INTERMAGNET Technical Note

Title: INTERMAGNET Definitive One-second Data Standard

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Purpose of document:

Terms of Reference

1. To document the derivation of an INTERMAGNET standard for definitive one-second data.
2. To derive the standard in conjunction with the INTERMAGNET Observatories and the Instrument & Data Acquisition Subcommittees, observatory operators, instrument developers and the user community

Date due:	**Date submitted:** **Date revised:**

Outcomes: *(Actions assigned and decisions made)*

Note for information

INTERMAGNET Technical Notes are designed to record information on how to accomplish technical tasks. They will often describe alternative approaches, and make recommendations on the practice to be adopted by INTERMAGNET. In many cases a Technical Note will be used as the basis for an entry in the Technical Manual.

The Secretary of the Operations Committee assigns the Document Number, maintains the metadata on the cover sheet, and keeps an index of all documents. Documents to be archived and indexed will be given integer version numbers. Working documents will have fractional version numbers. Only the lead author may edit the main text.

1. Introduction

This document records discussions held by the INTERMAGNET Operations Committee, instrument manufacturers and observatory operators in reaching a consensus on a standard applicable to future distribution of definitive one-second data via the INTERMAGNET network. The standard will be defined and, where possible, tested to be the minimum quality requirements for definitive one-second data to be distributed via the INTERMAGNET web site and DVD.

The INTERMAGNET network will continue to distribute one-minute data and the definitive one-minute standards are unaffected by the one-second standards defined here.

These standards apply to definitive one-second data and do not necessarily apply to preliminary one-second data.

Reference is made in this document to the existing one-minute data standard as documented in the current Technical Manual (V4.4 (2008)) and to INTERMAGNET Discussion Document DD17 (Digital filter for one-second data)

2. General Specification for one-second data

With the advent of developments in instrumentation, data acquisition and data dissemination, an increasing number of observatories are producing a filtered one-second data product in addition to traditional one-minute data, hourly means, daily means, monthly means and annual means. An INTERMAGNET survey of the user community in 2005 concluded that there is a desire for one-second data to be made available through the INTERMAGNET network and that, as is the case for one-minute data, a minimum quality standard should be set for definitive one-second data. The user community was also asked to provide a broad outline of what the minimum standard should be. The consensus of the eight responses was:

Data Resolution: 0.01 nT

Filter Preferences: Digital, uniform

Timing Accuracy: 0.01 s centred on the UT sec

3. Definitive one-second standard

The parameters listed below describe the specifications of a complete observatory system for a one-second vector data set including recording environment, magnetometer, and data processing procedure:

General specifications

- Time-stamp accuracy (centred on the UTC second): 0.01s[1]
- Phase response: Maximum group delay: ±0.01s[2]
- Maximum filter width: 25 seconds[3]
- Instrument amplitude range: ≥±4000nT High Lat., ≥±3000nT Mid/Equatorial Lat.
- Data resolution: 1pT
- Pass band: DC to 0.2Hz

Pass Band Specifications [DC to 8mHz (120s)]

- Noise level: ≤100pT RMS[4]
- Maximum offset error (cumulative error between absolute observations): ±2. 5 nT[5]
- Maximum component scaling plus linearity error: 0.25%
- Maximum component orthogonality error: 2mrad
- Maximum Z-component verticality error: 2mrad

Pass Band Specifications [8mHz (120s) to 0.2Hz]

- Noise level: ≤10pT/√Hz at 0.1 Hz
- Maximum gain/attenuation: 3dB

Stop Band Specifications [≥ 0.5 Hz]

- Minimum attenuation in the stop band (≥ 0.5Hz): 50dB[6]

Auxiliary measurements:

- Compulsory full-scale scalar magnetometer measurements with a data resolution of 0.01nT at a minimum sample period of 30 seconds.
- Compulsory vector magnetometer temperature measurements with a resolution of 0.1°C at a minimum sample period of one minute.

