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RESEARCH PAPER

Analysis of Several Years of DI Magnetometer Comparison Results by the Geomagnetic Network of China and IAGA

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The comparison of absolute geomagnetic instruments is an important component of geomagnetic observation. To promote high quality standards in geomagnetic data acquisition, the International Association of Geomagnetism and Aeronomy (IAGA) organizes an international comparison every two years. In China, this comparison is part of quality control process for geomagnetic observation data, and is organized by the Geomagnetic Network of China (GNC). In this paper, the comparison results from several years are analysed in detail, and some useful information is presented that will help to guide the observatory's future observation work and improve data quality. In addition, the quality of the absolute observation data of GNC and IAGA is evaluated using a statistical method. This should aid scientists who use these data to understand their research results.

Keywords: Data quality; Comparison; Absolute measurements; DI magnetometer; GNC; IAGA

1 Introduction

Geomagnetic observatories use variometers to record the continuous variations of the geomagnetic field. The continuous absolute geomagnetic field can be determined by adding a value, known as the baseline and calculated by the absolute measurement results, to the variations (Bitterly et al., 1984; Jankowski and Sucksdorff, 1996). Therefore, for a geomagnetic observatory, the absolute measurements play a decisive role in the quality of continuous absolute value. At different observatories, the differences between these absolute instruments cannot be ignored. Thus, comparisons of the absolute instruments become an indispensable part of geomagnetic observations. Currently, the absolute measurements are made by the modern high precision fluxgate theodolite (to measure declination, D, and inclination, I) and proton magnetometer (to measure the magnetic field, F). The comparisons are no longer needed as frequently as before. However, they are still useful for achieving high-quality data of the continuous absolute geomagnetic field.

To promote high-quality data in geomagnetic observation, the International Association of Geomagnetism and Aeronomy (IAGA) Division V Working Group V-OBS organizes an international comparison every two years. To date, 18 comparison sessions have been conducted and the results published online or in papers. In China, the comparison is also partly of the quality control work of the Geomagnetic Network of China (GNC), which is both the data centre and the quality control centre of the observatory's observation data (Zhang et al. 2016). Since the beginning of the observatory digitization, several types of declination-inclination magnetometers (DIMs) have been successively introduced into the observatory of the GNC for absolute measurements, for example, Chinese CTM DIM, Hungarian MINGEO DIM, British MAG-01 DIM, Chinese GEO DIM, and Chinese TDJ2E-NM DIM. As all of these DIMs are operated manually, the systematic differences between them and the individual differences between the observers are unavoidable in the measurement process. To achieve high data quality and unify the observation standards of observatories, the GNC so far has organized and completed several comparisons.

Absolute measurements are important for the defining continuous absolute observation data. Thus, this paper only focuses on the DIM comparison session, in which a large number of absolute measurements are made. The results from several years of the DIM comparison organized by GNC and IAGA are collected here. It hopes that some useful information can be found through detailed analysis, which will be helpful for identifying the error in absolute measurements and ensuring better quality control. The data quality also can be estimated by these results, which will help the researchers who use the data to understand the current quality level of absolute measurements and their research results. The measurement and comparison methods are described in Section 2, the results and analyses are displayed in Section 3, and the conclusions to this study are given in Section 4.

2 Measurement and comparison method

2.1 Measurement method

The geomagnetic field is a vector field that needs to be measured in terms of its size and direction. DIMs consists of a nonmagnetic theodolite and a fluxgate sensor, are the standard instrument for measuring the geomagnetic field direction (*D* and *I*). The fluxgate sensor mounted on the top of the theodolite's telescope is nearly aligned with the optical axis. The fluxgate sensor outputs a null signal when the geomagnetic field is perpendicular to the sensor direction. Thus, the direction of the geomagnetic field can be determined by looking for the position where the sensor's output is null, and the position can be recorded by reading from the circle of the theodolite. For any two directions read from the circle of the theodolite, the angle between them can be obtained by calculating the difference. This is the basic principle of measurement.

