20 YEARS OF EVOLUTION FOR THE DORIS PERMANENT NETWORK:

FROM ITS INITIAL DEPLOYMENT TO ITS RENOVATION

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Abstract

The ground network is one of the major components of the DORIS system. Its deployment, managed by IGN-France, 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). The first generation of transmitting antennas, whose installation procedures were adapted to the decimetre performance objective for the DORIS system, was followed by a new model allowing a more accurate survey. During this second era of the deployment of an ever denser network, the antenna layouts gradually evolved towards a better quality, thus improving the long term stability of the reference point. As the positioning accuracy of the DORIS system went on improving, it turned out to be necessary to review the antenna stability for the whole network. A somewhat subjective stability estimation, using criteria which are discussed, was followed by a major renovation action which started in 2000 and is now almost completed. New installation procedures, aiming at meeting much more stringent stability requirements, were enforced and resulted in a definite improvement of the overall network quality, through the renovation or installation of 43 stations in six years. Now that the renovation is almost completed, a more analytical approach has been taken to assess the potential stability of all DORIS occupations.

Besides deploying the network, IGN is also in charge of its operational maintenance, an intensive activity on account of a significant failure rate of the successive generations of equipment. Nevertheless, thanks to its unique density and homogeneity, DORIS has always maintained a very good coverage rate of the satellites orbits.

Through a large number of well-distributed co-locations with the IGS, SLR and VLBI networks, DORIS contributes significantly to the realisation of the IERS reference frame. Moreover, with many stations located near, and accurately connected to tide gauges, it participates in the monitoring of sea level changes.

Although it has several advantages over similar ones, there is still room for improvement for the DORIS network, towards even better orbit coverage and contribution to the IERS frame.

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

1. INTRODUCTION : HISTORICAL BACKGROUND

The realisation of the DORIS system was decided jointly in the early eighties by the French space agency (CNES: Centre National d'Études Spatiales), the French national mapping agency (IGN-F: Institut Géographique National – France) and a research group in the field of space geodesy (GRGS: Groupe de Recherche en Géodésie Spatiale). Because of its experience in the field of the installation of geodetic networks, IGN has taken care of the deployment of the ground network and of the determination and publication of the stations coordinates (Willis et al. 2005). For twenty years now, the geodetic department of IGN-F (SGN: Service de Géodésie et Nivellement) has been negotiating agreements with host agencies, installing the equipment, surveying the antennas, and keeping the DORIS stations in working condition. Since then, the DORIS system has evolved into a larger international cooperation, leading to the recent establishment of the International DORIS Service (IDS) (Tavernier et al. 2002; 2005).

An essential requirement for the precise computation of the orbits was to ensure an almost constant visibility of at least one ground station by the on-board receiver. 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. To meet the orbit coverage requirement for the SPOT-2 satellite (832km altitude), it was estimated that the network should be made of approximately 50 stations, as evenly distributed as possible around the globe.

In this paper we will be relating the genesis of this unique network, and its various evolutions over about 20 years. After a general description of the site selection and installation procedure, followed by a description of the sites and points naming conventions, we will go in detail through the history of the network's deployment and evolution. For each of the three major eras of this evolution, we will describe the equipment used, focusing on the various antenna layouts that may have a significant influence on the long term antenna stability, a growing concern as the accuracy of the DORIS data analysis results have been improving over the years. After listing the additional stations installed following proposals made in the frame of the International DORIS Service, we will explain how the network is maintained and give a few statistics on the equipment maintenance. Then we will review the current network status: after some general information about its configuration, the host agencies and the information to users, we will present a detailed antenna stability evaluation approach. In chapter 11 we will address all aspects related with the DORIS antennas surveying and coordinates determination: the definition of the reference points, the surveying procedures, and the determination of geocentric a priori coordinates. Co-location with other IERS space geodesy techniques on one hand, and with tide gauges on the other hand, will then be listed. We will finish off by presenting the planned evolutions 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 Sites selection criteria.

The initial list of potential DORIS station locations mainly ensued from the need of geocentric coordinates, the best source of which would be a co-location of the DORIS antenna 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 positioning, either already determined in the frame of international measurement campaigns or to be measured by IGN at the same time as the DORIS equipment installation. This was notably the case at many islands primarily selected in order to meet the density and homogeneous distribution criteria for the network, even though no space geodesy measurements had ever been performed at these sites.

The concern for co-locations between the DORIS stations and tide gauges appeared later, with the growing interest for sea level rise related studies.

2.2 Selection of a host agency.

After a site had been a priori selected, a host agency had to be found, who would agree to host the station and take care of its maintenance, and where the following needs could be met :

- The transmitting beacon and its backup power supply needed to be in a room with moderate temperature and temperature gradient, with mains power supply available.

- The antenna had to be installed outside with a clear view above 10 degrees, on a structure that would allow the use of the antenna supports – guyed tower or wall side mount – available at that time.
- The host agency should agree to carry out some occasional maintenance operations at IGN's request. This would include some minor verifications and adjustments, as well as sending out of order equipment for repair.
- It was necessary to check that the frequencies transmitted by DORIS would not be likely to interfere with existing receivers in the area. When this could not be avoided, the solution generally consists of a temporary interruption of the DORIS transmissions, either manual or automatic. The receiving systems that are likely to be affected by the DORIS signal are:
    - The VLBI antennas: such interference can 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.
    - Upper air soundings carried out by most meteorological stations. Only some models of Vaisala receivers are likely to be affected, and such interference occur only 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 been progressively evolving throughout the network's deployment, with a deeper and deeper preliminary survey being conducted as the requirements for antenna stability became more stringent (see chapter 7.2).

Then it was necessary to obtain the prospective host agency's agreement to host and maintain the DORIS station, which was in most cases materialised by a written agreement signed with IGN. 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. This negotiation stage generally took several months, but some projects – especially in the recent years, after all the "easy" ones had been achieved in the first years – took up to two or three years in succeeding.

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 several successive DORIS points may have been present) 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 30 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, "Galapagos" is the name of an archipelago made 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 Cristobal island, inaccurately named "Galapagos".

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).
- A four character ID or acronym, used in the data file names and built 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 chapters 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 acronym 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 acronym 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 IGS 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".
- The acronym 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 acronyms with start and end date for each occupation is provided in the Electronic Supplementary Material of this paper (file "DORIS-occupations.pdf").

4. SUMMARY OF THE NETWORK'S EVOLUTION

The very first DORIS station was Tristan da Cunha (code TRIA), which was installed by the Proudman Oceanographic Laboratory in June 1986. Then installation followed installation at a sustained pace, with about 10 new stations a year (figure 1) during the first two years, allowing the network to be operational when the first DORIS-equipped receiver (SPOT-2) was launched. Figure 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 chapter 5.

As of 1993, the network deployment went on at a slower pace. 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 agencies facilities, or to improve their co-location with other geodesy techniques. All these new stations were equipped with second generation antennas, and a few with second generation beacons.

As of 2000, a general renovation was initiated, in order to improve the overall stability of the antennas reference point. Many stations were completely renovated or moved to a new location. A few new stations were installed, all meeting the new, more stringent requirements stability wise. The deployment of the third generation beacons started in 2002.

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 (Figure 3), weighing 24 kg and designed to be integrated into a standard 19 inches rack, had to be installed inside a building with moderate temperature gradient. It could be programmed through an integrated man-machine interface consisting of a keyboard and a 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, providing backup power to the beacon during power outages lasting up to 72 hours.
- A dual frequency and omni-directional antenna (figure 4), manufactured by Alcatel. This antenna was bolted on an interface (consisting of a square horizontal plate welded to a vertical tube), which could be mounted on a variety of supports, in most cases a small lattice tower.
- A weather station (figure 4) measuring temperature, pressure and humidity. These parameters are transmitted through the 400 MHz modulated signal and can be used to correct for atmospheric propagation delays.

5.2 Alcatel antenna layouts

In order to be able to adapt to the various site layouts likely to be encountered, and for lack of detailed information allowing to determine beforehand exactly where and how the antenna and beacon would be installed, a standard set of antenna supporting devices was sent. This included several one-metre lattice tower sections, guy wires and a wall side mount for the antenna, and a home-made small rack for the beacon and batteries. The IGN technician who carried out the installation had to manage to find 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 meet the good visibility requirement despite this limitation, many antennas had to be installed on building roofs or on top of two or three metre high towers, if not 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 one of the following structures:

- A concrete pad on the ground, already available (figure 5)
- A concrete block specially built for the DORIS installation (figure 6)
- A building's top terrace. (figure 7)

At a few sites where the antenna was installed on a roof, a clear sky view allowed to use only one tower section. Conversely, four sections had to be used at a couple of locations in order to avoid nearby signal obstructions.

