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One second vector and scalar magnetic measurements at the low-latitude Choutuppal (CPL) magnetic observatory

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Abstract. One second measurements of the geomagnetic field variations, which meet INTERMAGNET quality and transmission specifications, require very special conditions to be maintained at the observatories over sustained periods of time, which pose serious challenges for the operators, particularly when infrastructural and environmental conditions are far from ideal. This work presents the progressive steps, which led to the successful setup of such measurements at the new magnetic observatory of the Council of Scientific and Industrial Research (CSIR)-National Geophysical Research Institute (NGRI) in the Choutuppal (CPL) campus, Hyderabad (HYB), India. The 1 s magnetic measurements in trial mode commenced in 2015 using the newly developed observatory-grade 1 s fluxgate magnetometer, GEOMAG-02MO, from Research Centre GEOMAGNET (GM), Ukraine, and the Overhauser proton precession magnetometer, GSM-90F1, along with the data acquisition system, Magrec-4B from Mingeo, Hungary. Iterative tuning of the setup led to the generation of good quality data from 2016 onward. The processes of commissioning this setup in low-latitude conditions, with the aim of producing 1 s definitive data, and the characteristics of the data from this new instrument are presented here.

1 Introduction

There is an increasing demand from the global geomagnetic community for the recording of 1 s vector and scalar magnetic data in addition to the traditional 1 min data, which would be more useful for (i) understanding the global-scale ultra-low frequency (ULF) waves and sudden impulses (Agapitov and Cheremnykh, 2013); (ii) synchronizing the ground observatory data with low-Earth-orbiting satellites for the development of high-resolution magnetic models (Matzka et al., 2010; Love and Chulliat, 2013; Stolle et al., 2016); (iii) development of real-time space weather applications using the geomagnetic pulsation indices (Nosé et al., 2012; Xu et al., 2013); (iv) studying the ionospheric magnetic fields, solar quiet field (Sq), equatorial electrojet and lower–middle atmospheric dynamics (Chulliat et al., 2016); and (v) investigations on high-latitude magnetospheric–ionospheric physics with magnetometer networks (e.g., IMAGE, CANOPUS). Data from magnetic observatories in combination with satellite magnetic data are widely used for (i) improving the global monitoring of the Earth's magnetic field in higher sampling frequencies by calculating time-varying core field models (Hulot et al., 2007; Jackson and Finlay, 2007; Love and Chulliat, 2013); (ii) studying rapid processes in the core, like geomagnetic jerks (Courtillot et al., 1978; Holme, 2007); (iii) studying the electrical current systems in the Earth's ionosphere and magnetosphere,

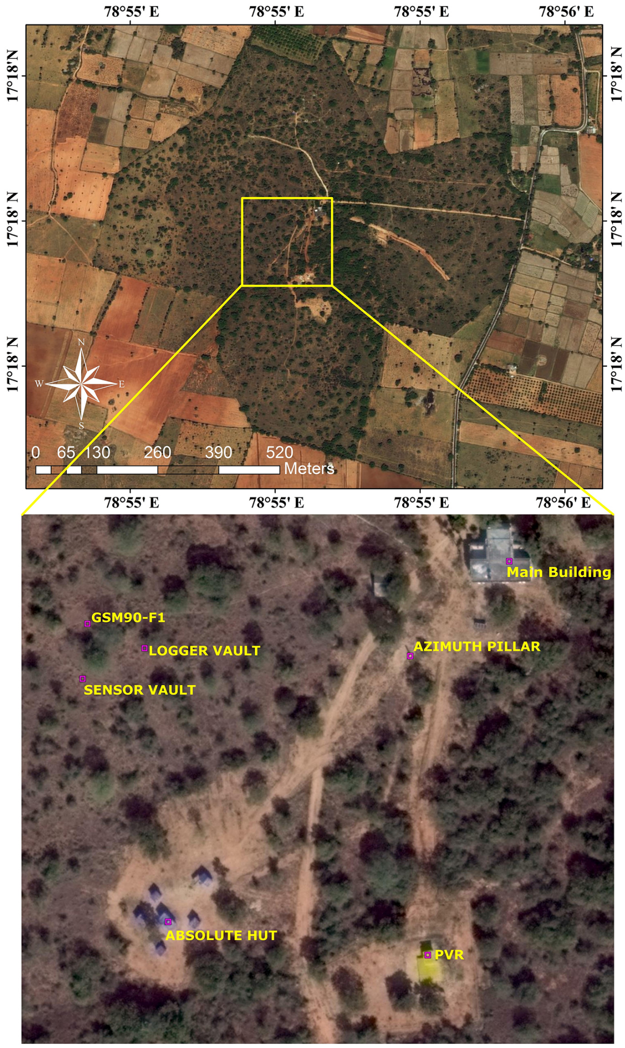

Figure 1. Overview of the Choutuppal campus of the CSIR-National Geophysical Research Institute (top panel); the highlighted text shows the location of the variometer vaults, azimuth pillar, absolute hut and primary variometer room (PVR) of the Choutuppal magnetic observatory (bottom panel).

Figure 2. Thermally insulated new variometer (NV) vaults using extruded polystyrene (XPS) foam sheets and sheds of environmentally friendly natural materials.

both during short events such as magnetic storms, substorms, sudden impulses and Pi2 pulsations (Kennel, 1996; Chi and Russell, 2005; Ghamry et al., 2015) as well as on longer timescales (McPherron, 2009).

Across the world, 200 magnetic observatories are in operation, of which 150 are INTERMAGNET magnetic observatories (IMOs) recording high quality 1 min vector and scalar Earth magnetic field data. Many of the IMOs started recording and producing 1 s magnetic field data, with the prominent ones being the 14 magnetic observatories operated by United States Geological Survey (USGS; Love and Finn, 2011), 3 Polish observatories maintained by Institute of Geophysics Polish Academy of Sciences (Reda and Neska, 2016), 4 observatories operated by the Japan Meteorological Agency (JMA; Minamoto, 2013), 6 observatories operated by EOST (École et Observatoire des Sciences de la Terre), 14 observatories operated by the Geological Survey of Canada (GSC), 16 observatories operated by IPGP (Institut De Physique Du Globe De Paris), 8 observatories of the British Geological Survey (BGS; Thompson, 2014) and 19 observatories operated by GFZ (GeoForschungsZentrum) which are producing 1 min magnetic field data (note that some of these observatories are operated in collaboration with other institutions not listed here; for more information on INTERMAGNET observatories, see http://www.intermagnet.org). The increased order of noise with increasing frequencies in the fluxgate sensors, which are the main staple of the observatories, is the main concern, and the development of suitable instruments (Chulliat et al., 2009; Korepanov et al., 2006, 2009; Dobrodnyak et al., 2014; Logvinov et al., 2014; Pedersen and Merenyi, 2016) and techniques for the evaluation and elimination of noise from the data is being pursued by several researchers (Turbitt et al., 2012, and references therein).

