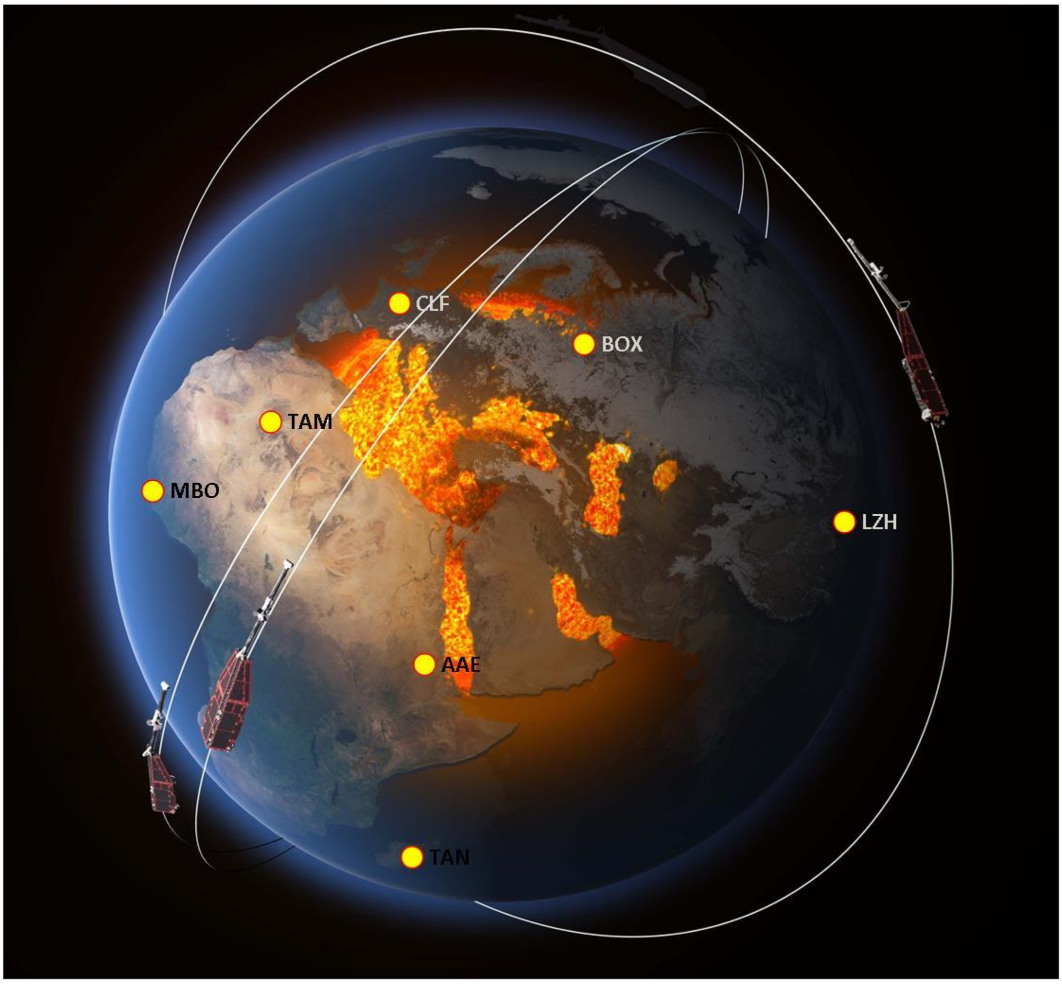
BUREAU CENTRAL DE MAGNÉTISME TERRESTRE
France

Bureau Central de Magnétisme Terrestre

Strategic plan 2014-2018



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Executive Summary

The *Bureau Central de Magnétisme Terrestre* (BCMT) is a French organization founded in 1921 and attached to the *Institut de Physique du Globe de Paris* (Paris IPGP). The primary mission of the BCMT is to provide ground geomagnetic observations of the highest quality to the scientific community, in France and abroad. The BCMT also serves industrial, military and societal users, provided their needs are aligned with scientific needs. Since 2008, the BCMT has been recognized as the *Service National d'Observation* (SNO) in Magnetism by the *Centre National de la Recherche Scientifique* (CNRS). Two French institutions are involved in BCMT operations, IPGP and *Ecole et Observatoire des Sciences de la Terre* (EOST) in Strasbourg, and several others, including CNRS-INSU and the *Institut Polaire Français* (IPEV), provide financial and/or human support. The International Service of Geomagnetic Indices (ISGI), hosted in the *Observatoire Versailles Saint Quentin* (OVSQ), is also attached to the BCMT. An international Scientific Council, set up in 2009, meets every two years to review BCMT activities and provides advice and recommendations to the BCMT.

To achieve its mission, the BCMT operates a network of 17 magnetic observatories distributed on 6 continents, including the National Magnetic Observatory located in Chambon la Forêt, Loiret, and a repeat station network in metropolitan France. The BCMT observatory network represents about 15% of INTERMAGNET, the global network of magnetic observatories, and contributes to filling geographical gaps in scientifically interesting locations. The BCMT develops its own line of dedicated instruments, taking advantage of the Chambon la Forêt site where unique testing and calibration facilities are available. In-house instrument development provides significant flexibility and reliability to BCMT operations. Several data products are distributed by the BCMT: preliminary one-second or one-minute data in real time (less than 5 min, 9 observatories) or near real time (less than 24 h, all observatories); quasi-definitive data with a one-month delay and definitive data with a one-year delay; repeat station data products such as a declination map; geomagnetic indices. BCMT data are available on its webpage (www.bcmt.fr), on INTERMAGNET's webpage (www.intermagnet.org) and on ISGI's website (http://isgi.latmos.ipsl.fr/).

The objectives of the BCMT for the upcoming five-year period (2014-2018) will be along three main scientific axes: geomagnetic field modeling and support to ESA's *Swarm* satellite mission (launched in November 2013); space weather and space climate; observatory techniques and instruments. New and/or noteworthy projects include: the full renovation of the Chambon la Forêt observatory, prompted by the inundation of the historical sensor vault; the setup and testing of long-term electric field measurements at some observatories, including Chambon la Forêt; the transfer of ISGI from OVSQ to EOST and its website refurbishment; the transmission of data in real-time from South Indian Ocean and Antarctica observatories; the development of new geomagnetic indices based upon BCMT data; the installation of GPS sensors at low-latitude BCMT observatories to jointly recover electric field and total electron content in the ionosphere; the development of a new, low-noise digital vector magnetometer.

Introduction

The *Bureau Central de Magnétisme Terrestre* (BCMT) is in charge of organizing and coordinating the French observations of the Earth's magnetic field. It was founded by a decree in 1921 and attached to the *Institut de Physique du Globe de Paris* (IPGP). In 2008, the *Institut National des Sciences de l'Univers* (INSU, one of the institutes of the *Centre National de la Recherche Scientifique*, CNRS) set up a *Service National d'Observation* (SNO) in Magnetism, which was delegated to the BCMT.

