

## **Presentation of the Prototype of an Automated DIFlux**

Sébastien A. VAN LOO and Jean L. RASSON

Royal Meteorological Institute of Belgium  
Centre de Physique du Globe, B-5670 Dourbes, Belgium  
e-mail: sebv1@oma.be

### **A b s t r a c t**

Recently, we developed the first prototype of an automated DIFlux. This instrument performs absolute measurements of the geomagnetic field orientation (declination and inclination), without requiring the intervention of a human operator, nor maintenance. New possibilities are offered to the geomagnetic surface observatories, which may be completely automated in the near future. This may be particularly important for measurements in locations that are difficult to access, such as remote areas and the seafloor, hence improving the distribution of observations on the Earth's surface. Obviously, the instrument itself should not disturb the field to be measured. In this context, automation is a big challenge because several key elements, like the sensors, the motors, the angular encoders and the electronic circuits, contain generally ferromagnetic elements and conduct electrical currents, which may disturb the observations. Solutions to carry out the operations of sensor rotation, precise electronic reading of the angles and automatic orientation in the reference frame (determined by the local horizontal plane and geographic North) without disturbing the magnetic field will be exposed.

### **1. Introduction**

At present, scientists do not have a physical model able to predict with sufficient precision the evolution of the geomagnetic field. The only way of determining it is to measure it. So the geomagnetic field is well-known only in the vicinity of the magnetic observatories. At the most inaccessible places, like the seafloor, high altitudes, and deserted areas, data is lacking, except for interpolations.

As a vector quantity, the complete definition of the magnetic field of the Earth, in a single point at a certain epoch requires evaluation of its absolute value (total field  $F$ ) and its direction (declination  $D$  and inclination  $I$ ). The first is commonly measured absolutely and automatically with a proton magnetometer. The variations of the field

direction are generally recorded automatically too, but its absolute determination must still be carried out manually, using a DIFlux magnetometer (Rasson 2005). If this last instrument could be automated, it would finally become possible to establish completely autonomous magnetic observatories, working without need for an operator nor maintenance. A total and uniform coverage of the planet would become feasible then (Chave *et al.* 1995).

That encouraged us in the 1990's to set up the AutoDIF project, the first phase of which will be completed in January 2008 (Rasson 1996, van Loo *et al.* 2006). The first phase is devoted to the development of a new totally automatic and absolute measurement instrument of the orientation of the geomagnetic field. Initially the reference to geographic North will be done similarly as in the traditional surface observatories, sighting a remote target of known azimuth. In the second phase, we will work on the automation of a gyroscopic North-seeker, in order to make the instrument more compact. The detailed specifications of our AutoDIF project are presented in Table 1.

Table 1  
Specification of the automatic declination-inclination magnetometer AutoDIF

	Errors in declination	Errors in inclination	Azimuth reference	Dedication
Phase 1	< 6 arcsec	< 6 arcsec	Automatic pointing of a distant target	Surface observatories
Phase 2	< 20 arcsec	< 6 arcsec	Automatic gyroscopic North-seeker	Stations where the available volume is limited (seafloor)

The realisation of such an instrument, being at the same time accurate, non magnetic and automatic, represents a serious challenge because several key elements, like the motors, the angular encoders and the electronic circuits, contain generally ferromagnetic elements and convey electrical currents which may disturb the natural field. We propose solutions in the following.

We start by briefly exposing how a fluxgate sensor can be used to determine the orientation of the ambient magnetic field. Then, we present a support to position the sensor in the field, consisting of a non magnetic theodolite, an accurate system of angle reading and piezoelectric motors, which do not disturb the field. Solutions are also proposed to determine the orientation of the measurement reference frame compared to the absolute reference frame of the Earth, defined by geographic North and the local horizontal plane. Finally, we evoke in a few words the data-processing and acquisition devices. These components of the AutoDIF instrument are shown in Fig. 1.

