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The procedure for preparing one-second variometer data of the Argentine Island geomagnetic observatory

Abstract. Magnetic observatories have been and continue to be basic elements for studying historical and contemporary changes in the Earth's geomagnetic field. In most cases, satellite data are used to characterize and study rapidly evolving processes in near-Earth space. However, in recent decades, data from ground-based observatories have been used to support satellite missions. These data must have high temporal resolution to analyze rapidly changing processes. Furthermore, processed data from observatories should be delivered with minimal delay. Advances in technology now allow geomagnetic observatories to be equipped with high-resolution instruments, enabling the rapid delivery of final data. This paper outlines the methods developed to obtain one-second ImagCDF data of the Quasi-definitive level using the geomagnetic records of the Argentine Island observatory (INTERMAGNET code AIA). The observatory's state-of-the-art equipment and absence of anthropogenic noise produce results that meet the INTERMAGNET requirements. The primary data were validated by analyzing the distribution of instrumental errors in the absolute measurements. The quality of the difference in the field's absolute value was assessed using statistical parameters, including the mean, standard deviation, and the absolute value of the maximum deviation. Peak and irregular noise values were identified by analyzing the results of numerical differentiation of the 10 Hz records from the LEMI-025№63 and the difference signals between this magnetometer and the proton magnetometer POS-1. Regular noises were identified from the signal spectra. Occasional spikes in the POS-1 readings were corrected by interpolating data between valid counts. One-minute temperature data of the sensor and electronic unit of the LEMI-025№63 variometer were aligned with the magnetic records (using identical digital filtering and resampling procedures). The data were processed using software recommended by INTERMAGNET.

Keywords: absolute observations, geomagnetic observatory, fluxgate magnetometer, proton magnetometer

1 Introduction

Experimental continuous measurements of magnitude (or scalar intensity) and variational components of the geomagnetic field in observatories are widely used to develop maps of the geomagnetic field's intensity and anomalies based on ground, surface, aerial, and satellite surveys.

High-temporal-resolution (one-minute, one-second) variational data are used to study rapidly evolved processes occurring in near-Earth space. The ionospheric and magnetospheric processes are so rapid that satellite data alone are sometimes insufficient to describe them, necessitating observatory data from the Earth's surface. The forecast of magnetic disturbances, which is currently quite relevant, will be more reliable when higher-cadence data are used.

The magnetic observatory Argentine Island (INTERMAGNET code AIA) performs continuous measurements of the force and angular components of the geomagnetic field, which are widely used for leveling and developing digital maps of the module and anomalies of the induction module of the geomagnetic field and studying how it changes over time and how magnetic disturbances manifest there compared with other regions of the Earth (Orlyuk & Romenets, 2008; Orlyuk & Romenets, 2018). The records are sent to the INTERMAGNET network. The scientific community can use them to solve a number of fundamental and applied problems of geomagnetism. Such problems include developing the IGRF-DGRF model of the Earth's normal magnetic field, the assessment of spatiotemporal variations of the geomagnetic field, including magnetic disturbances linked to solar activity, and evaluating the ecological state of the environment, among others (Orlyuk & Romenets, 2020).

A geomagnetic observatory of the INTERMAGNET network has to continually record components of the Earth's magnetic field with a certain accuracy and a minimal frequency of one measurement per minute. Daily packets of these primary one-minute data must be sent to the relevant Geomagnetic Information Node (GIN) within 72 hours (St-Louis, 2024).

In 2003, the meeting of the INTERMAGNET's Operations Committee and Executive Council in Dourbes, Belgium decided to introduce recording variometric data with a sampling rate of 1 Hz in addition to the one-minute records (Rasson, 2008).

This initiative emerged in response to the space physics community's demands for real-time space weather forecasts and for monitoring and modeling different electrical current systems in the Earth's ionosphere and magnetosphere (Macmillan & Olsen, 2013; Friedel et al., 2017; Iovannitti et al., 2019). One-second magnetic data were also useful for subsurface sounding (Di Mauro et al., 2009). In 2005, a survey confirmed the demand for one-second data, which should have become available in the INTERMAGNET network, and the desire to standardize device parameters and data quality, similar to the one-minute data. The relevant INTERMAGNET sub-committee developed such a standard. It was introduced in 2012 (Turbitt et al., 2013). Later, the requirements were made more precise for one-second data of the Definitive level (Turbitt, 2014). To archive and transfer such data, including auxiliary measurements and metadata a new data format, ImagCDF, based on the NASA CDF format, was introduced in 2017 (Flower, 2017).

In 2006, the Lviv Centre of Institute for Space Research (LCISR) initiated the design of an observatory magnetometer for one-second measurements (Korepanov et al., 2007). The end result was the LEMI-025 variometer installed at many geomagnetic observatories of Belgium (Royal Meteorological Institute of Belgium), Great Britain (British Geological Survey), Austria (Zentralanstalt fur Meteorologie und Geodynamik – the main variometer of the Conrad observatory), Italy (Istituto Nazionale di Geofisica e Vulcanologia), Spain (Instituto Geografico Nacional), Germany (Ludwig Maximilians University of Munich – the main variometer of the Furstenfeldbruck observatory), SAR (South African National Space Agency), Finland (Finnish Meteorological Institute and the University of Oulu) (Rasson et al., 2014; Nahayo et al., 2019; Marusenkov et al., 2019).

Currently, there are four grades of data sent to the network (St-Louis, 2024):

1. Variation or Reported: the raw, unadulterated records.

2. Provisional or Adjusted: some editing done (such as filling in the blanks in the measurements, deleting the outliers, and using the preliminary baselines if possible).

3. Definitive: the final data with no more expected changes.

4. Quasi-definitive: the data are more precise than the Provisional level but are sent into the GIN within three months of recording, which is much faster than the Definitive data.

This fourth grade, Quasi-definitive, was the most recently introduced (Peltier & Chulliat, 2010) to support some scientific efforts such as the joint processing of magnetic measurements during the Swarm satellite mission. Such data have to meet the three requirements (St-Louis, 2024):

a) they were corrected using the most precise available temporary baselines;

b) they become available less than three months after first recorded;

c) the average monthly difference between the Quasi-definitive and Definitive data for any of the X, Y, or Z components is less than 5 nT for every month of the year. This requirement is checked *a posteriori* by comparing the relevant files for the previous year.

Since 2011, some observatories have begun to send in Quasi-definitive data; by 2019, there were around 80 such observatories (Lewis, 2020). In 2021, 44 observatories decided to send in the Definitive one-second data (30 of them do it regularly).

