Liquid Nitrogen Cooled SQUID Magnetometer for TEM*

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Abstract

SQUID magnetometers used in Transient Electromagnetics (TEM) surveys have become a valuable tool for exploring difficult targets during the last decade. Over the past 12 years, IPHT has developed SQUID systems for TEM applications, based on "High Temperature" Superconductors (HTS, Yttrium-Barium-Copper-Oxide YBCO), cooled with liquid nitrogen at 77 K. Test measurements on many targets of very different geological and climatic conditions demonstrated that SQUID sensors are reliable and can outperform conventional induction coils, especially in late time applications. The latest version developed by IPHT uses ac-bias technology in order to overcome excessive low frequency noise and has recently been tested in Portugal. Excellent signal-to-noise-ratio at late time is shown in comparison to a Crone and Zonge coil; transients and profiles compare well to "LandTEM", a SQUID system developed by CSIRO in Australia (Leslie, 2003).

IPHT SQUIDs, based on Low Temperature Superconductors (LTS, Niobium Nb), cooled by liquid helium down to 4K, have been used in production mode for several years now in South Africa and Australia by Anglo American (le Roux, 2006).

Gradiometers SQUIDs are able to measure the magnetic gradient directly with a very high resolution of better than 1pT/m in a 10Hz bandwidth. A short introduction of the new instrument "Jessy Star" will also be given.

Introduction

Measuring the magnetic field B directly instead of its time derivative (proportional to the induced voltage in a coil) can be advantageous in different scenarios, mainly, where strong and large conductors are to be detected. Richard Osmond et al. demonstrated this clearly in his paper on Raglan. In such a case, the time derivative of the secondary field of a TEM measurement is small and hence sometimes not detectable by a coil. On the other hand, a magnetometer, such as a Fluxgate or a SQUID, will easily detect very long time constants; even a real superconductor (time constant infinity) will be visible by the offset of the two opposite secondary fields – but invisible for the coil since the rate of change will be zero.

A major problem in using SQUIDs for TEM is the rather high slew rate required near the transmitter loop: Standard TEM transmitters attempt to switch the primary field as fast as possible. Since SQUIDs are operated in a feedback loop, which keeps the magnetic field in the sensor itself constant, very high slew rates are necessary to keep the sensor operational.

The Method: TEM

The Transient Electromagnetic technique is widely used in mineral exploration since most of the mineralized ore bodies show a resistivity contrast between the conductive orebody and the host environment which is big enough to be detected.

A typically square transmitter loop is laid out on the Earth's surface. The current is switched on and off in a well defined regime with opposite directions. In this way, offset drifts of the receiver unit and the sensor can be cancelled out by averaging, and most of the noise sources can be eliminated. The length of the recorded transients varies depending on the target, between several milliseconds up to several seconds (for very good conductors, usually only measurable with SQUIDs).

After the primary field has been switched off, eddy currents are produced in any conductive material. These decaying eddy currents produce secondary magnetic fields which can be detected on the surface; the shape of the recorded secondary field can be interpreted to calculate a resistivity/depth model.

Two configurations are used:

1. Moving loop: the receiving sensor is placed in the middle of the loop and the whole setup is moved between the stations. This is only applicable for small loop sizes, typically up to 200m by 200m.
2. Fixed loop: the receiving sensor is moved across (and outside) a fixed transmitter loop on the survey lines (shown in Figure 1). In this setup the position of the transmitter loop should be optimized to have optimum coupling to the ore body.

SQUID System

SQUID is an abbreviation for Superconducting QUantum Interference Detector: a superconducting loop is interrupted by two weak links. If the SQUID is biased with an appropriate current (slightly above the critical current) the voltage across the SQUID is a function of the flux in the ring – and hence a function of the external magnetic field. Since the SQUID output voltage is sinusoidal (Figure 3) it cannot be used directly as a measurement of the magnetic field.

