



A new magnetic observatory in La Réunion Island

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Abstract. A new magnetic observatory has been set on La Réunion island in the Indian Ocean through a collaboration between the "Institut de physique du globe de Paris" (IPGP) local volcano observatory (OVPF) and its magnetic observatory service. This observatory is isolated and serves for monitoring the evolution of the magnetic field in that region. It is also particularly useful for large scale modelling of the core field and other contributions to the geomagnetic field. Three-component vector

- 5 magnetic field data are continuously collected at 1Hz using a fluxgate, while scalar data are collected at 0.2Hz with a proton magnetometer. The data are transmitted every 5 minutes to IPGP main site and made immediately available to the scientific community (see www.bcmt.fr). Due to the strong magnetic field generated by the surrounding volcanic rocks, the differences between the magnetic field strengths as recorded by the proton magnetometer and the strengths calculated from the recorded vector field values vary during a day. To circumvent this difficulty, constant offset values of -2400 nT, 280 nT and
- 10 -20 nT are systematically added to the X, Y and Z magnetic field components prior to the data distribution. We show that this efficiently reduces the differences between measured and calculated magnetic field strengths inside a day. Definitive observatory data have been calculated over the year 2023 and, although the baseline values present strong variations throughout that year, the derived data meet the quality required for an INTERMAGNET observatory. A Fourier analysis of the data shows that these are not contaminated by a significant noise even if peaks at 0.2Hz indicate a small cross-talk between vector and scalar
- 15 instruments.

1 Introduction

There are currently around 120 magnetic observatories around the world collecting data, most of them being part of INTER-MAGNET (Love and Chulliat, 2013); an international organization promoting high quality standards for magnetic data and acquisition processes, and free data distribution (www.intermagnet.org). These observatories allow to monitor the geo-

- 20 magnetic field changes over decades and serve not only for the study of the core magnetic field but also the fields generated in the ionosphere and magnetosphere together with those generated by their induced counterpart currents in the conductive bodies inside the Earth. Numerous other natural sources contribute to the observed magnetic data such as oceanic tides and currents. However, for having a global view of the magnetic field evolution, it is preferable to have a homogeneous distribution of observatories over the world (e.g. Langel et al., 1995). This is far from being the case with most of observatories being
- 25 located in Europe and Northern America while only few observatories are set in the Middle East regions, Africa and South America. Despite very difficult climatic conditions there are several observatories in Antarctica in contrast with oceanic areas





where only a few observatories are set on remote islands.

Building an observatory on an isolated island usually comes with specific challenges as these islands are typically of volcanic
origins and therefore are made of rocks presenting strong magnetization. It follows that, contrary to the traditional continental setup, observatories on these islands are often set in areas of strong magnetic field gradients. Such gradients do not preclude accurate measurements of the magnetic field strength and direction when modern instruments are used, but it is nonetheless difficult to reconcile the data acquired on different locations of the observatory site. These data are continuous series of vector magnetic field measurements made using fluxgate magnetometers, series of total field strength generally obtained with a pro-

