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VESTALE LOOP: a robust, versatile, reliable and remote controlled bench for environmental magnetic sensing at hectometric scale

Clément DEZORD[1], *Gilles* MICOLAU[1 2,*], *Chahine* ABBAS[1], *Arnaud* MESGOUEZ[1] and *Elisabeth* POZZO DI BORGO[1 2]

[1] UMR EMMAH 1114 INRAe - Avignon University, INRAe, Site de Saint Paul Agroparc 84000 Avignon, France
[2] UAR LSBB 3538 CNRS - Avignon University, La Grande Combe, F-84400 Rustrel, France

Abstract. Proofs of well-functionning of an original hectometric magnetic bench, located in the South of France, at the Low Noise Underground Laboratory (LSBB for french acronym), Rustrel, are presented. Two different kinds of electrical measurements are justified and exposed. They are based on the monitoring of electrical quantities as characteristics and spontaneous induced bias, over the time and during periods of several weeks. A very first correlation with meteorological data is also presented. The technical as the scientific perspectives are exposed at the end.

1 Introduction

At the Low Noise Underground Laboratory (LSBB) [1] in Rustrel, France, a conductive coil, which is called Vestale, lies on the top of the so-called "Grande Montagne" mountain, more than 500 metres above the tunnels of the Laboratory. It contains 11 wires with a diameter of 1.5 millimeters, forming a toron of a few centimeters wide. Its shape is mainly determined by the local topography, as shown in figure 1, and is inscribed in a circle of a hundred meters in diameter. Initially Vestale was installed to be used as an active magnetic antenna, dedicated to the excitation of the SQUID magnetometer located inside the main gallery of the LSBB, 500 meters below. The *Hypermagneto* scientific project consists in the instrumentation of Vestale to make it both a magnetic excitation source and a standalone environmental sensor, by improving the way it can be connected to scientific instruments. In a first approach, the underlying idea is the corellation of the measurements produced by such an unusual device, with different kinds of measurements existing on site as for instance gravimetry [2] or electromagnetic survey [3, 4]. The experimental developement of the measurement bench is already done, making it possible to monitor the electrical characteristics of the coil or to use it as a passive giant magnetic antenna. This bench is versatile and designed to receive, in the next future and without any changes of its architecture, various new devices. The proof of concept of this bench and its very first results have already been exposed [5].
This paper is devoted to show the the well-functionning of this bench and the scientific opportunities opened. We first present and justify the original architecture of the bench and

*e-mail: gilles.micolau@univ-avignon.fr

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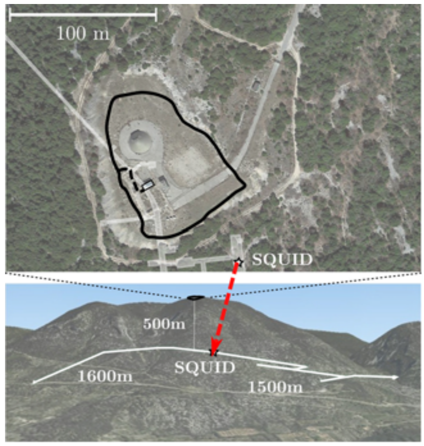

Figure 1. *Views of "La Grande Montagne de Rustrel". Top aerian view : in black the coil named Vestale, the white star indicates the projection on the surface of the ground of the underground location of the SQUID magnetometer. Bottom side view of "La Grande Montagne de Rustrel" from South. The white lines indicate the underground galleries and the location of the SQUID magnetometer inside.*

the choice of the presented measurements. Then we present different proofs and exemples of the well-functionning of the bench in the two different modes of measurements. Then a conclusion with perspectives at different timesfinalizes the paper.

2 Goals and means

Because of the harchness of the Vestale site (altitude of 1000 m, strong wind, storms, strong temperature variations, difficult and tedious access), the bench has to be remote-controlled, quasi automated, and protected of the external environment. Moreover, it also must be able to be connected to several different instruments such as low frequency and high power AC supply (in order to be used as a magnetic source) or standard electronics measurement devices (multimeter, RLCmeter, oscillosocpe, ... in order to be used as a sensor). In other words, we aim to build a bench with qualities of scientific and technical reliability, flexibility of use, versatility for the equipements and remote controlled. To do so, we use, on the one hand, an original architecture based on open-source hardware and software for the control of the bench, and on the other hand, well-known standard and very efficient scientific measurement instruments. The control is ensured by the association of a Raspberry Pi 3 with seven Arduinos Uno, controlling a set of electrical relays and driving the measurements devices. The data storage is done by the Raspberry Pi 3 and an hard disk. A very schematic presentation of this architecture is proposed in figure 2. The controller and the measurement devices are in a thermal tank (a domestic fridge controlled in temperature by one of the Arduino). The technical detailled aspects are the object of a forthcoming communication.