A flux locked loop (FLL) is used to keep the magnetic flux in the SQUID ring constant at the maximum slope of the output voltage by driving a current through a feedback loop. The FLL electronics is a major part of any SQUID system: it has to be adapted carefully to achieve a good noise limited magnetic field resolution as well as a high dynamic range and slew rate.

Due to the nature of the material, HTS SQUIDs show an increased noise at low frequencies due to fluctuations at the weak link or the superconducting ring. The noise contributed by the weak link can be cut significantly by using an ac bias technique, switching the bias current polarity and SQUID output with a very high frequency. On the other hand, this switching has negative effects on the achievable slew rate (FLL is blind during the switching slopes). IPHT has recently developed and implemented electronics with an adjustable ac bias frequency (2 – 10 MHz) that also achieves a very high slew rate. Compared to the previous HTS TEM SQUID the low frequency noise at 1 Hz could be reduced by at least one order of magnitude.

System operation has been drastically simplified; a micro-processor controlled auto-tune automatically sets up all the SQUID parameters. Data are output via symmetric banana plugs and is easily compatible with any geophysical receiver (to date tested with Crone PEM, Zonge GDP16 and GDP32, Protem, Laptem, Smartem IV and V).

Results

A test survey has been carried out in Portugal in order to compare different systems on the same line. A 650 m by 650 m big transmitter loop was powered with 25 Amps by a Crone transmitter with 5 Hz repetition rate (transients up to 50 ms). All data have been recorded by a Crone receiver on a profile outside the loop, where the first 10 windows (1.5 ms) represent the ramp of the current when switched off. Data are not recorded simultaneously, but in different field surveys.

Figure 5 shows comparisons between the performances of IPHT and CSIRO SQUIDs with a Crone coil (region between -1 and +1 is linear in these logarithmic plots). In the upper part of each figure raw data are shown. As one would expect from theory the B field decays slower than its time derivative measured by the coil. While coil measurements at late times are subject to noise, both SQUIDs still measure a smoothly decaying transient in this region.

For direct comparison and as a further verification, the lower plots in each figure show differentiated SQUID data. We see a good correlation between the coil data and the calculated dB/dt from the SQUIDs.

In Figure 6 a profile line is shown for the different sensors which demonstrates more convincingly the achievable resolution and target visualization (again a linear region in [-1,1]). The x-axis represents the distance from the transmitter loop; for the SQUID's raw data are shown in arbitrary units, while coil data are in nT/s. The colour bar to the right depicts the time windows of the transients. The early channels (shown in grey), increase in amplitudes from left to right as the loop is approached. It is also seen that the late time channels (shown in dark red/brownish colour) are not very much affected by noise close to the loop. Note that the scatter of the coil readings increases significantly compared to the SQUID readings, as the distance from the transmitter loop increases. Looking at the

SQUIDs only, both SQUIDs show comparable features along the profile line, with a slightly higher noise level at late times in the CSIRO recordings (especially at the left hand side).

Conclusions

A new generation of IPHT HTS SQUID magnetometer has been tested successfully in production mode by taking TEM measurements in a noisy and rural environment. The SQUIDs demonstrated their superior signal quality at late time as compared to a conventional receiver coil. It has to be emphasized that these field measurements can almost be viewed as early time data if one considers the full capability of a SQUID and their specific application to the measurement of very late time data. A target in rural environment with time constants of at least 100ms would clearly show the superior data quality in a much more pronounced fashion. Previous measurements with an IPHT HTS SQUID showed smooth transients up to 1 second (see Chwala, 2001 with data acquired in North Germany, and unpublished data acquired in 1999 in South Africa).

Further testing will be necessary for a direct comparison of the conventional dc biased SQUID with the ac biased HTS SQUID to check if the better magnetic field resolution at low frequencies has advantages in TEM applications.

Acknowledgments

The new IPHT HTS SQUID has been tested on real targets and all data presented here is by courtesy of Lundin Mining.