The measurement of the geomagnetic declination and inclination are realized in the horizontal and vertical plane of the theodolite, respectively. To measuring the declination *D*, the telescope axis must be in the horizontal plane, so the first task is to level the theodolite using its bubble levels and leveling screws. As the fluxgate sensor axis perpendicular to the magnetic meridian, *D* is determined by the horizontal geomagnetic field and the true north direction, so there are two main steps in measuring declination. The first step is to measure the true north direction. The observer should adjust the telescope to ensure that the optical axis is aligned with the azimuth mark, and then record the reading of horizontal circle, denoted by *M* and shown in **Figure 1**. The azimuth of the mark, represented by *A* is already known, so the position of the true north direction can be calculated. The second step is to establish the geomagnetic field direction. The observer should adjust the telescope on the horizontal plane so that the theodolite vertical circle reading is exactly 90° or 270°, then search for the position at which the sensor output is null and record

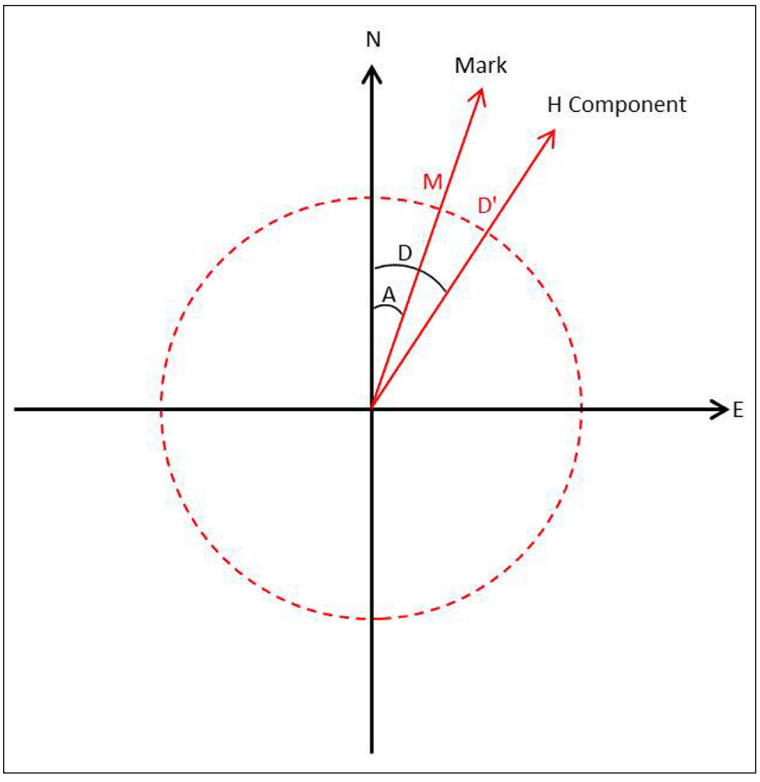

Figure 1: The main measuring principle of the declination.

the horizontal circle reading of the geomagnetic field, indicated by D'. Finally, the geomagnetic declination D can be computed from the circle readings as:

$$D = D' - M + A \tag{1}$$

To measuring inclination I, the telescope axis must be fixed in the geomagnetic meridian plane. The measurement is then performed by searching the sensor's null position. This is the same process as for the declination, although the measurement is carried out without a measuring mark. This is the main measurement process.

Note that a measurement with a DIM refers to a set of measurements, as elimination of instrumental errors necessitates at least four individual measurements for the declination D and two measurements for the inclination I (Rasson, 2005). In the actual measurement procedure, four observation positions of the telescope are needed to determine one direction: telescope towards East and sensor up (D_1), telescope towards West and sensor down (D_2), telescope towards East and sensor down (D_3), and telescope towards West and sensor up (D_4). Then mean of the four readings gives the final measurement result, expressed by

$$\overline{D'} = \left(D_1 + D_2 + D_3 + D_4\right)/4 \tag{2}$$

The same procedure is also applied to the inclination measurement. Again, four observation positions are possible, of which two are sufficient for error correction. In this case, the observation positions are telescope towards North and sensor up (I_1), telescope towards South and sensor down (I_2), telescope towards North and sensor down (I_3), and telescope towards South and sensor up (I_4). The final inclination is the mean of the four readings, i.e.,

$$I = \left(I_1 + I_2 - I_3 - I_4\right)/4 + 90 \tag{3}$$

The misalignment between fluxgate sensor and optical axis can be compensated in this way. In addition, there are two methods for the circle reading, namely the null method (exactly zero) and the offset method (near zero). The detailed measurements procedure is described in the IAGA guide (Newitt et al., 1996). The two methods have been discussed by Xin (2003), Lu (2008) and Deng (2011). They found that if the output of the theodolite was linear, the offset method could achieve the same accuracy as the null method, even if the observer had slightly magnetic material. Usually, the modern theodolite output is highly linear, so the offset method is frequently used for the measurement. The unique absolute vector geomagnetic field can be determined by D, I and F (measured by a proton magnetometer), and the baselines of each component of the variometer can be calculated. Note that considerable effort has been directed toward the development of new observation technology (Auster et al., 2003; Rasson et al., 2011). Recently, some automatic DIMs have been realized and are performing some observations (Gonsette et al., 2017; Hegymegi et al., 2017; Brunke et al., 2018). In the future, the automatic instruments would allow completely unattended magnetic observatory operation.

