# Acquisition of 1-second data in IPGP magnetic observatories

Arnaud Chulliat[1], Jean Savary[2], Kader Telali[2], Xavier Lalanne[1]

[1]*Institut de Physique du Globe de Paris, 4 place Jussieu, 75005 Paris, France*
[2]*Institut de Physique du Globe de Paris – Observatoire Magnétique, carrefour des huit routes, 45340 Chambon la Forêt, France*

**Abstract**

Since 2003, INTERMAGNET has been recommending that magnetic observatories produce vector data sampled every second, instead of every minute. The scientific motivations for this upgrade are mainly that: (a) there is a growing demand from the space physics community of one-second magnetic data at the global scale for studying ULF waves in the ionosphere and the magnetosphere; (b) observatory data need to be synchronized with magnetic data produced by low-Earth orbiting satellites such as Oersted and CHAMP, which are sampled at 1 Hz. A user survey lead by Jeff Love (USGS) in 2005 helped define the scientific requirements for observatory one-second data, such as data resolution and accuracy, time-stamp accuracy and filtering specifications. Following this survey and the operational standards issued by INTERMAGNET, IPGP has been developing a new version of its VM391 3-axis, fluxgate magnetometer and a new acquisition system in order to meet these standards. These new instrument and system are now installed in Chambon la Forêt (CLF) magnetic observatory and will be installed in most IPGP magnetic observatories in the coming years, before the launch of the upcoming ESA Swarm mission.

## 1. Introduction

INTERMAGNET magnetic observatories currently produce and distribute digital, one-minute data. Twenty years ago, when INTERMAGNET was born, distributing this type of data represented a significant improvement with respect to the analog, hourly data that were still the only data product for many observatories. However, it was realized a few years ago (at the INTERMAGNET Dourbes meeting, 2003) that observatories needed to move towards one-second data if they wanted to catch up with magnetometer networks (such as IMAGE, CANOPUS, GMC, etc.) and magnetic satellites (such as Ørsted and CHAMP), which were already routinely producing and distributing one-second data. A user survey carried out by Jeff Love in 2005 helped assess users' needs before the observatory community took action.

The biggest demand comes from the space physicists studying rapid variations of external origin, such as ULF waves (e.g., Uozumi *et al.*, 2000) and sudden impulses (e.g., Chi and Russell, 2005). For example, Pi 2 pulsations can be used to time and locate substorm onset (e.g., Kennel, 1996; see also R. McPherron's response to the survey). Due to its global geographical distribution (Love, 2008), INTERMAGNET would usefully complement regional magnetometer networks by providing one-second data in isolated locations not yet covered by magnetometer networks. In addition, it is not unreasonable to expect new insights into the long-term evolution of the ionosphere and the magnetosphere from observatory one-second data, since observatories are sustainable infrastructures aimed at operating over decades. Observatory one-second data would also be useful to the geomagnetism community studying ionospheric magnetic fields such as the Sq field and the equatorial electrojet (e.g., Manoj *et al.*, 2006). A CHAMP-like magnetic satellite flying in quasi-polar orbit at about 7 km/s covers around 420 km between two successive one-minute data at nearby observatories. This is to be compared with the width of 600 km of the equatorial electrojet. Synchronized ground and satellite data would help improving the spatio-temporal description of the ionospheric currents such as the equatorial electrojet.

Today, more and more observatories are producing one-second data and INTERMAGNET is setting up the capability to distribute these data in quasi-real time. Here we report recent efforts to produce one-second data in IPGP observatories. These involve an upgrade of IPGP's 3-axis fluxgate magnetometer and the development of a new data acquisition system able to properly handle one-second data.

## 2. Requirements

Jeff Love's user survey in 2005 lead to the following consensus requirements regarding one-second data:

- Data resolution should be 10 pT; data absolute accuracy is unimportant.
- The data should be centered on UT second with a time accuracy of about 10 ms. Some users expressed the need to have a better (1 ms) time accuracy for the purpose of studying wave propagation.
- One-second data should be obtained by filtering data sampled at higher frequency using a digital filter, for example a Gaussian filter with cut-off frequency between 0.3 and 0.5 Hz.

