is located.

In a few cases, the chosen site name turned out later not to be a very wise one. For example, "Galápagos" is the name of an archipelago made up of ten or so islands, extending over 300 km. Therefore a more accurate name (Santa Cruz, i.e. the name of the island) was chosen when a new station was installed in March 2005, in order to avoid confusion with the first station installed at Sán Cristóbal island, inaccurately named "Galápagos".

Each "DORIS point" (i.e. each location of a DORIS antenna reference point) is identified by:

- A DOMES number (e.g. 10202S003 for the current DORIS antenna at Reykjavik). DOMES (Directory Of MERIT Sites) is a numbering system for geodetic sites of common use within the IERS (International Earth Rotation and Reference Systems Service) community (see http://itrf.ensg.ign.fr/domes_desc.php) (Wilkins, 1989).
- A four character code, used in the data file names and defined as follows:
    - The first three characters are derived from the site name (e.g. La Réunion → REU, Cibinong → CIB, Ponta Delgada → PDL, etc.).
    - The last character identifies the antenna model: A for an Alcatel antenna, B for a Starec antenna (see sections 5.1 and 6.1)

When an antenna is changed from Alcatel to Starec within a DORIS site, the fourth character change – from A to B – is sufficient to distinguish between the two DORIS points. If an antenna is moved within a given DORIS site without the antenna model being changed, the third character of the code is incremented by one letter alphabetically to differentiate the new point. For example:

- The very first station at Reykjavik, equipped with an Alcatel antenna, was "REYA",
- After the Alcatel antenna was replaced with a Starec on the same tower, it was "REYB",
- Then in 2004 the Starec antenna was moved and identified as "REZB".

There have been a few exceptions to these rules:

- KOK were the first three letters for the code of the station "Kauai", from the name of the geodetic site and geographic entity "Koke'e Park". Moreover, when the first DORIS antenna at this site (KOKA) was replaced with a Starec antenna, it was named KOLB rather than KOKB in order to avoid confusion with the similarly named GPS station.
- SPI derives from the initial site name "Spitzberg" (a 39000 km^2 island) which was later changed to the more accurate site name "Ny-Ålesund", which is also the name used for the VLBI and GPS stations co-located on the same site.
- The code evolution at "Santiago" was SANA → SAOB → SANB (instead of first SANB, then SAOB).

Other numbering systems are used internally by CNES, notably for the programming of the on-board instruments.

A summary of all DORIS antenna codes with start and end date for each occupation is provided in the Electronic Supplementary Material (ESM) of this paper (file "DORIS-occupations.pdf"). Further information is available and regularly updated in the site logs on the IDS web site (see section 10.3).

4. Summary of the network's evolution

The first DORIS station was Tristan da Cunha (TRIA), which was installed by the Proudman Oceanographic Laboratory in June 1986. Other installations followed at a sustained pace, with about ten new stations installed in each of the first two years (Fig. 1), allowing the network to be operational when the first DORIS-equipped satellite (SPOT-2) was launched. Fig. 2 shows the distribution of the 32 stations that made up the network on the official start of the DORIS system operation (end of January 1990), with visibility circles corresponding to the 12° cut-off angle used at that time in the CNES pre-processing of the data. Then the deployment went on at a steady pace of about 5 new stations per year until the end of 1992. This date also marked approximately the end of the deployment of the first generation antennas, which will be dealt with in section 5.

(Place Fig. 1 around here)

As of 1993, the network deployment continued at a slower pace, as the "easiest" projects had succeeded. The number of stations reached 49, roughly the initial objective of 50 stations, by the end of 1993. A few new stations were added, and a few existing ones had to be moved to new locations either following the closure of host agency facilities, or to provide co-location with other geodesy techniques. All these new stations were equipped with second generation antennas, allowing a more accurate survey and a better stability, and a few with second generation beacons, requiring less energy and which should have been more reliable than the first generation.

(Place Fig. 2 around here)

In 2000, a general renovation program was initiated, in order to improve the overall stability of the antenna reference points, as required by the progressive improvement in the quality of the positioning results (nearing one centimetre, much better than the initial decimetre objective before the launch of SPOT-2). Many stations were completely renovated or moved to new locations. A few new stations were installed, all meeting the new, more stringent stability requirements. The deployment of the third generation beacons, featuring upgraded functions, commenced in 2001.

5. The deployment of the early network: the Alcatel era

5.1 Description of the equipment

The first version of the equipment that made up a DORIS station consisted of :

- The beacon, version 1.0, manufactured by Ceis, France. This element (Fig. 3), weighing 24 kg and designed to be integrated into a standard 19-inch rack, had to be installed inside a building with moderate temperature variations. It is programmed through a MMI (Man Machine Interface) consisting of a keyboard and an LCD screen. The beacon generates the DORIS signals: 401.25 MHz (6 W) and 2036.25 MHz (12 W).
- A box containing three 12V batteries, that provide backup power to the beacon during power outages lasting up to 72 hours.
- A dual-frequency omni-directional antenna (Fig. 4), manufactured by Alcatel. This antenna was bolted on an interface (consisting of a square horizontal plate welded on a vertical tube), which could be mounted on a variety of supports, in most cases a small lattice tower.
- A weather station (Fig. 4) measuring temperature (± 0.3°C), pressure (± 2 hPa) and humidity (± 4 %). These parameters are transmitted through the 400 MHz modulated signal and can be used to correct atmospheric propagation delays, but most analysis groups choose not to use them and rather estimate these corrections from the data (Snajdrova et al. 2006).

(Place Figs. 3 and 4 in this section)

5.2 Alcatel antenna layouts

IGN usually sent a standard set of antenna support devices in order to be able to adapt to the various site layouts likely to be encountered, for lack of detailed information beforehand on exactly where and how the antenna and beacon would be installed. These devices included several one-metre lattice tower sections, guy wires and a wall side mount for the antenna, and a small rack for the beacon and batteries. The IGN technician who carried out the installation sought suitable locations for both the beacon and antenna, compatible with what was generally the most restrictive limitation of the DORIS equipment set: the very short – 10 m – cable length between the beacon and the antenna, in order to reduce signal loss. In order to meet the good visibility requirement and this limitation, many antennas had to be installed on building roofs or on top of towers two or three metre high, sometimes higher.

The most frequently used antenna support was a triangular, 17 cm sided, galvanised steel lattice tower made of two or three one-metre sections, bolted together and set up on either an available concrete pad on the ground (Fig. 5), a concrete block specially built for the DORIS installation, or a terrace on the top of a building (Fig. 6).

(Place Figs. 5 and 6 around here, preferably side by side)

On a few sites where the antenna was installed on a roof, an open view allowed the use of a single tower section. Conversely, four sections had to be used at a few locations in order to avoid nearby signal obstructions.

When tower layouts were used, the tower itself was mounted on a square base plate, which was bolted to the concrete support using four expansion bolts. This base plate had a small vertical tube in its centre, which obstructed the ground mark if one had been set under the plate. In some cases the tube itself was used as the control mark. Such a control mark would be used in the future to check the antenna stability, and as a marker of the antenna location in case of movement or accidental destruction of the antenna.

Other designs have been more seldom used: a direct mount of the antenna interface on a roof, without using a tower (Fig. 7), a propped steel pole (Fig. 8), or a tower mounted on the side of a wall (Fig. 9). In a few of these cases, no ground mark was present, which had little consequence except at Amsterdam/AMSA and Tristan da Cunha/TRIA where, after the antenna was destroyed by a storm, the original location had to be “reconstructed” from the remaining parts of the support in order to determine the geodetic connection between the former antenna and the new one.

(Place Figs. 7, 8 and 9 around here, preferably side by side)

Most towers were supported with stainless steel cable wires and turnbuckles, providing strong and stable fastening of the tower. At a few sites the cable wires were very long, somewhat loose, or even nonexistent, which did not guarantee centimetre-level stability of the antenna. In the early stages, this was considered acceptable given the expected positioning accuracy of the DORIS system at that time (10 cm according to the pre-launch simulations, rapidly improving to a sub-decimetre level accuracy as shown by the first results). On the other hand, the effects of thermal expansion of the metal tower (about 1 mm for a 50°C temperature variation affecting a 2 m tower) on the vertical position of the antenna were and still are negligible.

By adjusting the tension of the stays, it was possible to centre the antenna base (i.e. reference point) above the ground mark when present. However, none of the above antenna support designs allowed precise vertical adjustment of the antenna to guarantee that the electrical phase centres – and notably the 2 GHz phase centre upon which the positioning measurements are performed – are on the same vertical line as the antenna reference point. This centimetre-level error could be ignored during the early years of the DORIS positioning, but it was taken into account – by measuring the phase centre offset with respect to the antenna base – when Alcatel antennas were surveyed prior to removal, during the network's renovation phase. It is now significant when taking into account the recent centimetre-level geodetic results obtained with the DORIS system (Cretaux et al. 1998, Willis et al. 2005).

6. The network densification: the Starec era

A new antenna model has been used since mid-1992, replacing the original Alcatel antenna, whose deployment ended in September 1992 with the installation of the two Australian stations at Canberra-Orroral and Yaragadee. The number of stations in the network increased through 1993, when it stabilised at around 50 stations, before increasing again slightly at the end of the 1990's. During this period (1994 to 1999) several stations were moved to new locations, and a few had to be upgraded following either beacon failures or damage caused to antennas by strong storms. Second generation beacons were installed on a few sites as of late 1995 (first one at Krasnoyarsk/KRAB), but they were never deployed on a very large scale: the maximum number of units operated simultaneously in the network was 14 (in 2003).

6.1 Description of the second generation equipment

The new antenna model (Figs. 10, 12 and 13), manufactured by Starec, France, offered several improvements with respect to the original Alcatel model:

- slimmer design, much less sensitive to the wind, making it less prone to damage by storms,
- better defined phase centre location (to within 1 mm, vs. 5 mm for the Alcatel antennas),
- slimmer and more rigid design allowing a more precise survey and centring.

(Place Fig. 10 around here)

From its very first deployment, this antenna model was mounted on a triangular plate machined at IGN's mechanical workshop, linked to the underneath support by screws and nuts that allow a very fine adjustment of the antenna verticality (Fig. 10). Three different materials have been used for this triangular plate: anodised aluminium, marine aluminium, and stainless steel. Unfortunately no record of the material used at each DORIS station was kept until the end of the 90's, and we discovered after the event that corrosion had affected a few anodised aluminium plates, thus causing significant antenna tilt at the following stations: Amsterdam/AMSB, Chatham/CHAB, Marion Island/MARB, Reykjavik/REYB, St Helena/HELB.

The new beacon (Fig. 11), called "2.0 DORIS beacon", manufactured by Sorep, France, had the following differences with respect to the original 1.0 beacon:

- Much lighter (8 kg) and more compact,
- Waterproof casing allowing its deployment in more humid environments,
- External power supply (the internal one on the first generation beacons has been the cause of most failures), in the form of a charger and two batteries in a dedicated waterproof box,
- Lower power consumption (30 W vs. 120 W for the 1.0 model) permitting installation at locations where electrical power is limited,
- User interface through an external computer. The beacon itself gives no indication of its current operating mode (the computer is required to know if it is transmitting, or in standby).

(Place Fig. 11 around here)

The meteorological station associated with the second generation beacon had the same functionalities as the first model, but was lighter and more compact, and used different sensors (precision: ± 0.25 °C for temperature, ± 1.5 hPa for pressure, and ± 5 % for humidity).

During this period the length of the antenna cables was increased from 10 to 15 m, allowing more freedom in the selection of antenna location. Twenty metre cables have been used at a couple of locations but, because of the higher signal attenuation they cause, their use has been and should remain limited.

A modified version of the first generation beacon (version 1.1) was developed, consisting of a 1.0 beacon whose failure-prone internal power supply unit was replaced with the external power supply box from the second generation beacon. A few such units were deployed in order to keep several stations operating at a time when the number of second generation beacons was not sufficient to replace the aging first generation ones.

6.2 Starec antenna layouts

The antenna supports used during the 1993-1999 period were more or less standardised: most Starec antennas were installed, using the triangular plate, on a 2 metre high, 17 cm sided steel lattice tower, fastened with stainless steel guy-wires and turnbuckles (Fig. 12). The base of the tower was bolted directly into the concrete support with three expansion or chemical anchors. A ground mark was always embedded in the concrete support, and would from then on be usable since the base square plate dealt with in section 5.2 was no longer used. Using both the antenna triangular supporting plate adjustment nuts, and the turnbuckles, the antenna's verticality and centring above the ground mark was carefully adjusted to within one millimetre.

(Place Fig. 12 around here)

The exceptions to this standard layout were:

- The Alcatel antennas that had to be moved (e.g. following host agency premises closures) were generally relocated exactly as they were initially, using the same support. Several such relocations were carried out by the host agency with no intervention by IGN.
- Three metre high (Cibinong/CIBB, Rio Grande/RIOB, Rapa/RAQB, Socorro/SODB, La Réunion/REUB) or even higher (6 m at Syowa/SYOB) towers were used in order to avoid nearby signal obstructions.
- One metre (or less) high towers were used: with guy-wires at Santa Maria/SAMB and Krasnoyarsk/KRAB, no guy-wires at Everest/EVEB, Ottawa/OTTB, Papeete/PAPB (later moved to PAQB), Libreville/LIBB and Fairbanks/FAIB. The half-metre tower without guy-wires turned out to be very easy to install on top of a

building wall while offering a very good rigidity, and was therefore retained during the renovation of the network dealt with in section 7.

