The French Approach to Modernize Its Vertical Reference

Françoise DUQUENNE, Alain COULOMB et François L'ECU, France

Keywords: Vertical Reference System, Leveling, GNSS, France

SUMMARY

IGN (French Geographical Institute or Institut national de l'information géographique et forestière) is in France the legal responsible of the references in geodesy and leveling. The decree 2011-1371 dated October 27th 2011 states that IGN is responsible in *"designing and building a consistent geodetic infrastructure in coherence with international systems and managing the national geographic, gravimetric and height reference systems."* As IGN was setting up its new geodetic reference (RGF93) and the access to this infrastructure via the permanent GNSS reference network (RGP), currently with more than 400 stations, IGN has arisen from year 2000 questions about the vertical reference infrastructure: should we maintain a network of materialized benchmarks, how to maintain it, how to couple traditional leveling measurement and GNSS measurement to improve productivity and to reduce costs? After an user survey, the proposal called the "triplets" was therefore specified that any inhabited area (village of over 200 inhabitants) should be at less than 5 km from a "triplet". that is to say a group of at least three nearby benchmarks, tied by precise leveling and allowing the user a quick check of stability through conventional leveling means. GNSS observations and leveling using triplets allowed to develop conversion elevation grids more and more accurate, improving the determination of altitude by GNSS. Finally, a new vertical reference may be considered in a European context with EVRS (European Vertical Reference).

SUMMARY (in french)

L'IGN (Institut national de l'information géographique et forestière) est l'organisme qui en France est le responsable légal des références de géodésie et de nivellement. Le décret 2011-1371 du 27 octobre 2011 précise que l'IGN est chargé de « *concevoir et constituer une infrastructure géodésique cohérente avec les systèmes internationaux, et assurer la gestion du système national de référence géographique, gravimétrique et altimétrique* ».

Alors qu'il mettait en place sa nouvelle référence géodésique (RGF93) et l'infrastructure d'accès à cette référence via le réseau GNSS permanent (RGP), comportant actuellement plus de 400 stations, l'IGN s'est posé dès 2000 des questions sur l'infrastructure de la référence verticale : fallait-il conserver un réseau matérialisé de repères de nivellement, comment l'entretenir, comment coupler les mesures traditionnelles de nivellement à des mesures GNSS pour améliorer la productivité et diminuer les coûts ? Après une enquête utilisateur, la proposition dite des « triplets » a donc consisté à spécifier que toute zone habitée (village de plus de 200 habitants) soit à moins de 5 km d'un « triplet », c'est-à-dire un groupe d'au moins trois repères proches, liés par nivellement de précision et permettant à l'utilisateur un contrôle rapide de stabilité par moyens classiques de nivellement. Les observations GNSS et nivellement dans le cadre des triplets permettent d'élaborer des grilles de conversion altimétriques de plus en plus précises, améliorant ainsi la détermination d'altitude par GNSS. Enfin, une nouvelle référence verticale peut être envisagée dans un contexte européen avec EVRS (European Vertical Reference).

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1. THE CONTEXT

The French vertical reference (NGF-IGN69) is classically defined by : the origin of the altitudes is close to the tide gauge in Marseilles, the type of altitudes is normal, access is provided to the user through a network of 256,000 km structured leveling lines made of four orders on which exist more than 350,000 benchmarks in good condition. Altitudes are obtained from geometric or trigonometric leveling, performed on foot or by vehicle, as well as gravimetric survey on the first order and second order in the mountains. This legal reference was established in the late 60s, after re-observation and calculation of the first order. At the end of the twentieth century, the situation is due to the economic inability to maintain the network as a whole, where choices have varied over time : additional 4th order in the 1990s, and renovation of a part of the first order a few years later, of rebuilding leveling lines after their deterioration. The network status itself is unclear, but it is known that there are more destroyed benchmarks than new erected each year.
The user survey conducted in 1998 as part of a working group within the National Geographic Information Committee (CNIG) highlighted the need to have an access to the vertical reference, at a millimeter level, via a network more distributed and frequently maintained. Users also stated they do not wish to change the vertical reference system, having remembered the difficulties caused by the change in 1969 from Lallemand NGF to NGF-IGN69. At the same time, the evolution of space geodesy techniques revolutionized geodesy and the new RGF93 French datum arose which became legal in 2000. In order to fix altitudes by GPS, the quasigeoid QGF98 is calculated and a conversion grid (RAF98) between ellipsoidal height RGF93 / GRS80 and NGF-IGN69 altitude is deduced. This grid allows altitudes determination from GPS observations within a centimeter accuracy (3 cm 95%) provided using precise GPS methods and also relate specifically to the datum RGF93. The permanent GPS network namely RGP, established since 1998, facilitates access to RGF93.