Notes:

[1]Maximum time-stamp error (from the UTC second) in any of the three variometer channels. Samples may be time-shifted to correct for latency.
[2]The system phase response should approximate to linear, the limits of which are given in terms of a maximum permissible group delay (i.e. the frequency derivative of phase).
[3] Imposed to minimise the time extent of the system response to a step input.
[4] Measured over a minimum time window of 10 minutes
[5] Maximum low frequency instrumental error, including instrumental & thermal drift.
[6] The system response must be such that aliased natural signal (i.e. above the Nyquist) will be attenuated to below the specified noise level of 10pT, assuming maximum input signal amplitude of 3nT. Non-natural signal (e.g. 50/60 Hz) must be separately attenuated to below 10pT/√Hz.

4. Time-stamp Accuracy

Maximum time-stamp error of 0.01s in any of the three variometer channels. Samples may be time-shifted to correct for latency, such that the total system delay (instrument response and analog & digital filter delays) is less than 0.01s and the system phase response, detailed below, is met.

An original proposal to restrict time-shifts to integer sample periods has been removed now that an allowance for a degree of non-linearity in phase has been adopted.

5. Phase Response

Ideally, the phase response would be linear i.e. the latency across all frequencies in the pass-band is fixed and complies with the specified time-stamp accuracy, which would imply a symmetrical, causal digital filter. However, this is not sufficiently specific for a real world system, where there will be a finite frequency-dependent latency. Specifying strictly linear phase (and hence a symmetrical filter) also restricts the time-shifting of samples to integer sample intervals, which restricts solutions to high-frequency sampling to overcome this.

Rather than specify linear phase, it is proposed to put some bounds on the linearity by means of specifying the permissible system group delay. Group delay is defined as the frequency derivative of phase. Hence a linear-phase system has a constant group delay and the value of the group delay is equal to the latency.

What the specification should ensure is that, at all frequencies in the pass-band, the timing error of the total system (including post-processing) is less than the time-stamp accuracy, hence the system response is specified as having a group delay within ±0.01s. This allows for a degree of non-linearity in phase and, by removing the necessity for a symmetrical filter, would permit phase rotation in post-processing. This would also permit a re-sampling of the Gaussian filter with a limited time-shift, provided that the resulting non-linear phase meets the group delay specification.

6. Maximum filter width

The maximum width of the digital filter is set to 25 seconds to minimise the time extent of the system response to a step input i.e. filter ringing.

7. Instrument Amplitude Range

Some studies suggest that extreme geomagnetic events could exceed the instrument range set above (e.g. Thomson et al., 2011), saturating the instrument. However, it is recognised that typical variometers have a limited dynamic range such that the instrument range cannot be increased without a detrimental effect on the minimum resolvable signal. Hence, to meet the noise levels specified above, the instrument amplitude range is specified to be the same as the one-minute data standard.

Although not part of the INTERMAGNET one-second data standard, it is recommended that the following are considered to reduce the probability of instrument saturation during extreme geomagnetic events,:

- Operation of separate low-gain instruments (i.e. instruments of large amplitude range)
- Offset of the H-component to compensate for the fact that the H-component tends to decrease during a magnetic storm
- Operation of auto-ranging instruments

8. Pass band

The system pass band of DC to 0.2 Hz has been set to adequately capture signal of interest with minimal attenuation, while allowing sufficient bandwidth between the pass band and the Nyquist to permit a high attenuation in the stop band.

9. Noise level

The noise level is defined by the 'data resolution' parameter resulting from the user survey and is taken to be the minimum resolvable signal by the system; hence a value of 10pT/√Hz at 0.1 Hz has been specified. 0.1 Hz is chosen to be representative of the signal of interest in the band 8mHz to 0.2Hz,

There is a possibility that large non-natural signals in the stop band (e.g. 50/60 Hz) could be aliased into the pass-band at frequencies other than 0.1Hz and still meet this specification, hence the recommendation to separately attenuate (e.g. by a notch filter) non-natural, large-amplitude signals above the Nyquist.

10. Maximum attenuation in the pass-band (≤ 0.2Hz)

An original specification of pass-band rippled "<10pT in the band DC to 0.2Hz at full dynamic range", implied attenuation at the corner frequency (0.2 Hz) at less than 11µdB at 8000 nT, which is unachievable in an analog system if the stop band attenuation is to be met.