- The antenna triangular supporting plate was installed directly on a concrete pillar, using three short threaded rods embedded into the concrete. This very stable design was first used in February 1997 at Ascension/ASDB (Fig. 13), then at Amsterdam/AMSB, Syowa/SYPB and St John's/STJB.
- A very rigid 3 metre steel pole was used at Mount Stromlo/MSOB.

(Place Fig. 13 around here. If needs be, Figs. 12 and 13 can be placed side by side)

7. The renovation era

The need for an improvement to the DORIS antenna stability emerged in the mid-1990's, after the increasing positioning accuracy of the DORIS system allowed it to be accepted as a new technique for the realisation of the ITRS (International Terrestrial Reference System) (Boucher et al. 1994; 1996). When an existing station had to be moved, or when a new one was installed, increased attention was paid to the installation of the antenna on a very stable support (Fagard and Orsoni 1998). Such a policy was applied until the end of the 1990's: monumentation improvements were realised only when we had to travel on-site for another reason. On-site interventions whose sole purpose was to improve the monumentation were carried out only as of 2000. Guy-wires were still used to fasten antenna supporting towers, but they were installed with more care than in the early years of the DORIS network (3 guy-wires at 120 degree spacing, identical lengths, stainless steel hardware).

At the end of 1999 IGN and CNES decided on a global renovation project to improve the stability of the antennas. This project was presented to the DORIS community during the "DORIS days" workshop in May 2000 (Fagard and Orsoni 2000), and initiated with the renovation of the Djibouti station in July 2000.

7.1 Network preliminary review

In order to plan this renovation action, it was first necessary to review the situation at all DORIS sites, in order to determine the necessity and urgency of a stability improvement. This evaluation took the following parameters into account:

- The type of antenna (Alcatel or Starec). Although neither antenna can be considered more stable per se, the Alcatel antenna has several characteristics (see sections 5.2 and 6.1) that allows it to be considered less stable a priori.
- The kind of antenna support (metal tower with or without guy-wires, concrete pillar, other designs).
- The nature of the structure on which this support was installed (building, rock, concrete block, etc.).
- The date of the installation, as recent installations could reasonably be considered of better quality.

This resulted in a one to three star stability grade given to each antenna (Fagard and Orsoni 2000). This evaluation was later refined for internal use by IGN, into four categories defined in Table 1.

(Place Table 1 around here)

These apparently objective evaluation criteria were modulated by a subjective feeling on the antenna support overall quality. The resulting stability estimate for the whole network is shown on Fig. 12.

(Place Fig. 12 around here)

It is important to note that the purpose of such an estimation was only to allow us to properly manage the network renovation and monitor its progress. The resulting estimate should neither be regarded as an indicator of the quality of the stations computed coordinates and velocities, nor be used to classify them, since the actual stability of an antenna can only be properly assessed by surveying it at different epochs with respect to a stable reference mark. A more refined stability assessment will be presented in section 10.4.

Moreover, this was a theoretical approach, and the actual behaviour of the antennas did in some cases differ significantly from our expectations, for better or for worse:

- Corrosion of the antenna triangular base plate (the anodised aluminium type) caused a several centimetre antenna tilt on a concrete pillar, for an “excellent”-rated antenna support (Fig. 15: Amsterdam/AMSB).
- The antenna centring turned out to be still within a few mm after more than ten years – which is quite good – for several Alcatel antennas installed during the very early years of the DORIS network, whereas such antenna configurations had been rated “poor”.

(Place Fig. 15 around here)

7.2 Quality requirements and monumentation designs

7.2.1 Requirements

In order to be compatible with the expected, and almost achieved accuracy of the DORIS positioning system at the centimetre-level, the objective in terms of stability of the DORIS antenna reference point was defined as one centimetre over ten years. Such a requirement had the following consequences on the design of the antenna supports that would be used for all future installations and for stations renovations:

- Guy-wires should no longer be used to fasten a supporting tower and adjust the antenna centring. Although such a design turned out to be very stable over many years, it is not 100% reliable, as accidental damage, or progressive slackening of one stay would result on an antenna horizontal shift, either sudden or progressive. While sudden antenna shifts may be well detected by analysis centres, progressive ones may be more difficult to detect, and in any case all such movements add unnecessary bias to the time series and should be avoided.
- Only the antenna supports described below should be used.

7.2.2 Design 1: concrete pillar

The preferred antenna support is a concrete pillar (Figs. 16 and 17), built according to “geodetic” specification, which take the nature of the ground into account. The pillar designs shown on Figs. 18, 19 and 20 have been derived from those used by the Canadian Geodetic Survey Division (Geodetic Survey Division, 1995). A triangular plate is set on three A4 stainless steel rods embedded in the concrete pillar, and a series of nuts to adjust the antenna verticality. The triangular plate, machined by IGN mechanical workshop, is made of either high quality stainless steel (AISI 316 L) or marine aluminium. Such a pillar should nevertheless be smaller than two metres in order to limit the antenna horizontal movements caused by the difference in thermal expansion between both sides of the pillar (such movements are about 1 mm for a 2 m tall, 40 cm diameter pillar, if the temperature difference is 20°C). For the same reason, pillars are generally painted in white in order to limit heating by the sun.

(Place Figs. 16 and 17 around here)

(Place Fig. 18, 19 and 20 around here)

7.2.3 Design 2: self-supporting metal tower

The second preferred support is a very rigid lattice tower (self-supporting type, not requiring guy-wires), installed on a very stable concrete structure at ground level. This concrete base is built according to the same specifications as the concrete pillar described above. In a few cases, existing concrete structures were used if they were in good condition and their dimensions seemed to guarantee a good long term stability.

The tower design is preferred when surrounding signal obstructions (often caused by the very building that hosts the DORIS beacon) requires that the antenna be higher on the ground than a concrete pillar would allow, and/or when an already available good quality concrete base, permits an easier and cheaper installation than specially building a concrete pillar.

(Place Figs. 21 and 22 in this section)

Finding strong enough lattice towers, available in one-metre sections (that fit easily even in the small airplanes that service some very remote DORIS locations) was not a easy quest. After trying a first model (installed at Santiago/SANB and Easter Island/EASB) whose finish left to be desired, 32 cm sided, galvanised steel towers manufactured by Leclerc SA, France, have been used at many DORIS stations and turned out to be satisfactory (Fig. 21). This tower model has an additional advantage: it can also support the third generation meteorological station after its standard installation set was slightly modified by IGN (Fig. 22).

7.2.4 Design 3: antenna on a building

At a few DORIS stations, even putting the antenna on a two metre tower, set on a concrete block protruding 30 cm or so off the ground – which puts the lowest phase centre almost three metres above the ground – is not sufficient to give enough clearance because of high nearby signal obstructions. In such cases, the only option is to put the antenna on a building, generally the one where the indoor DORIS equipment is located. Such a layout can give satisfactory results stability-wise, provided the following precautions are taken:

- The location where the antenna support is installed should be carefully selected with respect to the structure of the building (Fig. 23), in order to achieve the best possible long-term stability. Ideally, the antenna support should be installed on top of a load-bearing pillar, or at the corner of two load-bearing walls. If such a solution is not achievable, the closest approach is sought (e.g. not putting the antenna on the centre of a slab roof but rather near the junction to the underneath load-bearing wall). If necessary, the construction drawing of the building or advice from the builder can be used.

- The antenna support is as small as possible. Putting the antenna on top of a building saves a few metres and hence sometimes gets rid of most signal obstructions, therefore the antenna can be put on a very short tower. Using only one section of a 32 cm sided tower (Fig. 22), or a half-metre 17 cm sided one (Fig. 24) – which has the additional advantage of fitting on narrow concrete beams – guarantees an optimal and equivalent rigidity of the support.
- When possible, the tower should be bolted or embedded directly in the underneath load-bearing structure. This requires special precautions when a waterproof coating covers the roof.

(Place Figs. 23 and 24 in this section)

7.3 The third generation beacons

A new generation of beacons was introduced, and deployed as the renovation progressed (Tavernier et al. 2003). The first "standard" third generation beacon – i.e. apart from the master beacon at Toulouse – was installed at Tristan da Cunha in January 2002. Their development was stopped for a while as of February 2004 after a serial failure on the 2 GHz channel had been discovered, and resumed in July 2004 with retrofitted units.

(Place Fig. 25 around here)

This new set of equipment (Fig. 25) is composed of:

- The beacon, version 3.0, manufactured by SMP, France. Its appearance is very similar to the first generation one, with a bigger LCD screen and a more sophisticated MMI. It should be installed inside a building and fits in a standard 19-inch rack. The power consumption is approximately the same as the first generation beacon (130 W). Contrary to the previous models, the signal is modulated on both channels. It also has a new "Restart" operating mode allowing its signal to be received even if the time is not properly set. It is not necessary to set the time when starting such a beacon, since this mode allows us to monitor the beacon's time and frequency without disturbing the receivers, until proper corrections are performed upon request.
- A charger that supplies power to the beacon and monitors the charge of the backup battery.
- Three different configurations (30 Ah, 110 Ah and 220 Ah) for the 12V battery.

- The weather station (Fig. 22) is a Vaisala PTU200 unit. The precision of its sensors is: ± 0.5 °C (temperature), ± 0.25 hPa (pressure) and ± 3 % (humidity).
- The antenna (Starec model) is unchanged.

7.4 The progress of the renovation

As can be seen on Fig. 26, there has been a steady and definite improvement of the network quality stability-wise between 2000 and 2005. During this six year period the following improvements to the network took place:

- 31 existing stations were renovated (between 3 and 10 per year),
- 4 stations were added to the network,
- 8 new stations were installed as a replacement for existing ones which were closed,
- 2 stations have been removed and not yet replaced (Arlit and Guam).

(Place Fig. 26 around here)

The renovation turned out to be much longer and complicated a process than we first expected. Its progress was affected by the need for detailed site survey and the elaboration of many logistical details for the site preparation prior to new installations and renovations, with some projects requiring 3 years to complete.

8. The IDS network augmentations

In the context of the establishment of the IDS (Tavernier et al. submitted), groups made proposals to host additional DORIS stations not included in the permanent DORIS network, with varied scientific objectives and durations.

The following experiments have been carried out to date (Fig. 27):

- An ice sheet monitoring experiment was conducted by Geoscience Australia on two glaciers in Antarctica, by operating a DORIS station from Nov. 2001 to Jan 2002 (Sorsdall glacier), Dec. 2002 to Jan. 2003 (Lambert glacier) and Nov. 2003 to Jan. 2004 (Sorsdall glacier).

- Following a proposal of the German BKG (Bundesamt fûr Kartographie und Geodäsie) to operate DORIS stations at Wettzell (Germany) and within the Transportable Integrated Geodetic Observatory (TIGO) located at Concepción, Chile (Schlüter et al. 2002), a DORIS station was installed in May 2003 at Wettzell. It was removed in January 2004 after producing little data, due to interference to the VLBI on one hand, and an equipment failure on the other hand.
- A DORIS station was installed on the Gavdos island, South of Crete, in September 2003, as part of an altimeter calibration site (Pavlis et al. 2004). It was inactive for an extended period of time because of a beacon failure followed by a shortage of spare beacons, but a retrofitted third generation was installed in February 2006.
- A station was installed at the Antarctic Argentine base "Belgrano II" in January 2004, following a joint proposal by the IAA (Instituto Antártico Argentino) and the German AWI (Alfred Wegener Institute). Because of a failure of the second generation beacon shortly after its installation, it provided little data during the first year of operation, but it has worked very smoothly after a third generation beacon was installed one year later. Considering its excellent results and significant contribution to the network coverage and robustness in the Antarctic region, the "DORIS Mission Group" – consisting of representatives of CNES and IGN – decided in December 2005 to change its status from "IDS experiment" to "Permanent DORIS station".

(Place Fig. 27 in this section)

9. The network maintenance

9.1 Maintenance running

In addition to the deployment of the network, IGN is also in charge of its maintenance, the operation of which can be summarised as follows (Fig. 28):

- An anomaly is detected by the DORIS control centre (recently renamed "integrity team"), either in the form of a complete lack of measurements, or of a wrong parameter (time set, frequency, meteorological parameters, power cut, etc.)

- The DORIS control centre (now integrity team) sends – for each anomaly detected – an intervention request to IGN's maintenance team (SIMB: *Service d'Installation et de Maintenance des Balises* = beacons installation and maintenance service)
- IGN/SIMB contacts the host agency, asking it to carry out the necessary operation
- The host agency performs the requested operation, and reports to IGN/SIMB, which then reports back to the DORIS control centre (integrity team)

(Place Fig. 28 in this section)

9.2 Maintenance statistics

Equipment reliability has been a major issue throughout the life of the DORIS network. Over the whole DORIS system operation time period, the proportion of emitting beacons in the network averages to about 85 %, with lows at 73 % and highs reaching 95 %. On many occasions, stations have remained down for several months before equipment could be replaced, because of very long delays to carry out repairs, frequent shortages of spare units, long administrative and customs procedures, transport delays and seasonal constraints. This rate nevertheless allows the global coverage rate – ratio of time during which the on-board instrument receives a signal – to remain at a good level, thanks to the density and homogeneity of the network. This coverage rate, whose maximum theoretical value is 93% for the highest DORIS-equipped satellites like TOPEX-Poseidon and Jason-1 (both at 1330 km altitude), is still 80 % when 20 % of the stations are down.