2. NEW POLICY FOR MAINTENANCE OF THE LEVELING NETWORK : THE TRIPLETS

The new way to maintain the precise leveling network involves the concept of "triplet". A triplet is a group of at least three benchmarks with the following specifications:

- The distance between the two farthest benchmarks should be less than 1 km
- The difference in height between the highest and the lowest benchmark must be less than 30 meters

A triplet allows a quick and easy stability control, and therefore cheap. Mainly because of the economic activity, the most important needs in benchmarks are spatially correlated with population density. The triplets are therefore generally located in urban areas. This location also allows better preservation of benchmarks through sensitization of municipalities in conservation of benchmarks triplets.

Since 2000, IGN has adopted a new maintenance strategy for metropolitan France leveling network that offers the user the ability to determine the elevation of a point of the network (blue dot in the sketch) from another point tied to the leveling network (yellow dots on the sketch), measuring, using two GNSS receivers, the difference in height above the ellipsoid between the two sites.

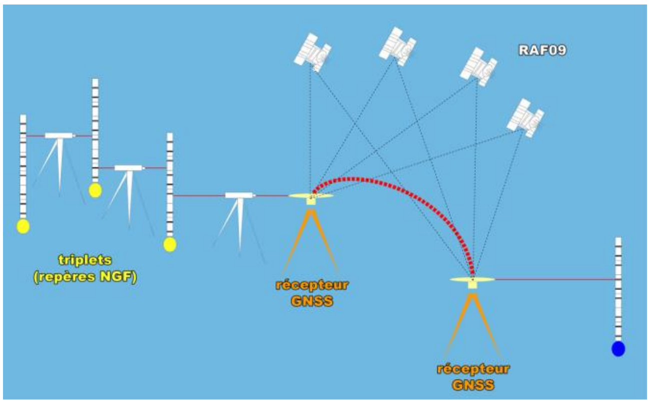


Fig.1: diagram of observations made possible by the existence of triplets

For obtaining quickly (a few tens of minutes) a centimeter accuracy with such a method, it is particularly necessary that both receivers are not too far away (distance between the two points less than 5 km). IGN therefore requires that all of the territory inhabited point (over 200 people) is less than 5 km from a triplet.
A connection with the leveling network requires performing, using traditional leveling tools (survey rod and level), an altitude control of the connecting benchmarks by a re-survey of vertical drop to the closest markers (operation called "stability control").
Except in special cases, leveling benchmarks not being part of a triplet are no longer subject to the new measurements.
Historically, the process included several phases:

- The first one from 2000 to 2008, consisted of a systematic inspection of the network status by a field visit, which also collected descriptive data to feed a database. At the end of this stage, it was found that approximately 13% of benchmarks were destroyed and 8% not found. This visit helped to identify existing triplets.
- A second phase from 2001 to 2007, has created new triplets (either using one or two existing markers, or by establishing three new benchmarks) to cover portions of the territory not yet covered by existing triplets identified during the first phase. This step was carried out using leveling and GPS observations, hence its name NIVAG (in French, leveling assisted by GPS). During this phase, 4,000 triplets were created.
- The third phase, called ERNIT (in French maintenance of leveling network using triplets), started in 2008 and scheduled over 12 years, is the first iteration of a systematic network maintenance, where 13,200 triplets identified on French territory are observed.

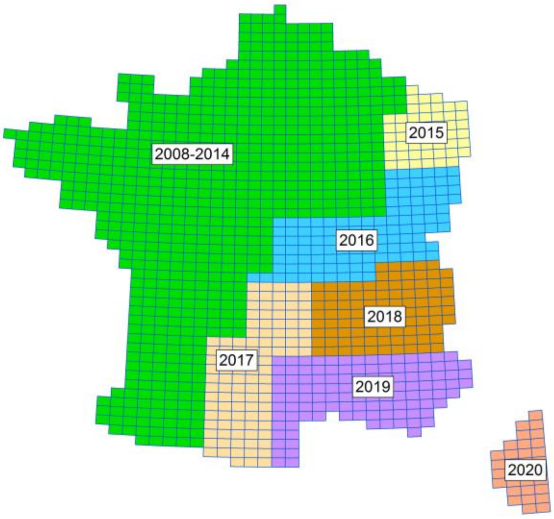


Fig.2 : forecast progress map for maintenance of leveling network by triplets

The methods of observations:
In both phases NIVAG and ERNIT leveling and GNSS observations are to be carried out. However, the methods are different because of the different objectives, but also because the methods of observations have evolved over time.

