SQUID-BASED ROCK MAGNETOMETER WITH OPEN-ENDED HORIZONTAL ROOM-TEMPERATURE ACCESS

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Abstract

We constructed a 3-channel SQUID-based rock magnetometer with an open-ended horizontal room-temperature access having an inner diameter of 38 mm. A refrigerator is incorporated for cooling two radiation shields so that an operating time can be realized of about 10 weeks with a reservoir volume of 26.7 litres. The temperature variation along the access is about 9 K.

The rock magnetometer is equipped with a special sensing-coil set of which the signal uniformity with respect to magnetic dipoles is about a factor of two better than that of conventional vertical-access systems. The intrinsic noise level of the system is 10^{-11} Am²/√Hz.

Introduction

A rock magnetometer that is equipped with an open-ended horizontal room-temperature access to the measuring space has some clear advantages compared to the conventional vertical-access systems. The most important two are a greater accessibility to the measuring space resulting in simpler sample-handling procedures and the possibility of performing long-core measurements. We started the development of such a horizontal-access rock magnetometer and the present status of the project is described in this paper.

The cryogenic design of the rock magnetometer is based on the experiences that we obtained with two prototype systems. Firstly, a special SQUID magnetometer was designed in order to test the construction of the open-ended horizontal access with respect to the cryogenics as well as the noise level of the system¹. Secondly, the incorporation of a refrigerator in a SQUID magnetometer in order to minimize the helium consumption, was tested in a prototype hybrid cryogenic system².

The required features of our horizontal-access rock magnetometer are more or less based on the specifications of commercial vertical-access systems. With regard to the cryogenics, the operating time between helium refills had to be longer than 6 weeks and the temperature variation along the access, having an inner diameter of 38 mm, should not exceed 10 K. Concerning the sensor assembly, the rock magnetometer had to be a 3-channel system sensing in three perpendicular directions so that the magnetization of a sample can be determined as a vector in space. The signal uniformity had to be comparable and preferably better than that of commercial rock magnetometers whereas the noise level should be limited to 10^{-11} Am²/√Hz in the low-frequency range. Furthermore, it would be nice to have a magnet facility for applying a magnetic field in the access in the magnitude range of the earth's magnetic field.

A schematic diagram of the rock magnetometer is presented in Fig. 1. The total system is about 2 m high, whereas the outer shell of the cryostat measures 80 cm in height and 44 cm in diameter, the helium reservoir having a volume of 26.7 litres. In the following discussion first attention is paid to the cryogenic construction, especially concerning the access configuration and the incorporation of the refrigerator. After that the sensor assembly and magnet facility are described and finally the sensitivity of the rock magnetometer is considered.

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Figure 1. Schematic diagram of horizontal-access rock magnetometer (not to scale).

1. helium reservoir	A: bellows
2: vacuum shell	B: yoke
3: radiation shields	C: damper
4: top plate	D: damper
5: supporting frame	E: flexible coupling
6: cold head	
7: access tube	

Cryogenic Construction

The superconducting elements of the rock magnetometer (SQUIDs and sensing coils) are not cooled by direct contact with liquid helium, but instead they are positioned in the vacuum space of the cryostat and rigidly mounted to the bottom plate of the helium reservoir. Because in this construction cooling is obtained by heat conduction to the helium bath, a good thermal conductivity of the intermediate materials is required. On the other hand the electrical conductivity and therefore the thermal conductivity as well had to be minimized in view of the thermal-noise contributions of these materials. As a compromise copper as well as beryllium-copper is used.

The helium reservoir is suspended from the top plate by means of three thin-walled tubes through which also the effluent helium gas is vented off. The thermal insulation of the helium bath is established by means of two copper radiation shields, positioned in the vacuum space, which are cooled by means of a CTI-21SC refrigerator. The radiation shields are also placed concentrically around the tube of the horizontal access. The construction of the cryostat, including the tubes of the access and the radiation shields, is such that the whole cryostat can be dismantled in less than one hour.

