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Fast 3-Component Variometer Based on a Cesium Sensor

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Abstract

New compact and fast three-component variometer measuring the total terrestrial magnetic field intensity in 20÷65 μT range and two transverse components in ±1 μT range is presented. The reproducibility of the field components measurements is 0.15 nT, the noise-limited sensitivity is 0.01 nT r.m.s. or 0.25″ at 0.1 s sample rate.

1. Introduction

In this paper, we present a vector magnetometer-variometer intended for simultaneous measurement of the total terrestrial magnetic field intensity in 20÷65 μT range and two transverse components in ±1 μT range with a rate of up to ten measurements per sond. The device is an implementation of the idea of a vector magnetometer based on a scalar sensor placed in a variable magnetic field (Fairweather 1972). The main features distinguishing the variometer from predecessors are the use of an optically pumped M_x-sensor (Alexandrov *et al.* 1996) and a continuous fast rotation of the transverse magnetic field. The same concept underlies the potassium magnetometer-variometer described in (Alexandrov *et al.* 2004). The idea is to place a fast quantum magnetometer at the center of a highly stable magnetic coils system producing magnetic field rotating around the geomagnetic field vector. As long as the magnetic coils system is aligned along geomagnetic field, the field detected by the sensor does not contain fast modulation; the situation changes if geomagnetic field deflects from the coils system axis – the field detected by the scalar sensor becomes modulated. If the modulation amplitude is not too big, the M_x-sensor is capable of following it. From the amplitude and phase of modulation the information about value and direction of the field deflection can be extracted; this information is used for creating fields compensating the field deflection.

2. Operation of the Device

Our variometer consists of a Cs magnetic sensor and a quartz coils system that are integrated into a 23×23×23 cm case mounted on a tilted quartz support, as well as of a pumping lamp and a microprocessor-controlled electronic unit positioned at a 2-3 m distance from the sensor.

The coil system is a combination of a precision solenoid with the axis directed along the geomagnetic field vector and two coils producing mutually orthogonal fields in the plane perpendicular to the solenoid axis. The coils are excited by a sinusoidal current with frequency f (several tens or hundreds of hertz) so that their current phases are shifted by 90° relative to each other. As a result, the coils produce a field rotating with frequency f in the plane perpendicular to the geomagnetic field. A direct current passing through the solenoid induces a magnetic field compensating for ~95% of the geomagnetic field. When all three currents are switched on simultaneously, the vector of a magnetic field formed at the center of the system processes about the geomagnetic field with an apex angle of about 45°.

The frequency of magnetic resonance detected by M_x-sensor depends on the magnetic field in the coil system, which, in turn, depends on remaining longitudinal magnetic field and the amplitude of the rotating transverse field. The magnetic resonance frequency remains constant if the external field is stable and the ring system axis is perfectly aligned with the field.

When the geomagnetic field transverse components change, the precession axis of the net magnetic field vector at the center of the system is deflected from the geomagnetic field vector. This leads to the modulation of the field magnitude at frequency f. A digital feedback system tracking the resonance frequency directly detects this modulation, and produces two orthogonal fields that completely compensate for these transverse components. The direct currents in the transverse coils become a measure of variation of the geomagnetic field transverse components. The longitudinal component of the compensated geomagnetic field can be found from the magnitude of the resultant field vector, solenoid current and the rotating component amplitude.

The 95% compensation of longitudinal magnetic field mentioned above allows one to increase approximately 10 times the angle between the rotating magnetic vector and the axis of rotation and to raise correspondingly the transverse sensitivity of the device.

Cesium was chosen as an appropriate working substance for the M_x-sensor because of a small quadratic splitting of magnetic lines into sub-levels. In magnetic field H, the resonance band of Cs appears as a set of equidistant lines spaced at $26.6\ \mathrm{Hz}\cdot H^2$, where H is measured in gauss. In applied small magnetic field of 0.07 G, the spacing is about 0.13 Hz, which is much smaller than the width of each of the lines. Thus, all the lines actually merge into an intense and nearly symmetric resonance. This ensures a low systematic error in measuring the field longitudinal component. On the other hand, relatively big linewidth of cesium resonance (comparing to potassium) provides faster sensor response.

3. Experiment

The variometer was tested in both a magnetic shield and a magnetic field stabilizer. All the measurements were carried at a temperature kept at (22±2)ºC.

The test results show that, when the parameters are adjusted to a maximal variation sensitivity, the geomagnetic field transverse components allowing the capture of the magnetic resonance signal do not exceed ±100 nT, otherwise the signal frequency modulation becomes too strong for M_x-sensor to follow the resonance frequency. The initial range of capture was extended ±750 nT by complicating the capture algorithm. As soon as the device is locked, the maximal variation of transverse field components is ±1000 nT.

The effective time constant T in the transverse (x and y) channels varies from 0.03 to 1 s depending on the amplification factor in the feedback loops. In subsequent experiments, the parameters were taken such that T fell into the range between 0.1 and 0.15 s. It was shown that the standard deviation of the variometer intrinsic noise in the transverse channels lies within 0.010 nT for measurement time of 0.1 s.

We also analyzed the start-to-start reproducibility of the variometer: the deviation did not exceed ±0.15 nT. Admittedly, the long-term stability was not investigated to the full extent. To reach a stability within ±0.1 nT in the z channel requires further exploration and minimization of drifts.

An automatic procedure of calibration of the constants of the x, y, and z coils, as well as of their cross-constants was developed and implemented in the device algorithm.

4. Conclusion

The vector magnetometer-variometer presented in this paper can be used as an instrument for geophysical observatories; it is characterized by a combination of high transverse sensitivity, data reproducibility, and speed .

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