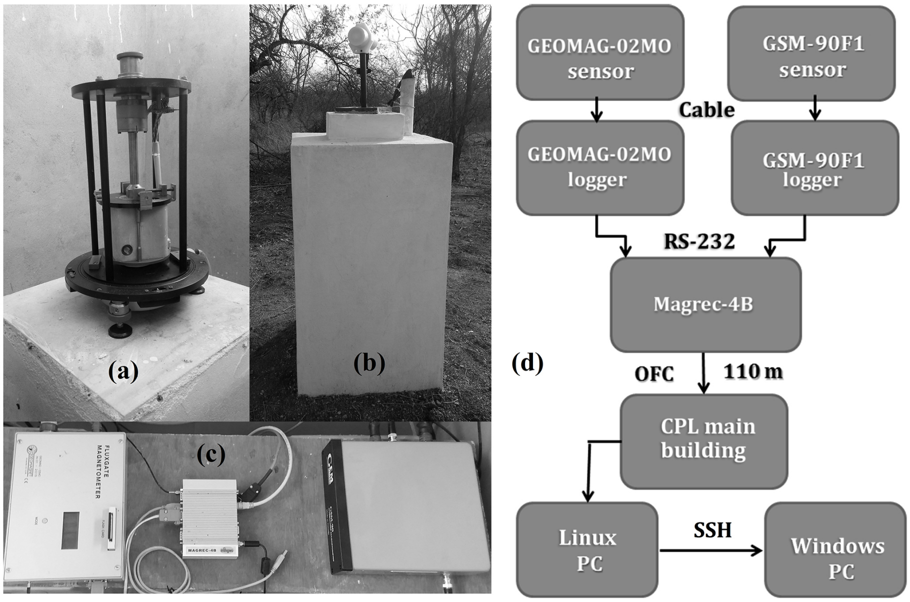

Figure 3. **(a)** Three-component GEOMAG-02MO; **(b)** GSM-90F1; **(c)** data loggers of the GEOMAG-02MO, GSM-90F1 and Magrec-4B data acquisition system; and **(d)** flow chart of connections used for the experimental setup.

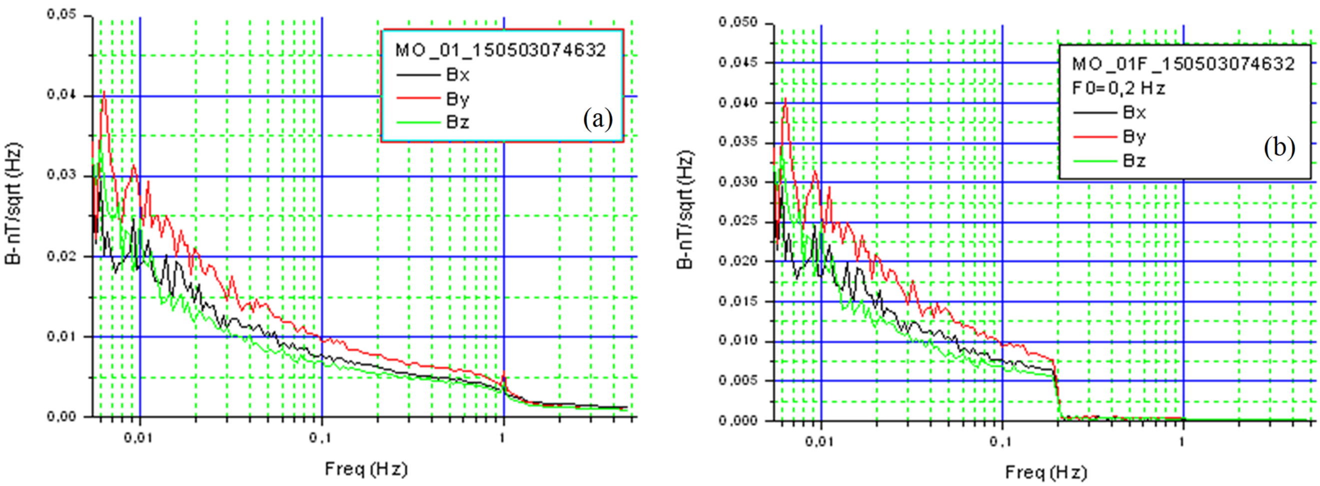

Figure 4. **(a)** Noise characteristics of different components of GEOMAG-02MO. **(b)** Noise characteristics as a result of digital filtering at F0 $= 0.2$ Hz.

While, on the one hand, we are living in an increasingly technology-driven society, where the essential pathways of high-speed communication are affected by minute changes in the magnetic field and space weather conditions, on the other hand, the very spread of human technology is an impediment to measuring changes in the Earth's natural magnetic field devoid of anthropogenic influences, which is rendered particularly difficult for the more populous countries. Establishment of a magnetic observatory demands the long-term availability of a suitable location away from major sources of artificial electromagnetic noise and a nonmagnetic and thermally insulated magnetometer housing, as well as access to trained manpower, uninterrupted power supply and high-speed internet for the transmission of data in real time to headquarters. Such a combination of requirements is not easily fulfilled in the prevalent socioeconomic conditions of many countries around the world; moreover, the allocation of funds for setting up and maintaining observatories is often a constant challenge. Notwithstanding such considerations, it is highly desirable to have observatories spread out over the different parts of the world to achieve the desired level of monitoring of the fluctuations of the magnetic field at a large variety of locations.