When such 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 prevented to see the ground mark if one had been set under the plate. In some cases the tube itself was used as the control mark instead. Such a control mark was destined to be used in the future to check the antenna stability on one hand, and as a marker of the antenna location in case of movement or accidental destruction of the antenna on the other hand.

Other designs have been used more rarely:

- Direct mount of the antenna interface on a roof, without using a tower (Figure 8)
- Propped steel pole (Figure 9)
- Tower mounted on the side of a wall (Figure 10)

In a few of these cases, no ground mark was present.

Most towers were propped using stainless steel cable wires and turnbuckles, allowing a pretty strong and stable fastening of the tower. Nevertheless at a few sites the cable wires were very long or somewhat loose or even nonexistent, which would not guarantee a centimetre-level stability of the antenna. This was yet acceptable considering the expected positioning accuracy of the DORIS system at that time (10 cm).

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 to precisely adjust the antenna verticality, i.e. to guarantee that the electrical phase centres – and notably the 2 GHz one on 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 when Alcatel antennas were surveyed prior to removal, during the network's renovation phase. It is now far from being negligible taking into account the recent geodetic results obtained by the DORIS system (Willis et al. 2005).

6. THE NETWORK DENSIFICATION: THE STAREC ERA

A new antenna model has been used as of mid-1992, instead of the original Alcatel design, 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 kept on increasing until the end of 1993, when it stabilised around 50 stations, before increasing again slightly at the end of the 90's. During this period (1994 to 1999) several stations were moved to new locations, and a few had to be upgraded either following beacons failures or damages caused to antennas by strong storms. A second generation beacon was installed at a few sites as of late 1995 (first one at Krasnoyarsk), but was never deployed at a large scale: a maximum of 14 units have been operating simultaneously in the network (in 2003).

6.1 Description of the second generation equipment

The new antenna model (Figure 11), manufactured by Starec, France, offered several improvements with respect to the original Alcatel model:

- Thanks to its slimmer design, it catches the wind far less, being therefore less prone to damage by storms,
- Its phase centre location is better defined (to within 1 mm, vs. 5 mm for the Alcatel antennas),
- Its slimmer and more rigid design allows a more precise survey and centring to be carried out.

From its very first deployments, 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. Three different materials have been used for this triangular plate: anodised aluminium, marine aluminium, and stainless steel. Unfortunately no exact 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, and causing a significant antenna tilt.

The new beacon (Figure 12), 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 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) allowing to install it in locations where electrical power supply is limited,
- User interface only through an external computer. The beacon itself has no indication of its current operating mode (transmission or standby).

The meteorological station associated with the second generation beacon had the same functionalities as the first model, but it was more compact and lighter.

Another apparently minor evolution equipment-wise during this period – the length of the antenna cables increasing from 10 to 15 m – had a significant influence in terms of antenna layout, as it allowed more freedom in the selection of the antenna location. 20 m cables have even been used at a couple of locations but, because of the higher signal attenuation they cause, they use should be as limited as possible.

On the other hand, a modified version of the first generation beacon, called version 1.1, was developed. It consisted of a 1.0 beacon without the failure-prone internal power supply unit, connected to the power supply box of a second generation beacon. Very few such units have been deployed but they allowed 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, via the triangular plate, on a 2 metre high, 17 cm sided steel lattice tower, fastened with stainless steel guy-wires and turnbuckles (Figure 13). 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 chapter 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 within one millimetre.

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 initially were, using the same support. Several such relocations were carried out by the host agency with no intervention by IGN-F.
- 3 metre high tower (Cibinong/CIBB, Rio Grande/RIOB (Figure 14), Rapa/RAQB, Socorro/SODB, La Réunion/REUB) or even higher (6 m at Syowa/SYOB) when imposed by nearby signal obstructions.
- 1 metre (or less) high tower: 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's wall while offering a very good rigidity, and was therefore retained during the renovation of the network dealt with in chapter 7.
- Direct installation of the antenna triangular supporting plate 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 (figure 15), then at Amsterdam/AMSB, Syowa/SYPB and St John's/STJB.
- A very rigid 3 metre steel pole was used at Mount Stromlo/MSOB.

7. THE RENOVATION ERA

The need for an improvement of the DORIS antennas stability emerged in the mid-90's, after the increasing positioning accuracy of the DORIS system allowed it to be accepted as a new technique for the realisation of the IERS Terrestrial Reference System (Boucher et al. 1994; 1996). When an existing station had to be moved, or when a new one was installed, increasing attention was paid to install the antenna on a very stable support (Fagard and Orsoni 1998). Such a policy has been applied until the end of the 90's, with no on-site intervention motivated only by the need for an antenna stability improvement during this period. Guy-wires were still used to fasten antenna supporting towers, although 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 a global renovation action, aiming at improving the stability of the antennas, was decided. This renovation project was presented to the DORIS community during the “DORIS days” in May 2000 (Fagard and Orsoni 2000), and actually started 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 if a stability improvement was necessary, and how urgent it was. Such an evaluation took the following parameters into account:

- The type of antenna (Alcatel or Starec). Although no antenna can be considered more stable per se, the Alcatel antenna has several characteristics – higher sensitivity to the wind, much heavier, less accurate survey, no verticality adjustment – that allows to consider it as 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-F, into four categories defined in table 1.

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 Figure 16.

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 chapter 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 (Figure 17: Amsterdam/AMSB).
- The antenna centring turned out to be still within a few mm after more than ten years for several Alcatel antennas installed during the very early years of the DORIS network, hence rated “poor”.

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, that may go unnoticed locally for quite a while.
- Only the antenna supports described below should be used.

7.2.2 Design 1: concrete pillar

The preferred antenna support is a concrete pillar (figures 18 and 19), built according to “geodetic” specification, who take into account the nature of the ground. The pillar designs shown on figures 20, 21 and 22 have been derived from those used by the Canadian Geodetic Survey Division (Geodetic Survey Division, 1993). A triangular plate is set on three A4 stainless steel rods embedded in the concrete pillar, and a series of nuts allowing to adjust the antenna verticality. The triangular plate, machined by IGN-F 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 movements caused by the difference in thermal expansion between both sides of the pillar.

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). Such a tower is 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.

This tower design is used 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 what a concrete pillar allows. It is also used when a good quality concrete base is already available, allowing an easier and cheaper installation than specially building a concrete pillar.

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 (figure 23). 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 (figure 24).

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 (figure 25), in order to achieve as good as possible a 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 best approaching one 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 allows to save a few metres and hence to sometimes get 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 (figure 24), or a half-metre 17 cm sided one (figure 26) – which has the additional advantage of fitting on narrow concrete beams – guarantees an optimal 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.

7.3 The third generation beacons

A new generation of beacons was introduced, and deployed as the renovation was progressing (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.

This new set of equipment (figure 27) 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 man-machine interface. It should be installed inside a building and fits in a standard 19 inches rack. The power consumption is approximately the same as the first generation one (130 W). Contrary to the previous models, the signal is modulated on both channel. It also has a new “Restart” operating mode allowing its signal to be received even if the time is not properly set.

- 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 (Figure 24) is a Vaisala PTU200 unit.
- The antenna (Starec model) is unchanged.

7.4 The progress of the renovation

As can be seen on figure 28, 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 evolutions have been taking place:

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

The renovation turned out to be much longer and complicated a process than we first expected. The more stringent requirements for the antenna stability required to gather a lot of information about the site (pictures, sketches, obstruction diagrams if available). Even though a contact with the host agency had been established for many years, sometimes long time to answer and the need to plan logistical aspects in detail – especially when a concrete monument had to be built – involved that the whole process could take well more than one year, and require that well more than 100 e-mail messages be exchanged between IGN and the host agency. This is even more true for the installation of a new site ex-nihilo, with a couple of projects extending over up to three years before being eventually carried to a successful conclusion.

8. THE IDS NETWORK AUGMENTATIONS

In the frame of the establishment of the IDS (Tavernier et al. 2005; submitted), various groups have made proposals to host additional DORIS stations not included in the permanent DORIS network, with varied scientific objectives and for varied durations.

The following experiments have been carried out to date (figure 29):

- An ice sheet monitoring experiment was conducted by Geosciences Australia on the Sorsdal glacier, Antarctica, by operating a DORIS station for about three months twice, during the austral summers 2002-2003 and 2003-2004.
- Following a proposal of the German BKG to operate DORIS stations at Wettzell (Germany) and within the Transportable Integrated Geodetic Observatory (TIGO) located at Concepción, Chile, 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 has been inactive for an extended period of time because of a beacon failure followed by a shortage of spare beacons, but a retrofitted third generation is on its way at the time of writing and should be 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 has been providing 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".

9. THE NETWORK MAINTENANCE

9.1 Maintenance running

In addition to the deployment of the network, IGN-F has also been in charge of its maintenance, the operation of which can be summarised as follows (figure 30):

- An anomaly is detected by the DORIS control centre, 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 sends – for each anomaly detected – an intervention request to IGN's maintenance unit (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.