2.2 Comparison method

To achieve high-quality data in geomagnetic observation, the differences between absolute instruments from different observatories should be checked. Thus, comparisons of the absolute instruments are an indispensable part of geomagnetic observation. There are two main ways to determine the difference between instruments: direct comparison by simultaneous measurements and indirect comparison by comparing the reference values. If two or more pillars are available for the absolute measurements, the instruments can be compared directly through simultaneous measurements. Both the instruments' difference and the pillars' difference can be obtained by interchanging the instruments' location and applying the same observation method. The instruments' difference for arbitrary component W and pillars' difference for two arbitrary pillars can be calculated by the following equation:

$$\Delta W_{pq} = [(W_{ps} + W_{po}) - (W_{qs} + W_{qo})]/2 \tag{4}$$

$$\Delta W_{so} = [(W_{ps} + W_{qs}) - (W_{po} + W_{qo})]/2 \tag{5}$$

where, p, q denote the different instruments and s, o represent the standard pillar and other observation pillar, respectively. ΔW_{so} is the pillar difference between the standard pillar and other observation pillar,

and ΔW_{pq} is the instruments' difference. As an example, W_{qs} represents the observation value measured by instrument q installed on pillar s.

As there are a limited number of the pillars, a large number of DIMs, and variable proficiency in the observation techniques of observers, it is difficult to complete the comparison using simultaneous measurement. As modern variometers are rather stable and offer high precision, the baselines are almost constant. Therefore, the comparison is usually achieved by comparing the adopted baseline values. The stability and accuracy of baseline values in one calibration day have been analysed by Zhang (2011), who stated that the baselines were stable during the calibration day from 8:30 to 16:30 local time, and the geomagnetic field activity showed no obvious influence on the accuracy of baseline values. Thus, it is feasible to complete the comparison by comparing baseline values. The equation for computing baseline value for arbitrary component W is given in the INTERMAGNET reference manual (St Louis, 2011) as:

$$W_B(k) = W_O(i:j) - W_R(k) \tag{6}$$

where, $(i:j)$ is the time interval (generally several minutes) for the measurement, (k) is the average time of the interval $(i:j)$, W_o is the observed absolute field value, W_R is the minute value recorded by variometer, and W_B is the computed baseline value.

In comparison session, the reference level for arbitrary components is usually adopted from the average of all the measurements performed by the participants on the reference pillar. Since absolute measurements were made on different pillars, the baseline values measured on other pillars should be calibrated to the reference pillar for comparison. The usual calibrating method is to add a pillar difference to the results of other pillars. The pillar differences are determined by extensive measurements made prior to the comparison session. The general form of the equation for computing the difference for arbitrary component W is:

$$\Delta W_{Bso} = W_{Bs} - W_{Bo} + \Delta W_{so} \tag{7}$$

where, s and o represent the standard pillar and the other observation pillar, ΔW_{so} is the pillar difference between the standard pillar and other observation pillar, W_{BS} and W_{Bo} are the computed baseline values, and ΔW_{Bso} is the final difference between two instruments. The fluxgate theodolites from different observatories can be compared in this way, and the quality of the absolute observation data can be evaluated using these results.

3 Results and discussion

Since observatory data first began to be digitized, several comparisons have been performed. Some of the DIM comparison results from GNC and IAGA are analysed here. The quality of the observed data is evaluated and certain problems are identified.