- 35 ton or optically pumped absolute magnetometer, and handmade calibration measurements typically made on a weekly basis. These three types of data are made at different places, few meters apart, and have to be processed to give a continuous series of calibrated vector magnetic data located on the absolute reference pillar of the observatory. It is this continuous series of second or minute mean calibrated data that is ultimately distributed by the observatories for scientific or technical applications.
- 40 In the Indian Ocean, as in the Atlantic or Pacific Oceans, there are currently very few observatories (See Fig. 1). To the East, Gingin (GNG), Learmonth (LRM) and Cocos Island (CKI) INTERMAGNET observatories, all under Australian institution responsibilities, are producing data. To the North, India is running several INTERMAGNET observatories: Alibag (ABG), Hyderabad (HYB), Choutuppal (CPL). There is also the Gan International Airport observatory (GAN) in Maldives Islands that has been set in 2012. The observatory in Antananarivo (TAN), stopped producing calibrated data in December 2007. A new observatory
- 45 has been set in Fihaonana (Madagascar) but is not yet distributing data. Further to the West data are distributed by the Maputo (LMM) and Nampula (NMP) observatories in Mozambique up to 2017 and 2019 respectively, and by Hartebeesthoek (HBK) observatory. To the South, three observatories on the Kerguelen, Crozet and Amsterdam islands have not been delivering calibrated data to Edinburgh World Data Center (wdc.bgs.ac.uk) since 2013, 2015 and 2013, respectively, although some variation i.e. non-calibrated, data are available on the BCMT database (www.bcmt.fr). In order to increase the observatory
- 50 density in the central part of the Indian Ocean, we set a new observatory on La Réunion Island, roughly 875 km to the East of the former Antananarivo observatory and more than 1800 km away from the closest currently active observatory in Nampula (Mozambique). The choice of this island comes primarily from the predicted evolution of main magnetic field given by the International Geomagnetic Reference Field, version 13 (IGRF-13), that forecasts a maximum increase of the south hemisphere magnetic field strength in this area. Besides, the "Institut de physique du globe de Paris" (IPGP) already runs a volcanic obser-
- 55 vatory in La Réunion to monitor the Piton de la Fournaise volcano. The scientists and technicians of the volcanic observatory eased the installation of the magnetic observatory and furthermore provide the required scientific and technical expertise to perform the weekly handmade calibration measurements. The presence of the magnetic observatory on this island is also a new asset for processing magnetic surveys or variometer station data acquired for monitoring the volcano activity.
- 60 In the next section the new observatory location and setting are described. In section 3 the data processing applied on the vector data to estimate the field on the observatory reference pillar is presented. In the following section are shown results of







Figure 1. Map of magnetic observatories in the Indian Ocean that have released data in recent years.

one full year of data acquisition. Definitive data for year 2023 are presented and analyzed. The last section is dedicated to the conclusion.

2 La Réunion observatory setting

- 65 The La Réunion island is a volcanic Island in the Indian Ocean, presenting large magnetic anomalies and gradients, due to strongly magnetized rocks. Several sites were considered for setting the magnetic observatory on the "plaine des caffres", a smooth and relatively flat area, south of the Island, between the 2 volcanoes. Aeromagnetic surveys were flown showing relatively low gradients in the area. The observatory installation was achieved within one year in 3 steps: surveys of potential sites, pillars construction and eventually equipment installation. The chosen site at 21°12'21.2" S, 55°34'35.3" E and 1580 m
- 70 altitude, is as isolated as possible and situated at 500 m from the volcanic observatory, where observers trained for calibration measurements and basic maintenance are available. The land is owned by the national forestry office. A 9-year agreement has been signed between our institutes. The installation needed to be as little intrusive as possible but autonomous. The area in this forest has little elevation change, is not dense and no endemic trees are present allowing us to clear the surrounding vegetation to guarantee the sun exposition of solar panels. Without magnetic constraints, one visual target was installed on a
- 75 single concrete pole for geographical reference at a distance of about 40 m from the measurement pillar. As secondary target, a natural peak on the volcano at around 5 km away is used. A good grounding and strong attach to ground of the built infrastructure has been necessary to avoid lightning strikes and to provide good resistance to hurricanes. The constructions are free from ferromagnetic (or magnetic) materials. Materials were tested using a magnetometer before use or installation. Fibered





reinforce concrete was used in place of the usual iron-reinforced concrete.

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Three types of data are collected on the observatory site:

- Variation vector magnetometer data:
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The vector magnetic field is sampled at 1 Hz, using a DVM-19 full range three-axial fluxgate instrument built in the Chambon-la-forêt French national observatory. This instrument has a relatively low noise level ($< 15\text{pT}/\sqrt{Hz}$) and can be rigorously calibrated thanks to its full-range ($\pm 70 \ \mu\text{T}$) capabilities. It has, as all fluxgate instruments, a dependence on temperature that is of the order of 300 pT/°C. The instrument is seated on the "variometer" pillar and because of possible movements of the pillar or slight temperature variations, the collected data cannot be seen as absolute data. The data collected form the variation vector data. The variometer pillar is small (~ 40 cm above ground). This reduces possible pillar movements but it sets the magnetometer in a volume strongly influenced by the local magnetic field generated by the surrounding rocks.