2.1 Functionnal schemes

Due to the difficult access to Vestale site, all the technical aspects of the experimental development have first been realised in the laboratory of the Physique Team of the Laboratory at Avignon University, in an air-conditioned room. A metric mock-up of Vestale have then

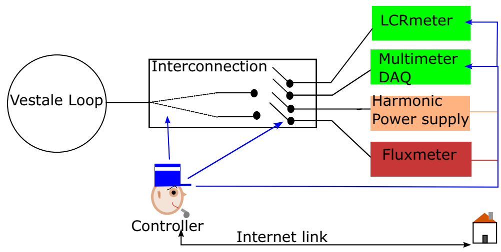

Figure 2. *Roughly representation of the technical scheme of the instrumental bench. A controller (Paspberry Pi3), connected to internet, can control several devices as electrical relays (via seven Arduino cards) allowing to configure the loop, and controlling different electrical measurement equipements. The internet connection allows to run automated mesurements, configure the loop, or update Arduinos codes.*

been mounted in a wood box, as already presented in [5] to challenge the robustness of the hard and soft developments before deploying them on site. This mock-up is called Ministale. Initially, this latest had no vocation to become a sensor.
The first technical point has consisted in developping a programmable system of interconnection with relays between the 11 wires. It allows to configure the whole coil in two possible ways. The first one corresponds to a 11 wires serial connection. This is the only configuration currently used for measurement. It is denoted configuration C_{11}. The second configuration consists in a 6 wires serial connection on one side, and a 5 wires serial connection on the other side. In this way, we have two intricated coils, as for an electric transformer, each of them being electrically independant from the other, but magnetically coupled by induction. While this configuration is operationnal, it is not yet used for measurements.
At this time, two kinds of measurements are operationnal and fully comply with our specifications in the C_{11} configuration. The first one, the most mature, is called active mode, since it consists in characterizing the complex impedance of the coil, by biasing it with an harmonic tension and by measuring the amplitude and the dephasing of the corresponding current. The second one is called passive mode and consists basically in measuring the inductive bias in the coil, produced by temporal modification of the magnetic field, with only a multimeter.

2.2 Active mode

This kind of measurements is operated by a commercial RLCmeter Keysight E4980A [6], controllled by GPIB bus. The coil is polarized by an harmonic bias of amplitude U, with frequency f_m choosen by the operator, and the RLCmeter measures the amplitude I of the current and the dephasing φ between I and U. Finally, it produces a complex impedance $\underline{Z}(f_m) = \left|\frac{U}{I}\right| \exp(j\varphi)$ depending on the operating frequency. To completely characterize the coil, on a large frequency range, the RLCmeter chains the measurements with different frequencies, from tipically $f_m = 20$ Hz up to $f_m = 10$ kHz, with a step defined by the operator. The scanning in frequency is called a frequency sweep. A typical instance of results of such measurements is shown in figure 3, for five succesive sweeps made the same day at Vestale antenna (each sweep takes 1h30min).
Those measurements show that Vestale presents a classical behaviour of a resonant circuit, involving the capacitance effect of a coil. The modulus is bell shaped, with a maximum at a frequency around $f_m \sim 3.7$ kHz denoted f_{max}. The dephasing is "stair-case" shaped, it

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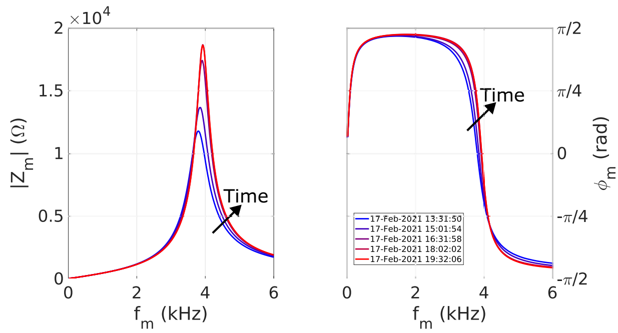

Figure 3. *Instance of five complete electrical characteristics of Vestale recorded during around six hours an afternoon of February 2021. Left : the modulus of the complex impedance versus operating measurement frequency (f_m); right : the angular phase of the complex impedance versus f_m.*

changes its sign at a frequency f_r which is defined as the resonnant frequency (the frequency f_m where φ is null).
On the figure 3, we can also see how this complex impedance varies over time at the scale of a few hours. The maximum of the modulus changes both in amplitude (from $1.2\ 10^4\ \Omega$ to $1.8\ 10^4\ \Omega$) and in frequency from 3.7 kHz up to quite 4 kZ. The dephasing φ varies too, particularly the frequency f_r. Those fluctuations are environmental, not due to the measurement devices, as we proof in the following.

