J. Ind. Geophys. Union (January 2016)
Special Volume-2/ 2016 pp: 9-18

WIDIF: A New DIFLUX Optimised for Field Use

J. Rasson, O. Hendrickx, J-L. Marin, F Humbled and Genzi Li[1]
Institut Royal Météorologique, Service Scientifique de l'IRM à Dourbes, B-5670 Viroinval, Belgium
jr@oma.be
[1]Beijing Aerospace Xinfeng Machinery Equipment Co., Ltd, No. 52 Yongding Road, Beijing, China

ABSTRACT
The project aims at solving the increasingly difficult problem of non-magnetic theodolite supply while at the same time providing the design a very compact DIflux electronics. Our design plans to integrate in one compact instrument the fluxgate sensor, electronics, a GPS receiver, clock, display and battery. Those elements should be made small enough to fit on the DIflux theodolite's telescope.

As all elements having a magnetic signature participate rigidly in transits with the telescope, their magnetic effects are compensated by the DIflux measurement protocol. In fact they are determined and eliminated as if they were part of the sensor magnetization.

The concept was tested on BOIF TDJ6E-NM nonmagnetic theodolites. It was tested in different magnetic observatories and repeat station conditions. Tests were carried out at different magnetic latitudes. They show a dependable behavior and the instrument is convenient in terms of use and transport.

The results of comparisons with classical DIfluxes are presented. The excellent absolute results demonstrate the validity of this new concept.

The TDJ6E-NM theodolite manufactured by the BOIF factory in Beijing, China in a nonmagnetic version was recently made available. We carried out extensive testing of metrological as well as magnetic properties on several units. The tests showed that the device is fully compatible with the requirements for a DIflux in an INTERMAGNET magnetic observatory.

Keywords: Geomagnetic measurement, Magnetic repeat station, Magnetic declination, Nonmagnetic, Diflux theodolite.

CONSIDERATIONS ABOUT THE DIFLUX

The DIflux is a relatively recent invention (*Tenani, 1941*). In the nineteen-seventies it has reached a level of maturity, thanks to the work of a number of colleagues (*Meyer and Voppel 1954, Serson and Hannaford 1956, Trigg 1970*). From 1971 Daniel Gilbert, Jacques Bitterly and Jean-Michel Cantin from IPG Paris continued the investigations and achieved a high level of precision so that it proved to be better in terms of accuracy, resolution and ease of use (*Bitterly et al. 1984*). Therefore the people in charge of making absolute geomagnetic measurements try to use it where ever possible and it is on its way to supplant other absolute geomagnetic measuring instruments, both in the observatory and in the field.

It is an instrument able to measure the value of the geomagnetic declination D and inclination I. The instrument consists of a non magnetic theodolite and a fluxgate sensor mounted on the telescope, so that optical and magnetic axes are parallel. The accuracy of a measurement with a DIflux depends on the accuracy of the theodolite and on its magnetic cleanliness. The accuracy of a theodolite can be measured by appropriate measurement techniques (*Deumlich 1980*) and the magnetic cleanliness can also be measured and improved so as to be below a given limit. Therefore we can put the DIflux in the class of the absolute instruments.

NON MAGNETIC THEODOLITE SUPPLY

We in the geomagnetic observatories are all concerned about the supply of nonmagnetic theodolites, an essential tool in our observation tasks. Concerns are of:

- Future availability,
- Rising costs,
- Decreasing quality.

Although we are producing the automatic Diflux AUTODIF, able to solve part of this supply problem, we realize that the manual DIflux will still be around for many years for reasons of cost, ease of use and portability. The present supply of nonmagnetic theodolites is based on discontinued units:

- ZEISS 010, 015 and 020
- Wild T16
- UOMZ 3T2KP.

These theodolites are mechanically demagnetized by exchanging the offending magnetic parts with nonmagnetic materials. Precision axles, screws, springs made of steel are replaced by aluminum, brass, and plastics.

