# IAGA quadriennal report for France

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## Introduction

The French community is very committed to the International Association of Geomagnetism and Aeronomy (IAGA/AIGA) since its creation during the first International Union of Geophysics and Geodesy (IUGG/UGGI) in Rome (1923). The involvement of its researchers in geomagnetism in the different IAGA bodies has never weakened since its creation, in its presidency, in the functioning of its administration, and in the mandates of the working groups of its various divisions.

This involvement is possible thanks to the attachment of researchers to open science for the benefits of research and the socio-economic world. Our community also benefits from strong institutional supports via the major French public research organizations (Ministère de l'enseignement supérieur, de la recherche et de l'innovation-MESRI, Centre National de la Recherche Scientifique-CNRS, Universities, Centre National des Etudes Spatiales-CNES). They all act very actively to the same ambitions at the political levels by promoting initiatives and supporting the maintenance and development of national, European and international structures towards open science and related services.

The present report summarizes on the major activities in geomagnetism carried out during the last five years (2019-2023) with a special focus on the Earth’s global scales physical processes inferred from the European magnetic Swarm mission, and on the efforts to maintain and deploy the high level of services.

For the purposes of synthesis, we have no other choice than to pass over in silence the very important bibliographical corpus pertaining to geophysical prospecting, electromagnetic studies of earthquakes and volcanoes, mathematical Geophysics, applied geomagnetism for resources, and all multidisciplinary sciences using geomagnetism as a tool.

## The European Swarm mission

The primary objectives of the Swarm mission are to identify, map and interpret the various magnetic fields produced by the dynamo of the core, the currents induced in the Earth, the

magnetized lithosphere, the currents induced in the masses of oceanic water in movement, as well as ionospheric and magnetospheric currents.

The Swarm mission is a European Space Agency (ESA) program launched in November 2013. It consists of three satellites flying in different orbital planes and covering different local times. They allow highlighting the spatiotemporal structures of the Earth's magnetic field at unprecedented spatial resolutions.

The nominal duration of the mission scheduled for 4 years was extended for the first time until 2022 and a new call for tenders has been launched by ESA to continue the scientific activities and the operation of the mission until 2032.

France, through the Institut de Physique du Globe de Paris, played a major role in the scientific preparation of the mission by being one of the three instigators of the initial project in close collaboration with Germany (GeoforschungsZentrum, Potsdam) and Denmark (the space division of the Danish Technical University). The DTU space is in charge of the European consortium.

French activities related to the Swarm satellite mission initially focused on the primary science objectives. They have since then undergone significant changes thanks to a dynamism that could not have been so sustained without the support of public national programs. These supports structured the community into efficient work teams with collaborations between scientists of complementary but traditionally separated disciplines (magnetic field measurements, observations and long term monitoring, external fields, mathematical modelling, numerical simulation of the dynamo physics) and between theoreticians of electromagnetic phenomena together with Earth’s near surface and mantle specialists.

Today, these fruitful collaborations are in turn influencing the planning of the orbital evolution during the scientific boards of the Swarm mission. They prompt new synergetic ideas, and made possible new funded scientific project research gathering specialists from raw observations to core physics at the national and the European levels.

## Data calibration/validation, mission planning

The French community is very involved in the instrumental and scientific monitoring and in the planning of the evolution of the Swarm mission. Several of its members are part of the board issuing recommendations for the scientific and orbital evolution of the Swarm mission.

This activity is carried out in close collaboration with the expertise and calibration developments provided by CEA-Leti, whose magnetometers equip each of the three satellites. In this context, CEA-Leti monitors the ASM (Absolute Scalar Magnetometers), the calibration of the vector data, the technical support for the "burst" mode, the maintenance in operational conditions of the instruments and participates in the various European workshops on the validation and calibration of Swarm data.

This collaborative activity between the academic and industrial worlds was initiated and maintained with the support of Centre National des Etudes Spatiales (CNES) through the recruitment of Research Engineers in the academic world. The “burst” mode of the CEA-Leti

magnetometer, initially in the prototype state, now delivers measurements at 250 Hz thanks to an operational production chain delivering “burst mode” calibrated data. These data are available to a very large international scientific community. Part of this community, close to space weather, is pursuing works on the physics of space, the scientific impact of which is still at the exploratory stage but already prolific.

Other technical innovations are specific to the characterization of the Earth’s internal dynamics and meet the primary objectives of the Swarm mission.

The French teams have set up data processing chains following semi industrial standards. They have been developed and kept operational within the framework of the European consortium set up by ESA (Data Innovation Science Cluster, DISC). These teams are in charge scientific processing chains which deliver models in “open science” for the production of lithospheric magnetic field models at high resolution, rapid core field models, models of the ionospheric field and for the electrical conductivity and temperature in the Earth’s mantle.

## The International Geomagnetic Reference Field

The success of this synergy is illustrated by French participations and collaborations in collective activities with strong societal benefits, such as the production of the International Geomagnetic Reference Field (IGRF).

IGRF models are updated and produced every 5 years from candidate models built by independent international teams. This work is carried out within the IAGA’s Division V in the international working group WG-V-MOD. This group is responsible for establishing the specifications defining the format of the magnetic model, its period of validity. It also supervises and evaluates the precision and accuracy of candidate models in compliance with quality criteria such as scientific protocols, reproducibility and free availability of the magnetic field measurements.

During the last edition of IGRF-13 in 2020, French contributions through their submissions of candidate models were the most abundant. Candidate models were derived using the experimental vector mode on Swarm’s absolute scalar magnetometer (ASM-V) or novel approaches to core field estimation by Kalman filter, applying data assimilation concepts based on Earth-like numerical dynamo ensembles, or by combining satellite and ground measurements and applying multivariate singular spectrum statistical analyses for forecasting the field.