9.2 Maintenance statistics

Equipment reliability has been a major issue throughout the life of the DORIS network. The proportion of emitting beacons in the network averages to about 85 %, with lows at 80 % and highs reaching 95 %. Because of very long repairing delays and frequent shortages of spare units, a few stations have remained down for several months before they could be replaced. 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 high altitude 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 (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 as of 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 will require the replacement of the remaining units by third generation beacons.

- Almost all third generation beacons installed between early 2003 and August 2004 have been 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 who took care of its installation. From then on, the operating rate for this model has increased to 90 %.

Because of the shipment waiting period, customs formalities and scarce service 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.

From the start of the DORIS system operation, IGN's maintenance unit has been handling about 150 intervention requests and 12 beacon exchanges a year on average.

The following types of operations are likely to be requested to the host agency :

- Time or frequency adjustment: 78 %,
- Reset of the beacon after a failure (automatic for the third generation beacons): 4 %,
- Checking through a self-test procedure: 8 %,
- Battery charging or replacement: 2 %,
- Replacement of the weather sensors: 2 %,
- Exchange of the beacon by a spare sent by IGN: 6 %. No on-site repairs are carried out by the host agency.

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

- Yellowknife and Syowa: during (infrequent) VLBI campaigns,
- Ascension and Libreville: during the tracking of the Ariane rocket upon each launch from Kourou,
- Mahe and Rapa: during the meteorological radiosoundings, once or twice a day.

10. THE CURRENT NETWORK STATUS

10.1 The current network configuration

In February 2006, the distribution of the different equipment types in the permanent network (56 stations) is :

- 42 third generation beacons,
- 7 second generation beacons,
- 7 first generation beacons (including one 1.1 beacon at Socorro)
- 54 Starec antennas
- 2 Alcatel antennas

Three stations – Toulouse, Kourou and Hartebeesthoek – have a special status as they are equipped with “master beacons” used for the programming of the on-board 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): 19 stations,
- Polar institutes: 8 stations,
- Meteorological stations: 6 stations,
- Other (a 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 the following information:

- General site information,
- Information about the successive antennas installed at the station
- Information about the successive beacons installed at the station
- List of available IERS co-locations (if any)
- Tide gauge co-location (if any)
- Local geodetic survey results
- Description of the meteorological instruments
- Contacts

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

10.4 The antenna stability evaluation

Now that the network renovation is almost completed, we have tried to assess more precisely the quality of the antenna support at all DORIS sites, in the frame of the definition of criteria for site quality aiming at identifying a set of core stations with accurate coordinates contributing to the ITRF (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 can be considered:

- An analysis of the structure of the antenna support.
- The results of the antenna centring check when available.
- A stability study based on the statistical analysis of several years of DORIS weekly station coordinates (Le Bail submitted).

The first approach will be described here in details. It has consisted 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.

The detailed result of this analysis is presented in the form of an Excel spreadsheet (file "Stability-assessment.xls"), in the Electronic Supplementary Material (ESM) of this paper.

Figure 31 shows the result of such an assessment, for the same network as on figure 16, but using this more detailed and less subjective approach, over the one explained in chapter 7.1.

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 comments fields of the ESM spreadsheet file.

A. Antenna and supporting plate:

- Antenna: none of both antenna types 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 drift (which already happened at several sites).
- Plate assembly: plate assembly that meet 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 chapter 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 amount of an antenna move (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 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 should 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 dependant 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.

Figure 32 shows the antennas stability degree at the time of writing, when the renovation of the network is almost completed. If the activity projects for 2006 can be carried to a successful end, the biggest circles on this map should have significantly shrunk by the end of the year.

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:

- 0 mm (perfect centring) for 6 antennas (including several guyed towers, installed near the end of the "Starec era" dealt with in chapter 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 (figure 17), Chatham / CHAB (not mentioned in the ESM file because the acronym 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. Moreover, it should be noted that such a centring check only allows to survey the stability of the antenna reference point with respect to the mark at the base of the antenna. It doesn't allow to detect a movement of the secondary support of the antenna (tower base or building), who can only be monitored through a footprint survey.

The third approach dealt with in (Le Bail submitted) assesses the actual antenna instability with respect to a global geocentric frame through a noise analysis in the time series, hence taking the effects from all instability sources into account.

11. DORIS: A SPACE GEODESY TECHNIQUE

11.1 Definition of the antennas reference point

The antenna reference point for all geodetic surveys and published antenna coordinates is defined as follows (figure 33):

- 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.

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, a one mm level accuracy could generally not 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-F has been used to force-centre a GPS antenna on the same triangular plate that supports the Starec antenna (Figure 34). 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 IDS 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 (figure 35) – 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.

11.3 Determination of a priori coordinates

Prior to the launch of the first DORIS instrument on board SPOT-2, IGN published 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 ITRF: 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 accuracy of the resulting coordinates was better than 10 cm.
- If the DORIS antenna was tied to a Doppler Transit 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. 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 coordinates 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 IERS terrestrial reference frame, which allowed coordinates for the DORIS antennas to be published in the ITRF 94 (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.
- 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

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 evolutions:

- Purple Mountain (no co-location) replaced with Jiufeng (first and only DORIS-SLR co-location in Asia),
- Colombo (no co-location) replaced with Male (IGS + tide gauge co-location),
- Richmond (former VLBI co-location, no longer active) replaced with Miami (IGS + tide gauge co-location),
- Galapagos (no co-location) replaced with Santa Cruz (IGS + tide gauge co-location),
- Goldstone (former SLR co-location, no longer active) replaced with Monument Peak (active SLR + IGS 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 (figure 36):

- GPS (part of the IGS network) at 37 DORIS sites,
- SLR at 9 DORIS sites,
- VLBI at 7 DORIS sites.

Among these, some are 3 technique co-location sites:

- GPS + SLR at 8 DORIS sites,
- GPS + VLBI at 7 DORIS sites

The four techniques contributing to the realisation of the ITRF are available at two sites: Greenbelt and Hartebeesthoek.

In this inventory and on the map (figure 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.

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).

11.5 Internal DORIS co-locations

Following the evolutions of the network dealt with in chapters 6 and 7, there has been more than one antenna location at most DORIS stations (see figure 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, 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 are 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 taking into account when planning the evolutions 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, and that of Galapagos 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 to progressively increase the number of such co-locations (figure 38) up to 19 available ties.

12. PLANNED EVOLUTIONS

12.1 Strengths and weaknesses of the DORIS network

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

- It is much more homogeneous. 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). The SLR network (Pearlman 2002) and VLBI network (Schlüter et al. 2002) are neither equally distributed.
- It has practically the right number of stations to meet its primary objectives. The PRARE network (Massmann et al. 1997), which initially aimed at achieving the same objectives at DORIS, has 10 stations operating, out of an initially planned network made of 30 or so stations.
- It makes the IERS network denser where needed, by adding points in regions where no other techniques are present.
- Unlike other IERS techniques, it is perfectly divided into the Northern and Southern hemispheres: there are exactly as many stations in both hemispheres, and out of 38 co-located sites, 18 are located in the Southern hemisphere.
- Its centralised management by IGN has allowed to carry out a major renovation effort, leading to an almost standardised equipment layout. All equipment changes are tracked by one group (the DORIS maintenance unit), which allows to detect serial problems and take the necessary corrective actions.

Although they are quite satisfying, the current network density, homogeneity and robustness – i.e. the network's ability to ensure a continuous tracking of the satellites orbits when a given station is down – could still be improved. The map on figure 39, 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 Eastern tropical part of the Northern Pacific Ocean, which has always existed, was made worse by the removal of the Guam station. A replacement site at Tarawa, Republic of Kiribati, is under way but not yet installed.
- Although the Kauai station has a central location in the Northern Pacific Ocean that allows a 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 is not tracked any more. 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 a successful end have remained fruitless yet. Sakhalinsk is also in somewhat an isolated situation 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 orbits coverage for the lowest satellites. The planned installation of a station at Tamanrasset (Algeria) would significantly improve the robustness while adding one more GPS (and maybe SLR) co-location.

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, and still more DORIS-VLBI 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. As regards the DORIS-SLR co-locations, figure 36 shows that there is a huge area between Metsähovi, Hartebeesthoek and Jiufeng where no such co-location is present. This gap could be filled by installing a DORIS station, and accurately tying it to the SLR station at Riyad, Saudi Arabia, which gives excellent results.

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 agencies closures have been causing long data gaps until a replacement solution was implemented. The main reason for DORIS data loss has essentially been the significant failure rate of the ground equipment. Despite evolutions of the transmitting beacons, many equipment failures, added to long repair times, have been causing several month data interruption at many sites, and shorter but repeated ones at other places. Nevertheless, the recent massive deployment of retrofitted third generation beacons lets us feel the first stirrings of hope for an operation ratio nearing 100 %.