Two French institutions are currently operating magnetic observatories: the IPGP and the *École et Observatoire des Sciences de la Terre* (EOST), located in Strasbourg. A third institution, the *Observatoire Versailles Saint Quentin* (OVSQ), attached to *Institut Pierre Simon Laplace* (IPSL) and *Université Versailles Saint Quentin* (UVSQ), hosts the International Service of Geomagnetic Indices (ISGI), which provides data products derived from magnetic observatory data. Additional funding and staffing is provided to the BCMT by INSU, the *Institut de Recherche pour le Développement* (IRD), the *Institut Polaire Français Paul-Émile Victor* (IPEV), the *Centre National d'Études Spatiales* (CNES) and the *Commissariat à l'Énergie Atomique* (CEA). BCMT observatory operations are made possible by collaborations with eight foreign institutions worldwide.

This document is the second multi-year strategic plan for the BCMT, after the "Strategic Plan 2010-2012" (hereafter referred to as SP1), released in September 2010. It covers 2014-2018, i.e., the same time interval as IPGP's recently adopted five-year plan. Its purposes are the same as those of SP1:

a. To be used as a reference document for the upcoming funding and staffing requests to participating and funding institutions, particularly the yearly requests to INSU, IPEV and CNES (which will include yearly reports and information on budgeting and staffing).
b. To be used as a reference document by the BCMT Scientific Council in its future reviews of the BCMT operations. (Note that ISGI has its own scientific council nominated by the Executive Council of the International Association of Geomagnetism and Aeronomy, IAGA).
c. To provide a framework for the BCMT management team to prioritize among the various projects and activities.

The general structure of this document is close to that of SP1, but includes several modifications. An executive summary was added. Section 2 lists data users and their needs. Section 3, which describes the current status of the BCMT, is an updated version of a similar section in SP1. The objectives for the next five years, presented in Section 4, are now organized along main scientific goals instead of areas of activities.

The BCMT Scientific Council reviewed an earlier version (version 1) of this document in November 2013. The present version (version 2) takes into account the comments and recommendations made by the Council.

1. Mission and vision

The following statement was adopted in 2010 (see SP1) and provides a more modern and accurate description of the mission of the BCMT than the funding decree:

> *The mission of the BCMT is to provide ground-based geomagnetic observations and data products of the highest quality, addressing the needs of the French and international geosciences research community, and those of the French administrations, businesses and citizens.*

In this statement, ground-based geomagnetic observations include data from magnetic observatories, magnetometer networks and repeat stations. Magnetic observatories differ from simple magnetometers in that they provide very accurate measurements of the Earth's magnetic field, typically within less than 2-3 nT, over long time intervals, typically decades. This is achieved thanks to the use of multiple instruments (typically one scalar magnetometer and one vector magnetometer) and the frequent reiteration of so-called absolute measurements, used to correct for baseline drifts (e.g., Rasson, 2007; Matzka *et al.*, 2010). Various data products are derived from magnetic observatories, including geomagnetic indices which are summary measures of geomagnetic disturbances (e.g., Mayaud, 1980; Menvielle *et al.*, 2011). Magnetic repeat stations are points at the Earth's surface were absolute measurements are made on regular basis, typically every one to five years, in order to improve the spatial resolution of geomagnetic secular variation models (e.g., Newitt *et al.*, 1996).

The vision adopted in 2010 is also unchanged for the upcoming five years:

> *The vision of the BCMT is to be one of the key components of the global geomagnetic observation system, combining a high level of consistency and robustness in its long-term operations and an ability to quickly innovate as a response to new scientific and societal needs.*

This statement stresses two important points. First, geomagnetism is a science that relies on global observations and therefore, to be relevant, the BCMT should be actively participating in initiatives and organizations aiming at improving the global geomagnetic observation system. These include IAGA, which coordinates geomagnetic observations, models and indices worldwide, and INTERMAGNET, the global network of digital magnetic observatories (Kerridge, 2001; Love and Chulliat, 2013). Second, innovation should be at the core of BCMT activities, because geomagnetism as a science is progressing fast and the primary mission of the BCMT is to address scientific needs.

2. Data users

In what follows, we list the current users of BCMT observations and data products, including some new users not mentioned in SP1.

2.1. Science users

Magnetic observatory data are used to investigate temporal variations of the Earth's magnetic field having time scales from a few seconds to several decades (e.g., Love, 2008). At the lower end of the frequency spectrum, observatories (complemented by repeat stations) provide long data series of the geomagnetic secular variation originating in the Earth's outer core. The secular variation is one of the very few observables providing direct information on dynamical processes within the core and the geodynamo (e.g., Finlay *et al.*, 2010a). Observatory data are also used to investigate higher frequency geomagnetic phenomena originating in the magnetosphere (ultra-low frequency waves, geomagnetic storms and substorms, field-aligned currents), ionosphere (equatorial electrojet, Sq currents, auroral electrojets, solar flare effects, e.g., Baumjohann and Nakamura, 2007), oceans (tidal flows, tsunamis, e.g., Manoj *et al.*, 2011) and mantle (e.g., Constable, 2007).

The accuracy of the baseline is essential when investigating slow variations of the field (e.g., geomagnetic secular variation studies), but also for some studies related to rapid variations, such as deriving geomagnetic indices. More generally speaking, all scientific uses benefit from the generally much higher quality of observatory data compared to data provided by magnetometers having no baseline control.

Magnetic observatory data and derived indices play a central role in geomagnetic field modeling; this includes main field and secular variation models, such as the International Geomagnetic Reference Field (IGRF, Finlay *et al.*, 2010b; Chambodut, 2011), as well as crustal, ionospheric and magnetospheric field models. Over the last decade, geomagnetic modeling has made huge progress thanks to high-precision vector magnetic data from the Ørsted and CHAMP low-Earth orbiting satellites (e.g., Hulot *et al.*, 2007, and references therein). High-precision ground data are included in model calculations or used for independent model validations, while indices are used for data selection and parameterization of external magnetic fields. Further progress is expected from the upcoming European Space Agency (ESA) *Swarm* mission, launched in November 2013 (Friis-Christensen *et al.*, 2006). The *Swarm* Satellite Constellation Application and Research Facility (SCARF) will jointly use observatory and satellite data in the preparation of level 2 data products (Olsen *et al.*, 2013). Advanced modeling where geomagnetic data are assimilated into dynamical models of the core is increasingly seen as a promising route toward forecasting of the secular variation (Fournier *et al.*, 2010).

Space weather is another research area related to geomagnetism that has been very active in recent years. Various ground magnetometer networks were installed in order to improve our understanding of ionospheric and magnetospheric processes, particularly during magnetic storms and substorms (e.g., Yumoto *et al.*, 2012). Magnetic observatories can be considered as a backbone network for such investigations, providing more accurate data than simple magnetometers and being more globally distributed at the Earth's surface (e.g., Love and Finn, 2011). Geomagnetic indices are widely used in space weather studies and solar-terrestrial physics in general, and new indices are currently being developed based upon higher frequency observatory data (e.g., Nosé *et al.*, 2012; Menvielle *et al.*, 2013).

