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A SQUID system for geophysical measurements cooled by a pulse tube cryocooler

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Abstract

Geophysical measurements, which rely on the acquisition of magnetic data, can take advantage of a superconducting quantum interference device (SQUID), which offers a higher field sensitivity at lower frequencies than conventional induction coils. Although cooling a SQUID in liquid helium provides for a simple and low-interference system, in remote areas a cryocooler could reduce the expenses of operation. We studied transient magnetic measurements with a SQUID cooled by a small pulse tube cooler operated by a 1 kW compressor, which can be powered by a portable generator or large truck battery.

Keywords: pulse tube cooler, cryocooler, SQUID, transient electromagnetic measurement, geophysics, dry cooling

(Some figures may appear in colour only in the online journal)

1. Introduction

Following pioneering experiments by Zimmerman *et al* [1] and Clarke *et al* [2], a number of groups [3–10] have employed with advantage a superconducting quantum interference device (SQUID) for the measurement of magnetic fields in geophysical surveys. Compared to the usually used induction coil, SQUIDs provide a higher sensitivity at lower frequencies and measure the magnetic field B instead of the $\mathrm{d}B/\mathrm{d}t$ provided by coils. As geophysical surveys have to be performed in remote areas over a longer time, special attention has to be given to cooling the SQUID. Despite the obvious advantages of cooling a SQUID with liquid helium, such as low-interference and the use of a simple cryostat, the (un)availability and cost of transportation of liquid helium could limit the applicability of such systems. In this paper, we study the use of a small, commercially available, pulse tube cooler for cooling a SQUID system, which we use to perform transient electromagnetic (TEM) measurements, to determine the conductivity of soil at larger depths. This small pulse tube cooler can be operated with an air-cooled 1 kW helium compressor powered by a one-phase 235 V source, a gasoline-powered generator, or even a truck battery. Our intention is not to develop the most sensitive system, but to study the merits and limitations of a cryo-cooled system, the potential problems, such as electromagnetic and mechanical interference caused by the cooler, and ways to amend these.

2. Measurement principle and configuration

The TEM method [11] is a standard method in geophysical surveys to determine the conductivity of the ground or water as a function of depth. In a sense, it resembles eddy current nondestructive evaluation (NDE), where an ac-magnetic field is used to induce eddy currents in the sample. The magnetic field produced by these eddy currents can be used to determine the sample's conductivity. By making use of the skin effect, inducing eddy currents at different frequencies and measuring their magnetic fields can provide a means for determining the conductivity in a certain depth. In contrast to eddy current NDE, where usually a single-frequency is used,

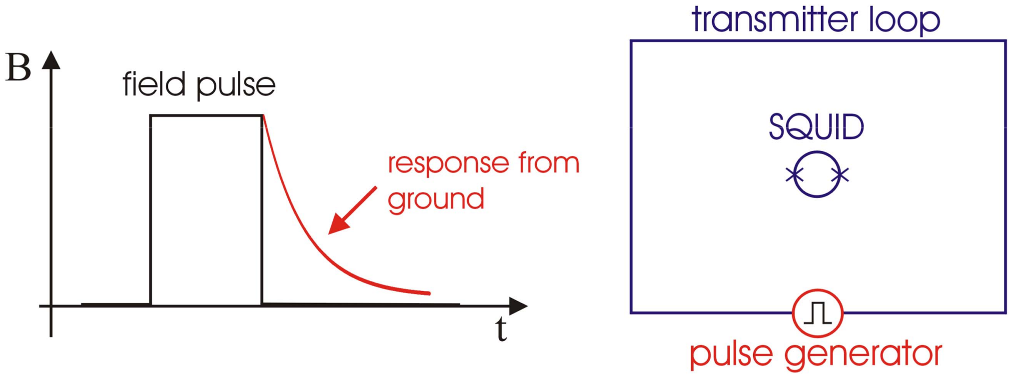

Figure 1. Measurement scheme (left) and measurement configuration (right) for transient electromagnetic measurements.

TEM relies on the generation of eddy currents in a wider frequency range by exciting with a magnetic pulse instead of a sine wave. In a typical TEM measurement, field pulses are produced by a square transmitter loop, and the resulting secondary field from the ground is recorded with a magnetic field sensor placed in the center of the loop, right after the transmitter pulse has been switched off (see figure 1). From the duration and shape of the decaying magnetic field, information can be gained about the depth-dependent conductivity of the ground.