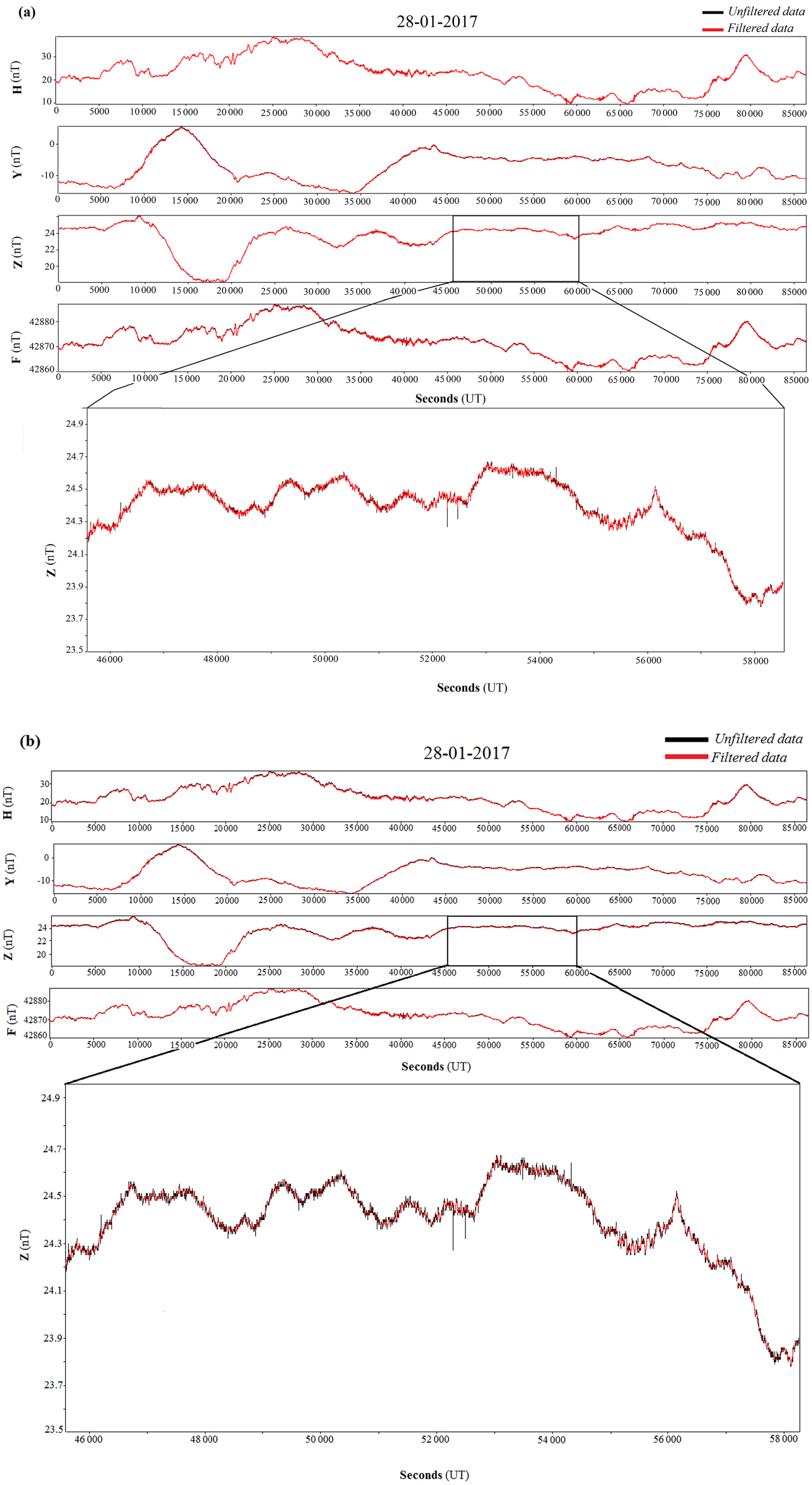

Figure 5. (a) Sample plots of 1 s raw (black color line) and filtered data (red color line) with a cutoff frequency of 0.2 Hz from the CPL magnetic observatory. **(b)** Sample plots of 1 s raw (black color line) and filtered data (red color line) with a cutoff frequency of 0.005 Hz from the CPL magnetic observatory.

Table 1. Technical specifications of GEOMAG-02MO.

Main technical characteristics of GEOMAG-02MO	
Measuring range of full magnetic field (MF)	±65 000 nT
Measuring range of MF variations	±4000 nT
Resolution of MF variation resolution	0.001 nT
Temperature drift	< 0.2 nT/°C
Tolerance of component non-orthogonality of magnetic field sensor	< 30 arcmin
Non-orthogonality error sensor component MF after compensation	< 5 arcmin
Automatic compensation for range of constant MF for each component	±65 000 nT
Measuring channel information sampling number	100 1 s
Operating temperature range	−10 to +40°
Connecting cable length between the sensor and electronic unit	Up to 50 m
Power consumption	12 V; 0.1 A
Capacity of flash card	64 MB to 64 GB
Data transfer and online magnetogram through logger software via RS-232 to USB	Windows platform
GPS timing and coordinates determination with elevation	0.01 s accuracy
Server connection from the desktop machine via logger software	Internet connection

Figure 1 shows the layout of the Choutuppal (CPL) observatory complex, 65 km east of Hyderabad (HYB): the primary variometer room (PVR), which houses the three-component FGE magnetometer from DTU (Danish Technical University) along with the GSM-90F1 Overhauser magnetometer and the MAG-01H theodolite for absolute declination and inclination observations. The new setup is confined to a couple of shallow vaults, approximately 20 m apart, about 150 m northwest of the PVR, where the recently developed observatory-grade 1 s magnetometer, GEOMAG-02MO, manufactured by the Ukrainian company Research Centre GEOMAGNET (GM) and corresponding electronics are installed separately.

The newly established 1 s system at the CPL magnetic observatory may serve as an example of a low-cost, rugged installation in high-temperature, low-latitude regions capable of producing data of desired standards. The details of the infrastructural setup including the safeguards used for minimizing temperature effects, instrument description and data acquisition system, and real-time data transmission facility, which enabled this achievement, are documented, which may encourage the establishment of a larger number of such simple and effective measurement setups for wider data coverage. The characteristics of the raw data from GEOMAG-02MO and GSM-90F1 through Magrec-4B at CPL are discussed and the methods used for noise removal are explained.

2 Installation setup and system description

2.1 Infrastructure

Two nonmagnetic vaults of dimension 1.22 m × 1.22 m × 1.22 m were constructed at the CPL observatory campus for deploying the three-component sensor and to house the data logger systems (Fig. 2), designated as new variometer (NV) vaults. Extruded polystyrene (XPS) foam sheets of 4 in (10.16 cm) thickness of dimensions 1.22 m × 2.44 m were used as thermal insulating material inside the vaults, designed as telescopic enclosures with a layer of air in between to minimize effects of temperature variations on the sensor and electronic units (Fig. 2). In the electronics vault, a specially designed outlet is installed to let the heat generated from the units escape. The daily temperature variation at CPL is of the range of 0.2 °C and annual variation is of the range 10 °C; as GEOMAG-02MO is having a typical temperature coefficient of ∼ 0.2 nT/°C and the vaults were relatively small, the design of the insulation played a critical role in generating good quality data. The vaults are protected by heavy wooden lids layered with the XPS sheets on the top and on the inside, over which $2.13 \times 2.13\,\mathrm{m}^2$ of white marble serves as a very effective coolant.

The NV and the GSM-90F1 pillar are separated by about 20 m, almost equidistant from each other (Fig. 2). The respective GPS receivers are enclosed in polyvinyl chloride (PVC) pipes for protection against weather and rodents (Fig. 2). GEOMAG-02MO and GSM-90F1 are installed on nonmagnetic pillars at the center of the vaults, as shown in Fig. 3a and b. A lightning arrester is mounted on the top of the data logger vault with the other end grounded deep into the Earth to protect the electronics of the recording systems during severe thunderstorms, which happen during monsoon season each year. Uninterrupted power supply is provided for the recording systems as well as to the computers using a 3 kW solar power source, located 100 m away near the CPL main building. GEOMAG-02MO and GSM-90F1 (oriented in east–west direction) sensors are connected to the respective data loggers via underground connecting cables of 30 m length. The data output from the two sensors is combined through a Magrec-4B data acquisition system via RS (Recommended Standard)-232 cables (Fig. 3c), which in turn is connected to computers located in the CPL main building about 100 m away via optical fiber cable (OFC) for archiving, analysis and dissemination (Fig. 3d).

Pier calibrations are regularly carried out to ensure that the spatial gradient between the fluxgate and total field pillars is constant. The 1 s raw data in real time is transmitted to the CPL main building from Magrec-4B and with a latency period of 2 min; the data are transmitted to the Hyderabad Magnetic Observatory (IMO-HYB) through the internet from a Linux machine.

