NIEDERSÄCHSISCHE STAATS- UND
UNIVERSITÄTSBIBLIOTHEK GÖTTINGEN

Werk

Jahr: 1984
Kollektion: fid.geo
Signatur: 8 Z NAT 2148:55
Digitalisiert: Niedersächsische Staats- und Universitätsbibliothek Göttingen
Werk Id: PPN1015067948_0055
PURL: http://resolver.sub.uni-goettingen.de/purl?PPN1015067948_0055

LOG Id: LOG_0014
LOG Titel: The influence of geomagnetic variations on pipelines and an application for large-scale magnetotelluric depth sounding
LOG Typ: article

Übergeordnetes Werk

Werk Id: PPN1015067948
PURL: http://resolver.sub.uni-goettingen.de/purl?PPN1015067948
OPAC: http://opac.sub.uni-goettingen.de/DB=1/PPN?PPN=1015067948

Terms and Conditions

The Goettingen State and University Library provides access to digitized documents strictly for noncommercial educational, research and private purposes and makes no warranty with regard to their use for other purposes. Some of our collections are protected by copyright. Publication and/or broadcast in any form (including electronic) requires prior written permission from the Goettingen State- and University Library.
Each copy of any part of this document must contain there Terms and Conditions. With the usage of the library's online system to access or download a digitized document you accept the Terms and Conditions.
Reproductions of material on the web site may not be made for or donated to other repositories, nor may be further reproduced without written permission from the Goettingen State- and University Library.

For reproduction requests and permissions, please contact us. If citing materials, please give proper attribution of the source.

Contact

Niedersächsische Staats- und Universitätsbibliothek Göttingen
Georg-August-Universität Göttingen
Platz der Göttinger Sieben 1
37073 Göttingen
Germany
Email: gdz@sub.uni-goettingen.de

J Geophys (1984) 55:31–36

Journal of Geophysics

The influence of geomagnetic variations on pipelines and an application for large-scale magnetotelluric depth sounding

Heinrich Brasse and Andreas Junge

Institut für Geophysik, Universität Göttingen, Herzberger Landstr. 180, D-3400 Göttingen, Federal Republic of Germany

Abstract. Geomagnetic variations affect the pipe-to-soil potential of pipelines and thus might endanger their cathodic corrosion protection. In winter 1982–1983 variations of the geomagnetic and telluric fields were recorded at three sites along a gas pipeline in northern Bavaria, together with fluctuations of the pipe-to-soil potential, which reached more than 3 V during a magnetic storm. Transfer functions between these quantities were investigated and the time duration of insufficient corrosion protection was estimated not to exceed 2 days per year.

The model of the pipe as an equipotential surface explains most of the observed phenomena. Thus the variations of the pipe-to-soil potential reflect the time-varying telluric field. Poor insulation leads to a local distortion of the telluric current density; in this case the pipeline represents a line conductor in the surrounding less conductive soil. On the basis of the first model, a mean regional telluric field was calculated by comparing the records of two sites, 47 km apart. The derived estimates of the transfer functions between geomagnetic and regional telluric fields yield an apparent resistivity of 50–60 Ωm in the depth range of 50–100 km, with a distinct decrease to 10 Ωm below a depth of 100 km.

Key words: Cathodic corrosion protection – Equipotential surface – Geomagnetic variations – Line conductor – Long-distance magnetotellurics – Pipeline – Pipe-to-soil potential

Introduction

The influence of geomagnetic variations on artificial conductors of considerable length, such as submarine cables, electric power lines and long pipelines, has been observed for more than a century. In auroral latitudes investigations on the trans-Alaska pipeline have been published recently by Campbell (1980) and Smart (1982). This paper will treat some aspects of induction phenomena in gas pipelines in mid-latitudes, where the geomagnetic disturbances are of a much smaller scale.