Conventional TEM systems use an induction (Faraday) coil to determine the secondary field. The relatively low sensitivity of such coils at low frequencies (Hz to tens of Hz) poses a limit to the maximum survey depth. When using a more sensitive magnetic sensor, this limit can be moved to larger depths; moreover, a sensor measuring the field B instead of dB/dt can provide a better estimate of the soil conductance [12, 13].

As the TEM method covers a wider frequency range (usually a few Hz to a few kHz), it is quite sensitive to magnetic interference. All magnetic fields in this frequency range will show up in the data. We note that in eddy current NDE, detecting the single-frequency response can be performed with a lock-in method, which greatly suppresses external interference. Spies [14] has published a method, which can substantially suppress external interference in TEM measurements. He reverses the polarity of every second pulse and adds the inverted data to that of the previous pulse (see figure 2). If the interfering fields have frequencies which are integer multiples of the pulse frequency, and if their phases and amplitudes do not change during the measurement, they can be nearly completely suppressed. In this way, very high field sensitivities can be obtained even in the presence of strong interference from the power-grid, so that measurement depths on the order of 1 km are possible.

3. The pulse tube cooler

Pulse tube coolers are periodically working cryocoolers with gaseous helium in a closed cycle [15]. In contrast to other cryocoolers, such as Stirling- or Gifford-McMahon-coolers, they have no moving parts within the cold part of the cooler. The first multi-stage pulse tube coolers were developed in the 1990s [16], shortly followed by the introduction of a two-stage pulse tube cryocooler for liquid helium temperatures [17, 18]. Since then, the development in pulse tube coolers went mostly towards higher cooling power near 4 K [19]. To achieve this, bigger pulse tube coolers and helium compressors with higher input powers were used. On the other hand, as the cooling power required to cool a SQUID is very small, a pulse tube cooler dedicated for sensor cooling can be operated with an input power of only 1 kW [20]. In principle, only thermal radiation received by the SQUID and heat produced by the lines connecting the SQUID to its room-temperature readout needs to be removed.

TEM measurements rely on determining the decaying secondary field produced by the ground right after the TEM pulse. Obviously, any metal mass inside the transmitter coil will also produce a decaying field due to induced currents. This is not a problem if the SQUID is immersed in liquid helium contained in a fiberglass dewar, as larger pieces of metal can be avoided here. A pulse tube cooler, however, consists of numerous metal parts, all of which can potentially produce a secondary field due to eddy currents. Thus, at a first glance, performing TEM measurements with a SQUID cooled by a cryocooler seems to be difficult. Fortunately, secondary fields produced by the cooler, which decay much faster than that of the surveyed ground, can be safely ignored. In a typical TEM measurement with a SQUID, the decay times of interest are on the order of milliseconds to hundreds of milliseconds. If the cooler can be constructed such that the inductance of all eddy current paths is low (small dimensions and small-diameter holes), and their resistance is high (by using high-resistivity material such as stainless steel), the L/R decay times potentially can be made smaller than a millisecond, which is sufficiently small for a number of meaningful measurements. In addition to the cooler, the required helium compressor will also produce secondary fields, but, as the compressor can be placed quite far away from the cooler (20 m), these fields should be sufficiently low at the location of the SQUID.

Figure 3 shows the pulse tube cooler used in our experiments [20]. It is a two-stage Gifford-McMahon type pulse tube cooler with a remotely mounted rotary valve. This allows for a greater distance between the electrically driven