2.2 GEOMAG-02MO instrument and software

Different fluxgate magnetometers are in operation for recording 1 s data, with the most widely used ones being the three-component FGE magnetometer by DTU (Pedersen and Merenyi, 2016), LEMI by the Lviv Centre of Institute of Space Research (Marusenkov, 2014), vector magnetometer 391 by Institut de Physique du Globe de Paris (Chulliat et al., 2009), Narod ring-core triaxial fluxgate magnetometer by Narod Geophysics (Narod and Bennest, 1990) and GEOMAG-02 by Research Centre GEOMAGNET (Dobrodnyak et al., 2014; Rakhlin et al., 2005; Reda and Neska, 2016). The three-component sensor of GEOMAG-02MO (upgraded version of GEOMAG-02) is a precision cardan suspension system, which provides the long-term stability of the spatial position of the sensor with compact electronics, having very low power requirements, which makes it suitable for installations in locations of minimal infrastructure.

The GEOMAG-02MO magnetometer was designed for use in a magnetic observatory, conforming to the INTERMAGNET technical note (Turbitt et al., 2014), with attention focused on the following issues:

- reduction of the noise level,
- digital data filtering,
- reduction of the non-orthogonality of components of the magnetic observatory sensor,
- real-time data plotting and FTP (File Transfer Protocol) server access.

2.2.1 Noise reduction

The noise level of the fluxgate magnetometer is determined mainly by the operation modes of the sensor excitation circuit, namely the following factors: (i) noise characteristics of the core and its volume, (ii) the amplitude and frequency of the excitation field and its stability, and (iii) the content of even harmonics in the current supplying the excitation circuit.

Optimization of the excitation mode of the sensor by increasing its excitation field greatly improved the noise characteristics of the GEOMAG-02MO. The following requirements for the noise characteristics of the GEOMAG-02MO in the frequency range of DC to 0.2 Hz are set as per the recommendations made by the INTERMAGNET definitive 1 s data standard (Turbitt et al., 2012): (i) noise level in the frequency band DC is set to 8 mHz$- \leq 100$ pT RMS (root mean square) and (ii) noise level in the frequency band 8 mHz is set to 0.2 Hz$- \leq 10$ pT/$\sqrt{}$Hz at 0.1 Hz.

Figure 4a represents the basic frequency–noise response of the GEOMAG-02MO under controlled conditions at manufacturing location (Lviv, Ukraine), with a noise density of 10 pT/$\sqrt{}$Hz at 0.1 Hz. Figure 4b shows a graph of noise density in the frequency range from 8 mHz to 0.2 Hz as a result of the low-frequency digital filtering at a cutoff frequency of 0.2 Hz, with the width of the window being 25 s.

Experimentally obtained graphs confirm the achievement of the necessary noise characteristics (as is shown in Fig. 4).

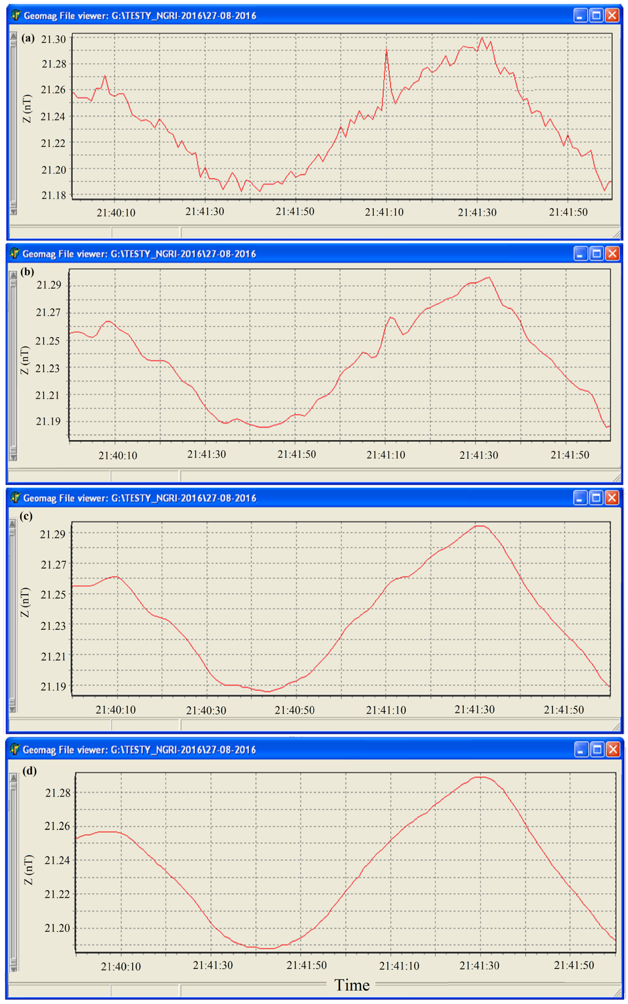

Figure 6. Application of LPF-GEOMAG software showing detrending of the observed spike at 21:41:10 UT on 27 August 2016: **(a)** without use of filter (spike amplitude: 0.045 nT), **(b)** with a cutoff frequency of 0.2 Hz (spike amplitude: 0.023 nT), **(c)** with a cutoff frequency of 0.1 Hz (spike amplitude: 0.01 nT) and **(d)** with a cutoff frequency of 0.05 Hz (spike amplitude: 0 nT).

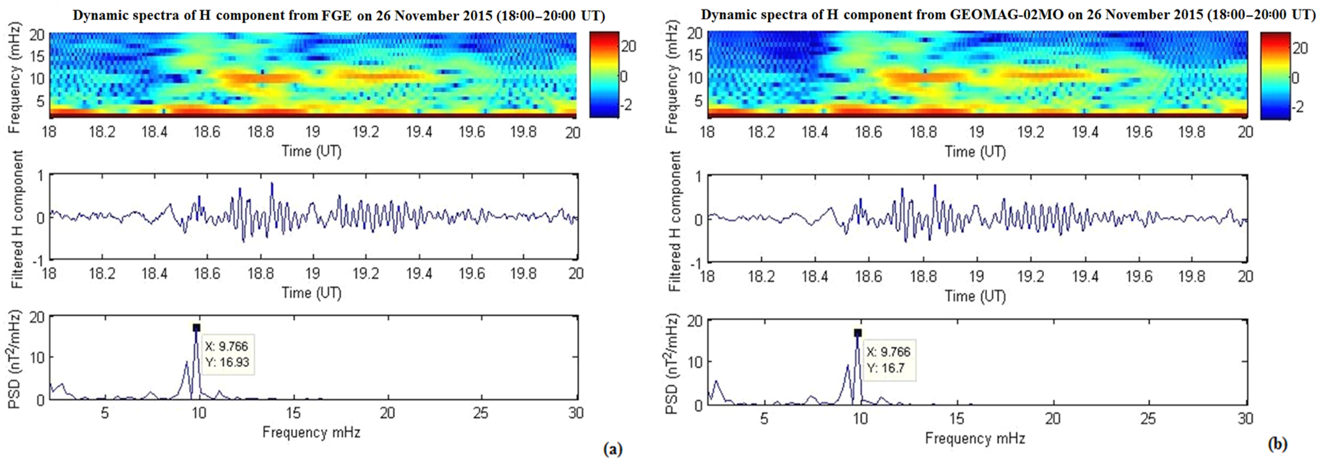

Figure 7. (a) Spectral decomposition of quiet day nighttime data from FGE on 26 November 2015. **(b)** Spectral decomposition of quiet day nighttime data from GEOMAG-02MO on 26 November 2015. PSD stands for power spectral density.