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 ones.

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 Riyad (Saudi Arabia). Figure 40 shows the location of these planned new stations.

Equipment wise, the deployment of the third generation beacons will continue, until all stations are equipped with this kind of beacons, except a few ones where power supply issues impose the use of less consuming second generation ones.

More IDS experiments will be started when a sufficient number of beacons are available, after proper selection by the IDS Stations Selection Group.

13. CONCLUSION

The quality, density and homogeneity of the DORIS network have been continuously improving throughout its 20 year evolution. With 56 stations equally distributed around the globe, it guarantees an excellent orbit coverage for the DORIS-equipped satellites (usually more than 85 % for the altimetry satellites), 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 terrestrial reference system 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 guarantee from now on an excellent long-term stability of the antenna reference point. Moreover, the massive deployment of third generation beacons gives us hope of a near 100 % 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 agreeing to criticize ourselves, we allowed the network quality to progress significantly, but we should be ready for further improvements if needs be.

This very unique network is an essential component of a high accuracy orbit determination and point positioning system. We trust it will continue to evolve in the future, thus adapting to changing needs, under the supervision of the International DORIS Service.

14. ACKNOWLEDGEMENTS

We would like to express our gratitude to all the agencies throughout the world who have been contributing 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 that have been hosting 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 plot all maps in this paper, as well as for the continuous management of the network's evolutions.

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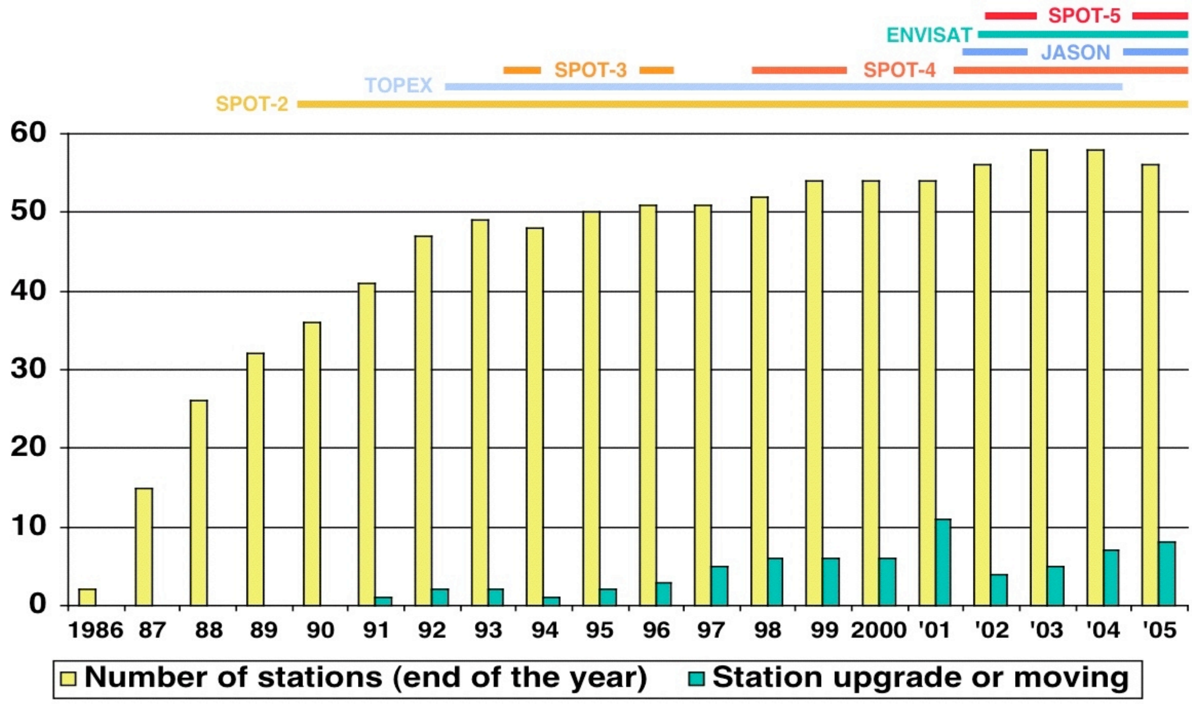

Figure 1: evolution of the DORIS network

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. DORIS meteorological station on the right.

Figure 5:

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

Figure 6:

2 m tower on a concrete block (Marion Island/MARA)

Figure 7:

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

Figure 8:

Antenna interface mounted directly on a roof ; no tower

(St Helena/HELA)

Figure 9:

High steel pole, propped by very long guy-wires

(Dakar/DAKA)

Figure 10:

Side mount of a 3 m tower against a load-bearing pillar. No guy-wires…

(Hartebeesthoek/HBKA)

Figure 11

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

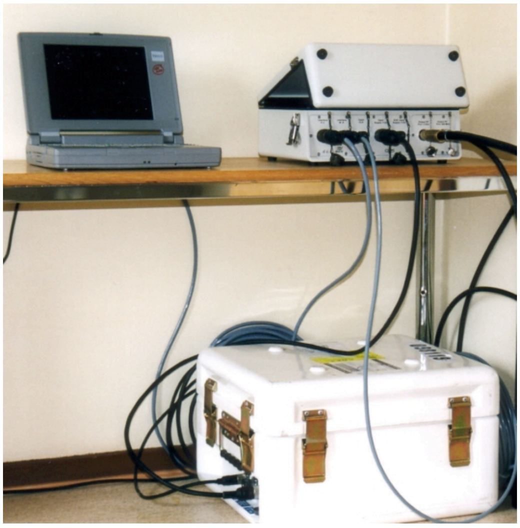

Figure 12

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

Figure 13

Standard layout:

2 metre tower, guyed

(Santiago/SAOB)

Figure 14

3 metre tower, guyed

(Rio Grande/RIOB)

Figure 15

The first DORIS antenna mounted on a

concrete pillar (a former antenna pedestal)

(Ascension/ASDB)

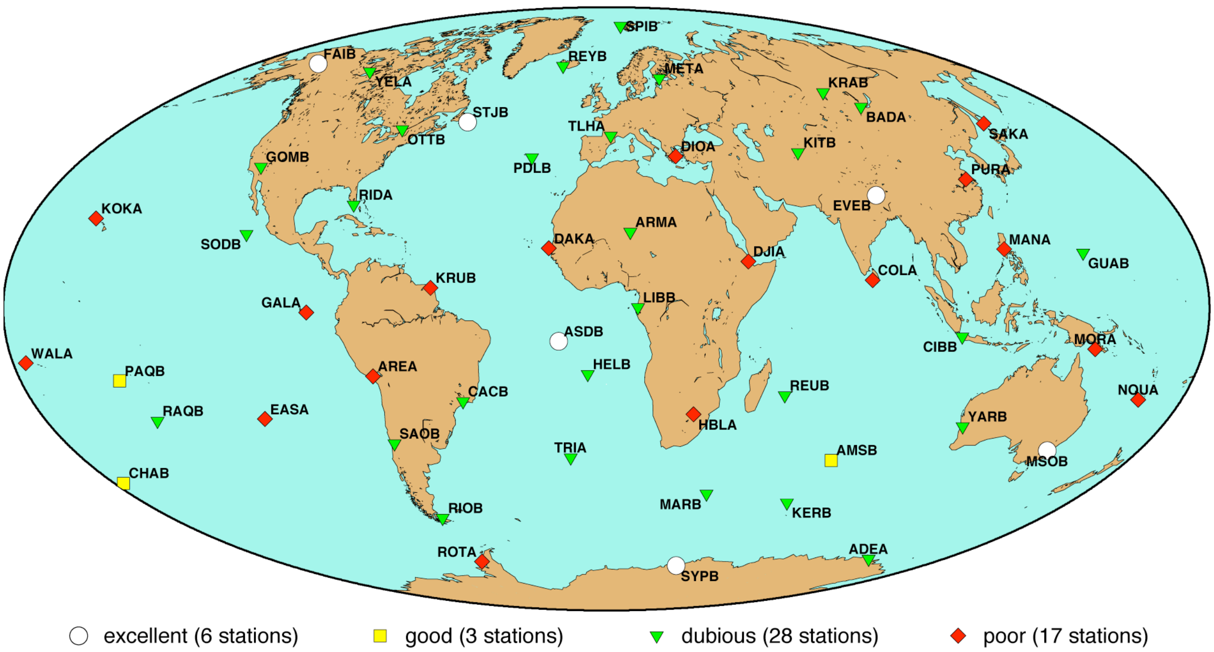

Figure 16

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

Figure 17

Antenna tilt resulting from the

corrosion of the base plate

(Amsterdam/AMSB)

Figure 19

Base plate embedded in a pillar.