The French geomagnetism community is active in many of these research fields. The IPGP is a member of the consortium supporting Swarm level 2 products; it is in charge of the SCARF lithospheric and ionospheric field models (Thébault *et al.*, 2013; Chulliat *et al.*, 2013) and collaborates with NOAA in the development of the SCARF equatorial electric field inversion chain (Alken *et al.*, 2013). The IPGP and the *Institut des Sciences de la Terre* (ISTerre), Grenoble, teamed up in the "AVSGeomag" project, funded by the *Agence Nationale de la Recherche* (ANR), which aims at better understanding the physical mechanisms governing the geomagnetic secular variation by resorting to the techniques of data assimilation (Gillet *et al.*, 2013; Fournier *et al.*, 2013). The IPGP is in charge of the "WAMNET" project, funded by CNES, which goal is to improve our understanding of electrical currents and fields in the equatorial ionosphere (Alken *et al.*, 2013). The OVSQ and EOST are developing advanced geomagnetic indices (Chambodut *et al.*, 2013). The OVSQ, EOST and *Institut de Planétologie et d'Astrophysique de Grenoble* (IPAG) team up to develop and assess new proxies to describe the geomagnetic forcing of the thermosphere, in the frame of the "Advanced Thermosphere Modeling for Orbit Prediction" (ATMOP) project, funded by the European Commission (FP7-SPACE-2010-1 / Project #261948).

2.2. Industrial, military and societal users

Geomagnetic data are of interest for a wide range of non-scientific applications. The following customers have recently been using data from the BCMT:

- Companies specializing in geophysical surveys (Fugro, Arkex, Bridgeporth, EDCON-PRJ, CGG) routinely use BCMT observatory data to check for local or regional geomagnetic activity and to process their survey data.
- The French Air Force and the Space Weather Prediction Center (NOAA/SWPC) receive data in real-time from nine BCMT magnetic observatories. The Air Force uses this data in the framework of the FEDOME project, which aims at testing the deployment of a system able to monitor space weather for military purposes. BCMT data are integrated in SWPC's alert and forecasting algorithms.
- Civil aviation authorities rely on the declination map and field calculation software ("Caldec") developed and updated every five years by the BCMT for the calibration of plane compasses.

3. Current status

This section briefly presents the current observational infrastructure of the BCMT and its data products. It is an updated version of a similar section in SP1.

3.1. Observational infrastructure

The BCMT currently operates a network of 17 observatories throughout the world and a network of 11 repeat stations in metropolitan France. In addition, the BCMT develops, builds and calibrates its own lines of vector and scalar magnetometers, providing significant flexibility to its operations.

3.1.1. Observatories

The Earth's magnetic field has been continuously recorded in the Paris area since 1883, first in Parc St Maur (1883-1900), then in Val Joyeux (1901-1935) and now in Chambon la Forêt (since 1936). The Chambon la Forêt magnetic observatory, located 100 km south of Paris, in the Loiret department, is the National Magnetic Observatory and the headquarter of the IPGP technical team (Figure 1).

Figure 1: Absolute pavilions (left) and magnetometer vault (right) at the Chambon la Forêt magnetic observatory.

The expansion of the BCMT network outside metropolitan France started in 1952, with the installation of the MBour observatory in Senegal. Today, the BCMT is in charge of 17 observatories throughout the world (Table 1 and Figure 2), including eight observatories operated in collaboration with foreign institutions. The typical cooperation agreement stipulates that the BCMT provides the instruments, trains the observers and prepares the final data products, while the local institution operates the observatory on a day-to-day basis and performs regular calibration measurements.

IAGA code	Observatory name	Current institution(s)	Country	Starting / closing date
AAE	Addis Ababa	IPGP / IGSSA AAU	Ethiopia	1997 (1957)
AMS	Martin de Viviès	EOST / IPEV	France	1981

BNG (*)	Bangui	IRD	Central African Rep.	1955 - 2011
BOX	Borok	IPGP / BGO IPERAS	Russia	2004 (1976)
CLF (previously PSM , VLJ)	Chambon la Forêt (previously Parc St Maur, Val Joyeux)	IPGP	France	1883
CZT	Port Alfred	EOST / IPEV	France	1974
DLT	Da Lat	IPGP / IG VAST	Vietnam	2011 (1978)
DMC	Dôme C	EOST / INGV / IPEV / PNRA	Antarctica	2005
DRV	Dumont d'Urville	EOST / IPEV	Antarctica	1957
IPM	Isla de Pascua Mataveri	IPGP / DMC	Chile	2009
KOU	Kourou	IPGP / CNES	France	1995
LZH	Lanzhou	IPGP / LIS CEA	China	2001 (1959)
MBO	Mbour	IPGP / IRD	Senegal	1952
PAF	Port-aux-Français	EOST / IPEV	France	1957
PHU	Phu Thuy	IPGP / IG VAST	Vietnam	1993 (1961)
PPT	Pamatai	IPGP / CEA	France	1968
QSB (*)	Qsaybeh	IPGP / NCGR	Lebanon	2000 - 2007
TAM	Tamanrasset	IPGP / CRAAG	Algeria	1993 (1932)
TAN	Antananarivo	EOST / IOGA	Madagascar	1983 (1889)

Table 1: List of the 19 magnetic observatories affiliated to the BCMT and of the French and foreign institutions operating them (see Appendix A for a list of acronyms). Asterisks (*) indicate closed observatories. Starting dates indicate when observatories joined the BCMT network, while dates in parenthesis indicate when observatories were founded, if different.

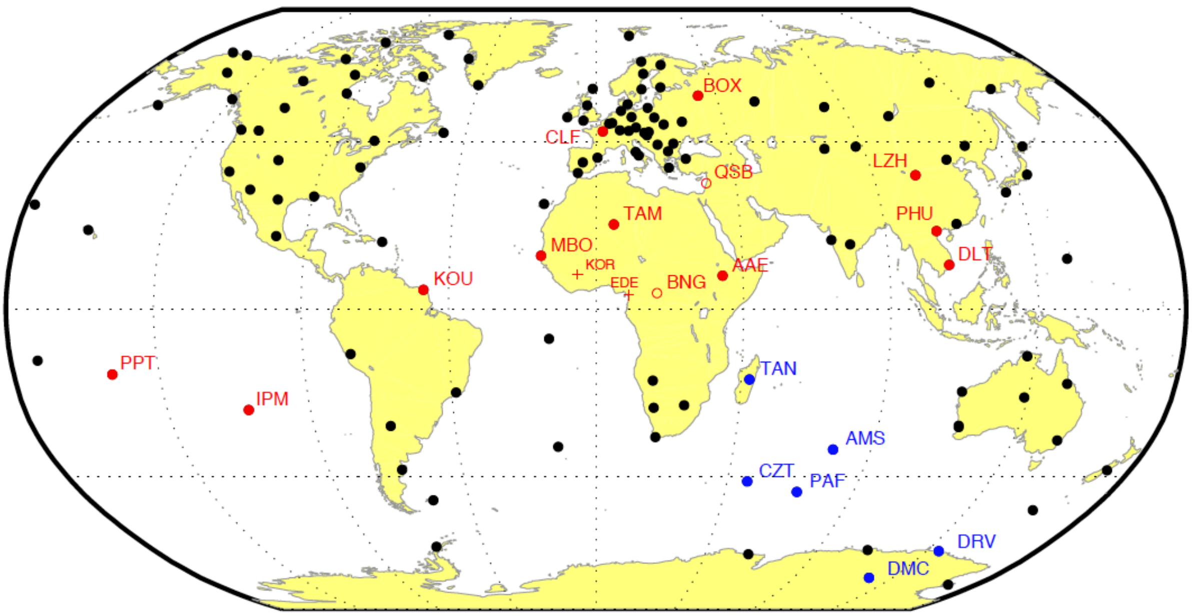

Figure 2: Map of the 123 INTERMAGNET magnetic observatories in 2013 (plain dots). Among these, 17 are affiliated to the BCMT (through IPGP, red dots, or EOST, blue dots). Two BCMT observatories are closed (empty dots) and two are in project (crosses).

