Appendix A – DIF observations

Most observatories use three-component fluxgate magnetometers as the main observatory variometer. Therefore, in this appendix, the absolute measurement protocol (the null method) and derivation of base values will be demonstrated through data processing template for the LON supplement variometer LEMI-035.

Every DI-flux measurement begins with levelling of the theodolite. At the start and end of each set, the circle readings of the azimuth mark when the fluxgate sensor is above or under the telescope are taken (Fig. A1, table "Myra readings"). In LON, the azimuth mark is located north-east from the reference pillar at the distance of 512 m. True bearing of the azimuth mark with respect to the reference pillar is A_Z = 64°58'08''.

Measurement of declination: Before each reading we need to set the telescope exactly horizontal (the vertical scale reads exactly 90° or 270°). By turning the theodolite until the sensor measures almost no magnetic field, the sensor is then brought almost perpendicular to the horizontal component of the field. At this moment, we need to check if the sensor is exactly horizontal. A small deviation from horizontal can occur due to imperfect levelling of the theodolite. If this is the case, the telescope must be adjusted so that vertical scale shows exactly 90° or 270°. Next, the theodolite is finely adjusted until the sensor measures no magnetic field, i.e. the electronic unit displays 0 nT. The exact time and angle at which this occurred are noted. In LON, we initiate the sequence of measurement with position E_{UP}, indicating that the theodolite telescope has been turned toward the east with the fluxgate sensor on the upper side of the telescope. In the given example (Fig. A1), zero-field reading was taken at 09 hours, 13 minutes and 20 seconds according to UTC time and associated angle is 311°30'50''. The next position W_{UP} (telescope toward the west and the sensor is on the top) is obtained after turning the theodolite by approximately 180° around its vertical axis. Again, we need to check and adjust the telescope if necessary so that vertical scale shows 90° or 270°. After fine tuning, we read the exact time and angle of zero-field position. The third horizontal reading E_{DN} is taken after turning the telescope around its horizontal axis by 180° and finding (after fine tuning) the position giving a zero reading on the magnetometer. The last declination reading, W_{DN}, is found by turning the theodolite approximately 180° around its vertical axis to the opposite null position. This way, we obtain four observations (Fig. A1, green cells in table “D”) that compensate misalignment between the magnetic axis of the sensor and the optical axis of the telescope, and for zero-field offset of the fluxgate magnetometer. The observations can be taken in any order, but it is advisable to always use the same order.

Measurement of inclination: Immediately after the measurement of declination four circle readings (Fig. A1, green cells in table “D”) are used to calculate the position of magnetic meridian. The magnetic meridian is the mean of the four declination readings and is used to orientate the theodolite telescope in the vertical plane of the magnetic meridian. In our example, this means that the sensor and telescope lie in the vertical plane that corresponds to the horizontal circle reading of 221°32’11’’. The null readings in in the inclination observation are found by rotating the telescope around its horizontal axis and vertical circle readings are noted. The first reading, N_{DN}, indicates that the theodolite telescope has been turned toward the north with the fluxgate sensor under the telescope. In this and all other positions in the inclination observation, the null reading is achieved when the sensor axis is perpendicular to the total field vector. The second position, S_{UP}, is obtained by turning the telescope around the horizontal axis by approximately 180°. This brings the telescope toward the south with the fluxgate sensor on the upper side of the telescope. After this reading, we need to rotate the theodolite around its vertical axis by exactly 180°. In this position, the sensor and telescope lie in the same plane of the magnetic meridian, but now the horizontal circle reading corresponds to 41°32’11’’. The remaining two readings N_{UP} and S_{DN} are done in analogue way as N_{UP} and S_{DN}.

Measurement of the total field: Ideally, we would like to measure *F* simultaneously at the same place as *D* and *I* measurements. This is not possible because *F* is measured with a different instrument, which is far enough from the absolute pillar so it does not disturb the DI-flux measurements. The *F* difference between the absolute pillar and the remote site of the scalar sensor is easy to determine by measuring *F* at both places many times so the difference is known to 0.1 nT. This difference has to be checked at least once a year, but more frequently is recommended. This, of course, depends on the magnetic homogeneity of the observatory location. In general, this difference changes very slowly or can be considered as constant for a long time (except during intensive magnetic storms). In the ideal case, simultaneous measurements of *F* should be done after each DI-flux measurement. At LON, this difference in 2016 was -3.4 ± 0.1 nT, which means that the difference is practically constant, and *F* at the main pillar was 3.4 nT lower than at the scalar magnetometer site. Complementary *F* for LEMI magnetometer is provided by dIdD magnetometer. The dIdD *F* recording is most complete, with the smallest number of data gaps and is closest to the LEMI sensor. The table on Fig. A4 contains the variation and *F* recordings during the observational times.

