SQUID based receivers for electromagnetic exploration

Chwala, A. [1], Schmelz, M. [1], Schönau, T. [1], Zakosarenko, V. [2], Meyer, M. [2], and Stolz, R. [1]

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1. Leibniz Institute of Photonic Technology, Albert-Einstein-Straße 9, 07745 Jena, Germany
2. Supracon AG, An der Lehmgrube 11, 07751 Jena, Germany

ABSTRACT

Some exploration targets, mostly the ones with long time constants in Time Domain Electromagnetics (TEM), are easier to detect by measuring the magnetic field instead of its time derivative. As a consequence, ***S****uperconducting* ***QU****antum* ***I****nterference* ***D****evices (SQUIDs) are almost perfectly suited for this task due to their high sensitivity and perfectly flat frequency response. New technologies and read-out schemes for SQUIDs are evolving which enable new EM receivers, with highest sensitivity, to overcome the limits of earlier SQUID instruments in terms of slew rate and dynamic range.*

WHY WE LIKE TO MEASURE "B" – AND YOU SHOULD AS WELL

Electromagnetic measurements are common practice in mineral exploration. Depending on the targets and their depth, different methods are applied: deep contrasts in electric conductivity are often investigated by Magnetotellurics (MT), where the natural variation of telluric currents is monitored at very low frequencies (far below 1 Hz). On the other hand, mineral exploration often uses active techniques, especially TEM. In both cases, induction coils, herein abbreviated as coils, were the instruments of choice for a very long time. With the continuing improvements other sensors such as fluxgates and SQUIDs have been used more and more, especially for low frequency signals where the sensitivity of induction coils is reduced (*cf.* next chapter).

It can be shown that measuring the magnetic field instead of the induced voltage is advantageous in many real geological settings. Let us calculate the response of a conductive ore body in a less conductive half space. The B-field over a conductive half space decays with [1]

$$\boldsymbol{B_h} = \boldsymbol{A_h}\, \boldsymbol{t}^{-\frac{3}{2}}, \qquad (1)$$

while the induced voltage in a coil, time derivative of (1), will decay much faster:

$$\boldsymbol{U_h} = -\frac{d\boldsymbol{\Phi}}{dt} = -\frac{3}{2}\boldsymbol{A}\boldsymbol{A_h}\, \boldsymbol{t}^{-\frac{5}{2}}. \qquad (2)$$

For a compact ore body with certain conductivity, the B-field decays at late delay times with [1]

$$\boldsymbol{B_c} = \boldsymbol{A_c}\boldsymbol{e}^{-\frac{t}{\tau}}, \qquad (3)$$

which translates for the induced voltage to

$$\boldsymbol{U_c} = -\frac{d\boldsymbol{\Phi}}{dt} = -\frac{\boldsymbol{A}\boldsymbol{A_c}}{\tau}\boldsymbol{e}^{-\frac{t}{\tau}}. \qquad (4)$$

Here, $\boldsymbol{A_h}$ and $\boldsymbol{A_c}$ are scaling factors; $\boldsymbol{A}$ is the area of the receiver coil.

For the comparison of the two sensor configurations one can assume the simple case of a good confined conductor in a much less conductive host material with homogenous conductivity. By summing up (1) and (3) or (2) and (4), respectively, we get the following approximation to the decays for the B-field and the induced voltage:

$$\boldsymbol{B} = \boldsymbol{B_h} + \boldsymbol{B_c} = \boldsymbol{A_h}\, \boldsymbol{t}^{-\frac{3}{2}} + \boldsymbol{A_c}\boldsymbol{e}^{-\frac{t}{\tau}}. \qquad (5)$$

$$\boldsymbol{U} = \boldsymbol{U_h} + \boldsymbol{U_c} = -\frac{3}{2}\boldsymbol{A}\boldsymbol{A_h}\, \boldsymbol{t}^{-\frac{5}{2}} - \frac{\boldsymbol{A}\boldsymbol{A_c}}{\tau}\boldsymbol{e}^{-\frac{t}{\tau}}. \qquad (6)$$