In our opinion, the AIA geomagnetic observatory of the Ukrainian Antarctic Akademik Vernadsky station is capable of sending in high-quality one-second data given its geographic position, recent equipment updates, and removal of several local sources of noise and environmental influences.

2. Materials and methods

2.1 Data

Our study analyzed records of the Earth's magnetic field collected at the AIA geomagnetic observatory of the Akademik Vernadsky station. The data, gathered between December 2022 and October 2023, were obtained using a novel magnetometric complex comprising the fluxgate magnetometer LEMI-025№63, the proton Overhauser magnetometer POS-1, and a personal computer with an adapted Debian 9.6 operating system with specially developed software.

2.2 Methods and approaches

INTERMAGNET provides two examples of preparing the Quasi-definitive data: a daily procedure (Clarke et al., 2013) and a monthly one (Peltier & Chulliat, 2010). We based our research on the monthly one.

Processing the AIA's absolute measurements and analyzing the baselines of the LEMI-025№63 variometer were conducted using two techniques recommended for the INTERMAGNET observatories. Special attention was paid to verifying the primary data by analyzing the distribution of instrumental errors.

As in (Peltier & Chulliat, 2010), the set of baseline values for every component of the variometer was approximated by a cubic smoothing spline. This approximation algorithm was proposed by Carl de Boor (De Boor, 2001). The function for this is available in different programming languages, in this study the Python version was used [https://csaps.readthedocs.io/en/latest/formulation.html].

The robustness of the LEMI-025№63 output was tested against the raw POS-1 records. The three orthogonal components of the LEMI-025№63 readings were used to calculate the absolute value of the magnetic field. Such comparison (the so-called ΔF test) is a data control method for the geomagnetic observatories' measurements (St-Louis, 2024).

The quality of the total field difference ΔF signal was evaluated using statistical parameters as the mean, standard deviation, and the absolute maximum deviation.

For the re-discretization of digital signals (e.g., from 10 Hz to 1 Hz, from 1 Hz to 1/60 Hz), we used low-frequency digital filters with impulse response parameters and coefficients recommended by INTERMAGNET (St-Louis, 2024; Appendix F).

Appendices A and B1-B3 describe the programs applied for data processing and instructions for how to work with them.

3. Results

3.1 Processing absolute measurements

Since March 2022, the absolute measurements have been done using new equipment: the non-

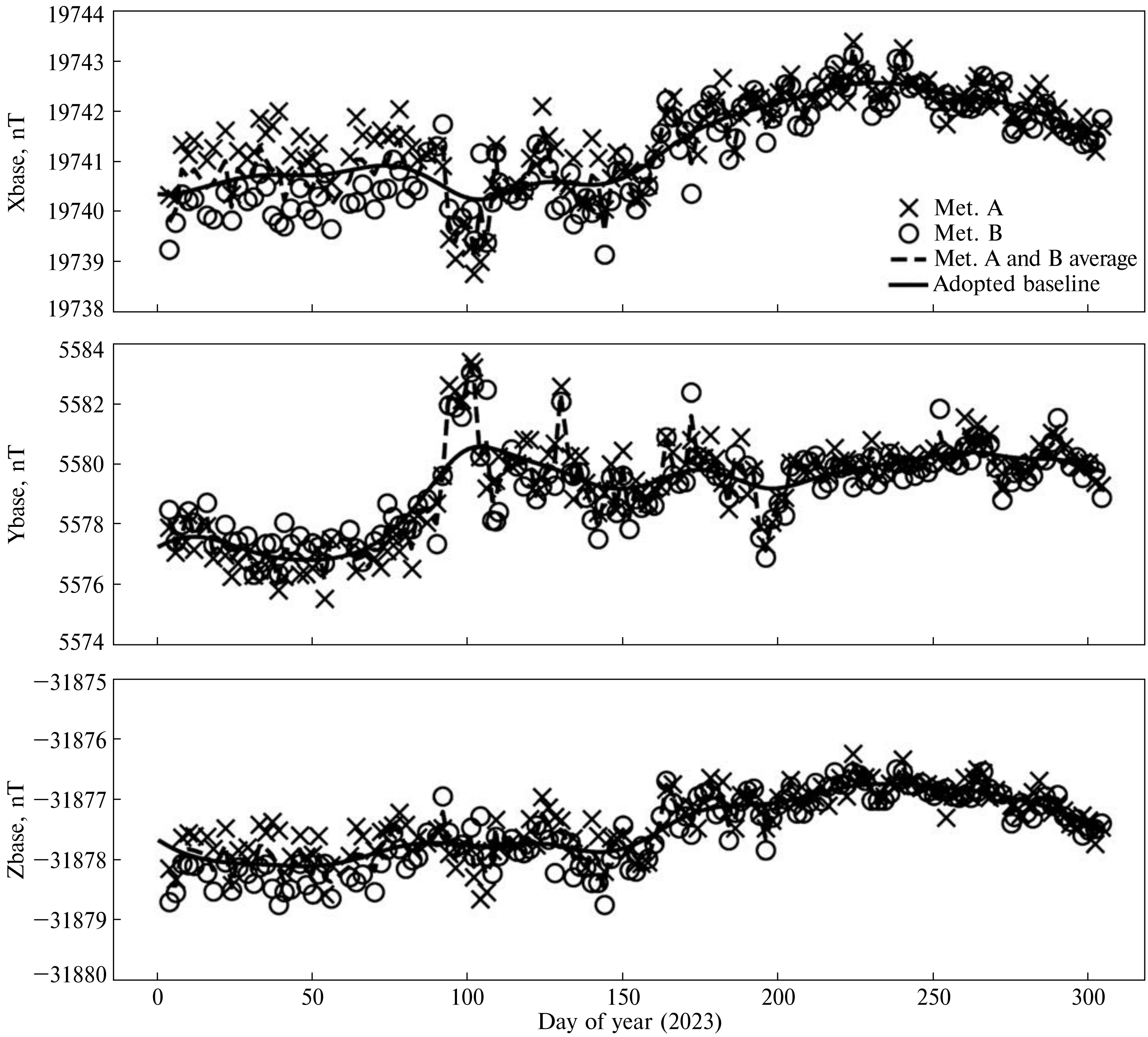

Figure 1. Baseline components of the LEMI-025№63 variometer from January to October 2023. Absolute observations for method A are marked with "×", and for method B – with circles; dashed lines represent the averaged results for methods A and B, and solid lines show spline approximations for baselines

magnetic theodolite Wild T1 with a MagA fluxgate sensor and electronics unit of the Mag-01H magnetometer installed on its telescope (Sumaruk et al., 2022). The new theodolite allowed the team to measure the angles more precisely and easily than the old THEO-020B. The absolute measurements were done by two methods, A and B (the null method and the residual method) (Worthington & Matzka, 2017; Sumaruk et al., 2022). The absolute value of the magnetic field's induction was measured by a proton magnetometer PMP-8 on a separate pillar in the Absolute Measurement Room. Another proton magnetometer (POS-1) was operated in a different room. To adjust the magnetometers' readings with the theodolite's position, we used the following gra-