Hence, the decision was made to split the pass-band into the existing low-frequency band for one-minute data (DC to 120s) and the extended band for one-second data (0.008Hz – 0.2Hz). The low-frequency band is where absolute accuracy and low ripple is required and the high-frequency band is where these parameters can be relaxed to meet the roll-off characteristics necessary to achieve stop-band attenuation.

It is proposed to set the maximum attenuation in the high-frequency band [0.008Hz – 0.2Hz] to 3dB, thus preserving signal in this extended band whilst allowing roll-off the transition band (0.2Hz – 0.5Hz) to meet the stop-band attenuation.

Attenuation in the low-frequency band [DC – 120s] is discussed separately below.

11. Minimum attenuation in the stop-band (≥ 0.5Hz)

A value of 50dB is sufficient to attenuate typical natural signal amplitude in the stop band (< 3nT) to below 10pT to meet the noise specification for aliased signal in the pass band.

As indicated previously, this specification alone will not sufficiently attenuate large amplitude (up to full range) signal, such as 50/60 Hz, hence the recommendation to separately attenuate (e.g. by a notch filter) non-natural, large-amplitude signals above the Nyquist.

12. System response in the low-frequency band (DC to 0.2Hz)

This band matches that covered by the pre-existing one-minute standard. However the one-minute standard does not adequately describe the absolute accuracy and low noise specifications required in this band. Data in this band are typically the product of more than one instrument (variometer and absolute) and the band is too broad to be identified by a single attenuation parameter.

As an illustration; the pre-existing one-minute absolute accuracy standard of ±5 nT is equivalent to an attenuation of <14mdB on a ±3000nT signal - the maximum measurable signal at mid-latitude - which is difficult to achieve as it sets a very tight specification on the instrument parameters including linearity, scale value and orthogonality. On the other hand, the specification is very loose in that it allows a noise signal of ±5nT at a period of two minutes.

To resolve this, the specifications in this band are proposed as stated to be more closely aligned to the instrumentation.

<u>Noise level</u>: If magnetometer noise power spectral density (PSD) was solely 1/f dependent, then a specified noise limit at 10 minutes (1/600 Hz) could be derived from the noise PSD at 0.1 Hz:

$$e_1^2 = e_2^2 \frac{f_2}{f_1}$$

Given that the noise amplitude limit is specified as 10 pT/√Hz (e_2) at 0.1 Hz (f_2), the purely 1/f noise PSD limit at 1/600 Hz (f_1) would be approximately 80 pT/√Hz.

To express this as an RMS value, the noise is integrated over the band. Still assuming that the noise is purely 1/f in nature, the total RMS noise in the band (f_1 - f_3) is given by:

$$e_{RMS}^2 = \int_{f_1}^{f_3} e_2^2 \frac{f_2}{f}\, df = e_2^2 f_2 \left(\ln f_3 - \ln f_1\right)$$

Hence, for the band defined by the minimum time window in the specification (1/600 Hz to 0.5 Hz), e_{RMS} for purely 1/f noise would approximate to 8pT RMS, which is considerably less than the value of 100 pT RMS proposed in the specification. However, the noise in this band is not solely 1/f in nature, with sources from component drift, man-made noise and temperature. Because of this, and the fact that the geomagnetic spectrum attenuates with frequency (Constable and Constable, 2004), the noise amplitude specification in the DC to 0.2Hz band has been set at a more relaxed limit.

By the same approximation (i.e. assuming that the system noise is purely 1/f in nature), a noise limit of 10 pT/√Hz at 0.1 Hz is equivalent to a limit of 4pT RMS over the band 0.1 Hz to 0.5 Hz.

<u>Maximum offset error</u>: This term specifies a maximum low frequency instrumental error, including instrument drift and thermal drift. Designed to replace the one-minute specified accuracy of ±5 nT and the requirement to make observations every two weeks. Instead, there is no specification on the frequency of absolute observations, other than they must be sufficient to achieve the specified maximum offset error under quiet geomagnetic conditions. This means that observations may be less frequent for systems with stable baselines.