The data format corresponds to the Recommended Standard: text line format, sensitivity threshold 1 pT and time-stamp accuracy (centered on the UT second) better than 0.01 s.

2.2.2 Digital filtering

The GEOMAG-02MO comes with a Windows-platform-based low-pass filter (LPF)-GEOMAG software, for the despiking of noise in the data as per the standards recommended by the INTERMAGNET council (Turbitt et al., 2012). LPF-GEOMAG performs the following processing functions: (i) despiking of three-component data by a digital SINC (sine cardinal) low-pass filter with a cutoff frequency of 0.001 to 0.990 Hz and window length of 1.0 to 49.0 s as well as filter types Hanning, Hamming and Blackman; and (ii) averaging over a predetermined time interval (i.e., from 5 to 60 s). After filtering, the LPF-GEOMAG window shows the report of generated files: (i) filtered data and (ii) noise data.

Samples of 1 s raw data from GEOMAG-02MO are filtered using LPF-GEOMAG software with a cutoff frequency of 0.2 Hz (Fig. 5a) for the day 28 January 2017. The black color line shows the unfiltered data and the red color line shows the filtered data. The sample of the noise-free data is further enlarged at the bottom panel of the figure (highlighted with the black rectangular box) shown for a small portion of the Z-component dataset of the same day. It is evident from Fig. 5a that the noise in the Z component (last bottom panel) is not completely removed with a cutoff of frequency 0.2 Hz. With the application of the filter with a cutoff frequency of 0.005 Hz, (Fig. 5b), it was possible to remove the noise in the Z component. Caution has been exercised while using the filter with a cutoff frequency of 0.2 Hz (Fig. 5a; as all pulsation signals, which can be identified using 1 s GEOMAG-02MO, fall significantly below this cutoff frequency) recommended by INTERMAGNET. Figure 6 shows the response to filtering with different cutoff frequencies. More information about the description of filter parameters can be found in Fig. S1 of the Supplement.

Application of the LPF-GEOMAG software with different cutoff frequencies for a selected portion of the observed spike in the raw data file of the Z component recorded on 27 August 2016 at 21:41:10 UT is shown in Fig. 6a. Figure 6b–d shows the output of the filtered data of the Z component with cutoff frequencies 0.2 (Fig. 6b), 0.1 (Fig. 6c) and 0.05 Hz (Fig. 6d). The LPF-GEOMAG software was tested for many days at IMO-HYB prior to the installation of GEOMAG-02MO at the CPL observatory.

2.2.3 Orthogonality

At installation, the GEOMAG-02MO sensor is oriented close to the magnetic north, leaving Y in an uncompensated mode (i.e., measuring the declination of the Earth's magnetic field), which allows for automated compensation for the external field, which is iteratively adjusted to bring it to null by fine-tuning the orientation. The GEOMAG-02MO housing allows for achieving the non-orthogonality error and deviation of the Z component from the vertical axis (i.e., 2 mrad) due to the two-level correction: mechanical balancing of the Z-component position and algorithmic correction of the non-orthogonality of the component axes. During long-term operation this value remains stable due to the use of artificial glass (Sitall) or marble that has a high stability in a wide range of temperatures and time. Further reduction of non-orthogonality can be achieved by using digital compensation. The method of compensation allows for the reduction of the error up to several arcmin. Specifications of GEOMAG-02MO are given in Table 1.

2.2.4 Data plotting and FTP server

The GEOMAG-02MO includes Windows-platform-based software: (i) the GEOMAGNET logger and (ii) the GM logger server software. The GM logger software receives the data files, produces real-time plots and archives the data to the hard disk of the computer via RS-232 to USB (Universal Serial Bus) connector. The GM logger server software enables the (a) receiving of files from multiple sensors via FTP servers, (b) expansion of the received files in specified folders on the computer, (c) saving of header information in log files, (d) visualization in calendar view and (e) concatenation of several succession log files to one.

Prior to the permanent installation, trial measurements were performed at IMO-HYB; 1 s nighttime horizontal field variations from GEOMAG-02MO on a quiet day (i.e., 26 November 2015) are compared with data from the FGE by using the spectral decomposition technique. It is evident from the dynamic spectra of Fig. 7a and b that the characteristics of data from the two sensors are closely comparable.

3 Data acquisition system: Magrec-4B

The Magrec-4B data acquisition system manufactured by Mingeo Ltd., Hungary, is a dual-core Intel® Atom™-processor-based small-size fan-less data acquisition computer equipped with a PalmAcq GPS timing module (http://www.mingeo.com/prod-magrec4b.html). At CPL, the Magrec-4B data logger is used to integrate the three-component vector data from GEOMAG-02MO (input files from the GEOMAG-02MO logger) and scalar data from GSM-90F1. Magrec-4B plays a vital role in storing the GSM-90F1 data, which does not have any internal memory, as well as in tracking the time-stamping differences between the fluxgate magnetometers, if any. Magrec-4B also provides backup data for GEOMAG-02MO, sent/received commands between the host PC and instruments, latest acquired data and their changes, short- and long-term real-time plots of acquired and filtered data, logs of different events and errors of the recording systems, and the information about the unexpected shutdown of the systems in any case. The various stages of development of the GEOMAG-02MO installation and the parameters associated with it are shown in Fig. 8.

Figure 8a shows the window providing the details of the observatory and the operating instruments, log reports on the time of initiation of measurements, sampling interval, time-stamping error and restart time of logger systems. This information is stored in monthly files to record complete details of the recording systems. Magrec-4B offers multiple plotting tools for visualization of 1 s real-time data from GEOMAG-02MO and scalar field data from GSM-90F1 (Fig. 8b) as well as the sensor and logger temperatures of GEOMAG-02MO (Fig. 8c). Further details of the usage of Magrec-4B are discussed in Figs. S2 and S3.