- Variation scalar magnetometer data:

The scalar instrument is a Geomag SM90R, Overhauser-type, scalar absolute magnetometer sampling the magnetic field at 0.2Hz. These types of instruments are sensitive to magnetic field gradients, and therefore it has been set at 1.7m above ground, away from the vector magnetometer reducing, this way, possible interference between the two instruments. These types of data are called the variation scalar data.

- Handmade absolute measurements:

The handmade absolute data are collected on the observatory main pillar using a Bartington Mag01H single-axis fluxgate magnetometer probe mounted on a Zeiss 010A non-magnetic theodolite. Each data is a combination of a series of eight handmade Declination and Inclination measurements. The data angles are completed with absolute measurements of the magnetic field strength. The technique used has been described for example in Newitt et al. (1996). These types of data are collected at least once a week.

As partly described above, to set the instruments two pillars in fibered concrete were build. A large and deep one, at chest height, for absolute calibration measurements and, 30m away, a small one to rest the variation vector magnetometer in a box on the ground, that is also filled with water bottles for increased temperature stability. The full field scalar magnetometer sits

- 105 on a 1.7m tall mast, fixed in concrete and covered in a PVC tube. This variometer pillar, the variation scalar magnetometer site and their respective electronics are roughly 6m from each other, forming a triangle shape (See picture in Figure 2). Vector and scalar data are acquired by an IPGP ENO4 data logger, which is based on a beaglebone platform, and transmitted to the Paris main servers via GSM signal, typically every 5 minutes although a qtt real-time transmission protocol is integrated and used for monitoring purpose. The observatory has been designed to require low electric power and to be autonomous in power and
- 110 communication with a single solar panel and a GSM transmitter placed 25m away from the sensors.







Figure 2. Picture showing the La Réunion observatory layout. In front, the absolute pillar during a training session with in the background, from left to right, the grey concrete pole with the azimuth target attached, the meteorology type white box containing the sensors electronics, the grey vertical PVC tube partly hidden behind the trees containing the variation scalar magnetometer and the plastic box containing the variation vector magnetometer, covered with a thermal white blanket.





Variation data and absolute measurements started in December 2022. The island is subject to seasonal hurricanes/tropical cyclones, but the observatory did not suffer from the hurricane Belal in January, 15, 2024. Only GSM connection was down for a few days. There are no frequent thunder strikes in the area. We do not foresee major difficulties in the operation of this
observatory regarding its general infrastructure for the coming decade.

3 Data processing

3.1 Variation data and processing technique

The calibrated data distributed by the observatory are series of 1Hz variation vector magnetic data and 0.2Hz variation scalar data but estimated on the main observatory pillar site such that they fit the handmade measurements. The differences between the magnetic field strengths computed from the variation vector measurements and variation scalar data, as estimated on the main pillar, define a data quality criteria. These differences are expected to stay within ~ 1 nT around zero to meet the INTER-MAGNET quality standard (INTERMAGNET, 2020).

125 In the specific case of observatories installed in an area of strong magnetic gradient this criteria is particularly difficult to meet, even for time series of less than a day for which the pillars can be assumed to be steady and temperature variations to be negligible. Let us assume that the magnetic field at the variometer pillar is:

$$\mathbf{b}_{v} = \begin{vmatrix} x_{v} \\ y_{v} \\ z_{v} \end{vmatrix}, \tag{1}$$

where x_v , y_v and z_v are the three magnetic field orthogonal components in the magnetometer reference frame. The associated magnetic field strength is:

$$F_v = \sqrt{x_v^2 + y_v^2 + z_v^2},$$
(2)

but the strength of the field on the observatory main pillar is:

$$F_p = \sqrt{(x_v + \delta x)^2 + (y_v + \delta y)^2 + (z_v + \delta z)^2},$$
(3)

