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INTERMAGNET's efforts to improve the quality and availability of 1-minute Definitive Data

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Abstract. The global INTERMAGNET network provides the scientific community with geomagnetic time series data from its more than 100 member observatories. These time series include near real-time data (Reported) as well as delayed data products, such as Quasi-Definitive (QD) and Definitive (DD) data. QD data is published online with a delay of up to three months, while DD data becomes available on the INTERMAGNET website after the end of each calendar year. Additionally, the DD data and metadata are published with a unique identifier (DOI). DD data publications cover the records since 1991, and occasionally include updates of previously published DD datasets. All datasets are publicly accessible online.

QD and DD data allow the analysis of both short-term magnetic field variations and long-term secular variation. Monitoring these long-term changes distinguishes INTERMAGNET from other networks that focus primarily on short-term geomagnetic variations.

INTERMAGNET ensures high-quality DD geomagnetic data through a rigorous two-stage, peer-reviewed quality control process. Although this process delays publication, it guarantees the final DD datasets' highest possible accuracy and reliability.

This article discusses key aspects of the collection, processing, and publication of DD data within the INTERMAGNET network.

1. Introduction

The global INTERMAGNET network (International Real-Time Magnetic Observatory Network) is a highly valuable initiative dedicated to the collection and provision of high-quality geomagnetic data (Love and Chulliat, 2013). While all INTERMAGNET observatories (IMOs) are affiliated to the International Association of Geomagnetism and Aeronomy (IAGA), not all IAGA observatories are part of INTERMAGNET. Although INTERMAGNET and IAGA serve different roles, they work closely together. IAGA establishes the scientific foundation and guidelines for observing Earth's magnetic field, whereas INTERMAGNET develops and implements the technical standards in practice, ensuring homogenous time series and the timely delivery of data. These efforts are essential for both scientific research and practical applications.

All INTERMAGNET observatories (IMOs) provide 1-minute data, while some IMOs also provide 1-second data. The data products they provide can be divided into two main categories.

1. **Near real-time data** – these datasets, referred to as **reported data**, are transmitted almost immediately after being recorded. However, their low latency offers rapid availability, they are not yet fully calibrated or verified by experts. Near real-time data are primarily used for operational monitoring, such as quality control, space weather forecasting, and the protection of critical infrastructure sensitive to high geomagnetic activity, both on Earth and in space.
2. **Delayed data** which include:
    - **Definitive Data (DD**) – These are the most accurate geomagnetic records, containing both geomagnetic variations and absolute field values, corrected using absolute measurements. They are processed after the end of each calendar year. The preparation process involves the removal of artificial disturbances, and the filling of data gaps using backup datasets when available. These datasets are thoroughly verified by experienced magnetologists before publication.

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- **Quasi-Definitive Data (QD)** – provided by INTERMAGNET observatories for over a decade, QD data are made available within three months of recording, Their quality is comparable to DD data (Peltier and Chulliat, 2010; Clarke et al., 2013). They are particularly relevant for the Swarm satellite mission (Macmillan and Olsen, 2013).

DD and QD data make INTERMAGNET stand out from other networks monitoring the Earth's magnetic field. They provide critical information about secular variation - slow changes in the Earth's internal magnetic field caused by core dynamics. Understanding secular variation is essential for studying the spatial and temporal properties of the geodynamo (Matzka et al., 2010). These datasets also contribute to the development of global models and maps, such as the International Geomagnetic Reference Field (IGRF) and the World Magnetic Model (WMM) (Macmillan and Quinn, 2000).

Here, we discuss the one-minute DD datasets provided by IMOs after the end of the calendar year. INTERMAGNET has established a peer-review system for these data. This cross-checking process involves expert evaluations by specialists in geomagnetic observations, ensuring that the published DD data are highly reliable and trusted by scientists, engineers, and decision-makers worldwide.

In the last section ~~(6)~~, we describe the policies and recent initiatives aimed at maintaining the highest data quality standards and at improving the timeliness and availability of these datasets

2. Policy for ensuring data quality

Since its inception, INTERMAGNET has emphasized the quality of data provided by observatories (Reda et al., 2011), particularly the Definitive Data set. This commitment is crucial as these data are used in scientific studies of the Earth's magnetic field and various geomagnetic models.

Only observatories that meet high-quality standards can join the INTERMAGNET network (St-Louis et al., 2020). One of the primary evaluation criteria is the analysis of baseline plots, that show the difference between the recording vector instrument and the manual absolute measurements. These plots provide important information about the quality of geomagnetic observations, including:

- Frequency and regularity of absolute measurements,
- Deviation of absolute measurements,
- Stability of the vector magnetometer used for recording geomagnetic field variations,
- Impact of external factors (e.g., seasonal, temperature) on recording equipment,
- Method and accuracy of determining adopted baselines.