All BCMT observatories belong to INTERMAGNET, the global network of magnetic observatories transmitting their data in near real time and fulfilling high quality standards. This represents about 15% of the current INTERMAGNET network (Figure 2). The BCMT contribution to INTERMAGNET is significant due to its size and geographic coverage. BCMT observatories cover all magnetic latitudes, from the equatorial zone (with one observatory, Addis Ababa, at the dip-equator) to the polar caps. Several BCMT observatories are very isolated and cover areas where no other magnetic observatory program is operating, particularly in Northern and Central Africa, Southern Indian Ocean, Southern Pacific Ocean and Antarctica. The Isla de Pascua observatory, located more than 4000 km away from the closest observatory in Huancayo (Peru), is the most remote magnetic observatory in the world (Chulliat *et al.*, 2009a).

Since the release of SP1 in 2010, one new observatory, Da Lat, has been installed (Heumez *et al.*, 2013); two observatories, Da Lat and Dôme C (Chambodut *et al.*, 2009), have been accepted as INTERMAGNET Magnetic Observatories (IMO); two observatories, Bangui and Qsaybeh, have been closed, mostly due to safety concern. The MBour observatory, which used to be under full IRD responsibility, is now operated under an IPGP/IRD agreement.

Each observatory is equipped with two sets of instruments:

- a tri-axis fluxgate magnetometer and a scalar magnetometer located in a thermally insulated vault, pavilion or box, and recording the geomagnetic field variations on a continuous basis;
- a "DI-flux" (i.e., a non-magnetic theodolite with a mono-axis fluxgate magnetometer mounted on top of it) and, often, a second scalar magnetometer located in a pavilion or hut where weekly calibration measurements ("absolute measurements") are performed.

A data acquisition system collects the data from the continuously recording magnetometers and sends them via the internet to the BCMT data center and INTERMAGNET Geomagnetic Information Node (GIN) located in Paris. The instruments and data acquisition system are powered by the local power supply, solar panels, or both.

BCMT observatories are operated according to standard procedures recommended by IAGA and INTERMAGNET. In particular, a trained operator performs weekly absolute measurements in order to frequently recalibrate the vector magnetometer. These measurements are extremely important, as all existing vector magnetometers unavoidably drift in time (over only a few weeks) and there currently exists no automatic system able to replace a human operator. In order to meet the high quality standards set by INTERMAGNET, BCMT observers are trained on a regular basis, either on-site, at the Chambon-la-Forêt observatory (IPGP and IRD) or at the Welschbruch geophysical station (EOST), near Strasbourg. This time consuming and sometimes underappreciated activity is a critical part of operating a global network of magnetic observatories.

3.1.2. Repeat stations

From 1947 to 2007, the BCMT operated a repeat station network of up to 32 stations in metropolitan France. Stations were reoccupied every five years. However, the scientific relevance of this network became less clear in the 2000s when high-precision vector data from low-Earth orbiting satellites became available. Following discussions at the 2011 Scientific Council meeting, it was decided to set up a new network of 11 stations only, located on airport runways (Figure 3). The geographical distribution of the stations was optimized in order to allow computation of a regional secular variation model with the same spatial resolution and precision as the IGRF, while reducing the number of stations to a minimum. Also, a new measurement method was developed, relying on GPS measurements for azimuths determination and night-time magnetic measurements in order to minimize external field contributions (Lalanne *et al*., 2013).

The new repeat stations network was installed between May and July 2012 and first reoccupied in 2013, thus providing the secular variation at epoch 2013.0. The reduced number of stations and the improved method made the whole process of reoccupying the network much lighter and less costly, while slightly improving the overall precision of data.

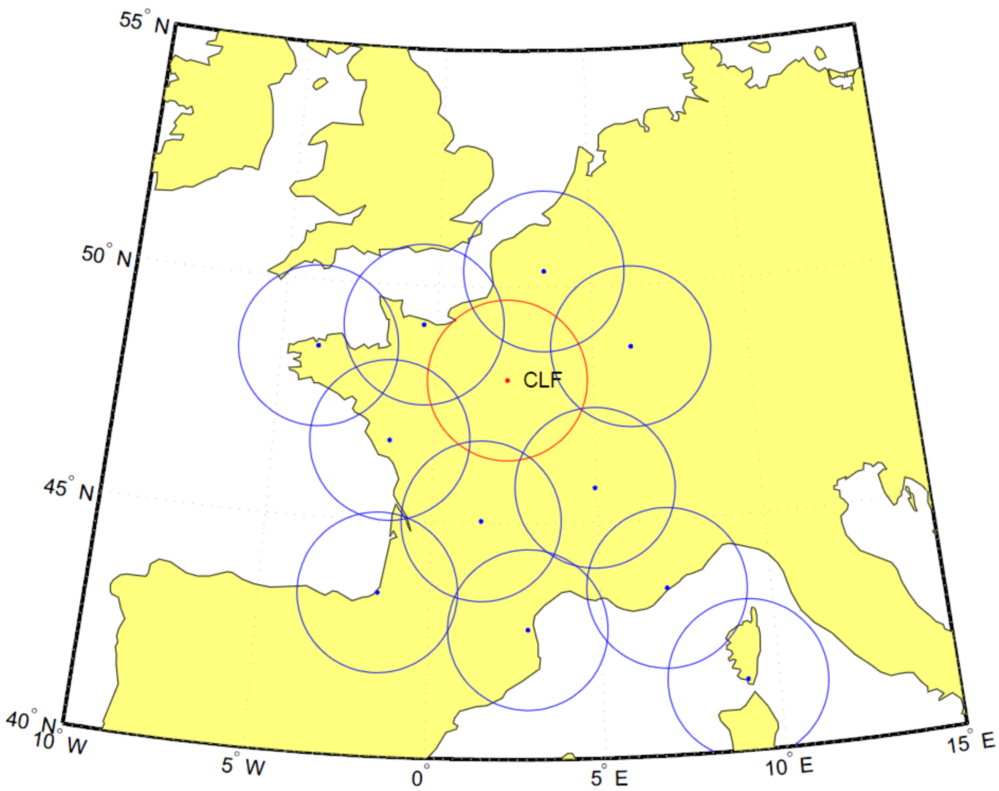

Figure 3: Map of the BCMT repeat stations network set up in 2012 and first reoccupied in 2013. Circles are centered on each station and have a radius of 1.7°.

3.1.3. Instruments, calibration facilities and data acquisition systems

The BCMT is among the very few (less than five) organizations in the world building tri-axis vector magnetometers stable enough for long-term magnetic observatory operations. This situation results from developments initiated in the 1980s in collaboration with industrial partners. BCMT vector magnetometers were an essential part of the "Observatoire Magnétique Planétaire" project which led to the installation or modernization of several observatories in partnership with foreign institutions in the 1990s. The latest version of the BCMT vector magnetometer is named IPGP VM391 (Figure 4). It is installed in all BCMT magnetic observatories currently operated by the IPGP (11 in total, see Table 1).

Figure 4: The IPGP VM391 tri-axis fluxgate magnetometer.