References

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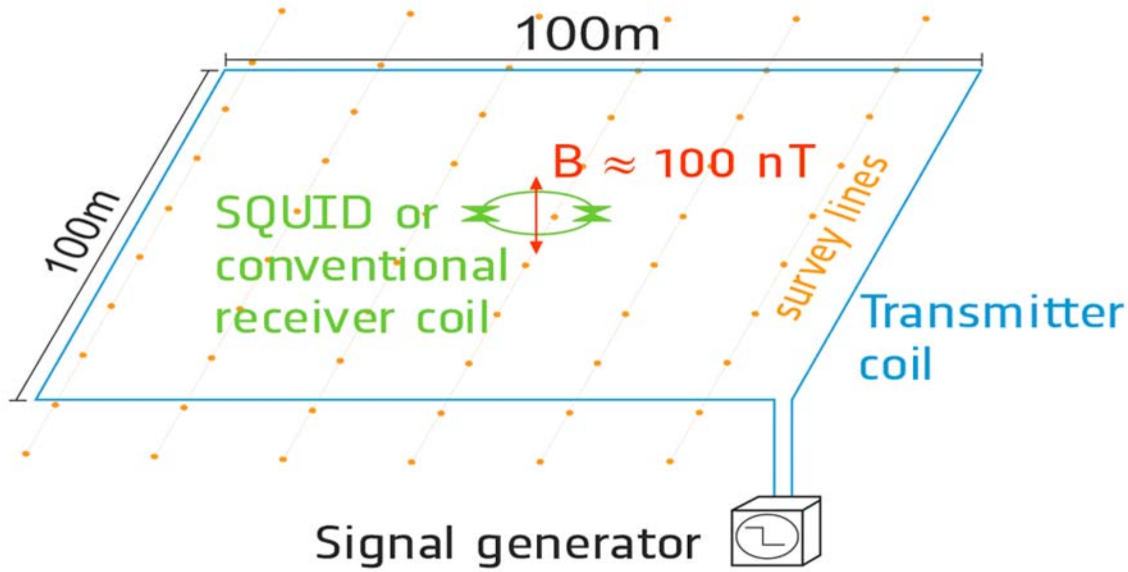

Figure 1. Typical layout for a TEM measurement.

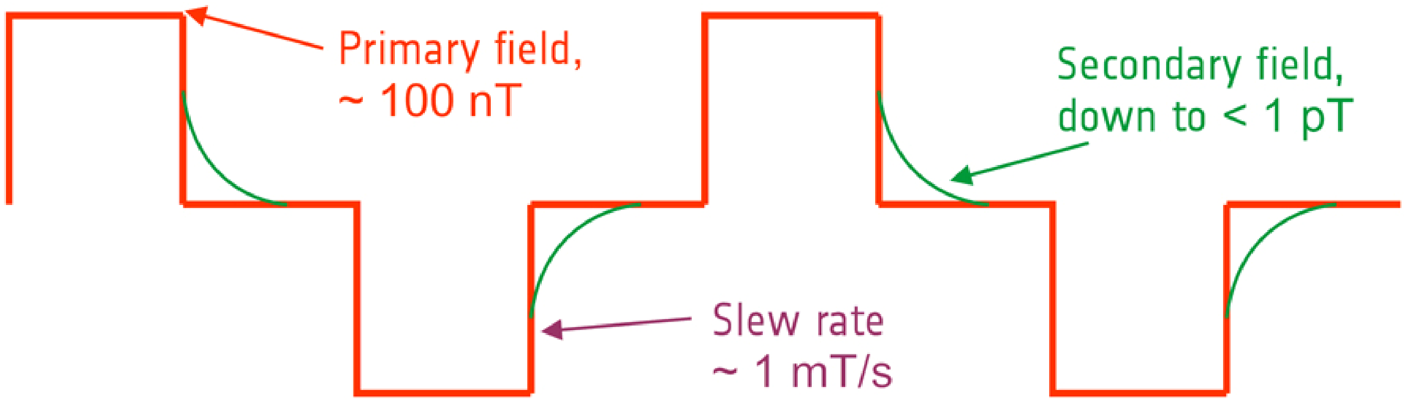

Figure 2. TEM waveform and secondary field.