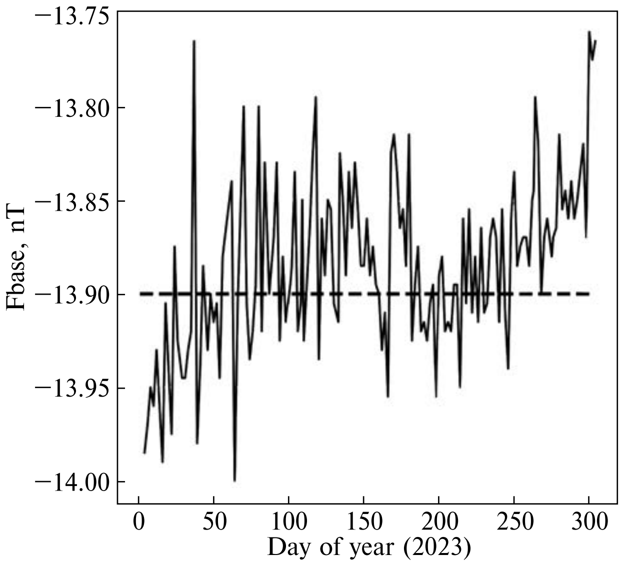

Figure 2. Baseline values of the POS-1 scalar magnetometer from January to October 2023. The solid line represents the averaged values for the methods A and B, the dashed line is the adopted baseline

dients between pillars: P1 = +3.35 nT to correct the PMP-8 readings, and P2 = −13.85 nT to correct the POS-1 readings.

The processing was done for a series of 15—18 sets of absolute measurements collected over a month. Together with calculating the baseline values of the three components (X, Y, Z) of the LEMI-025№63 variometer, we evaluated the difference values for the absolute values of the field using the readings of the two scalar magnetometers (PMP-8 and POS-1), the calculated values for the LEMI-025№63 variometer, and the error of the DI-magnetometer (the non-magnetic theodolite Wild T1 with the fluxgate magnetometer Mag-01H). For some days of the year (days 2, 14, 20, 58, 60, and 100), the absolute measurements did not agree with the general dataset; these data were not included in further analysis.

Further calculations yielded an approximation of baseline values using cubic smoothing splines (with the **csaps** function of the Python programming language, [https://csaps.readthedocs.io/en/latest/formulation.html]). Similar to previous years, the smoothing parameter for all three components was set up as $p_x = p_y = p_z = 0.0003$. The baseline values and baselines are shown in Figure 1. Notably, methods A and B gave dissimilar baseline values for the X and Z components in the first months of 2023.

The plot for the averaged baseline values of the scalar magnetometer POS-1 is shown in Figure 2. Since the baseline values remained relatively stable from January to October, a constant value of −13.9 nT was chosen as an approximation.

3.2 Applying the baselines

To the Variation (Reported) data processed in **testcorr**, we applied the baselines from the file **aia2023.blv** and drew up one-second and one-minute Quasi-definitive files in the IAGA-2002 format. We then plotted the results in **Xmagpy** (Fig. 3). The same program calculated the difference in the field's absolute value from the results of the variometer and the scalar magnetometer (the lower plot DELTA F, in Fig. 3).

The parameter is within ±1 nT, confirming the correctness of the applied baselines. Some deviation at the start of the year is probably connected to the gradual transition from the values for December 2022, calculated from the absolute measurements only for method A. As discussed above, in the first months of 2023, baseline values for the X and Z components obtained by method A differed somewhat from the findings of method B. Therefore, the smoothed baselines calculated in 2023 using the two methods' averages do not completely agree with the smoothed baselines for 2022, obtained for method A only. The rest of the substantial deviations of the DELTA F signal occurred mostly during the geomagnetic field's disturbances, for example, on March 23—24 and April 23—24, 2023. There are also short-term deviations around 13:00 on March, 15, probably caused by local noise.

4 Discussion and conclusions

The records of the geomagnetic field's components must correspond as accurately as possible