Processing of the D absolute measurements: Since the theodolite circle has a scale from 0° to 360° (or 0-400 in grad-scale), two *D* readings are rewritten as follows:

$$E_{UP} \rightarrow E_{UP} - 180°$$

$$W_{DN} \rightarrow W_{DN} - 180°$$

To obtain correct absolute and base values, the next step is to reduce every reading to the reference time, i.e. reading. The reference time can be arbitrary, and in the LON case, this is the time of the first *D* reading. Because geomagnetic field is continuously changing between individual readings, the purpose of temporal reduction is to obtain readings as if they are all taken at the same moment. For this, we also need simultaneous vector and scalar recordings. To explain this let us look at "D" table (Fig. A1). The column denoted with (2) presents the previous column in decimal degrees. Raw variation values of *D* (Var_D) in nT are in column (3). Conversion of Var_D in nT to Var_D in decimal degrees (colum (4)) is done according to formula

$$Var_D° = Var_D^{nT}/(H^{nT} \sin(1°)) = Var_D^{nT}/(F^{nT} \cos(I°)0.0175). \quad (1.A)$$

Relative variations, i.e. variations with the respect to the first variation value are given in column (5). By subtracting the values in column (2) with corresponding values in column (5), we obtain readings reduced to the reference time (denoted with [1] in some tables) in column (6). The average *D* reading reduced to the reference time is A_D and the magnetic declination is

$$D = A_D - 90° + A_Z - A_M . \quad (2.A)$$

In the formula above the subtraction by 90° comes because, in fact, we measure the position perpendicular to *D*. To convert (A_D – 90°), i.e. the *D* value in the theodolite system into *D* in the geographical system, we need to know the average direction of azimuth mark reading (A_M) and true bearing of the mark (A_Z).

Processing of the I absolute measurements: Again, since the theodolite circle has scale from 0° to 360°, some of *I* readings are rewritten as follows:

$$N_{DN} \rightarrow 360° - N_{DN}$$

$$S_{UP} \rightarrow 180° - S_{UP}$$

$$S_{DN} \rightarrow S_{DN} - 180°$$

Temporal reduction of *I* readings is performed using Var_H^{nT} and Var_Z^{nT} variometer outputs. Firstly, we compute *I* variations in nT according to formula

$$Var_I^{nT} = \cos(I_p^{\circ})\, Var_Z^{nT} - \sin(I_p^{\circ})\, Var_H^{nT}, \quad (3.A)$$

where I_p stands for preliminary uncorrected inclination, the average of column (8) (Fig. A2, table "I"). To convert Var_I to degrees using expression

$$\text{Var}_\text{I}° = \text{Var}_\text{I}^{\text{nT}} / (F^{\text{nT}} \sin(1°)), \quad (4.A)$$

the raw dIdD F recordings during the I observations are used (Fig. A3, table "F", column (15)). $\text{Var}_\text{I}°$ obtained in this manner is presented in column (11) (Fig. A3). Relative variations with respect to the reference time (the first D reading) are in column (12), while in column (13), we have reduced inclination readings. The magnetic inclination is the average of column (13).

Processing of the F measurements: In Fig. A3, table "F", column (15), contain the raw dIdD F recordings at the time of the first D reading and during the I readings. Firstly, we reduce F to the main pillar by -3.4 nT. Using $\text{Var}_\text{H}^{\text{nT}}$ and $\text{Var}_\text{Z}^{\text{nT}}$ variometer outputs and I_p, we can calculate $\text{Var}_\text{F}^{\text{nT}}$, i.e. the variometer F output using formula

$$\text{Var}_\text{F}^{\text{nT}} = \cos(I_p^{\circ})\ \text{Var}_\text{H}^{\text{nT}} + \sin(I_p^{\circ})\ \text{Var}_\text{Z}^{\text{nT}}. \quad (5.A)$$

Values obtained according to the above expression are presented in column (18), Fig A3. These values are equivalent to the F variometer output if the sensor orientation was in the spherical *DIF* frame. Relative variations with respect to the reference time are in column (19), and column (20) is obtained by subtracting column (15) and (19). This means we have used F variations at the variometer site to reduce F measurements at the main pillar. Finally, the total field at the main pillar is the average of column (20).