2.1 NIVAG : GPS-aided leveling

The advantage of this method is to transfer the NGF-IGN69 altitude to any relatively remote areas within the existing leveling network. Rather than a long precise leveling operation altitude is obtained via GPS measurements and RAF98 grid. Practically, a GPS receiver (pivot) is set up close to benchmarks, and a tying-in to NGF by precise leveling is performed (including a stability control). Also this pivot is linked to RGF93 geodetic reference system by setting a receiver onto a marker of the geodetic French Basic Network (RBF) (Fig.3). The observation time is 48 hours on the pivot. The pivot is used as reference by many triplets and a GPS receiver is set up close to each triplet in turn and at less than 15 km from the pivot. The observation time is 3 hours. The GPS antenna is tied in to the triplet by precise leveling.

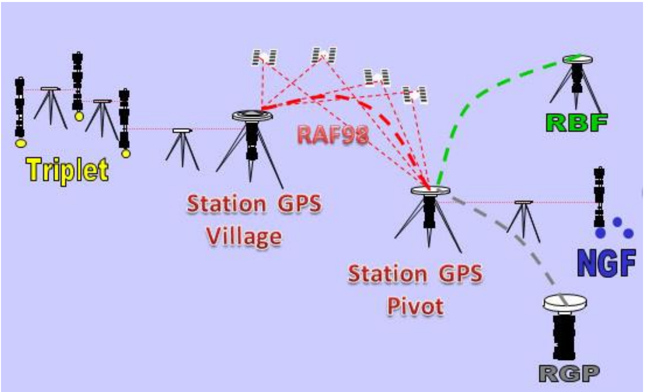
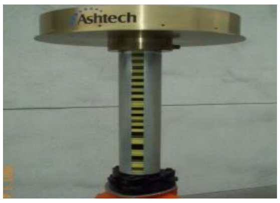


Fig.3: diagram of NIVAG observations

The difference in height between each point and the pivot in town is converted into altitude difference using RAF98 grid. This one being used relatively the accuracy of this conversion is close to the centimeter. The set of pivots is a sample of about 1000 leveled GPS points, which was used to test the absolute accuracy of the RAF98 grid, and then to calculate the RAF09 grid.

Equipped utility vehicle



GPS antenna and barcode tape

Fig.4: equipment for NIVAG

2.2 ERNIT : maintenance of the leveling network using triplets

The purpose is to check, using precision leveling, the stability of benchmarks constituting the 13,200 triplets and assign to all these markers ellipsoidal height above the GRS80 RGF93 system by setting up a GNSS station nearby the triplet and calculating RGF93 coordinates from several stations RGP.
Thus, in unstable areas, it will then be easy to monitor by GNSS the height variations and deduce variations of altitudes from the stations of RGP whose movements are monitored continuously to the nearest millimeter. This method is obviously lighter and less expensive than leveling traverses that can be long to reach a stable area. The internal stability of the triplet will of course always be verified by precise leveling.
As to the progress of the work, this set of 13,200 leveled GPS point will be used to achieve a new RAF grid, which it is hoped a precision better than one centimeter over 90% of the territory.
Observations on triplets:

– precise leveling between the markers of the triplet (Trimble Dini levels and barcode rod).
– determining the ellipsoidal height of the triplet (dual-frequency receivers, choke ring antennas, 2.5 hours of observation as a minimum, measurement acquisition rate: 30

seconds, cut-off angle: 10 °).

Fig 5: equipment used for ERNIT observations
GNSS antenna equipped with a barcode rod and Trimble DINI level

On January 1st 2008, the average age of the triplets was 28 years. On January 1st 2015, this age was 12 years. The aim is to achieve in 2020 an average age of 6 years.
The database and the web site for dissemination of description sheets, show the evolution of the use of the leveling network. Consultation of sheets decreases very slowly but the number of monthly consultations, close to 20,000 reflects a still very important use of leveling network.

