A 1D-Forward algorithm for the interpretation of ground based and airborne SQUID/ Coil TDEM data from arbitrarily shaped sources

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Abstract

There is a rise of interest in interpreting magnetic field data measured with SQUID-magnetometers as these may have superior data quality compared to coil data for late times and thus a higher depth of investigation. Moreover, airborne measurements, e.g. using helicopters, speed up the data collection a lot and allow for high data coverage. Therefore, the 1D inversion code for electromagnetic data of the University of Cologne (EMUPLUS) has been extended by this facility. The algorithm based on Weidelt (1986) has been implemented for both, polygonal loop sources as well as extended dipole sources in the presence of a 1D-layered earth model. The implemented code has been combined with pre-existing inversion routines and then applied on fixed-loop SQUID data collected in Bad-Frankenhausen (Thuringia, Germany).

Forward calculation

By using the scalar potential approach of Weidelt (1986) we separate a divergence-free vector field into a toroidal and a poloidal part. This separation can be applied in source-free regions on the current density $\vec{j}$ and the magnetic flux density $\vec{B}$. As we are only interested in the magnetic field within the air-halfspace, where $\sigma = 0$ holds, we solely consider the TE-mode:

$$\vec{B}_E = \nabla \times \nabla \times (\vec{e}_z \varphi_E). \tag{1}$$

To find an expression for the TE-potential φ_E, a partial differential equation is formulated by inserting equation (1) into Ampere's law in quasi-static approximation. The solution due to a HED-source on the surface is given in cylindrical coordinates within the frequency-domain by Weidlelt (1986) as

$$\tilde{\varphi}_E(r,z,\omega) = \frac{\mu_0 \tilde{d}(\omega)}{4\pi} \left\{ \frac{r}{R+|z|} - \int_0^\infty \frac{B_E(\kappa,\omega)-\kappa}{B_E(\kappa,\omega)+\kappa} e^{-\kappa|z|} \frac{1}{\kappa} J_1(\kappa r) d\kappa \right\} \sin\varphi. \tag{2}$$

The desired cartesian magnetic field components in frequency domain can be found by inserting the TE-potential (2) into the general magnetic field formulation (1). In EMUPLUS it is now possible to calculate cartesian magnetic field components (SQUID-Rx) and their time derivatives (Coil-Rx) from cable sources in the time domain. Especially observation of the induced fields in air is facilitated.

Extended dipole and loop sources

Magnetic fields arising from extended dipole and loop sources, as used in the TEM and LOTEM method, can be calculated by superposition of several HED-sources. A coordinate transformation approach for shifting an HED source w.r.t. the observer position allows for a high flexibility in forming the transmitter. Each element itself contributes to the total field at the observer position. Possible transmitter examples are illustrated in Figure 1.

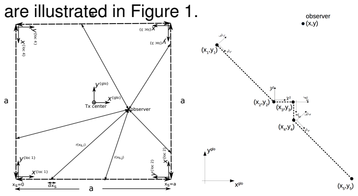

Figure 1 : Discretization of a large horizontal loop (left) and an arbitrarily shaped extended dipole (right) into HEDs, each contributing to the total field created at the observer position.

Acknowledgements

We would like to thank the IPHT Jena, the University of Jena and in particular Raphael Rochlitz for providing the SQUID-data. Great thanks also to Tilman Hanstein for providing his time transformation routine, especially for his filter coefficients, and fruitful discussions.

References

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[2] Rochlitz, R., Queitsch, M., Yogeshwar, P., Janser, S., Günther, T., Kukowski, N. and Stolz, R., Capability of Low Temperature SQUID for Transient Electromagnetics under Anthropogenic Noise Conditions, Geophysics (submitted).

Verification and performance of the forward calculation

The developed code has been tested successfully against reference solutions. One example is given in Figure 2.

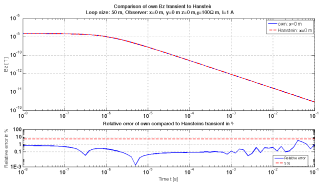

Figure 2 :
Top: Magnetic field response $B_z(t)$ for a loop source of the new code plotted against a reference solution provided by Tilman Hanstein.
Bottom: Relative error between both solutions in %.

Accuracy of the forward calculation for various dipole densities and times

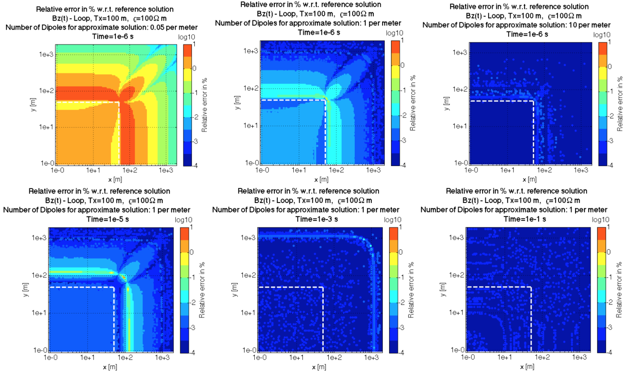

Figure 3 : Accuracy analysis of the forward calculation for various receiver positions. The colours indicate the relative deviations in per cent from a highly accurate solution (100 dip/m). The white dashed line is a quarter of the loop source.

Inversion of fixed loop SQUID data from Bad Frankenhausen

SQUID data has been recorded about one third of a decade longer than coil recordings due to lower noise level:
SQUID data: $t = 2.38 \cdot 10^{-4}$ to $1.78 \cdot 10^{-1}\,\mathrm{s}$
Coil data: $t = 2.38 \cdot 10^{-4}$ to $8.75 \cdot 10^{-2}\,\mathrm{s}$

Example station A09:

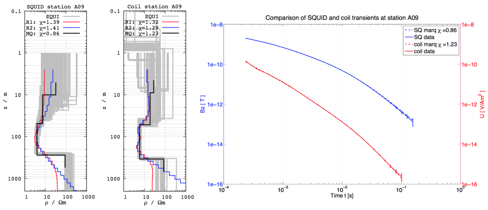

Figure 4 :
SQUID (left) and coil (centre) inversion results for station A09.
Right: Fitting and comparison of SQUID and coil transients.

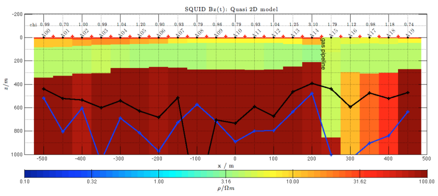

Figure 5 :
Resulting earth model according to 1D inversions of fixed loop SQUID-data.
Blue line: DOI based on the SQUID data.
Black line: DOI according to coil data (measured at the same sites).

- Predominant 1D structure: Highly conductive layers ($4 - 11\,\Omega m$) between a thin surface layer ($\approx 30\,\Omega m$) and a high resistive bottom layer ($90 - 100\,\Omega m$).

⇒ Comparison of the DOIs from both data sets: SQUID receivers in this case have mostly a higher depth of investigation than coil receivers.