(Nouméa/NOWB)

Figure 18

Concrete pillar on rock.

(Rothera/ROTB)

Figure 23

Leclerc tower (Thule/THUB)

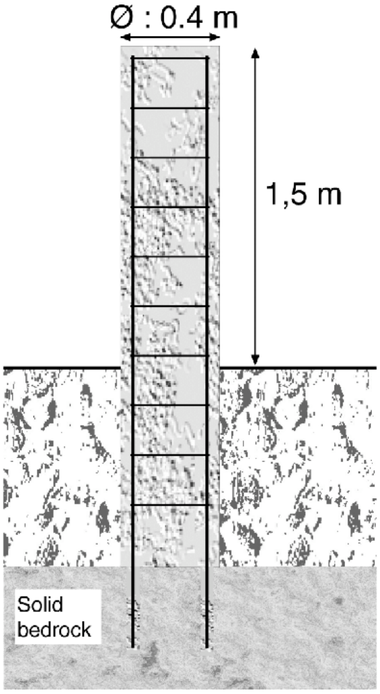

Figure 20

Pillar design when bedrock is present near the ground surface

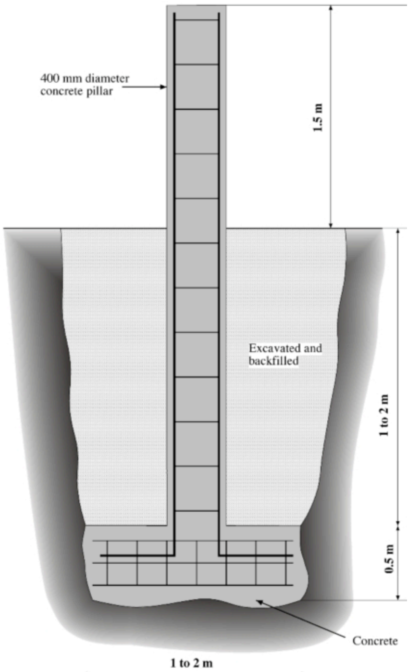

Figure 21

Pillar design for hard soil pillar

Dimensions may vary depending on soil hardness

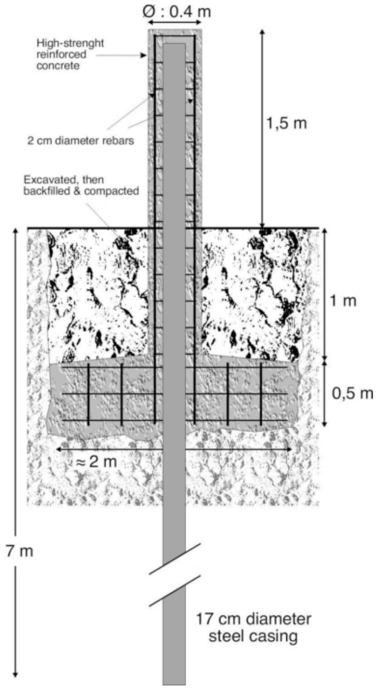

Figure 22

Pillar design for soft soil pillar

Dimensions may vary depending on soil hardness

Figure 27

Third generation beacon, charger

and backup battery in a 19” rack

Figure 24

One-metre high, 32 cm

sided tower on roof.

(Badary/BADB)

Figure 25

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 26

Half metre high, 17 cm sided

tower on top of a building.

(Kauai/KOLB)

