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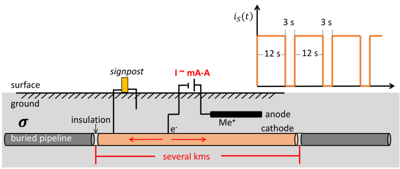
Using impressed cathodic protection currents on pipelines for subsurface imaging - analysis of data from a test site near Herford

Summary

Low-frequency electromagnetic (EM) signals generated by networks of technical infrastructure such as power-lines, pipelines or railways may provide a cheap and efficient means to perform EM depth sounding of the upper few kilometers of the Earth. Here, we report our attempts to utilize the signals emitted by an impressed current cathodic protection (ICCP) system of a 35 km long gas pipeline segment in north-western Germany. The installed ICCP system employs a periodical 12s-on / 3s-off current switching scheme, which resembles current waveforms used in controlled source electromagnetics(CSEM). In contrast to CSEM, where a grounded electrical dipole is employed as the source, the current flow in pipelines is not constant along its legs. Our efforts were therefore concentrated towards the determination of the temporal and spatial behavior of the electrical current within the investigated pipeline segment. While the time-dependency of the current can be measured directly at the injection point, the spatial distribution is only accessible through indirect observations.

Here, we employed fluxgate magnetic field measurements at multiple locations directly above the pipeline to infer the local source current and its frequency-dependency and phase lag. We observed that the current decays roughly exponentially away from the injection point, exhibits a position-dependent frequency-dependency and experiences a phase shift that accumulates to more than 30 degrees at the ends of the segment. These effects can be consistently explained with a transmission line model. Having determined the current distribution, we can represent the pipeline as an EM source superposed of point dipoles. The estimated source model allows us to predict the electric (and magnetic) fields at remote locations. To verify our approach, we deployed an array of telluric recorders in the vicinity of the pipeline, estimated frequency-domain transfer functions, and inverted the data into a three-dimensional electrical conductivity model using smoothness-constrained inversion techniques.



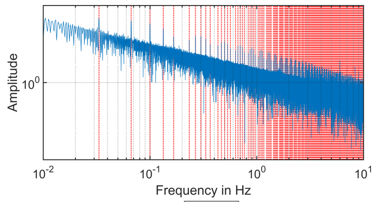


Figure 1: **Left:** *Depiction of a typical ICCP Setup. The pipeline is split into multiple, electrically isolated segments. Each segment is equipped with its own ICCP system, which consists of an anode and a DC power source. In addition, the pipeline is protected by an isolating coating (e.g. bitumen). The coating may be damaged at various locations, causing the current to leak into the surrounding earth. Standard switching patterns are 12s-On and 3s-Off.* **Right:** *Spectrum of the electric field component Ex recorded at site P23. Red lines indicate the harmonics of the 25-5-switching pattern used in our experiment.*

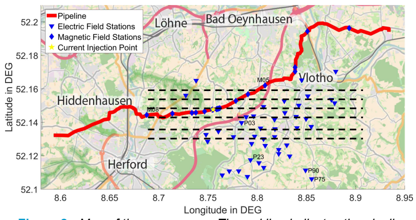


Figure 2: *Map of the survey area. The red line indicates the pipeline path used as a source in the model. The blue triangles depict the location of the telluric measurement sites. Blue diamonds are the locations of the magnetic field sites used for determining the source current distribution in the pipeline. The yellow star denotes the current injection site. Black dashed lines indicate the profile locations for the model slices in Figure 6.*