The community widely contributed at all levels in the working group considering lessons learned since the early time of IGRF. Its works included the management and evaluation process of the different candidate models, the weighting process leading to the new generation of IGRF, frontier analyses regarding the state-of-the-art of methods in forecasting of secular variation, and suggestions for possible future directions. This activity has also served the Division I of IAGA by delivering magnetic field models for the characterization of the geodynamo within the SEDI Working Group and by prompting new efforts towards Earth’s like dynamo simulations.

The next update of the IGRF should be delivered by December 1, 2025 and research teams already mobilize their forces via partners supporting these activities, as for example Shom.

## The World Magnetic Anomaly Map (WDMAM)

The WDMAM project aims at compiling all aeromagnetic, marine and satellite measurements available in the public domain in a global magnetic map describing the magnetic structures of the Earth's lithosphere. This is a long standing effort carried out by an international team of volunteers. The first version of the WDMAM was released in 2007 (Korhonen et al. 2007) after years of efforts from a dedicated IAGA task force. It resulted from the cooperation of several groups. The project is now supervised at Institut de Physique du Globe de Paris and maintains strong international collaboration for its achievement. During the last quadrennial, new measurements were processed and compiled and the version 2.1 of WDMAM is now almost ready. It incorporates the large scale structures of the lithospheric magnetic field components derived from the European Swarm mission. The progresses and the future of WDMAM will depend on the discussions that will be carried out at the IUGG in 2023 with the community involved.

## Magnetic ground monitoring

Continuously monitoring the Earth's magnetic field at observatories is a long tradition in France. The Bureau Central de Magnétisme Terrestre (BCMT) operates the French National Magnetic Observatory, a network of 18 overseas and remote observatories and a network of 11 repeat stations in metropolitan France. The mission of BCMT is to provide ground-based geomagnetic observations and data products of the highest quality in order to meet the specifications of the International Real-Time Magnetic Observatory Network (INTERMAGNET). Currently, 17 out of the 18 observatories under the BCMT responsibility are within INTERMAGNET.

The BCMT is implementing a long-term strategic plan leading to the establishment of magnetic observatory services dedicated to magnetic field monitoring and space weather activities. Magnetic data measured at observatories constitute time series over several decades. They are almost systematically used in all models of magnetic fields and global electrical conductivity of the Earth's mantle. Some observatories are located in strategic geographic location, particularly those in Antarctica, remote regions and near the equator. Recent efforts have been made towards monitoring permanently the magnetic field near the magnetic equator where the main field is particularly complex. This zone is close to the South Atlantic intensity Anomaly (SAA), which evolves rapidly and provides access to essential information on the dynamics of the internal magnetic field and its interactions with external fields. This minimum zone of intensity of the global geomagnetic field is known as a risk zone for satellites subjected to the influence of the solar wind and its electrically charged particles. Other initiatives have been carried out to deploy a national network of variometers to monitor the magnetic field continuously. A prototype station was installed in Clermont-Ferrand (France), a second is about to be installed in Brest (France), and other locations abroad are currently evaluated for permanent installations in order to complement the magnetic observatory network.

## Magnetic indices services

Ground magnetic observation networks deliver continuous magnetic field measurements. Time series are processed into magnetic indices monitoring the activity of the Earth's magnetic fields and the interactions between these fields and the Earth system. These indices are explicitly and systematically used in works relating to space weather and geomagnetism, and are as such referred as “auxiliary products”. We estimate from bibliometric samples that geomagnetic indices are used in more than 80% of scientific articles published in geomagnetism.

The International Service of Geomagnetic Indices (ISGI) is hosted by France and benefits from a leading international reputation. It is also part of the IAGA Working Group V-DAT in close relation with the IAGA Working Group V-OBS and is part of the World Data System. This data service benefits from recognition labels at the national and the European levels and is integrated within the European infrastructure EPOS, the French infrastructures DataTerra, Form@Ter, The Organization for Applied Resarch in Meteorology, etc. It collaborates with many actors from the academic and civil worlds.

The ISGI project aims at maintainig the long-term near real time production of geomagnetic indices but also to analyze series of older indices, statistically extract new trends, and explore the relevance of new magnetic indices describing new physical processes. Current doctoral and post-doctoral researches propose to link specific geographical variations of these indices to the electrodynamic state of the magnetosphere. The comprehensive products delivered in real-time by ISGI are used in fundamental and applied research programs and have multiple societal applications.

## The NanoMagsat satellite mission

The NanoMagsat satellite mission is a joint initiative of academic and industrial partners. NanoMagSat is a 12 nanosatellites project that aim to complement the ESA Swarm constellation by adding satellites with inclined but circular orbit. This configuration would allow a quick local time coverage and a better monitoring of rapid global temporal variations of the geomagnetic field.

The project considerably evolved during the last five years in terms of technology, flight configuration, adaptation, integration, complementarity with in flight or anticipated international missions and its integration in the European Space Agency program.

These constraints made possible to precisely define new scientific and societal objectives and challenges. The primary objective of the mission would be to ensure a continuous monitoring of the Earth's magnetic field, subsequently to the European Swarm mission.

The mission would be dedicated to the study of: the internal magnetic field (core and lithospheric), electrical currents circulating in the ionosphere, both globally and locally, magnetic signals produced by large scale magnetospheric currents, couplings between the magnetosphere and the ionosphere at high latitudes, the magnetic signal of ocean tides; currents induced in the mantle by currents produced by the magnetosphere, ionosphere and

ocean tides, allowing to probe the conductivity of the mantle and the state and dynamics of the ionosphere.

The scientific increment is therefore huge. This project is supported by a large scientific community from 16 ESA member countries. The project is now consolidated and the technical demonstration were very favorably evaluated. The consortium is now waiting for the mission program information.

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