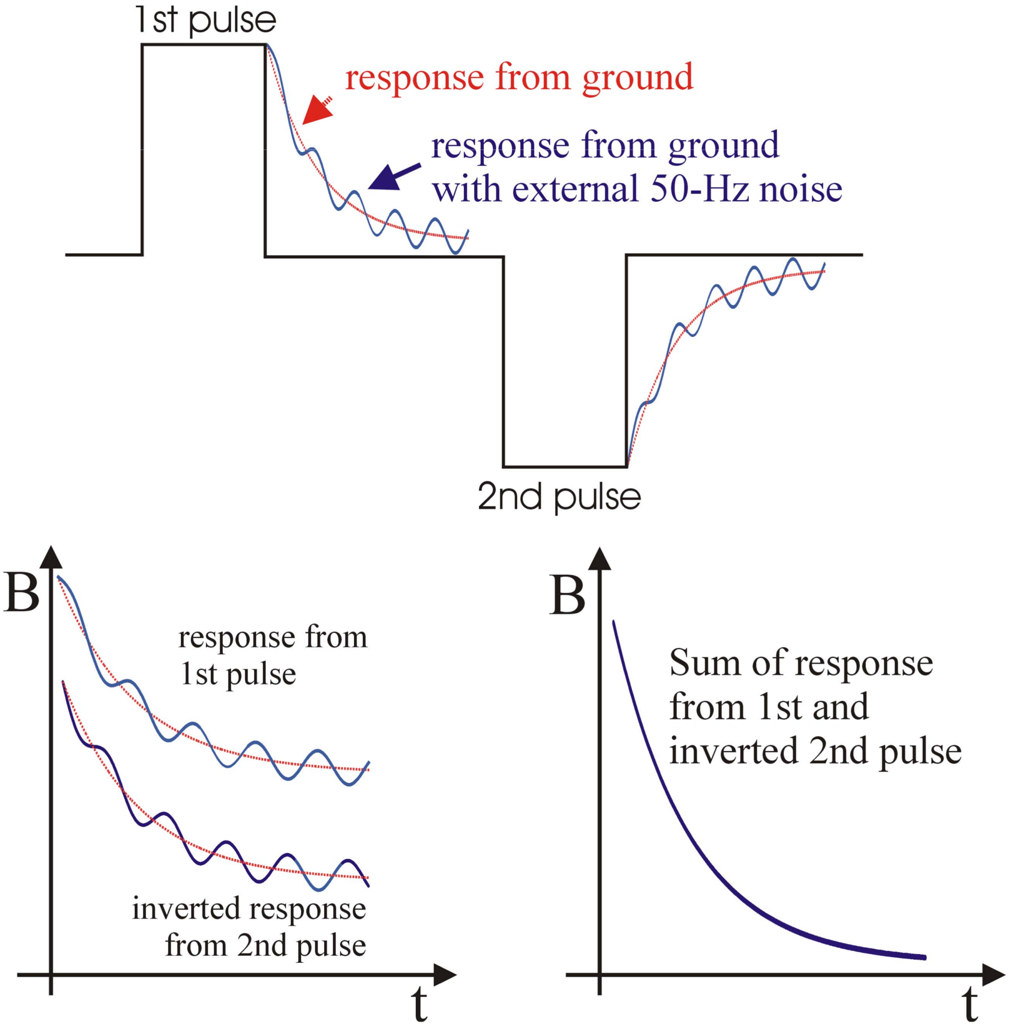

Figure 2. Method to suppress external magnetic interference in TEM measurements. Top: pulse sequence and decaying field with interference. Bottom left: response from first pulse and inverted response from second pulse. Bottom right: adding response from first and inverted response from second pulse suppresses interference.

rotary valve and the SQUID. Also, the relatively low working frequency of the cryocooler (2 Hz, compared to the higher frequencies of Stirling-type pulse tube coolers with ~50 Hz), provides a measuring window of several tens of ms within the helium oscillation cycle.

The cooler essentially consists of a pair of stainless-steel tubes with diameters of ~1 cm and two copper plates forming the first and second cold stage. On top of the cooler is a small buffer volume and needle valves to adjust the helium gas flow in the cooler. The first cold stage reaches a lowest temperature of ~45 K, the second cold stage one of ~2.5 K. The low-temperature part of the cooler is surrounded by a slotted copper and phosphorous-bronze radiation shield and super-insulation. The outer vessel is made from fiberglass. The SQUID is glued to a 2 cm long fiberglass (G-10) rod, which is pressed to the superconducting lead shield of the cold stage by a fiberglass plate. Heat conduction along the miniature coaxial cable connecting the SQUID to a connector thermally anchored to the lead shield keeps the temperature of the SQUID below 4 K. The thermal conduction of the superconducting lead is still sufficiently high (~300 W m^{-1} K^{-1}) to assure cooling of the SQUID.

The pulse tube cooler was run by a 1 kW input power helium compressor. This relatively low input power allowed for a smaller cooler design, reducing eddy currents and intrinsic thermal and mechanical variations. Also, one kilowatt of power can be supplied by a portable generator or a truck battery. The cryocooler is equipped with a rotary valve to generate the pressure oscillations needed for the cooling process. This valve is operated by a synchronous 50 Hz motor. Electric interference from the motor was suppressed by means of a galvanic decoupling unit between the rotary valve and the cooler, which prevented low-frequency currents from flowing between valve and cooler. The cooling power of the second stage is 70 mW at $T = 4.2$ K and the first stage had 1 W at 50 K.