Base values: When we know the direction (D, I) and intensity of the field (F), it is trivial to find other intensive elements. Observed geomagnetic elements referred to the main pillar at the reference time 09:34:30 UTC [1] are shown in Fig. A3, table "Absolute values". D and I are expressed in degrees and decimal minutes, while intensive elements are in nT. Now, variometer base values are simply

$$\begin{aligned} H_B &= H - \text{Var}_\text{H}^{\text{nT}} \\ D_B &= D - \text{Var}_\text{D}^{\text{nT}} \\ Z_B &= Z - \text{Var}_\text{Z}^{\text{nT}} \end{aligned} . \quad (6.A)$$

Recordings of F from an independent scalar magnetometer should also be reduced to the main pillar for the absolute verification of the final vector data. Scalar base values (S) are defined as a difference between F at the main pillar minus raw scalar F_{GSM} at the reference time. Variometer and scalar baselines are shown in Fig. A3, table "Base values". Later, during the preparation of the definitive data, a full year of the observed base values is used to calculate continuous baselines and calibrate scalar and vector data.

Calculation of the offset of the fluxgate electronics and misalignment of the fluxgate sensor

Parallel with computing the absolute *D* and *I* values from the observations described above it is recommended that one should also calculate two angles (δ, ε) between the direction of the fluxgate sensor and the optical axis of the theodolite, and the offset of the fluxgate electronics (S_0). δ is the angle between the direction of the fluxgate sensor and optical axis of the theodolite in the horizontal plane when the telescope is horizontal and ε is the corresponding vertical angle. Both ε and S_0 can be found from the *D* and *I* observations according to formulas:

$$\delta = \frac{(A_1 + A_2 - A_3 - A_4)}{4}$$

$$\varepsilon_D = \frac{(A_1 - A_2 - A_3 + A_4)}{4 tan I}$$

$$S_{0D} = \frac{(A_2 - A_1 + A_4 - A_3)}{4 sin(1°)} H$$

$$\varepsilon_I = \frac{(V_1 + V_2 - V_3 - V_4)}{4}$$

$$S_{0I} = \frac{(A_1 - A_2 + A_3 - A_4)}{4 sin(1°)} F$$

where ε_D and S_{0D} correspond to the *D* observations while ε_I and S_{0I} correspond to the *I* observations. A_i (i = 1,…4) are values in column (6) in table “D” (Fig. A1). Similarly, V_i are values in column (13) in table “I” (Fig. A2). As demonstrated in Fig. 3A, quantities δ, ε and S_0 should be calculated in connection with every absolute measurement, because they provide a good check of the fluxgate theodolite and are good indicators of the observation quality.

Geomagnetic Observatory Lonjsko Polje (LON)
Department of Geophyisics, Faculty of Science, Zagreb,Croatia
Analysis of DI-Flux-Measrements - H - D - Z
Green fields should be filled

Location:	**LON**
Date:	**15.9.2015**
Pillar:	**Absolute**
First reading:	**9:34:30**
Absolutes:	THEO-010A
Variations:	LEMI-035
Observer: Igor Mandić	

Myra readings:

	Degrees °	'	"				
Myra Sensor up:	282	33	31	102	33	31	102,55861
Myra Sensor down:	102	33	28	102	33	28	102,55778

Mean Myra reading:

	°	'	"	
A_M =	102	33	30	102,55819

	°	'	"				
Azimuth A_Z =	64	58	8	64	58	8	64,96889

	Sens.	A Nr. [ ]	UTC (1)	Theodolite Readings °	'	"				D/° (2)	Var. D/nT (3)	Var D/° (4)	Red.Var/° (5)-(5)[1]) (5)	Red.Abl./° (2)-(6) (6)
D	E_{up}	1	9:34:30	311	30	50	131	30	50	131,51389	18,462	0,0472	0,00000	131,51389
	W_{up}	2	9:36:25	131	35	19	131	35	19	131,58861	18,165	0,0465	-0,00076	131,58937
	E_{dn}	3	9:39:10	131	31	39	131	31	39	131,52750	17,461	0,0447	-0,00256	131,53006
	W_{dn}	4	9:41:25	311	30	57	131	30	57	131,51583	16,976	0,0434	-0,00380	131,51963
	Means:								A_P=	131,53646	$\sin D_P$= 0,06884		A_D=	131,53824
											$\cos D_P$= 0,99763			

$D = A_D + A_Z - A_M - 90 =$ 3,94893 °

$D_p = A_p + A_Z - A_M - 90° =$ 3,94715 °

(4) Var. D/° = (3) / (0.01745 * F_P * $\cos I_P$)

δ/ ' = 0,80
ε/ ' = -0,68

Figure A1. Template for processing the *D* measurements.