Each generation of beacons has had its own share of specific problems:

- The first generation beacons' main source of problems was the internal power supply which caused 70 % of the failures. Other failures were due to the oscillator or to the synthesizer.
- An amplifier problem on the second generation beacons caused a few month interruption in their deployment around 1996. Apart from this temporary anomaly, which was corrected in 1997, this model did not turn out to be more reliable than the first generation. In 2005, a new problem (power supply defect creating spurious in the signal) was detected, which could require the replacement of the remaining units by third generation beacons.
- Almost all third generation beacons installed between early 2003 and August 2004 were affected by a failure on the 2 GHz channel, which required these units to be retrofitted. After this problem was solved, the

deployment of this model has resumed, either on the occasion of a major site renovation or by simply shipping a new model to the host agency that took care of its installation. From then on, the operating rate for this model has increased to 90 %.

From the start of the DORIS system operation, IGN's maintenance team handled on average 150 intervention requests and 12 beacon exchanges a year.

Several types of operations are likely to be requested to the host agency. The most frequent ones are time or frequency adjustment (78 %), which are not problem corrections but mere adjustments, since in most cases a shifted time or frequency does not hamper the proper reception of the signal and hence does not affect the system reliability. To correct a beacon failure, a reset of the beacon (4 %) – automatic for the third generation beacons – or checking through a self-test procedure (8 %) may have to be performed. In some cases, equipment may need to be exchanged: battery charging or replacement (2 %), replacement of the weather sensors (2 %), or exchange of the beacon by a spare (6 %). No on-site repairs are carried out by the host agency. Because of the shipment waiting period, customs formalities and scarce transport services to some remote DORIS locations, the necessary time to have a spare beacon delivered on site can vary tremendously, from a couple of weeks to as long as one year.

On the other hand, planned interruptions of the emissions to avoid interference with other receiving systems occur at the following sites:

- Yellowknife and Syowa: during 24 h VLBI campaigns, about ten times a year
- Kourou, Ascension and Libreville: during the tracking of the Ariane rocket upon each launch from Kourou, lasting for a few hours about ten times a year
- Mahe and Rapa: during the meteorological radiosoundings, once or twice a day for about one hour

10. The current network status

10.1 The current network configuration

In February 2006, the distribution of the different beacon types in the permanent network (56 stations) is : 42 third generation beacons, 7 second generation beacons, and 7 first generation beacons (including one 1.1 beacon at Socorro). As far as the antennas are concerned, there are only 2 Alcatel antennas left, all others (54) are Starec antennas.

Three stations – Toulouse, Kourou and Hartebeesthoek – have a special status as they are equipped with "master beacons" (Jayles et al. submitted) used for the programming of the on-board satellite instruments.

10.2 The host agencies

The host agencies who kindly host and maintain the 56 stations that make up the DORIS network can be divided into the following categories:

- National survey agencies: 10 stations
- National space agencies: 12 stations
- Scientific institutes (mainly dealing with Earth sciences), including universities: 19 stations
- Polar institutes: 8 stations
- Meteorological stations: 6 stations
- Telecommunication station: 1 station

There are in total 43 distinct host agencies (some of them host several DORIS stations at different locations), representing 32 different nations.

10.3 Information to users

For each DORIS station, a sitelog is made available to the users in the form of a text file, on the IDS web site (http://ids.cls.fr/html/doris/sitelog.html). It contains general site information, information about the successive antennas and beacons installed at the station, accurate coordinates of the current antenna, list of available IERS and tide gauge co-locations (if any), local geodetic survey results, description of the meteorological instruments and contact for further information.

Each major evolution of the DORIS network (e.g. new station, antenna change, station removal, etc.) is announced to the DORIS community in the form of a DORISmail (Tavernier et al. 2005).

10.4 The antenna stability evaluation

Now that the network renovation is almost complete, we have tried to assess more precisely the quality of the antenna support at all DORIS sites, in order to define criteria for site quality so as to identify a set of core stations with accurate coordinates that might contribute to the ITRF (International Terrrestrial Reference Frame) (IDS 2004).

The best way to actually assess the antenna stability would be to carry out stability surveys on a regular basis. Since this would require human and financial means well beyond those allocated to the maintenance of the DORIS network, other approaches had to be considered:

- An analysis of the structure of the antenna support.
- The results of the antenna centring check when available.
- A time series stability study based on the statistical analysis of several years of DORIS weekly station coordinates (Le Bail, submitted), that is influenced by several factors among which is the antenna stability.

The first approach will be described here in detail. It consists in assessing all elements in the antenna support (i.e., from top to bottom, all items between the antenna and the ground) that may contribute to some extent to the antenna instability. The more elements between the antenna and the ground, the higher the risk of experiencing an antenna reference point and/or phase centre displacement in the long term. Each potential source of instability contributes (with an appropriate weighing factor) to the "instability degree" = ID.

The higher ID, the less presumably stable the antenna. With the marking system and weights that were chosen, ID ranges between 7 (best) and 44 (worst) for all former or current DORIS antennas. Table 2 gives the minimum, maximum, mean and standard deviation of ID at two different epochs (before and near the end of the renovation). The detailed result of this analysis is presented in the form of an Excel spreadsheet (file “Stability-assessment.xls”) in the ESM of this paper.

(Place Table 2 around here)

Fig. 29 shows the result of such an assessment, for the same network as on Fig. 14, but using this more detailed and less subjective approach, over the one explained in section 7.1.

(Place Fig. 29 around here)

To explain how this evaluation was carried out, we will go from top to bottom through the different elements which make up an antenna support. The different values for a given criterion can be seen in the pop-up comment fields of the ESM spreadsheet file.

A. Antenna and supporting plate:

- Antenna: neither antenna type is more stable than the other one. But because the Starec antenna is easier to survey and has better defined phase centres, it is considered better.
- Supporting plate: here we assess the plate's material, which is likely or not to corrode and cause an antenna tilt (which already happened at several sites).
- Plate assembly: plate assembly that meets the installation specification ensures that the antenna is rigidly fastened to the tower, and that the antenna's verticality can be precisely adjusted. This is the case at almost all sites but a couple, which were given two "instability points" instead of one on this criterion.

B. Primary support: this is the element below the antenna supporting plate and the assembly device. It can be either a concrete pillar, or a metal tower.

B.1. Concrete pillar or metal pipe:

- Construction type: marks the way the pillar was constructed (according to IGN's specifications dealt with in section 7.2, or not).
- Ground hardness: bedrock, hard soil or soft soil.
- Height: because even a concrete pillar can be bent by temperature differences between the sunny side and the shady one, and this deformation is in proportion to it height, a concrete pillar should not be too high.

B.2. Metal tower: we have been using two main tower types in the network: Normand, and Leclerc.

- Tower model: "Leclerc" (32 cm sided, self-supporting) is better than "Normand" (17 cm sided, needs to be guyed if height is more than one metre).
- Height (Leclerc tower): although this kind of tower is very rigid, the smaller the better.

- Height (Normand tower): weight=3 for this criterion because the amplitude of an antenna movement (if a guy-wire breaks or becomes loose, which cannot be completely ruled out and actually already happened) increases very much with height.
- No guy-wire (Normand tower): the lack of guying will have between "no influence" (for a half-metre section) and "a lot of influence" for a very high tower.
- Guying quality (Normand tower): good guy-wires have turned out to be very efficient in maintaining a mm-level centring over several years at some sites. Moreover, a bad quality guying will have of course a different influence on antenna stability, depending on the tower's height.

C. Secondary support: this is the element below the primary support. It can be either a concrete block in the ground, or a building. If the primary support is a concrete pillar or a metal pipe anchored into the ground, there is no secondary support.

C.1. Concrete block or pad on the ground: same criteria as the concrete pillar.

C.2. Building:

- General structure: here we have marked how stable the building is likely to be, according to the kind of structure and materials used.
- Primary support location with respect to the most stable parts of the building.
- Height of tower base above ground: stability-wise, the lower the building the better. Nevertheless as the influence of this parameter is difficult to evaluate (presumably less important than, and highly dependent on the building’s structure and the location of the antenna), it was assigned a very small weight.

D. Whole site / geological stability: little can be done as far as this criterion is concerned, other than choosing another site. For lack of detailed information, this was set to 2 for most stations, and the weight was set to 1, so that it would have little influence anyway on the result of the assessment. Nevertheless, this criterion should be properly assessed in the future.

Fig. 30 shows the antennas stability degree at the time of writing, when the renovation of the network is almost complete. If the activity projects for 2006 can be carried to a successful end, the biggest circles on this map should have significantly shrunken by the end of the year.

(Place Fig. 30 around here)

The second approach used in assessing the antenna stability consisted in measuring its eccentricity with respect to the reference ground mark below the antenna, when one was present, on the occasion of an antenna upgrade or move. This was done at 32 out of the 102 antenna positions. The resulting antenna eccentricities are distributed as follows:

- Less than one mm (not measurable) for 6 antennas (including several guyed towers, installed near the end of the "Starec era" dealt with in section 6.2
- Up to 1 cm (more likely resulting from an imperfect centring at the time of the installation, rather than from an antenna movement) for 12 antennas
- 1 to about 3 cm for 9 antennas, where a shift is likely to have occurred, due to poor quality guying
- Two Alcatel antennas had eccentricities between 4 and 6 cm
- The following Starec antennas were affected by corrosion of their base plate causing a several cm shift of the 2 GHz phase centre: Amsterdam / AMSB (Fig. 17), Chatham / CHAB (not mentioned in the ESM file because the code was not changed after the tilt was corrected), and St Helena / HELB (before it was corrected in July 2002)

No correlation can be seen between the antenna stability index on one hand, and the actually measured antenna eccentricity at these sites. But such an eccentricity check was carried out on too small a number of stations to be significant. Moreover, it should be noted that such a centring check only allows the stability of the antenna reference point to be surveyed with respect to the mark at the base of the antenna. It doesn't allow detection of movement of the secondary support of the antenna (tower base or building), which can only be monitored through a footprint survey.

The third approach (dealt with in Le Bail, submitted) assesses the actual antenna coordinates stability with respect to a global geocentric frame through a noise analysis in the weekly time series, hence taking the effects from many elements (antenna stability, operating rate and performance of the system, ionospheric scintillation, radio-frequency jamming, etc.) into account.

11. DORIS: a space geodesy technique

11.1 Definition of the antenna reference point

The antenna reference point for all geodetic surveys and published antenna coordinates is defined as follows (Fig. 31):

- Alcatel antenna: intersection of the antenna axis, and the plane containing the top of the small edge at the base of the antenna
- Starec antenna: intersection of the antenna axis, and the plane containing the red ring on the antenna body. This point is also the 400 MHz phase centre.

Table 3 gives the phase centre height with respect to the antenna reference point, for both antenna models.

(Place Fig. 31 and Table 3 in this section)

11.2 Surveying a DORIS antenna

Initially, all Alcatel antennas were surveyed when they were installed, using conventional surveying techniques, by intersecting the antenna from several surrounding points. The sightings were done to the left and right side of the antenna base, in order to determine the reference point position. No attention was paid to a possible antenna tilt, which could anyway not be adjusted with the interface between the antenna and its supporting tower. The height of the antenna with respect to the ground mark (if any) was measured with a tape, but because of the layout of the antenna base and interface, only few mm level accuracy could generally be achieved in doing so.

Starec antenna have also been surveyed by conventional geodetic survey methods for a few years, but as of 1997 a special interface designed and machined by IGN has been used to force-centre a GPS antenna on the same triangular plate that supports the Starec antenna (Fig. 32). This allows a direct and very accurate GPS connection between another geodetic point on one hand, and the Starec antenna base on the other hand. The connection of the reference point was derived from the antenna verticality adjustment and the measurement of its height above the antenna base.

Over the last few years, the most common survey process has been to measure a direct connection between the Starec antenna and an existing permanent GPS station, in most cases part of the IGS (International GNSS Service, formerly International GPS Service) network (Moore and Neilan 2005). When possible, a spirit levelling connection between the DORIS and the GPS antennas is also measured in order to guarantee a more accurate determination of the vertical component.

As of 2000, a forced-centring interface (Fig. 33) – built from a recycled Alcatel antenna base – was also used to survey the Alcatel antennas upon their removal, thus allowing a direct GPS determination of the Alcatel reference point.

(Place Figs. 32 and 33 in this section, preferably side by side)

11.3 Determination of a priori coordinates

Prior to the launch of the first DORIS instrument on board SPOT-2, IGN provided CNES with an initial set of coordinates for the DORIS network, labelled JCOD0. These coordinates were expressed either in the BTS87 realisation of the BTS system (BTS: BIH Terrestrial System, the predecessor of the ITRS) or in the early realisations of the ITRS: ITRF88 or ITRF89. The reference epoch was 1984.0. This set of coordinates was later complemented as new stations were deployed after the start of the DORIS system's operation, in the form of updates of the initial set, labelled JCOD0.n.