Potential sources of magnetic fields produced by eddy currents in the cooler are the copper plates of the two cold stages, and a stainless-steel flange at the top of the cooler. As the second cold stage reaches a temperature of about 2.5 K, inducing eddy currents in it can easily be prevented by

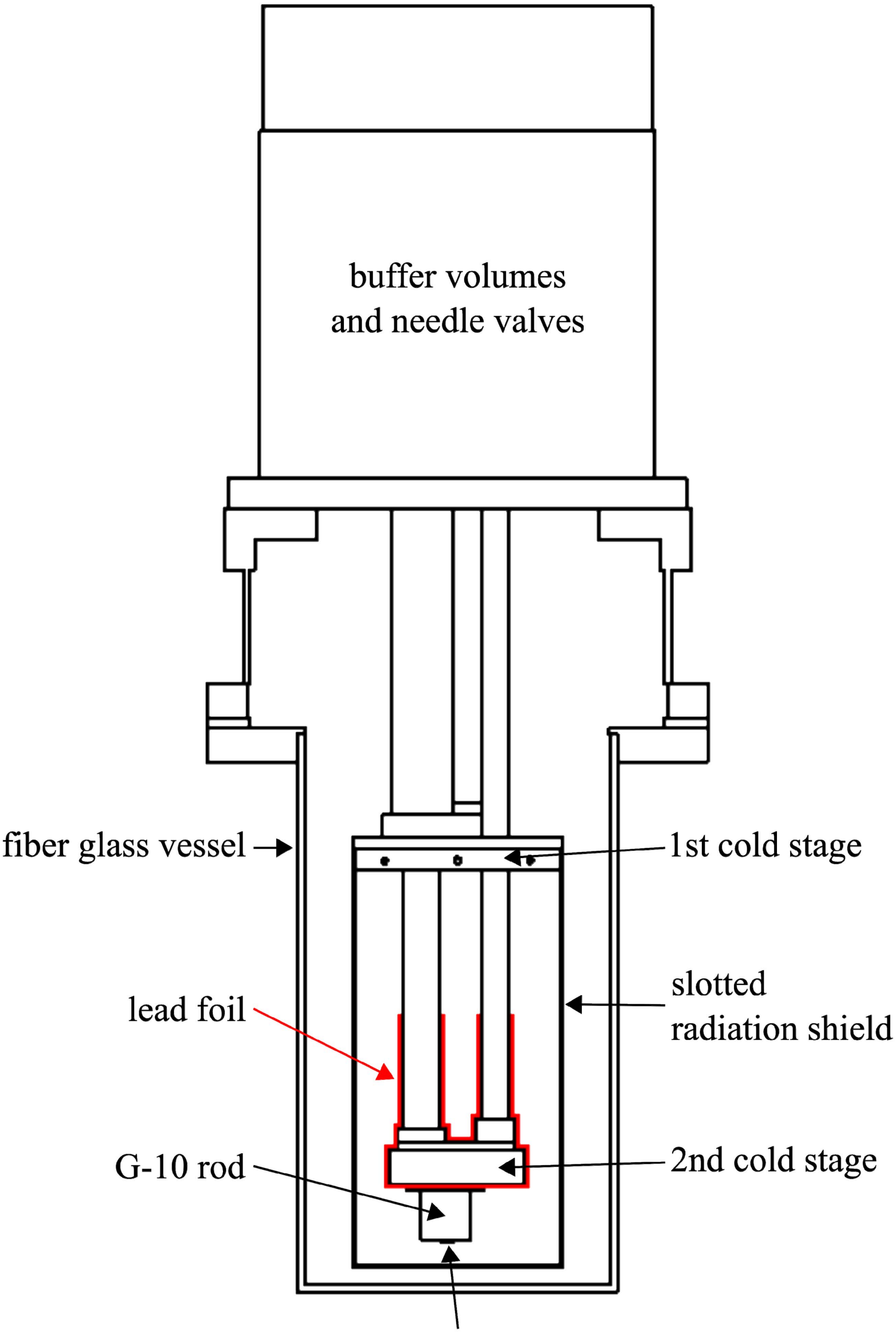

Figure 3. Schematic drawing of the pulse tube cooler. The second cold stage was wrapped in superconducting copper foil. A slotted radiation shield was mounted to the first cold stage. The SQUID itself was thermally coupled to the second cold stage via a G-10 rod and the electrical wiring.