NON MAGNETIC THEODOLITE QUALITY

Unfortunately, as our contacts with manufacturers and users of non-magnetic theodolites show, mechanical and

Figure 1. The TDJ6E from Beijing Optical Instrument Factory (BOIF). This instrument with a basic 6 arc seconds accuracy is available in a nonmagnetic version TDJ6E-NM

optical characteristics and specifications of the theodolites are degraded in the demagnetization process:

- Manufacturer 1 admits that their modified ZEISS are not as wear resistant as the original factory issue,
- Our use of Manufacturer 1 modified ZEISS has shown rather severe shortcomings: glass and metal parts loosen under vibration,
- Errors in eccentricity of graduated circles result in severe ambiguities for the reading of circles,
- A full calibration check of Manufacturer 1 modified ZEISS theodolites in a foreign optical workshop showed significantly degraded optical and accuracy specifications,
- In our experience, modified non-magnetic theodolites never come with detailed optical or metrological specifications.

We concluded: "There is a need for a quality, new-in-box, non-magnetic theodolite, available in quantity, obeying strict metrological, optical and non-magnetism specifications".

A COLLABORATION WITH BOIF

The Beijing Bofei Instrument Co., LTD (BOIF) in China is still able to produce the non-magnetic theodolites TDJ6E-NM (Figure 1). They were first demonstrated to us in the Kakioka IAGA workshop in 2004 by the staff of the Chinese Earthquake Administration (CEA). During the strict instrument testing sessions at this workshop, the TDJ6E-NM obtained good results in the DIflux intercomparison: systematic errors were below 3 arc seconds and the dispersion in the results were below 5 arc seconds in I and 6 arc seconds in D.

The decision was taken to approach BOIF to purchase a batch of their non-magnetic theodolites so that we could start the work on a new Diflux based on the BOIF instrument. During the next IAGA observatories workshop in Changchun, China in 2010 and with the help of the CEA, we met a BOIF engineer and had in depth discussions about their theodolites. As a result, the TDJ6E-nm model, 0.1 arc minute accuracy class device was selected for our project.

As can be seen in the specifications below, the TDJ6E is similar to the ZEISS-020, well known and used in the Observatory community.

DETAILED SPECIFICATIONS OF TDJ6E-NM

Setting the non-magnetism specifications

In our discussions with BOIF, we set the specifications for the overall non-magnetism of the theodolite. These are based but exceed the military specification STANAG 2897 (Ed. 3). This specification comprises two steps: idealization and magnetic signature testing. The specification calls for a magnetic signature after idealization below 1nT at a distance of 5 cm. The distance of 5cm is dictated by practical considerations so that the test can be carried out manually in front of a fluxgate sensor. Shorter distances would make the method too sensitive to distance errors and longer distances would be unrealistic compared to

Table 1. Results of the preproduction testing for non-magnetism.

	description	id1	id2	Magnetic Signature		
				as received	after idealization	
First_batch					@ 10mmm	@ 50 mm
a-1	telescope_tube	2A12	'2024	< 0.1 nT	< 0.1 nT	< 0.1 nT
a-2	mirror_support	2M2-M	ADC12	< 0.1 nT	0.4nT	< 0.1 nT
a-3	Brass_cup	CW4S2K	CuSM6	< 0.1 nT	0.3nT	< 0.1 nT
a-4	nut	NS105	Bzn15-20	< 0.1 nT	< 0.1 nT	< 0.1 nT
a-5	diagonal_eyepiece	2A12	-	< 0.1 nT	< 0.1 nT	< 0.1 nT
Second_batch						
b-1	bracket	nm-04-41		< 0.1 nT	< 0.1 nT	< 0.1 nT
b-2	cover_plate_left	nm-06-16A/B		< 0.1 nT	< 0.1 nT	< 0.1 nT
b-3	plummet_obj_mount	nm-08-01-		< 0.1 nT	0.6nT	0.1 nT
b-4	diopter_ring	nm-01-26		< 0.1 nT	< 0.1 nT	< 0.1 nT
b-5	levelling_knob	nm-02-6		< 0.1 nT	0.3nT	< 0.1 nT
b-6	horiz_axis	nm-04-33-0		< 0.1 nT	5nT	0.9nT

the distance between the Diflux fluxgate sensor and the theodolite 's alidade.

It is however difficult to relate the angular error on magnetic declination and inclination to the size of the magnetic signature because this depends on the magnetic latitude where the measurement is taken. The location of the magnetic pollution on the theodolite is also important to assess this relation: for instance a magnetic pollution located on the horizontal telescope axis is likely to be eliminated by the Diflux measurement protocol (*Gilbert & Rasson 1998*). On the other hand, magnetic pollution in the tribrach or in the lower part of the theodolite will for sure cause errors in the inclination.