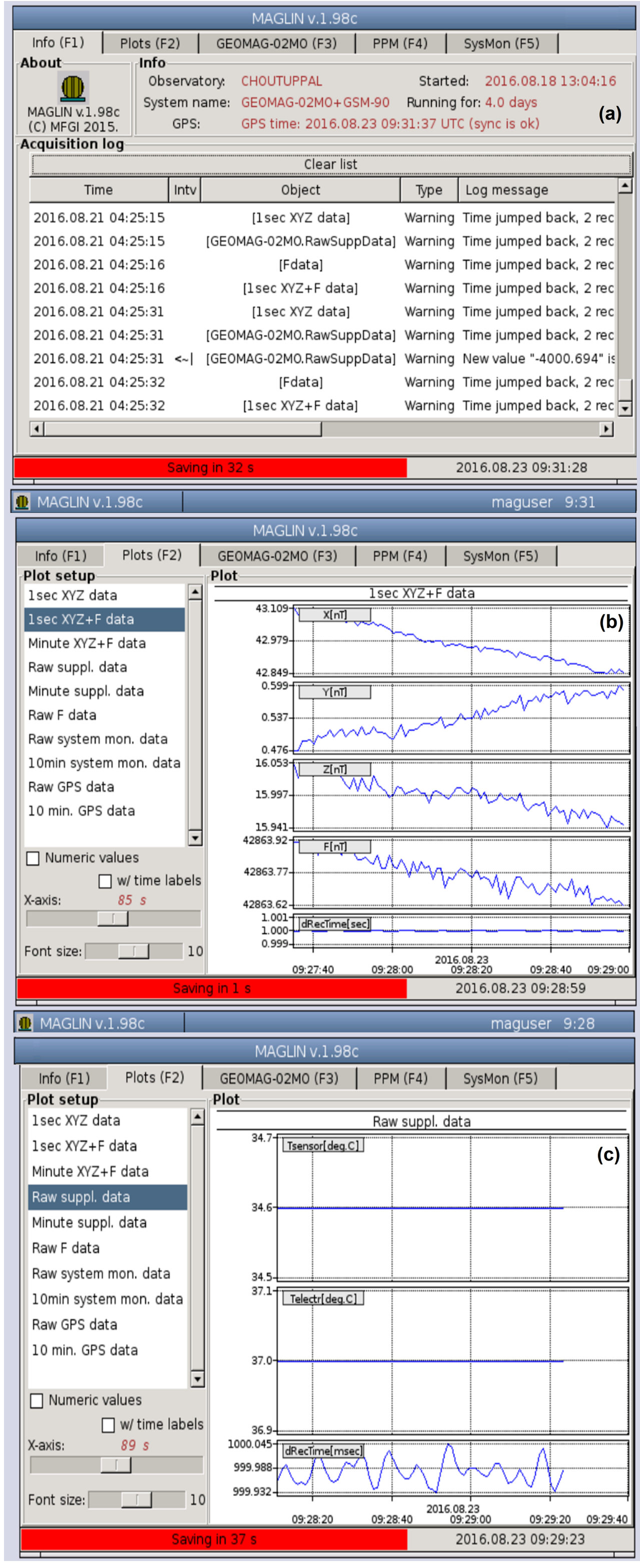

Figure 8. Details of data logging and real-time plotting tools of the Magrec-4B data acquisition system.

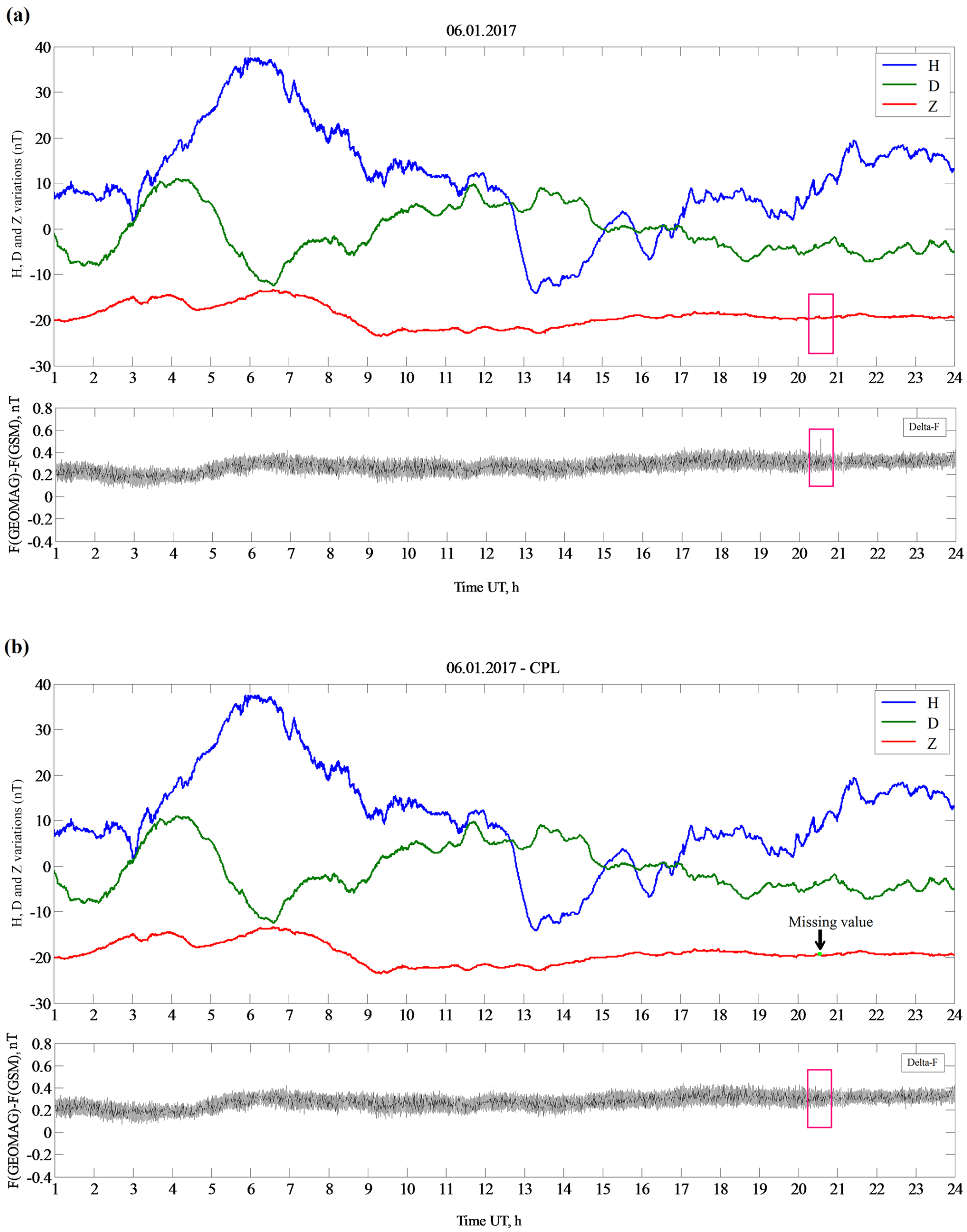

Figure 9. **(a)** The 1 s vector variations and ΔF from GEOMAG-02MO and GSM-90F1 and the observed spike in the Z component and ΔF (highlighted rectangular box) on 6 January 2017; **(b)** removal of the spike in the Z component (green color dot with highlighted black circle, top panel) and ΔF (highlighted rectangular box, bottom panel) on 6 January 2017 using the Matlab script and replacement of the data with the missing value.