Baseline plots analysis plays a key role in determining whether an observatory qualifies for inclusion in the INTERMAGNET network.

Final data should meet the standards of both IAGA and INTERMAGNET. For IAGA, the most important publication about geomagnetic observatories for nearly 30 years has been the IAGA guide written by J. Jankowski and C. Sucksdorff (1996), available at: http://www.iaga-aiga.org/data/uploads/pdf/guides/iaga-guide-observatories.pdf

The specific INTERMAGNET requirements outlined in the Technical Manual ((St-Louis et al., 2020), which is regularly updated. The latest version can be found here: https://tech-man.intermagnet.org/_/downloads/en/stable/pdf/

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All definitive data sets are reviewed before acceptance. If any concerns arise, feedback is sent to the observatory, requesting clarification or correction. Specific data or metadata issues are addressed through direct communications with the observatory, typically via email.

A fundamental principle of INTERMAGNET's policy is that the received data is never altered – any necessary corrections must be made by the observatories themselves as part of a self-correction process. The quality control of Definitive data is carried out by a team of volunteers experts from the Data Checking Task Team (DCTT), working in close collaboration with the INTERMAGNET Definitive Data Subcommittee.

3. Data Checking Task Team

The Data Checking Task Team (DCTT) is responsible for the review and verification of definitive datasets. This team consists of experienced volunteers, each assigned to a specific group of INTERMAGNET observatories (IMOs). The review process extends beyond analysing the time series of geomagnetic field components but also includes :

- Baseline values and their stability,
- Historical annual means,
- File formats and metadata,
- Compliance with INTERMAGNET standards,
- Overall data consistency.

Whenever possible, data are compared with those from nearby observatories, helping to detect unexpected jumps in absolute levels. The final approval for data publication on the INTERMAGNET website lies with the INTERMAGNET Definitive Data Subcommittee.

The review process promotes communication and knowledge sharing, benefiting for all participants. INTERMAGNET's quality control system ensures that users can trust the quality and reliability of Definitive data from the INTERMAGNET network.

More detailed information on the INTERMAGNET quality control system and the current list of DCTT members is available at: ~~https://intermagnet.org/data_checkers.html~~. The list of IMOs and their assigned data checkers may change from year to year. A detailed list is sent to observatories at the beginning of each year as part of the "Call for Data."

INTERMAGNET recognizes and appreciates the dedication of the ~~Data Ch g Team~~ members and their home institutions for their contribution to improving the quality of geomagnetic data.

4. Scope of control of 1-min Definitive data set

The complete dataset submitted by observatories at the end of the year includes several files (St-Louis et al., 2020) :

- Twelve final 1.minute binary data files (*.bin), oriented XYZG,
- One baseline file (*.blv),
- One observatory readme file,
- One yearmean file, listing annual mean values for the observatory,
- One country readme file (text),
- One About-screen (graphic) for the country file.

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These files vary in type and format, including binary files, text files and graphics files. Most are binary files, in IAF format, containing 1-minute mean data series of the XYZF geomagnetic field or K magnetic activity índices, along with essential metadata, such as :

- IAGA code of the observatory,
- Geographic coordinates and elevation,
- Code of the parent institution,
- K9-limit for magnetic activity indices,
- Original sampling period of the recording equipment,
- Original sensor orientation
- Hourly means
- Daily means
- K values

Readme text files provide information about the observatory, parent institutions, observers and responsible personnel, and observations notes. Files with the BLV extension contain valuable information about absolute measurements of the Earth's magnetic field and adopted baseline. Yearmean files contain yearly mean values observed since the beginning of the observatory's operation.

Since some metadata such as geographic coordinates appears in different files, an important aspect of quality control is detecting inconsistencies within the dataset.

When reviewing 1-min data time series, the visual assessment of the magnetic field recordings is a key step to detect discrepancies between Fv ($Fv = \sqrt{Fx^2 + Fz^2}$) and Fs (Fs recorded by an absolute scalar magnetometer like proton or overhauser magnetoemter). Additionally, visually comparing the time series of a given observatory with those from neighboring observatories often provides valuable insights.

Accepted Definitive data are publicly available at:

1. INTERMAGNET Website : https://imag-data.bgs.ac.uk/GIN_V1/GINForms2,
   Provides 1-minute XYZF time series following approval by a DCTT volunteer and the INTERMAGNET organization.
2. DOI publication of the INTERMAGNET Reference Dataset (IRDS), available at:
   https://intermagnet.org/data_download.html#downloading_data_using_dois,
   It contains the most recent data updates for the entire INTERMAGNET network, dating back to 1991 along with time series, baselines, K indices, historical yearly averages and readme files.