3.1 The comparison results of GNC

Six comparisons have been organized by the GNC. Previously, the comparison is organized every two years following the IAGA's guide; recently, due to the frequent turnover of staff, it is made every year. They were carried out at Changchun observatory in 2010; at Qianling, Dalian and Shaoyang observatories in 2012; at Qianling observatory in 2014 and 2016; at Urumqi observatory in 2015 and 2017. Most of DIMs from geomagnetic observatories in China have taken part in the comparison. The comparison information is list in **Table 1** and the DIM types and observatories are presented in **Table 2**. The difference between the observation instruments and standard instruments were calculated by comparing with the standard baselines which measured by skilled observer using the standard instruments. Now, all the comparison results are collected together and sorted by DIMs. The difference in declination and inclination are, respectively, displayed in **Figures 2** and **3**. As shown in **Figure 2**, the colored dots represent the mean value, the sizes of the dots indicate the standard deviation and the colors represent the different years; the grey dots on the right show the scale of the colored dots. The grey bars, corresponding to the right-hand vertical axis, indicate the standard deviation of the comparison results of each instrument over the six years of comparisons. The right-hand panel shows the frequency distribution of all of these results. The mean and standard deviation of these results over the six years are 0.01′ and 0.15′ for ΔD, –0.02′ and 0.07′ for ΔI, respectively.

As shown in **Figures 2** and **3**, almost all coloured dots are distributed within one standard deviation of the mean. For ΔD and ΔI, 75% and 77% of the comparison results are within this range, respectively. To some extent, the standard deviation represents the quality of absolute observation data of the GNC. To estimate the quality, a value range of 90% of the cumulative probability is considered as the quality level

Table 1: List of DIM comparisons performed by GNC.

No.	Date	Year	Observatory	Instruments Number	Elements
1	14–17 September	2010	Changchun	15	ΔD and ΔI
2	10–12 September, 17–19 October, 24–26 October	2012	Qianling, Dalian, Shaoyang	31	ΔD and ΔI
3	21–26 October	2014	Qianling	41	ΔD and ΔI
4	15–20 September	2015	Urumqi	41	ΔD and ΔI
5	21–29 September	2016	Qianling	40	ΔD and ΔI
6	12–20 September	2017	Urumqi	41	ΔD and ΔI

Table 2: List of instrument types and observatories.

No.	Instrument	Observatory	No.	Instrument	Observatory	No.	Instrument	Observatory
1	Mingeo	Beijing	22	Mingeo	Lanzhou	42	GEO-DI	Taian
2	Mag01	Changli	23	Mag01	Lijiang	43	CTM	Taian
3	CTM	Changli	24	Mingeo	Luoyang	44	Mag01	Tianshui
4	Mingeo	Chengdu	25	Mingeo	Malingshang	45	Mingeo	Tonghai
5	Mag01	Chengdu	26	Mingeo	Manzhouli	46	Mingeo	Wujiahe
6	Mag01	Chongming	27	CTM	Manzhouli	47	Mingeo	Urumqi
7	TDJ2E-NM	Chongming	28	Mag01	Mengcheng	48	Mingeo	Wuhan
8	Mingeo	Dalian	29	CTM	Mengcheng	49	Mag01	Wuhan
9	Mingeo	Dedu	30	Mingeo	Qianling	50	CTM	Wuhan
10	Mingeo	Enshi	31	Mag01	Qianling	51	CTM	Xichang
11	Mingeo	Golmud	32	CTM	Qianling	52	Mag01	Xilinhot
12	Mingeo	Guiyang	33	Mag01	Qiemo	53	Mag01	Xiannushan
13	CTM	Hangzhou	34	Mingeo	Qiongzhong	54	Mingeo	Yinchuan
14	Mag01	Hangzhou	35	Mingeo	Quanzhou	55	Mingeo	Yongning
15	Mag01	Hongshan	36	CTM	Quanzhou	56	CTM	Yulin
16	TDJ2E-NM	Hongshan	37	Mingeo	Shaoyang	57	Mingeo	Changchun
17	Mingeo	Jiayuguan	38	Mingeo	Sheshan	58	Mingeo	Zhaoqing
18	Mingeo	Jinghai	39	Mag01	Shexian	59	Mag01	Zhaoqing
19	Mag01	Jinghai	40	Mingeo	Shiquanhe	60	TDJ2E-NM	Zhaoqing
20	Mingeo	Kashi	41	Mingeo	Taiyuan	61	Mag01	Chongqing
21	Mingeo	Lhasa						

Table 3: The statistical results of all the comparison data.