wrapping the stage with thin superconducting lead foil, which will completely shield the copper. Shielding the first cold stage this way is not possible, as it reaches a temperature of only 45 K. Nevertheless, as the holes through which the pulse tubes run, are only small, their inductance is quite low ($\approx$10 nH). Making the copper plate relatively thin can reduce the L/R time of this stage further. The stainless-steel flange on top of the cooler has a larger diameter (10 cm) and thus a higher inductance ($\approx$80 nH), but as its resistivity is high ($\approx$70 $\mu\Omega$ cm), the corresponding L/R time of the flange is well below 1 ms. The radiation shield surrounding the second cold stage (see figure 3) consists of a thin copper tube which is closed at the bottom by a 100 μm thick phosphor-bronze sheet. Slits in the copper tube reduce eddy currents to a tolerable level. As the tube is in parallel to the excitation field, the effective inductance of the shield for currents induced by the excitation field is very small, reducing the L/R time of the shield to below 1 ms. The phosphor-bronze sheet at the bottom of the shield is transparent for magnetic fields with frequencies below about 100 kHz. Thus, TEM measurements for the time range of milliseconds to hundreds of milliseconds seem to be feasible with this cooler.

4. Measurement configuration

The field pulses inducing eddy currents in the ground are produced by a microcontroller and a current amplifier. During a measurement, the pulses are repeated every fifty 50 Hz cycles (one second), and their width is 80 ms (four 50 Hz cycles); every second pulse is inverted by a MOSFET bridge similar to the one described by Ji *et al* [10]. The pulse repetition time and pulse width is synchronized to the 50 Hz power-grid frequency. We also synchronized the helium pulses operating the cooler to the power-grid by using a synchronous motor for the rotary valve. The helium-pulse frequency is 2 Hz.

The SQUID was a conventional thin-film washer dc SQUID with an inductance of 75 pH, a field-to-flux transfer ratio of 25 nT/Φ_0, and a white noise of $1 \times 10^{-6}\ \Phi_0\ \mathrm{Hz}^{-1/2}$. We use an ac-flux modulated flux-locked loop readout electronics with a modulation frequency of 450 kHz. The slew rate of this readout is about $7 \times 10^5\ \Phi_0\ \mathrm{s}^{-1}$, but can be potentially higher [21]. As the field pulses are switched off in about 300 μs, the slew rate of the SQUID readout limits the maximum field of the pulses to about 5 μT in the absence of external interference. However, our measurements were performed with a field of 1 μT, which is comparable to fields employed by other groups [10], although a somewhat higher sensitivity could have been obtained with a higher field.

Our measurements were performed in a garden inside a smaller town. The geological structure of the ground is clay shale with iron (an iron mine 10 km away from the measurement location was in full production until the 1980s). Due to space restrictions, the transmitter loop could only by made 20 m long and 10 m wide. We used a two-turn loop, which produced a field of 1 μT from a pulse current of 4.5 A. The pulse tube cooler with the SQUID was rigidly mounted to a wooden table, which could be buried if necessary. The helium compressor was placed about 10 m away from the cooler, just outside the transmitter loop. This distance could be doubled to 20 m without sacrificing any cooling power. Usually we applied 100 successive positive and negative pulses and averaged (stacked) these data. With a pulse repetition time of 1 Hz, such a measurement took 200 s. Data acquisition started 375 μs after the pulse was switched off, and 512 field values were acquired every 375 μs in a measurement time of 200 ms.

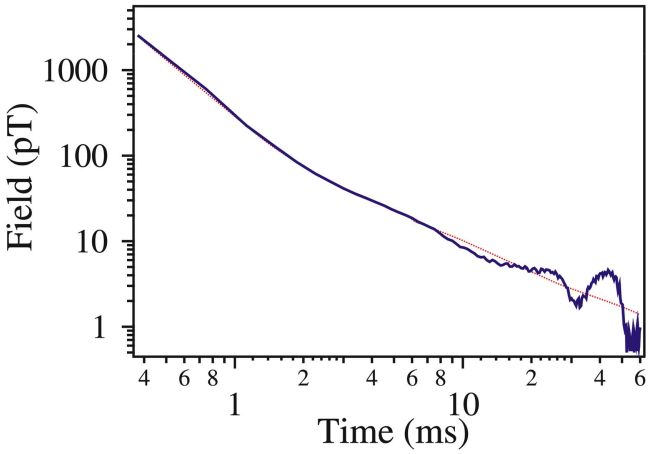

Figure 4. Blue solid curve: magnetic field versus time after transmitter pulse was switched off, data averaged over 100 measurements. The red curve is a guide to the eye, showing the expected field decay without 50 Hz interference.