A simulated response using this approach is depicted in Figure 1 for a time constant of τ = 200 ms (in order to plot B and U into the same graph A is assumed to be 10^{-3} m^2). Full lines visualize the combined signal that would be measured, while the dashed lines correspond to the half space response and the dotted lines represent the response of the ore body. The vertical (red) lines mark the time t_0 where the signal measured is 30% larger than the signal of the half space (in logarithmic units). For the described case t_0 amounts to 41 ms for the magnetic field sensor compared to 153 ms for the coil. This means, that a conductor can be recognized about three times earlier for a B-field measurement, which leads to a reduction in the necessary number of stacks or for the same number of stacks to a much cleaner signal.

In order to draw a readable graph, we have assumed that the signal from the conductive ore body A_c is 1000 times larger than that for the host material, which is the half space response A_h. The ratio would be similar for other situations as well, but the contrast would be much smaller in both cases if the signal from the conductor is weaker – making the direct *B*-field-measurement even more important.

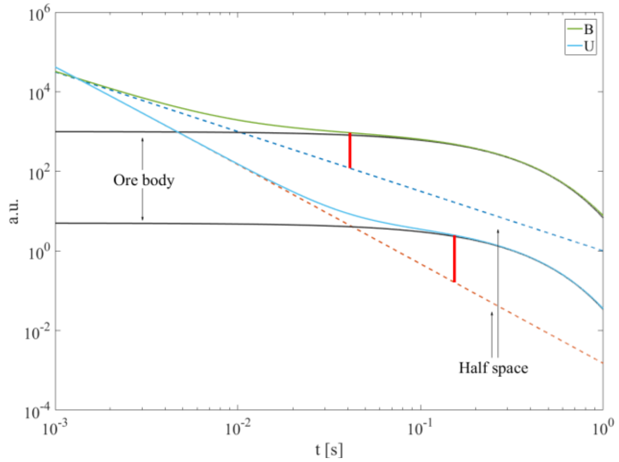

Figure 1: Sum of signals of a conductive ore body (black lines) and a less conductive half space (dashed lines) for a *B*-field (B) sensor and a coil (*U*).

Induction coils

An induction coil is (in principle) a very simple magnetic field sensor: just take some wire, surround a sufficiently large area (A) with it and measure the induced voltage. In order to avoid the need of large areas, the coil may have many turns (N) and a high permeability core. Maybe add a low pass filter and pre-amplifier(s) and record the voltage with an analog-to-digital converter (ADC). In this configuration, the recorded signal is strongly frequency dependent, since the induced voltage is

$$U_{ind} = -N\,A\,\frac{dB}{dt}.$$

Of course a real sensor is much more complicated, because one has to deal with resonances due to a large inductance together with parasitic capacitance. Furthermore, a sensitive coil needs a well-adapted, low noise preamplifier. One can also introduce a current feedback in order to flatten the frequency response and have a pseudo *B* field sensor. RMIT developed in collaboration with Abitibi such a sensor (Armit) that has been successfully applied in TEM [2]. One important processing step in using these coils is the robust and temperature independent deconvolution of the high pass response as described in [3], requiring the exact knowledge of the coil bandwidth. Due to their operational principle, every coil-based sensor inherently has lower sensitivity at frequencies below a critical value.

A comprehensive overview on coils is given *e.g.* in [4].

SQUID magnetometer

In 1961 Doll and Näbauer experimentally proved that the flux in a superconducting ring is quantized [5] in $\Phi_0 = h/(2e) \approx 2.07\times10^{-15}$ Wb. 1962 Brian Josephson predicted phenomena caused by the tunneling of Cooper pairs (the particles that conduct the supercurrent) through a weak link [6]. Jaklevic and co-authors showed in 1964 that a magnetic flux sensor could be built from those effects [7].