## 2. Detection of the Orientation of the Magnetic Field

To detect the orientation of the ambient magnetic field, we use a fluxgate sensor, like the one used in the traditional DIFlux manual. We refer the reader for the details

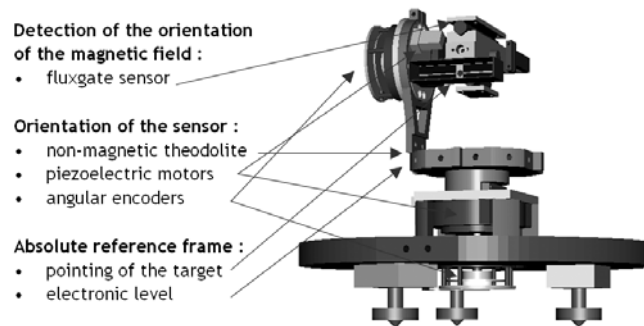


Fig. 1. Disposition of the fundamental devices of the AutoDIF.

of the working principle of a fluxgate sensor to the paper by Primdahl (1979). Let us simply remember that the fluxgate produces a signal, which is proportional to the component of magnetic field parallel to its axis (in fact it realises the scalar product of the magnetic field and the axis of the probe vectors).

The so called zero measurement method consists in seeking the positions of the probe, which produces a null signal, the field to be measured being then exactly perpendicular to the fluxgate axis. Thus the magnetic declination is measured after putting the fluxgate horizontally by turning it around a vertical axis. The inclination is obtained after placing the fluxgate in the magnetic meridian plane, rotating it around a horizontal axis.

### 3. Orientation of the Sensor

#### 3.1 *Non magnetic theodolite*

In order to be able to orient the sensor in all the possible directions, the fluxgate probe is mounted on a theodolite. As shown in Fig. 2, in spherical coordinates, the orientation of the sensor is entirely determined by the angle  $\phi$  around the vertical axis (reading on the horizontal circle) and the angle  $\theta$  around the horizontal axis (reading on the vertical circle).

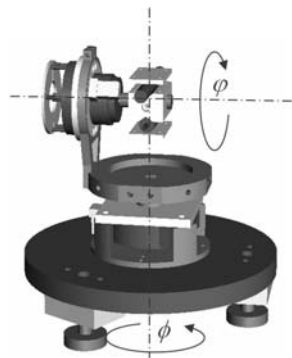


Fig. 2. Orientation of the fluxgate in space using a theodolite.

The evolution of the theodolite prototypes that we realised, which of course were built of non magnetic materials, is displayed on Fig. 3.

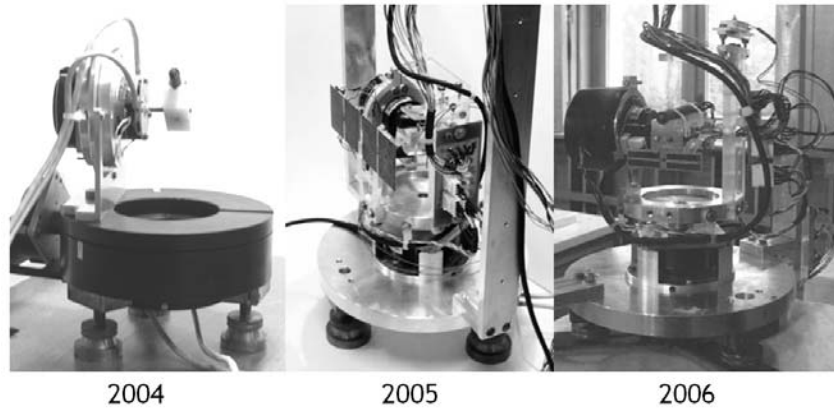


Fig. 3. Evolution of the AutoDIF prototypes during the last three years.

In order to eliminate the mechanical errors related to the manufacture of the theodolite, the values of the declination and inclination are calculated after averaging the measurements taken in the four possible positions, presented in Table 2.