Elements	Mean (μ)	Std. (μ)	Percentage (μ ± σ)	Value range of 90% (±u)	Institution
ΔD	0.01′	0.15′	75%	±0.24′	GNC
ΔI	–0.02′	0.07′	77%	±0.11′	GNC

of the GNC in this study. In this way, obviously wrong data can be excluded and the true level of observation quality can be accurately reflected. From **Table 3**, the value ranges are ±0.24′ for ΔD and ±0.11′ for ΔI. Therefore, the absolute measurement accuracy of the GNC reaches 0.24′ in declination and 0.11′ in inclination. The gray bars in the figures show the standard deviation of the instruments over the six comparison

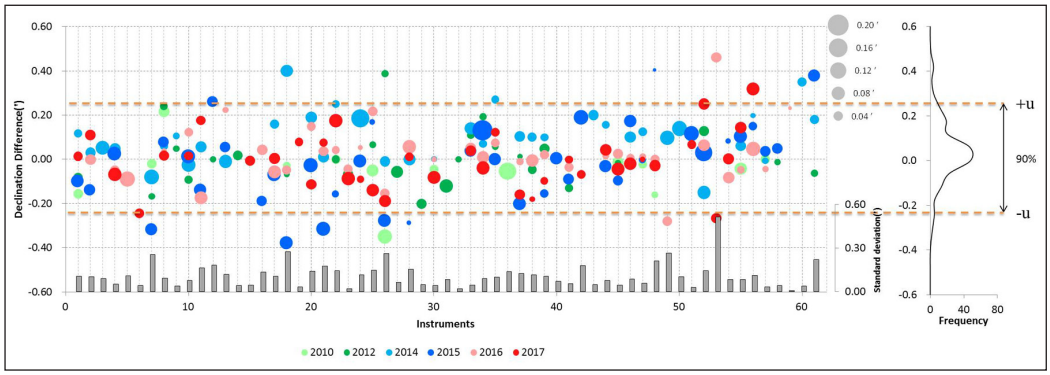

Figure 2: The difference of the declination of GNC. The balls represent the difference, the size of the balls is the standard deviation, and the scale is on the right. The grey bar, corresponding to the right vertical axis, is the standard deviation of the balls above it. The right panel is the frequency distribution of all of these results.

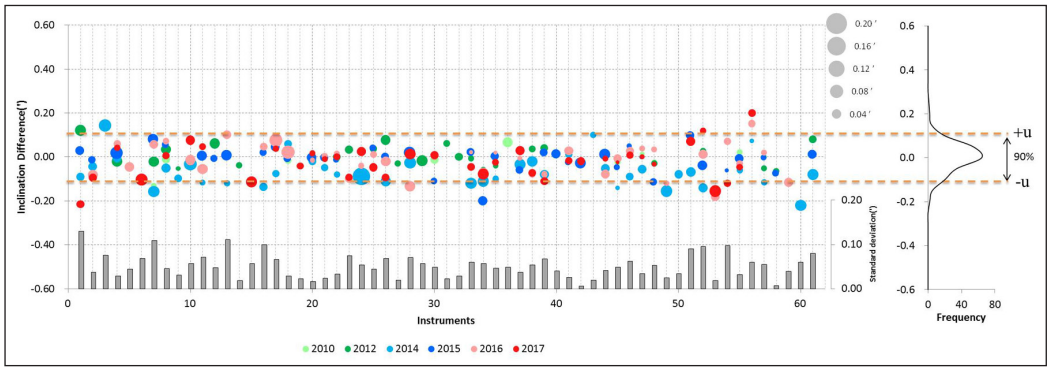

Figure 3: The difference of the inclination of GNC. The symbols have same meaning as those in Figure 2.

years, revealing the absolute measurement quality level of the observatories at which that instrument is located. The sizes of the dots represent the observation precision of each observer. **Figures 2** and **3** show that the absolute measurement quality of most observatories and the observation level of most observers are relatively high.

By comparing **Figures 2** and **3**, it is clear that the distribution of the coloured dots in **Figure 2** is more discrete than that in **Figure 3**. This indicates that the quality of the inclination observation data is superior to that of declination data. One reason for this difference may be that observers should adjust optical axis to align with the azimuth mark in the declination measurement, but it is difficult to adjust to the exactly same position each time. Thus, the declination measurement is more susceptible to error than the inclination measurement, and more observation errors may be included in declination results.