Continuous records of the pipe-to-soil potential, carried out by the gas supply company, Ruhrgas AG (Essen, FRG), showed large fluctuations during geomagnetic activity, questioning the efficiency of the applied cathodic corrosion protection and its monitoring. Therefore the correlations between pipe-to-soil potential and magnetic and telluric field variations were investigated by setting up several field sites along a pipeline in north-east Bavaria on soils with different resistivity. The digitized time series were filtered in the time domain and Fourier analysed, before frequency-dependent transfer functions between the observed quantities were calculated.

Under the assumption that direct induction in the pipeline can be neglected, two different models are discussed to explain the results: channelling of near-surface telluric currents plays a major role in grounded and inefficiently coated pipelines, while if there is good insulation the pipeline may be regarded as an equipotential surface. Then, the pipe-to-soil potential reflects the time-varying telluric field and may be used for magnetotelluric studies. Furthermore, the statistical prediction of the pipe-to-soil potential from the magnetic variations serves to estimate roughly the duration of insufficient cathodic protection.

Principles of cathodic protection

In an electrolyte-like soil or water, a metallic surface is oxidized by the electrochemical process of corrosion. Metallic ions, like Fe^{2+}, leaving the surface correspond to an electric current from the metal to the electrolyte. In addition to coating with bitumen or polyethylene, the method of cathodic protection is most frequently used to avoid corrosion of steel pipelines. The amount of corrosion decreases if a negative (cathodic) potential is applied to the pipe and approaches zero at the „protection potential" U_P.

Cathodic protection might be achieved in different ways:

A. The pipeline is connected to an anode consisting of a base metal buried in the ground, yielding a closed electric circuit between pipe and anode (Fig. 1). Thus corrosion will be transferred to the anode due to different redox potentials.

B. In addition to method A, the protection potential is obtained by transforming and rectifying the voltage of the electrical network (v. Baeckmann and Schwenk, 1980). The trans-Alaska pipeline is an example of the application of the first method, while the second method was used on the pipeline investigated here.

The potential U_R of the pipeline is related to a Cu/$CuSO_4$-electrode buried in the surrounding ground ("pipe-to-soil potential"). Without cathodic protection it amounts

---

Offprint requests to: H. Brasse

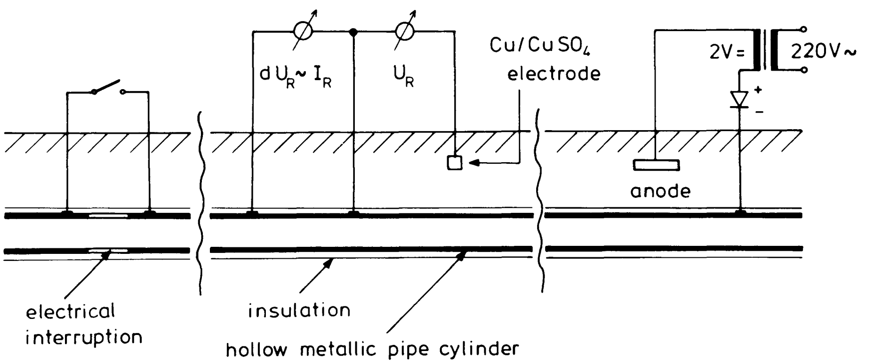


Fig. 1. Principles of cathodic protection of pipelines (*right*), recording of pipe-to-soil potentials and pipe currents (centre), and bridging of an electrical interruption (*left*)