These requirements were later adopted by INTERMAGNET. The data resolution requirement was increased to 1 pT at the Golden meeting in 2008.

Another requirement that emerged from this survey and follow-up discussions was that the magnetometer noise spectrum should not exceed the geomagnetic signal spectrum at frequencies between 0 and 1 Hz. However, the geomagnetic signal spectrum steeply decreases with frequency and its typical value is 1 pT/sqrt(Hz) at 1 Hz. This makes such a requirement unrealistic for most (if not all) existing fluxgate magnetometers, which have a larger intrinsic noise at 1 Hz. New, low-noise fluxgate magnetometers would have to be developed if one wants to fully satisfy the noise requirement.

## 3. Upgraded fluxgate magnetometer

The VM391 vector magnetometer currently in operation in IPGP magnetic observatories (including those in cooperation with other institutions, see Courtillot and Chulliat, 2008) is a ring-core, 3-axis and homocentric fluxgate magnetometer (Fig. 1). It was originally developed in the 1990s, and its electronics was subsequently upgraded several times. In order to satisfy the above requirements for the production of 1-second data, two improvements were made to this instrument:

- Some changes were made in the analog part of the electronic (feedback integrator, filters), in order to have a cutoff frequency at 2 Hz for 5 Hz sampling, and a time accuracy for the time lag for all three components of about 10 ms.
- A new 24-bits ADC board, in order to have a 10 pT resolution, was designed and built with one ADC per component and all components sampled at the same time.

A synoptic view of the upgraded magnetometer is represented in Fig. 2.

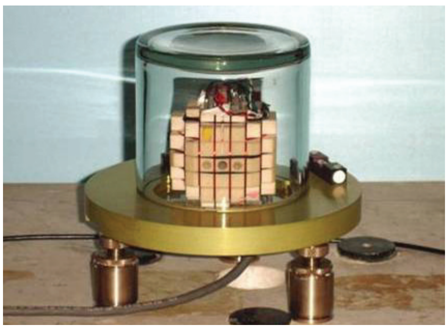

**Figure 1: The IPGP VM391 fluxgate magnetometer**

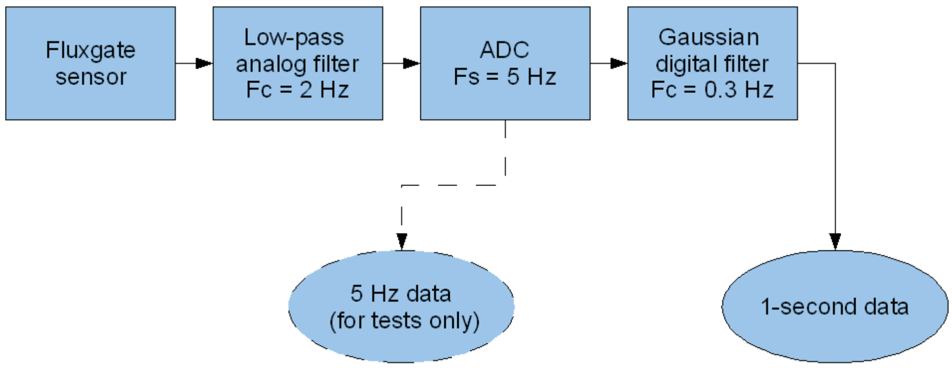


**Figure 2: Synoptic view of the upgraded VM391 magnetometer.**

The frequency response of the analog part of the VM391 was measured by placing the sensor in a magnetic shield including a cylindrical coil and submitting it to a sinusoidal magnetic field at various frequencies between 0.001 and 10 Hz. The results are displayed for each component in Figs. 3 (amplitude) and 4 (phase, converted to time delay). As expected, the cutoff frequency for the analog part is 2 Hz. Note that the effects of the 50 Hz and 60 Hz mains effects are filtered out by a digital notch filter in the ADC.