Table 2

Different sensor positions allowing the measurement of the declination and the inclination

Measurement	Position of the sensor compared to the horizontal axis	Position of the vertical circle compared to the vertical axis
Declination	above	in the North
	under	in the North
	under	in the South
	above	in the South
Inclination	above	in the West
	under	in the West
	under	in the East
	above	in the East

### 3.2 Angular encoders

The electronic sensing of angles is ensured using optical angular encoders. One system is set up for each of the two principal axes of the theodolite.

A graduated disk, fixed on the relevant axis, rotates between a light source and a detection system (Fig. 4). Gratings, with the same period as the graduated disk, are placed behind the light source in order to amplify the signal obtained by optical Moiré

effect. These gratings are shifted a quarter of a period in order to obtain two sinusoidal signals. The disk is also equipped with an additional track, producing only one reference pulse per rotation.

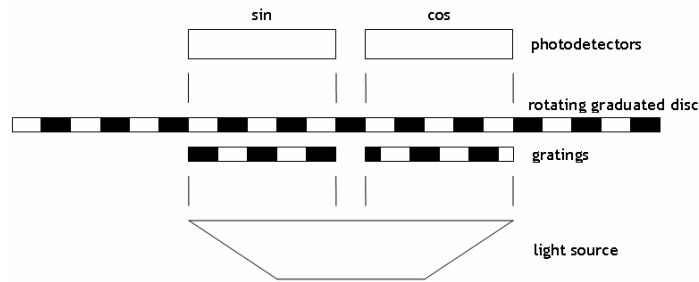


Fig. 4. General diagram of an optical encoder.

Since we use disks with 2500 graduations, a resolution of  $0.0360^\circ$  is obtained simply by counting the periods (using a quadrature x4 counter). As the two sinusoidal signals are in phase quadrature (Fig. 5), calculating the arctangent of the signals leads to continuous evaluation of the angles at a precision of about 1 arcsec, depending mainly on the accuracy and quality of the encoders, the electronic disturbances, and the mechanical alignment of the system. The reference pulse is used to make this incremental encoder absolute.

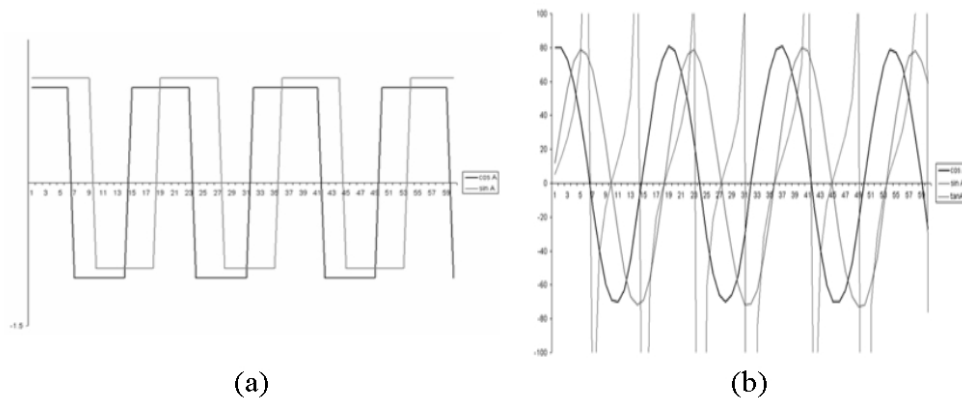


Fig. 5. Electric signals allowing (a) the period count and (b) the continuous sensing of the angle by interpolation between the period increments.

It can be understood easily that the precision of the angle reading is conditioned by the quality of the electronic signals. The errors related to the encoder and electronics quality, like amplitude modulation and undesired offset are corrected in real-time by a digital processing algorithm.

Errors related to mechanical misalignment of the encoder compared to the rotation axis are corrected putting two encoders around the same disk, at more or less  $180^\circ$  (Fig. 6). In this case the average of the two measured angles produces a result free from eccentricity errors.