5. Software for data quality control

Over several decades of INTERMAGNET's operation, various software tools has been developed for viewing, analyzing, converting format, and verifying geomagnetic data from geophysical observatories. Some of these tools are publicly available and are regularly updated for anyone interested. A list of available software, along with download links, can be found on the INTERMAGNET website https://intermagnet.org/software.html .

The notable programs are:

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- IMCDViewer — A Java application designed to work with IAF binary files and other types of files provided by observatories at the end of the year. The program enables the visualization of minute, hourly, and daily data, baseline values, three-hour local geomagnetic activity indices (K), readme and graphical files (Dawson et al., 2009). It is useful for data quality control and allows data comparison between observatories. The program requires data to follow the structure defined for INTERMAGNET CD/DVDs. An example of data visualization using IMCDViewer is shown in Fig. 1.
- MagPy — A Python-based software package for analyzing and visualizing geomagnetic data (Leonhardt et al., 2013). It allows file conversion of various formats, data plotting, and mathematical calculations related to geomagnetism, such as baseline determination and trend analysis. An example of MagPy's visualization capabilities is shown in Fig. 2.
- gm_convert — A Java application for converting between various geomagnetic data formats: WDC, IMFV, IAGA2002, ImagCDF, and Intermagnet-DKA. It can operate in both graphical and command-line modes.
- check1min — A Windows console command-line tool that checks whether files comply with required formats. It focuses mainly on verifying the consistency of IAF files with other files in the yearly dataset. A key feature is the ability to compare annual averages from yearmean files with those computed from IAF files.

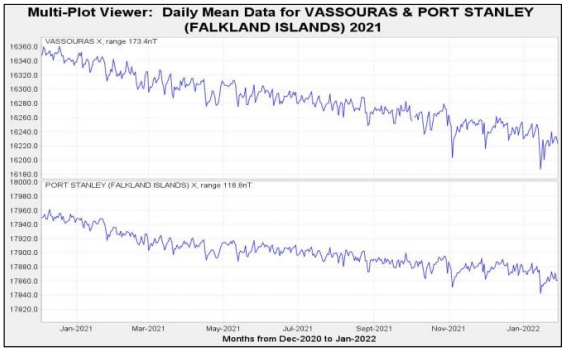

Fig. 1. IMCDVIEW. Data quality control by comparing the X component of two observatories (here VSS and PST) for December 2020 to January 2022.

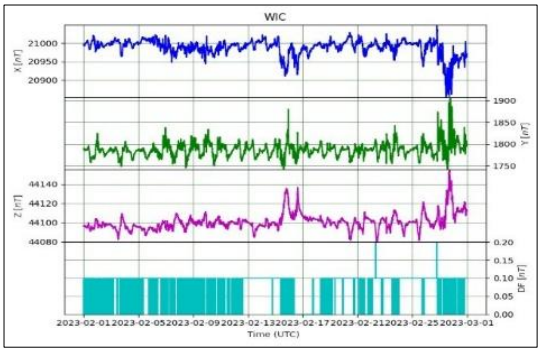

Fig. 2. MagPy. Graphical visualization of XYZ for one month (here for observatory WIC).

6. Policy for improving data availability

In recent years, INTERMAGNET has made significant efforts to improve the availability and timeliness of Definitive Data. Recognising the scientific community's growing need for faster access to high-quality datasets, much effort has gone into streamlining the data review process. Volunteers from the Data Checking Task Team (DCTT) are adopting improved workflows leading the elaboration of a condensed, standardised guidelines for data checking. They also communicate more frequently with

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observatories to accelerate the identification and resolution of issues. Furthermore, the process for publishing datasets with Digital Object Identifiers (DOIs) is undergoing an important evolution. Historically, INTERMAGNET would wait until datasets from all participating observatories (IMOs) were finalised before issuing the annual DOI publication. Moving forward, the DOI publication process will become incremental, allowing individual observatory datasets to be published as soon as they pass review. This change will eliminate the bottleneck caused by delays at individual observatories, ensuring that high-quality Definitive Data are made available to users more rapidly while maintaining rigorous quality standards.

7. Conclusion

Thanks to its rigorous quality assurance policy, two-stage verification process, and the dedication of volunteer experts, the INTERMAGNET network provides high-quality Definitive Data (DD). The C g Task Team (DCTT), plays a key role in reviewing and validating submission, ensuring accuracy and consistency of DD. This thorough verification process makes DD a reliable source of information for both scientific research and practical applications. Although DD ~~data~~ undergo publication delays**,** they provide the accuracy and long term homogeneity of the time series that is necessary for analyzing secular changes in the Earth's magnetic field and for space climate studies. Further development of quality control methods and the development of analytical tools for data verification will be crucial for maintaining INTERMAGNET's high quality data standards.

Author contribution

Reda J. and Heumez B. collected the information needed for the article. Reda J. and Matzka J. developed the overall concept and structure of the paper. All authors contributed to editing and revising the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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