2.3 Passive mode

To implement the passive mode, a digital multimeter DMM Keythley DAQ6510 [8], with a memory buffer of $5\ 10^6$ points of measurements has been installed on the bench. Depending on the sampling frequency, it allows to monitor the bias appearing on Vestale during periods from few minutes up to several days. It proposes 3 different calibers (10 V, 1V, 100mV) encoded on 16 bits. At this time, it is directly connected to Vestale through the bench, without any conditionning of the signal : neither preamplifiers, amplifiers or antialising filter. Depending on the kind of signal observed, it will be necessary or not to integrate some of those devices.
Some other international experiences are running on the top of the Great Mountain, monitoring the electromagnetic field produced by atmospheric phenomena. Particularly, a survey at low frequency (from 0 Hz up to 1 kHz) is operated by [7]. This survey is disturbed by the active mode of Vestale in the range of f_m included in the band below 1 kHz. Thus, we activate either one of the two modes after concertations with our colleague leading this experience.

3 Proof of functionning with first results

3.1 Ministale non expected results

Initially Ministale has been built to test electronic hardware and software before their deployment on the Vestale site. To insure the reliability of our developement, we acquired data in active mode, during long periods, particularly during holidays (very quite period for anthropic activities near the loop), in our laboratory at Avignon University, a usual standard room with air conditionning insuring a mean temperature around 25^o C. Moreover, the RLCmeter is a

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precise and sensitive industrial device, designed to maintain its measurement accuracy in a temperature range of 0 degrees to 50 degrees. We observed then some well defined oscillations of particular point of the complex impedance, including a very regular daily fluctuation. To insure that the bench is not responsible of those fluctuations, and in order to characterize its sensibility, we placed Ministale in the Anti Blast Gallery (GAS for french acronym) of the LSBB. This latest is a blind gallery, located around 60 meters below the surface, widely insulated from the rest of the laboratory, and naturally presenting very stable environnement (temperature, hygrometry, quite always in the dark) with natural walls (no concrete). In order to protect the electronic equipment from the humidity of the gallery, the measuring device and the controller were placed in a thermal enclosure (a simple refrigerator) as for Vestale loop, regulated in temperature.

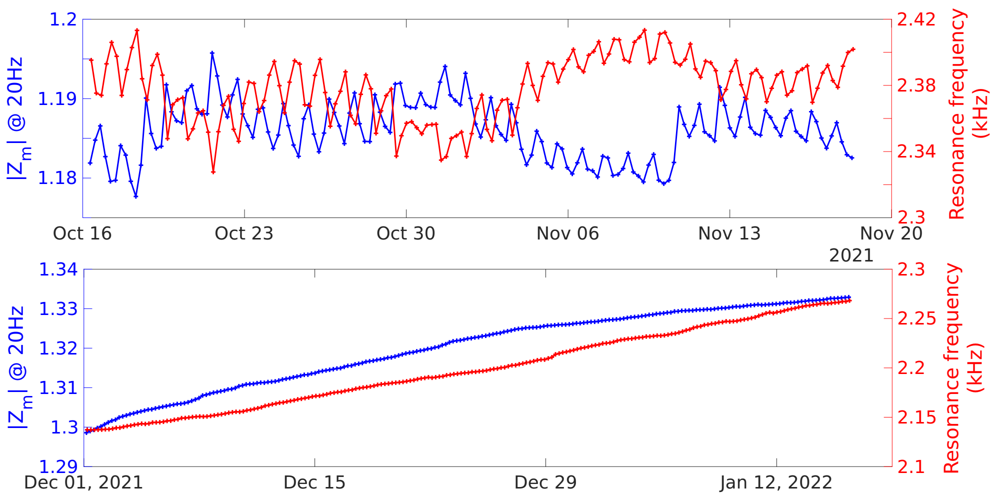

Figure 4. *Top : modulus of the complex impedance at* 20 *Hz of Ministale (blue) and resonnant frequency f_r (red) versus time during a period of 33 days between October and November 2021, obtained in the Laboratory of Avignon University, with a zoom on the November 6th. Bottom : same quantities in same legend obtained in the GAS gallery of the LSBB during a period of 46 days between December 2021 and January 2022. The measurements have been made with exactly the same material, with exactly the same setups.*