However, there are some outliers that are significantly beyond the range one standard deviation from the mean. Some of these large values can be traced back to the changes in the instruments themselves. For example, the declination difference of Manzhouli's instrument was –0.37′ in 2010, as shown by the light green dot (No. 26) in **Figure 2**. This became 0.39′ in 2012 after maintenance, as displayed by the green dot (No. 26). In 2014, when sensor when was mounted on the top of the theodolite from Jinghai observatory, the difference was 0.40′, as presented by the light blue dot (No. 18). This became –0.38′ in 2016 after maintenance, as shown by blue dot (No. 18). Although the cause of these changes is not clear, it is certain that this is a systematic error, which can be tracked through the course of the comparisons.

Some other instrument problems also can be observed in these results. Because of the limitation of non-magnetic materials, the horizontal axis (the rotation axis of the telescope) and vertical axis (the rotation axis of the alignment part) of the theodolite are not as hard as the other parts. If they were damaged, the measurement accuracy would be reduced. For example, the DIM at Luoyang observatory had some problems on the vertical axis in 2014, meaning that it could not be kept horizontal during measurements. That caused the absolute observation data to be unstable and have a large standard deviation, as shown in light blue dot (No. 24) in **Figures 2** and **3**. There are other factors that affect the final results. The environment of some observatories in southern China is very humid, so the interior of the theodolite are become mouldy and

the reading line of the theodolite can be unclear (e.g. Qiongzhong observatory, No. 34 both in **Figures 2** and **3**). A bad contact between the sensor and the cable can lead to unstable observation data; looseness of the sensor, resulting in its axial direction not being parallel to the optical axis of the telescope, can reduce the measurement accuracy. All of these problems can be identified through the comparison process and rectified by professionals.

The observation technology used by the observer is another important factor influencing the quality of observation data. In recent years, the staff turnover of observatory has been relatively high. For instance, in the 2015 comparison, nearly 30 percent of observers were novices. As shown in **Figure 2**, the degree of dispersion of the blue dots in 2015 is obviously greater than that in other years. A lack of systematic training on the principles and methods of observation means that new observer may make some mistakes in the measurement process. For example, when the telescope was not placed exactly on a horizontal plane, the declination errors of instruments No. 7 and No. 53 are –0.66′ and 0.46′, respectively, in 2016, as displayed in **Figure 2**; following an incorrect observation process, the declination and inclination of No. 60 are 2.37′ and 2.23′ in 2017 respectively, beyond the range shown in the figure.

3.2 The comparison results of IAGA

The international DIM comparison is organized by IAGA Working Group V-OBS, and has completed 18 sessions. Several years of the results, which are available on IAGA website, are collected here. Detailed information about these sessions and the sources of comparison results are shown in **Table 4**. The comparison results are sorted by country because of a lack of information on instrument types. The country serial numbers are listed in **Table 5**. The units of the comparison results in some years have been converted from arc second to arc minute. The mean and standard deviation of the difference of each instrument are shown in **Figures 4** to **7**. The symbols in the four figures have the same meaning as those in **Figure 2**. Additionally, the mean and standard deviation of different elements of all the comparison results in these years are

Table 4: List of DIM comparisons performed by IAGA.

No.	Date	Year	Observatory	Country	Elements	Data source
1	15–24 April	2002	Hermanus	South Africa	ΔD, ΔI, ΔH and ΔZ	Loubser, 2002
2	09–12 November	2004	Kakioka	Japan	ΔD and ΔI	Masami et al., 2005
3	19–24 June	2006	Belsk	Poland	ΔD and ΔI	Reda et al., 2007
4	09–18 June	2008	Boulder	United States	ΔD, ΔH and ΔZ	Love et al., 2009
5	13–23 September	2010	Changchun	China	ΔD and ΔI	He et al., 2011
6	05–08 June	2012	San Fernado	Spain	ΔD, ΔH and ΔZ	Hejda et al., 2013

Table 5: The list of the countries.

No.	Country	No.	Country	No.	Country
1	Algeria	14	France	27	Poland
2	Argentina	15	Germany	28	Romania
3	Australia	16	Hungary	29	Russia
4	Austria	17	India	30	Samoa
5	Belgium	18	Indonesia	31	Slovakia
6	Bulgaria	19	Japan	32	South Africa
7	Canada	20	Kazakhstan	33	South Korea
8	China	21	Macedonia	34	Spain
9	Colombia	22	Maldives	35	Switzerland
10	Croatia	23	Mexico	36	Ukraine
11	Czech Republic	24	Mozambique	37	United Kingdom
12	Denmark	25	Pakistan	38	United States
13	Finland	26	Peru	39	Venezuela