Such geocentric coordinates could be obtained in different ways (Boucher and Fagard 1991) from the geodetic tie between the DORIS antenna and another geodetic point in the vicinity:

- If the DORIS antenna was tied to a VLBI antenna or SLR telescope, which were generally already part of the BTS87 or ITRFnn solution, the resulting coordinates' accuracy was better than 10 cm.
- If the DORIS antenna was tied to a Transit Doppler point, either already determined or observed simultaneously to the DORIS installation, the resulting coordinates had to be transformed from the ephemeris system (such as NSWC-9Z2, NWL-9D or WGS84) into BTS87 using a seven-parameter transformation (BIH 1988). The resulting coordinates accuracy was around one metre if precise ephemerides had been used in the computation of the Transit point, vs. 2 to 10 metres with broadcast ephemerides.
- In a few cases, the DORIS antenna could only be connected to the local geodetic network, and the coordinates expressed in the national datum were transformed to BTS87 using available transformation parameters, notably those determined by the Defense Mapping Agency (Defense Mapping Agency 1987).

Depending on the accuracy of the transformation used, the resulting accuracy for the coordinates was between 2 and 10 metres.

After the DORIS system had begun operating, a series of coordinates sets labelled JCODn were successively published by IGN (Willis et al. 2005). Each of these coordinate sets resulted from the combination of solutions obtained by different groups from the analysis of DORIS data. As of 1994, DORIS was accepted as a new technique for the realisation of the ITRS, which allowed coordinates for the DORIS antennas to be published in the ITRF94 (Boucher et al. 1996), ITRF97 (Boucher et al. 1999), and later ITRF2000 (Altamimi et al. 2002) solutions.

Nevertheless, as new stations were deployed, or antennas moved, there has been a constant need for a priori coordinates for these new DORIS points. Such coordinates, which are made available to the DORIS users community in the DORISmail that announces the station installation or moving, are determined – following a geodetic survey during the installation of the new antenna – in one of the following manners:

- If one or several IERS techniques (in addition to, or other than DORIS) are available nearby, the antenna is connected to at least one of these techniques (generally a permanent GPS), and all observations are adjusted with one IERS point held fixed to its ITRF2000 coordinates (Altamimi et al. 2002).
- If only a former DORIS antenna is available, it is used as the fiducial point and the new antenna coordinates result from the connection between the new and old antennas.
- If no IERS point is available nearby, GPS measurements are performed on the new antenna location, and geocentric coordinates are derived by processing very long baselines between the unknown point and several surrounding IGS stations, using the Bernese software (Hugentobler et al. 2001).

11.4 Co-locations with other IERS techniques

A co-location is defined by the fact that two or more space geodesy instruments occupy simultaneously or subsequently close locations which are very precisely connected in three dimensions by means of a geodetic survey (Altamimi 2003). The shorter the distance between both instruments, the more accurate is the survey tie likely to be. Moreover, the likelihood that both points have distinct movements due to tectonic plate movement or local geological phenomena generally increases with the distance between these points. Therefore unless surveys are repeated on a regular basis in order to control the stability of the tie vector, it is safer to limit the size of a co-located site. In the inventory below and on the map (Fig. 36), only the co-locations for which the inter-technique distance is less than 10 km, and the survey results are available, were taken into account. This value was selected since it allows to retain almost all potential co-locations between DORIS and other techniques, while rejecting a couple of much longer distance ones.

Having as many co-locations as possible with other space geodesy techniques has always been a major objective throughout the deployment and evolution of the DORIS network. We also had this objective in mind when planning the renovation of the network carried out between 2000 and 2006, which led to the following evolution:

- Purple Mountain (no co-location) replaced with Jiufeng (first and only DORIS-SLR co-location in Asia),
- Colombo (no co-location) replaced with Male (GPS + tide gauge co-location),
- Richmond (former VLBI co-location, no longer active) replaced with Miami (GPS + tide gauge co-location),
- Galapagos (no co-location) replaced with Santa Cruz (GPS + tide gauge co-location),
- Goldstone (former SLR co-location, no longer active) replaced with Monument Peak (active SLR + GPS co-location).

At present, there are co-locations between DORIS antennas and other active IERS techniques at 38 out of 56 permanent DORIS stations. These co-locations are distributed as follows (Fig. 34): with GPS at 37 sites (only the stations part of the IGS network are taken into account), with SLR at 9 sites, and with VLBI at 7 sites. Among these, some are 3 technique co-location sites: GPS + SLR at 8 sites, and GPS + VLBI at 7 sites. Lastly, the four techniques contributing to the realisation of the ITRS are available at two sites: Greenbelt and Hartebeesthoek.

A more complete inventory, that includes former DORIS stations and formerly operating other techniques, is available in the ESM of this paper (file “DORIS-co-locations.pdf”).

(Place Fig. 34 in this section)

11.5 Internal DORIS co-locations

Following the evolution of the network dealt with in sections 6 and 7, there has been more than one antenna location at most DORIS stations (see Fig. 37 and the “DORIS-occupations.pdf” file in the ESM). In order to ensure both the continuity of the time series, and an optimal contribution of DORIS to the IERS by allowing us to compute a better geodetic velocity, it is essential that all successive antenna locations be accurately tied together through a geodetic survey. This has been done for most sites where the distance between two successive antenna locations is less than 10 km.

11.6 Co-locations with tide gauges

Like other space geodesy techniques, DORIS can be used to provide an absolute geodetic reference for tide gauges. As of the mid-90’s, with the growing interest for the monitoring of the sea level, a geodetic connection was measured between the DORIS antennas and a nearby tide gauge if available. Moreover, the possibility to add more such co-locations was taken into account when planning the evolution of the network. This concern had some consequences on the design of the current network:

- The Mahe and Crozet station installations were motivated by the possible co-location with a tide gauge, whereas adding a new station in such well-equipped regions was not absolutely necessary, as far as the network density was concerned.
- The replacement of Colombo by Male, Richmond by Miami and Galápagos by Santa Cruz, was partly motivated by the possible co-location with a tide-gauge.
- The location of the Sal station, which was a replacement for Dakar following the closure of the host agency at that site, was selected so that the DORIS station would be on the same island – out of 10 or so forming the Cape Verde Republic – as the tide gauge.
- Additional stations were suggested at Bermuda and Fernando de Noronha in the Atlantic Ocean, Pohnpei and Midway in the Pacific Ocean, but eventually abandoned after several years of fruitless attempts to bring these projects to a successful conclusion.
- The current projects for new stations in the Pacific Ocean (Tarawa, Kiritimati, and Adak) are all tide gauge equipped sites.

Moreover, measuring a few missing DORIS – tide gauge ties on the occasion of the network renovation allowed us to progressively increase the number of such co-locations (Fig. 36) up to 19 available ties, which contribute, thanks to the very good vertical precision of DORIS (Willis et al. 2005), to sea level studies (Cazenave et al. 1999). The list of co-locations between currently operating DORIS stations and tide gauges is available in the ESM of this paper (file "DORIS-co-locations.pdf").

(Place Fig. 36 in this section)

12. Planned evolution

12.1 Strengths and weaknesses of the DORIS permanent network

Compared to other space geodesy networks, the DORIS network has the following unique advantages:

- It is much more homogeneous, hence making the IERS network denser where needed, by adding points in regions where no other techniques are present. Whereas the IGS network (Moore and Neilan 2005) has many more stations (about 300), it has a very heterogeneous distribution, with very dense areas over Europe and the USA, and large gaps over the Pacific Ocean, Southern Indian Ocean, and Africa (North of the Equator). In addition, neither the ILRS (International Laser Ranging Service) network (Pearlman et al. 2002) nor the IVS (International VLBI Service) network (Schlüter et al. 2002) are equally distributed.
- It has practically the right number of stations to meet its primary objectives. The PRARE (Precise RAnge and Range rate Experiment) network (Massmann et al. 1997), which initially aimed at achieving the same objectives at DORIS, has 10 stations currently installed, out of an initially planned network made of 30 or so stations.
- Unlike other IERS techniques, it is perfectly divided into the Northern and Southern hemispheres: there are exactly as many (currently 28) DORIS stations in both hemispheres. Moreover, out of 38 co-located sites, 18 are located in the Southern hemisphere.
- Its centralised management by IGN and CNES has facilitated a major renovation effort, leading to an almost standardised equipment layout across the network. All equipment changes are tracked by one group (the DORIS maintenance team), which permits recurrent problems to be detected and the necessary corrective actions to be taken.

Although quite satisfying, the current network's density, homogeneity and robustness (i.e. its ability to ensure continuous tracking of the satellite orbits when a given station is down) could still be improved. The map on Fig. 37, on which the visibility circles of the stations were drawn for the lowest DORIS-equipped satellites (832 km altitude) and for a cut-off elevation angle of 12°, shows a few weak areas:

- A large gap in the southern Pacific Ocean, which will remain impossible to fill for lack of islands in this area.
- Another gap in the western tropical part of the northern Pacific Ocean, which has always existed, was made worse by the removal of the Guam station. A new replacement site at Tarawa, Republic of Kiribati, is likely to be installed in 2006.
- Although the Kauai station has a central location in the northern Pacific Ocean that allows good quality coverage, the network's robustness is not sufficient in this area since a failure of this station means that a significant part of the orbit will no longer be tracked. Additional stations, one north and one south of Kauai would be highly desirable, but IGN's efforts over several years to bring these difficult projects to fruition have failed so far. Sakhalinsk is also somewhat isolated and would be well off being backed up by an additional station south of Japan.
- Less striking but nevertheless improvable robustness wise, the removal of Arlit left a less densely covered area over North Africa, where a failure of Libreville leads to a gap of the orbit coverage for the lowest satellites. The planned installation of a station at Tamanrasset (Algeria) would slightly improve the robustness while adding one more GPS (and maybe SLR) co-location.

(Place Fig. 37 around here)

As far as the co-locations with other techniques are concerned, DORIS-IGS co-locations are in sufficient number. Nevertheless, adding a few more would do no harm and could be achieved without any modification of the DORIS network, by simply including existing permanent GPS stations in the IGS network (e.g. Rothera, Port Moresby, Futuna). But more DORIS-SLR co-locations, and still more DORIS-VLBI co-locations should definitely be added, as stated in one of the recommendations of the IDS plenary meeting in May 2004 (IDS 2004). Putting a DORIS station near a VLBI antenna is likely to cause some interference to the VLBI as experienced at a few sites, but this is not systematic and this issue deserves to be investigated. In regard to the DORIS-SLR co-locations, Fig. 36 shows that there is a huge area between Metsähovi, Hartebeesthoek and

Jiufeng where no such co-location is present. This gap could be partially filled by installing a DORIS station, and accurately tying it to the SLR station at Riyadh, Saudi Arabia, which gives excellent results.

Equipment-wise, a problem was recently detected on the connection between the beacon and the antenna, at some sites using the concrete pillar design. Because of the short clearance between the top of the pillar and the base of the antenna, and the stiffness of the antenna cable, a N-type bent adaptor must be used to connect the cable to the antenna in such layouts. As this adapter is not designed for outside use, especially in the very harsh conditions encountered at some DORIS sites, its corrosion may cause a loss of transmitted power.

In regard to the antenna stability control, the stability assessment presented in this paper, although more refined than the first approach used, cannot pretend to replace an actual measurement through repeated footprint surveys.

Lastly, it should be noted that a sometimes insufficient tracking of the DORIS on-board instruments, was seldom due to the network design and management, although some host agency closures have caused long data gaps until a replacement solution was implemented. The main reason for DORIS data loss was essentially the significant failure rate of the ground equipment. Administrative and customs procedures delaying equipment changes, and seasonal access constraints contributed to make out of order periods longer, while absence of data distribution by CNES at the beginning of the operation of a new station, and during the first three years of the system's operation also had a large impact on the data availability. Despite evolution of the transmitting beacons, many equipment failures, added to long repair times, have caused several months of data interruption at many sites, and shorter but repeated periods at other places. Nevertheless, the recent massive deployment of retrofitted third generation beacons lets us feel the first stirrings of hope for a significant improvement of the operation ratio.

12.2 Evolution plans and proposals

The DORIS stations at Dionysos, Kourou, Toulouse, Socorro and Krasnoyarsk still have to be renovated, and this should hopefully happen in 2006. The last two remaining Alcatel antennas in the network – Dionysos and Toulouse – will then have been replaced with Starec antennas.

A new station should be installed at Rikitea (Polynesia), which will eventually replace the one at Rapa. Moreover, new stations are in project at Tarawa and Kiritimati (Republic of Kiribati), Adak (Aleutian Islands), Tamanrasset (Algeria) and Riyadh (Saudi Arabia). Fig. 38 shows the location of these planned new stations. Apart from these projects, a further densification of the network is not currently necessary from the orbit determination point of view, although it would contribute to a better modelling of the orbits of satellites with complicated shapes, through a more reduced-dynamic orbit determination. In any case the deployment of the next generation DORIS receivers, which will have more than two channels, will make it easier to add more stations to the network, either following proposals made in the framework of the IDS or as permanent stations.

(Place Fig. 38 around here)

Equipment-wise, the deployment of the third generation beacons will continue, until all stations are equipped with this kind of beacons, except a few where power supply issues impose the use of less consuming second generation beacons. There are currently no plans for a fourth generation beacon. In regard to the antenna support design, a new support is being designed to allow more clearance below the antenna when installed on a concrete pillar, hence avoiding the use of corrosion-prone bent adapters. Ideally, this new device will have to be designed so that it can installed over the existing one by host agency staff with no geodetic skills, while retaining the initial centring of the antenna.

In order to provide a reliable long-term stability control for the antenna, control geodetic markers should be installed near the antenna (Geodetic Survey Division 1995) and footprint surveys should be repeatedly carried out.