For setting a specification for maximum magnetic signature we consider relationships linking the Diflux fluxgate measurements dD and dI in nanoTesla units with the angle readings δD and δI in degrees at mid-latitude, where H~20000nT and F ~50000nT:

$$\mathrm{atan}(dD/H) = \delta D \qquad \mathrm{atan}(dI/F) = \delta I \qquad (1)$$

The relations (1) give a value for dD=dI=1nT:

δD = 10 arc second,

δI = 4 arc second.

We believe this upper limit on the angular error level is adequate, given the angular accuracy specifications (see below). Moreover, these slight magnetic signature related effects bear mostly on δI (*Gilbert & Rasson 1998*).

TDJ6E-NM Theodolite specifications for non-magnetism

This specification is established as the result of a two steps approach: idealization procedure and magnetic signature measurement.

Idealization procedure

The idealization simulates the magnetic field environment to which the object under test will be subjected in its useful life. This environment is obviously both DC and AC fields. Therefore, the idealization magnetic field is the sum of:

- A DC field of 0.6 mT,
- An AC field (1Hz) starting at 6 mT decreasing to 0.2 mT, decrease occurring in steps not greater than 0.2 mT.

Magnetic signature measurement method

We use the Observatory DIflux in the Inclination measurement position in quiet field's conditions. We approach the object under test along the fluxgate axis until 5 cm from fluxgate. We then rotate randomly the object under test and record the max and min fluxgate readings. The magnetic signature M_s is defined as:

$$M_s = (\mathrm{max}-\mathrm{min})/2$$

Preproduction magnetic signature testing of theodolite parts

In order to strictly respect the non-magnetism specifications, BOIF sent us batches of theodolite parts for testing (Figure 2) of their non-magnetism.

We give in Table 1 the results of the magnetic signature testing both before and after idealization. It is noteworthy that the parts indeed get a detectable magnetic signature after the idealization procedure while they were all delivered with signature levels below 0.1nT. Item b-6 almost fails the test and was corrected by BOIF at production.

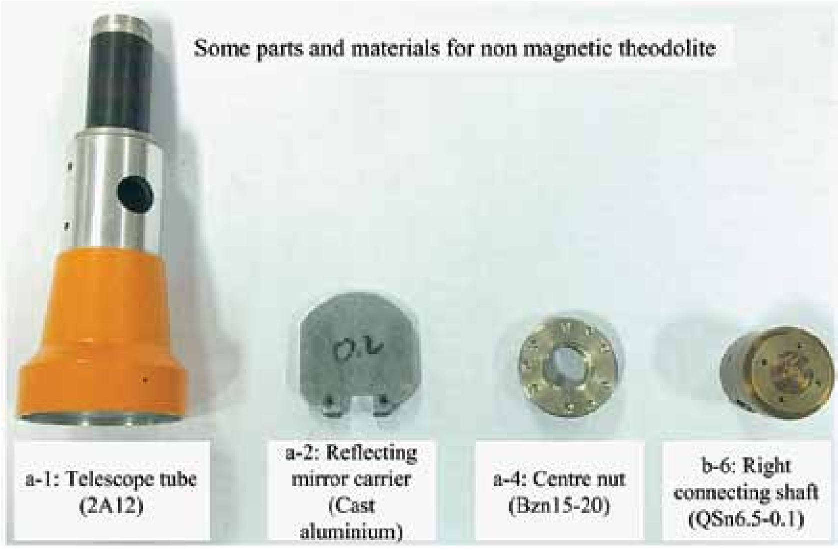

Figure 2. Theodolite parts from the TDJ6E-NM delivered for preproduction testing of the non-magnetism in Dourbes. See Table 1 for the results

TDJ6E-NM Theodolite specifications: operational, environmental, mechanical, metrological and optical

- Temperature operating range -20 to +50°C
- Ingress Protection rating: IP54
- Diameter of the horizontal circle: 94mm
- Diameter of the vertical circle: 76mm
- Circle graduation accuracy to ISO 17123-3 :±6 arc second or better for Vertical and Horizontal angular circles
- Reading microscope magnification Horizontal circle: 68x
- Reading microscope magnification Vertical circle: 65.4x
- Reading microscope image: erected, also with the diagonal eyepiece
- Color coded microscope reading field; simultaneous vertical and horizontal angle reading
- Telescope image: erected, also with the diagonal eyepiece
- Telescope magnification: 30x
- Optical plummet image (not erected) range of focusing: 0.5 - ∞ m
- Optical plummet magnification: 3x
- Optical plummet field of view: 5 degrees
- Tubular spirit level of the alidade tilt sensitivity: 30 arc seconds = 2mm
- Automatic vertical circle index accuracy: better than 1 arc second
- Automatic vertical circle index compensation working range: +/-2 arc minute
- Possibility to lock the automatic vertical circle index pendulum
- Height of horizontal axis: 207mm
- Dimensions: 286x163x130mm
- Weight: 4.3 kg