A SQUID is a superconducting ring, interrupted by one (rf SQUID) or two (dc SQUID) weak links, the so called Josephson junctions. If a dc SQUID is biased with an appropriate current, the voltage across the Josephson junctions becomes a periodic function of the magnetic flux in the ring (*cf.* Figure 2), which is linked to the external magnetic field via it's effective area: $\Phi = B * A_{eff}$. In order to linearize the voltage-flux- characteristics and operate the SQUID at the steepest slope (highest sensitivity), a so called flux locked loop (FLL) is used, which keeps the flux in the SQUID ring constant.

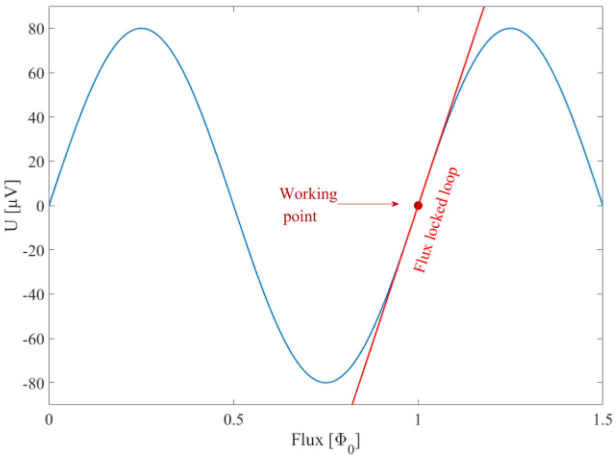

Figure 2: Voltage flux characteristics for a dc SQUID.

The next paragraphs will explain some important parameters of SQUIDs, especially for active electromagnetics.

Slew Rate

Based on the FLL principle one can explain a very important parameter of SQUID systems for unshielded operation: the maximum slew rate. If the flux changes faster than the FLL can provide feedback, it can happen that the SQUID locks on a new working point on the periodic characteristics with a different flux offset – visible by a voltage jump on the output of the FLL. Such a jump would happen, depending on the bandwidth of the FLL, in typically less than 1 µs. The height of the jump is an exact multiple integer of the voltage corresponding to one flux quantum. A typical FLL nowadays can handle between 0.1 MΦ_0/s and 50 MΦ_0/s [8]. This mainly depends on the SQUID's voltage swing, feedback coupling and electronics implementation.

Depending on the size of the superconducting ring (or the coupling to an even larger superconducting antenna) the effective area A_{eff} of SQUIDs for geophysical applications ranges typically between 0.5 and 5 mm^2. Therefore, a very sensitive SQUID with an effective area of 5 mm^2 would have a field-to-flux transfer coefficient ($1/A_{eff}$) of about 0.4 nT/Φ_0. With a slew rate of 1 MΦ_0/s (usually, sensitive SQUIDs have a rather week feedback, because the electronics would otherwise dominate the noise), this amounts to a maximum allowable slew rate of 0.4 mT/s. That means that a transmitter with 10 A on a 100 m x 100 m sized loop producing a 113 nT primary field in the center must not switch faster than 280 µs, otherwise the SQUID would jump. Therefore, a good SQUID for TEM is less sensitive and has a stronger feedback: with a transfer coefficient of 2 nT/Φ_0 and a slew rate of 5 MΦ_0/s it could follow a magnetic field rate of change of

10 mT/s. Therefore, the transmitter could switch in the same situation as fast as 11 µs and not exceed the system slew rate.

Bandwidth

The bandwidth of a SQUID system is determined by two components: the bandwidth of the FLL [9] and the transparency of the rf shield around the SQUID or the cryostat. In most cases the systems are built such that the bandwidth of the rf screen is the limiting factor, because this helps to avoid the earlier discussed flux jumps. The SQUID response itself is very fast, very often in the GHz range. But if the detected signal comprises frequency components which are beyond the FLL bandwidth and exceed one flux quantum $\Phi_{0,}$ jumps will occur.

Usually, the bandwidth of the FLL amounts to several MHz. The bandwidth of the rf shield is a compromise between system response to the primary TEM field and the stability of the system. In most cases it will amount to several 100 kHz.