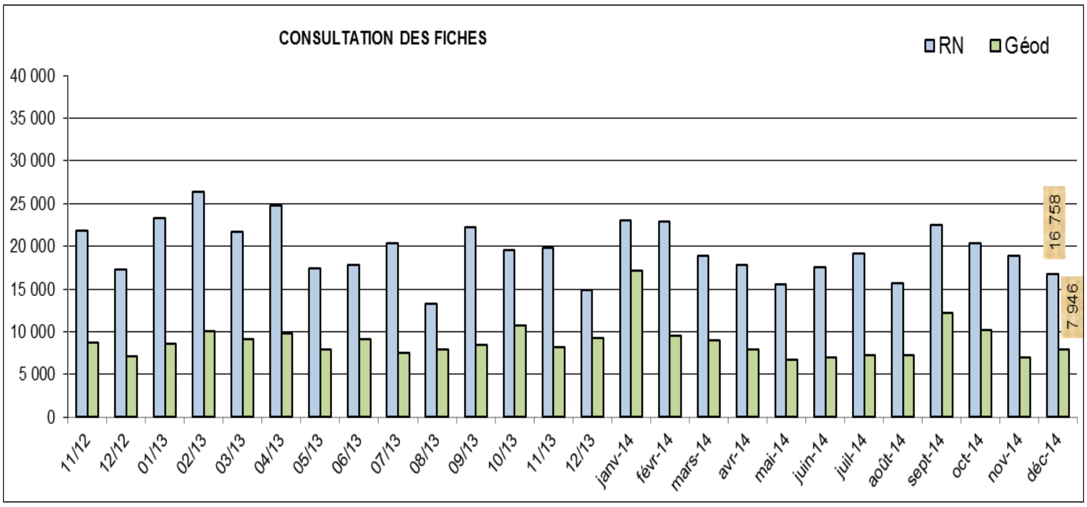


Fig.6 : Consultation of description sheets of benchmarks and geodetic markers

3. DURING THIS TIME THE GNSS METHODS ADVANCE IN FRANCE

The method of triplets requires a very precise determination of the ellipsoidal height, which is the most difficult component to achieve with regards to GNSS precision. It is also necessary to have a precise and high resolution grid for conversion from ellipsoidal height above the GRS80 ellipsoid of French datum RGF93 to IGN69 altitude. So GNSS observations and calculations must ensure optimum accuracy in the determination of the height but also in the tying-in to RGF93.
The means in accessing to the national geodetic reference have advanced during the implementation of this triplets approach, facilitating access and improving accuracy.
The RGF93 is the French component of the European datum ETRS89 (European Terrestrial Reference System). The implementation of this system began in 1993 with the establishment of the reference network (RRF) made of 12 materialized stations, which were observed in the European campaign EUREF 89. Spatial geodetic observations consisted in GPS but also in VLBI (Very Long Base Interferometry) and laser satellite.
This network has been densified between 1994 and 1996 by the RBF (French basic network) network of around 1,000 points materialized and spread evenly over the territory (one point every 25 km). It is through this network that users were able to start working within RGF93 frame which became the national standard by a decree in 2000. Since 1998, GPS permanent stations are starting to be installed, thus facilitating access to the reference RGF93, since the user is no longer obliged to set up a reference receiver on the materialized marker.
RGP is a network of permanent GNSS stations managed by IGN, set up in 1998 as part of a public-private partnership and currently has more than 400 stations. These stations are installed by public or private organizations, and observations are made available free of charge via the Internet with a maximum of one hour for delivery. IGN collects this data, performs quality controls, and makes it available on the internet via a FTP server and a Web site. The partnership now has 34 permanent stations managing partners, 12 hosting partners for IGN stations, 7 partners managing GNSS real time networks.

Fig.7 : Permanent GNSS network web site

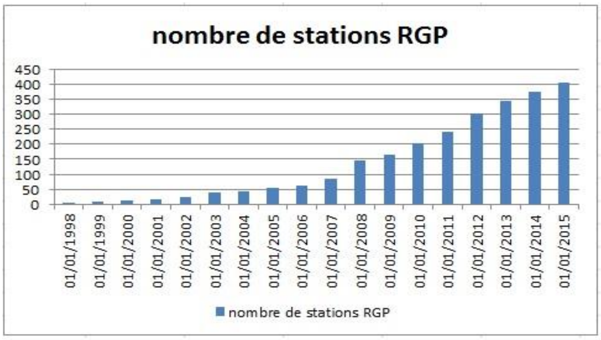


Fig.8 : diagram of the number of RGP stations per year from 1998 to today

The GPS permanent network became GNSS permanent network progressively in integrating receivers able to receive Glonass signals then Galileo signals since 2012. Initially, the RGP stations were linked to RGF93 using GPS observations on RBF points nearby to ensure compatibility of the two networks. Then in 2009, following the publication of the realization of the ITRS (ITRF2005), and in the context of the EUREF commission of the IAG, all the observations of RGP since 2000 has been reprocessed.

This processing has been enhanced by a new version of the Bernese Software (Version 5), the absolute antenna modeling and correction models improvements (oceanic loading, troposphere ..).