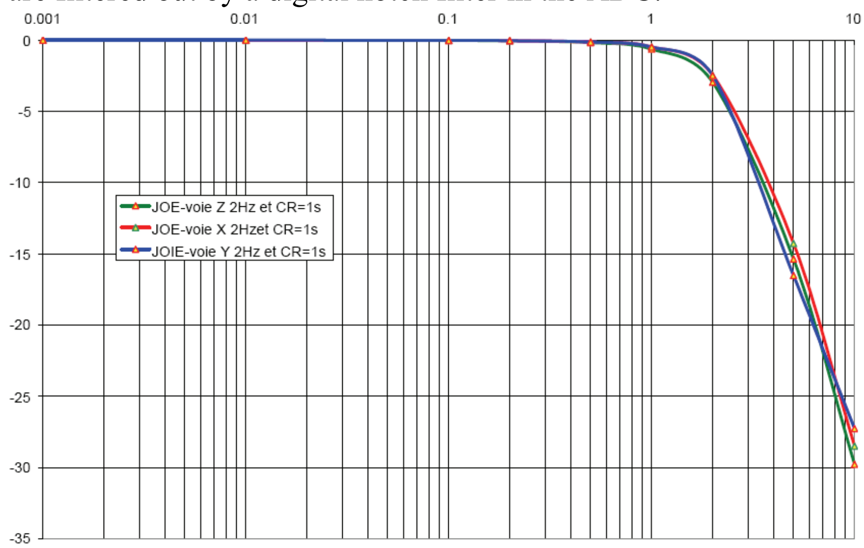


**Figure 3: Frequency response of the upgraded magnetometer: amplitude (in dB) vs. frequency (in Hz).**

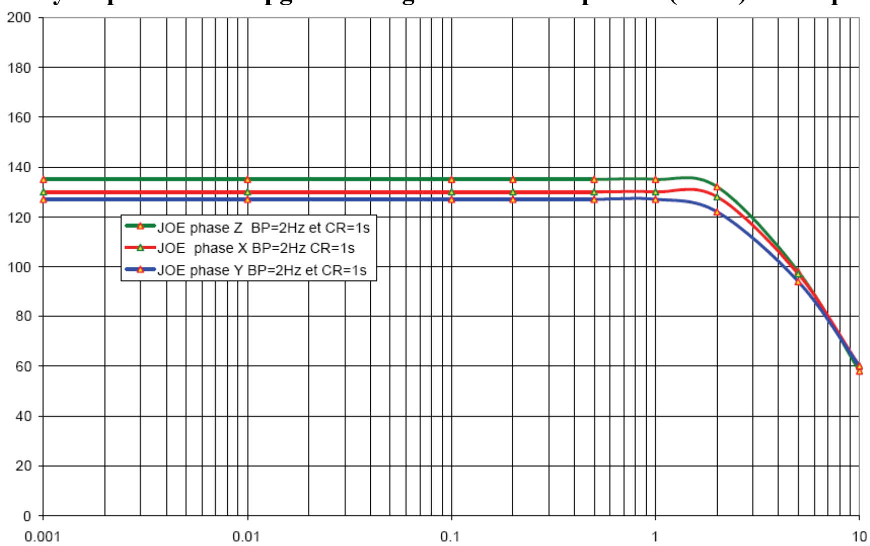


**Figure 4: Frequency response of the upgraded magnetometer: time delay (in ms) vs. frequency (in Hz).**

The time lag for all components is around 130 ms for the tested instrument. This average value is used as a parameter by the data logger, which adds it to the other sources of time delay in the acquisition chain in order to correct them (see next section). The difference in time delay between the three components is smaller than 10 ms. Therefore, using the same value for the three components does not violate the above requirement on time accuracy.