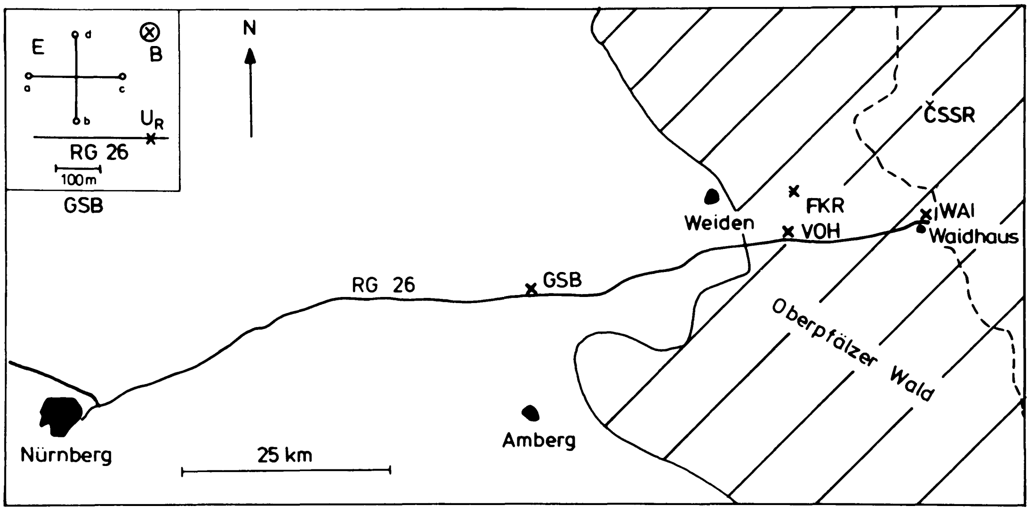


Fig. 2. Location of recording sites along Ruhrgas pipeline RG 26 and installation of the instruments at GSB (*upper left*), *B* magnetic field, *E* telluric field, U_r pipe-to-soil potential *Hatched*: Palaeozoic of the Oberpfälzer Wald, *blank*: Mesozoic sediments

to $U_R \simeq -0.55$ V, while complete protection is given at $U_P \simeq -0.85$ V. Since damage of the sheathing cause potential drops, rectifier stations at about every 30 km feed a voltage of $U_R \simeq -2$ V. The state of the cathodic protection is controlled periodically by measuring the pipe-to-soil potential U_R in short steps along the pipeline. As time-varying geomagnetic fields induce telluric fields in the ground and thus influence U_R, the cathodic protection and the results of its monitoring are questioned.

The survey and record examples

The field measurements were carried out in north-east Bavaria along Ruhrgas pipeline RG 26, which is polyethylene-coated and insulated electrically from the rest of the pipeline system at two points about 100 km apart (Waidhaus and Nürnberg, Fig. 2). In the eastern section the pipeline crosses the presumably highly resistant palaeozoic granite intrusions and metamorphics of the Oberpfälzer Wald. In the western section low resistant Jurassic sediments are dominant. Cathodic protection is applied at three points along the pipeline between Waidhaus and Nürnberg.

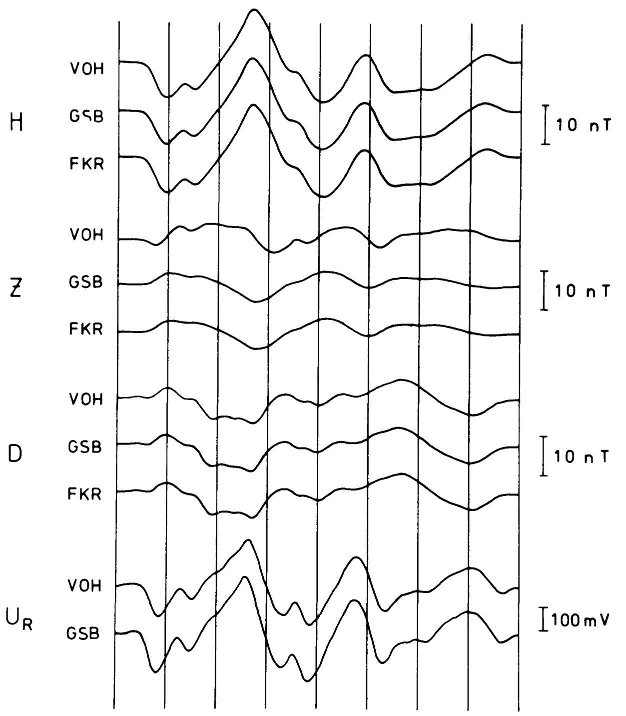
Variations of the magnetic and telluric fields, together with pipe-to-soil potentials, were recorded continuously from October 1982 until March 1983 at two sites corresponding to the different geological conditions. The distance between the pipeline and instruments was 250 m at Großschönbrunn (GSB) and 90 m at Vohenstrauß (VOH). Frankenrieth (FKR) served as a magnetic reference station, situated 5 km from the pipeline. In addition, the pipe-to-soil potential was recorded at Waidhaus (WAI), near the electrical interruption of the pipe. The components of the magnetic field variations *H*, *D*, and *Z* were recorded with induction-coil magnetometers for short periods of less than 10 min and with fluxgate magnetometers for longer periods. The pipeline did not cause a compass distortion of *H* and *D*. The horizontal telluric field was measured with two pairs of Ag/AgCl probes placed perpendicularly in east-west and north-south directions (Fig. 2, upper left).

