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Professional paper

Results of the magnetometer inter-comparisons during the 2nd Cycle of Geomagnetic Information Renewal in the Republic of Croatia

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Between 2017 and 2021, the 2nd Geomagnetic Information Renewal Cycle was carried out on the Croatian Geomagnetic Repeat Stations Network (CGRSN). On several occasions, before and after the survey at CGRSN, the magnetometers used in the survey were tested at the Lonjsko Polje Geomagnetic Observatory (LON). This paper presents the methods and results of these tests. The results verified the correctness of the used magnetometers and confirmed that their absolute accuracy is within the targeted measurement accuracy at the secular point. Despite the favourable results, a detail analysis revealed the presence of a small magnetic offset. This offset was introduced during the comparison process and did not affect the CGRSN measurements results in any way. In this paper, we share our experience which could be instructive for other observers performing similar work. Further testing is needed to determine the exact direction and magnitude of this systematic offset.

Keywords: geomagnetic measurements, absolute instruments, repeat stations, geomagnetic observatory, instrument inter-comparison

1. Introduction

Measurements on national secular networks complement the global network of magnetic observatories, and contribute to the development of more reliable local and global geomagnetic models (*e.g.*, Vujić et al., 2011; Vujić et al., 2015; Chulliat et al., 2015; Alken et al., 2021). These measurements also provide a more detailed insight into the temporal and spatial distribution of secular variation and its prediction. Many scientific studies have confirmed the unpredictable behavior of the geomagnetic field, indicating that reliable extrapolation of geomagnetic field values cannot be achieved beyond 5–6 years from the last epoch of geomagnetic survey (*e.g.*, Barraclough and De Santis, 1997; De Santis et al., 2002). To obtain reliable geomagnetic information, such measurements must be conducted cyclically at intervals 2 to 5 years. At the request of the State Geodetic Administration and the Ministry of Defense, for the purpose of the geomagnetic information renewal over the national territory, employees of the Faculty of Geodesy (FG), University of Zagreb, carried out measurement campaign in the period between 2017 and 2021. As part of the Project, measurements were conducted at the main secular point in Pokupsko (POKU) in the autumn of 2017. In 2018, measurements were carried out at 10 locations of the Croatian Geomagnetic Repeat Station Network (CGRSN, Brkić et al., 2006; Brkić and Šugar, 2008; Vujić et al., 2011; Brkić et al., 2012), and the same was repeated in 2021.

Achieving high measurement accuracy is the top priority for every measurement on the secular network. During measurements of the geomagnetic field and its secular variation, the desirable measurement accuracy should be comparable to that achieved in the high-quality observatories; ≤ 1 nT. For observatories located at middle latitudes, the accuracy of 1 nT corresponds to about 0.1 arc-minutes (') for angular elements. In theory, modern instruments used in observatories and also for measurements at secular networks, such as "Overhauser" proton precession magnetometer (PPM) and Declination-Inclination Magnetometer (DIM), have a sufficiently high precision to achieve the targeted accuracy (Hrvoić and Newitt, 2010). However, in practice, during observations and data reduction at the secular point, errors are much larger compared to the observatory measurements (Newitt et al., 1996). In general, it is very challenging to assess the contribution of individual errors during measurements at the secular point. These errors mainly originate from human errors during optical observation, non-ideal thermo-mechanical conditions during the outdoor observation, short-term field variations caused by ionospheric and magnetospheric currents, inductive effects, the lack of a mobile variometer, errors caused by reducing data on the geomagnetic epoch, etc. For this reason, the cumulative measurement error at the secular point is significantly larger compared to the observatory. A realistic estimate of the measurement error at the secular point is about 5 nT. At middle geomagnetic latitudes this error is roughly equivalent to 1' in declination (D) and about 0.5' for inclination (I). At the Earth surface in most areas, the annual changes of the field are comparable to typical errors at the repeat station. During the last decade, the annual changes of the angular elements in Croatia were around 7'/year for D and 1.5' for I. The total intensity (F), horizontal intensity (H) and vertical intensity (Z) have changed at rates of 45 nT/year, 5 nT/year and 50 nT/year, respectively. Achieving an accuracy of some nT is highly challenging and in many situations, even impossible. Results with lower accuracy are also acceptable and can be used at intervals 2 to 5 years, where secular changes are sufficiently large compared to the measurement errors at the repeat station.

The fundamental prerequisite for successful surveying is the correctness and accuracy of the used instrumentation. Therefore, the Project envisages verifying the correctness and accuracy of the Executor's instruments before and after the measurement at the main secular point POKU in 2017, and at the CGRSN locations in 2018 and 2021. The Executor's magnetometers used in repeat measurements were compared with reference magnetometers at the Lonjsko Polje observatory (LON), Faculty of Science, University of Zagreb. In this work, the results of the instrument comparison for 2017, 2018, and 2021 are presented.

2. DIM and PPM observations

The CGRSN survey was performed with Declination-Inclination Magnetometer (DIM_{FG}, Zeiss THEO-010B, ser. no. 106210, electronic unit: Bartington, serial number 484-MAG 10H) and "Overhauser" Proton Precession Magnetometer GSM-19G (PPM_{FG}, ser. no. 4041365). This magnetometer has two sensors, so-called the "upper" and (ser. no. 42118) and the "lower" (ser. no. 83184), because when this instrument works in the gradiometer mode, both sensors are mounted on the vertical shaft, one in the upper position and other in the lower position. Typically, the separation between them is about 1 meter.

At the LON geomagnetic observatory, absolute observations are usually made once per week using similar instrumentation; DIM_{LON} (Zeiss THEO-010A ser. no. 810303, electronic unit: Danish Technical University, Model G, ser. no. DI0041) and "Overhauser" Proton Precession Magnetometer GSM-19F (PPM_{LON}, electronic unit ser. no. 5051619 and sensor ser. no. 21936), which is usually used for determination of F at the reference site. The purpose of these observations at the observatory is to calibrate the recording magnetometers, at given intervals.

During the Project, we conducted 6 test sessions during 6 observational days in the period 2017–2021. Each observational day included 5 absolute observations with DIM_{LON} and DIM_{FG}. One observation set included four observations of the geomagnetic orientation point (also known as the azimuth mark), four observations of D and four observations of I. The well-known null method was used. For more information about observational protocol at the LON observatory, see Mandić (2017), Appendix A. It is advisable to perform these observations during low geomagnetic activity when local geomagnetic activity index (K) is less than 3. However, in the observatory conditions with a low gradients and available variometer recordings it is possible to achieve high accuracy even if geomagnetic activity is increased.

LON is remotely operated observatory without permanent staff, with small facilities for hosting magnetometers, acquisition units, components of the solar power supply, etc. The observatory is visited only for the purposes of absolute observations and maintenance (for more details on LON see Mandić et al., 2017). The dimensions of the absolute hut are 3 m × 3.5 m with one pillar standing inside. This (absolute) pillar is the reference location of the observatory (Fig. 8a). Due to the high humidity, we always keep our theodolite in a nonmagnetic-waterproof box to prevent condensation in the theodolite optics. Before the start of observations, the theodolite is placed on the absolute pillar and the hut's window is kept open. Mechanical and temperature stabilization takes at least one hour before the start of the first observational set. The window is also open during the observation period to avoid heating of the hut due to presence of the observer, this is especially important during the winter period. During the DIM comparisons, all sessions started with DIM_{LON}. After completing five sets, we removed DIM_{LON} and placed DIM_{FG}. After the stabilization period (more than one hour), five observational sets are performed with DIM_{FG}. Therefore, most of observations have been conducted in the period between 09 and 13 UTC. Three observers were involved in the observation protocol (IM, DP – the LON observer, MP – the CGRSN observer) during these six sessions. The abbreviations of their names are given in Tabs. 1 and 2 after the date of the session they performed. In some cases, two observers worked with the same instrument (on 18^{th} September 2017, IM conducted fourth set with DIM_{FG} and on 25^{th} July 2018, IM conducted the first two sets with DIM_{LON}).