In the last few years, the BCMT has also been developing of a new, optically pumped helium magnetometer providing scalar measurements of the geomagnetic field. This instrument is at the prototype stage and has not yet been deployed in observatories.

BCMT magnetometer developments are carried out by IPGP's technical team based at the Chambon la Forêt observatory, where testing and calibrating facilities are available, including an amagnetic room and a set of Helmholtz coils. A new non-magnetic thermal chamber was built in 2011-2012, allowing magnetometers to be tested at all temperatures from -5°C to 45°C and their temperature coefficients to be precisely determined.

The Chambon-la-Forêt site and calibration facilities are often made available to users not related to the BCMT. For example, the CEA-LETI and CNES tested the ASM scalar magnetometer that will fly on the upcoming ESA Swarm mission, as well as a special version of the ASM for ground-based measurements. The *Laboratoire de Physique des Plasmas* (LPP, Ecole Polytechnique) tested the flight models of the upcoming NASA MMS mission; to this aim, a new coil system was built within a dedicated building, in collaboration with IPGP. Calibration facilities are also used by companies such as IXSea, MBDA and Thalès.

The BCMT also develops data acquisitions systems to be used in its magnetic observatories. In recent years, new systems able to acquire one-second data were developed by IPGP and EOST. These developments took into account the various characteristics of the BCMT observatories and are now completed.

All instruments and data acquisition systems, whether manufactured by the BCMT or acquired, are fully tested and calibrated before being installed in magnetic observatories. These tests are made either at the Chambon la Forêt observatory (IPGP and IRD) or at the Welschbruch geophysical station (EOST).

3.2. Data products

3.2.1. Preliminary data

The data sampling frequency at BCMT observatories has regularly increased since the 1950s, from hourly to 1-minute and now 1-second measurements (Figure 5). This evolution was made possible by advances in instrument and data transmission technologies. In 2009, the IPGP VM391 magnetometer and its data acquisition system were upgraded to produce filtered 1-second data (Chulliat *et al.*, 2009b); EOST data acquisition systems were also upgraded. Today, 1-second data are produced at 15 BCMT observatories out of 17 (Table 2).

In accordance with INTERMAGNET requirements, all BCMT observatories transmit their preliminary data (1-minute and 1-second) in less than 72 h to the Paris INTERMAGNET GIN, which then forwards them to the INTERMAGNET central website in Ottawa, Canada (www.intermagnet.org). Data are also distributed on the BCMT website (www.bcmt.fr).

Since 2011, a real time data transmission to the Paris GIN has been set up at 9 IPGP observatories (Table 2) using the Earthworm software (originally developed by the United States Geological Survey, USGS). The typical delay time for transmitting these data is less than two minutes. Earthworm is also used to redistribute data to users such as the French Air Force (FEDOME project) and the Space Weather Prediction Center at NOAA (see section 3.2). A software able to detect storm sudden commencements (ssc) in real-time was developed in 2011; although still in experimental mode, this software sends alerts by email, sms and twitter to subscribers each time a ssc is detected.

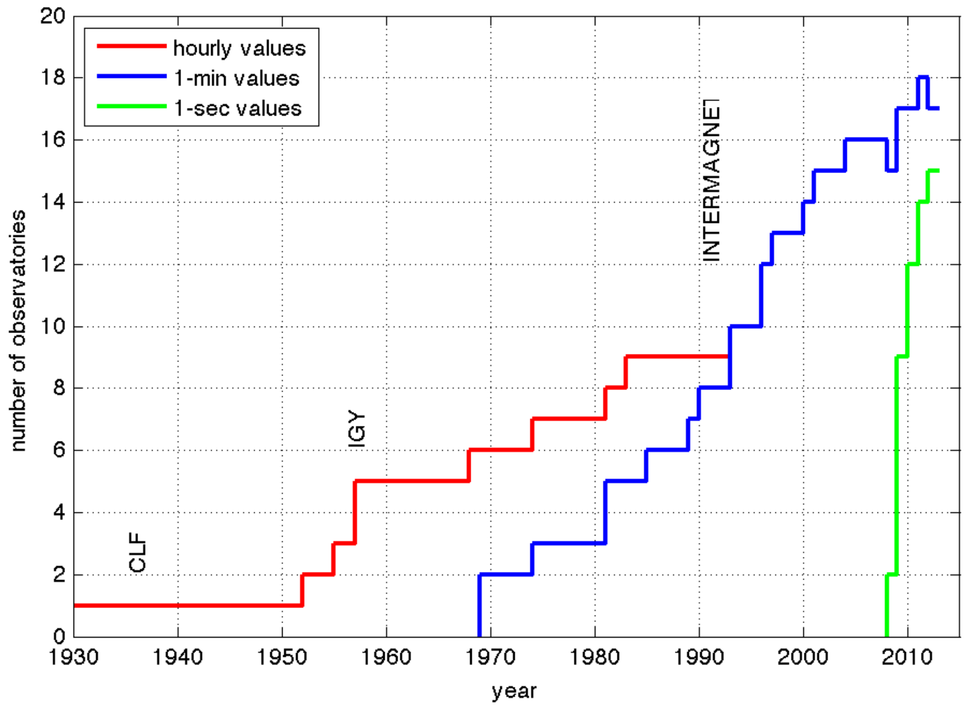

Figure 5: Evolution of the number of BCMT observatories producing hourly, one-minute and one-second data since 1930.

IAGA code	1-second data	Real-time data (< 5 min delay)	Quasi-definitive data
AAE	yes	yes	yes
AMS	yes	no	no
BOX	no	no	yes
CLF	yes	yes	yes
CZT	yes	no	no
DLT	yes	yes	yes
DMC	yes	no	no
DRV	yes	no	no
IPM	yes	yes	yes
KOU	yes	yes	yes
LZH	yes	no	yes
MBO	yes	yes	yes
PAF	yes	no	no
PHU	yes	yes	yes
PPT	yes	yes	yes
TAM	yes	yes	yes
TAN	no	no	no

Table 2: Availability of one-second, real-time and quasi-definitive data from BCMT observatories, as of October 2013.

3.2.2. Quasi-definitive and definitive data

Geomagnetic data require a significant amount of processing before they can be used for studying the geomagnetic secular variation and other slowly varying phenomena. The BCMT produces two types of processed data, classified according to their latency (Figure 6):

- *quasi-definitive data*, released a few days after the end of each month, after having checked all data for spikes, jumps and other anomalies, collected all absolute measurements for that month and used them to recalibrate the vector magnetometer;
- *definitive data*, released a few months after the end of each civil year, after having thoroughly checked the processing made at the quasi-definitive stage, and solved the problems that were too complicated to be solved at that stage.

Quasi-definitive data are a new data product, launched in July 2009 and now available at 10 BCMT observatories (Table 2). Its development was prompted by the need of the geomagnetic modeling community to receive high-quality observatory data soon after their acquisition during the *Swarm* satellite mission. IPGP took a leading role in the development of quasi-definitive data (Chulliat *et al.*, 2009c; Peltier and Chulliat, 2010). Today, about 40 INTERMAGNET observatories routinely produce quasi-definitive data and send them to the INTERMAGNET website, where they are distributed to users.