During NIVAG campaigns, all RBF markers were observed per session of 48 hours, and combining these observations with those of the nearest simultaneous RGP stations, RBF coordinates were reprocessed. The differences in coordinates with the previous set were less than 3 cm horizontal and could exceed 10 cm in height, mainly due to improvement in the processing of the vertical component.

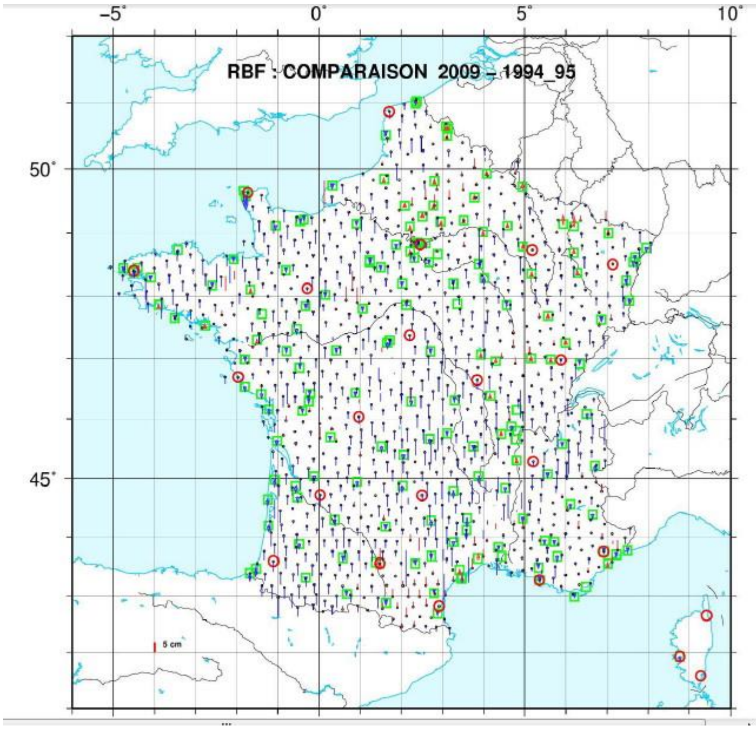


Fig.9 : reobservation RBF 2000-2009,
vertical differences from the initial calculation 1993 (Harmel A. 2010)

4. AN ALTIMETRIC CONVERSION GRID MORE AND MORE ACCURATE

To determine altitudes from ellipsoidal heights, you need a conversion process to altitudes and usually a "geoid" is said to be used. This is not rigorous, because on one hand with the type of altitude it is either a geoid (orthometric height) or a quasi-geoid (normal height), on the other hand whether achieving a geoid model or vertical reference system, they have their biases to be taken into account. The process adopted in France (Fig 10) therefore is to calculate a high-resolution quasigeoid using regional gravity and to adapt it to a set of GPS points (GNSS) leveled.

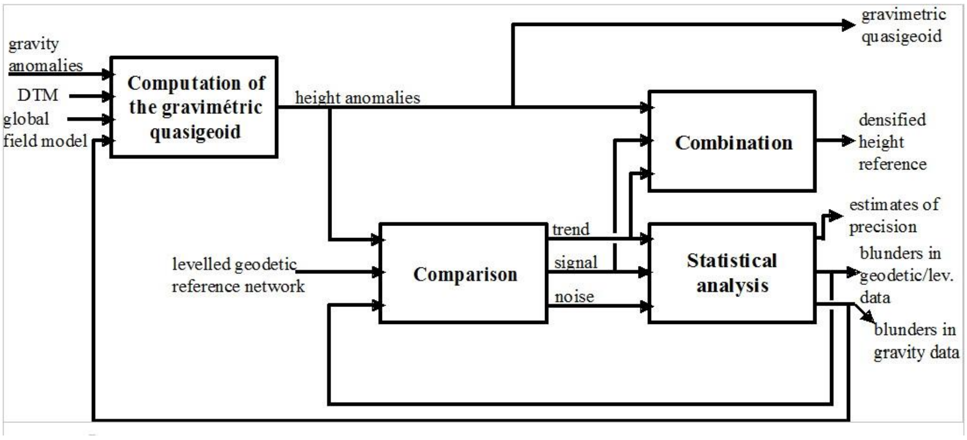


Fig.10: process of building a conversion grid (Duquenne H.1999)

4.1 The quasigeoid QGF98

The French quasigeoid QGF98 is the result of research and development conducted from 1996 to 1998 at IGN and ESGT (Ecole supérieure des géomètres et topographes). The method for determining this quasigeoid is the method of Stokes with removal and restoration, terrain residual method and conventional integrations. A digital terrain model at a 140x140 m resolution allows for terrain corrections with a radius of 110 km, and a Stokes integration radius of 2 °. The global geoid model used is OSU91, gravity data is derived from the International Gravimetric Bureau database: 400,000 terrestrial measurements, shipborne offshore data, and Sandwell model from satellite altimetry. The calculations are performed using Gravsoft software (Forsberg and Tscherning).