The time-varying pipe-to-soil potential $U_R(t)$ is decomposed into a constant part U_C and a varying part $\Delta U_R(t)$

$$U_R(t) = U_C + \Delta U_R(t), \tag{1}$$

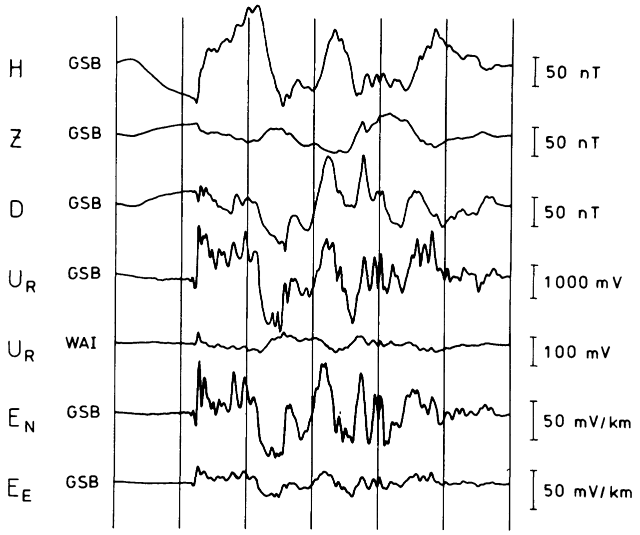
and referred to a $Cu/CuSO_4$ electrode buried in the ground close to the pipeline. At VOH changes of the electrical current in the pipe were obtained by measuring the voltage drop on a segment 30 m long with known resistance and using Ohm's law (Fig. 1). All data were recorded digitally on magnetic tape by battery-powered automatic stations with a sampling rate of 4 s for induction coil and 30 s for fluxgate magnetometers.

Figures 3–5 show some examples of magnetic pulsations and variations and their influence on the pipe-to-soil potential. The pulsation event in Fig. 3 indicates a distinct spatial



10.12.82 8:00 - 8:16 UT

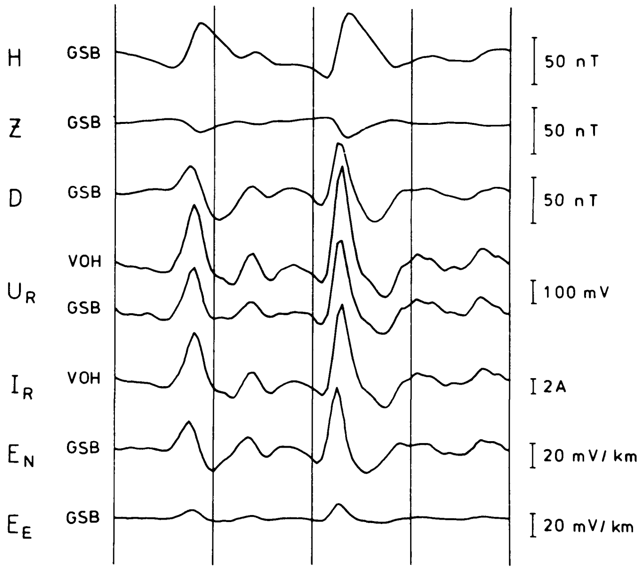
Fig. 3. A pulsation event on December 10, 1982 at 8.00 UT at the stations GSB, VOH and FKR; the distance between time marks is 2 min. H, D, Z, U_R: variations of the components of the geomagnetic field vector and the pipe-to-soil potential