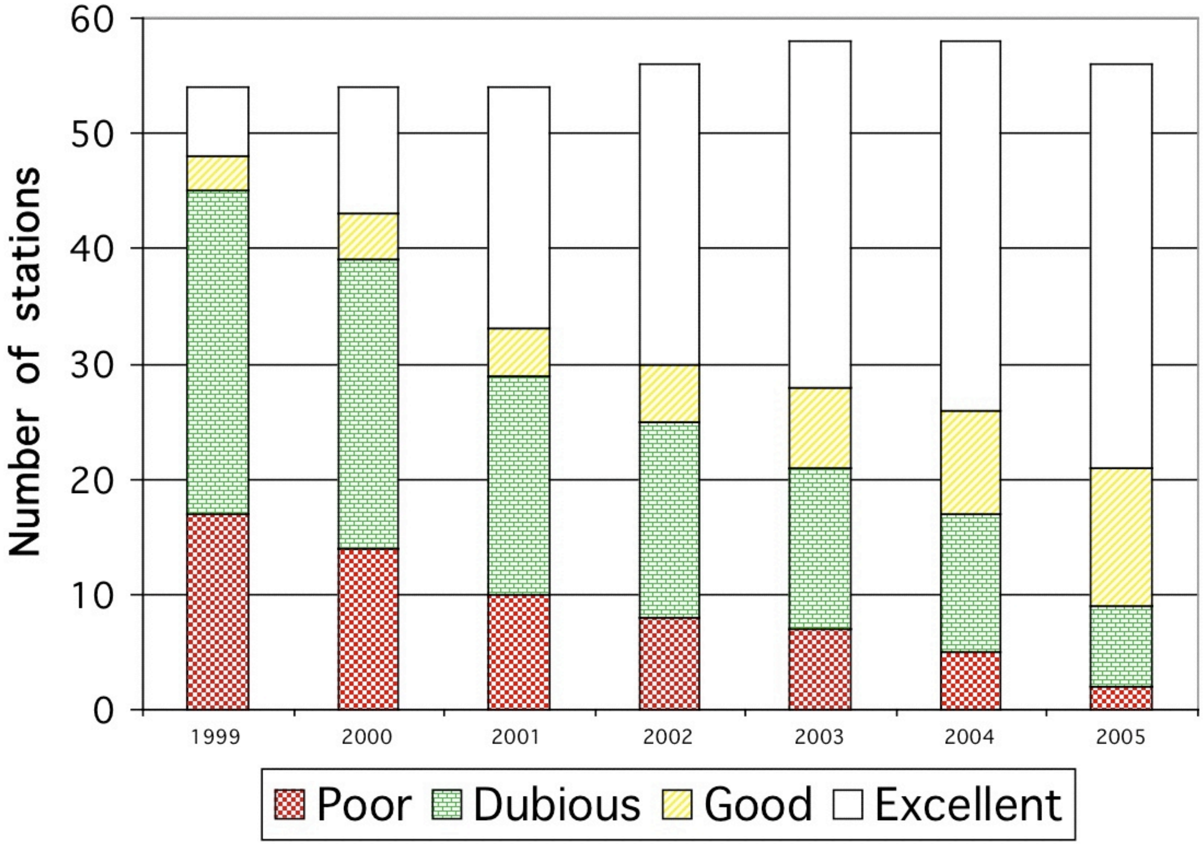

Figure 28: Improvement of the estimated antenna stability

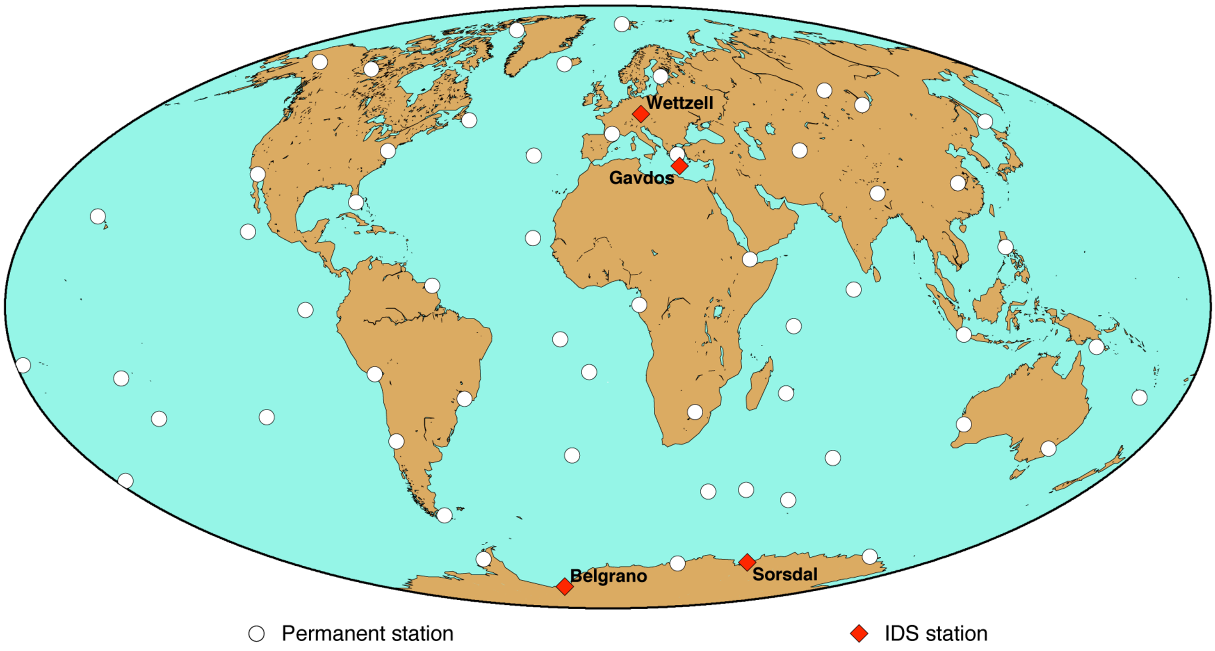

Figure 29: IDS experiments carried out to date

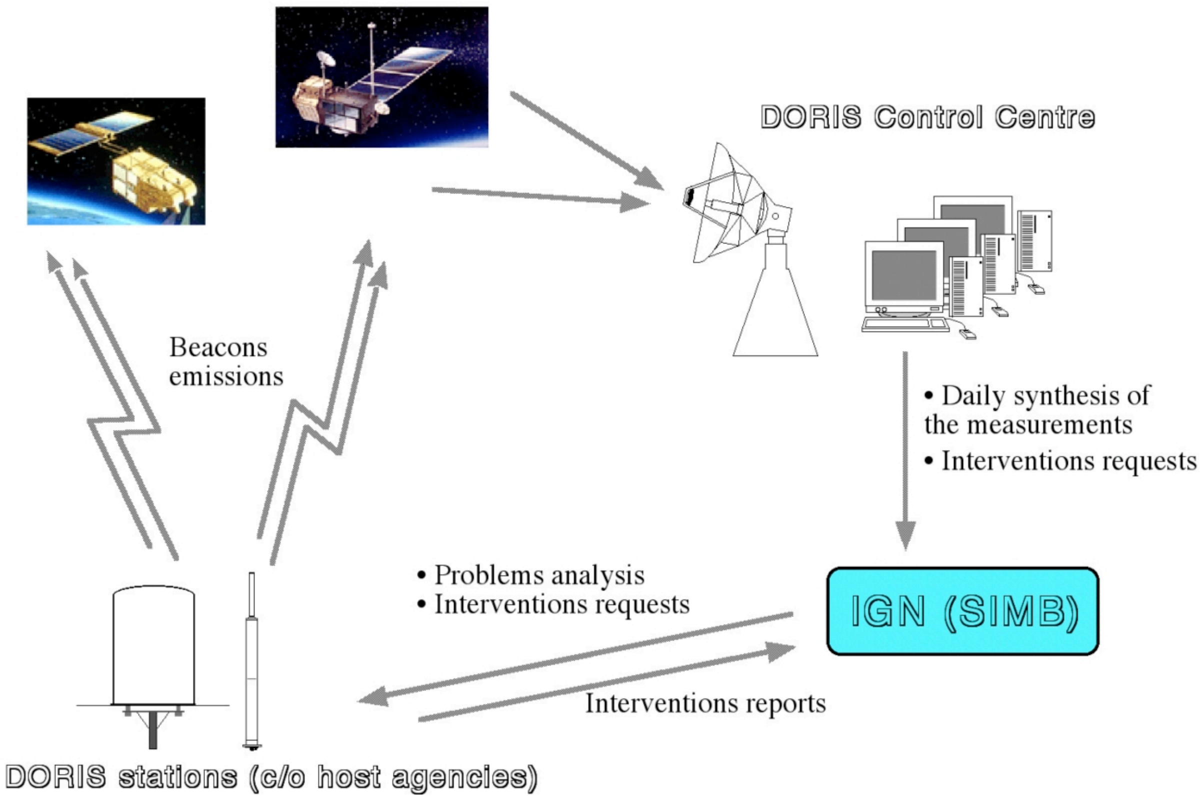

Figure 30: Measurements and maintenance flow

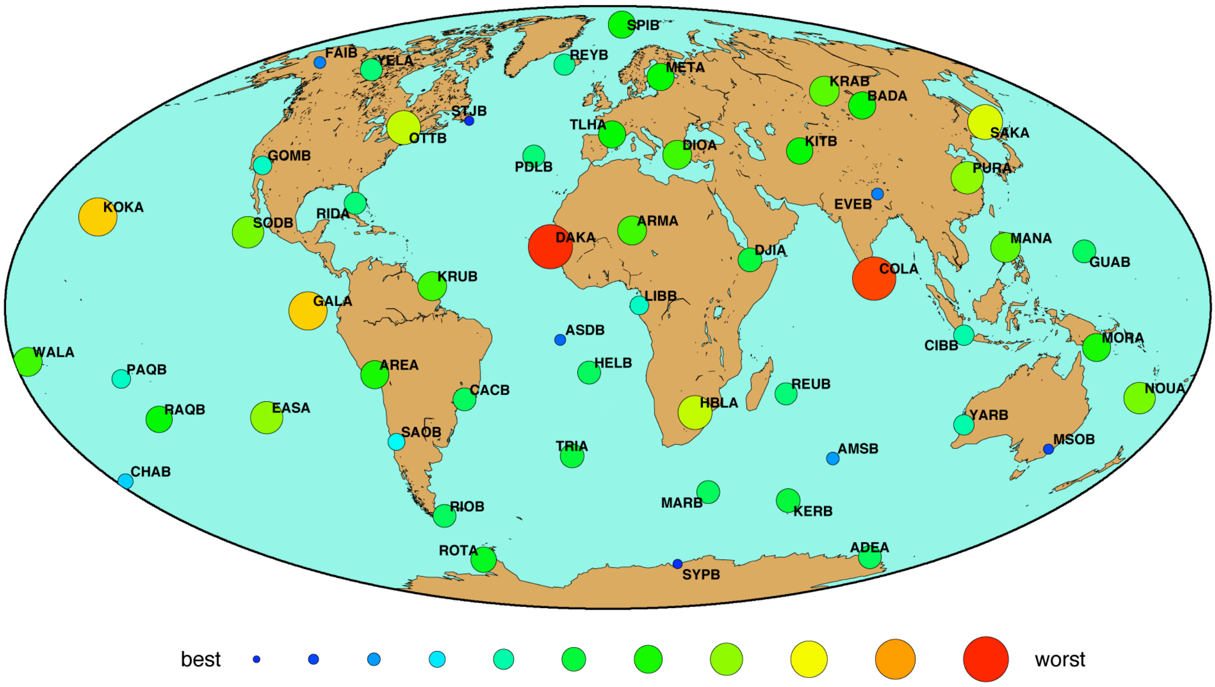

Figure 31