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where δx , δy and δz are the differences in the magnetic vector field on the main pillar relative to the field recorded on the variometer pillar, in the same reference frame. It can be assumed that these differences are constant in time, which is consistent with the assumption that the magnetic field gradient observed on site is exclusively due to the magnetization of local rocks and is not linked to external, induced or core field signals. It can be shown (see appendix A) that, to the first order in perturbations, the magnetic field strength difference between the recorded magnetic field at the variometer pillar and its value on the observatory



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main pillar is:

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$$\Delta F = F_p - F_v \simeq \hat{\mathbf{b}}_v \cdot \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}, \tag{4}$$

where $\hat{\mathbf{b}}_v = \mathbf{b}_v/F_v$ is the unit vector giving the magnetic field direction at the variometer pillar site. As the magnetic field on the variometer pillar changes in direction over time – e.g. due to the S_q system of currents in the dayside ionosphere, it is clear that ΔF changes with time even if δx , δy and δz are constant. The variations on ΔF over a day are generally small, but cannot be neglected for observatories set in areas of strong magnetic field gradients – i.e. where the δx , δy and δz values can reach a thousand of nanoTesla (nT) or more. This is the case for La Réunion observatory where the variometer pillar is small and

145 a thousand of nanoTesla (nT) or more. This is the case for La Réunion observatory where the variometer pillar is small and therefore where the surrounding rock magnetization contributes significantly to the recorded magnetic field components (see section 2). On longer term, for example a year, ΔF may change significantly with temporal variations of δx , δy and δz due to – e.g. temperature or environmental changes.

- 150 Keeping the daily ΔF variations within small values is a prerequisite for deriving definitive calibrated data in La Réunion observatory. A simple but efficient way to solve this problem is to set up a method for estimating the δx , δy and δz values in the sensor reference frame. This is precisely what the baseline estimation method presented in Lesur et al. (2017) does. We recall briefly this approach in the remaining of this section.
- 155 The calibrated magnetic vector field estimated on the observatory main pillar in a local geodetic reference frame is:

$$\mathbf{b}_{p} = \mathbf{R}_{\theta} \begin{bmatrix} x_{v} + \delta x \\ y_{v} + \delta y \\ z_{v} + \delta z \end{bmatrix},$$
(5)

where \mathbf{R}_{θ} is a rotation matrix for an angle θ , positive anti-clockwise, around the local vertical axis. There are four calibration parameters to be estimated, namely the θ , δx , δy and δz . We assume that θ takes a constant value over several months whereas the other parameters are taking constant values only over a single day. The vertical direction on the variometer pillar is assumed to be the same as on the main pillar. It follows that δz is independent from the θ angle, whereas the δx and δy depend strongly on this angle value. We note that the vector magnetic instrument is oriented such that its *x* component is roughly in the direction of the local magnetic North, and it follows that the θ angle is close from $(-1\times)$ the Declination angle¹ when the δx and δy parameters are small. However, that angle may be significantly different from the Declination when δx and δy parameters are large – i.e. when there are local strong gradients of the magnetic field on the observatory site.

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To estimate the calibration parameter values we require the calibrated magnetic vector field to fit the absolute observations made on the observatory main pillar. However, this is not a requirement strong enough to robustly estimate the angle θ , so

¹the Declination is positive clock-wise





we further require the calibrated magnetic vector field to fit hourly spot values of the magnetic field strength F_s estimated from the variation scalar data. This imposes to introduce a further parameter $\delta F = F_p - F_s$, also constant over one day, that describes the magnetic field strength difference between the main pillar position and the scalar variometer position. Assuming δF constant is equivalent to consider that the magnetic field gradients are small between these two positions. This is a valid approximation because the main pillar and the scalar proton magnetometer are at 1.5m and 1.7m over ground, respectively, and therefore are in an area of smaller magnetic gradients. This approximation can be however tested using an additional scalar magnetometer by recording the magnetic field strength simultaneously on the observatory main pillar and with the variation scalar magnetometer. This has been tested using data from the 23rd of June 2023, and difference variations do not exceed

500pT inside that day.