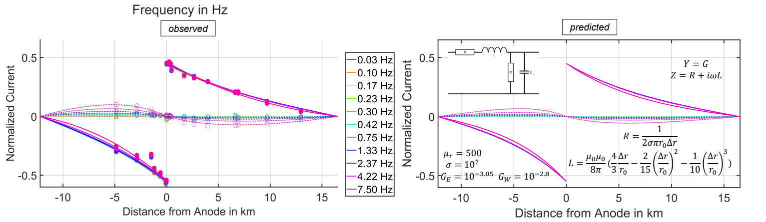


Figure 4: ***Left:*** *Pipeline current determined from the magnetic field measurements using a fluxgate magnetometer (dots) and the function fitted to the data (lines). Empty circles and dotted lines indicate the imaginary parts, whereas solid circles and lines depict the real part of the current.* ***Right:*** *Source current caclulated for the transmission line model as suggested by Mousatov et al. (2012) (see circuit diagram) for an examplory set of parameters. The East- and Westward facing branches have the same set of parameters, with the exception of the grounding resistance G. The pipe radius $r_0 = 0.15$ m and the wall thickness $\Delta r = 0.008$ m are assumed to be constant as well as the pipeline conductivity σ and the relative magnetic permeability μ_r. The capacitance C is neglected and set to 0 (Mousatov et al. 2012). The predictions from the model are in good agreement with the current determined from the measurements.*

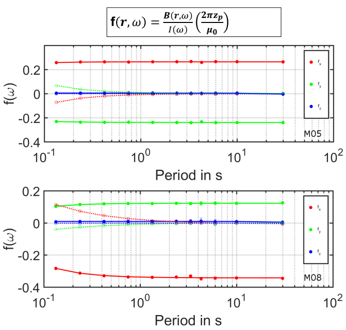


Figure 3: *Example of the source current estimated from the transfer functions between the magnetic fields and the source current at two magnetic field measurement sites using Biot-Savarts Law. Circles indicate the the current calculated from the data, whereas the lines indicate the function fitted to the data. Solid lines and circles indicate the real parts, whereas dotted lines and empty circles depict the imaginary parts. Imaginary parts increase with frequency as well as distance from the source point, i.e. the current exhibits a frequency dependent phase shift as it travels through the pipe.*

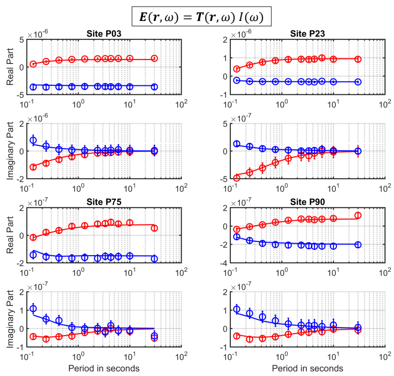


Figure 5: *Example of transfer functions calculated for four telluric measurement sites. Circles indicate the transfer functions calculated from the data, whereas the lines indicate the model response from the final inversion model (Figure 6). Solid lines and circles indicate the real parts, whereas dotted lines and empty circles depict the imaginary parts.*

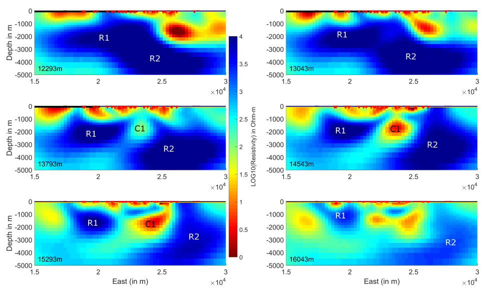


Figure 6: *Final subsurface model of the 3D inversion using INV3D (Grayver 2013). Shown are East-West-slices through the model. In the inversion, errors of 10% with an error floor of 1E-8 V/A were used. The source current is determined from the fit to the magnetic fiel data shown in Figure 3. The model shows a conductive top layer with a more resistive base below. In the south, the resistor is disturbed by the conductor C1. The model has an rms of 1.22. Removing the conductor C1 from the model results in a locally worse datafit, also increasing the overall rms to 1.8. Subsequent inversion using the modified model as an input results in a partial recovery of the conductor. Overall, the inversion of the field data using the current distribution derived from the magnetic field measurements yields a reasonable subsurface model with good datafit.*

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Literature:

Mousatov, A., O. Delgado-Rodriguez, E. Nakamura-Labastida, and V. Shevnin, 2012, Technical inspection of pipeline groups using surface electromagnetic methods: Near Surface Geophysics, 10, 129-140.

Grayver, A. V., 2013, Three-dimensional controlled-source electromagnetic inversion using modern computational concepts: PhD thesis, Freie Universität Berlin.