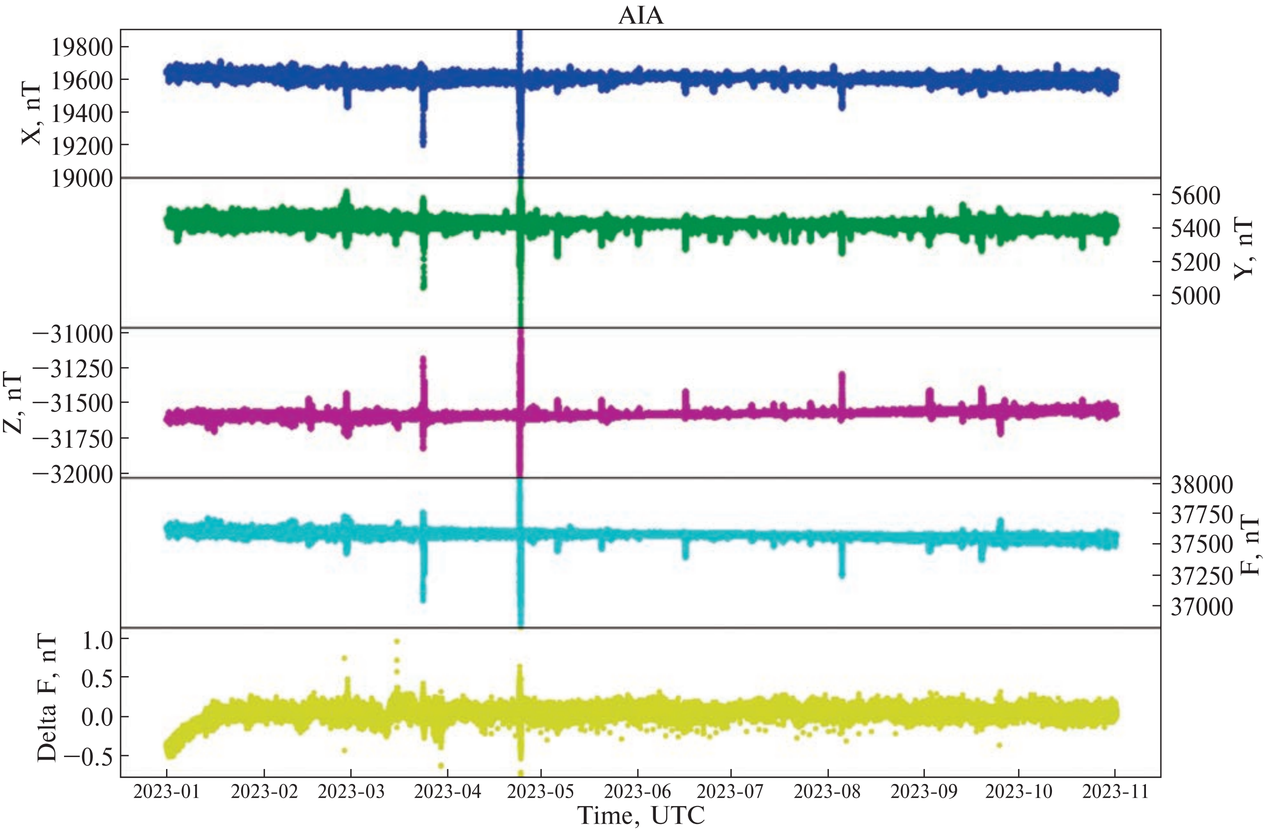

Figure 3. One-minute Quasi-definitive data (LEMI-025№63 and POS-1), plotted in **Xmagpy**

to their real values, requiring constant improvement and updates of hardware and software and algorithmic support. We describe how to obtain one-second ImagCDF data at the Quasi-definitive level using the geomagnetic records of the AIA. The observatory variometer's robustness was checked by comparing the output of the POS-1 proton magnetometer with that of the LEMI-025№63 variometer. The POS-1 data were read directly from the device, but the absolute value of the magnetic induction obtained by the LEMI-025№63 variometer was calculated from the three measured orthogonal components.

The absolute measurements carried out at the Akademik Vernadsky station were processed using two methods recommended for INTERMAGNET observatories. The analysis of the baselines of the LEMI-025№63 variometer also accounted for these recommendations.

The primary data were verified by analyzing the distribution of instrumental errors in absolute observations.

The baseline values of the variometer were approximated by a cubic smoothing spline.

By comparing the readings of the POS-1 proton magnetometer with the readings of the LEMI-025№63 variometer, the variometer's stability was checked. The POS-1 data were used directly, and the LEMI-025№63 data were used to calculate the magnetic field scalar intensity from the readings of the three orthogonal components of the variometer.

The quality of the total field difference signal was evaluated using such statistical characteristics as the mean, the standard deviation, and magnitude of the maximum deviation.

Excessive noise and irregular interference were detected by analyzing the results of numerical differentiation of 10 Hz LEMI-025№63 recordings and the difference signals between this magnetometer and the POS-1 proton magnetometer. Regular noise was detected by analyzing the signal spectra.

By interpolating the data between the correct readings, the spikes in the POS-1 measurements were corrected.

The formation of one-minute temperature data of the fluxgate sensor and the electronics unit of the LEMI-025№63 variometer was performed in accordance with the formation of magnetic records, i.e., using identical procedures for digital filtering and resampling.

The data were processed using the software recommended by INTERMAGNET.

The combined application of the above procedures and methods made it possible to develop a methodology for calculating one-second geomagnetic observation data of the Quasi-definitive level in the ImagCDF format using the magnetometer system of the AIA geomagnetic observatory.

Data collected by the new equipment of the AIA geomagnetic observatory were analyzed and corrected. Interference in the POS-1 proton magnetometer records and the LEMI-025№63 fluxgate variometer records was eliminated.

Absolute measurements were recalculated after applying the aforementioned correction procedures. As a result, one-second data of the Quasi-definitive level of the new magnetic measuring complex (LEMI-025№63 and POS-1) were prepared in the ImagCDF format.

The methodology for processing magnetic data was developed, further improving the quality of data transmitted from the Akademik Vernadsky station to the international network INTERMAGNET.

The main magnetic and auxiliary temperature data recorded at the AIA geomagnetic observatory are presented in the ImagCDF format for the first time. One-minute and one-second magnetic data quality meets INTERMAGNET requirements for the Quasi-definitive and Definitive data.

According to a query on the website https://imag-data.bgs.ac.uk, no more than 11 (no more than 10%) INTERMAGNET observatories transmitted one-second data of the Quasi-definitive level in 2022—2023. Only one of these observatories (Papeete, French Polynesia) is located in the Southern Hemisphere, several thousand kilometers from the AIA. This suggests that the one-second Quasi-definitive data prepared in this study are likely the only ones in the Antarctic region.

Using modern software and algorithms, a technique for the comparative analysis of various processing procedures for the absolute measurement data, the search for and correction of mis-measurements was proposed and employed.

A software tool for visualizing and editing the ImagCDF files was used and adapted. This allows us to compute the total field difference (DELTA F), present the data in different coordinate systems (XYZ, HDZ, or DIF), correct the transformation and offset coefficients, remove the noisy sections, calculate the statistical parameters, and review and edit the metadata.

The data of the new magnetometer complex were analyzed and corrected. As a result, noise and spikes in the records of the proton magnetometer POS-1 and the fluxgate variometer LEMI-025№63 were removed. The total field difference (DELTA F) is within ±1 nT according to both magnetometers' findings, confirming the correctness of the applied baselines.

The absolute values of the magnetic field's components were re-calculated using the corrected data. This allowed us to reduce the scatter of the X, Y, and Z components obtained from the absolute measurements.

The high-quality one-second ImagCDF data of the Quasi-definitive grade as per the INTERMAGNET specifications were calculated.

Data availability. Not applicable.