Let assume that we have a set of absolute data on the main pillar, and that a rotation angle θ is chosen, then, there are two types of equations that can be used to find the daily values of δx , δy , δz and δF :

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$$\begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix} - \begin{bmatrix} \tilde{x}_v \\ \tilde{y}_v \\ \tilde{z}_v \end{bmatrix} = \mathbf{R}_{\theta} \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} + \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \end{bmatrix}, \quad \text{with} : \begin{bmatrix} \tilde{x}_v \\ \tilde{y}_v \\ \tilde{z}_v \end{bmatrix} = \mathbf{R}_{\theta} \begin{bmatrix} x_v \\ x_v \\ x_v \end{bmatrix}, \quad (6)$$

and

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$$F_{s} - F_{v} = \hat{\mathbf{b}}_{v} \cdot \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} - \delta F + \epsilon_{s}, \tag{7}$$

where x_a, y_a, z_a are the three components in a geodetic reference frame of the magnetic field vector derived from of the hand-made absolute measurements of the Declination, Inclination and total field strength on the reference pillar of the observatory.
185 ε_x, ε_y, ε_z and ε_s are the errors that should reduce to observation errors once the δx, δy, δz and δF values have been adjusted. ε_s includes also the errors associated with the linearization in equation (4).

The variances of the errors in the right-hand side of equations (6) and (7) are minimized iteratively by adjusting δx, δy, δz and δF, where the iterations combined with a classic re-weighting approach allow to handle the weak non-linearity in equation (7)
as well as the possible non-gaussian distributions of residuals (see e.g. Farquharson and Oldenburgh, 1998). We observe that the quality to the fit to the data depends heavily on the chosen θ angle value.

3.2 Application to La Réunion observatory data

The first step required to process the data is to estimate the θ angle. For this we define a data set that includes handmade absolute measurements x_a, y_a, z_a and the total intensity measurements F_s sampled every two hours, from January the 1st to

195 June the 7^{th} , 2023. The data set is shown in Figure 3. Calibration data, in green, can be compared with variation vector data at the same instant, in red, indicating large magnetic gradients on the observatory site, although the reference frames for the







Figure 3. Data sets, top row X and Y components, bottom row Z component and total intensity data. In black are shown variation data decimated to one point every 2 hours and in red are shown variation data at the reference times corresponding to the calibration data. Scales are on the left-hand side of the figures. In green are shown the calibration data for the X,Y and Z component, and $F_v - F_s$ for the total intensity data. Scales are on the right-hand side of the figures. The X and Y axis of the calibration data are in geodetic reference frame, but are in the instrument reference frame for variation vector data.

variation vector data and the calibration data are different. The magnetic field strength differences $F_v - F_s$ are of the order of 675 nT, they show variations that can exceed 2 nT during a single day.

200 Our ability to minimise the left-hand side of equations (6) and (7), by adjusting the δx , δy , δz and δF values, has been tested for θ values in the range [0:45] degrees. Results are shown in Figure 4 where the misfits for the horizontal, vertical and total







Figure 4. Misfits to data as a function of the θ rotation angle. The misfits for the horizontal component are shown in purple, misfits for the vertical component in green, misfits for the total intensity in blue. The misfit definitions are given in equations (8).

intensity are defined by:

$$M_{H} = \sqrt{\sum_{\{i\}} (\epsilon_{xi}^{2} + \epsilon_{yi}^{2}) / \sigma_{i}^{2}} ,$$

$$M_{Z} = \sqrt{\sum_{\{i\}} \epsilon_{zi}^{2} / \sigma_{i}^{2}} ,$$

$$M_{F} = \sqrt{\sum_{\{i\}} \epsilon_{si}^{2} / \sigma_{i}^{2}} ,$$
(8)

respectively, where the errors ϵ are defined in equations (6, 7), and σ_i^2 are the expected variances of the corresponding errors.