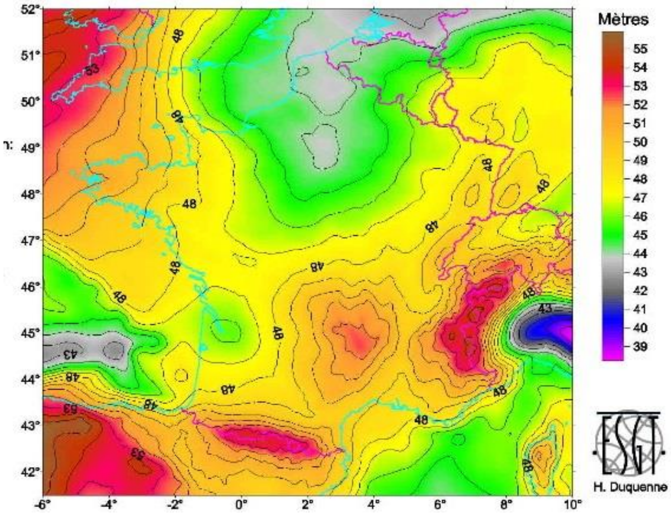


Fig.11 : QGF98 quasigeoid

4.2 RAF98 grid

Comparing QGF98 with 978 GPS leveled points highlights differences ($\zeta_{GPS} = h - H$) given as trend, signal and noise.

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	Parameter	*Unit*	*Value*
a	constant bias	m	0.060
b	northward tilt	m/1000 km	–0.5258
c	eastward tilt	m/1000 km	0.7852
Min *v*	minimal residual	m	–0.379
Max *v*	maximal residual	m	0.676
σ_v	RMS of residuals	m	0.109
σ_s	RMS of signals	m	0.104
σ_n	RMS of noises	m	0.034

Tab.1 : parameters of RAF98 adaptation

The trend:

Parameters *a*, *b*, *c* are coming from the differences between the zero field model and IGN69 one, from its North-South bias, errors at wavelengths field model (OSU91) and from the fact that the datum of the quasi-geoid is not RGF93.

The signal: is the correlation of the residuals, due of errors in regional field model, in gravimetry, in RBF, in leveling.

Noise: due to local errors in the RBF and in the leveling network, observation errors (GPS, leveling, gravimetry).

The residuals are spread by the collocation method on a grid called RAF98 (référence altimétrique française or French altimetric datum).

Tests provided on one hand by users, and on the other hand by the use for NIVAG, established that the accuracy of the grid RAF98 is 3 cm at 95%.

Comparing QGF98 with leveled GPS points, it appears a significant problem in the south of France and Corsica, due to errors in the OSU91 field model and also bad gravity data in the Mediterranean Sea, making impossible the establishment of a grid in Corsica.
In 2001, 2510 km of airborne gravity survey were made between Corsica and the south of France, and quasigeoid QGC02 is calculated with new data and new field model: EGM96. The RAC09 grid conversion between RGF93 height and altitude IGN78 is deduced in 2009 by adaptation to 40 leveled GPS points.

4.2 RAF09 grid

Recalculation of RBF and RGP geodetic networks, having induced significant changes in ellipsoidal height component, it became necessary to issue a new conversion grid. The RAF09 grid is calculated by adapting QGF98 and QGC02 quasigeoid on 941 leveled GPS points: the pivots and RBF markers observed for NIVAG.

The adaptation parameters are essentially the same as RAF98 ones but residuals are lower, confirming a higher quality in the GNSS height component.