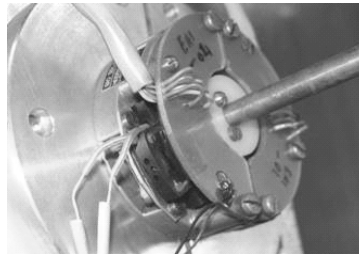


Fig. 6. Two encoders placed around the horizontal axis.

Encoders that are available on the market are generally not magnetically clean. Moreover it is impossible to arrange two of them side by side symmetrical on the same disk. So some parts, essentially the detector board, have to be replaced by specially designed circuits, as illustrated on Fig. 7.

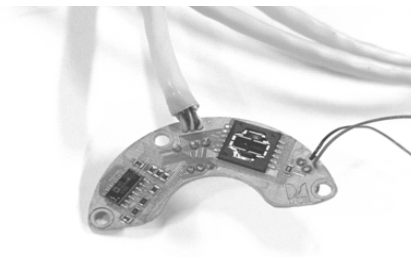


Fig. 7. Example of a detector board for the angular encoder including a ready-made IC as detector and a linear amplifier.

### 3.3 *Piezoelectric motors*

Considering the fluxgate probe, the non-magnetic theodolite and the angular encoders, we have all the components of a digital DIFlux theodolite, but not robotised yet. The rotations around the two axes of the theodolite are achieved by piezoelectric motors, which are commercially available in totally non-magnetic versions.

The principle of operation of such a motor is based on the generation of a deformation wave which is propagated on the surface of an annular piezoelectric crystal, constituting the fixed part of the motor (the stator). The rotation of the mobile shaft is obtained by pressing its base against the stator, where it is pulled by the movement of the deformation wave (see Fig. 8). This traveling wave is obtained by stimulating the crystal with two high voltage signals (300 Vpp), one cosinus and one sinus, at a frequency of about 40 kHz. In this way, power is applied by a small, non-disturbing AC current.

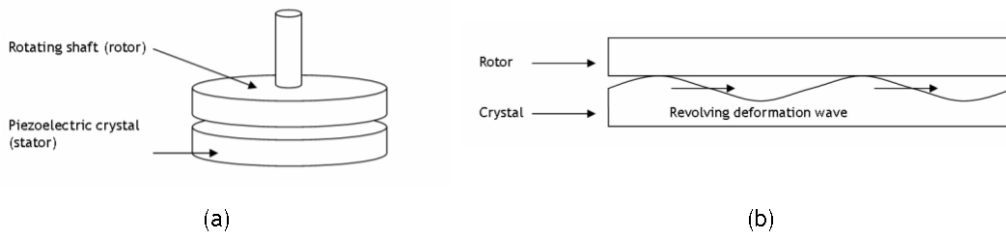


Fig. 8. (a) General diagram of a rotary piezoelectric motor, (b) Detail of the interface between rotor and stator.

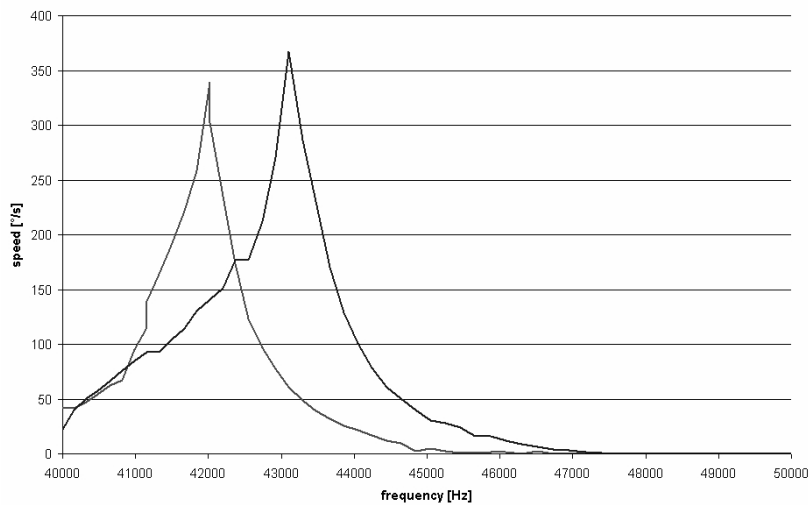


Fig. 9. Rotation speed of a Shinsei USR60 piezoelectric motor in the two directions of rotation.