205 The quantities M_H , M_Z and M_F in equations (8) are unitless and the summations are over all available calibration measurements. Figure 4 shows that the smallest misfit to the data can be achieved for $\theta = 22.0^{\circ}$. For this angle, the values of δx , δy , δz and δF range in the intervals [-2402: -2391] nT, [322: 366] nT, [-21: -8] nT and [-715.5: -713.2] nT, respectively. These ranges are large, particularly for δy and δz . This occurs because we used an L₂ norm minimizing process that does not down-weight outliers. It is however obvious that the ΔF variations inside a day, defined by equation (4), are due to the very

210 large δx values.

In order to produce in near-real time data with ΔF values nearly constant over a day, we decomposed the calibration process leading to definitive data values for this observatory in two steps:



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- (i) Apply in near-real time a first correction with δx_1 , δy_1 , δz_1 , δF_1 and θ_1 values, constant over a year. These data are distributed five to ten minutes after acquisition as observatory variation data.
- (ii) Apply a second correction with δx_2 , δy_2 , δz_2 and δF_2 varying from day-to-day, but being constant over a day. The value of θ_2 remains constant over the full year and is, for 2023 and 2024, such that $\theta_1 + \theta_2 = 22^{\circ}$. These data are distributed in the following year as observatory definitive data.

The offset values δx_1 , δy_1 , δz_1 , δF_1 can be set arbitrarily, but in order to have ΔF variations that remain small over a day, they should have values close to the δx , δy , δz , δF intervals given above. We use:

$$\delta x_1 = -2400 \text{ nT} \quad \delta y_1 = 280 \text{ nT} \delta z_1 = -20 \text{ nT} \qquad \delta F_1 = 0 \text{ nT},$$
(9)

for an angle value $\theta_1 = 0.95^{\circ}$. This latter value has been set arbitrarily, but controls the values obtained for δx_1 and δy_1 . To illustrate the effect of the step (i) the bottom-right image of Figure 3 is shown again in Figure 5, but with the offsets applied to the variation vector data. Typical values of the magnetic field strength differences $F_v - F_s$ have changed from around 675

 $rac{1}{225}$ nT to -713 nT and although overall variations have similar trend and amplitude, it is clear that short-time variations have been drastically reduced within a day.

The baseline daily values: δx₂, δy₂, δz₂ and δF₂, are estimated using the same algorithm described in section (3.1), in 10 iteration, with a θ₂ value set to a constant value θ₂ = 21.05°. We used a data set made of 108 absolute Declination, Inclination and total Intensity measurements collected between 02/01/2023 and 29/01/2024, typically one double measure per week, to estimate x_a, y_a and z_a values. We assumed that these absolute data have standard variations of 0.05°, 0.025° and 1 nT in Declination, Inclination and total Intensity, respectively. Field strength difference F_v - F_s values in equation (7) are minimized at 02h00 in the morning and 22h00 in the evening, for each day over the year. Standard deviations for variation scalar and vector data were all set to 400pT. The derived baseline values were assumed to be uncorrelated random variables following normal distributions. The expected mean values were set to 50 nT, 35 nT, 40 nT and -715.5 nT for δx₂, δy₂, δz₂ and δF₂, respectively. Variances were set to 50 nT² for δx₂, δy₂, δz₂ and 3 nT² for δF₂. Details on the algorithm and on the way these variances can be estimated are given in Lesur et al. (2017).

The estimated baseline values are shown in Figure 6 in a HDZF format (Horizontal component, Declination, Vertical down component and Total intensity). The baseline data values H_0 , D_0 , Z_0 and F_0 , shown in red are linked to equations (6,7) by:

$$H_{0} = \sqrt{x_{a}^{2} + y_{a}^{2} - \tilde{y}_{v}^{2} - \tilde{x}_{v}}$$

$$D_{0} = \arctan(y_{a}/x_{a}) - \arctan(\tilde{y}_{v}/(H_{0} + \tilde{x}_{v}))$$

$$Z_{0} = z_{a} - \tilde{z}_{v}$$

$$F_{0} = F_{s} - F_{v}.$$
(10)







Figure 5. Total intensity values sampled every two hours are shown in black (left scale), and in green $F_v - F_s$ (right scale) where the rotation and offsets given in equations (9) have been applied to the raw data.