After completion of DIM sessions, the PPM_{FG} sensors were individually tested in the total field mode. At different times, they were mounted on the absolute pillar using our PPM_{LON} sensor holder. This holder ensures that the total field sensor is at the approximately same height as a fluxgate sensor mounted on the theodolite telescope. This means that all scalar sensors, two PPM_{FG} and PPM_{LON}, were taking measurements at the same point. The duration of F measurements with each PPM_{FG} sensor ranged between 10 and 30 minutes. Recordings from both PPM_{FG} sensors were compared with the DIDD total field recordings measured inside the variometer hut, and the gradiometer differences ΔF_1 and ΔF_2 were calculated. These differences were then compared with the reference difference $\Delta F_0 = F(PPM_{LON}) - F(DIDD)$. Figure 5 shows the PPM intercomparison procedure on 18^{th} September 2017.

3. Results

As an example, we will use the measurement results from 18^{th} September 2017 to demonstrate the methodology of data processing and analysis. Together with the absolute values, the baseline values of the DIDD magnetometer were also calculated from each observational set. Comparing the observed base values D_0 (for declination) and I_0 (for inclination) of the DIDD magnetometer is much more practical than comparing the absolute values of declination and inclination. The geomagnetic field absolute values vary over time (see Fig. 1 – up), so simultaneous measurements with two DIMs on two different pillars should be done to compare the absolute values of declination and inclination. Moreover, it is necessary to have precise knowledge about the D/I differences between these pillars.

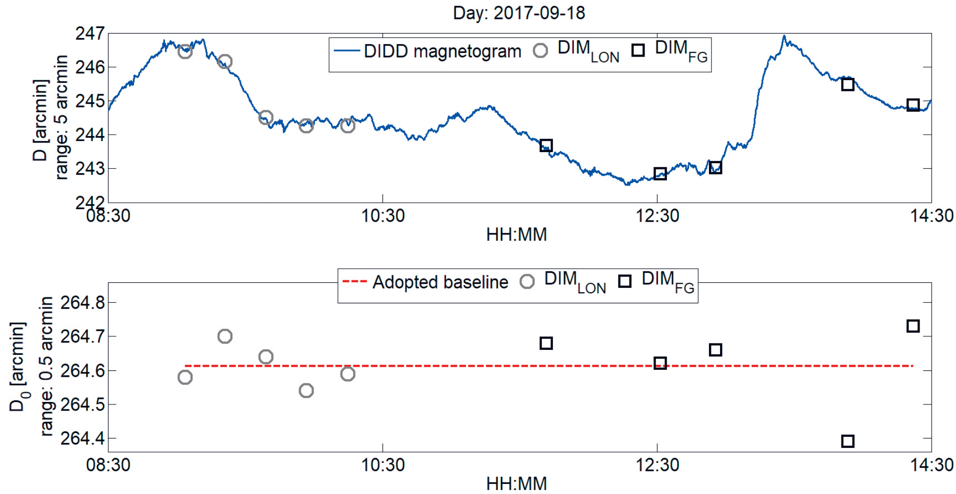

Figure 1. *Up*: Variation of declination during test measurements (blue line) on 18th September 2017. Circles present the measurement results for DIM_{LON} and squares for DIM_{FG}. *Down*: The observed base values and the reference baseline.

On the other hand, the baseline values do not contain natural geomagnetic variations and it is reasonable to assume that the baseline of the observatory magnetometer remains constant within a few hours. This means that we are observing a constant value over time with both DIMs. As a result, the scattering of the base values is much smaller than the scattering of the absolute values, as shown in Fig. 1. This "baseline" method for checking the DIM's correctness and accuracy is recommended by International Association for Geomagnetism and Aeronomy (IAGA) and is commonly used at international IAGA workshops (*e.g.* Love, 2009).

In our case, the reference (adopted) baseline is calculated as arithmetic mean of all observations obtained from both DIMs. In Figs. 2 and 3, we can see that during all test sessions the scattering of all observations was within 0.5 arc-minute range, Therefore, we decide not to identify some potentially suspicious observations as outliers. The correctness of both DIMs was inspected through two parameters. The first is the difference between the observation average (stars in Figs. 2 and 3) and the adopted baseline. In Tab. 3 this parameter is labelled as ΔD for declination and ΔI for inclination. The second parameter for correctness is the standard deviation of 5 observations for each DIM per session. In Tabs. 1 and 2 this parameter is labelled as $\sigma(\Delta D)$ and $\sigma(\Delta I)$ for declination and inclination, respectively.

In addition to $\Delta D/\Delta I$ and $\sigma(\Delta D/\Delta I)$, so-called "DIM's parameters" were also calculated: magnetometer offset (S_0), vertical misalignment between the the-

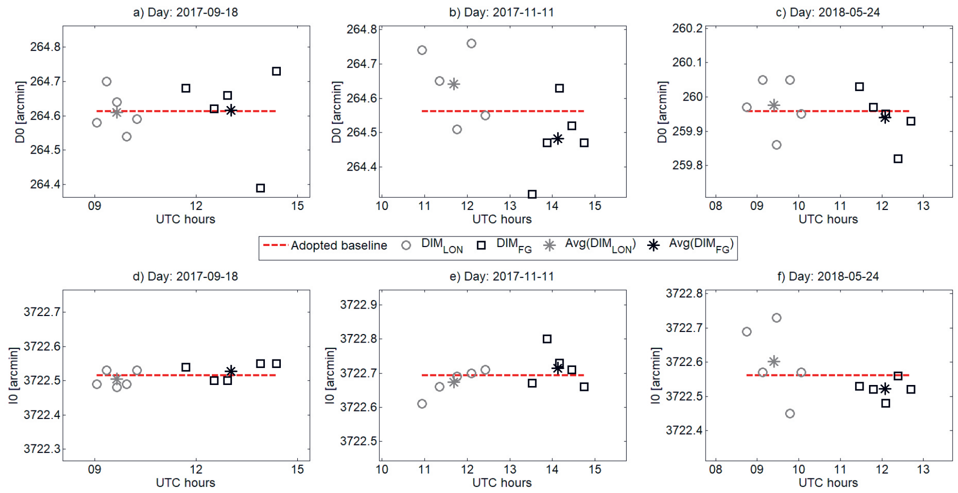

Figure 2. The adopted and observed base values for the first three test sessions. (The ordinate axis has a constant range of 0.5 arc-minutes.)

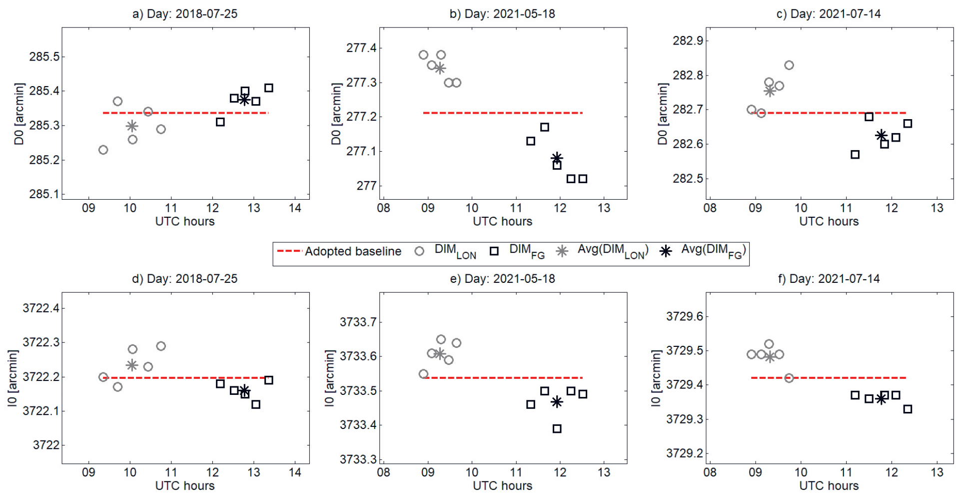

Figure 3. The adopted and observed base values for the last three test sessions. (The ordinate axis has a constant range of 0.5 arc-minutes.)

odolite's optical and sensor axis (ε), and horizontal misalignment between the theodolite's optical and sensor axis (δ), (Matzka and Hansen, 2007; Jankowski and Sucksdorff, 1996).