SPECIFICATION VERIFICATION IN DOURBES

As a sizeable batch of theodolites was purchased, it was decided to test the specifications of 8 randomly chosen units from the delivery. The tests concerned non-magnetism and angular accuracy specifications. The ISO 17123-3 standard was used for graduation accuracy test of the horizontal and vertical graduated circles.

Postproduction specifications testing: angular accuracy

A special pillar was set-up with 5 targets well distributed in azimuth for the horizontal circle test. Also the pillar was installed in front of a tall object (ionospheric sounder antenna) so that 4 targets covering 30° on the vertical circle were visible (Figure 3).

The results of this testing are given in Table 2. All theodolites passed the test since the results are within +/-6 arc seconds.

Postproduction specifications testing: magnetic signature after idealization

We used a large solenoid in order to apply the AC and DC magnetic fields required for the idealization (Figure 4). The observatory Diflux was used for the magnetic signature measurements.

We tested separately the theodolite, the tribrach and the two diagonal eyepieces (coudés). The results are presented in Table 3. All the theodolites under test passed.

Figure 3. Special set-up for testing the circle graduation accuracy according to the ISO 17123-3 standard

Figure 4. Our set-up for idealization. The reading on the teslameter is in Gauss.

Table 2. Final results of the 8 different TDJ6E-NM theodolites angular accuracy test.

Angular Accuracy ["] of Theodolites – summary of results

Theodolite reference #:	001	007	021	023	031	034	044	050
Horizontal Circle	4	4	4	4	6	4	6	5
Vertical Circle	2	4	4	2	3	4	1	2

Table 3. Magnetic signature of the theodolite elements in nT @ 5 cm. Coudé = Diagonal eyepiece.

Magnetic Signature [nT] after idealization – summary of results

Theodolite #:	001	007	021	023	031	034	044	050
Theo [A]	**0,2**	**0,4**	**0,0**	**0,3**	**0,2**	**0,4**	**0,1**	**0,2**
Tribrach [B]	**0,4**	**0,3**	**0,1**	**0,2**	**0,2**	**0,3**	**0,2**	**0,2**
Coudé ocular [C]	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
Coudé µscope [D]	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**

Figure 5. The WIDIF Diflux as a combination of the TDJ6E-NM and the blue magnetometer console, mounted on the telescope. The console also comprises a GPS receiver, a clock, a battery and three LCD displays, one of them being visible here. Note also the second under plate, allowing using pillars fitted with 120° v-grooves.

THE WIRELESS DIFLUX (WIDIF) AND FLM4/A

The Wireless DIflux WIDIF is based on the TDJ6E-NM theodolite. The projected new Diflux is designed so as to mount the fluxgate sensor and the complete electronic console on the telescope (Figure 5). WIDIF is a compact DIflux magnetometer: the fluxgate sensor, fluxgate electronics, a GPS receiver, clock, several displays and a battery are kept small enough to fit onto the telescope. In that way we do not need a wired connection between the theodolite bearing the fluxgate sensor and the electronics console. We indeed do away with the cable joining the theodolite and the console.

How is it possible to get good measurements with the electronic console (which has a non-zero magnetic signature) so close to the fluxgate sensor? Elements with magnetic signature participate rigidly in all transits with the telescope: they are determined and eliminated as if they were part of the sensor magnetization error. So their magnetic effects are compensated by the DIflux measurement protocol just as the sensor magnetization error (*Gilbert and Rasson 1998*).

Widif electronics for a BOIF TDJ6E-nm theodolite is mainly intended for repeat station work. More conservatively, the FLM4/A electronics console connected by a wire to the theodolite is also available, mainly for Observatory work or when a backlit display is necessary (measurements at night), see Figure 10. Whatever the console execution, the theodolite electronics console consists of:

- 0.1 nT resolution fluxgate magnetometer with a LDC-20A Pandect fluxgate sensor
- GPS receiver disciplining a clock and able to indicate the Latitude and Longitude
- Circuitry to electronically trim of the sensor magnetization error
- A lithium polymer battery for powering the console during up to 6 h.