4.2.83 15:00 - 21:00 UT

Fig. 4. A storm sudden commencement (ssc) on Feb. 4, 1983 at 16.14 UT, recorded at GSB and WAI. E_N, E_E: components of the telluric field vector. Distance between two time marks is 1 h

homogeneity for the geomagnetic components H and D at the three locations GSB, VOH and FKR. The variations of the pipe-to-soil potential ΔU_R on the mainly EW-running pipeline correspond essentially to $\partial H/\partial t$. In this period range the peak-to-peak voltage reaches about 500 mV and thus does not affect the corrosion protection. Due to the short distance (90 m) between magnetometer and pipeline, the influence of the varying pipe current appears in the Z-component at VOH.



4.3.83 19:00 - 23:00 UT

Fig. 5. An event with an additional record of pipe current I_R at VOH

A characteristic storm sudden commencement (ssc) occurred on February 4, 1983 (Fig. 4). During the main phase of this geomagnetic storm, with planetary indices of $Kp=8$, peak-to-peak voltages of ΔU_R reached 3 V at GSB, remarkably higher than at WAI. In addition, Fig. 5 shows the record of pipe current fluctuations of up to 12 A for an event with $Kp=5$.

Transfer functions between geomagnetic field and pipe-to-soil potential

To predict the fluctuations of the pipe-to-soil potential from the variations of the geomagnetic field we restrict ourselves to the investigation of events with periods $T>5$ min, because the amplitudes of ΔU_R for shorter periods were significantly smaller. For a number of suitable events the time series were Fourier-transformed into the frequency domain. Thus the measured quantities are described as complex functions of the frequency f. The linear relationship between the different quantities, e.g. ΔU_R, H and D, is considered by choosing the bivariate approach:

$$\Delta U_R(f)=\alpha(f)\,H(f)+\beta(f)\,D(f)+\delta\Delta U_R(f) \qquad (2)$$

where α and β are complex and frequency-dependent transfer functions with units mV/nT, and $\delta\Delta U_R$ is the uncorrelated part of ΔU_R. A first bivariate analysis showed no significant correlation between ΔU_R and D; therefore β will not be discussed. Obviously no large-scale distortion of the telluric currents exists in the area of the mainly EW-running pipeline. The electrical interruption of pipeline RG 26 at Waidhaus was bridged for several weeks during the survey (Fig. 1). Thus the conducting pipe was elongated by 50 km into Czechoslovakia. The elongation led to an increase in α at GSB by a factor of 3, in contrast to that at VOH, where α remained unchanged. For this time interval Fig. 6 shows the real and imaginary part of α for fre-