The intrinsic noise of the VM391 magnetometer was determined by putting it into a 60 cm long mu-metal 3-layer cylinder, which was itself put into a 2.3 m x 1.7 m x 1.7 m non-magnetic room located on the premises of the Chambon la Forêt observatory (Fig. 5). This room is made of two layers of mu-metal reinforced by an aluminium structure. The static magnetic field in the room is less than 100 nT and less than a few nT at the sensor level. The results of the tests are represented in Fig. 6 for the X component (they are very similar for the other components). The magnetometer noise is about 10 pT/sqrt(Hz) at 1 Hz, which is ten times the requirement on noise mentioned in section 2. However, this is not far from the noise of the less noisy fluxgate magnetometers, around 7-8 nT. (One such magnetometer, a Thomson VFO, has actually been used to test that the non-magnetic chamber filters out natural variations down to a lower noise level than that of the VM391.) The intersection between the magnetometer noise spectrum and the spectrum of geomagnetic variations in Chambon la Forêt occurs around 0.3 Hz, where both signals have an amplitude near 20 pT/√Hz. We concluded from this test that the cut-off frequency of the digital filter (see Fig. 2) should be less than or equal to 0.3 Hz.

A Gaussian digital filter was designed accordingly. We decided to use a sampling frequency of 5 Hz and to have a smallest filter coefficient of 0.1 and a cutoff frequency of 0.3 Hz, thus obtaining the following 15-point filter, centered on UT second:

$$f(t) = \exp\left[-\frac{1}{2}\left(\frac{t}{\tau}\right)^2\right],$$

where $\tau = 0.442$. The filter is represented in the time domain and frequency domain in Fig. 7. This filter was implemented in the ADC of the upgraded VM391 electronics.