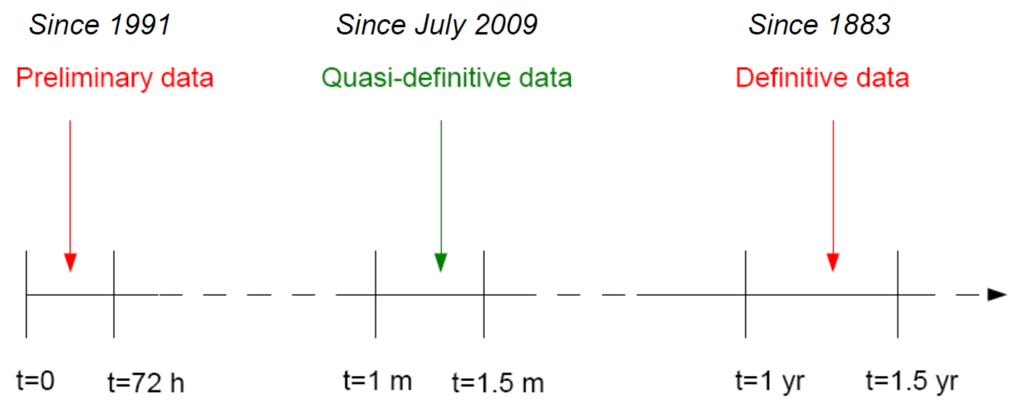

Figure 6: Latencies of the BCMT data products.

Once definitive data are ready (at the 1-minute and 1-second sampling rates, when available), averages over longer periods of time are prepared: hourly means, daily means, monthly means and annual means. Definitive (1-minute) data are sent to INTERMAGNET where they are one more time checked by a dedicated team of data experts before being distributed on the INTERMAGNET website and annual DVD. All definitive data and derived means are also distributed on the BCMT website.

3.2.3. Repeat stations data products

After each measurement campaign, repeat stations data are processed according to standard practices, using field variations recorded at Chambon la Forêt for data reduction. Final data are made available on the BCMT website and sent to the World Data Center (WDC) in Edinburgh. Two products derived from repeat stations data are also prepared after each campaign at year Y:

- a regional declination map covering metropolitan France;
- a software ("IPGP Caldec") providing estimates of the declination in metropolitan France until year Y+5.

3.2.4. Geomagnetic indices

In accordance with the current observatory practice recommended by IAGA, K indices are calculated for each BCMT observatory. These indices are made available through the yearly BCMT bulletins and INTERMAGNET DVDs.

ISGI is the international reference for dissemination of geomagnetic indices. Appointed by the IAGA Executive Committee and member of the World Data System (WDS, formerly FAGS), ISGI is in charge of the elaboration and dissemination of geomagnetic indices and lists of remarkable magnetic events, by directly using magnetic observatory data. ISGI activities are carried out with the help of ISGI Collaborating Institutes.

One of the contributions of ISGI is the computation of *am* and *aa* planetary geomagnetic indices:

- Quick-look values of *aa* and *am* indices are routinely made available on line through the ISGI website (http://isgi.latmos.ipsl.fr) 30 minutes after the end of the 3-hour interval (since 2003), and on day D+2 (since 1996), respectively. The quick-look values are computed using minute values transmitted by about 20 INTERMAGNET observatories, including four BCMT observatories (AMS, CLF, CZT, PAF). Besides, the Chambon la Forêt observatory is the Hartland backup station in the computation of *aa* quick look values.

- Provisional values of *aa* and *am* indices are made available six to eight weeks after the end of the month. They are computed on the basis of K indices transmitted by observatories to ISGI by that time. The K indices from four BCMT observatories (AMS, CLF, CZT, PAF) are used in the computation of the *am* indices. Provisional values of K indices from these stations are sent to ISGI on a 2-week basis (AMS, CZT, PAF), or a monthly basis (CLF).
- Definitive values of *am* and *aa* indices are computed when definitive K indices are published in the annual INTERMAGNET DVD.

3.2.5. Global databases

In addition to its activity as a data producer, the BCMT maintains two global geomagnetic databases:

- ISGI is in charge of the dissemination of geomagnetic indices and lists of remarkable events prepared by the ISGI Collaborating Institutes. These data are routinely transmitted to ISGI and made available through its website, which is a worldwide reference website for geomagnetic indices and remarkable events.

- The World Monthly Means Database (WMMD), managed by IPGP and available on the BCMT website, contains quality-checked monthly means from INTERMAGNET observatories, going as far back in time as possible (Chulliat and Telali, 2007). This database complements hourly and annual means data archives at the WDCs.

4. Strategy

The BCMT strategy for the period 2014-2018 is developed along three general axes:

- geomagnetic field modeling and *Swarm* support,
- space weather and space climate,
- observatory techniques and instruments.

It is mostly aimed at addressing the needs of science users identified in subsection 3.1, particularly French users and international users related to the upcoming *Swarm* satellite mission. Current non-science users (subsection 2.2) will continue to be served, as long as their needs are similar or close to those of science users; extra developments for non-science users will be billed to them.

Unlike in the previous strategy (SP1), specific objectives are not arranged by area of activity (for example, instrumentation or data processing). Within each of the three general axes, they are ranked by order of priority, from A+ down to C.

This strategy is in good agreement with both IPGP's and EOST's 5-year contracts with the Ministry of Higher Education and Research (respectively, *Contrat Quinquennal 2014-2018* for IPGP and *Contrat Quinquennal 2013-2017* for EOST), where in each contract a section is devoted to Magnetic Observatories. Most projects listed below appear in IPGP's and EOST's 5-year contracts, although in a less elaborate form as these contracts were written one or two years ago. It is worth noting that permanent observatories are a key element of the general strategies of both IPGP and EOST. In IPGP's 5-year contract, special emphasis is put on the scientific use of observatory data: "We intend to enhance usage of the high-quality data that are coming out of the Observatories in two different ways. One is to ensure easy access to the data, which will be done through our new Data Center, and the other is to rally scientists in larger numbers by providing funds for innovative research on observatory data."

Magnetic observatories (and permanent observatories in general) are also a key element of CNRS-INSU's scientific strategy, as has been reflected in CNRS-INSU's funding and staffing priorities in recent years. Following the 2008 reorganization of French permanent observatories in SNOs, CNRS-INSU closely monitored the evolution of each SNO and kept constant the funding and staffing of the BCMT. It is now deeply involved in the European Plate Observing System (EPOS), a European Union funded project aiming at establishing an integrated solid Earth Sciences research infrastructure at the European level. The BCMT has taken an active role in this endeavor, contributing to the preparatory work of EPOS Working Group 9, "Magnetic Observations".

4.1. Axis #1: Geomagnetic field modeling and *Swarm* support

The number one priority of the BCMT in the coming years will be to provide adequate support to geomagnetic field modeling activities. This includes, but is not limited to, geomagnetic modeling activities based upon *Swarm* data, including level 2 activities of the SCARF (cf. subsection 2.1). The following projects are derived from this priority.

(1a) Chambon-la-forêt observatory reconstruction [A+]

The Chambon-la-forêt observatory will be partly reconstructed as the original sensor vault (built in 1935) is now too often inundated. After exploring several options, it was decided to build three new, temperature controlled magnetometer pavilions on the observatory site: one during the winter 2013-2014, as a temporary site for the reference magnetometer, and two more in 2014-2015, after the historical vault (and the building above it) will have been demolished. This is big project, which will be partly funded by IPGP through its "estate" budget line. The goal is to have new, modern magnetometer pavilions set up and fully tested at the end of 2016, and lasting for several decades.