From a single set of absolute observation it is possible to calculate S_0 and ε in two different ways, making use only the declination readings, or only the inclination readings. The mean values of the parameters for both DIMs are given in Tabs. 1 and 2 together with their standard deviations. The mean values of δ were calculated solely from the declination readings and presented in Tabs. 1 and 2. The K values during the observation period (with both DIMs and PPM)

Table 1. ΔD and ΔI represent the average differences between the DIM_{LON} and adopted base values for D and I. Standard deviations σ(ΔD/ΔI) are calculated with respect to the average observational result (stars on Figs. 2 and 3). In the last two columns ΔD/ΔI and σ(ΔD/ΔI) are expressed in nT. Remaining columns contain the average values of the DIM parameters together with their standard deviations.

Date		DIM_{LON} (arc-minutes)						DIM_{LON} (nT)			
		$\Delta D/\Delta I$	$\sigma(\Delta D/\Delta I)$	δ	$\sigma(\delta)$	ε	$\sigma(\varepsilon)$	S_0	$\sigma(S_0)$	$\Delta D/\Delta I$	$\sigma(\Delta D/\Delta I)$
18 Sep 2017, IM	D	0.00	±0.06	0.68	±0.06	–0.27	±0.02	6.6	±0.3	0.0	±0.4
	I	–0.01	±0.02	/	/	–0.26	±0.07	6.5	±0.2	–0.2	±0.3
11 Nov 2017, IM	D	0.08	±0.10	0.28	±0.08	0.38	±0.12	5.1	±1.1	0.5	±0.7
	I	–0.02	±0.04	/	/	0.33	±0.04	5.9	±0.2	–0.3	±0.5
24 May 2018, IM	D	0.02	±0.08	0.34	±0.06	–0.20	±0.05	6.7	±0.7	0.1	±0.5
	I	0.04	±0.11	/	/	–0.18	±0.08	6.0	±0.5	0.6	±1.5
25 Jul 2018, DP, IM	D	–0.04	±0.07	2.38	±0.05	0.43	±0.04	6.5	±0.4	–0.2	±0.4
	I	0.04	±0.06	/	/	0.40	±0.04	6.5	±0.5	0.5	±0.9
18 May 2021, DP	D	0.13	±0.09	–0.57	±0.03	0.07	±0.05	6.8	±0.4	0.9	±0.6
	I	0.07	±0.07	/	/	–0.01	±0.04	7.0	±0.5	1.0	±1.0
14 Jul 2021, DP	D	0.06	±0.09	–0.35	±0.03	0.01	±0.03	7.6	±0.5	0.4	±0.6
	I	0.06	±0.03	/	/	–0.07	±0.04	7.1	±0.2	0.9	±0.1

Table 2. The table is for DIM_{FG}, numerical values are presented in the same way like in Tab. 1 for DIM_{LON}.

Date		DIM_{FG} (arc-minutes)						DIM_{FG} (nT)			
		$\Delta D/\Delta I$	$\sigma(\Delta D/\Delta I)$	δ	$\sigma(\delta)$	ε	$\sigma(\varepsilon)$	S_0	$\sigma(S_0)$	$\Delta D/\Delta I$	$\sigma(\Delta D/\Delta I)$
18 Sep 2017, MP, IM	D	0.00	±0.13	0.69	±0.09	–0.01	±0.10	5.0	±0.3	0.0	±0.9
	I	0.01	±0.03	/	/	0.09	±0.05	4.8	±0.9	0.2	±0.4
11 Nov 2017, IM	D	–0.08	±0.11	0.89	±0.04	–0.56	±0.07	5.7	±0.4	–0.5	±0.7
	I	0.02	±0.06	/	/	–0.50	±0.06	4.9	±0.3	0.3	±0.8
24 May 2018, IM	D	–0.02	±0.08	0.68	±0.04	0.29	±0.08	–5.2	±0.7	–0.1	±0.5
	I	–0.04	±0.03	/	/	0.31	±0.06	–6.8	±0.4	–0.6	±0.4
25 Jul 2018, IM	D	0.04	±0.04	0.60	±0.01	0.44	±0.02	–0.8	±0.7	0.2	±0.3
	I	–0.04	±0.03	/	/	0.45	±0.05	–2.0	±0.4	–0.5	±0.4
18 May 2021, IM	D	–0.13	±0.07	0.72	±0.07	–0.07	±0.09	–1.8	±0.5	–0.9	±0.4
	I	–0.07	±0.05	/	/	–0.07	±0.06	–2.5	±0.9	–1.0	±0.7
14 Jul 2021, IM	D	–0.06	±0.04	0.61	±0.02	0.26	±0.04	–5.2	±0.2	–0.4	±0.3
	I	–0.06	±0.02	/	/	0.25	±0.04	–6.3	±0.3	–0.9	±0.3

Table 3. The average absolute gradiometer differences. G_1 refers to the "upper" sensor and G_2 to the "lower" sensor. The K values during the observation period (with both DIMs and PPM) are given in the last column.

Date	G_1/nT	G_2/nT	K index
18 Sep 2017	0.14	0.07	4, 3
11 Nov 2017	0.05	0.03	2, 2
24 May 2018	0.06	0.10	1, 2
25 Jul 2018	0.04	0.10	2, 2
18 May 2021	0.15	0.08	3, 2
14 Jul 2021	0.01	0.09	3, 4

are displayed in Tab. 3. The $\Delta D/\Delta I$ and $\sigma(\Delta D/\Delta I)$ tabular values are also graphically displayed in Figs. 4a and 4b. The differences between S_0 and ε calculated from the declination and inclination readings are presented in Figs. 4c and 4d. The length of vertical lines above markers (circles/squares) present the standard deviations calculated from the declination readings. Similarly, the vertical lines below markers present the standard deviations calculated from the inclination readings.

Due to temporal variations of the geomagnetic field (Fig. 5 - up), the verification of PPM_{FG} absolute accuracy was conducted based on gradiometer differ-

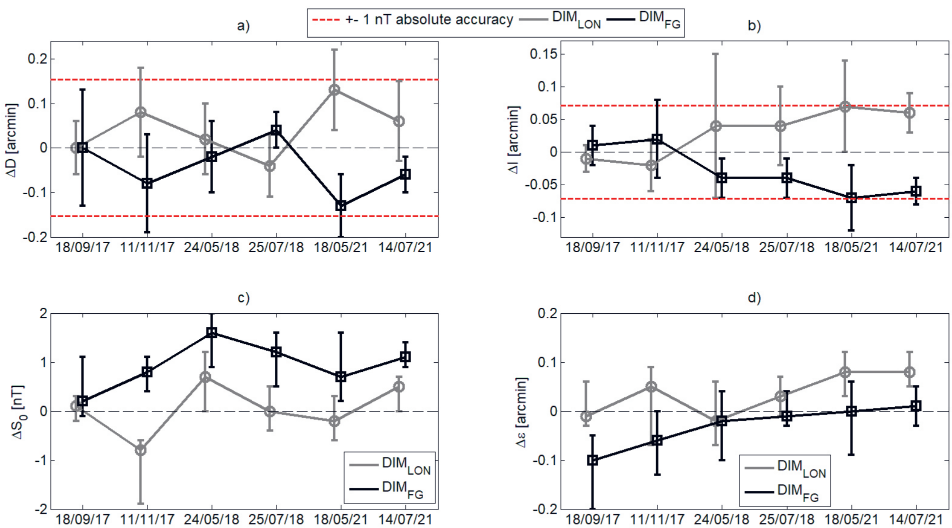

Figure 4. *Up*: The average differences ($\Delta D/\Delta I$) between observations and adopted baselines for D and I. Horizontal lines in *a*) and *b*) diagrams represent the absolute accuracy limit of ±1 nT for the area of Croatia. *Down*: Differences between the DIM parameters calculated independently from the D and I readings. Standard deviations are presented with vertical lines (see text for details).