Geomagnetic Observatory Lonjsko Polje (LON)
Department of Geophyisics, Faculty of Science, Zagreb, Croatia
Analysis of DI-Flux-Measrements - H - D - Z
Green fields should be filled

Location:	**LON**
Date:	**15.9.2015**
Pillar:	**Absolute**
First reading:	**9:34:30**
Absolutes:	THEO-010A
Variations:	LEMI-035
Observer: Igor Mandić	

	Sens.	A Nr. [ ]	UTC (7)	Theodolite Readings °	'	"				I/° (8)	Var. H/nT (9)	Var Z/nT (10)	Var. I° (11)	Red.Var/° (11)-(11[1]) (12)	Red.Abl./° (9)-(14) (13)
		1	9:34:30								30,129	128,433	0,04016	0,00000	
I	N_{dn}	5	9:46:05	297	55	44	62	4	16	62,07111	31,529	127,808	0,03833	-0,00183	62,07294
I	S_{up}	6	9:48:20	117	56	43	62	3	17	62,05472	32,214	127,673	0,03753	-0,00263	62,05736
I	N_{up}	7	9:54:00	62	5	45	62	5	45	62,09583	30,224	127,638	0,03961	-0,00055	62,09638
I	S_{dn}	8	9:55:10	242	4	48	62	4	48	62,08000	30,149	127,597	0,03967	-0,00049	62,08049
	Means:								I_p =	62,07542	$\sin I_p$ = 0,88356			I =	62,07679
											$\cos I_p$ = 0,46831				

(11) Var. I/° = ($\cos I_p$ * (10) - $\sin I_p$ * (9)) / U_I

εI/ ' = -0,70

Figure A1. Template for processing the *I* measurements.

Geomagnetic Observatory Lonjsko Polje (LON)
Department of Geophyisics, Faculty of Science, Zagreb, Croatia
Analysis of DI-Flux-Measrements - H - D - Z
Green fields should be filled

Location:	**LON**
Date:	**15.9.2015**
Pillar:	**Absolute**
First reading:	**9:34:30**
Absolutes:	THEO 010A
Variations:	LEMI-035
Observer: Igor Mandić	

	A Nr [ ]	UTC (14)	GSM F/nT (15)	Reduced to A pillar (15) -3,4	Var. H/nT (16)	Var. Z/nT (17)	Var. F/nT (18)	Red.Var F/nT (19-(19[1]) (19)	A pillar F/nT (red. Var.) (20)
	1	9:34:30	47840,28	47836,88	30,129	128,433	127,589	0,000	
	5	9:46:05	47840,20	47836,80	31,529	127,808	127,692	0,103	47836,70
F	6	9:48:20	47840,36	47836,96	32,214	127,673	127,893	0,305	47836,66
	7	9:54:00	47839,37	47835,97	30,224	127,638	126,931	-0,658	47836,63
	8	9:55:10	47839,25	47835,85	30,149	127,597	126,859	-0,729	47836,58

Means: F_p = 47839,80 U_I = 0,01745 * F_p = 834,80 F = 47836,64
H_P = 22403,80 U_D = 390,95

(18) Var.F/nT = $\cos I_p$ * (16) + $\sin I_p$ * (17)

$H_P = F_P * \cos I_P$

Absolute values:

UTC [1]	D ° '	I ° '	F/nT	H/nT F · cosI	X/nT H · cosD	Y/nT H · sinD	Z/nT F · sinI
9:34:30	**3 56,94**	**62 4,61**	**47836,64**	**22401,31**	**22348,13**	**1542,72**	**42267,31**

Base values:

UTC [1]	H_B nT	D_B ° '	Z_B Z - (10[1]) nT	I_B ° '	S = F - F_{GSM} F/nT -(15)[1]
9:34:30	**22371,18**	3,901713 ° **3** ° **54,10** '	**42138,87**	62,036633 ° **62** ° **2,20** '	**-3,64**

H_B = H - 9[1]	δ/ '= 0,80	
D_B = D - 4[1]	DEC: ε/ ' = -0,68	DEC: S_0 /nT= 6,36
Z_B = Z - 10[1]	INC: ε/ ' = -0,70	INC: S_0 /nT= 6,57

Figure A3. Final absolute and base values obtained from absolute observations in conjunction with scalar and variometer recordings (Fig A4).

Date	Time	Var H/nT	Var D/nT	Var Z/nT	F/nT		
15.9.2015	9:34:30	30,129	18,462	128,433	47840,28	[1]	
15.9.2015	9:36:25	30,649	18,165	128,290	47840,40		
						D	
15.9.2015	9:39:10	31,144	17,461	128,057	47840,37		
15.9.2015	9:41:25	31,223	16,976	127,846	47840,26		
							LEMI-035
15.9.2015	9:46:05	31,529	16,055	127,808	47840,20		
15.9.2015	9:48:20	32,214	15,215	127,673	47840,36		
						I	
15.9.2015	9:54:00	30,224	14,815	127,638	47839,37		
15.9.2015	9:55:10	30,149	14,652	127,597	47839,25		

Green fields should be filled

Figure A4. Variometer and scalar recordings during the DI-flux zero-field positions. The first reading presents the reference time.