13. Conclusion

The quality, density and homogeneity of the DORIS network have continuously improved throughout its 20 year evolution. With 56 stations equally distributed around the globe, the network guarantees an excellent orbit coverage for the DORIS-equipped satellites, usually more than 80 % for Envisat and 95 % for Jason-1 (Jayles et al submitted), thus playing a key role in the success of the DORIS system. Such a density makes the DORIS network an essential contributor to the realisation of the ITRS on one hand, both by making the IERS network denser and through the co-locations available at 2 DORIS stations out of 3, and to the sea level monitoring on the other hand, through co-locations with tide gauges available at one third of the stations. Thanks to the general renovation process that was carried out over six years on the network, almost all antenna supports should ensure from now on excellent long-term stability of the antenna reference point. Moreover, the massive deployment of third generation beacons gives us hope of a 90 to 95 % operating rate.

Managing the DORIS network has been a very long-term task for IGN, requiring a lot of patience to bring projects to a successful end. We sometimes had to cast doubt over formerly adopted procedures, in order to adapt to the improvements of the DORIS system results in all its scientific application fields, by defining ever more stringent quality requirements. By learning lessons, we allowed the network quality to progress significantly, and are ready for further improvements if need be. Improved antenna supporting device for concrete pillars, as well as footprint surveys aiming at monitoring the long-term stability of the antennas, are such improvements that should be considered here and now.

This very unique network is an essential component of a high accuracy orbit determination and point positioning system which produces positioning on weekly basis at the centimetre level, and contributes to the success of altimetric missions. We trust it will continue to evolve in the future, thus adapting to changing needs, in the framework of the IDS.

14. Acknowledgements

We would like to express our gratitude to all the agencies throughout the world who have contributed to the successful deployment, evolution, and operation of the DORIS network, either by helping IGN to bring new station projects to a successful end, or by hosting and taking care of one or several stations. Such gratitude also applies to the agencies who have hosted former stations for many years, before the removal of these stations from the network. We also wish to thank the developers of the Generic Mapping Tools software (Wessel and Smith 1998), which was used to create all maps in this paper, as well as those used for the continuous monitoring of the network's evolution. Last but not least, we thank all IGN personnel who have been or currently are part of the DORIS installation and maintenance team (SIMB) and thus have played a role in this two decade venture.

References

Altamimi Z, Sillard P, Boucher C (2002) ITRF2000, a new release of the international terrestrial reference frame for earth science applications. J Geophys Res 107(B10): 2214 DOI: 10.1029/2001JB000561

Altamimi Z (2003) ITRF and co-location sites. Proceedings of the IERS Workshop on site co-location, IERS Technical Note n°33, Matera, Italy, Oct. http://www.iers.org/documents/publications/tn/tn33/tn33_008.pdf

BIH (1988) Annual report for 1987. Observatoire de Paris, France

Boucher C, Fagard H (1991) DORIS stations coordinates. Proc International DORIS orbit computation workshop, Toulouse, France, Oct

Boucher C, Cazenave A, Dufour JP, Essaïfi N, Feissel M, Gambis D, Willis P (1994) Proposal to include DORIS as a new technique in IERS. Rapport Technique GRGS n°12, Groupe de Recherche de Géodésie Spatiale, France

Boucher C, Altamimi Z, Feissel M, Sillard P (1996) Results and analysis of the ITRF94. IERS technical note n° 20, Observatoire de Paris, France

Boucher C, Altamimi Z, Sillard P (1999) The 1997 International Terrestrial Reference Frame (ITRF97). IERS Technical Note 27, Observatoire de Paris, France

Cazenave A, Dominh K, Ponchaut F, Soudarin L, Cretaux JF, Le Provost C (1999) Sea level changes from TOPEX-Poseidon altimetry and tide gauges, and vertical crustal motions from DORIS. Geophys Res Lett 26(14):2077-2080

Cretaux JF, Soudarin L, Cazenave A, Bouille F (1998) Present-day tectonic plate motions and crustal deformations from the DORIS space system. J Geophys Res Solid Earth 103(B12):30167-30181

Defense Mapping Agency (1987) Department of Defense World Geodetic System 1984 - Its definition and relationships with local geodetic coordinate systems. DMA Technical Report 8350.2

Fagard H, Orsoni A (1998) The DORIS network: review and prospects. Proceedings of the DORIS days, Toulouse, April, Centre National d'Études Spatiales, France

Fagard H, Orsoni A (2000) Current status and evolution prospects of the DORIS network. Proceedings of the DORIS days, Toulouse, France, May http://ids.cls.fr/html/report/doris_days_2000/fagard.pdf

Geodetic Survey Division (1995) Guidelines and specifications for ACP and CBN site selection and monumentation. Natural Resources Canada, Canada Centre for Remote Sensing, 615 Booth Street, Ottawa, Ontario K1A 0E9, Canada

Hugentobler U, Schaer S, Fridez P (2001) Bernese GPS Software - Version 4.2. Astronomical Institute, University of Bern, Switzerland

IDS (2004) Recommendations of the IDS plenary meeting, Paris, France, May http://lareg.ensg.ign.fr/IDS/events/recom_2004.pdf

Jayles, Nhun Fat and Tourain (in press), DORIS: system description and control of signal integrity. J Geod, same issue, DOI: 10.1007/s00190-006-0046-8

Le Bail (submitted) Estimating the noise in space-geodetic positioning. The case of DORIS. J Geod, same issue

Massmann FH, Flechtner F, Raimondo JC, Reigber C (1997) Impact of PRARE on ERS-2 POD. Adv Space Res 19(11):1645-1648

Moore AW, Neilan RE (2005) The International GPS Service tracking network: Enabling diverse studies and projects through international cooperation. J Geodyn 40(4-5): 461-469, DOI 10.1016/j.jog.2005.10.009

Pavlis, EC., Mertikas SP and the GAVDOS Team (2004) The GAVDOS Mean Sea Level and Altimeter Calibration Facility: Results for Jason-1. 3rd Jason special issue, Mar Geod: 27(3-4):631-655 DOI: 10.1080/01490410490902106

Pearlman MR, Degnan JJ, Bosworth JM (2002) The International Laser Ranging Service. Adv Space Res 30(2):135-143 DOI: 10.1016/S0273-1177(02)00277-6

Schluter W, Himwich E, Nothnagel A, Vandenberg N, Whitney A (2002) IVS and its important role in the maintenance of the global reference systems. Adv Space Res 30(2):145-150 DOI: 10.1016/S0273-1177(02)00278-8

Schlüter W, Hase H, Böer A, Riepl S, Cecioni A (2002) TIGO starts its operation in Concepción in 2002. CSTG bulletin n°17, International Association of Geodesy

Snajdrova K, Boehm J, Willis P, Haas R, Schuh H (2006) Multi-technique comparison of tropospheric zenith delays derived during the CONT02 campaign. J Geod 79(10-11):613-623, DOI: 10.1007/s00190-005-0010-z

Tavernier G, Soudarin L, Larson K, Noll C, Ries J, Willis P (2002) Current status of the DORIS Pilot Experiment and the future International DORIS Service. Adv Space Res 30(2):151-156 DOI: 10.1016/S0273-1177(02)00279-X

Tavernier G, Granier JP, Jayles C, Sengenes P, Rozo F (2003) The current evolution of the DORIS system. Adv Space Res 31(8):1947-1952 DOI:10.1016/S0273-1177(03)00155-8

Tavernier G, Fagard H, Feissel-Vernier M, Lemoine F, Noll C, Ries J, Soudarin L, Willis P (2005) The International DORIS Service (IDS). Adv Space Res 36(3):333-341 DOI: 10.1016/j.asr.2005.03.102

Tavernier G, Fagard H, Feissel-Vernier M, Le Bail K, Lemoine F, Noll C, Noomen R, Ries JC, Soudarin L, Valette JJ, Willis P (submitted) The International DORIS Service: genesis and achievement. J Geod, this issue

Wessel P, Smith W (1998) New, improved version of the Generic Mapping Tools released. EOS Trans. AGU, 79, 579

Wilkins GA (1989) Review of the achievements of project MERIT for the intercomparison of techniques for monitoring the rotation of the Earth, in The Earth's Rotation and Reference Frames for Geodesy and Geodynamics. Proc. IAU Symp., vol. 128, edited by A. K. Babcock and G. A. Wilkins, pp. 227– 232, Kluwer Acad., Norwell, Massachusetts

Willis P, Boucher C, Fagard H, Altamimi Z (2005) Geodetic applications of the DORIS system at the French Institut Geographique National. C.R. Geoscience: 337(7):653-662 DOI: 10.1016/j.crte.2005.03.002

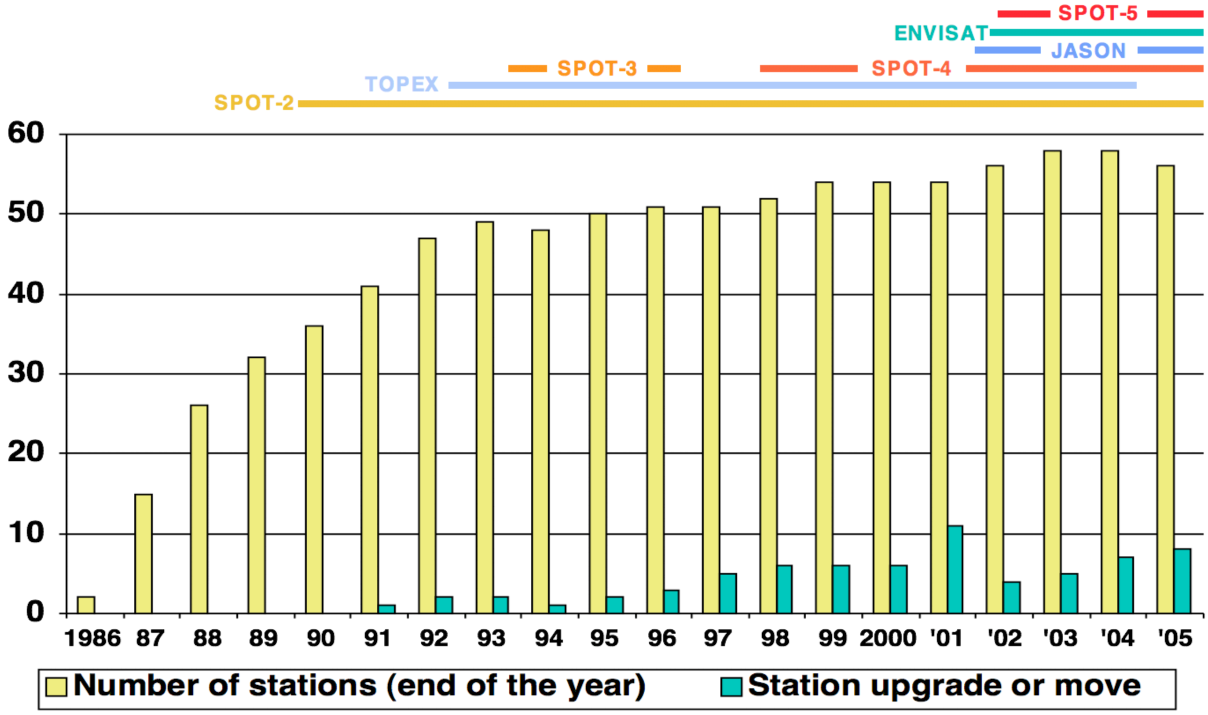

Figure 1: Evolution of the DORIS network

Figure 2: Map of the DORIS network upon SPOT-2 launch (January 1990)

Figure 3:

DORIS beacon 1.0 (top) and Battery case (bottom) in a homemade rack

Figure 4:

DORIS Alcatel antenna (left) on a one-metre tower and side wall mount (Rothera/ROTA).

DORIS meteorological station on the right.