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Реферат. Магнітні обсерваторії були і залишаються основними елементами вивчення вікових і сучасних змін геомагнітного поля на поверхні Землі. Для опису та дослідження швидкоплинних процесів, які відбуваються в навколоземному просторі, в більшості випадків використовують дані з супутників. Однак в останні десятиліття для підтримки супутникових місій використовують дані з наземних обсерваторій. Ці дані повинні бути високодискретними, щоб з їх допомогою проводити аналіз швидкоплинних процесів. Крім цього, оброблені дані з обсерваторій повинні постачатись якомога швидше. Завдяки технологічному розвитку стає можливим оснащувати геомагнітні обсерваторії високодискретними приладами та отримувати кінцеві дані з мінімальною затримкою. У статті описуються методи, розроблені для отримання односекундних даних ImagCDF квазідефінітивного рівня з використанням геомагнітних записів обсерваторії «Аргентинські острови». Сучасне обладнання обсерваторії та відсутність техногенних забруднень дають результати, які відповідають вимогам INTERMAGNET. Первинні дані перевірялись шляхом аналізу розподілу інструментальних похибок абсолютних вимірювань. Якість різниці абсолютного значення поля оцінювалася за такими статистичними параметрами, як середнє значення, стандартне відхилення та абсолютне значення максимального відхилення. Пікові значення шумів і нерегулярні шуми були виявлені шляхом аналізу результатів чисельного диференціювання 10 Гц записів LEMI-025№63 та різницевих сигналів цього магнітометра і протонного магнітометра ПОС-1. Регулярні шуми були ідентифіковані за спектрами сигналів. Випадкові скачки пристрою POS-1 оцінювались шляхом інтерполяції даних між правильними вимірами. Однохвилинні температурні дані датчика та електронного блоку варіометра LEMI-025№63 вибудовували відповідно до магнітних записів (тобто з ідентичними процедурами цифрової фільтрації та передискретизації). Дані оброблялися за допомогою програмного забезпечення, рекомендованого INTERMAGNET.

Ключові слова: абсолютні спостереження, геомагнітна обсерваторія, протонний магнітометр, ферозондовий магнітометр

APPENDICES

A. Programs testcorr and supfromtxt

For re-formatting, processing, and visualizing the data, we used the following software: **lemi025**, **testcorr**, **supfromtxt** (LCISR, Ukraine), **magpy** [https://github.com/geomagpy/magpy], **imcdview** [https://geomag.bgs.ac.uk/data_service/intermagnet/resource/imcdview/imcdview-1.98.jar], **convert_gm** [https://geomag.bgs.ac.uk/data_service/intermagnet/resource/gm_convert/gm_convert-1.6.jar], **DataCheck1S** [https://geomag.bgs.ac.uk/data_service/intermagnet/resource/DataCheck1s/DataCheck1s-1.51.jar], **autoplot** [Faden et al., 2010], and **CDF V3.9.0** [https://cdf.gsfc.nasa.gov/html/sw_and_docs.html].

The **testcorr** program is used for:

a) removing outliers in the records of the scalar magnetometer in the one-second files of the IAGA-2002 format;

b) simultaneously re-calculation of the relevant one-minute data;

c) formally checking the correspondence between the one-second and one-minute IAGA-2002 files and their correction if necessary.

The **testcorr** program processes one-day-long records. During the removal of the POS-1 outliers, the user is advised to note the intervals with suspicious deviations in the records of the LEMI-025 variometer, as the notes will be useful for further data cleaning by other programs. The **testcorr** packet was used twice a month as the archived data came in from the station (that is, for days 1—15 and 16—30(31) of each month). Figure A1 shows screenshots of working with **testcorr**.

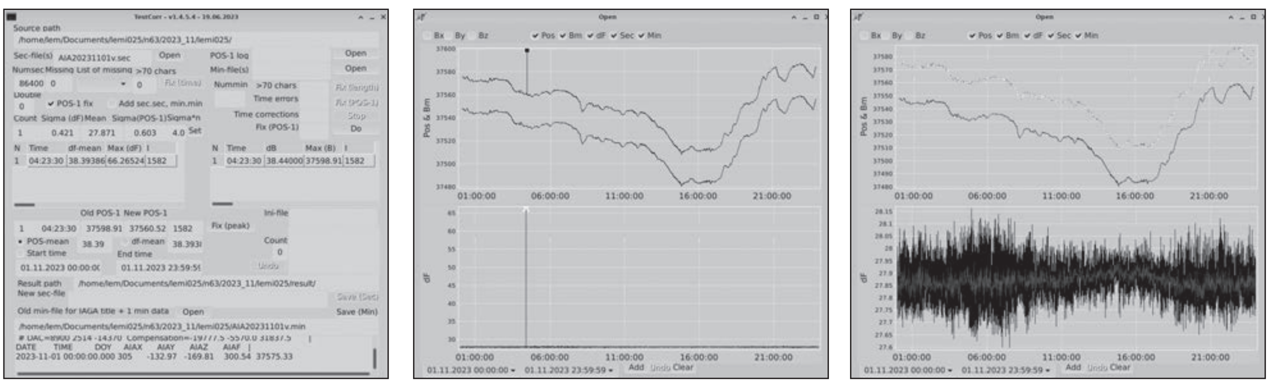
The **supfromtxt** program is used for:

a) extraction of auxiliary measurements, such as the temperature of the fluxgate sensor and electronic unit of the LEMI-025 variometer, its voltage, and the GPS receiver status, from the original 10 Hz files, which also contain magnetic channels;

b) filtration of the auxiliary data and their recording as one-second (.sec.sup) and one-minute (.min.sup) files.

The **supfromtxt** program was used after the entire monthly dataset was available. It processes all the data for one month all at once. Notably, for the first one-minute value of the first day, it is necessary to have the data for the previous month. If the dataset has blanks, they are automatically filled with “999.99” for the temperature channels, “99.9” for the voltage, and “99” for the GPS receiver.

Both programs were developed by LCISR specifically for the treatment of AIA data.



(a) (b) (c)

Figure A1. An example of processing data using the testcorr program: a) the main window; b) the plots before outlier removal from the POS-1 data; c) the same plots with outliers removed

B1. Formatting data as ImagCDF. A review of programs for re-formatting.

With the data for magnetic channels (three channels of the LEMI-025 variometer and one channel of the POS-1 proton magnetometer) as the IAGA-2002 files, the one-second Definitive data must be saved as ImagCDF format introduced in 2015. Unlike the IAGA-2002 format, ImagCDF allows for storing and transmitting all necessary information (main magnetic channels and additional channels such as temperature or metadata about the measurement environment) (Flower, 2017). In particular, according to the IAGA-2002 format, data are rounded to 0.01 nT. However, one of the requirements for the one-second Definitive data is that the vector magnetometer's (variometer's) data resolution must be 0.001 nT (Turbitt, 2014; St-Louis, 2024). This requirement reduces the quantization noise, for which the root mean square of the spectral density is 4.1 $pT/Hz^{0.5}$ if one-second data are rounded to 0.01 nT (Turbitt, 2014; St-Louis, 2024). By comparison, the root of the spectral density of the LEMI-025 variometer's noise is 5–6 $pT/Hz^{0.5}$ at 0.2 Hz. However, the Quasi-definitive data are not subject to this requirement. Thus, to produce Quasi-definitive data in the ImagCDF format, converters from IAGA-2002 to ImagCDF can be used. For one-second Definitive files, another procedure is needed. For example, the direct transformation of the 10 Hz data obtained by the LEMI-025-based equipment complex, rounded up to 0.001 nT, can be used. Also, the IAGA-2002 format does not allow for saving auxiliary measurements such as the variometer's temperature.