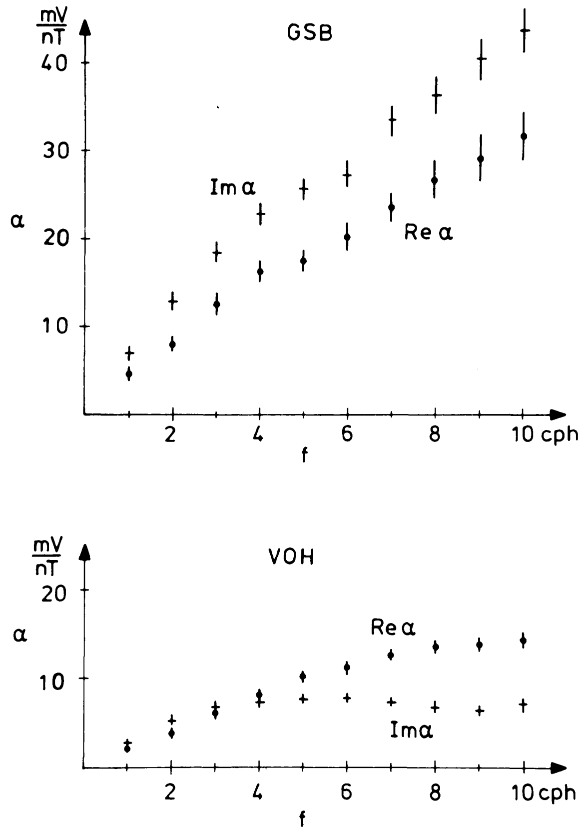


Fig. 6. Real and imaginary part of the transfer function α [Eq. (2)] for the sites VOH and GSB. The unit of frequency f is cph = cycles per hour

quencies of 1–10 cph (cycles per hour). The absolute value of α increases monotonically with frequency at both sites, while its phase is remarkably stable at GSB but obviously frequency-dependent at VOH. At WAI a characteristic phase jump of 180°, together with a decrease of α, occurred during the period of elongation (Fig. 7).

The transfer function γ between pipe-to-soil potential ΔU_R and pipe current ΔI_R, measured at VOH,

$$\Delta I_R(f) = \gamma(f)\, \Delta U_R(f) = \gamma(f)\, \alpha(f)\, H(f), \tag{3}$$

is real and constant with $\gamma = 21.2$ mA/mV, thus yielding currents of more than 50 A for large magnetic disturbances.

The temporal distribution of the geomagnetic planetary indices *Kp* and the transfer function α at a given location, e.g. GSB, allow a rough estimation of the integrated time interval Δt, during 1 year, in which the corrosion protection is insufficient: $U_R - U_P > 0$ with $U_P = -0.85$ V. Since only rough spectral estimates of the magnetic variations exist, we assume *Kp* to be determined by a harmonic disturbance in H with a period of 40 min, i.e. $Kp = 6$ would refer to a mean amplitude of 80 nT in mid-latitudes. The corresponding value of $\alpha = 12$ mV/nT at GSB (Fig. 6) leads to a mean amplitude $\Delta U_R = 0.96$ V of the pipe-to-soil potential. According to Siebert (1971), the average annual frequency of $Kp = 6$ is less than 2%, thus yielding $\Delta t \simeq 1$ day during 1 year. Taking into account the other relevant *Kp*-indices, $Kp > 6$, the total time duration of insufficient protection was estimated and does not exceed 2 days/year. This result corresponds to the observed time interval of insufficient corrosion protection during the campaign. It can be concluded that geomagnetic variations do not affect the efficiency of the cathodic corrosion protection of the investigated pipeline.

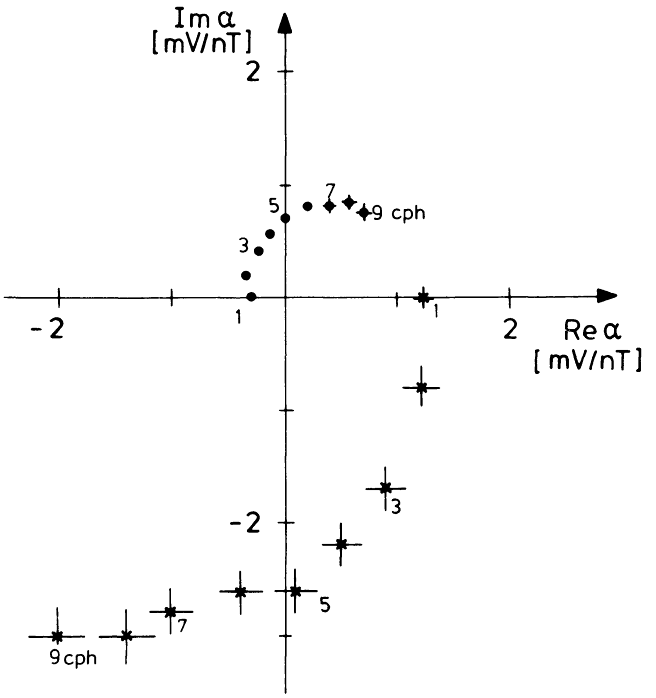


Fig. 7. The 180° phase shift of the transfer function α for the site WAI in the complex plane. *Dots* with, *crosses* without electrical connection to Czechoslovakia