Figure 4 presents the time evolution of the impedance modulus measured at 20 Hz, $\underline{Z_{20}}$, in blue, and f_r in red in the laboratory at Avignon (left) and in the GAS gallery (right). In the Avignon laboratory, we observe very regular daily fluctuations for $|\underline{Z_{20}}|$ as for f_r. The relative variations during the whole period are higher than 1%. The daily relative variations are roughly a few tenths of a percent while the relative variation of the mean on a day is half the size. The evolutions are much more regular in the GAS gallery, without fluctuations. The two curves present a slow growth behaviour.
During the measurement period proposed here, the temperature measured (by a Pt100 probe) inside the fridge varied from 32.2^o C (minimum) to 32.8^o C (maximum). Generally, the most important parameter in the stability of electronic measurement devices is the temperature. The RLCmeter is twice protected : by the fridge and its own conception. So, we interpret the drift of the measurements in GAS as the consequences, on the coil electrical characteristics, of the long time range evolution of the conditions in the gallery, mainly the temperature

and the moisture ratio. From those curves we can assure 3 facts. First, the active mode is operationnal and reliable. Second, the bench is not responsible of the observed fluctuations. Third, the coil is significantly sensible to its direct environment.

3.2 Vestale results

3.2.1 Active

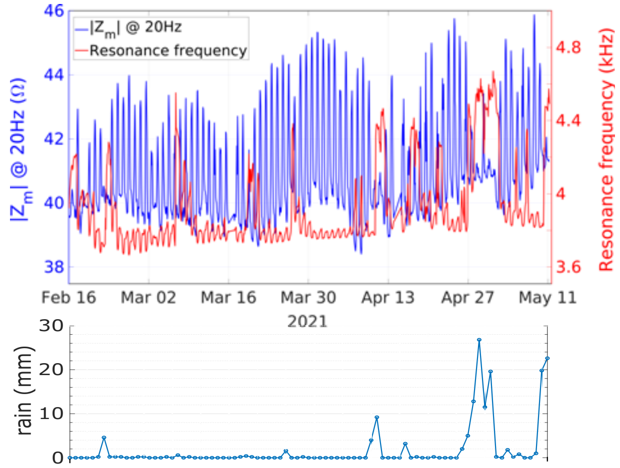

Figure 5. *Top: same legend as Figure 4 with results obtained with Vestale antenna during quite 3 monthes between February and May 2021. Bottom rain precipitations in mm, for the exact same period, with one data per day, recorded at Cabrières Station (few kilometers from Vestale).*

The same measurements than explained in figure 4 has been performed on Vestale. They are presented in figure 5. For both f_r and $|\underline{Z_{20}}|$ we observe again very regular daily oscillations overlaid on slow variations. However, each presents various slow dynamics. While $|\underline{Z_{20}}|$ presents both daily fluctuations combinated with slow variations, of several weeks, f_r seems to present regular daily fluctuations, combinated with strong and quick variations of one or two days. As already exposed in [5], f_r seems to be sensitive to rain events, quite immediately. So we plot, with the help of [9], the daily water precipitations. The curve of f_r presents steep variations (see for instance what happened on april 27^{th}) concomitant with rain falls. However, the variations of $|\underline{Z_{20}}|$ presents other dynamics, very much slower. One of our hypothesis of interpretation lies in the magnetic coupling of the coil with the soil. At very low frequencies, the skin depth of the ground is relatively large. It is possible that the coil interacts, at 20 Hz, with the water deeply in the ground. The variations of the level of this deep water are very slow in front of the level of the water at the surface.

3.2.2 Passive

We present the very first results of the passive mode on Vestale antenna. It is well known that in magnetic and inductive measurements, the electric network is a main source of noise at its servive frequency of 50 Hz in Europe. So we use it to confirm the well-functionning of this mode of measurements, by sampling the induced bias on Vestale at 250 Hz. The calibre is arbitrarily fixed at 100 mV. The rough data contains 1415 measurements whose the value is 10^{37}, which is the greatest value encodable by the multimeter. Those points are called overloads and they correspond to measurements greater than the calibre. The sign of the measurement is lost in this overflow. In view to represent the recorded signal, these overloads are processed in two different ways. The first one consists in replacing the overload point by a null value, the second by a value fixed at the maximum of non-overload recorded value, affected by a random sign either positive or negative. An instance of a record processed using these two methods is presented in figure 6.