The vibrations of the refrigerator are isolated from the cryostat by mounting its displacer unit (the cold head) on a yoke which is supported by a frame independently from the cryostat, see Fig. 1. The cold head is connected to the cryostat by means of a flexible metallic bellows (A). The atmospheric pressure that otherwise would cancel the flexibility of the bellows, is intercepted by the yoke (B) and transported to the

legs of the frame. In order to prevent vibrations in the yoke being transferred into the cryostat, four dampers (C) are placed between the yoke and the frame. Vibrations of the frame, originating from the cold head or from floor vibrations are damped by means of eight dampers positioned between the frame and the top plate of the cryostat (D). Furthermore, the cold stages of the refrigerator are flexibly connected to the radiation shields, in a similar way to that described in ref. 2 (E). The calculated resonance frequency of the cold-head suspension is about 15 Hz and that of the cryostat suspension 4.5 Hz.

During operation of the system without the SQUIDs being mounted, the shields are cooled down to temperatures of about 140 K and 30 K. An important heat load to the helium bath appeared to be due to the recirculation of the helium gas in the vent-off tubes. Without taking any precautions the helium-evaporation rate is 63 ml/h whereas a rate of roughly 12 ml/h can be expected based on an inner-shield temperature of about 30 K. By means of two provisional plugs of polystyrene with aluminium foil in two of the three tubes the evaporation rate was reduced to 29 ml/h. As yet it has not been possible to insert a plug in the third tube but this will be done in the near future. By optimizing these plugs an evaporation rate of about 12 ml/h can be realized. With a reservoir volume of 26.7 litres this will result in an operating time of about three months.

The three SQUID sensors are all mounted in separate copper holders whereas the sensing coils of the magnetometer are attached to a beryllium-copper cylinder which is fastened to the bottom plate of the helium reservoir. The SQUIDs are connected to the electronics outside the cryostat by means of semi-rigid coaxial cables. In order to reduce the conductive heat flow to the bath, special cables have been used with a low thermal conductivity which were thermally anchored to the two radiation shields.

When the SQUIDs are mounted the shields attain temperatures of about 150 K and 33 K. The helium evaporation increases due to the conductive heat flow through the cables and, as a secondary effect of the cables, it also increases due to the conductive heat flow through other connections which is enlarged by the increase of the inner radiation-shield temperature from 30 to 33 K. Calculations indicate that both effects result in an additional evaporation of about 1.5 ml/h. The overall helium evaporation therefore will amount to about 15 ml/h provided that the effect of helium-gas recirculation is properly reduced. This evaporation results in an operating time of more than 10 weeks.

As mentioned before, the tubes of the access and the radiation shields had to be constructed from materials with a relatively low electrical conductivity, so as to realize a low noise level of the system. It will be illustrated in the section concerning sensitivity that a noise level of 10^{-11} Am²/√Hz could be attained by means of beryllium-copper tubes with a thickness of 30 μm. Because beryllium-copper is not commercially available in this thickness we constructed the tubes out of glass-fibre reinforced with epoxy and beryllium-copper strips having a width of 4 mm and a thickness of 0.2 mm. The small electrical conductivity of the tubes implies a poor thermal conductivity as well. This results in relatively large temperature gradients along the tubes. As a first step to reduce these temperature gradients, the heat exchange between the tubes has been reduced by glueing one layer of superinsulation to both the outside and the inside of the tubes, superinsulation having a much lower emissivity than epoxy. The temperature variation along the access has been further reduced by a special construction of the access tube. Instead of a single glass-fibre/epoxy tube with beryllium-copper strips, the access tube has been designed as a separate glass-fibre/epoxy tube sustaining the atmospheric pressure inside the tube and a thin cylindrical radiation shield

around it. This shield, consisting of glass-fibre/epoxy with beryllium-copper strips is attached to the ends of the inner access tube. In this way a temperature gradient mainly occurs along the additional radiation shield whereas that along the access is strongly reduced. A schematic representation of the complete horizontal-access configuration is given in Fig. 2. During operation of the rock magnetometer, the difference between room temperature and the temperature at the centre of the access appeared to be 9 K. Calculations indicate that without additional shield around the access this temperature difference would be roughly twice as high.