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

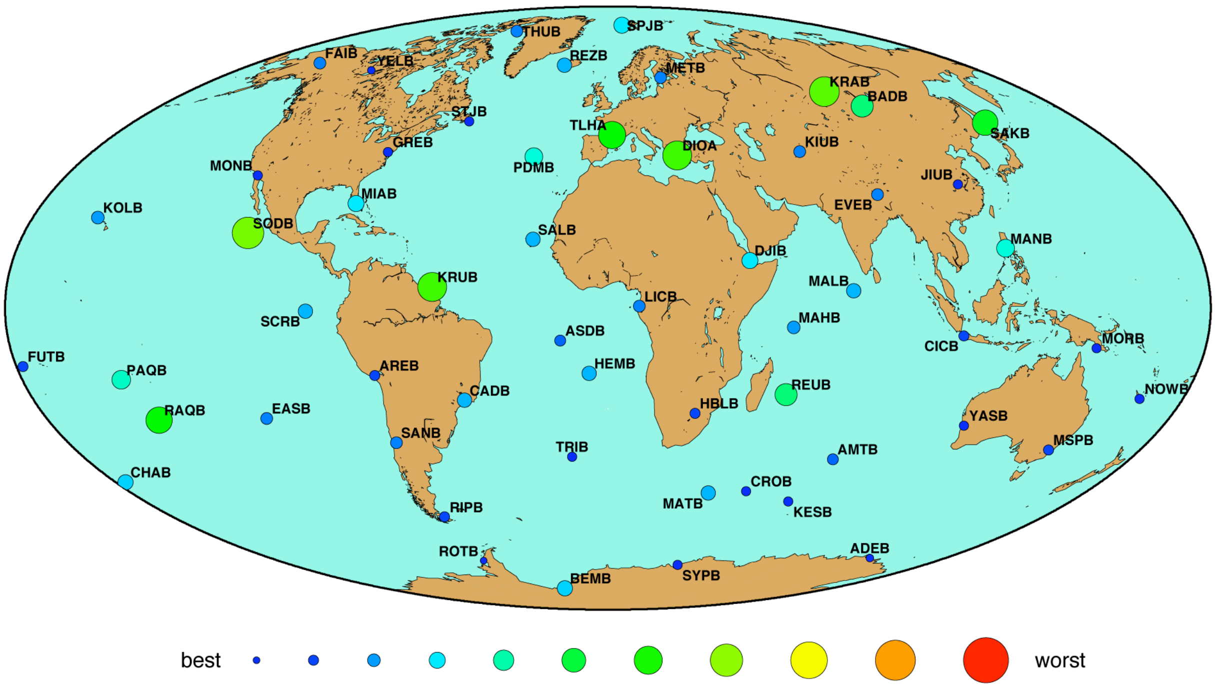

Figure 32

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

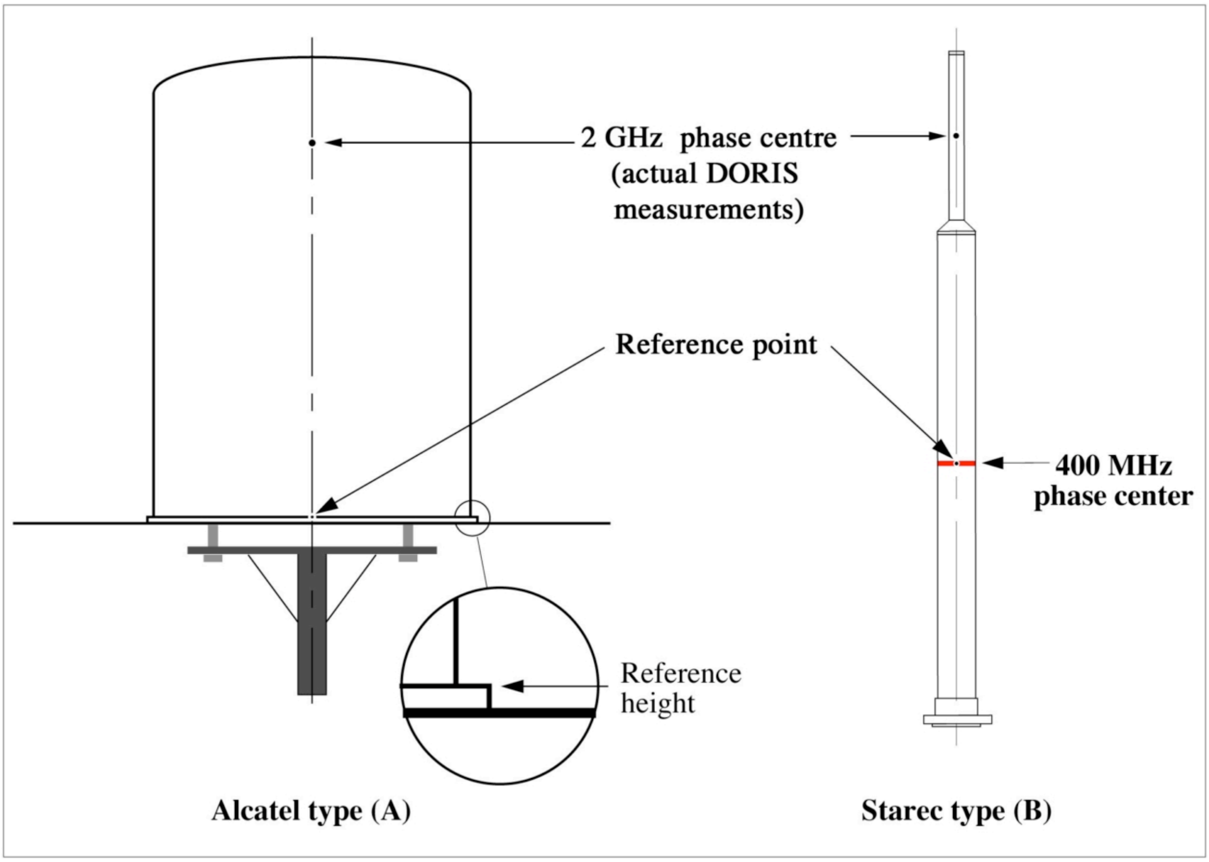

Figure 33: Definition of the antennas' reference point

Figure 34

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.