Long-time archiving of data is done on a computer on the Linux platform, which communicates with Magrec-4B via the internet or LAN (local area network), so that once the data are received from the instruments by Magrec-4B they will simultaneously be transferred to this computer automatically (Fig. 3d). We have installed a special script in Magrec-4B to perform this process. During durations of network failure the script transfers the data via LAN, and when the network connection is reestablished the script rechecks the data which are last transmitted and again sends the data from where it was stopped through the WAN (wide area network) to make sure that the data are secured without any loss at the control room in the CPL main building.

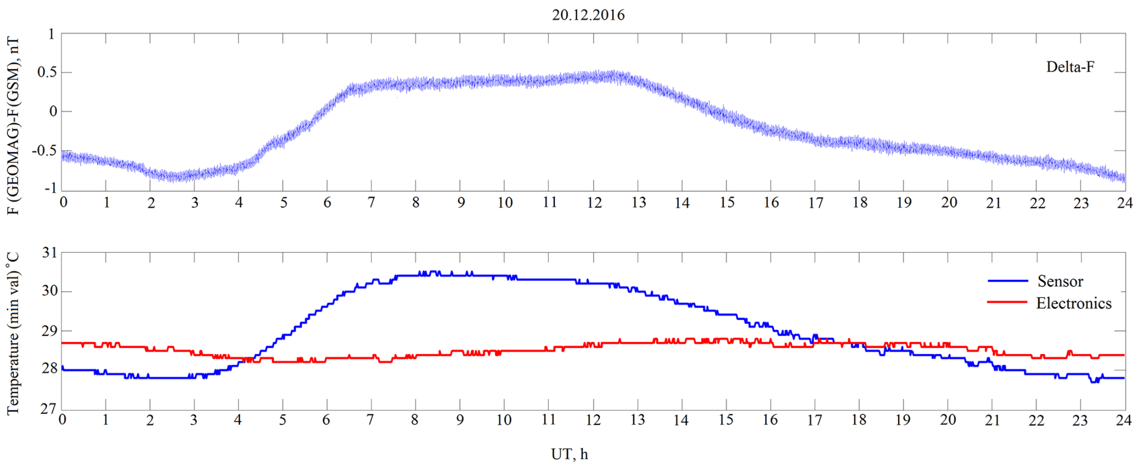

Figure 10. Example plot showing the influence of sensor–electronics temperatures on ΔF observed on 20 December 2016.

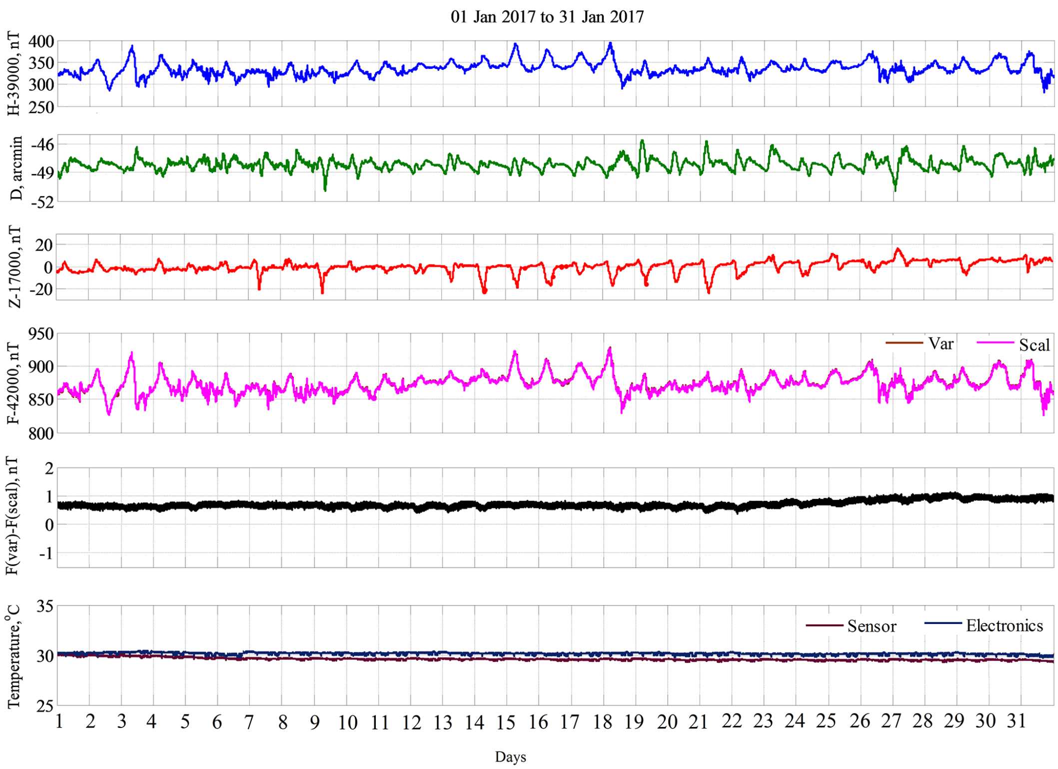

Figure 11. Example of 1 entire month, January 2017, of magnetic field measurements and sensor–electronics temperatures.

4 Near-real-time data transmission from CPL to the HYB magnetic observatory

The data are transmitted to IMO-HYB in real time for processing and analysis, where a Windows machine with a public Internet Protocol (IP) and WinSCP (Windows Secure Copy protocol) and cognate.exe files is configured to receive data from the CPL Linux machine (as shown in Fig. 3d). From the Choutuppal town to the CPL magnetic observatory, 2.5 km of OFC has been laid for this purpose. The computer at Hyderabad is configured with WinSCP and the related .exe files which check the continuity of data flow from CPL and, in cases of interruption, rewrite the data once the connection is reestablished. Thus, data are secured at the HYB archiving center as well as the CPL Linux machine. For more details see the Supplement.