Outstanding features of the electronic console

The electronics package has been kept small so that it can fit in the tight space available on the telescope of the theodolite. It is necessary to leave all the telescope (focus and ocular) and theodolite controls readily accessible while maintaining the possibility to allow 360° transits and rotations of the telescope. It is also desirable to keep the centre of gravity of the telescope assembly on the horizontal and vertical rotation axes, so that the telescope keeps its position when released. As the instrument is to be deployed for fieldwork mainly, a quasi waterproof and mechanical protection is provided to the console.

Another key operational property resides in the fact that it must keep a constant magnetic signature over the course of a full DIflux measurement protocol of the declination and inclination. Besides it must provide access and view to the measured values whatever the position of the telescope is. Practically this means that 3 different

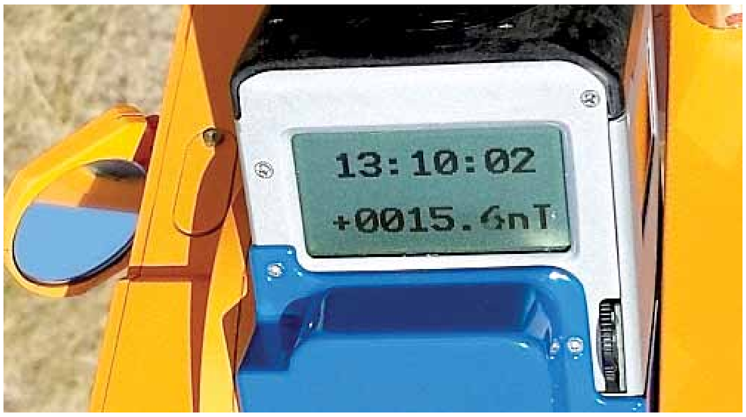

Figure 6. The WIDIF display during a measurement session. The display will change its orientation to fit the telescope position.

Figure 7. Measurement menu of the WIDIF at switch-on. Note the rocker switch (upper right) allowing to navigate the menu. It is extremely soft to activate and when idle, remains in the same position so as to keep the magnetic signature unchanged.

digital LCD displays are set-up around the telescope. Moreover the writing on the displays must always appear left-to-right and head up, so an automatic orientation of the displays must take place, controlled by a gravity sensing device on the telescope.

As several measurement menus are programmed in the console, a switch is provided for the operator to select between the different functions. Activating this switch should not disturb the measurement in any way, so it must be very soft to activate and not modify the magnetic signature. Finally, since the battery size is limited due to available space, the electronics design should ensure very low-power operation and save any microwatt where possible.

TESTING

Tests carried out in Dourbes

In order to test the finished WIDIF, intercomparison tests were carried out in our Dourbes magnetic observatory. We used the standard procedure of measuring the baseline of a variometer on the same pillar using

- The reference observatory Diflux,
- The WIDIF under test.

The tests in Dourbes involved a ZEISS010 with DImag88 electronics from EOPG, France. The WIDIF and ZEISS intercomparison was performed for a period of 90 days in the year 2014. The variometer is a LAMA fluxgate triaxial device installed in DFI orientation. Therefore D and I baselines can be computed without involving any other instrument.

Concerning the Declination D baselines, the agreement between the two is within 0.001° as shown by the black (WIDIF) and orange (ZEISS) fitted baselines. This level of agreement is quite satisfactory, as the angle reading resolution of the WIDIF is 0.0016° (0.1 arc minute), see Figure 8.

Concerning the Inclination I baselines, the agreement between the two is initially within 0.002° and tapering off to 0.001° and less at the end of the comparison session. This level of agreement is also quite satisfactory, as the vertical angle reading resolution of the WIDIF is 0.0016° (0.1 arc minute) albeit with less magnification as for the horizontal circle, see Figure 9.