(1b) Consolidation of existing BCMT observatories [A]

The BCMT will ensure that the data from its network are of the highest quality and distributed in a timely fashion to the geomagnetic modeling community. This will require maintaining a workforce of dedicated and well-trained observers at remote observatories, repairing observatories with minimal delays in case of technical hitches, processing data at the highest quality level in a timely fashion and maintaining an effective and reliable IT infrastructure. Special emphasis will be put on maintaining good working relationships with the exceptionally large network of foreign partner institutions on which these operations rely.

(1c) Rescuing of BCMT observatories in Africa (new BNG, TAN) [B]

The ongoing project of rescuing BCMT observatories that were closed or discontinued in recent years will be continued. IPGP will move on with the installation of a new observatory in Edea, Cameroon, as a replacement of Bangui; in case this is unsuccessful, an installation in Benin, collocated with EOST superconducting gravimeter in Djougou, will be considered. EOST will complete the re-installation of the Antananarivo observatory outside the city. There is no reopening plan for Qsaybeh, due to ongoing safety concerns in Lebanon.

(1d) Reoccupation of the new repeat station network [B]

The new repeat stations network (installed in 2012) will be reoccupied every year during the *Swarm* mission in order to compare the secular variation derived from it with the secular variation derived from *Swarm* data. This low-cost network is considered as a safety net for secular variation modeling over France in case *Swarm* fails or no satellite is launched after *Swarm*.

(1e) Long-term electric measurements [B]

Long-term electric field measurements in Chambon-la-Forêt will be continued during the *Swarm* mission. These measurements, which started in September 2012, are expected to provide a local mantle conductivity profile, to be compared with 3D mantle conductivity models derived from *Swarm* data. In case this project is successful, similar measurements could be started at other BCMT observatories, for example Tamanrasset.

(1f) Installation of new observatories [C]

No more expansion of the network is planned, except specific opportunities. Among these, there could be the installation of observatories in Noumea, New Caledonia, in collaboration with IRD, or Korhogo, Ivory Coast, in collaboration with the University of Cocody-Abidjan. Another possibility would be to team up with a private company interested in installing a new observatory for applications such as directional drilling or geophysical surveying (something similar to what was done recently by USGS and Schlumberger in Deadhorse, Alaska). However, such projects are not the priority in the coming years, as the BCMT network is already very large by international standards.

4.2. Axis #2: Space weather and space climate

Space weather is the second scientific area where BCMT observations are expected to be most relevant in the coming years. In order to address the needs of the French and international research community, as well as institutional and industrial users, the BCMT will implement the following projects.

(2a) Real-time data transmission from all BCMT observatories [A]

The upgrade of BCMT observatories so that they transmit their data in real-time will be continued. EOST will work with IPEV so that real-time data transmission can be set up at Indian Ocean and Antarctica observatories. Also, data will be sent in real-time to the INTERMAGNET central website once it is ready to receive such data. Institutional users of real-time data (such as the French Air Force, SWPC) will continue to be served and their needs will be accommodated as long as no significant extra funding is required. Industrial users will be sought after and will be billed for real-time data delivery.

(2b) Transfer of ISGI to EOST [A]

The transfer of ISGI from OVSQ to EOST, initiated in 2012, will be completed. Local teams at both institutes are closely cooperating to make the transition as smooth as possible for the users. Besides being moved, the ISGI website will be upgraded in order to satisfy current website standards regarding data mining and dissemination of geomagnetic indices and their metadata. The background databases will allow requesting geomagnetic indices in various formats, in order to fulfill the needs of the internal and external geophysics communities. The new website will include the following features: a public database of references for each index; references and links to the ISGI Collaborating Institutes; the possibility for the user to subscribe online to the ISGI bulletins; a "Playground area" where new geomagnetic indices will be made available to the scientific community for testing purposes.

(2c) Development of new, real-time indices based upon BCMT data [B+]

New indices based upon BCMT data will be developed. Real-time calculation of these indices will be implemented, so that they can be used for space weather monitoring and forecasting. They will be available on the new “Playground area” of the ISGI website for testing purposes and dissemination to users.

(2d) Installation of GPS receivers in some low-latitude BCMT observatories [B]

The possibility of adding GPS receivers to BCMT observatories in Africa and Vietnam will be explored. GPS receivers provide observations of the Total Electron Content (TEC), which usefully complement ground magnetic measurements when investigating the dynamics of the low-latitude ionosphere (Valladares and Chau, 2012). Also, the installation of additional magnetometers such as to form pairs of magnetometers perpendicular to the geomagnetic dip-equator will be continued, provided funding is obtained for this activity. Three of such magnetometers were already installed in Ivory Coast and Mali within the CNES-funded WAMNET project, and another one will be installed in Djibouti. Such magnetometers provide ground-based estimates of the ionospheric equatorial electric field, to be compared with similar estimates from satellite data (Alken *et al*., 2013).

(2e) Archiving, cataloging and digitizing of old magnetograms [C]

Old magnetograms stored in IPGP and EOST archives will be archived in a safe environment and catalogued. The possibility of digitizing some of them for scientific use will be evaluated. Some magnetograms may provide valuable data for studying historical geomagnetic storms and the long-term evolution of geomagnetic activity, i.e., space climate.

4.3. Axis #3: Observatory techniques and instruments

There is an urgent need in the international community for a low-noise, stable vector magnetometer able to produce high-quality 1Hz data. Unlike most commercial manufacturers, the IPGP VM391 magnetometer is very near to meeting the requirements for high-quality 1Hz data. However, due to the limited number of sensors built in the 1990s, no more VM391 can be manufactured by IPGP and all existing ones have already been installed in observatories or are used as backup instruments. Taking a larger perspective, the setup of a fully automatic observatory (i.e., not requiring weekly calibration measurements) has never been so close, thanks to progress made in instrumentation in recent years. The instrumentation strategy of the BCMT in the coming years will be as follows.

(3a) Development of a new tri-axis, low-noise fluxgate magnetometer [A]

A new fluxgate vector magnetometer will be developed, in order to replace the VM391. This new instrument will have a new, low-noise sensor (currently under development at IPGP), and its electronics will be fully digital in order to reduce thermal effects and long-term drifts. Once completed and tested, this instrument will equip all BCMT observatories. It will also be made available (for a price taking into account the manufacturing cost) to the international community.

(3b) Development of innovative calibration techniques [B]

Another project is to explore innovative calibration techniques in order to reduce the need to make regular absolute measurements at remote observatories. Currently, the INTERMAGNET recommendation is to recalibrate vector magnetometers every week. Other groups in Belgium and Germany have developed highly sophisticated instruments, able to perform automatic calibration measurements. However, these instruments are very expensive and their long-term reliability is not fully proven. The BCMT will explore a simpler route, taking account the increasing stability of its vector magnetometer, coupled with nearby scalar magnetometers, in order to step-by-step reduce the periodicity of calibration measurements to once a month or even less.

4.4. Staffing and funding

The present strategy is based upon the assumption that the staffing and funding of BCMT institutions operating observatories (IPGP and EOST) will remain stable in the coming years. The financial situations of the BCMT main funders (CNRS-INSU, IPGP, IPEV) would make it unrealistic to assume a growth of resources. The present situation is summarized in Figure 7.