For example, when a position has to be reached with great precision, or in order to avoid brutal starts and stops, the rotation speed has to be controlled very finely. As shown in Fig. 9, speed can be modulated using the excitation frequency of the crystal. But since the behaviour of the motors varies largely, depending on their temperature, their wear and even on the direction of rotation, the frequency has to be corrected continuously, especially for very slow motion, using the angular encoders data as a feedback signal.

Under these conditions, the shafts of the motors are appropriate to be used directly as axes for the theodolite, with no need for a transmission, or reduction system.

#### 4. Orientation of the Instrument in an Absolute Reference Frame

As presented above, the instrument is able to measure the orientation of the magnetic field related to its own reference frame. In order to qualify the instrument as absolute, it remains to determine the orientation of the instrument compared to the absolute reference frame of the Earth, which we can define by the local horizontal plane and the direction of geographic North.

#### 4.1 Electronic level

The electronic level provides a reference to the horizontal. It is built in the same manner as a traditional bubble level, but is filled with a liquid containing an electrolyte, which has the properties of a three-terminals variable resistor, varying according to the position of the bubble (Fig. 10).

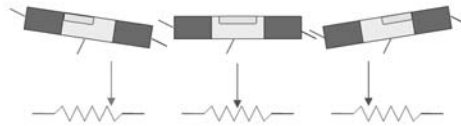


Fig. 10. The electronic level presented in analogy with a three-terminals variable resistor.

The horizontality is then accurately measured using a Wheatstone bridge, and the angles around the horizontal axis (read on the vertical circle) can be corrected by software easily.

#### 4.2 Electronic target

In the first phase of the project, the orientation of the instrument compared to geographic North is obtained by pointing a distant target with known azimuth, as is usually done in magnetic observatories (Fig. 11).



Fig. 11. (a) The corner cube reflector used as a target, (b) The photocells receiving the light reflected from the reflector.

A laser diode module is installed in place of the telescope. It points a corner cube reflector, which is centred at a point with precisely known azimuth (actually the visual target). According to properties of the corner cube reflector, the incident light ray is reflected  $180^\circ$ , but translated by a distance  $e$  depending on the angle  $\alpha$  between the incident ray and the line which connects the centre of the corner cube to the vertical axis of the theodolite (Fig. 12). Two solar cells are disposed around the laser in order to evaluate the translation of the reflected ray. The difference of light falling on the two solar cells is directly related to the pointing of this electronic target: when the reflected ray returns precisely in the middle, the laser points exactly the centre of the target.



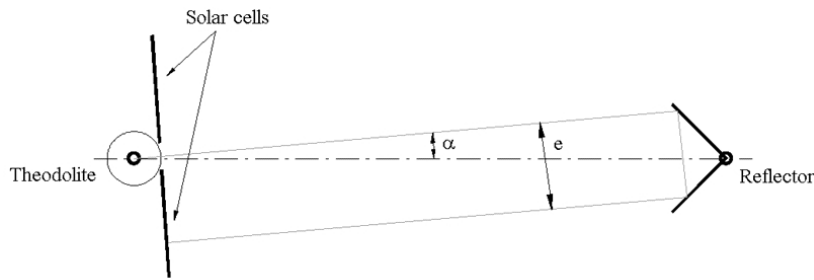


Fig. 12. Geometrical optics with the corner cube reflector.

The laser diode module that is used as light source is a little magnetic. But its effect on the final magnetic measurements results is eliminated because it accompanies the fluxgate sensor in the four positions taken for declination and inclination. In order to reduce mechanical errors of the theodolite, the target is also sighted in two positions (probe up and probe down). The goal of the second phase of the project is to replace this system by an automatic gyroscope. This certainly will make it possible to work in a more confined volume.