Maximum Signal / Dynamic range

The maximum signal is strongly correlated with the dynamic range (the ratio between the smallest detectable signal and the largest one that can be measured without saturation). According to the application in mind the system has to be appropriately designed. As discussed earlier, very sensitive SQUIDs (<1 nT/Φ_0) would rather be operated with a weak feedback of several 100 Φ_0, resulting in a maximal signal of several hundreds nT. For TEM application this is in most cases not sufficient. Therefore, less sensitive SQUIDs (several nT/Φ_0) are used with a stronger feedback (up to 1000 Φ_0), resulting in a maximal signal of several µT. This is sufficient in most cases, but new transmitters with up to 100 A are now pushing the limits again for small loops or receiver locations close to the loop. It also should be noted, that modern FLL electronics provide a dynamic range of up to 170 dB [10] – which is far more than any ADC can digitize.

Noise

Every magnetic field sensor has its typical noise characteristics, determining the smallest signal that can be measured. For the stacking in TEM measurements, the low frequency noise (known as 1/f noise) is very important because it does not stack out so effectively as the white noise (the noise at high frequencies) [11].

Investigating noise characteristics is important to understand the noise contributing mechanisms: SQUIDs based on high temperature (HT) superconductors (HTS) can have quite good white noise for frequencies above 10 kHz, but the low frequency noise is often compromised. This can partially be overcome by the use of ac bias techniques, but this only suppresses noise contributions originating from critical current fluctuations. Other noise sources, like trapped flux in the superconducting material, need to be eradicated by design measures. In the near future, HT SQUID system with improved low noise performance will be available.

Low temperature (LT) SQUIDs, typically operated at 4.2K in liquid helium, have in comparison a much lower *1/f* noise, and in many cases it is very difficult to distinguish the intrinsic noise measured at low frequencies from external sources.

Measuring the noise level of SQUIDs is quite difficult at low frequencies, because very good and expensive magnetic shielding is required. At least 4 layers of mu-metal are necessary in an urban environment, where most laboratories are situated (*cf.* Figure 3). For LT SQUIDs there is a good chance to get rid of the external noise by an almost perfect superconducting shield.

Some noise sources could be larger in the Earth’s magnetic field because the chance of trapped flux in the material becomes much higher. Unshielded measurements require the use of correlation techniques in order to measure the system noise at low frequencies, which is very much below the noise of the Earth’s magnetic field even in rural environments [12].

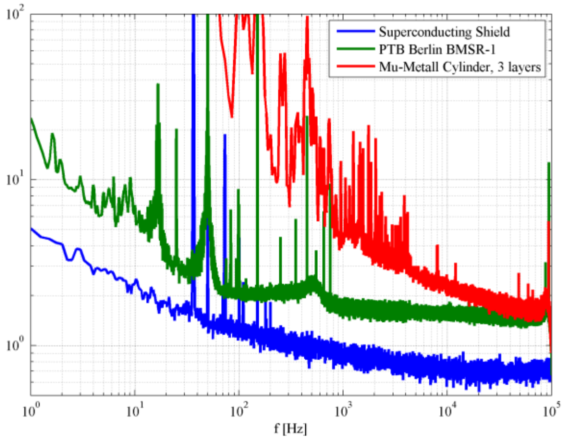

Figure 3: Noise of high sensitive LT SQUID in superconducting shield (blue, lower curve), in 3-layer mu-metal cylinder (red, upper curve) and in the shielded room BMSR-1 at the PTB Berlin (green, curve in the middle). Reprinted from [12], © IOP Publishing. Reproduced with permission. All rights reserved.

SQUID and geophysics

First geophysical applications with SQUIDs were carried out in the 1970s, mostly in passive measurements of the Earth’s magnetic field variation [13]-[15]. But due to the difficult cryogenics at that time, all SQUIDs were operated in liquid Helium at 4.2 K (low temperature superconductors, LTS), no field-worthy instruments could be built and hence the SQUID did not really find its way into in geophysical exploration. After the discovery of high temperature superconductors (HTS) in 1986 with a critical temperature of 35 K, many groups were looking for even higher critical temperatures. In 1987, YBCO with a critical temperature of 92 K was found and cooling with liquid nitrogen at 77 K became practical, allowing for the first time, to use simpler cryostats in field-worthy equipment. CSIRO pioneered the application of SQUIDs in geophysical exploration in the early 1990, although only published later [16]-[20]. Also other groups around the world started the application of SQUIDs for geophysical methods in that decade, *e.g.* [21], [22].