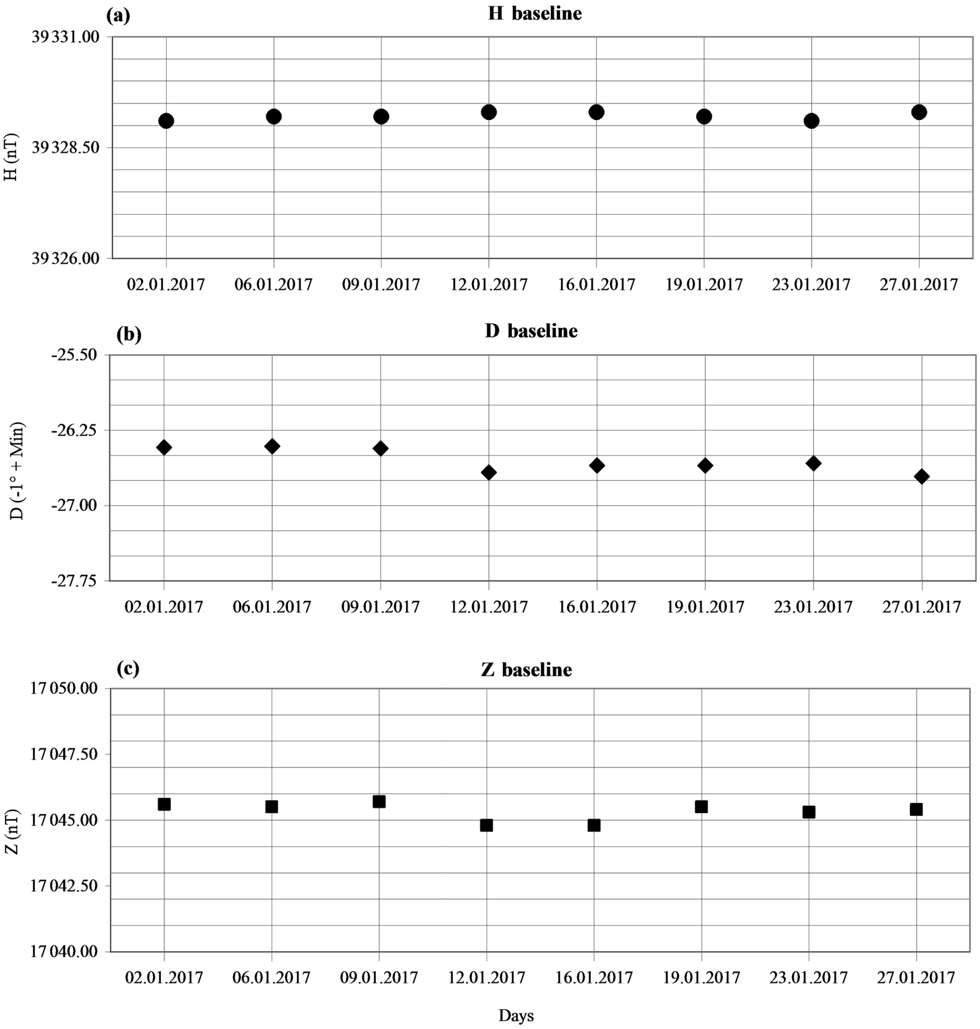

Figure 12. Baselines of January 2017 for GEOMAG-02MO.

5 Data

5.1 Raw and filtered data sample from GEOMAG-02MO and GSM-90F1 through Magrec-4B

Spikes (sudden jump or sharp increase in the magnitude in one component or in all components) in the data need careful evaluation to identify them either as signals from natural sources or as signatures of artificial disturbances, based on comparisons with a high-precision scalar magnetometer. Matlab scripts have been developed to perform the identification and removal of spikes. Figure 9a shows the vector plot of field components and the computed ΔF (ΔF is the difference between the total field calculated from the vector magnetometer and the recorded total intensity from the scalar magnetometer), which is used as a primary quality check of the data. A constant value of ΔF represents the offset between the F value at the position of the scalar magnetometer sensor and F value reduced to the position, where the absolute measurements are carried out. Spikes in the ΔF plot indicate the noise in the data. Figure 9a shows an example for 6 January 2017 to illustrate the despiking of the observed spike at the CPL observatory. Around 20:55:12 UT, a spike was observed only in the Z component (Fig. 9a, top panel, highlighted with the rectangular box). The observed spike in the Z component is further clearly visible in ΔF (Fig. 9a, bottom panel, highlighted with the rectangular box). In the processing stage the observed spike was removed (shown as a green color dot highlighted with a black arrow in Fig. 9b, top panel) and replaced with the missing value, e.g., 99999.99. The spike is now no longer evident in ΔF as shown in Fig. 9b (bottom panel, highlighted with the rectangular box).

5.2 Effects of temperature and time-stamping errors

The temperature sensitivity is an important parameter affecting the long-term stability of the magnetometer data used in the observatory. The stable temperature environment is required in the magnetometer hut to achieve high-precision measurements. Attempts were made to test the influence of temperature on the magnetic measurements at the CPL observatory. For this, the GEOMAG-02MO sensor and logger units were first installed in the newly constructed variometer vaults without any thermal insulation. The clear signature of the temperature influence on the 1 s ΔF daily variation is shown for 20 December 2016 as a sample (Fig. 10). Good correlation is observed between ΔF and the variation in sensor vault temperature (shown in Fig. 10). The temperature variation of 2.5 °C over 1 day is observed in the sensor vault (blue color) and 0.8 °C is observed at the logger vault (red color), which resulted in 1.3 nT variation in ΔF over 1 day (Fig. 10).

The daily changes in temperature are controlled by using XPS material, as described in Sect. 2.1. Figure 11 shows 1 s raw daily variations of the H, D and Z components; the F value; and ΔF as well as variations from the recording system in a temperature-controlled environment for the complete month of January 2017. It is evident from Fig. 11 that the range of ΔF variations over 1 day is 0.3 nT and the temperature variations in sensor and logger vaults are almost constant over 1 day in the range of 0.2 °C.

Short notes on the observed time-stamping error between the recording systems and the improvements made to achieve accurate measurements are described in Sect. S5.3 of the Supplement.

6 Baselines

Absolute observations are made twice a week at the CPL magnetic observatory using a MAG-01H D/I (declinometer–inclinometer) system mounted on a nonmagnetic pillar for providing baselines. Sample baseline trends for the month of January 2017 obtained for GEOMAG-02MO are shown for the H (Fig. 12a), D (Fig. 12b) and Z (Fig. 12c) components.

During the initial phases of installation, the fluctuations in the baselines are observed to be on the order of 6 nT in the H, 8 nT in the Z and 1 min in the D component. Now with the improved measurement techniques, as discussed in the paper (Sects. 2.1 and 5.2), the baseline measurements are on the order of 0.3 nT in the H, 0.6 nT in the Z and 0.3 min in the D component over a period of a few months (but a plot is only shown for 1 month in the paper). With an extensive set of measurement points for 1 complete year, the variations in baselines are expected to be $< 5\,\mathrm{nT\,yr^{-1}}$ and will definitely comply with the specification recommendations by INTERMAGNET (St.-Louis, 2012).

The continuity and the functioning of the instruments at CPL are evaluated at IMO-HYB on a daily basis by remotely connecting the data acquisition systems via the internet. During unexpected shutdown of the instrument or power fluctuations, or during the failure of the batteries, inverter, charge controllers or internet connectivity, the team at IMO-HYB needs to visit the CPL observatory physically to resolve the technical glitches. All these cannot be prognosticated or checked remotely unless the team members at IMO-HYB visit the CPL observatory to rectify the situation.

7 Conclusions

At the CPL magnetic observatory, India, 1 s data recording was initiated in 2015 in addition to the standard 1 min data, which began in 2012. This paper documents various aspects of our evolving efforts towards achieving quality 1 s data despite substantial resource and environmental constraints. With the use of a new fluxgate variometer attached to the standard data acquisition system from Mingeo, installed in a low-cost instrument housing, it was possible to establish the protocol to record stable and good quality 1 s data from January 2017 onward. This may serve as encouragement to initiate more sites with near-real-time 1 s magnetic data recording.

Data availability. CPL observatory data are available upon request (kusumita@ngri.res.in). The data will be available in the public domain once INTERMAGNET status is achieved.

Information about the Supplement

More information about the description of filter parameters described in Fig. S1 and various stages of development of the GEOMAG-02MO installation and the parameters associated with it are shown in Figs. S2, S3 and S4.

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