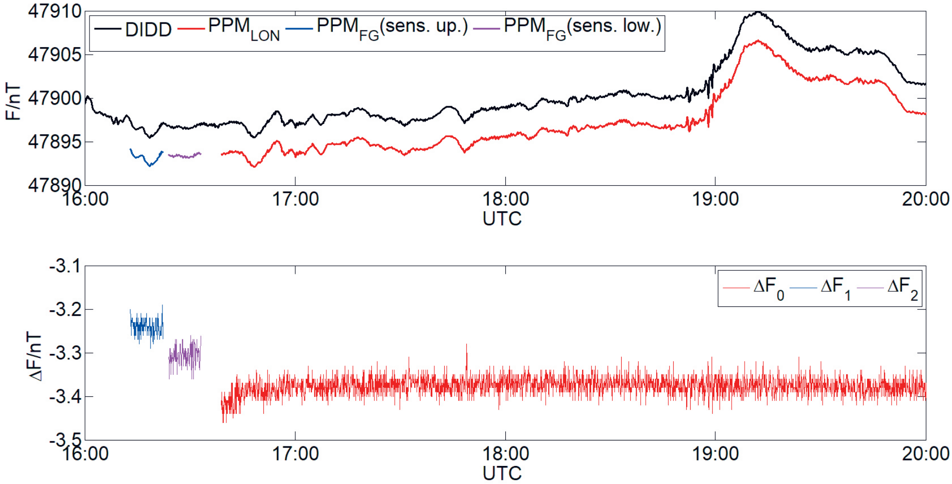

Figure 5. *Up*: Variations of the geomagnetic field total intensity on 18 Sep 2017. *Down*: Gradients of the total field intensity, *i.e.* differences of three scalar sensors at the reference location and the DIDD total field recordings.

ences. This means that we compared the differences between $\mathrm{PPM_{FG}}$ (both sensors individually) and DIDD with the reference gradiometer record, *i.e.* the difference between $\mathrm{PPM_{LON}}$ and DIDD. In Fig. 5 (down), the reference gradiometer difference is represented with red line. Gradiometer differences for $\mathrm{PPM_{FG}}$ with the "upper" sensor (ΔF_1) and the "lower" sensor (ΔF_2) are shown with blue and magenta lines. The average (absolute) gradiometer deviation of $\mathrm{PPM_{FG}}$ from

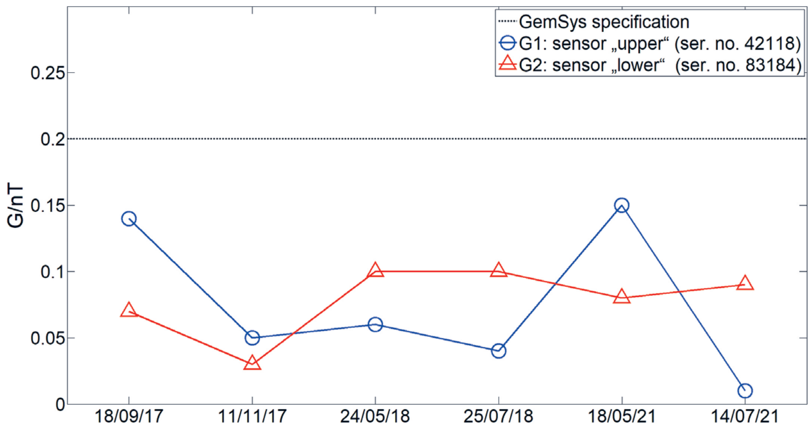

Figure 6. Absolute gradiometer differences during tests in 2017, 2018, and 2021. The horizontal line represents the absolute accuracy of $\mathrm{PPM_{FG}}$ according to the manufacturer's technical specifications (Gem Systems, 2003).

the reference was used as a measure of the absolute accuracy. These average deviations ($G_1 = \text{avg}\,|\,\Delta F_1 - \Delta F_0\,|$ – "upper" sensor, $G_2 = \text{avg}\,|\,\Delta F_2 - \Delta F_0\,|$ – "lower" sensor) for all test measurements are given in Tab. 3 and graphically displayed in Fig. 6.

4. The state of DIM_{LON} during the inter-comparison period

Since DIM_{FG} was compared with DIM_{LON} and most observations were conducted by IM, in this short paragraph we will briefly report the DIM_{LON} results from the last three IAGA workshops (WSs). International IAGA WSs are held cyclically every two years. Observers from magnetic observatories around the world attend these workshops to verify the correctness of their instrumentation or identify any potential issues. The last three IAGA WS inter-comparisons were performed 2016 in Belgium (Dourbes Observatory), 2018 in Austria (Conrad Observatory), and 2023 in Hungary (Tihany Observatory). IAGA WSs were not held between 2018 and 2023 due to the Covid19 pandemic and the war in Ukraine.

The 2016 WS results are presented in "Results of the instrument inter-comparisons and checking", compiled by J. L. Rasson and are available on-line (http://dourbes.meteo.be/images/iaga/final%20results.pdf, accessed 17th April 2024). Figures 5 and 6 of the report show the DIM inter-comparison results. In Fig. 5, the instrument with ID = 9 corresponds to DIM_{LON}. In Fig. 6 the observer with ID = 11 is IM. From both figures it is clear that excellent results were achieved at the IAGA WS in Dourbes.

Measurement results from the 2018 and 2023 WS have been kindly provided by the organizers (personal communication) and are presented in the supporting materials (https://hrcak.srce.hr/ojs/index.php/geofizika/article/view/31680/16076). Excellent results were also achieved in 2023. However, during WS in June 2018 certain problems with DIM_{LON} were revealed, particularly in the inclination readings. During observations in the tunnel of Conrad observatory, IM also noticed some problems with DIM_{LON}. In addition, experts in calibration of Zeiss theodolites from "Firma Wenger" checked DIM_{LON} and recommended reparation. The instrument was immediately sent to the manufacturer for inspection and repair, during which they identified and replaced a problematic micro-holder spring. The parallaxis error of the vertical and horizontal image was fixed, the compensator was readjusted and the instrument was finally checked on the collimator. Therefore, DIM_{LON} was fully checked and repaired before the comparison test in July 2018.

IAGA WSs are great opportunity share experiences and compare instruments. However, it is important to mention that even experienced observers with correct DIMs may occasionally achieve somewhat weaker results. This is mostly due to a new environment, measurement sequence, different circle readings, etc. If observation sessions are organized outdoors, in some positions during the declination/inclination readings, observers encounter difficulty in finding the source of natural light required for reading the scale of a theodolite. Discussion between observers working in a team (one is observing and the other is taking notes) may disturb the third observer who is measuring on the neighbouring pillar. Even simple changes in accessories (different clock for timekeeping, writing desk, calculator, etc.) can introduce a certain amount of distraction for the observer. In general, the DIM result is the unison of the observer performance and the correctness of DIM. Not accounting for large outliers, typically caused by observer, it is challenging to separate contribution of the observer and instrument error in the final result.