The programs that convert IAGA-2002 files to ImagCDF are available in Java (**convert_gm** v1.6 [https://geomag.bgs.ac.uk/data_service/intermagnet/resource/gm_convert/gm_convert-1.6.jar] and **DataCheck1S** v1.51 [https://geomag.bgs.ac.uk/data_service/intermagnet/resource/DataCheck1s/DataCheck1s-1.51.jar]) and Python (the **MagPy** package, including its graphical version called **Xmagpy**).

The Java converters do not allow for including the variometer temperature data in the ImagCDF file and therefore suitable only for the Quasi-definitive level and not above. **MagPy** is more flexible as it allows for reading and writing files in many formats, including IAGA-2002, ImagCDF, and the LEMI-025 files with a discretization frequency of 10 Hz, text or binary (from the Compact-flash memory card). It is also easy to extend this software's functionality using other Python packets. Given the future necessity to prepare one-second Definitive files, we used the **MagPy** packet to combine the magnetic and temperature channel records and save them as ImagCDF files. Since the variometer's temperature changes slowly, it is sufficient to associate the one-second magnetic data with one-minute temperature data. It may also be convenient to have one-minute ImagGDF files along with the one-second versions. A simplified procedure looks like this:

1. We have the one-second and one-minute IAGA-2002 files and the one-minute files with auxiliary measurements (the .min.sup files yielded by **supfromtxt**) for the same period.
2. Using the *read* function of the **MagPy** packet, we read the one-second and one-minute IAGA-2002 files for the same day and store these data in the array variables *n63s* and *n63m,* respectively.
3. Using the *loadtxt* function of the **numpy** packet, we read the one-minute file for the same day (.min.sup). We process the "999.99" values, indicating missing temperature data, appropriately.
4. Using MagPy's _put_column function, the two columns containing the temperatures of the LEMI-025 unit and the fluxgate sensor are added to the n63m array containing the one-minute magnetic data.
5. Using the *mergeStreams* function of **MagPy**, we copy one-minute temperature channels from the variable *n63m* to the variable *n63s* (where the one-second magnetic data are saved). This step automatically copies the timestamps of the one-minute temperature channels.
6. We update the metadata obtained from the IAGA-2002 files and saved as the headings of the variables *n63s* and *n63m* with the necessary information. In particular, we fill in the data of 'DataPublicationLevel', 'DataStandardLevel', 'DataPartialStandDesc', 'unit-col-t1', and 'unit-col-t2'.
7. Using the *write* function of **MagPy**, we save the content of the variables *n63m* and *n63s* in the one-second and one-minute ImagCDF files.

B2. Formatting data as ImagCDF. Some specifics of filling in the metadata

Let us review in more detail the type of information that should be included in the 'DataStandardLevel', 'StandardName', and 'DataPartialStandDesc' cells. The 'DataStandardLevel' cell can have one of the three values (Flower, 2017):

1. 'None': the data do not meet any standard, in which case 'StandardName' and 'PartialStandDesc' cells are omitted.
2. 'Partial': the data partially meets some relevant standard.
3. 'Full': the data fully meets a standard, so 'PartialStandDesc' can be omitted.

For the 'Partial' and 'Full' data, the cell 'StandardName' should contain a value appropriate for the data: 'INTERMAGNET_1-Second', 'INTERMAGNET_1-Minute', or 'INTERMAGNET_1-Minute_QD'.

To select the content of 'DataPartialStandDesc', Appendices C, D, E, and F outline the correspondence of the LEMI-025 and POS-1 devices to the standard requirements for the one-minute and one-second Definitive data. In general, all requirements are met expect for two: IMOM-16 and IMOS-5. The IMOS-5 requirement does not pose strict constraints since it can be met by direct transformation of the 10 Hz data and rounding to 0.001 nT, rather than by transforming the data from the IAGA-2002 files.

As for the IMOM-16 requirement (temperature drift <0.25 nT/°C), there are some doubts. The temperature tests of LEMI-025№63 conducted by LCISR had shown that it meets this standard. Meanwhile, during the device's first year of operation at observatory, substantial temperature drift of the Z component was observed (approx. 0.6 nT/°C). After the sensor was insulated in September 2020, the evaluated component's drift decreased to 0.4 nT/°C. Given that the sensor's temperature in, for example, 2023 was mostly kept as 6.2–6.6 °C, and only five days in March was there a 2.3 °C, deviation of the magnetic channels should not have exceeded 0.92 nT (even with a temperature coefficient of 0.4 nT/°C). The actual deviation of the DELTA F signal did not exceed −0.35 nT (Fig. B2), and its behavior significantly differed from the sensor's temperature deviation pattern. A formal estimate of the temperature coefficient for the DELTA F signal is −0.35/2.3 = −0.15 nT/°C. Evaluating the temperature drift of separate components from the available data is impossible. Notably, both the calculated (0.92 nT) and the actual (−0.35 nT) values meet the IMOS-12 requirement for the cumulative variometer error within ±2.5 nT between two consecutive absolute measurements.

LEMI-025 meets the requirements for the amplitude and phase-frequency parameters and the accuracy of count synchronization with Coordinated Universal Time (IMOS-01, 02, 03, 06, 22, 31) (Marusenkov, 2018). The requirements for the noise level and component orientation accuracy (IMOS-14, 15, 21) were shown to be met in (Marusenkov et al., 2019).