Figure 5:

2 m tower on a concrete pad (Goldstone/GOMA)

Figure 6:

3 m tower on the upper terrace of a building (Galapagos/GALA)

Figure 7:

Antenna interface mounted directly on a roof ; no tower (St Helena/HELA)

Figure 8:

High steel pole, propped by very long guy-wires (Dakar/DAKA)

Figure 9:

Side mount of a 3 m tower against a load-bearing pillar. No guy-wires. (Hartebeesthoek/HBKA)

Figure 10

Base of the Starec antenna on a triangular plate mounted on top of a guyed lattice tower

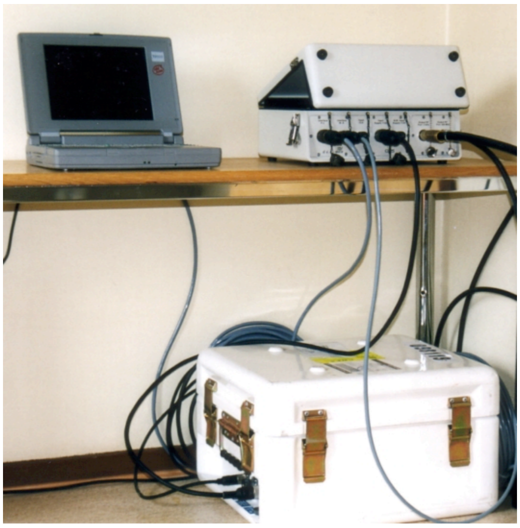

Figure 11

The DORIS 2.0 beacon (upper right) and its power supply (on the ground)

Figure 12

Standard layout:

2 metre tower, guyed

(Santiago/SAOB)

Figure 13

The first DORIS antenna mounted on a

concrete pillar (a former antenna pedestal)

(Ascension/ASDB)

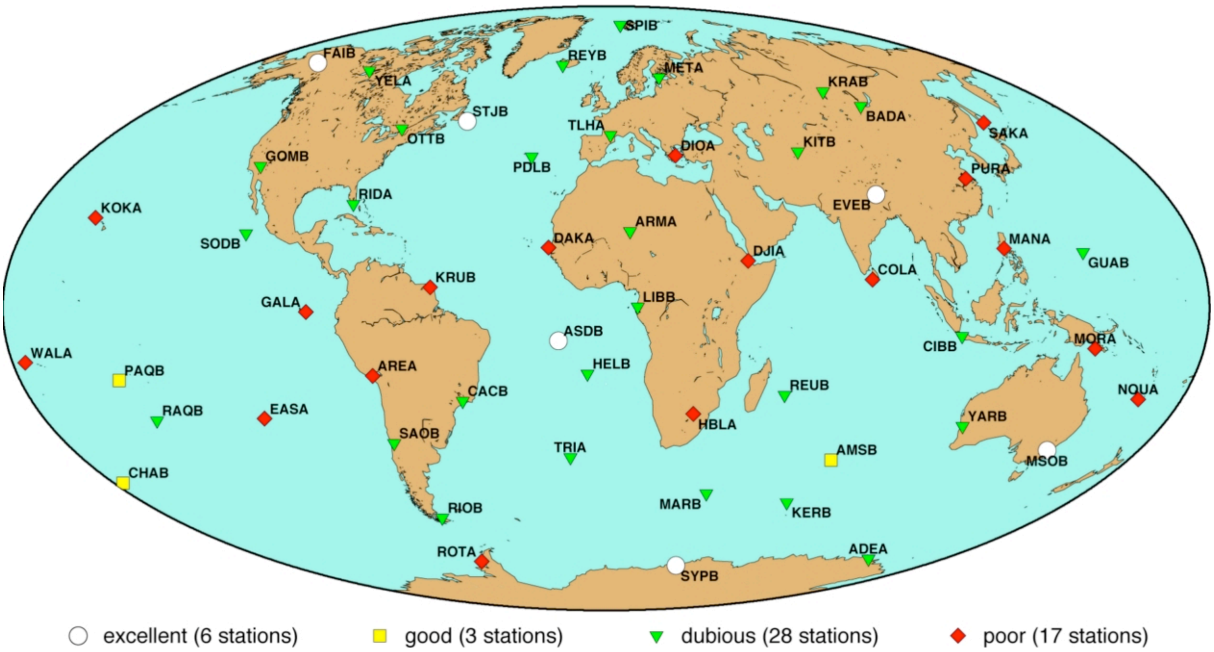

Figure 14

Map of the DORIS network at the end of 1999, showing the estimated stability of the antennas

Figure 15

Antenna tilt resulting from the

corrosion of the base plate

(Amsterdam/AMSB)

Figure 17

Base plate embedded in a pillar.

(Nouméa/NOWB)

Figure 16

Concrete pillar on rock.

(Rothera/ROTB)

Figure 21

Leclerc tower (Thule/THUB)

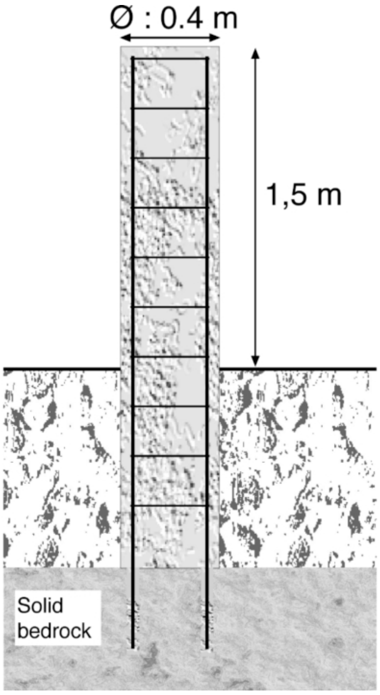

Figure 18

Pillar design when bedrock is present near the ground surface

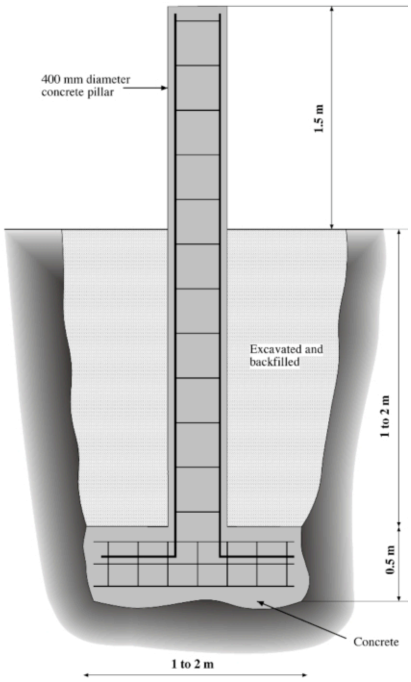

Figure 19

Pillar design for hard soil pillar Dimensions may vary depending on soil hardness

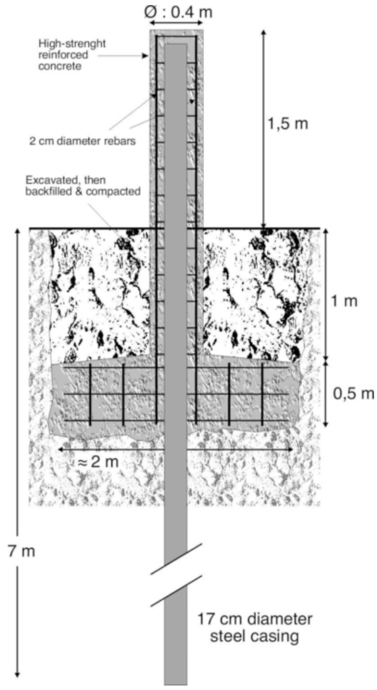

Figure 20

Pillar design for soft soil pillar Dimensions may vary depending on soil hardness

Figure 22

One-metre high, 32 cm

sided tower on roof.

(Badary/BADB)

Figure 23

One-metre tower on the roof slab of a building

with a very involved structure.

The tower is not “somewhere on the roof”, but

exactly on top of a load-bearing concrete pillar.

(Santa Cruz/SCRB)

Figure 24

Half metre high, 17 cm sided

tower on top of a building.

(Kauai/KOLB)

Figure 25

Third generation beacon, charger

and backup battery in a 19” rack

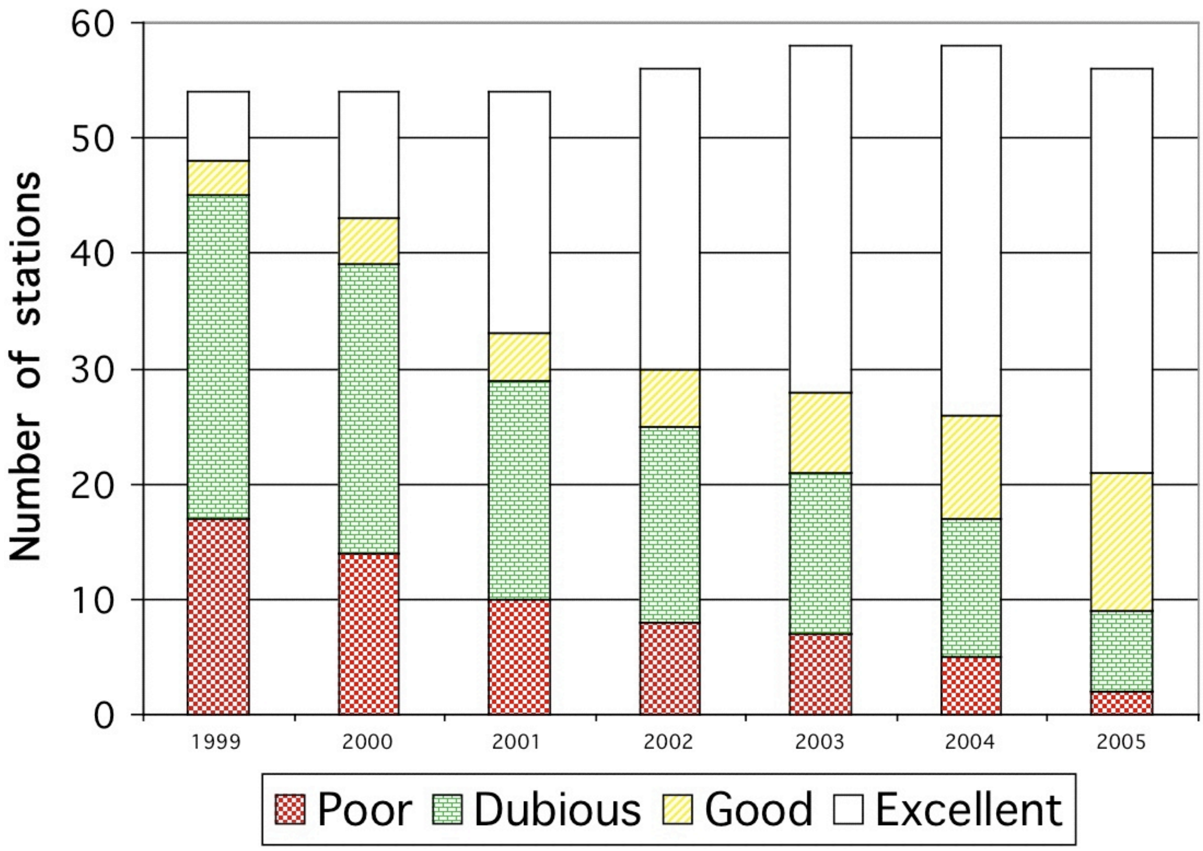

Figure 26: Improvement of the estimated antenna stability

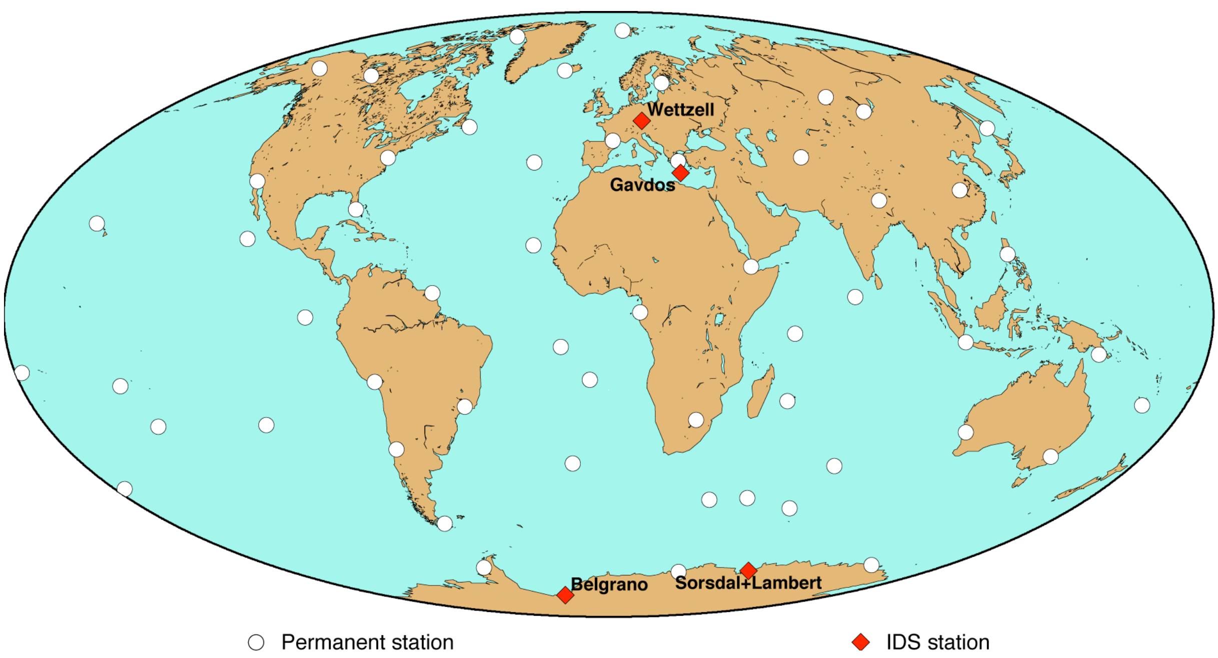

Figure 27: IDS experiments carried out to date

Belgrano was included in the permanent network after one year of successful operation