ADVANTAGES OF SQUID IN TIME DOMAIN ELECTROMAGNETICS

As discussed earlier, measuring the magnetic field has advantages compared to induction coils, especially in the presence of conductive overburden or targets with a high conductivity. SQUIDs already helped in many cases to discover or delineate targets.

The literature shows many examples of transients and profile plots of SQUIDs in comparison with coils, eg. [23]-[29]. A typical comparison between induction coil (Crone PEM receiver) and LT SQUID TEM data over a good conductor, from a recent test survey, is given in Figure 4 [30].

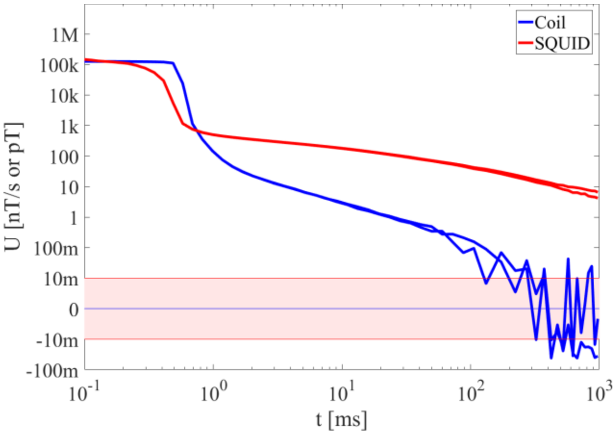

Figure 4: Coil and LT SQUID transients over a good conductor. Note the mostly logarithmic scale, while the scale between -10m and 10m (-10 pT/s to 10 pT/s) is linear. Reprint from [30], © 2015 IEICE, Permission Number 17RA0030.

The source of this long decay is in this case not a real ore body, but the so-called North German conductive anomaly [31] which is a good conductor at a depth of about 300 m. The literature given here and in the last chapter explains in detail the advantages of such long, noise-free transients that can be recorded with SQUIDs.

WHERE TO GET SQUID INSTRUMENTS FOR GEOPHYSICAL EXPLORATION

A comprehensive overview on laboratories and companies working on SQUID development can be found in [36].

Many institutions worldwide have developed SQUID instruments for geophysical applications. Not all of them published their results and parameters, and not all of them are still in that business. Table 1 lists institutions that to our knowledge are currently dealing with SQUID magnetometers for geophysical applications and typical parameters (as far as known). Of course we cannot guarantee for completeness. Availability in that context means if the systems can be bought or rented without restrictions from the geophysical community. JOGMEC for instance is using their SQUIDs mainly for in-house projects only. Keep in mind that it is difficult to compare system parameters from published values only, because measurement setup, definition of parameters and calculation methods may differ.

OTHER GEOPHYSICAL METHODS WHERE SQUIDS COULD BE USEFUL

Magnetotellurics

Of course SQUIDs could be successfully applied in MT, where the recording of the magnetics at very low frequencies is required. Apart from the high sensitivity one big benefit would be the flat frequency response of SQUIDs due to the superconducting effects. Furthermore, a full triaxial SQUID magnetometer could be built into one cryostat – making the digging of holes somewhat easier, especially for the vertical component. Although tests were performed already in the 1970s [15], the MT community still “believes” in their coils. The main argument is that the noise floor of the coils is still lower than the variation of the Earth’s magnetic field to be measured, but certainly the signal to noise would be better with a high sensitivity SQUID magnetometer. Costs and refilling intervals of the cryostat (in the best case up to one week) are probably the current show stoppers for SQUIDs.