5. Discussion

At first glance, from Figs. 2 and 3, it is evident that many cases, the results point to the linear drifting of the DIDD baseline. Our detailed analysis of the DIDD baseline stability revealed that these linear trends in observations are not caused by drifting of the DIDD instrument. This analysis goes beyond the scope of this paper and a separate manuscript will be devoted to this topic. In the paragraph below, we will only present a small part of our analysis to support our claims.

In LON, magnetic variations are also recorded with the secondary vector magnetometer LEMI-35. Therefore, we have the possibility to compare the DIDD and LEMI-35 recordings, before and after the linear correction of the DIDD recordings. Furthermore, LON is surrounded with several INTERMAGNET observatories (IMOs) within the radius of 500 km. Therefore, we can make additional comparison using data from surrounding IMOs. During the preparation of LON definitive data, we often use data from surrounding IMOs to conduct the final data checking. Considering that geomagnetic variations in the area of South-eastern Europe are quite uniform, we can easily detect noises or sudden jumps within a range of 1 nT. On the other hand, due to differences in local geomagnetic effects, slowly-varying drifts are difficult to detect when comparing data from different observatories. Therefore, we used data from surrounding IMOs to model geomagnetic variations in LON during the periods of absolute observations. Data from THY (191 km NE – the distance and direction from LON), GCK (334 km E), DUR (486 km SW) and WIC (287 km N) were used as input to the Inverse-Distance-Weighted (IDW) interpolation model (Shepard, 1968; Tovar, 2024). After calculation of the IDW values for LON during the observation period, a comparison with the DIDD data was conducted. The comparison is done for two cases; before and after the linear correction of DIDD recordings.

For the session on 18th May 2021, Fig. 7 (left) shows the difference between DIDD and IDW model (grey line), as well as the difference between DIDD and LEMI35, without the linear correction of the DIDD recordings (red line). In addition, the difference between DIDD and THY is also shown (blue line). For better visual representation, the beginning of all differences is centred at zero and the values of declination/inclination residuals are expressed in nT. The right subplots in Fig. 7 show the same differences, but in this case the DIDD data are corrected with the linear baseline. From the results presented in Fig. 7 one can clearly see that the linear baseline, calculated as the linear fit to the observed results, introduces additional artificial drift into the DIDD time series. Hence, we may infer that the clustering of observations does not arise from instabilities of the DIDD magnetometer. This suggests that the most probable reason for the clustering of observations is the presence of a small ferromagnetic object near the sensor of one, or both DIMs.

A bit larger differences between the averages of DIM_{LON} and DIM_{FG} in Fig. 3 than those in Fig. 2 indicates the possibility of magnetization of DIM_{LON} during reparation in the summer of 2018. However, the MinGeo's staff guarantees that all replacement parts are non-magnetic. Additionally, after taking over the instrument in Budapest, several absolute observations were conducted with DIM_{LON} at the THY observatory. The results were consistent with the THY reference values.

At LON, measurements were conducted in relatively small hut, leading one to speculate that this effect could be attributed to the magnetic contamination caused by differences in the DIM electronics units, *i.e.* maybe the separation

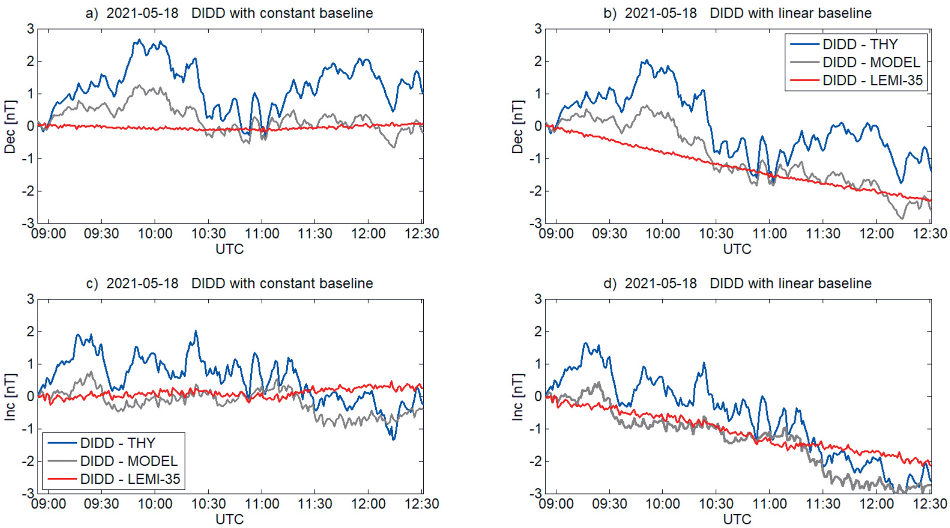

Figure 7. *Left*: The difference between DIDD and THY, DIDD and IDW, DIDD and LEMI-35, before the linear correction of the DIDD recordings. *Right*: The difference between DIDD and THY, DIDD and IDW, DIDD and LEMI-35 after the linear correction of the DIDD recordings.

between the DIM_{FG} Bartington unit and THEO-010B was not sufficient. During all sessions both electronics were kept at the same place (as well as the clock for timekeeping), as shown in Fig. 8a). Note that on 18th September 2017, practically identical results were obtained with both DIMs, therefore this is not likely.

At this point, the conclusion emerges that the clustering of observations is the result of a small (random) magnetic contamination caused by the carelessness of observers. The comparison period is quite long and it is not easy to remember all circumstances that could lead to this effect. However, we recalled one significant circumstance. As shown in Fig. 8, to fix a theodolite on the LON absolute pillar it is necessary to disassemble the theodolite baseplate (see Figs. 8b and 8c) and remove the triangular plate which is used for mounting the theodolite on a non-magnetic tripod. To avoid disassembling of the THEO-010B baseplate, except the first session (18th September 2017), in later sessions we were supplied with the backup "non-magnetic" Zeiss baseplate that is already dissembled. During the preparation of this manuscript, we conducted a quick-check and noticed that this (backup) baseplate is slightly magnetic at a very short distance, approximately at the distance of the D/I position "sensor down". Unfortunately,

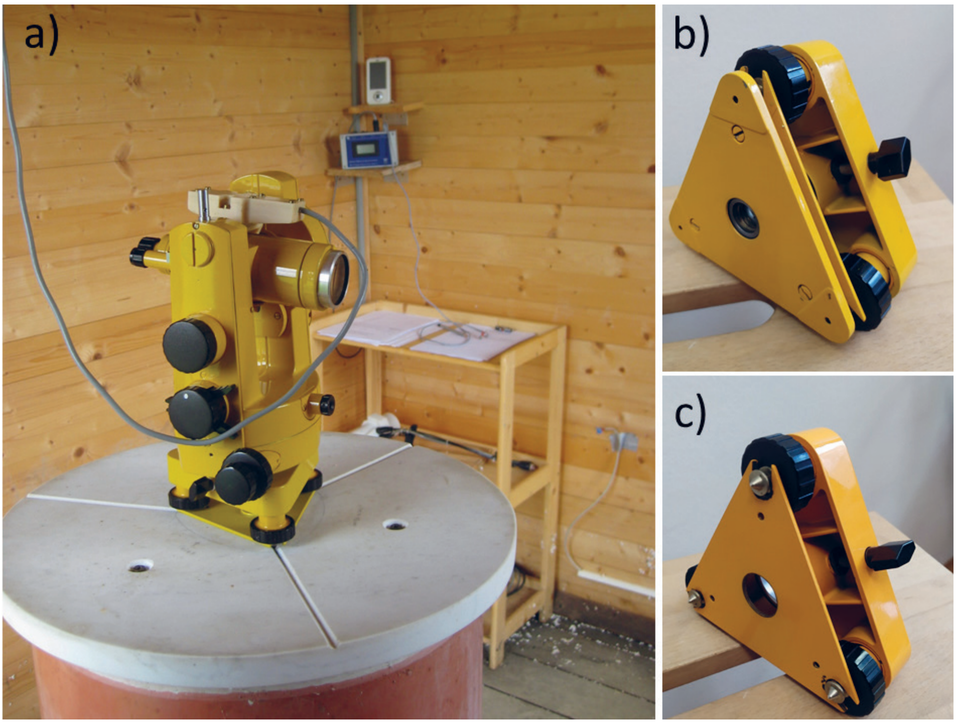

Figure 8. *a*) DIM_{LON} on the absolute pillar in LON. *b*) and *c*) Example of a baseplate with and without the triangular plate required for mounting the theodolite on a tripod.