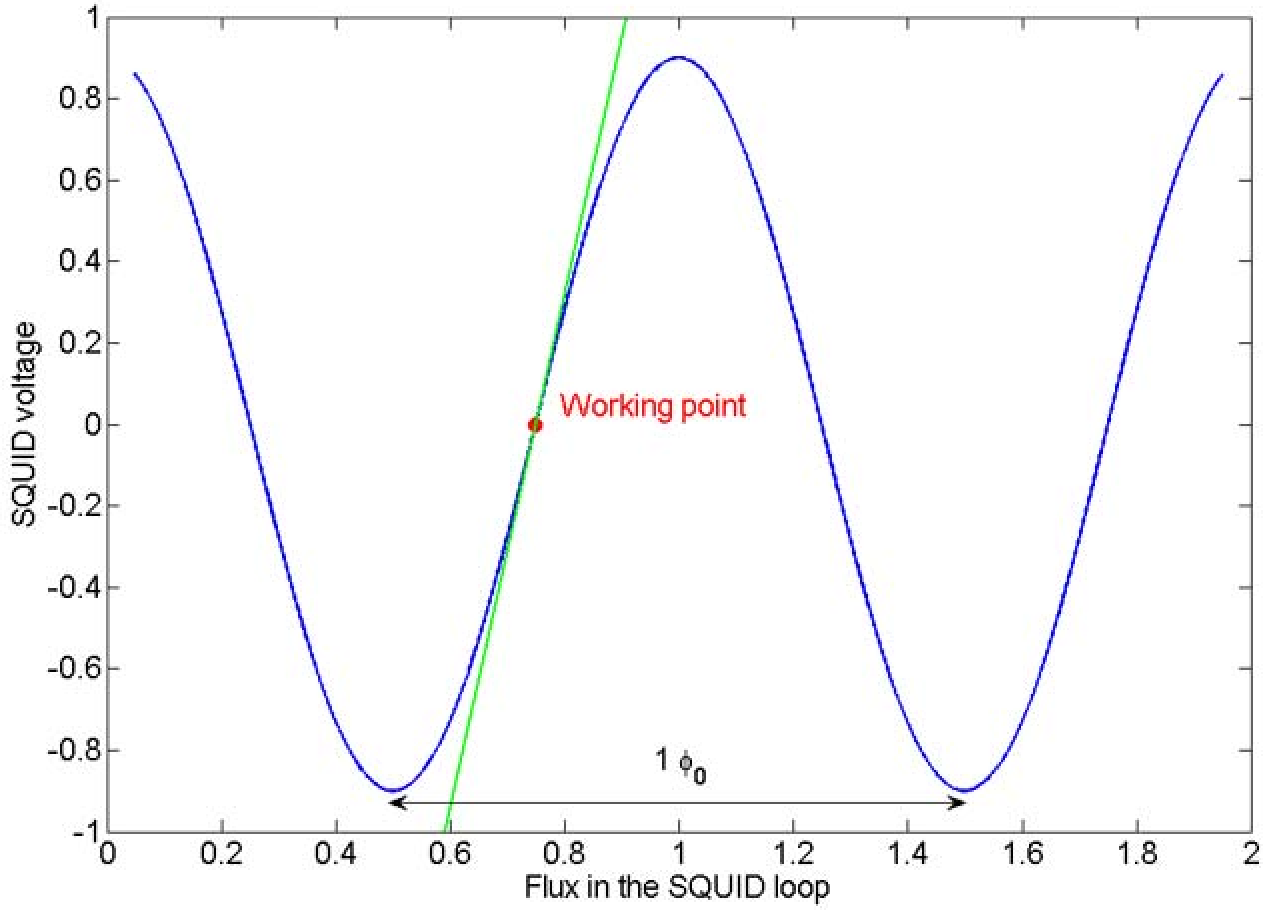

Figure 3. SQUID working principle.