Who	Maximum Slew Rate (mT/s)	Type	White noise fT/√Hz (> 10 kHz)	Number of Systems	Available	Reference
CSIRO Landtem		HTS	< 350	10	Yes	[32]
CSIRO		LTS	< 100 @ > 1Hz	1	No	[32]
SIMIT	> 2.4	LTS	10	1	Soon	[33]
Supracon	> 2	HTS	< 50	15	Yes	[30]
Supracon	> 65	LTS	< 20	10	Yes	[30]
SUSTERA, MINDECO and JOGMEC	10	HTS	30		No	[34]
Tristan		HTS	< 50	>3	(Yes)	[35]

Table 1: Typical parameters of SQUID systems for geophysical application that are currently in service.

Surface Nuclear Magnetic Resonance (SNMR)

SNMR can directly detect hydrogen protons and allows therefore the detection of subsurface water. While detecting T2 and T2* with coils is easily possible, directly measuring the slow decay time T1, representing the relaxation of the magnetization back to its equilibrium, is rather a dc measurement and needs fT resolution. This might be possible to register with a very sensitive SQUID and a remote reference of the same sensitivity. Furthermore, a setup of three orthogonal SQUIDs can measure SNMR in all three components, while the typically flat surface coils only measure the vertical component. First field tests successfully demonstrated the possibility to use SQUIDs for SNMR [37], but further development is necessary in order to better adapt the systems for this application.

Borehole TEM

Bringing sensitive EM sensors into boreholes is not an easy task, but would help to increase the depth of investigation or the delineation of conductors drastically. Bringing SQUIDs into boreholes has been requested from several companies, but the cooling in this harsh environment is a difficult task, as liquid cooling would require venting the gas in a way that the liquid inside the cryostat can boil at atmospheric pressure and withstand the high ambient pressure. A first successful SQUID operation in a borehole is reported by a SUSTERA, MINDECO and JOGMEC in 2016 [38]. But the outer diameter of the tool (100 mm) would not allow its use in boreholes for mineral exploration.

Airborne TEM / EM

Of course airborne EM measurements are highly favorable, because they can cover larger areas in a short amount of time and can hence be cost effective. CSIRO and BHP Billiton pioneered the use of HT SQUIDs in airborne TEM in the 1990. They developed jointly a fixed-wing slingram (separate loop) instrument. Lee et all. [19][20] reviewed the results of these tests. He came to the conclusion that the HT SQUID instrument delivered only comparable data quality to the induction coil sensors.

IPHT Jena developed an in-loop airborne TEM system based on LT SQUID magnetometers from 2006 to 2008 together with Spectrem Air and Anglo American [41], installed on a helicopter towed platform from Aeroquest. This development was much more complex since this setup is connected with much stronger primary field amplitude which had to be bucked out by a secondary coil around the SQUID instrument [42]. Although airborne trials where promising, the project was put on hold due to a changing focus towards the development of new SQUID based receivers. Recent progress on high slew rate systems would probably allow for high performance SQUID operation in airborne TEM.

New SQUID magnetometers with exceptional dynamic range of larger than 160 dB are in development within the R&D project DESMEX for a semi-airborne instrument (airborne sensors, grounded dipole transmitter) for exploration of deep situated conductive targets. First successful airborne operation in comparison to induction coil has been done recently.

FURTHER DEVELOPMENTS

Apart from the evolution of existing SQUID sensors and FLL electronics, new concepts could prove beneficial for applications where high dynamic ranges or slew rates are required. But already, very often the high resolution of (especially LT) SQUID systems can be used only in conjunction with remote referencing, either because the low frequency variation of the Earth's magnetic field is higher than the noise of the sensor or the exploration takes place in urban or mine environment.