we do not have sophisticated test facilities, *i.e.* magnetic laboratory and our main testing device is $\mathrm{DIM_{LON}}$. The test is conducted by rotating the baseplate near the $\mathrm{DIM_{LON}}$ sensor in the position "close to zero". Considering the contribution of natural magnetic variations, it is not possible to determine the exact magnitude of this small magnetic effect and its influence on the declination and inclination readings. It should be noted that each separation and connection of the baseplate with the theodolite's alidade will result in a different orientation of the baseplate in respect to the alidade, *i.e.* in respect to the body and telescope of theodolite. This implies that the magnetic contamination originating from a small ferromagnetic object within the baseplate will be different in each session. At this moment, this appears to be the most likely reason for the clustering of observations, especially during observations conducted on 18th May 2021 and 14th Jul 2021. However, it is necessary to conduct an additional carefully designed experiment in order to conclusively prove this. Therefore, at this point we decided to use the average value, of all observations with measured with $\mathrm{DIM_{LON}}$ and $\mathrm{DIM_{FG}}$, as the reference baseline.

From Tabs. 1 and 2 we can see that the DIM parameters (δ, ε, S_0) change over the time. It is well known that these parameters are temperature dependent and sudden changes of the parameter values may occur during the movement of DIM (packing/unpacking, transportation, or simple movement from one pillar to another, see Matzka and Hansen, 2007). At LON, during observations the temperature inside the absolute hut is the same as the outdoor temperature. Over the years, we have also observed that the $\mathrm{DIM_{LON}}$ parameters vary with the seasonal temperature changes. For example, $S_0(\mathrm{DIM_{LON}})$ is approximately 7 nT during summer and close to 0 nT during winter. However, sometimes we notice the sudden jumps in the parameter values between weekly absolute observations. On a few occasions, we also needed to readjust the misalignment parameters. Therefore, it is advisable to keep an observatory DIM in the temperature-stabilized hut at the main pillar without moving it. Unfortunately, in our case this is not possible. However, the long-term stability of the parameters is not crucial. It is important that these parameters do not change during one observational set, which typically lasts around 10 minutes with the null method. When observations are conducted properly, without significant observer errors, with properly working DIM, the values of ΔS_0 and $\Delta\varepsilon$ should be small – close to zero. In our case, the averages and standard deviations of ΔS_0 and $\Delta\varepsilon$ do not exceed 2 nT and 0.1', respectively. We found these results very satisfactory, together with a relatively small scattering of the clusters $\mathrm{DIM_{LON}}$ and $\mathrm{DIM_{FG}}$, in D_0 and I_0. A bit larger scattering in I_0 for $\mathrm{DIM_{LON}}$ can be seen on the day 25th May 2018 (before the 2018 WS). It is possible that a part of the problems detected at the 2018 WS started to occur before. However, we are quite sure that significant degradation of the instrument occurred during transportation to the workshop.

Figure 4c and Tab. 2 also present one interesting result. Note that in the last five sessions with $\mathrm{DIM_{FG}}$, the values of S_0 calculated from the declination readings are slightly higher, around 1 nT, than those calculated from the inclination readings. We assume that this effect is related to a small ferromagnetic contribution of the DIM_{FG} non-original baseplate that was used in the last 5 sessions. Gilbert and Rasson (2008) conducted an experiment with the 2000 nT magnet positioned at various spots of the theodolite. For both elements D and I, in certain positions, the effect of the magnet is completely eliminated. However, the ferromagnetic effect had influence on the DIM parameters, especially on the S_0 parameter. This is an additional argument that supports our assumption about the baseplate as the most likely reason for the offset between DIM_{LON} and DIM_{FG} observations.

At the end of this discussion, let us briefly examine the results of the PPM inter-comparison. From Fig. 6 and Tab. 3, it is clear that the absolute accuracy of the examined PPM_{FG} is well within the limit specified by the manufacturer.

6. Conclusions

In general, magnetic observatories provide almost ideal measurement conditions for achieving an absolute accuracy better than 1 nT. In the territory of Croatia, the accuracy of 1 nT corresponds to approximately 0.15' for declination and about 0.08' for inclination. At the LON geomagnetic observatory, in the framework the 2nd Geomagnetic Information Renewal Cycle, inter-comparison of instruments has been conducted in 2017, before and after measurements at the main repeat station POKU, as well as in 2018 and 2021, before and after measurements at the CGRSN network. The inter-comparison test measurements were conducted six times and included the DIM and PPM inter-comparisons. Validation of the instrument correctness was performed based on the differences between the DIM_{FG} and PPM_{FG} measurements and the reference values. For PPM_{FG}, the results are straightforward, confirming that the accuracy of PPM_{FG} agrees with the manufacturer specifications.

In the case of DIMs, the situation is not so trivial. Despite this, the results are quite satisfactory and within the achievable accuracy at the repeat station. Due to certain doubts, presented in Chapter 5, we decided to use the constant baselines as the reference. These baselines are calculated as the average value of all observations within one session. As shown in Tabs. 1 and 2, and in Figs. 4a and 4b, the average differences of DIM_{LON} and DIM_{FG} from the reference baselines, *i.e.* $\Delta D/\Delta I$ are within ±1 nT. The standard deviations $\sigma(\Delta D/\Delta I)$ calculated in respect to the average observational result for each DIM (stars on Figs. 2 and 3) are also within ±1 nT. Furthermore, it is noteworthy that employing a first-degree polynomial fit to obtain the D_0 and I_0 reference baselines, would have resulted in significantly smaller deviations of $\Delta D/\Delta I$. In this way, we would effectively eliminate a very small magnetic offset, most likely originating from the DIM_{FG} non-original baseplate. It is important to highlight that the original MinGeo's baseplate was used during the CGRSN survey. Therefore, the disputed baseplate could not affect the CGRSN results in any way. If we take the session from 18th Sep

2017 as referent one, because the disputed baseplate was not used during this session, we can observe that both DIMs can achieve almost identical results. In Figs. 2 and 3 we can see that the scattering of the DIM_{FG} clusters is similar or even smaller than the scattering of the DIM_{LON} clusters. This shows that during all stages of the CGRSN survey the correctness and stability of DIM_{FG} was excellent (according to the grading system in the supporting materials).

As mentioned in Chapter 4, the DIM result is the unison of the observer performance and the correctness of DIM. Therefore, the $\sigma(\Delta D/\Delta I)$ results, along with the accompanying statistics of the DIM parameters may be considered also as the observer score. Note that DP and IM share the score on 25th July 2018 in Tab. 1. Similar, in Tab. 2 MP and IM share the score on 18th September 2017, where IM performed only the fourth set which is not consistent with MP's observations in declination. If we do not account this poorly-performed set, MP's score is $\sigma(\Delta D) = 0.05'$ (or 0.3 nT) and $\sigma(\Delta I) = 0.03'$ (or 0.4 nT). This indicates that the observations at the CGRSN network were conducted from the side of a skilled observer.