Figure 2. Horizontal-access configuration (not to scale): (see also Fig. 1)

- 1: inner access tube
- 2: access radiation shield
- 3: copper end-pieces of the access tube (total length of the tube about 60 cm)
- 4: tube for the 150-K radiation shield
- 5: tube for the 30-K radiation shield
- 6: beryllium-copper sensing-coil holder
- 7: beryllium-copper cylinder

Sensor Assembly

In order to obtain the maximum signal from a magnetic dipole in the access, the diameter of the sensing coil has to be as small as possible. There is, however, a practical limit to this diameter because the distances between the successive tubes of the radiation shields cannot be made too small in order to avoid contact due to thermal shrinkage. The thicknesses of the tubes of the horizontal-access construction vary from 1.5 mm for the inner tube to 0.3 and 0.6 mm for the radiation shields. The intermediate distances between the tubes vary from 1 to 4 mm. Based on an inner access diameter of 38 mm, the minimum inner diameter of the sensing-coil holder resulted in 66 mm and because the thickness of this holder could not be made smaller than about 0.6 mm the inner sensing-coil diameter had to be 67.25 mm.

The suppression of environmental noise is established by means of a superconducting cylinder. Compromising between noise rejection on the one hand and signal reduction due to the cylinder's image effect³ on the other, a diameter of 92 mm for the shield was chosen. The cylinder having a length of 300 mm is made of thin lead foil (0.12 mm thick) wrapped once around the beryllium-copper cylinder and soldered with Woods metal. It provides a noise-flux reduction of $2.4 \cdot 10^5$ in the centre for homogeneous disturbing fields⁴. In view of the cylinder's geometry, the largest environmental-noise contribution is measured in the sensing coil that detects the flux applied in the axial direction. The effective noise reduction over the total area of this sensing coil is in the case of homogeneous fields calculated to be $5 \cdot 10^5$. The magnetic field of a solenoid input-coil was measured to be suppressed by a factor of $1.2 \cdot 10^8$ so that the calculated reduction factor for homogeneous fields is quite reliable.

The sensing-coil set has been constructed as a Helmholtz-type coil set for the axial direction and two saddle-coil sets for two perpendicular radial directions. Taking into account the image effect of the lead cylinder on the signal obtained from a magnetic dipole³, the sensing-coil set was designed in such a way

that the dipole-signal uniformity is maximum in a one inch diameter spherical volume. The dipole-signal uniformity that is realized in this way is given in Tab. 1. Also a comparison is given with the SCT commercial rock magnetometer, model C102. It appeared that in our design the dipole-signal uniformity is about a factor of 2 better than that of the SCT system.

Table 1. Dipole-signal variations in the rock magnetometer

	UT	SCT
1" diameter spherical volume:		
Helmholtz coil set	4.8%	12%
Saddle-coil set	6.6%	13%
standard volume (ϕ 1", 1" long):		
Helmholtz coil set	7.7%	21%
Saddle-coil set	7.2%	15%

Each sensing coil is connected to a SHE-330 rf-SQUID system. The superconducting wire that is used is 0.1 mm in diameter and has a copper stabilization which, in the case of the rock magnetometer, is required for adequate cooling of the flux transformer in the vacuum space of the cryostat. The wire is led through a small lead tube in order to reduce the effect of environmental-field fluctuations. Optimum signal transfer (i.e. optimum inductance matching) from the sensing coil to the SQUID (effective signal-coil self-inductance 2 μ H) is realized by taking the number of turns of each of the sensing coils as two. The effective self-inductance of a saddle-coil set is calculated to be 2.9 μ H and that of the Helmholtz set 2.1 μ H⁵.