Figure 4. IPHT HTS TEM SQUID system. Left: Cryostat and electronics on top. Centre: Power supply and control unit. Right: BNC adaptor box for laboratory work.

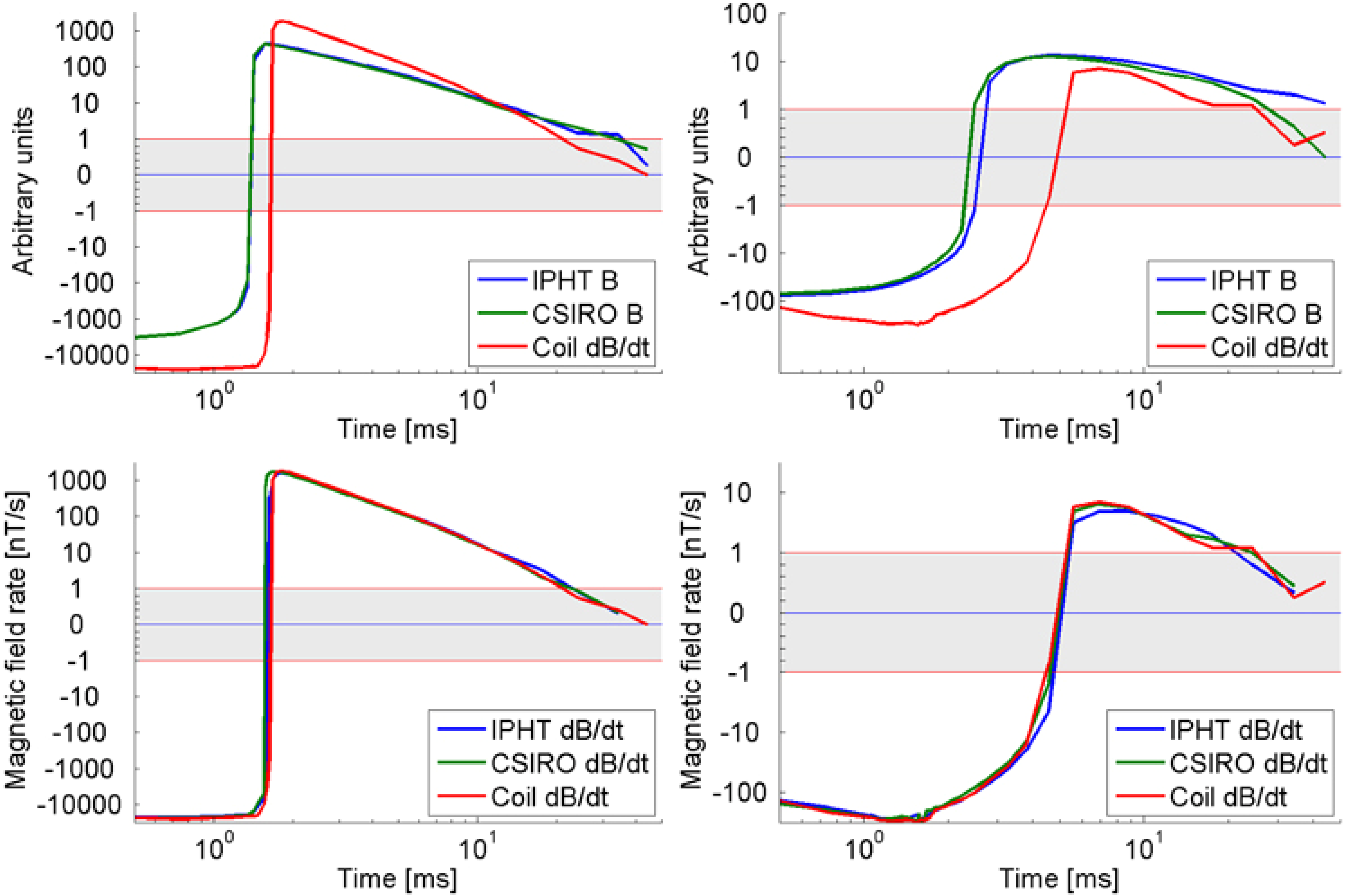

Figure 5. Transients 100m (left hand side) and 1000m (right hand side) outside the loop for SQUIDs and coil. Lower graphs with recalculated dB/dt for comparison.

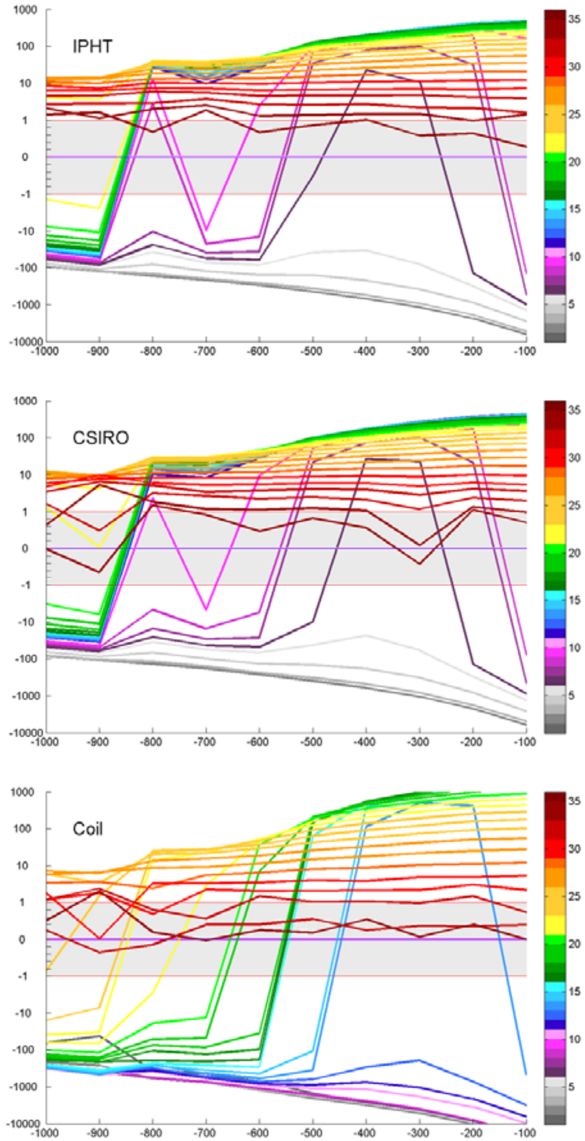

Figure 6. Profile line for SQUIDs (B) and coil (dB/dt) outside the transmitter loop (arbitrary units).

Measured Physical Quantity	Vertical B field
Bandwidth	DC … 10 kHz, flat frequency response
Field sensitivity	Better than 50 fT/√Hz above 100 Hz; 1/f corner < 10Hz
Power	Internal battery, 12V / 7Ah, 12 hours continuous operation
Output	Symmetric 50 Ohm via banana plugs (±1 V) Asymmetric BNC (±10 V)
Cryogenics	Liquid Nitrogen, 24 hours refilling interval
Total weight	Cryostat: 8 kg empty, 10 kg with liquid Nitrogen Power supply, incl. cable, 7 kg
System setup	Single push button, (or via RS-232 by computer for maintenance)
Features	Cable check, Analogue monitor, Battery status, Liquid level meter

Table 1. Parameters of the HTS SQUID system.