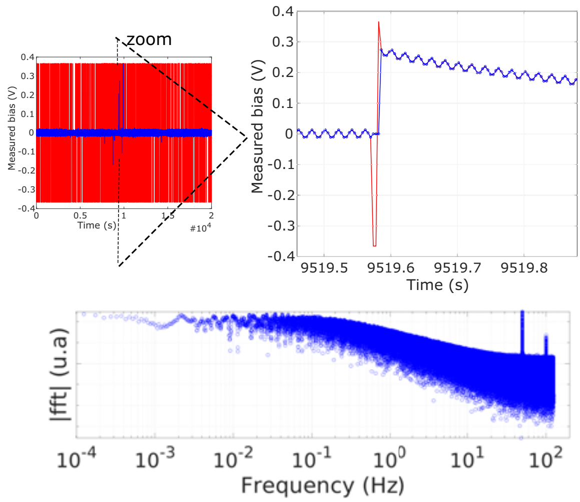

Figure 6. *Top left, measurements of measured bias versus time in passive mode with replacements of the overloadsby a zero value (blue) and by an arbitrary non null value (red). Top right a zoom around the* 9519 *s during around* 0.5 *s. Bottom, modulus of the spectral density of measured bias versus positives frequencies, obtained by classical fft. Sampling frequency is* 250 *Hz, with* 5.10^6 *points of measurement corresponding to* 2.10^4 *s of measurement (5 hours).*

Due to the huge amount of points, the complete signal recorded (top left) is not exploitable with either processing method. At this scale of representation the overloads seem to be preponderant (red curve). However, the signal for which we cancel the overloads appears clearly (blue curve). A zoom of the signal on the region located at 9519.5 s, with a duration of 0.4 s allows to show an overload event containing 5 consecutive saturated values (top right). This event could probably be interpretad as an electromagnetic event of amplitude greater than the calibre (100 mV) and with a duration shorter than the limit of Shannon criterion. The blue curve also shows clearly the 50 Hz frequency of the elctrical network (5 points by period corresponding to the sampling frequency). A power spectral density, obtained by a single elementary Fast Fourier Transfom of the signal (using the 0 value processing of the overloads), is represented in blue (botom). This representation enlights the network frequency (50 Hz) and its second harmonic (100 Hz). Moreover, the signal seems to contain coherent part in the range between 10^{-3} to 10^{-2} Hz.
This instance shows that the bench is reliable, correctly remote controlled, and can switch easily from a mode of acquisition to the other. Technically, this swicth is constrained by two complementary facts. First, we observed that in passive mode, if the RLCmeter is on, the passive measurements can be perturbed, probably due to an interaction between the wires of

the RLCmeter and the interconnecting card. Second, the RLCmeter is not designed to be switched on and off several times a day. So at this time it is not possible to process a system of measurements combining this two modes successively, several times a day.

4 Conclusion and Perspectives

In this paper, we presented the two modes of measurements of an instrumented hectametric magnetic loop. We have shown that the bench is technically reliable, quasi completely remote-controlled, and that it is sensitive to its environement. The measurements are scientifically significant and exploitable. Future perspectives can be envisaged according to three time horizons. In the short term, we will work on a pertinent massive data processing on the active mode, because we begin to have a lot of measurements set. To do so, we aim to correlate our data with the multiphysic measurements made on site (gravimetry, meteorology, hydrogeology, magnetometry inside LSBB) with the help of elementary electrocinetics model of the loop. In the medium term, we are beginning to work on different reliable electronic systems allowing to filter, preamplify and compress signal in passive mode. Moreover, we have to optimize the process of sampling and integrating the signal in the multimeter device. This job should be done with the help of others users of the Vestale site [3][7], and would be driven by the kind of signals of interest. Because of the existing system of antennas and the hugeness of Vestale, we can expect that the frequency range of interest would be very low in frequency. In the long term, we are already working on a combo-active-passive-mode using a counter-reaction on the coil itself. This mode is similar as the one used in metal detectors or eddy-current sensors. It consists in connecting the different wires of the coil as they form two imbricated coils, traversed by two opposite currents, insuring a generated quasi null magnetic field. Measuring the counter-reaction should allow to estimate the magnetic perturbation occuring in the first coil.

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