The overall magnetic-dipole sensitivity from a saddle-coil set to the output of the corresponding SQUID system was measured as $(9.1 \pm 0.1) \cdot 10^5$ V/Am² which is equivalent to an overall flux sensitivity of $(3.70 \pm 0.04) \cdot 10^{10}$ V/Wb. The measured sensitivity of the Helmholtz set is $(14.9 \pm 0.2) \cdot 10^5$ V/Am² being equivalent to $(4.65 \pm 0.06) \cdot 10^{10}$ V/Wb. The above sensitivities are slightly dependent on the specific set of SQUID-electronics that is used because the signal transfer from SQUID flux to output (usually about 20 mV/ Φ_0) may deviate mutually by about 10%. The self-inductances of the sensing coils can be evaluated from the above-mentioned overall signal transfer and turned out to be (3.3 ± 0.3) μ H for a saddle-coil set and (2.2 ± 0.2) μ H for the Helmholtz set.

The dipole-signal uniformity of the sensing-coil set is measured by means of a small coil of 30 turns having a diameter of 2 mm. The signal uniformity with respect to the axial position is measured on several radial positions, the results for a radial position of 12 mm being presented in Fig. 3. It can be concluded from these measurements that the calculations correctly predict the dipole-signal uniformity and that therefore the foregoing considerations with respect to the signal uniformity of the rock magnetometer are valid.

Magnet Facility

The magnet coil is wound around the lead shield and consists of 3 layers each of about 900 turns of NbTi multi-filament wire with copper stabilization (ϕ 0.31 mm). The applied magnetic field can be trapped in the superconducting lead cylinder by locally heating the cylinder in a manner similar to the prototype system¹. The magnetic field in the centre for a certain current through the coil is measured as (10.80 ± 0.05) mT/A. Fields up to 6 mT can be trapped in a reproducible way. The homogeneity of the trapped magnetic field was measured along the axis of the cylinder and appeared to be the same as that of the magnetic field of the coil. The variation of the applied field within a standard rock-sample volume positioned at the centre is

calculated to be less than 0.1%. The behaviour of the cylinder with respect to the maximum attainable field and the field uniformity has been previously considered concerning the prototype system¹. These considerations are valid for the lead shield of the rock magnetometer as well.

Figure 3. Signal in the sensing-coil set due to a small current-carrying coil simulating a magnetic dipole pointing in the direction of maximum sensitivity positioned at a radial position of 12 mm. The signal is given as a function of the axial dipole position and normalized to the signal in the centre of the coil set. dashed curves: calculated without shield solid curves: calculated with shield ■: measurements

Sensitivity

As in the case of the prototype system, the noise level of the rock magnetometer is mainly determined by the thermal noise of the metal system components located inside the lead cylinder.

We calculated the RMS noise flux in the sensing coils due to the components of the cryogenic construction that are located inside the lead shield^{1,5}. These components, which are depicted in Fig. 2, are made of beryllium-copper and glass-fibre reinforced with epoxy in order to realize a low electrical conductivity combined with an acceptable thermal conductivity. The tubes of the radiation shields can be considered as beryllium-copper cylinders having a thickness of 30 μ m. The calculated noise contributions are presented in Tab. 2.

Table 2. Calculated noise contributions in the sensing coils in $\Phi_0/\sqrt{\text{Hz}}$

system element	Helmholtz set	Saddle-coil set
BeCu cylinder	0.092	0.115
sensing-coil holder	0.091	0.121
30-K shield	0.059	0.075
150-K shield	0.073	0.099
access-tube shield	0.062	0.092
SQUID intrinsic noise	0.043*	0.054**
Total	0.176	0.233

* sensing-coil self-inductance 2.2 μ H

** sensing-coil self-inductance 3.3 μ H

The noise level of the system presented as a minimum detectable magnetic-dipole moment can be evaluated from Tab. 2 and the magnetic-dipole sensitivity of the sensing coils. Because the noise-flux contributions are evaluated excluding the effect of the lead cylinder the sensing-coil sensitivities also have to be considered without the lead cylinder. These sensitivities are $55.1 \mu\text{Wb}/\text{Am}^2$ for the Helmholtz-type coil set and $44.9 \mu\text{Wb}/\text{Am}^2$ for the saddle-coil set. The resulting noise levels are respectively $7.10^{-12} \text{ Am}^2/\sqrt{\text{Hz}}$ and $11.10^{-12} \text{ Am}^2/\sqrt{\text{Hz}}$.