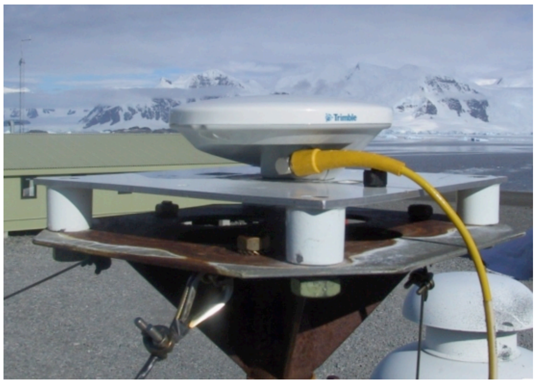

Figure 35

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

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

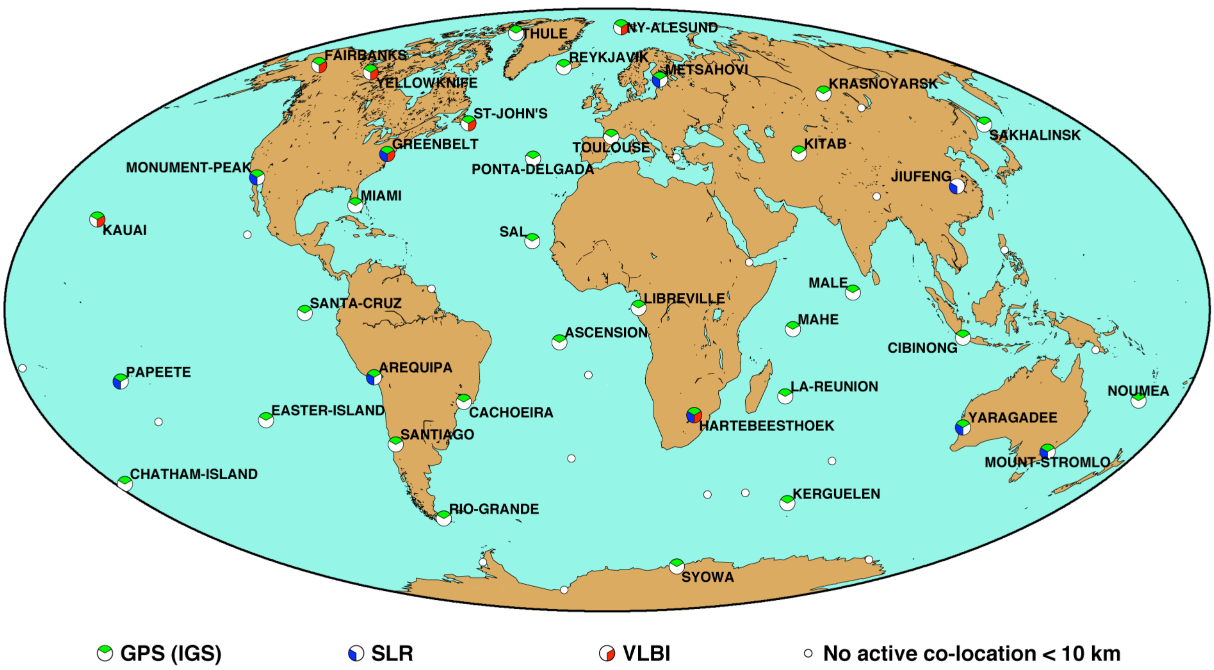

Figure 36

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

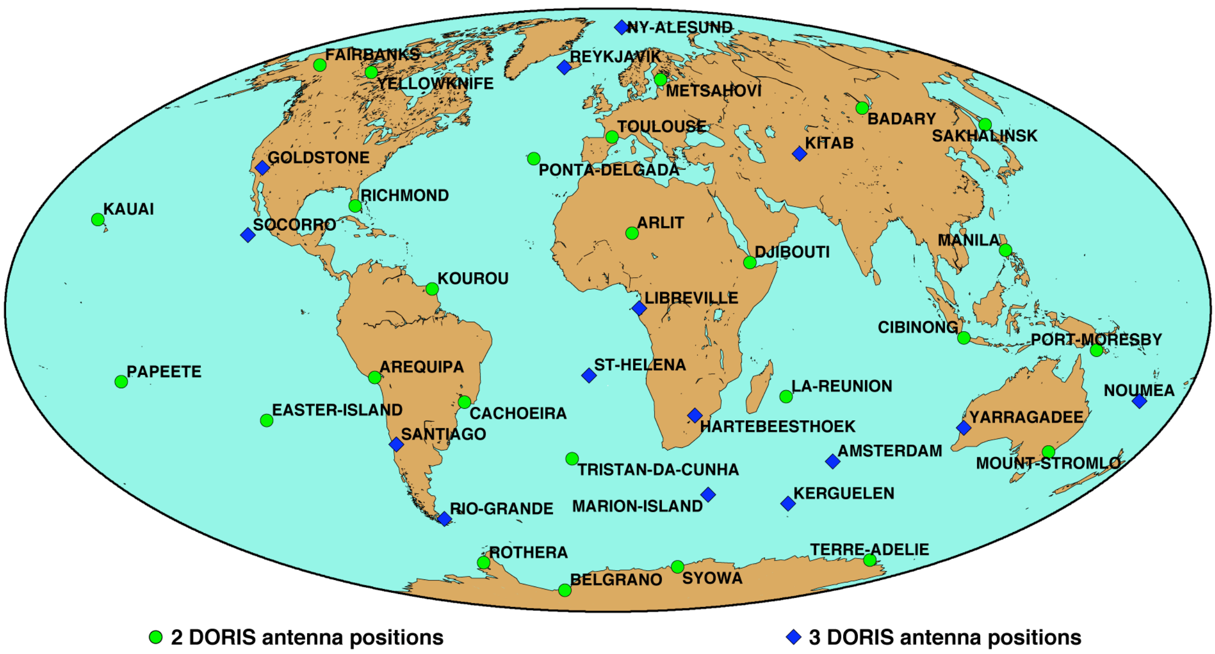

Figure 37

Multiple antenna positions at DORIS stations

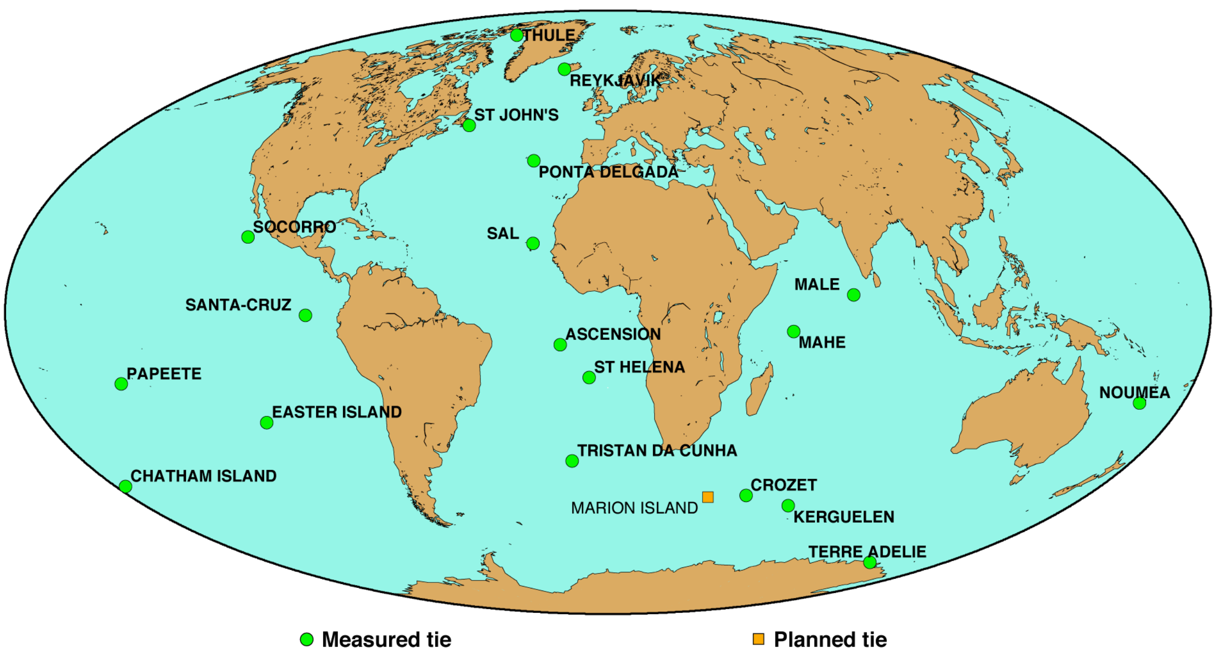

Figure 38

Co-locations between DORIS and tide gauges

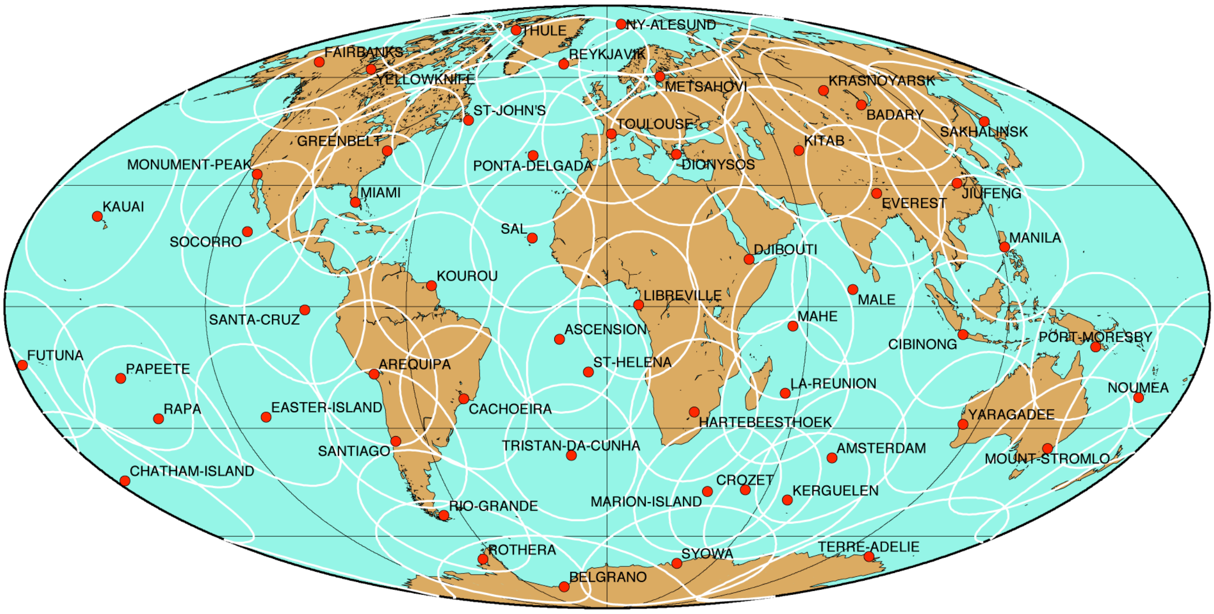

Figure 39

Visibility areas for the current DORIS network

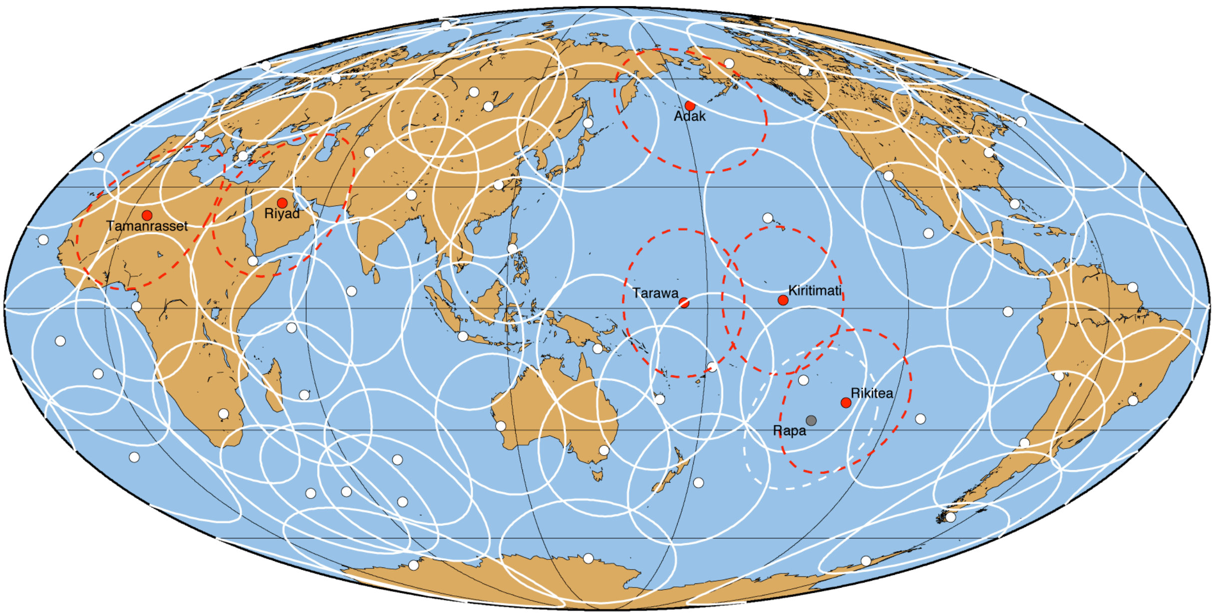

Figure 40

Planned new DORIS stations

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.	The 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 (chapter 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 (chapter 5)

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