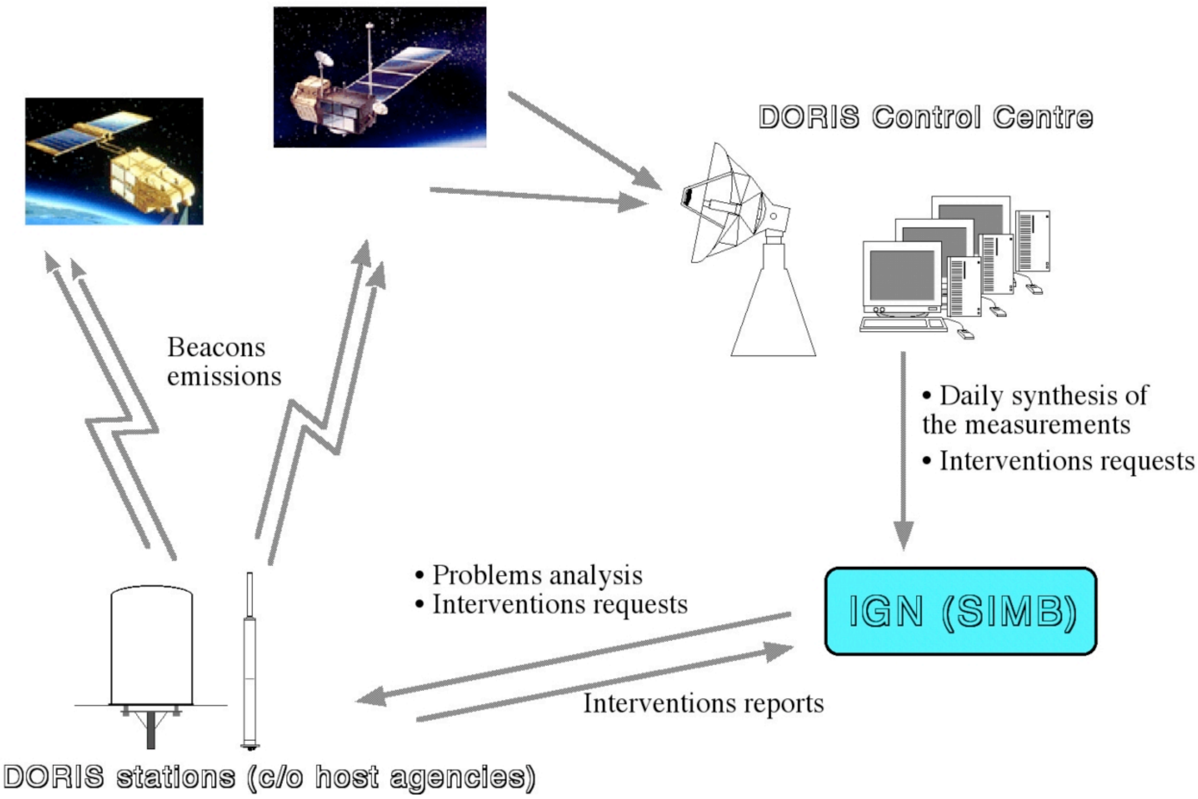

Figure 28: Measurements and maintenance flow

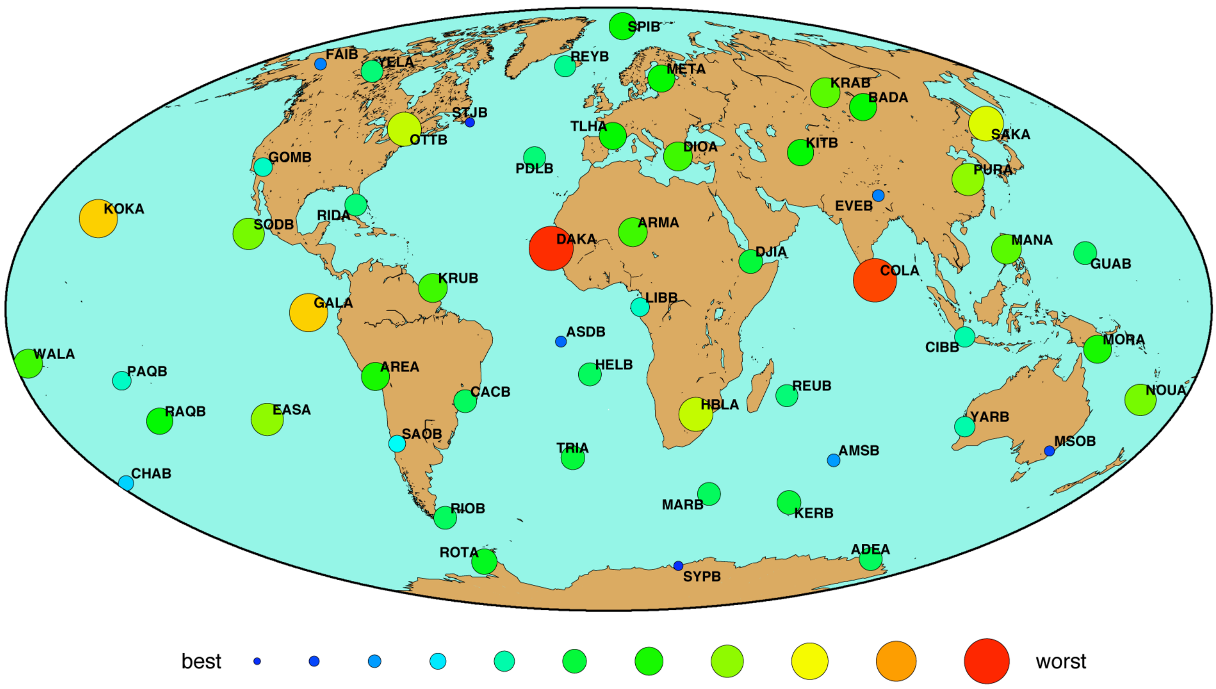

Figure 29

Antenna stability evaluation before the start of the network's renovation (end of 1999)

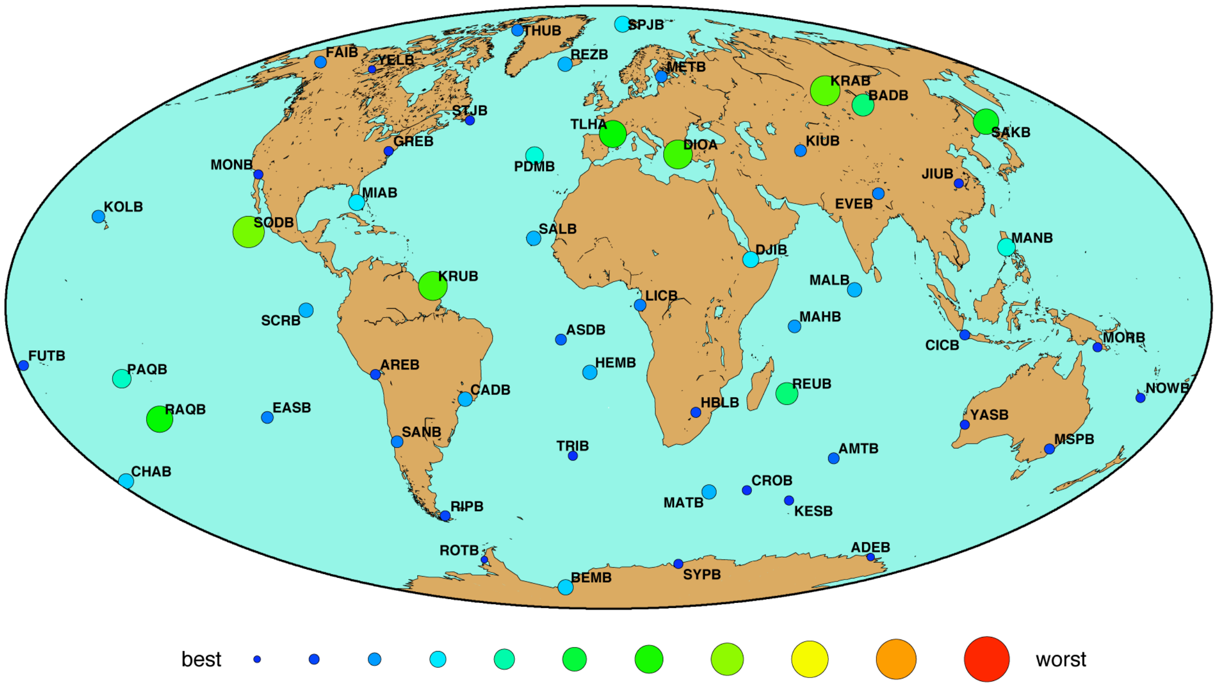

Figure 30

Antenna stability evaluation near the end of the network's renovation (end of 2005)

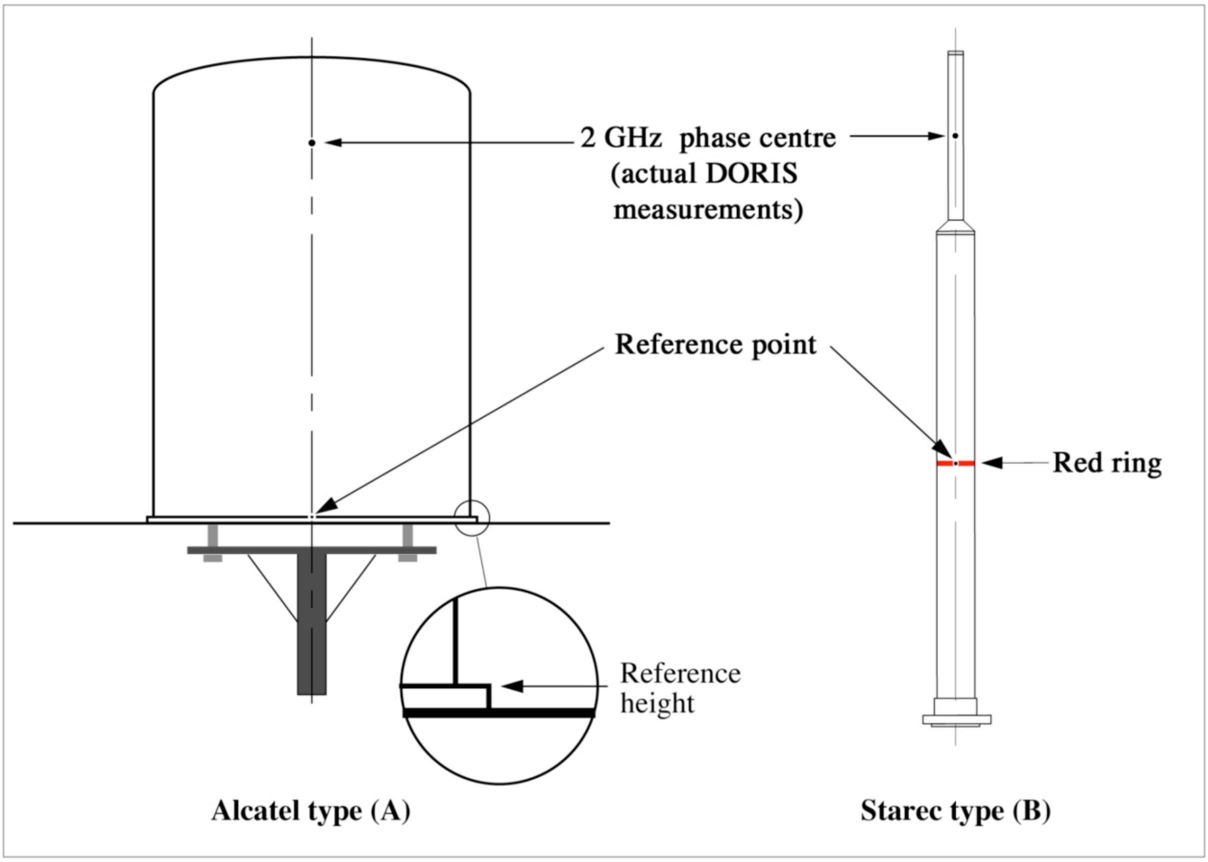

Figure 31: Definition of the antennas' reference point

Figure 32

GPS choke-ring antenna force-centred on a Starec antenna triangular supporting plate.

The DORIS/GPS interface is the thin aluminium disk between the GPS antenna base and the plate.

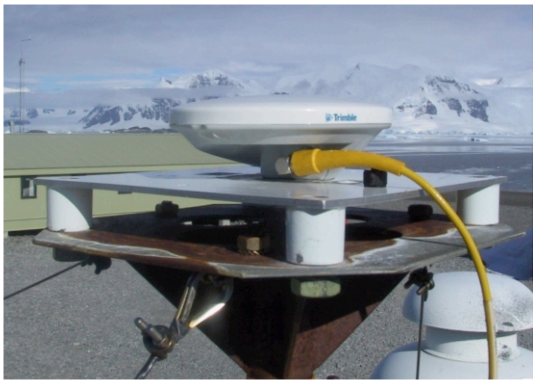

Figure 33

GPS antenna force-centred on an Alcatel antenna (rusted) steel supporting plate.

The interface is the square aluminium plate mounted on four white cylinders.