The effect of the lead cylinder on the noise-flux contributions is quite difficult to calculate. A qualitative impression of the effect, however, can be deduced from Fig. 3. The larger the axial distance between a sensing coil and a dipole, the larger the reducing effect of the superconducting cylinder on the dipole flux threading the sensing coil will also be. Because the metal components are relatively long compared to the size of rock samples, the lead cylinder will result in an increase of the signal-to-noise ratio and the noise level of the Helmholtz-type coil set as well as that of the saddle-coil set will be below $10^{-11} \text{ Am}^2/\sqrt{\text{Hz}}$.

The present status of the project is that we are studying the noise level of the rock magnetometer by means of an HP 3582 A spectrum analyzer. So far, we have recorded the noise spectrum at the output of the SQUID system that is connected to the Helmholtz coil set. As a preliminary result this spectrum is presented in Fig. 4.

Figure 4. Output noise level of SQUID system connected to the Helmholtz coil set presented as an equivalent magnetic dipole located in the centre of the sensing-coil set. dashed curves: without cold-head motor running solid curves: with cold-head motor running

The minimum noise level is attained for frequencies above about 100 Hz and amounts to $5.6.10^{-12} \text{ Am}^2/\sqrt{\text{Hz}}$. Because thermal noise is principally white (i.e. constant spectral density), this indicates that the above-mentioned calculations of the system noise level gave quite reliable results. There are a large number of

peaks in the spectrum, firstly due to power-line interference (50 Hz and higher harmonics), secondly due to environmental vibrations (peaks around 10 Hz) and finally due to internal resonances in the system (e.g. 63 Hz and about 4 Hz due to the cryostat suspension). In the intermediate frequency range 3-25 Hz the basic noise level is roughly $10^{-11} \text{ Am}^2/\sqrt{\text{Hz}}$ but for frequencies below 3 Hz the level increases to above $10^{-10} \text{ Am}^2/\sqrt{\text{Hz}}$. This increase is a direct result of problems that we have with the compressor of the refrigerator. During the noise recordings, the compressor could not be operated so that the radiation shields were not properly cooled (inner-shield temperature about 110 K). As a result the heat load to the detection elements increases to such an amount that the small lead tube surrounding the flux-transformer connection between sensing coil and SQUID does not become superconductive. This results in a relatively high sensitivity to environmental-field variations. Measurements with a fluxgate magnetometer indicate that these variations especially occur in the low-frequency range.

Due to the problems with the compressor it was up to now also not possible to properly measure the effect of the refrigerator on the noise level of the rock magnetometer. However, a good impression of this effect could be obtained by activating the drive motor of the displacer in the cold head. Fig. 4 shows that the influence of the cold-head motor is quite small. In the low-frequency range only a peak occurs at 2.8 Hz which is the operating frequency of the displacer. The high-frequency range shows a number of peaks due to internal resonances in the cold-head construction. Further research concerning the noise level of the system is in progress.

Conclusions

We have constructed an open-ended horizontal-access rock magnetometer of which the specifications are comparable to those of commercial vertical-access systems. Besides the horizontal-access configuration the main advantages of our system are: the dipole-signal uniformity is about a factor of two better, and concerning the cryogenics, the temperature inside the access is only 9 K below room temperature and the cryostat can be dismantled in less than one hour.

At present, attention is paid to the elimination of the helium recirculation in the suspension tubes so as to realize an operating time of about 10 weeks with a reservoir volume of 26.7 litres. Furthermore, final test experiments are performed in order to verify the intrinsic-noise level of $10^{-11} \text{ Am}^2/\sqrt{\text{Hz}}$ for all channels. We expect that by the end of 1986 the rock magnetometer can be used for paleomagnetic research.

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