Journal of Geodesy: Checklist for Reviewers

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Title: 20 years of evolution for the DORIS permanent network, from its initial deployment to its renovation
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Responsible Editor: P. Willis

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{ small editorial cleanup.

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C6. Are all the references cited and widely accessible? ☑ Yes ☐ No

C7. Can any material be moved to ESM or an appendix? ☐ Yes ☑ No

D. Detailed technical comments:

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 ~~mains~~ power ~~supply~~ 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 – guyed tower or wall side mount – available at that time.
- 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 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 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, 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 to use 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), 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).

Twenty awkward to start sentence with number.

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. 20 m 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 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:

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 noise to the time series and should be avoided.
- Only the antenna supports described below should be used.

not only noise, but perhaps bias

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).

(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 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 (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 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.

(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 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.

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 %.

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

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 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 Terrestrial 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 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 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 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.

do you insulate the concrete pillar

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 shrunk 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 to survey the stability of the antenna reference point 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.

I think this is what you mean

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.

- 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 threshold 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):

- GPS (only the stations part of the IGS network are taken into account) 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 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)

- 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 deepness. As regards the DORIS-SLR co-locations, Fig. 36 shows that there is a huge area between Metsähovi, Hartebeesthoek and Jiufeng where no [illegible] 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.

As regards 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 lack of data. Despite evolution of the transmitting beacons, many equipment failures, added to long repair times, have caused 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 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 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 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. Nevertheless, the deployment of the next generation DORIS receivers, which will have more than two channels, will make easier to add more stations 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 ones. There are currently no plans for a fourth generation beacon. As regards 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 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

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