	Parameter	*Unit*	*Value*
a	constant bias	m	0.030
b	northward tilt	m/1000 km	–0.5524
c	eastward tilt	m/1000 km	0.7911
Min v	minimal residual	m	–0.326
Max v	maximal residual	m	0.584
σ_v	RMS of residuals	m	0.119
σ_s	RMS of signals	m	0.094
σ_n	RMS of noises	m	0.030

Tab.2 : parameters of RAF09 adaptation

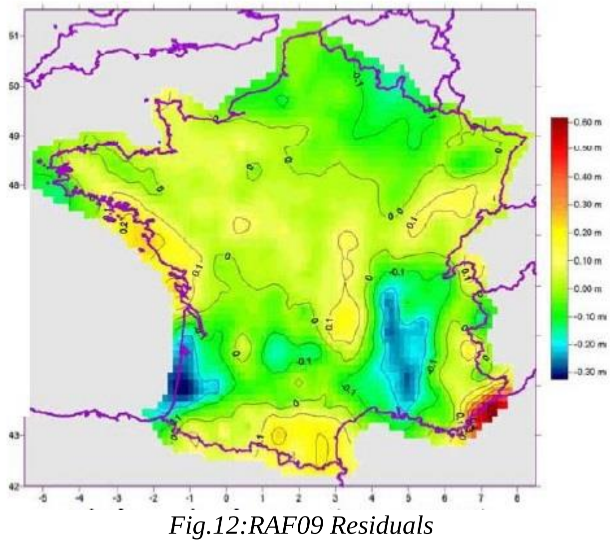

Fig.12:RAF09 Residuals

From 2010, a first evaluation on different data sets estimated the precision of RAF09 between 1 and 2 cm. The 6,200 points observed during ERNIT campaigns between 2008 and 2013 allowed us to get an estimate of precision, better distributed, although not yet complete on France. As shown in the figure below, the majority of the points (76.5% of them) have a RAF09 vs observation bias less than 2 cm absolute, with a standard deviation of 1.7 cm calculated on all this dataset.

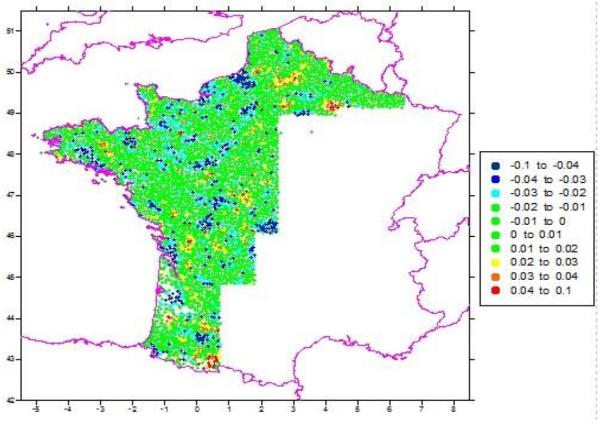

Fig.13: comparison of RAF09 at ERNIT locations (in meters)

4.2 A new RAF conversion grid

A new quasigeoid over France is being calculated, benefiting from new terrestrial gravity, marine, airborne and space (satellites Grace and Goce) data. In particular, the airborne gravity data in the Mediterranean Sea, which were used in calculating the quasigeoid QGC02 for Corsica, will be used. It should help us to smooth out problems impacting QGF98 in Provence. The field model used will be EGM08. The DTM will consist mainly of the one coming from the BDTopo at IGN for its terrestrial part, combined with the Sandwell and SRTM models for the marine component.
A new altitude conversion grid will then be deducted from the adaptation of this quasigeoid to 13,200 triplets.

5. A NEW VERTICAL REFERENCE WITHIN THE EUROPEAN CONTEXT?

The last change in vertical reference in France, which occurred in 1969, from the so-called NGF-Lallemand system to NGF-IGN69 system has created a real trauma for the users, some altitudes being changed of up to 60 cm. There had been re-surveying the first order network, then a new calculation and a change of altitude definition (from orthometric to normal). That is why it was not a question of changing the vertical reference again, although systematic errors in IGN69 altitudes have been known for a long time.
However this can be considered in the context of European vertical reference which, for the time being, is primarily used for low-precision data exchange between European countries. EVRF2007 (European Vertical Reference Frame) is the latest implementation of this European system, whose origin is located in the North Sea, and observations coming from networks of 27 European countries.