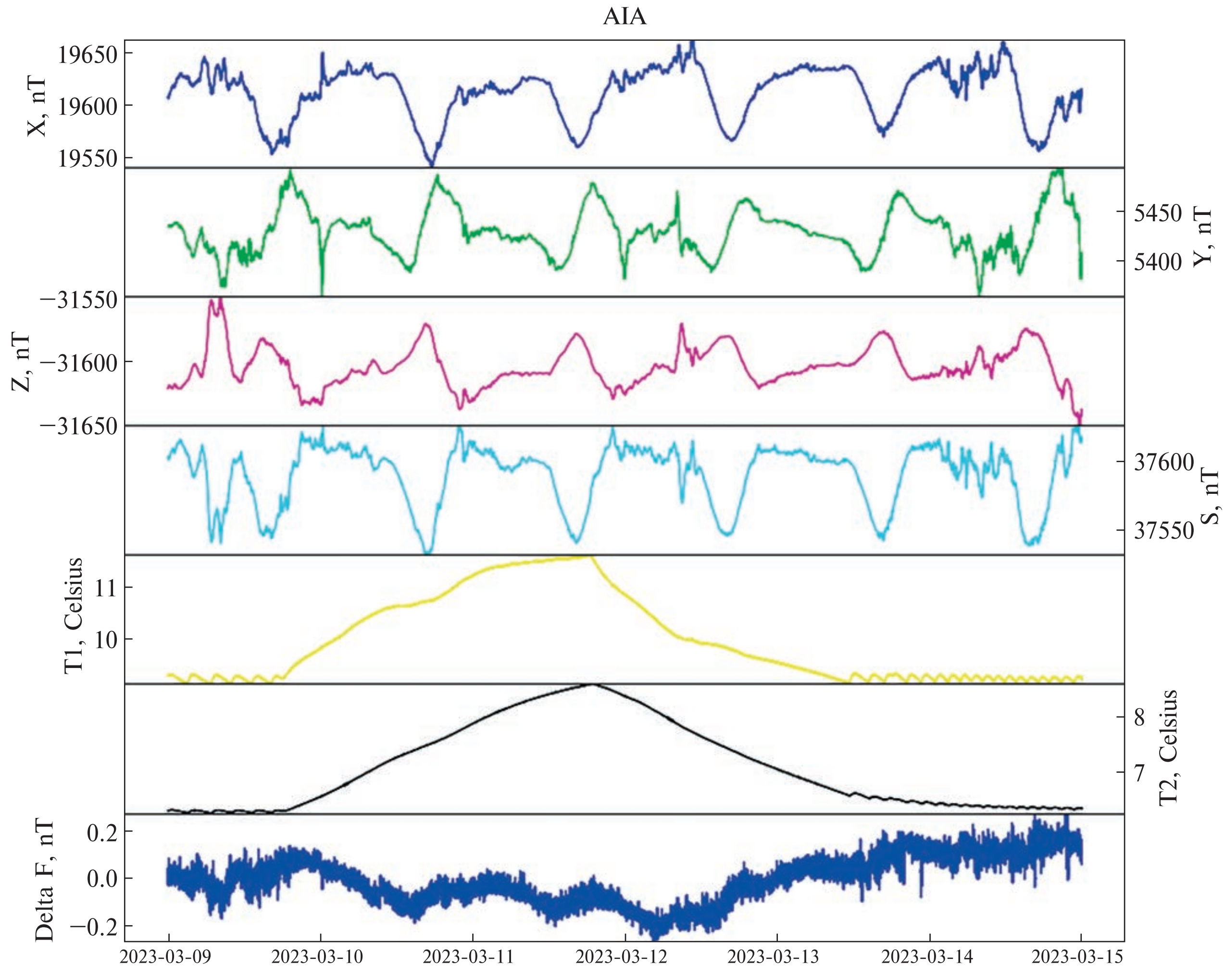


Figure B2. The Quasi-definitive geomagnetic data during temperature fluctuations in March, 2023. Temperature channel markings: T1 — the temperature of the LEMI-025№63 electronics unit, T2 — the LEMI-025№63 fluxgate sensor

B3. Formatting data as ImagCDF. Software for viewing and editing the ImagCDF files

Data formatted as ImagCDF can be visualized in **xmagpy** (Fig. B2) or **autoplot** (Fig. B3). The former program allows a limited set of data transformations frequently used for geomagnetic data. For example, it can compute the DELTA F signal, presenting the data in different coordinate systems (XYZ, HDZ, or DIF), correcting the transformation and offset coefficients, deleting noisy sections, computing statistical parameters of the signals, etc. It is also possible to review and edit the metadata. The **autoplot** program provides a wide selection of graphic data presentation and mathematical processing. This can be used, for example, when plotting signal spectrograms; in particular, it allows users to identify the coherent noise in the LEMI-025№63 and POS-1 records (Fig. B3). Also, the program allows reviewing the metadata more conveniently than **xmagpy**.

If one needs to access the command-line interface, the **CDF** software packet is a convenient tool. In particular, the **cdfedit** program allows to review an ImagCDF file content and correct it if necessary.