## 5. Data Processing and Remote Control

The signals produced by all the electronic acquisition systems (reading of angle, fluxgate, level, pointing of target) are collected by a microcontroller using analog to digital converters. They are then processed and instructions are sent to the motor drivers, in order to carry out the desired operations. The data storage, the time synchronisation, and the user interface are ensured by a computer, connected to the microcontroller via USB bus. Figure 13 shows the user interface, as displayed on the host computer.

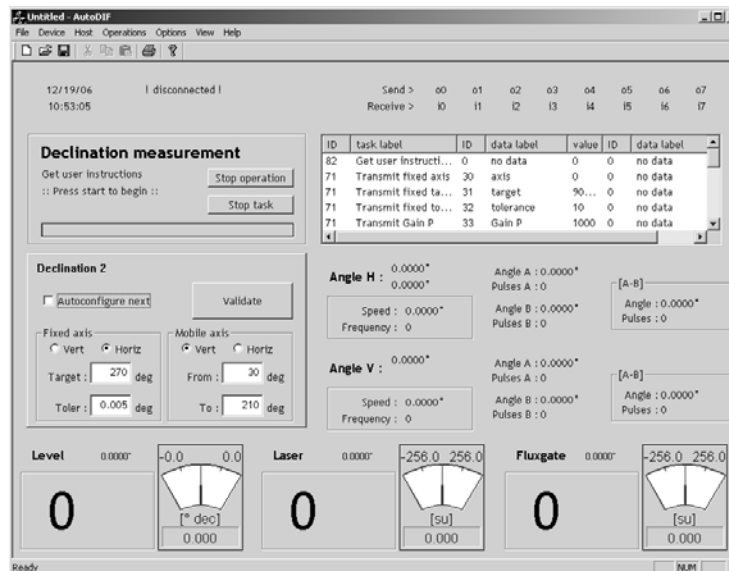


Fig. 13. Screenshot illustrating the AutoDIF user interface.

## 6. Conclusion

Presently, our instrument performs absolute measurements of the orientation of the geomagnetic field vector automatically, using the manual DIFlux measurement protocol. But a human operator is no longer needed.

Our first prototype, entering the qualification phase, is presently in service in the magnetic observatory of the Centre de Physique du Globe de l'IRM in Dourbes. The first results are evaluated daily and seem encouraging.

## References

- Chave, A.D., A.W. Green, R.L. Evans, J.H. Fillioux, L.K. Law, R.A. Petit, J.L. Rasson, A. Shultz, F.N. Spiess, P. Tarits, N. Tivey and S.P. Webb, 1995, *Report of a Workshop on Technical Approaches to Construction of a Seafloor Geomagnetic Observatory*, Technical Report WHOI-95-12, Woods Hole Oceanographic Institution, Woods Hole, USA.
- Primdahl, F., 1979, *The fluxgate magnetometer*, J. Phys, E: Sci. Instrum. **12**, 241-253.
- Rasson, J.L., 1996, *Progress in the design of an automatic DIFlux*. **In:** Proceedings of the VIth Workshop on Geomagnetic Observatory instruments, Data Acquisition and Processing, JL Rasson Ed., Publ. Sci. et Tech. No 003, Institut Royal Meteorologique de Belgique, Brussels, 190-194.
- Rasson, J.L., 2005, *About Absolute Geomagnetic Measurements in the Observatory and in the Field*, Publication Scientifique et Technique No 040, Institut Royal Meteorologique de Belgique, 43p.
- van Loo, S.A., and J.L. Rasson, 2006, *Development of an Automatic Declination-Inclination Magnetometer*. **In:** J.L. Rasson and T. Delipetrov (eds.), "Geomagnetics for Aeronautical Safety", NATO Science Series, 177-186

*Accepted February 8, 2007*