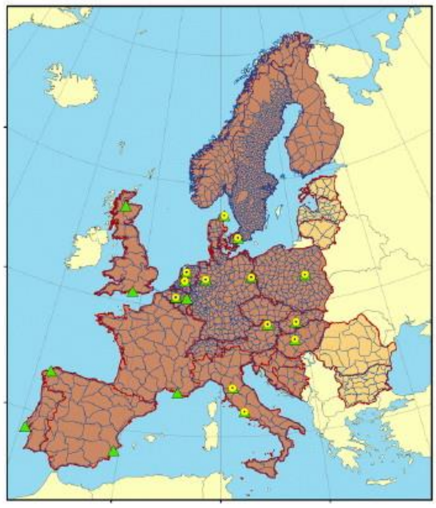

Fig.14 : EVRF2007 : networks

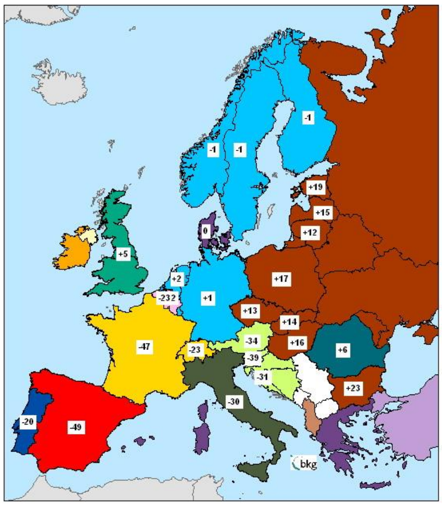

Fig.15: correction from national heights in Europe to EVRF2007 in cm

The French contribution is of old observations of the first order and the shift from IGN69 altitude to EVRF2007 altitude is minus 47 centimeters.
But in 1983, a South-North traverse, from Marseilles to Dunkirk has highlighted a bias of about 20 cm. To provide a new participation in the European Vertical Reference, IGN began as early as 2000 new high precision survey: NIREF (French reference leveling).

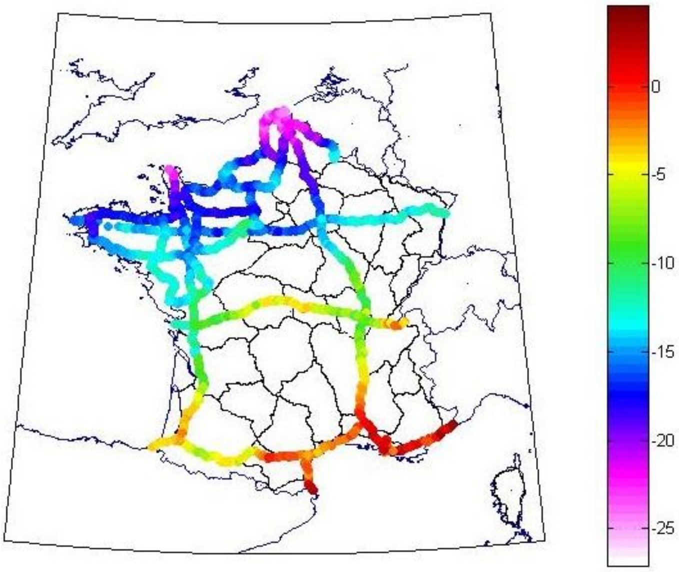

Fig.16 : distribution of North-South bias of IGN69 as seen by NIREF

These major leveling traverses are joining networks of neighboring countries and are connecting all the tide gauges on the French coast. A North-South bias of 23 cm in IGN69 is confirmed.

The integration of these traverses in the next EVRF realization will correct this bias in the European reference.

Fig.17: NIREF : motorized precision leveling

CONCLUSION

In 2020, IGN will have achieved its goal of having for France a vertical reference materialized by a network, well distributed, well maintained and easily accessible thanks to the triplets. It will then initiate a second stage, in re-observing triplets, with a likely greater frequency on areas known to be unstable. This will also allow to know better the movements in these areas (mining, groundwater, karst region).

The user will have the choice to link its site in altitude with an accuracy of :

- millimeter (1-5 mm) by precision leveling measurement from triplets,
- infra-centimeter (0.5 to 1 cm) ultra-precise GNSS technology and the new altimetric conversion grid used in relative,
- centimeter (1 to 5 cm) GNSS standard technique such as RTK, coupled again to the new altimetric conversion grid used in absolute.

In a context of unification of vertical references, either at a continental or at a global scale, regardless of the realization (by a geoid or otherwise), by having the ellipsoidal height (ETRS89, ITRS) on all triplets, assigning new heights on the markers of the French network will be immediate and the development of new grid conversions for these new reference will be easy. So even though these vertical references are not adopted at national level, specific transformations will be available.

ACKNOWLEDGEMENTS

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CONTACTS

Françoise DUQUENNE
Association Française de Topographie
73 avenue de Paris
94165 SAINT-MANDE CEDEX
FRANCE
Email:fh.duquenne@wanadoo.fr
web :www.aftopo.org

Alain Coulomb
IGN/SGN
73 avenue de Paris
94165 SAINT-MANDE CEDEX
FRANCE
Email : alain.coulomb@ign.fr
web :www.ign.fr

Francois L'ECU
IGN/SGN
73 avenue de Paris
94165 SAINT-MANDE CEDEX
FRANCE
Email : francois.l-ecu@ign.fr
web :www.ign.fr