In this paper, except the results, we shared our experiences that could be instructive for other observers who conduct similar work. If possible, the detailed data analysis should be done immediately after a survey or testing devices. This approach enables the detection of some systematic errors and their elimination from future measurements. In our case, preliminary results were very satisfactory from a statistical standpoint, and doubts arose after the comparison conducted in 2021 where we noticed a significant grouping of observations conducted with two different DIMs. We believe that this dataset, together with additional tests, will give us opportunity to link our findings with the work presented by Marsal and Torta (2007), Csontos (2012) and Yufei et al. (2019).

The analysis presented in Chapter 5 confirms that the LON observatory may serve as a good reference is similar investigations. The same instrument inter-comparison is recommended to be conducted within the framework of the next cycle of geomagnetic information renewal in the Republic of Croatia.

Acknowledgments – This work was developed in cooperation with the Faculty of Geodesy, University of Zagreb and supported by the project "2nd Cycle of Geomagnetic Information Renewal in the Republic of Croatia" financed by the State Geodetic Administration and the Ministry of Defense. The results presented in this paper rely on data collected at magnetic observatories. We thank the national institutes that support them as well as INTERMAGNET for promoting high standards of magnetic observatory practice.

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SAŽETAK

Rezultati usporedbe magnetometara tijekom II. ciklusa obnove geomagnetske informacije Republike Hrvatske

Igor Mandić, Dino Curman i Eugen Vujić

Između 2017. i 2021. izvršen je II. ciklus obnove geomagnetske informacje na Hrvatskoj Mreži Geomagnetskih Sekularnih Točaka (HMGST). U nekoliko navrata, prije i nakon izmjere na HMGST, obavljeno je ispitivanje magnetometara korištenih u izmjeri u Geomagnetskom opservatoriju Lonjsko polje (LON). U ovom radu predstavljene su metode i rezultati ovih ispitivanja. Rezultati su verificirali ispravnost korištenih magnetometara i potvrdili da je njihova apsolutna točnost unutar ciljane točnosti izmjere na sekularnoj točci. Bez obzira na povoljne rezultate, detaljna analiza otkrila je prisutnost malog magnetskog odstupanja. Ovo odstupanje javilo se prilikom postupka usporedbe i ni na koji način nije utjecao na rezultate mjerenja na HMGST. U ovom radu dijelimo naše iskustvo koje bi moglo biti poučno za druge motritelje koji rade sličan posao. Potrebno je provesti dodatna ispitivanja kako bismo odredili točan smjer i iznos ovog sistematskog odstupanja.

Ključne riječi: geomagnetska mjerenja, apsolutni instrumenti, sekularne postaje, geomagnetski opservatorij, usporedba instrumentarija

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Appendix – Supporting materials

Results of the magnetometer inter-comparisons during the 2nd Cycle of Geomagnetic Information Renewal in the Republic of Croatia

IM's results achieved with DIM_{LON} during the **18th IAGA workshop** at the Conrad observatory (Austria). Below is the report compiled by the workshop organizers, personal communication with Barbara Leichter. The report is presented in its original form.

Table 1. Theodolites used by Igor Mandic

Theodolite	N	S_0^D [nT]	δ_H^D [nT]	ϵ_Z^D [nT]	S_0^I [nT]	ϵ_Z^I [nT]	s
Zeiss-010A-xxx	5	-1.40±2.20	-0.52±0.59	-6.02±1.21	-0.76±2.11	-6.16±0.82	nd

Note. — The table lists the theodolite, the number of measurements, collimation data and the scale value s (if available by the measurement protocol). If more than one measurement has been performed, uncertainty levels of collimation data are reported. Good data is characterized by relatively small collimation values, very small standard deviations and similar values of S_0^D and S_0^I as well as ϵ_Z^D and ϵ_Z^I. For details on collimation values please refer to Lauridson (1985).

1 Igor Mandic

We present a summary of DI measurements by Igor Mandic during the XVIII IAGA workshop at the Conrad Observatory in Austria. Measurements were performed on the on the following dates: '2018-06-24': 4, '2018-06-22': 1. The theodolite(s) used by Igor Mandic are listed in Table 1 together with the collimation angles and scale values s calculated from the measurements. Scale values are provided only if the residual DI method has been used, otherwise the are marked by *nd*. Additionally we provide uncertainty ranges of the parameters obtained by simple component-wise arithmetic calculations. These uncertainties give an idea about stability and validity of the given parameters and ideally should be small. Scale values, if determined, should ideally be close to 1. Altogether four different piers were dedicated to comparison measurements during the workshop. Igor Mandic performed measurements on the pier(s) as listed in Table 2. From each DI measurement, base values are calculated in relation to a LEMI036 variometer and a GP20S3 potassium scalar magnetometer located in the North-eastern part of the Conrad Observatory tunnel system. Table 2 lists the averages of the base values for each given pier separately. Delta D and delta I values of different piers are not considered here, as all analyses are performed for the used pier. In order to estimate the quality of DI measurements, two main quality indicators are checked. Firstly, we test the internal consistency of all measurements, i.e. the reproducability between individual measurements for each pier. The variables c_D and c_I in Table 2 provide a numerical quality parameter. c_D denotes the average standard deviation of individually measured horizontal base values in seconds of arc. c_I corresponds to the average standard deviation of vertical base values in nT. c-values within the 1σ range of reference values (see below) are considered to be excellent. Secondly, the deviation from the observatory reference values for each pier are tested. The observatory reference is obtained by analyzing all DI measurements from observatory personnel between September 2017 and October 2018, calculating the average base values and the standard deviations. This procedure is perfectly justified as all values can be well fitted by a straight horizontal adopted baseline. The individual measurements of Igor Mandic in comparison to the average reference base value are shown in Fig 1. The average value and its deviation from the reference values are shown in Fig 2. Overlapping one σ uncertainties indicate that both data sets are statistically similar. For a quality estimate we check the maximum difference between the 1σ range of the observer relative to the reference range for baseD, baseH and baseZ. Maximum differences of less than one σ are excellent, values within 2σ is very good, and so on. Please note that good data requires both excellent internal consistency and excellent agreement to the reference. Analysis has been done using MagPy 0.4.5.

Figure 1: Base values of individual measurements (black dots) of Igor Mandic, in comparison with the reference value for the respective pier (green shaded area). The green area depicts the arithmetic average value including one σ of all base value measurements from the Conrad Observatory team between September 2017 and September 2018.

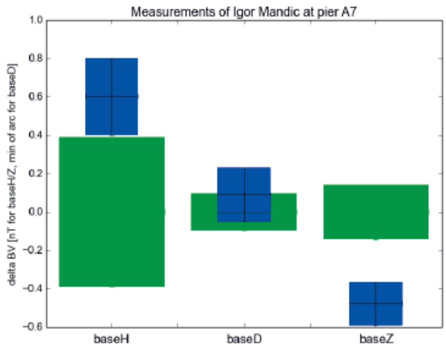

Figure 2: Base values with associated standard deviation relative to average reference values for each pier. The reference is plotted in green shades, measurements by Igor Mandic are depicted in blue shades.

Table 2. Average values for each pier

Pier	N	baseH	baseD	baseZ	c_I[nT]	c_D[sec]	c_{int}	q_{ref}
A7	5	24.78±0.20	3.67±0.00	-18.97±0.11	0.16	8.38	excellent	very good

Note. — BaseH,D,Z are the average base values with uncertainty estimate for all measurements at the given pier. c_I and c_D are directly obtained from the uncertainties (c_I is the average devation of baseH and baseZ in nT, c_D the uncertainy of baseD in seconds). These values provide a quantitative estimate of the consistency of repeated measurements. c_{int} denotes the qualitative consistency of all measurements, q_{ref} gives a qualitative estimate of the difference to the reference data.