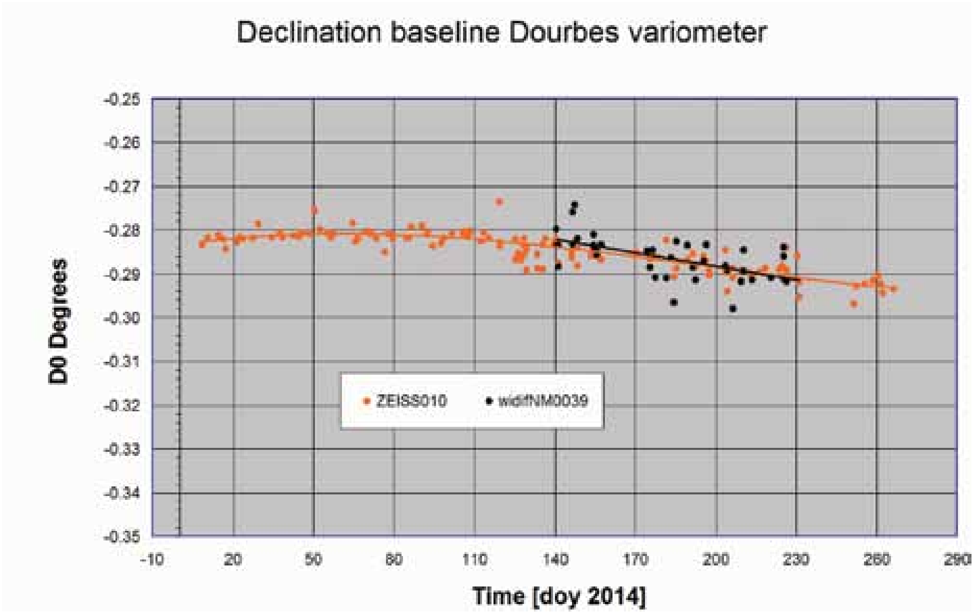

Figure 8. Declination baseline of the LAMA DFI variometer as measured by the ZEIS010 and WIDIF DIfluxes.

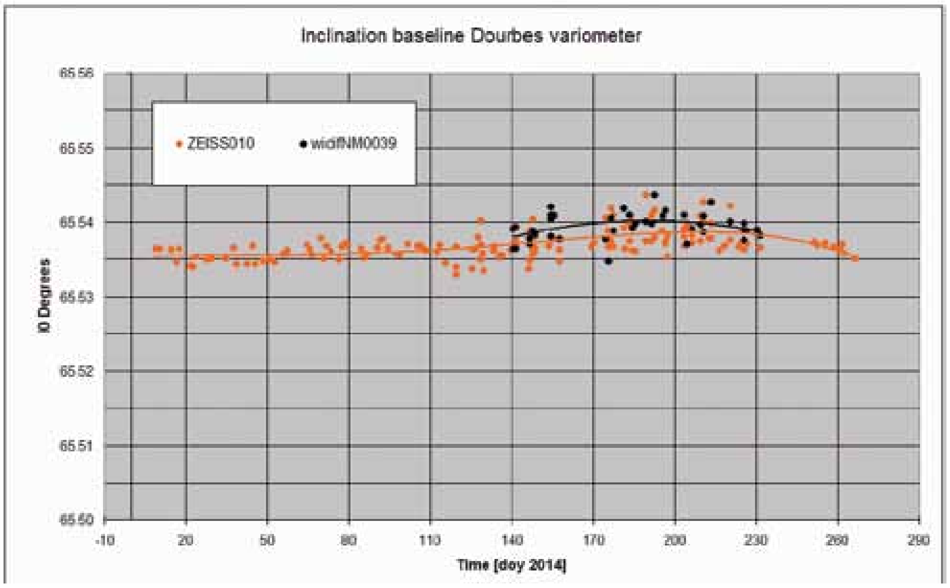

Figure 9. Inclination baseline of the LAMA DFI variometer as measured by the ZEIS010 and WIDIF DIfluxes.

Testing under different magnetic and illumination conditions

We gathered extensive experience of using the WIDIF for fieldwork and in the process, tried to improve the device. For instance, several modifications in the display interface were introduced as a result of the feedback from the field operators.

In general, the WIDIF proved to be very handy in the field. The GPS receiver providing accurate timing and geographical coordinates on the spot is very useful in repeat station work and when an astronomical geographic North determination has to be made (e.g. sun shot). We also had the opportunity to use the WIDIF for airport compass rose certification (Brussels airport) and for runway azimuth determination (Liège Airport) and appreciated its compact and lightweight construction. For compass rose work, about 20% less time was necessary to complete the job. One has to get used to the pendulum clamp however, which is activated for transport of the instrument. One should not forget to unclamp the pendulum before making readings on the vertical circle, as otherwise the automatic vertical circle index will be giving erroneous readings.