<u>Maximum component scaling plus linearity error</u>: This parameter specifies the limits of the system calibration in the low frequency band. It is recognised that in setting a limit of 0.25%, this creates an inconsistency with the specified maximum offset error of ±2.5nT for variations in the magnetic field over 1000nT. Such large disturbances are considered to be of sufficiently

short duration that it is reasonable to specify errors during these periods in terms of percentage accuracy at the expense of absolute accuracy. In other words, the scaling & linearity error could be considered to apply to the higher frequencies in the DC to 0.2Hz band and the maximum offset error to the lower frequencies without explicitly specifying a delineating frequency. The inconsistency between the two standards is deemed necessary in order to specify an achievable system calibration parameter, whilst also specifying an absolute accuracy level that applies during normal conditions i.e. the significant proportion of the time series.

13. Data resolution

Data resolution only refers to the size of the number field in the data format and not the resolvable signal in the data. A data format of 1pT resolution is necessary to avoid quantisation errors of the order of the noise level set for one-second data (10pT/√Hz).

To illustrate this, IAGA-2002 data format has a fixed resolution of 10pT for X, Y, H, Z and F-components. This introduces an RMS quantisation error given by:

$$e_q = q/\sqrt{12}$$; where q is the quantisation in pT (1)

Equation (1) is a generally accepted estimate of quantisation error for an ideal digitiser and an ac input signal (http://www.analog.com/static/imported-files/tutorials/MT-001.pdf). In practice, the quantisation error will be larger than this as decimation by the digitiser may not be ideal (e.g. unevenly distributed rounding errors in the conversion process to IAGA-2002) and the input signal may not be normally distributed (as in the case of natural geomagnetic variation). The quantisation error in equation (1) is uniformly distributed across the band of interest, so can readily be converted to linear spectral density value e'_q in pT/√Hz:

$$e'_q = e_q/\sqrt{\Delta f}$$; where Δf is the bandwidth (2)

The one-second data specification defines a maximum noise budget (e_n) at 0.1 Hz of 10 pT/√Hz, which is the power sum of all the noise sources including quantisation noise from equation (2):

$$\sqrt{e_s^2 + e'^2_q} = e_n$$; where e_s is the actual system noise limit (3)

Hence the allowed system noise limit is given by rearranging equation (3):

$$e_s = \sqrt{e_n^2 - e'^2_q} = \sqrt{e_n^2 - \frac{e_q^2}{\Delta f}}$$ (4)

Substituting the one-second data bandwidth Δf=0.5 Hz, the IAGA-2002 quantisation q=10pT and the maximum noise budget into equation (4) gives an actual system noise limit of 9.1 pT/√Hz at 0.1 Hz rather than intended the 10 pT/√Hz. Hence, to avoid introducing significant quantisation noise, one-second data resolution should be 1 pT or better,

14. Component Orthogonality

This is specified as final data component orthogonality rather than the sensor orthogonality to allow for non-orthogonality correction to raw sensor data. The specified value of 2mrad is the maximum error on existing DTU FGE sensors and equates to 0.0002% error to the measured component, or 0.2% error to an orthogonal component, however, gross errors can occur when a component is used to align the variometer, but is contaminated by another, larger component.

As an example: for a fluxgate magnetometer oriented in HEZ configuration, the deviation from horizontality of the E-sensor (θ) is critical as it results in an effective offset in the E-sensor:

Eoff = Zsin(θ)

When aligning the sensor, this offset is erroneously compensated for by rotating the E-sensor by an angle (α) about the vertical axis until the E-sensor output is zero:

Eoff = Hsin(α)Hcos(θ) which approximates to Hsin(α)
i.e. Zsin(θ) ≈ Hsin(α)

Given that at mid-latitude, the proportion between H and Z is of the order of 1:3, the proportion of $\alpha:\theta$ is approximately 3:1 i.e. contamination in E of 0.6% of the H variation for an original offset θ=2mrad.

15. References

Constable, C.G., & S.C. Constable, 2004. Satellite magnetic field measurements: applications in studying the deep earth. In “The State of the Planet: Frontiers and Challenges in Geophysics”, ed. R.S.J. Sparks and C.J. Hawkesworth, American Geophysical Union. DOI 10.1029/150GM13, pp. 147–160.

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