We observed that the baseline values drift rapidly around mjd= 8680 (i.e. October 2023) very likely due a change of environment around the variometer pillar associated with rain or wind. Small pillar movements are possible as the observatory infrastructure has been built only a year before, over 2022.

245 3.3 Definitive data for year 2023

Definitive data, estimated from the variation vector data using the baseline values of Figure 6, are presented in Figure 7. The horizontal component presents the expected large amplitude fast variations that are associated with perturbations of the ionosphere-magnetosphere system by the sun activity. There is nonetheless a small trend of increasing intensity by roughly 50nT over 2023. The trend is even stronger on the vertical component that increases by around 100 nT in absolute value in the

- 250 year. The combined effect of these variations produces an increase of the magnetic field strength approximately from 39420 nT to 39530 nT i.e. an annual variation of the order of 100 nT/y that corresponds roughly to what was predicted by the International Geomagnetic Reference Field (IGRF) version 13 (Alken et al., 2021): 104 nT/y in 2023. For this same IGRF, and same location as the observatory, the expected variation in the vertical component is largely underestimated and so is the expected variation in Declination. The values of the field components as provided by the IGRF model, differ also significantly
- from the measured values. The IGRF gives on 2023-06-01: -19.515° in Declination, 22690 nT in the Horizontal component,







Figure 6. Estimated baseline values of La Réunion observatory, presented in a HDZF format, for year 2023. In red are shown the values derived from absolute observations and in black the estimated daily values.

-31458 nT in the Vertical component and 38787 nT in Total intensity. The observed differences are easily explained by the strong lithospheric signal generated by the surrounding volcanic rocks that is not accounted for in the IGRF.

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On the same Figure 7 the bottom right plot presents also, in green, the calculated ΔF values for the year. The scale is given on the right side of the plot. Values vary well inside 1 nT around zero. This is a clear indication that the process applied to estimate the baseline values is a success.

As a final test to assess the quality of the observatory recorded signal, we computed the Discrete Fourier Transform (DFT) amplitude spectra of the vertical and horizontal components of the observed, de-trended, magnetic field variation second-data over six months from July to December 2023 (see Figure 8). Over this time interval, only 5 consecutive second-data records







Figure 7. Estimated definitive hourly mean magnetic data at La Réunion observatory. The data are presented in a HDZF format, for the whole year 2023. In green are shown the ΔF values derived from the hourly means of the vector and scalar values. The corresponding scale is shown on the right side of the plot.







Figure 8. DFT amplitude spectra derived from time series of second-data recorded in La Réunion magnetic observatory, from 1^{st} of July 2023 to the 31^{st} of December 2023. Left, spectrum derived from the vertical down component, Right, spectrum derived from the horizontal component.

were missing. The gap has been filled by linear interpolation. Of course, as only variation data have been used, the time series have not been treated to remove possible anthropological noise, and furthermore the longest periods of the spectra are not reliable as the baseline correction has not been applied. Strong peaks are obvious at periods of 24h, 12h, 8h, 6h, 4.8h and 4h (see also Figure 9 for a zoom on periods range from 4 hours to 13 hours). These periods correspond to the S1 to S6 Solar diurnal tidal constituents (see e.g. Love and Rigler (2014) regarding tidal signals in observatory data). However, in magnetic data these peaks result mainly from the rotation of the Earth inside the magnetosphere combined with the signal associated with the S_q system of currents in the Ionosphere. There are no other clear tidal periods peaking out of the spectra outside, possibly, at 12.42 hours for the M2 (Lunar semi-diurnal) tide in Figure 9 (Left). However, this period does not correspond to a peak in the horizontal component spectra. There are few peaks in the lowest periods of Figures 8, in particular for a period of 5 seconds. This is clearly due to a cross talk of the scalar/vector electronics as 5 seconds is our sampling period for scalar

variometer data. At even shorter periods the spectra collapse due to the filtering of the lowest periods applied to second data, as recommended in INTERMAGNET (2020). Overall this Fourier analysis does not reveal major difficulties in the observatory data. There is a relatively low level of anthropological noise at the La Réunion observatory site.