Figure 10. The FLM4/A DIflux electronics. This has the same functionalities as the WIDIF.

Table 4. The different observatories where the WIDIF was test

Observatory	Geomagnetic Inclination
Sodankyla, Finland	77°
Chambon-la-Forêt, France	64°
Sonmiani, Pakistan	38°
Chouttupal, India	24°
Trelew, Argentina	-43°

The reading of the WIDIF displays is easy and at all time convenient. Enough light must be available however, as the displays are reflective. For low light levels we recommend using the FLM4/A, which has a backlit display. In order to make sure the WIDIF Diflux is operational on the whole Earth, we carried out measurements in a variety of magnetic observatories, looking to get a high span of geomagnetic inclinations in the process. These observatories with their inclination values are listed in Table 4.

The WIDIF proved to be fully functional at those places. One of the 3 LCD displays would always be visible for zeroing the fluxgate output during the Diflux measurement protocol. The diagonal eyepiece was necessary to read the microscope in Chouttupal and Sonmiani, because the telescope is then in too steep a position to look directly in its ocular.

DETAILED SPECIFICATIONS OF WIDIF AND FLM4/A MAGNETOMETER CONSOLES

WIDIF fluxgate sensor & electronics specifications

Analog filtering of fluxgate output: Second order low-pass filter with 3 dB cut-off at 10Hz
Sampling frequency of the fluxgate signal: 30 Hz
Digital filtering of fluxgate signal: Box-car average over 900 ms
Displaying rate of fluxgate output: 5 Hz
Scale value accuracy: 1%
Range: +/-600nT
Automatic fluxgate sensor magnetization suppression with manual fine tuning.
Fluxgate sensor magnetization suppression range: +/-600nT

Battery life: 6 h including 1 GPS fix
Battery charging time: 2 h
LCD display technology: reflective

Version with wire FLM4/A:

This magnetometer console may also be used on the ZEISS 020/015/010 series of theodolites. It has the same functionalities as for WIDIF but plus:

- Larger battery
- Back-lit display
- Hi-reliability LEMO connector

The electronics console fits in the standard ZEISS theodolite boxes.

Ancillary devices

Lithium polymer battery charger
90° eye-pieces for microscope and ocular(non-magnetic, erect view)
Non-magnetic tools
120° V-groove under plate
Non-magnetic tripod
Sun shot filter
Operation manual

ACKNOWLEDGEMENTS

We thank the many colleagues who helped in the design and testing of the WIDIF: Pascal Jamme, Sebastian Pelliciuoli, Tero Raita, Benoît Heumez, Kader Telali, Kusumita Arora, Madeeha Ashfaque and Ayyaz Ameen. Dongmei Yang kindly connected us with BOIF.

REFERENCES

Bitterly, J., Cantin, J.M., Schlich, R., Folques, J. et Gilbert, D. 1984. Portable magnetometer theodolite with fluxgate sensor for earth's magnetic field component measurements, Geophysical Surveys v.6 p233-239.

Deumlich, F. 1980. Instrumentenkunde der Vermessungstechnik, VEB Verlag für Bauwesen, Berlin 1980.

Gilbert, D. and Rasson J.L., 1998. Effect on DIflux Measuring Accuracy due to a Magnet located on it, Proceedings of the VIIth Workshop on Geomagnetic Observatory Instruments, Data Acquisition and Processing, Scientific Technical Report STR98/21, pp168-171, Geo Forschungs Zentrum Potsdam.

Meyer, O. and Voppel, D. 1954. Ein Theodolit zur Messung des Erdmagnetischen Feldes mit der Förstersonde als Nullindicator, Deutsche Hydrographische Zeitschrift, v.12 p73-77.

Serson, P.H. and Hannaford, W.L.W., 1956. A portable electrical magnetometer, Canadian Journal of Technology, v.34 p232-243.

Tenani, M., 1941. Nuovo Metodo di misura della declinazione e della inclinazione magnetica, La ricerca scientifica, v. 20, p1135-1140.

Trigg, D.F. 1970. A portable D and I magnetometer, Geomagnetic Laboratory Report n°70-3, Direction de la Physique du Globe, Energie, Mines et Ressources, Ottawa, Canada.