Flux counting SQUID

A virtually unlimited dynamic range can be obtained by the method of flux quanta counting. The basic idea of this concept is to reset the FLL before reaching its maximum output voltage, resulting in a large amount of quantized steps in the acquired data. By taking advantage of the step height quantization, the underlying signal can, in principle, be reconstructed flawlessly in a post processing step. The reset-event detection and flux-quanta counting is usually implemented in the FLL electronics [39]-[45], however, also pure software-based solutions have been reported [46]. A further promising approach is to implement the flux feedback "on-chip" [47] instead of using a room temperature FLL. By this means, the reset time and the signal propagation delay are significantly reduced, allowing for a much larger bandwidth. Flux quanta counting magnetometers with large dynamic range and slew rate have also been implemented in **R**apid **S**ingle **F**lux **Q**uantum (RSFQ) technology, a kind of superconducting digital electronics. The resolution of pure RSFQ-based "digital SQUIDs" is restricted to about one flux quantum Φ_0, which would translate to a resolution of no better than 0.1 nT with reasonable pickup loops. Therefore, some effort was spent to combine them with conventional SQUID magnetometers in order to enhance the resolution to the sub-Φ_0 regime [48].

SQUID cascade

A fundamental problem of all flux-quanta counting methods is their vulnerability to high-frequency disturbances, like urban noise or atmospheric discharges. These usually occur during mobile operation in unshielded environment and may lead to significant miscounts. A way to circumvent this problem is to replace the flux-quanta counting by a reference measurement method, as suggested in [49][50]. Like before, the offset of each measurement value is corrected by the quantized step height $n \cdot \Phi_0 / A_{eff}$, $n \in \mathbb{Z}$, with A_{eff} and n being the effective pickup area of the SQUID as defined earlier and an integer number, respectively. But, as illustrated in Figure 5, n is now chosen such that the reconstructed magnetic field B_{SQ} matches the measurement value B_{Ref} of a low precision absolute vector magnetometer. As a result, the reconstruction process does not depend on the previously acquired data, meaning that the setup "recovers" from temporarily disturbances without changing the offset.

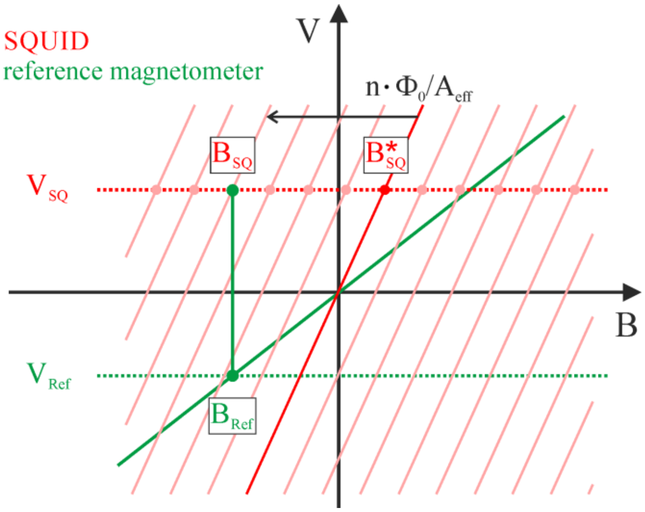

Figure 5: Illustration of the reconstruction process of the SQUID-cascade approach [9], [10]. Due to the Φ_0-periodicity of the SQUID's flux voltage characteristics, the SQUID's output voltage V_{SQ} corresponds to a set of possible magnetic field strengths, each separated by Φ_0/A_{eff}. In contrast to flux quanta counting methods, the correct value $B_{SQ} = B^*_{SQ} + n\cdot\Phi_0/A_{eff}$ is obtained by using a lower resolution absolute reference magnetometer.

CONCLUSIONS

Especially for TEM as a tool for mineral exploration, SQUID systems have reached a reasonable market share because of their superior performance in conductive environments or for highly conductive targets.

New coil designs and readout schemes, like the Armit coils, may fill the a gap between SQUIDs and conventional coils with respect to noise especially at lower frequencies. But their intrinsic high pass filter characteristic needs to be reliably deconvolved from the signal in TEM measurements.

In the past few years new SQUID concepts and associated technologies have also evolved which will allow the application of SQUID instruments to other electromagnetic applications. Many developments are currently on hold, but the next exploration boom will help to show how much more potential superconducting technology has.

ACKNOWLEDGEMENTS

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