IM's results achieved with DIM_{LON} during the **19th IAGA workshop** at the Tihany observatory (Hungary). Below is the report compiled by the workshop organizers, personal communication with Barbara Leichter. The report is presented in its original form.

DI-flux results from the 19th IAGA Workshop

Important initial note

If your report is not a pdf-file: This report was originally written in Markdown language. You can open it in any text editor. If you want a formatted output then open this file in a markdown interpreter. You can use for example an online markdown reader like Dillinger.

Analysis methods

All DI-Flux measurements have now been checked. Digital data inputs were cross checked against your paper sheets whenever we found some inconsistencies during the analysis. If we found discrepancies between paper sheets and digital inputs, data from the paper sheets was used to correct digital inputs. The only other correction eventually applied to the original data was the replacement of the respective pillars azimuth value with the given numerical value in degree or gon. We also considered pre-analysis communications regarding analyses not to be considered for evaluation. DI-flux analysis makes use of variometer and scalar data from Tihany. For pillar A, reference values for the adopted baseline are existing, however, not for the other pillars. An alternative way to determine reference values makes use of the median of all basevalue measurements during the workshop (with a few obviously wrong records related to false input values removed). A median is preferred in order to minimize the influence of single outliers. For pillar A this *workshop reference* is statistically indistinguishable from the *site reference*. Therefore, all further analyses are related to the workshop reference of all three pillars. DI flux analysis is performed using MagPy 1.1.4. Basevalues are determined in an XYZ system. A detailed description of the theory and further references can be found here.

For each observer the following parameters are determined. An **observer value** describes the average standard deviation of all three basevalue components, and the mean of these three standard deviations. This value describes the consistency of successive measurements and ideally this value is small. In order to defines a simple grade for the quality of this value we use an index, directly related to the average standard deviation of all measurements from this observer. An average deviation below 1 nT results in grade 1, a deviation below 2 nT results in grade 2. Deviations above 4 nT are rated as grade 4. For determination of the observer value we consider subsequent measurements with the same instrument. An **instrument value** describes the difference of the median baseline values from the workshop reference of the respective pillar, hereinafter referred to δ_{ref}. For this purpose we calculate the virtual distance between reference and observed base value:

$$\delta_{ref} = \sqrt{(x - x_{wsref})^2 + (y - y_{wsref})^2 + (z - z_{wsref})^2}$$

We also determine the standard deviation of all measurements to obtain a measure of the quality of the workshop reference, hereinafter called σ_{ref}. The values of σ_{ref} are different for each pier and largest for pillar C. An average δ_{ref} below 1 σ_{ref} results in grade 1, below 2 σ_{ref} results in grade 2 and so on. The instrument value is determined for each observer separately and, if several observers used the same instrument, we provide a summary for the instrument combining all these measurements. The individual report will also contain collimation values which are determined in nT by multiplying delta (in radian) with H (in nT) and epsilon (in radian) with Z (in nT). If residual measurements were performed, fluxgate orientation and fluxgate scale values for the instruments are determined. Fluxgate orientations were estimated by comparing inline and opposite analysis. If residual are small this technique is not conclusive.

Please note, neither **observer value** nor **instrument value** are solely dependent on observer respectively instrument. Furthermore, the *workshop reference* is not really a reference, as it is neither independent nor provenly correct. Nevertheless, this approach is widely objective and „the best we can do“ with the given data.

Reference values

Pillar	X_{wsref}[nT]	Y_{wsref}[nT]	Z_{wsref}[nT]	X_{oref}[nT]	Y_{oref}[nT]	Z_{oref}[nT]
A	21559.79	1915.06	43410.71	21560.06	1914.01	43410.28
	+/- 2.28	+/- 4.28	+/- 1.11			
B	21561.80	1918.39	43409.62			
	+/- 3.19	+/- 1.72	+/- 1.58			
C	21559.36	1914.24	43411.44			
	+/- 3.50	+/- 4.09	+/- 1.32			

Given are the workshop reference values ($_{wsref}$), as obtained by median values and standard deviations. Outliers exceeding the basevalues by +/- 20 nT were not considered. An observatory reference value ($_{oref}$) for the baseline is only existing for pillar A.

Reporting

Each observer receives an individual report. If you have any questions, recommendations, suggestions or corrections, please contact us within the next 4 weeks. Afterwards we will prepare a final report, which will consider all feedback and shows the individual values of all participants. If outliers related to obviously wrong reading values on the paper sheet or disturbances near the measurement position are either reported or detected, and more than two measurements have been conducted, then an analysis without these outliers is performed. Details are given in the individual report. For the overall summary you will find the total number versus number of measurements considered for the analysis. We do not provide an average grade for persons who only conducted a single DI flux measurement. The parameter *fluxgate orientation* denotes what orientation has been used for the analysis. The orientation leading to minimal deviations has been chosen, although in most cases the differences between inline and opposite analysis are negligible, as expected for very small residuals. If the given orientation is wrong please notify us. The overall analysis will contain only one result for each observer. For those who used different instruments and/or slots, only the best set will be shown in the final summary.

Individual results - I. Mandic

Measurement

Basic measurement parameters

Date	Pillar	Instrument
2023-05-22	B	THEO_010A_810303_DTUMODELG-0041

collimation values and basevalues

Time	S_0(D) [nT]	dH(D) [nT]	eZ(D) [nT]	S_0(I) [nT]	eZ(I) [nT]	BaseX [nT]	BaseY [nT]	BaseZ [nT]
12:43:20	-0.56	4.41	-2.91	-0.24	-3.97	21562.17	1919.42	43409.36
13:13:20	-0.19	5.06	-2.35	0.20	-3.63	21561.87	1917.89	43409.53
13:39:40	-0.10	4.26	-2.40	-1.74	-5.16	21562.18	1918.41	43409.39
Median	-0.19	4.41	-2.40	-0.24	-3.97	21562.17	1918.41	43409.39
and	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Stdev	0.24	0.43	0.31	1.02	0.80	0.17	0.78	0.09

Result summary

Type[1]	Fo[2]	Scale	N[3]	Obs. value	Inst. value	Total[4]
zero		0.99	3/3	1	1	**1**

[1]: Type denotes zero field or residual measurements [2]: the fluxgate orientation was determined by comparing inline and opposite analysis [3]: N denotes amount of measurements used for analysis versus totally performed measurements [4]: the total grade is a measure for quality: 1 = excellent, 2 = good, 3 = satisfactory, 4 = improvable

In addition to the above report, below is the plot of numerical values presented in the tables "Reference values" and "collimation values and basevalues" from the 19th IAGA workshop. IM was observing on B pillar.

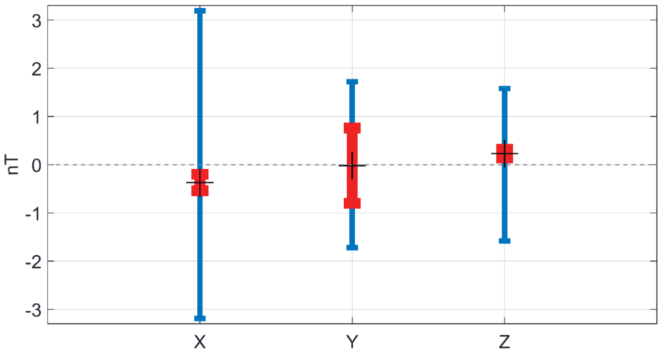

Figure S1. The differences between the workshop and DIM_{LON} medians (black crosses). Thick red vertical lines represent the standard deviation of DIM_{LON}, while blue lines denote the workshops standard deviations. Blue lines are symmetrical with respect to zero (i.e. the reference value in this figure).