4 Conclusions

280 We shortly presented the setting, location and data processing algorithms and results of the La Réunion Island observatory. This observatory has been set to fill a geographical gap without magnetic observatory in the Indian Ocean. Calibrated data have been estimated for the full year 2023.







Figure 9. Zoom in the 4 to 13 hour period interval of the DFT amplitude spectra derived from time series of second-data recorded in la Réunion magnetic observatory, from 1st of July 2023 to the 31st of December 2023. Left, spectrum derived from the vertical down component, Right, spectrum derived from the horizontal component.

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As other observatories situated on a volcanic island, the magnetic field generated by local rocks is strong and presents large gradients. We have shown that one of the effects of these gradients is a variation during a single day of the differences of field strength between two sites only few meters apart. To reconcile the magnetic field strength observed on the variometer pillar by the vector instrument with the magnetic field strength measured by the variation scalar magnetometer, one has simply to estimate the large local contributions to the observed vector magnetic field of the magnetized rocks. These estimates do not have to be very accurate and in the case of La Réunion observatory they are of -2400 nT, 280 nT and -20 nT in the X, Y and 290 Z vector component respectively, in the sensor reference frame.

The obtained calibration parameters – i.e. the "baseline values", show a strong drift within the year 2023, particularly during the month of October. This is very likely due to the fact that pillars have been built only recently on the observatory site. We therefore expect the baseline values to stabilise and present only minor drifts in the years to come. For 2023, we are however confident that the definitive observatory vector data are reasonably accurate as the drift of the δF values remain weak, and the fit to the absolute observation is good.

The IAGA code given to this observatory is : REU.

Data availability. Definitive and variation data derived from La Réunion (REU) observatory are available on www.bcmt.fr





300 Appendix A: Derivation of equation (4)

The total intensity on the variometer pillar is:

$$F_v = \sqrt{x_v^2 + y_v^2 + z_v^2},$$
 (A1)

whereas on the observatory main pillar it is:

$$F_p = \sqrt{(x_v + \delta x)^2 + (y_v + \delta y)^2 + (z_v + \delta z)^2}.$$
(A2)

305 The latter quantity can be approximated by:

$$F_p \simeq \sqrt{x_v^2 + y_v^2 + z_v^2 + 2(x_v\delta x + y_v\delta y + z_v\delta z)},\tag{A3}$$

where terms in second order of δx , δy or δz are neglected. It follows that:

$$F_p \simeq F_v \sqrt{1 + 2(x_v \delta x + y_v \delta y + z_v \delta z)/(x_v^2 + y_v^2 + z_v^2)},$$
(A4)

or alternatively:

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$$F_p \simeq F_v [1 + (x_v \delta x + y_v \delta y + z_v \delta z) / F_v^2], \tag{A5}$$

where the quantity $(x_v \delta x + y_v \delta y + z_v \delta z)/F_v^2$ is assumed to be small. Here again, higher order terms are neglected. The difference $F_p - F_v$ is therefore:

$$F_p - F_v \simeq (x_v \delta x + y_v \delta y + z_v \delta z) / F_v, \tag{A6}$$

and noticing that the right-hand side of equation (A6) is the result of a vector scalar product, equation (4) follows. The same result can be obtained by simply using a first order Taylor series for the total field intensity at the main observatory pillar:

$$F_p \simeq F_v + \frac{\partial F_v}{\partial x_v} \delta x + \frac{\partial F_v}{\partial y_v} \delta y + \frac{\partial F_v}{\partial z_v} \delta z.$$
(A7)

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