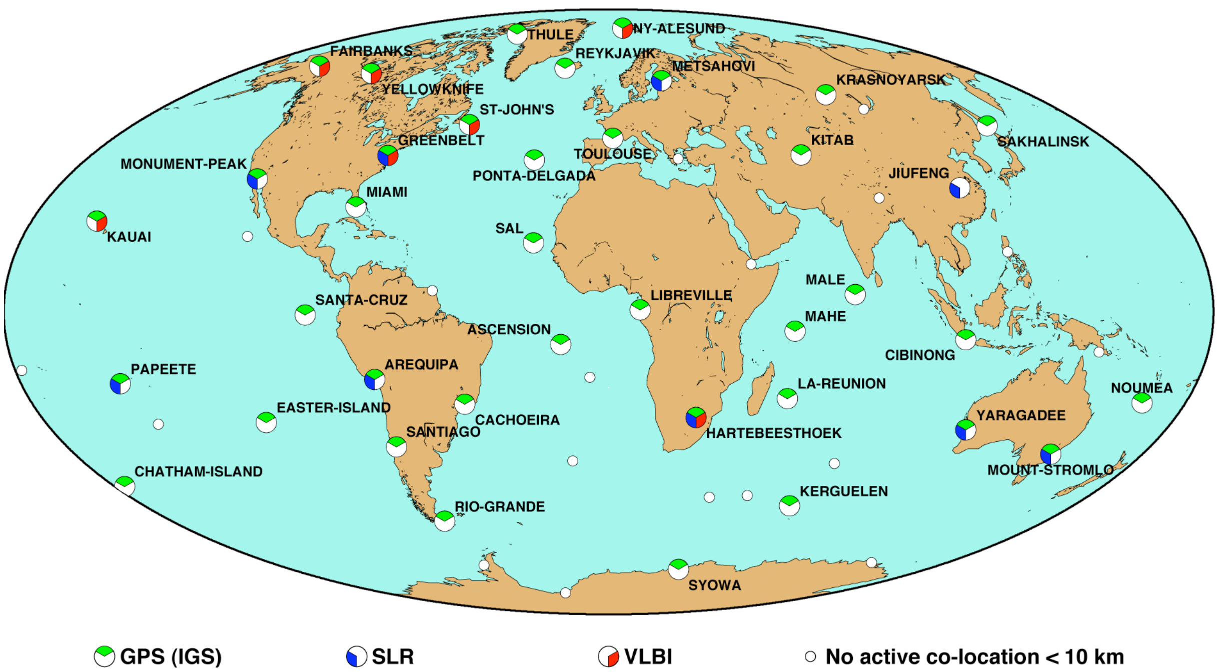

Figure 34

Co-locations with other active IERS techniques in the current DORIS permanent network

(see detailed list in the ESM)

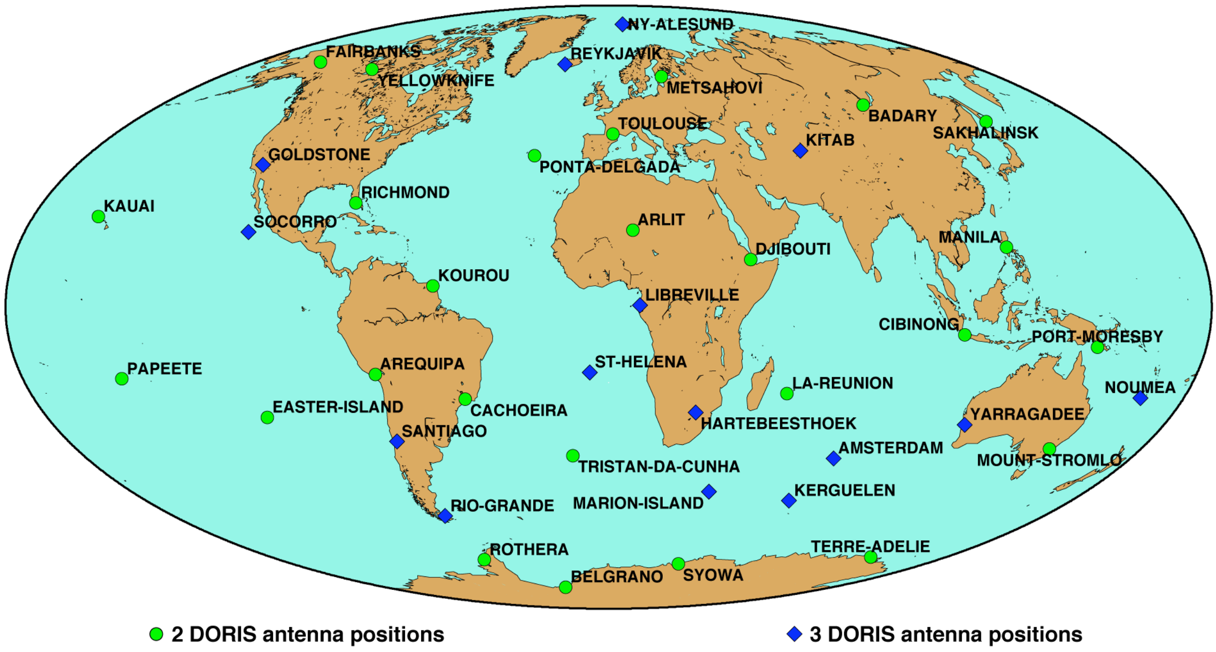

Figure 35

Multiple antenna positions at DORIS stations

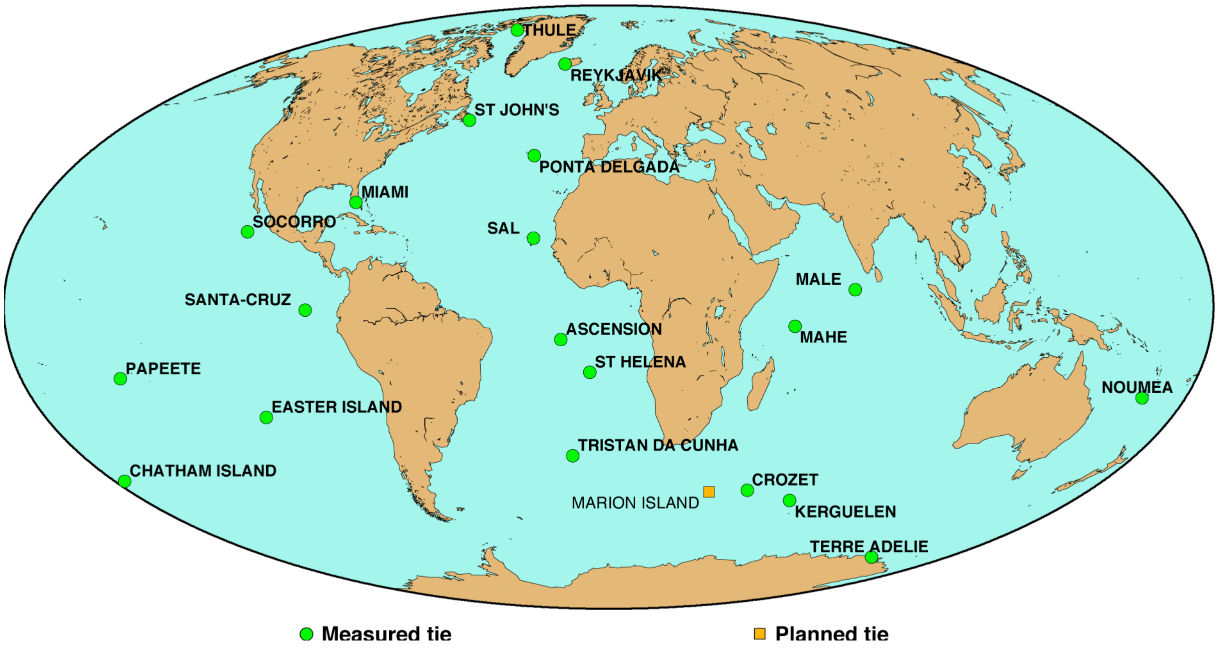

Figure 36

Co-locations between DORIS and tide gauges

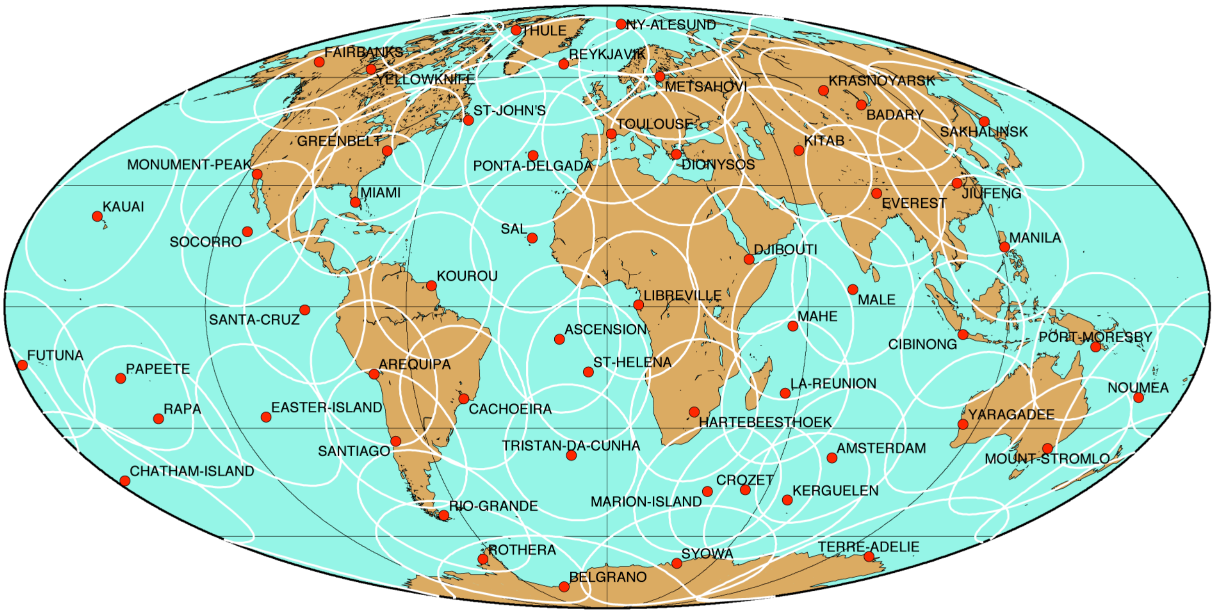

Figure 37

Visibility areas for the current DORIS network (February 2006)

Visibility circles drawn for SPOT and Envisat satellites, cut-off angle 12 degrees

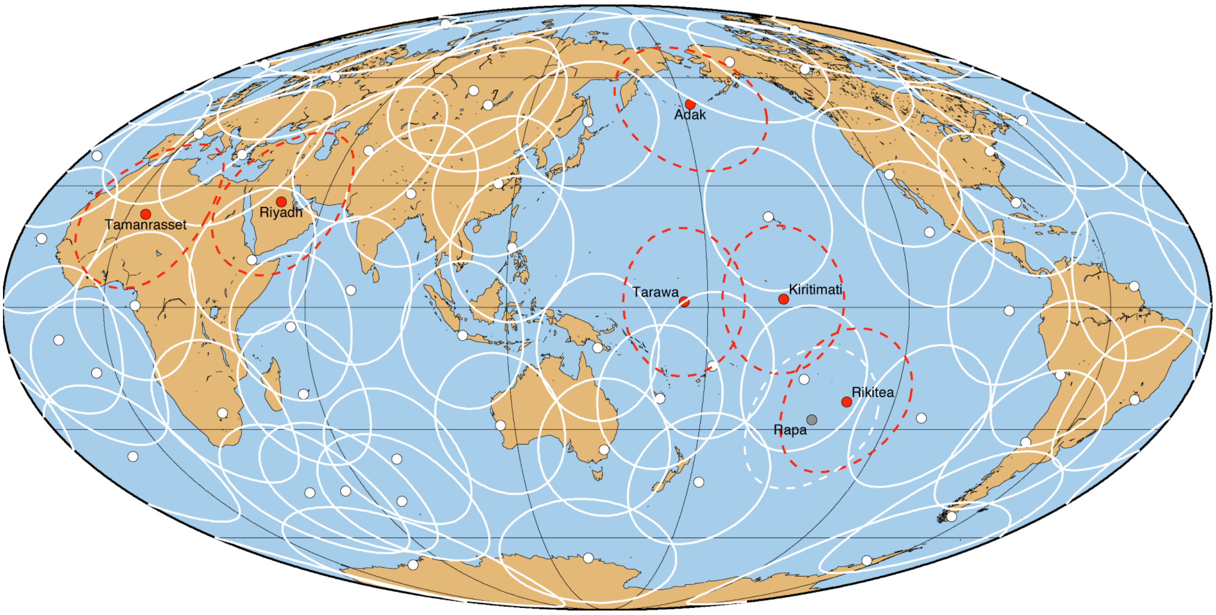

Figure 38

Planned new DORIS stations (dotted lines)

Visibility circles drawn for SPOT and Envisat satellites, cut-off angle 12 degrees

Category	Examples of layout	Comments
Excellent	Concrete pillar on rock, or with deep foundations. Self-supporting tower on a concrete structure on the ground. Starec antenna only.	Objective to be achieved for the whole network
Good	Self-supporting tower on a concrete structure with not so deep foundations. Rigid tower on a building. Starec antenna only.	The secondary objective, when local constraints prevent from achieving the "excellent" status.
Dubious	Guyed tower on the ground (up to three metres) or on a building (up to two metres), recently installed. Early days setups if rigid fastening to a low elevation building.	Applies to most "standard layouts" installed during the Starec Era (section 6)
Poor	Towers (> 3 m on the ground, > 2 m on buildings, or poorly guyed, or installed a long time ago).	Most original layouts from the early stations (section 5)

Table 1: stability evaluation criteria used prior to the network renovation

Instability degree variation	Minimum	Maximum	Mean	Std dev.
Before the renovation (end of 1999)	9	44	24.7	8.0
Near the end of the renovation (April 2006)	7	31	14.3	6.3

Table 2: distribution of the antenna instability degree

Antenna	Alcatel	Starec
Height (400 MHz phase centre)	335 mm	0
Height (2 GHz phase centre)	510 mm	487 mm

Table 3: height of the antenna phase centres with respect to the antenna reference point