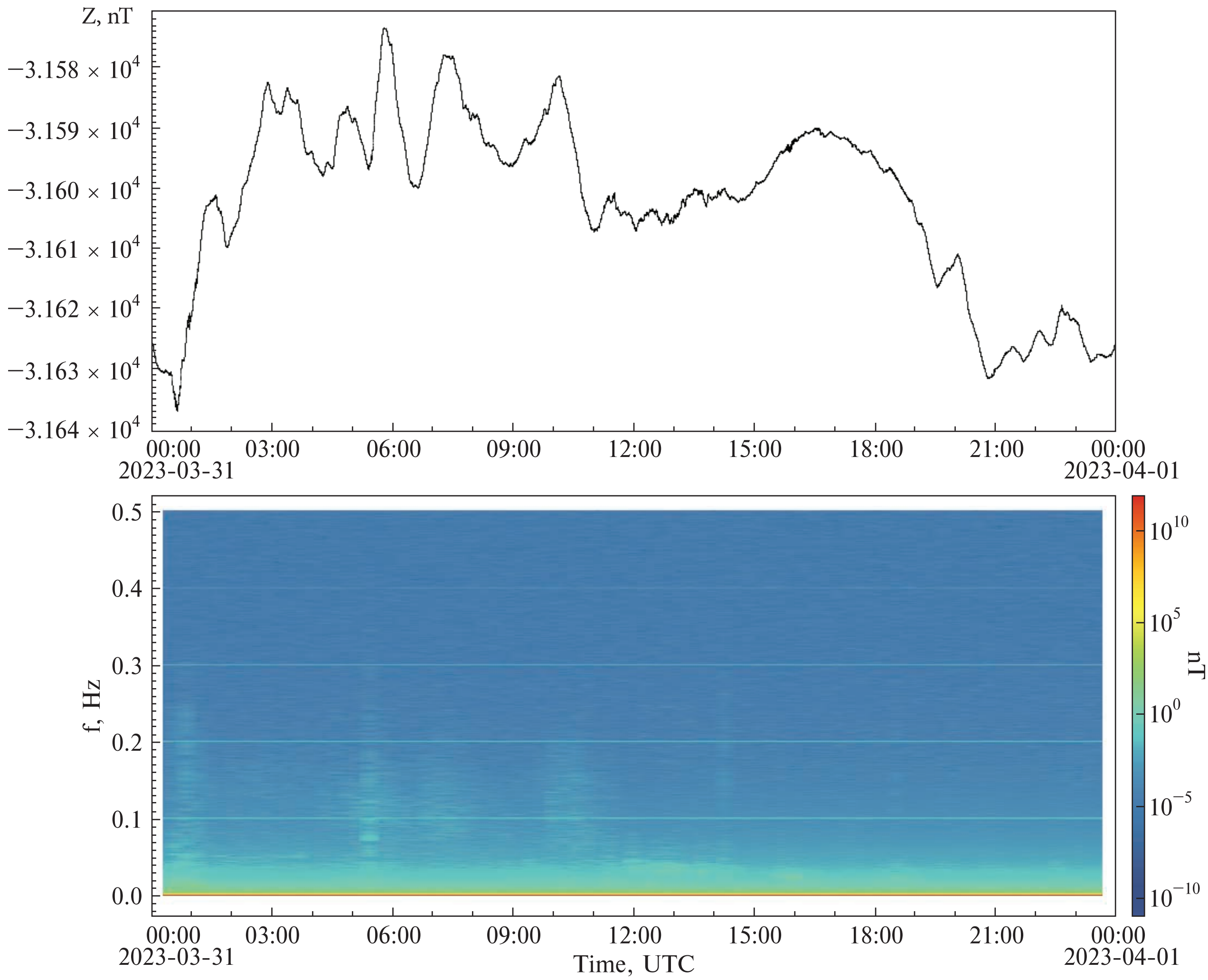


Figure B3. An example of visualization of the Z component using an ImagCDF file. The horizontal lines on the spectrogram at 0.1, 0.2, 0.3, and 0.4 Hz are noises of the POS-1 magnetometer

C. The correspondence of the parameters of the LEMI-025 variometer and the respective INTERMAGNET standards (to fill in the PartialStandDesc data in the one-minute ImagCDF files)

Code of the PartialStandDesc cell	Description	Parameters of the LEMI-025
IMOM-01	Timestamp accuracy (centered on the Coordinated Universal Time (UTC) minute): 5 s	0.001 s
IMOM-11	Absolute accuracy: ±5 nT	±2 nT
IMOM-12	Resolution: 0.1 nT	0.001 nT
IMOM-13	Dynamic range: >4000 nT at high latitudes, >3000 nT at middle/equatorial latitudes	±4000 nT
IMOM-14	Band pass: D.C. to 0.1 Hz	D.C. up to 3.7 Hz for the 10 Hz data
IMOM-15	Minimum sampling rate: 1Hz	10 Hz
IMOM-16	Thermal stability: 0.25 nT/°C	
IMOM-17	Long-term stability: 5 nT/year	<4 nT/year
IMOM-18	Filtration to one-minute data: INTERMAGNET-recommended Gaussian filter	Yes

D. The correspondence of the POS-1 scalar magnetometer's parameters to the INTERMAGNET's standards (to fill in the PartialStandDesc cell in the one-minute ImagCDF files)

Code of the PartialStandDesc cell	Description	POS-1 parameters
IMOM-01	Timestamp accuracy (centered on the UTC minute): 5 s	0.2 s
IMOM-21	Resolution: 0.1 nT	0.001 nT at the device's output 0.01 nT in the IAGA-2002 files
IMOM-22	Absolute accuracy: ±1 nT	±1 nT
IMOM-23	Minimum sampling rate: 0.033 Hz (30 s)	0.1Hz

E. The correspondence of the LEMI-025 variometer's parameters and the respective INTERMAGNET standards (to fill in the PartialStandDesc cell in the one-second ImagCDF files)

Code of the PartialStandDesc cell	Description	Parameters of the LEMI-025
	General specifications	
IMOS-01	Timestamp accuracy (centered on the UTC minute): 0.01 s	0.01 s
IMOS-02	Phase response: maximum group delay ±0.01 s	±0.005 s
IMOS-03	Maximum filter width: 25 s	6 s
IMOS-04	Dynamic range: >4000 nT at high latitudes, >3000 nT at middle/equatorial latitudes	±4000 nT
IMOS-05	Resolution: 0.001 nT	0.001 nT at the device's output 0.01 nT in the IAGA-2002 files
IMOS-06	Band pass: DC to 0.2 Hz	DC до 0.2 Hz
	Pass band requirements [DC to 8 mHz (120 s)]	
IMOS-11	Noise level: ≤100 pT RMS[1]	<20 pT RMS
IMOS-12	Maximum offset error (the cumulative error between two consecutive measurements): ±2.5 nT[2]	±1 nT
IMOS-13	Maximum component scaling and linearity error: 0.25%	0.02 %
IMOS-14	Maximum component orthogonality error: 2 mrad	0.5 mrad
IMOS-15	Maximum Z-component verticality error: 2 mrad	0.5 mrad
	Pass band specifications [*8 mHz (120 s) to 0.2 Hz*]	
IMOS-21	Noise level: ≤10 pT/√Hz at 0.1 Hz	≤10 pT/√Hz at 0.1 Hz
IMOS-22	Maximum gain/attenuation <3 dB	<2.34 dB
	Stop band specifications [≥0.5 Hz]	
IMOS-31	Minimum attenuation in the stop band (≥0.5 Hz): 50 dB	≥51 dB

[1] measured for a period of 10 min at least.
[2] maximum errors of the device, including the long-term and temperature drift

F. The correspondence of the LEMI-025 and POS-1 equipment complex to INTERMAGNET standards (to fill in the PartialStandDesc cell in one-second ImagCDF files)

Code of the Partial-StandDesc cell	Description	Device parameters
	Requirements for auxiliary measurements	
IMOS-41	Compulsory full-scale scalar magnetometer measurements with a data resolution of 0.01nT at a minimum sample period of 30 seconds.	POS-1 magnetometer resolution 0.01 nT sample period 10 s
IMOS-42	Compulsory vector magnetometer temperature measurements with a resolution of 0.1 °C at a minimum sample period of one minute.	LEMI-025 magnetometer resolution 0.01 °C sample period 1 s

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