**Figure 5: Non-magnetic room in Chambon la Forêt observatory.**

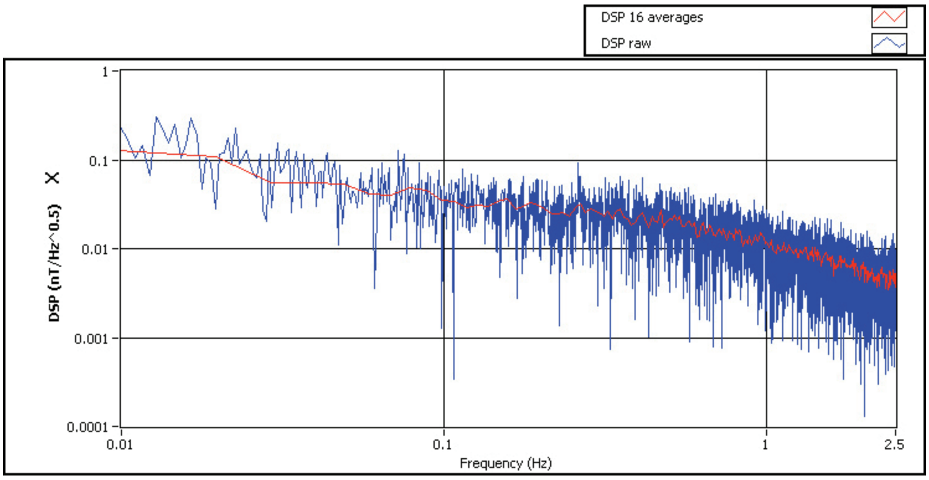


**Figure 6: Instrumental noise (X axis) recorded in the non-magnetic room.**

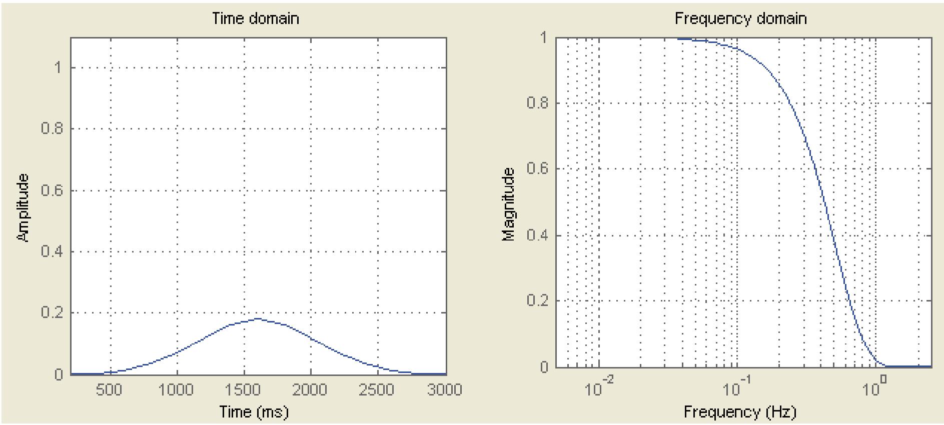


**Figure 7: Time (left) and frequency (right) domain plots of the selected Gaussian digital filter.**

## 4. New data acquisition system

A new data logger was developed for the purpose of acquiring 1-second data satisfying the requirements listed in section 2. This system, named "ENO3" ("ENO" is an acronym for "Enregistreur Numérique d'Observatoire") includes the following functionalities:

- GPS time synchronization
- Time lag correction
- Configuration through a web interface
- Data storage in IAGA2002 format
- Data transmission through the Internet where available
- Local or WEB control display (Fig. 8)

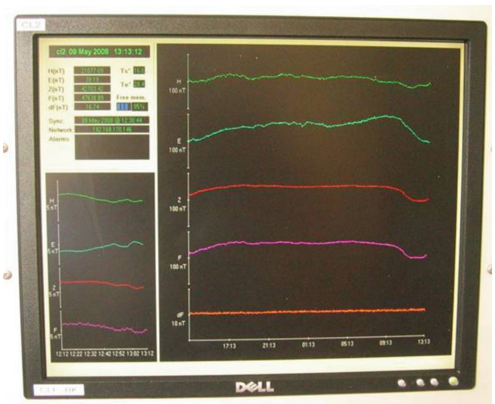

**Figure 8: View of the control screen of the new "ENO3" data acquisition system.**

The time lag correction is obtained by interrogating the vector magnetometer at $t_0+\Delta t$, where $t_0$ is the desired measurement time and $\Delta t$ is the total time delay to be corrected for the complete chain. For example, in the case of the VM391, $\Delta t$ is the sum of: (a) the time lag of the analog part of the fluxgate magnetometer (which needs to be determined experimentally for each individual instrument, as shown in section 3); (b) one sampling time step of 200 ms allowing some additional time delays (smaller than 200 ms) introduced by the numerical chain; (c) an additional 2000 ms allowing the calculation of the Gaussian digital filtered data. As a result, $\Delta t = 2330$ ms for the tested instrument, which an uncertainty of about 10 ms, thus satisfying the time accuracy requirement of section 2.

## 5. Summary and perspectives

In order to acquire filtered one-second data satisfying the requirements of INTERMAGNET and the scientific community, in particular that investigating ULF waves, the IPGP VM391 fluxgate magnetometer was thoroughly upgraded and tested. Its new characteristics are as follows:

- 2 Hz cutoff frequency
- 10 ms time accuracy
- 10 pT resolution
- 10 pT/√Hz @ 1 Hz noise

A new, low-noise sensor will have to be developed if one wants to achieve a lower instrumental noise. However, discussions during the 2008 IAGA Workshop in Golden did not demonstrate the urgent need to do so. The digital part of the magnetometer applies a Gaussian digital filter with cutoff frequency at 0.3 Hz to produce 1-second data. These data are retrieved by a newly developed data acquisition system, ENO3.

As of February 2009, the new one-second system is installed and running in the Chambon la Forêt, Addis Ababa and Easter Island (Chulliat et al., 2009) observatories. It will soon be deployed in other IPGP observatories, including those in cooperation with other institutions.


## Acknowledgements

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