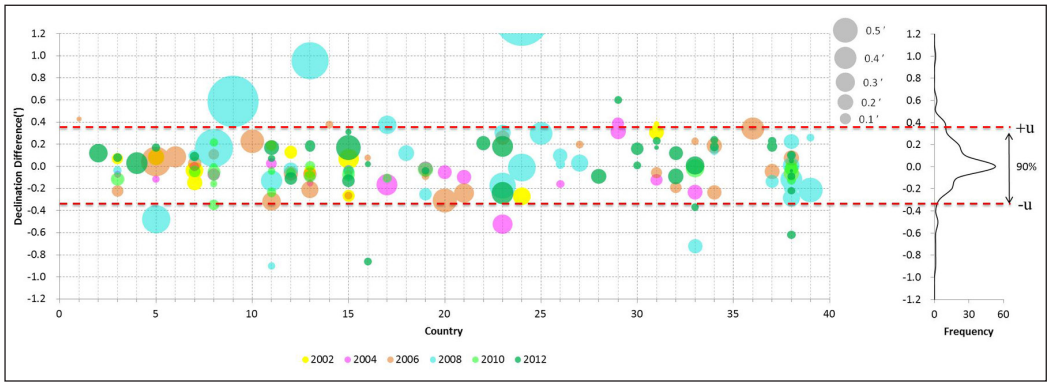

Figure 4: The difference of the declination of IAGA. The symbols have same meaning as those in Figure 2.

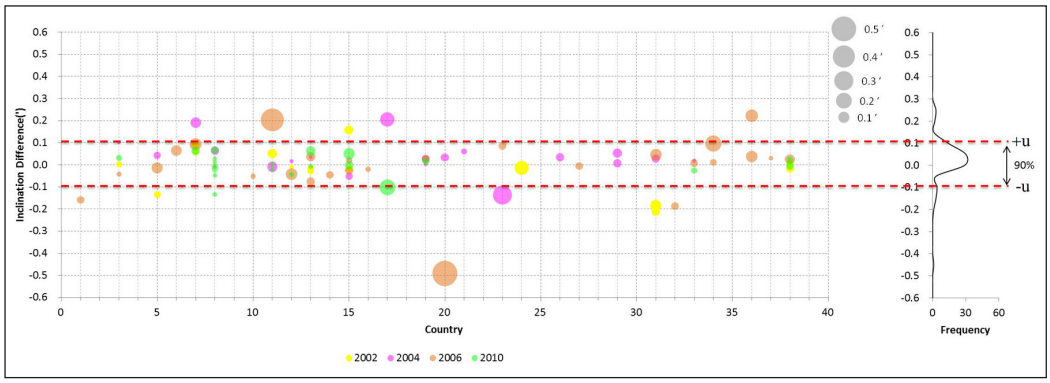

Figure 5: The difference of the inclination of IAGA. The symbols have same meaning as those in Figure 2.

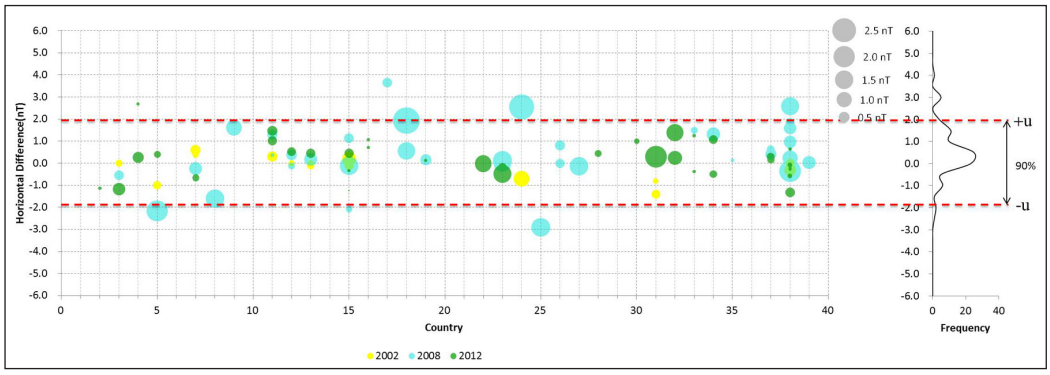

Figure 6: The difference of the horizontal intensity of IAGA. The symbols have same meaning as those in Figure 2.