Before taking data from the ground, we tried to detect fields generated by eddy currents in the metal parts of the cooler. To this end, we placed the cooler with the SQUID in the center of a small transmitter loop having a diameter of 30 cm. When we applied field pulses with an amplitude of about 5 μT, we did observe a decaying magnetic field at the SQUID, which, however, was only small (a few pT at 1 ms after the pulse was switched off), and was completely gone after a few ms. Obviously, there was some small interference produced by the cooler itself, which could be either due to eddy currents in the first cold stage or imperfections in the superconducting lead shield of the second stage. Making the first stage thinner, or increasing its electrical resistance by reducing its width could further reduce this interference. Nevertheless, for the measurements presented below, the small interference from the cooler was not of substantial influence. The level of 50 Hz noise produced by the rotary valve could be reduced to less than one flux quantum ($\sim$25 nT), by moving the valve until a minimum in the coupling between valve and SQUID was reached. This noise level was comparable to that produced by the environment.

Figure 4 shows data from a typical measurement. About 400 μs after the transmitter pulse is completely off, we begin taking field data. At that time, the field generated by currents in the ground is on the order of about 1 nT. The field decays with a rate of nearly two decades per decade time, until it vanishes in the noise after about 60 ms. The minimum obtainable noise of the system is determined by the intrinsic noise of the SQUID, the measurement bandwidth, and the number of averages. A SQUID rms noise of 25 fT $\mathrm{Hz}^{-1/2}$ corresponds to a peak-to-peak noise of 70 fT $\mathrm{Hz}^{-1/2}$. We measure in a 7 kHz bandwidth, which is necessary to resolve decay times on the order of 1 ms. In this bandwidth, the SQUID peak-to-peak noise is about 5 pT, and can be reduced to about 350 fT, when averaging over 200 pulses. In our measurement environment, however, residual 50 Hz noise with an amplitude of a few pT peak-to-peak poses the limit for the usable system sensitivity. This 50 Hz noise is visible in figure 4 at later times with maxima at 24 and 44 ms. We attribute this noise to fluctuations in the amplitude and frequency of the power-grid field, which cannot be eliminated by the pulse reversal scheme. Fluctuations in the power-grid frequency are usually on the order of 0.4 parts per thousand, which would limit the 50 Hz suppression by the pulse reversal scheme to a factor of several thousand. Indeed, in our case the amplitude of the 50 Hz noise in figure 4 is a few pT, whereas the absolute 50 Hz noise was on the order of about 20 nT at the measurement site.

5. Conclusion

In this paper we have presented a fully functional SQUID system for geological measurements which is dry cooled by a dedicated small power pulse tube cryocooler. It seems feasible to cool a SQUID with a pulse tube cooler for performing certain geophysical measurements. To reduce interference produced by the cooler, several prerequisites have to be fulfilled: all ac-magnetic noise sources in the cooler should be synchronized to the power-grid frequency. This can usually be achieved by operating the rotary valve, which produces the helium pulses in the cooler, by a synchronous motor, so that the pulse frequency is exactly one or two hertz. If, for a transient electromagnetic measurement, the field pulses are synchronized to the power-grid frequency, 50 Hz noise and interference from the cooler then can be sufficiently suppressed. Additionally, care must be taken to sufficiently suppress eddy currents in the cooler. This can be achieved by wrapping superconducting foil around highly conducting normal metal parts at low temperatures, and using material with low conductivity wherever possible. Cutting slots into metals to increase their resistivity to eddy currents will also help. Although we could not completely suppress eddy currents (presumably in the first cold stage), they could be reduced to a level at which meaningful measurements were possible.

Performing measurements with a cryo-cooled SQUID system is quite convenient, as no liquid coolants have to be handled; the cooler has simply to be switched on, and data can be taken after about two hours. In remote areas without access to the power-grid, a gasoline-powered generator or a truck battery can be used to operate the cooler. A 24 V truck battery with a capacity of 225 Ah and a power inverter can operate the cooler for about 5 h, allowing for a measurement time of about 3 h. This opens the path for SQUID based geological measurements in remote and difficult accessible areas.

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