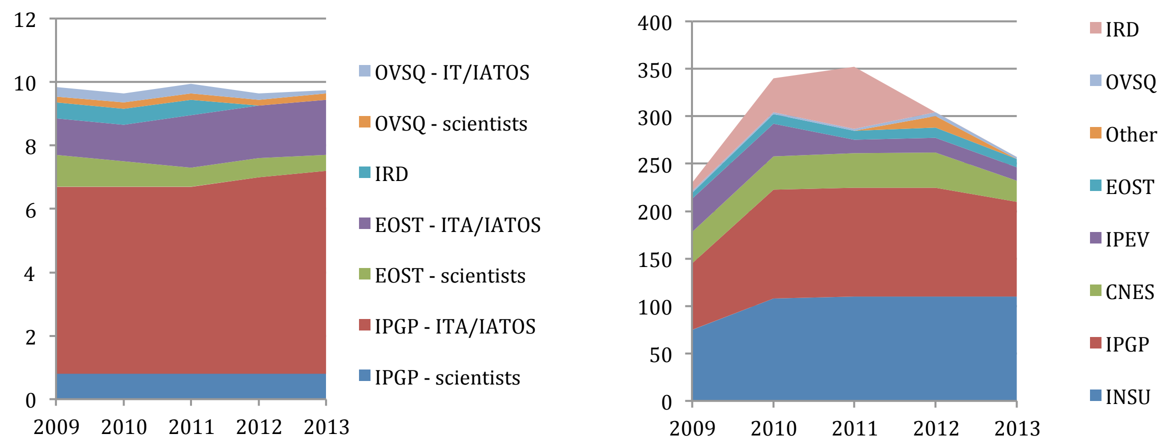

Figure 7: BCMT staffing (left, in full-time equivalent) and funding (right, in k€).

4.5. Timeline

Projects (a) to (m) will be implemented according to the timeline given in Table 3, based upon the staffing and funding assumptions made in the previous subsection. This timeline is only indicative and represents an estimate of what the BCMT is aiming to achieve in the coming years. Major milestones in the coming 5-year period will be the upcoming Scientific Council meetings in 2015 and 2017.

4th SC meeting (between 2015 and 2016) — 5th SC meeting (between 2017 and 2018)

			2014	2015	2016	2017	2018
		Axis #1: Geomagnetic field modeling and *Swarm* support					
(1a)	A+	**Chambon-la-Forêt observatory reconstruction**					
		Construction of pavilion #1 & transfer of instruments	■				
		Tests of the new set-up (intercomparison with existing vault)	■	■			
		Construction of pavilion #2 and 3 & transfer of instruments		■	■		
		Tests of the new set-up (intercomparison with pavilion #1)			■		
(1b)	A	**Consolidation of existing BCMT observatories**					
		Regular operating activities following the highest standards	■	■	■	■	■
(1c)	B	**Rescuing of BCMT observatories in Africa (new BNG, TAN)**					
		"new BNG": Decision Edea (Cameroon) vs. Benin	■				
		"new BNG": Installation of the new observatory in Edea (or Benin)	■	■			
		"new BNG": Tests and INTERMAGNET application			■	■	
		TAN: Installation of the new observatory	■	■	■		
		TAN: Tests and INTERMAGNET application			■	■	
(1d)	B	**Reoccupation of the new repeat station network**					
		Every one or two years, depending on Swarm results	■	▨	■	▨	■
(1e)	B	**Long-term electric measurements**					
		Regular operation and data processing at CLF	■	■	■	■	■
		Set-up and operation in another observatory			▨	▨	▨
(1f)	C	**Installation of new observatories**					
		Partnering, installation and tests	▨	▨	▨	▨	▨
		Axis #2: Space weather and space climate					
(2a)	A	**Real-time data transmission from all BCMT observatories**					
		Upgrade of observatories in Southern Indian Ocean and Antarctica	■	■	■	▨	
(2b)	A	**Transfer of ISGI to EOST**					
		Development and testing of the new ISGI website	■	■			
		Other transfer activities (funding, partnerships, communication, etc.)		■	■		
(2c)	B+	**Development of new, real-time indices based upon BCMT data**					
		Design and testing of new indices	■	■	■	▨	▨
		Implementation in an operational setting		■	■	■	▨
(2d)	B	**Installation of GPS receivers in some low-latitude BCMT observatories**					
		Preparations and first installations		■			
		Data processing and exploitation; other installations if appropriate			■	■	▨
(2e)	C	**Archiving, cataloging and digitizing of old magnetograms**					
		Archiving and cataloging	■	■			
		Digitizing			■	■	■
		Axis #3: Observatory techniques and instruments					
(3a)	A	**Development of a new tri-axes, low-noise fluxgate magnetometer**					
		Development of a new, digital electronics	■	■			
		Development of a new, low-noise sensor		■	■		
		Tests and calibrations in Chambon la Forêt			■		
		Installation in 2-3 BCMT observatories per year				■	■
(3b)	B	**Development of innovative calibration techniques**					
		Developments and tests in Chambon la Forêt	■	■			
		Installation in some BCMT observatories (if successful)			▨	▨	▨

Table 3: Timeline of BCMT projects for 2014-2018.

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Appendix A: List of abbreviations and acronyms

ANR	Agence Nationale de la Recherche
BCMT	Bureau Central de Magnétisme Terrestre
BGO IPERAS	Borok Geophysical Observatory, Institute of Physics of the Earth of the Russian Academy of Sciences
CEA	Commissariat à l'énergie atomique et aux énergies renouvelables
CNES	Centre National d'Études Spatiales
CNRS	Centre National de la Recherche Scientifique
CRAAG	Centre de Recherche en Astronomie, Astrophysique et Géophysique
DGAC	Direction Générale de l'Aviation Civile
DMC	Dirección Meteorológica de Chile
EOST	École et Observatoire des Sciences de la Terre
ESA	European Space Agency
FAGS	Federation of Astronomical and Geophysical Data Analysis Services
GIN	Geomagnetic Information Node
IAGA	International Association of Geomagnetism and Aeronomy
IGN	Institut Géographique National
IGRF	International Geomagnetic Reference Model
IGSSA AAU	Institute of Geophysics, Space Sciences and Astronomy, Addis Ababa University
IG VAST	Institute of Geophysics, Vietnamese Academy of Science and Technology
IMO	INTERMAGNET Magnetic Observatory
INGV	Istituto Nazionale di Geofisica e Vulcanologia
INSU	Institut National des Sciences de l'Univers
IOGA	Institut et Observatoire Géophysique d'Antananarivo
IPAG	Institut de Planétologie et d'Astrophysique de Grenoble
IPEV	Institut polaire français Paul-Émile Victor
IPGP	Institut de Physique du Globe de Paris
IPSL	Institut Pierre Simon Laplace
IRD	Institut de Recherche pour le Développement
ISGI	International Service of Geomagnetic Indices
ISTerre	Institut des Sciences de la Terre
LIS CEA	Lanzhou Institute of Seismology, China Earthquake Administration
NCGR	National Center for Geophysical Research
OVSQ	Observatoire Versailles Saint Quentin
UVSQ	Université Versailles Saint Quentin
WDC	World Data Center
WDS	World Data System
WMMD	World Monthly Means Database