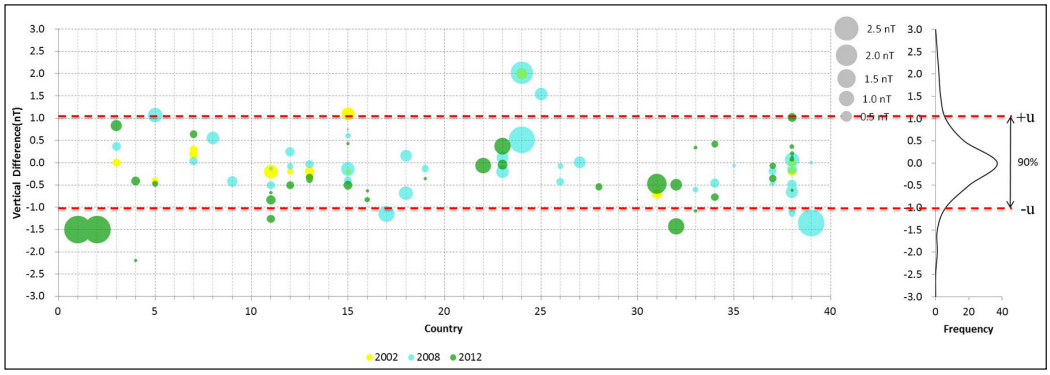

Figure 7: The difference of the vertical intensity of IAGA. The symbols have same meaning as those in Figure 2.

Table 6: Statistical results of all the comparison data.

Elements	Mean (μ)	Std. (σ)	Percentage (μ ± σ)	Value range of 90% (±u)	Institution
ΔD	0.00′	0.28′	87%	±0.35′	IAGA
ΔI	0.00′	0.09′	81%	±0.10′	IAGA
ΔH	0.30 nT	1.08 nT	75%	±1.9 nT	IAGA
ΔZ	–0.18 nT	0.68 nT	78%	±1.1 nT	IAGA

calculated; they are, respectively, 0.00′ and 0.28′ for Δ*D*, 0.00′ and 0.09′ for Δ*I*, 0.30 nT and 1.08 nT for Δ*H* and –0.18 nT and 0.68 nT for Δ*Z*, as listed in **Table 6**.

As shown in **Figures 4** to **7**, most of the coloured dots are distributed within one standard deviation of the mean. The percentage of the data within this range is 87%, 81%, 75% and 78% for Δ*D*, Δ*I*, Δ*H* and Δ*Z*, respectively. A value of 90% was adopted as the evaluation criterion in this study. The value ranges corresponding to this percentage are ±0.35′, ±0.10′, ±1.9 nT and ±1.1 nT for Δ*D*, Δ*I*, Δ*H* and Δ*Z*, as given in **Table 6**. This means that absolute measurements around the world achieve fairly good observational levels. In addition, it can also be found that quality of declination is better than that of inclination in this result. A possible reason for this was discussed in Section 3.1. As depicted in **Figure 4**, some larger values, with large standard deviations, are obviously beyond the range of one standard deviation from the mean. A lack of sufficient information in the measurement process makes it difficult to investigate the causes. As discussed previously, it may be the result of instrument failure or operational errors. In any case, these results are good indication of the quality level of the observatory's absolute measurements.

4 Conclusions

The observatories of the GNC have been digitalized and equipped with several types of DIMs for taking absolute measurements. Systematic differences are unavoidable between these instruments. Thus, comparisons are necessary to achieve high-quality data, and it is vital to control the data quality and unify the observation standards.

The working status of DIMs, including their precision, accuracy, and linearity, is comprehensively checked during comparison events. Problems with the instruments or operation can be found during the comparisons. However, the operator difference, position errors (the azimuth error caused by inexact positioning), and pillar errors (the error from pillar differences) are included in the final instrument difference (He et al., 2019). To identify these components, detailed inspections are required.

The comparisons are not only a platform for comparing instruments, but also for communication about working experiences. The observers can learn from each other, allowing good practice and methods to be spread and applied and the mistakes to be remedied. Maintenance and repair work can be performed to overcome problems with the instruments. This provides a strong guarantee of the operational status of DIMs and the quality of their observation data.

Several years of results from the DIM comparisons run by GNC and IAGA have been collected. The quality of the absolute observation data was estimated using these results. The absolute measurements of both GNC and IAGA achieve fairly good observational levels. This is helpful for researchers who use these data to understand the current quality level of absolute measurements and for the analysis of their results.

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Competing Interests

The authors have no competing interests to declare.

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