Theoretical aspects and the regional telluric field

In explanation of the observations presented here, two different models will be discussed: (1) the pipeline as an equipotential surface and (2) the pipeline as a line conductor ("channelling" of telluric currents). Direct induction in the pipe as a source of the observed ΔU_R can be excluded, as the following argument shows: the skin depth δ of a quasi-homogeneous magnetic surface field of period T in a conducting homogeneous halfspace with resistivity ρ is

$$\delta = \sqrt{\rho \mathrm{T} / \pi \mu_0}. \tag{4}$$

With the resistivity of steel, $\rho = 0.18 \times 10^{-6}\ \Omega$m, and $T = 100$ s, as a lower limit for the considered period range, a skin depth of $\delta = 2.1$ m is calculated. Since the pipe is a hollow cylinder with a wall thickness of ~10 mm, the penetrating magnetic field is hardly attenuated, so that the amount of direct induction can be neglected.

Model (1)

No voltage drop occurs in the pipeline in the case of perfect insulation from the surrounding soil. Therefore, the pipe represents an equipotential surface, and time variations of the pipe-to-soil potential refer solely to the telluric field induced by the geomagnetic field. Assuming a homogeneous excitation by the geomagnetic H-component, a linear voltage drop U_S is generated in a homogeneous subsoil along an EW-running (y-direction) pipeline:

$$U_S(t, y) = E_E(t) \cdot y. \tag{5}$$

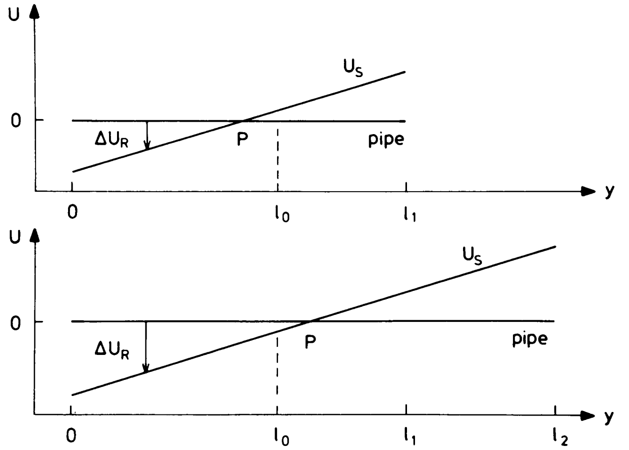


Fig. 8. Behaviour of the potentials for magnetic H-excitation in the case of a perfectly insulated pipeline in homogeneous subsoil at $t=$const. The variations of the pipe-to-soil potential ΔU_R are solely determined by U_S. The pipeline lengths, l_1 and l_2, lead to different records of ΔU_R

While the pipe remains at the constant potential U_C, the EW telluric field $E_E(t)$ and $U_S(t)$, respectively, determine the variations of the pipe-to-soil potential:

$$\Delta U_R(t, y)=U_S(t, y). \tag{6}$$

Figure 8 demonstrates the relation of the potentials at a given moment, $t=$const., and with U_C set to zero for pipelines of lengths l_1 and l_2. The varying voltages ΔU_R observed on either side of the intersecting point P, which is located at $l_1/2$ and $l_2/2$, respectively, should have opposite signs, i.e. display a phase shift of 180°. If the pipeline is electrically elongated, P moves towards the side of elongation and might cross a fixed observation point at l_0, leading to a similar phase jump. This was actually observed at WAI and is demonstrated in Fig. 7. For lateral inhomogeneities of the resistivity distribution the voltage drop is no longer a linear function of distance, yielding an irregular distribution of ΔU_R. On the basis of this model (1), a mean "regional" EW telluric field $\bar{E}_E(t)$ between two points at $y=\mathrm{O}$ and $y=d$ can be calculated:

$$\bar{E}_E(t)=[\Delta U_R(t, d)-\Delta U_R(t, \mathrm{O})]/d. \tag{7}$$

Equation (7) will now be related to magnetotellurics, carried out with short lines of approximately 200 m. In the frequency domain, the relation between the horizontal geomagnetic and the local telluric field is given by:

$$\begin{aligned} E_N(f)&=Z_{xx}(f)\, H(f)+Z_{yx}(f)\, D(f)\\ E_E(f)&=Z_{xy}(f)\, H(f)+Z_{yy}(f)\, D(f), \end{aligned} \tag{8}$$

where Z_{xx} ... denote the elements of the impedance tensor **Z**. If the conductivity is only a function of depth, Z_{xx} and Z_{yy} vanish and $Z_{xy}=-Z_{yx}$. For lateral inhomogeneities the columns of Z refer to the distortion of the electric field excited by H and D, respectively. Then, by inserting $\bar{E}_E$ from Eq. (7) for E_E in Eq. (8), α and β in Eq. (2) can be interpreted in terms of impedance tensor elements Z_{yx} and Z_{yy}.

Model (2)

In the case of missing or damaged insulation, the pipeline represents a line conductor in the surrounding less-conducting soil. Assuming H-excitation, this leads to a quasi-direct, i.e. real and frequency-independent distortion of the large-scale induced EW telluric field near the surface. The pipeline does not act as a conductor for the NS current systems induced by the geomagnetic D-component. As regards the impedance tensor **Z**, the pipeline only influences the elements Z_{xx} and Z_{yx}. Contrary to the first model, it cannot be considered as an equipotential surface, because the channelled currents result in a voltage drop along the pipe. Due to the condition of sheathing, this effect is of a local nature. Indications for the validity of the latter model are the amount of observed pipe currents (Fig. 5) and the behaviour of the telluric field distortion at GSB. After electrical elongation of the pipe, the tensor elements Z_{xx} and Z_{yx} increased by a real and frequency-independent factor of 1.2, while the other tensor elements Z_{xy} and Z_{yy} did not change. This suggests a rise of the local telluric current density excited by the magnetic H-variations.

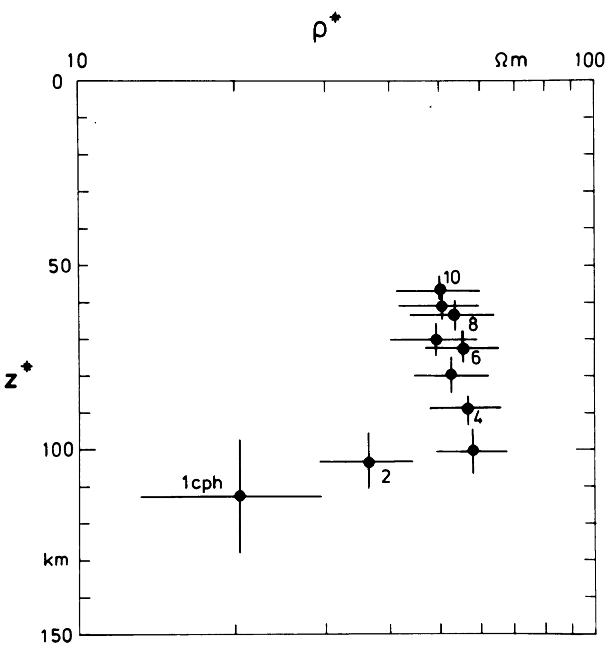


Fig. 9. Complex penetration depths calculated from variations of a regional telluric field by means of apparent resistivity ρ^* and depths z^* in the frequency range between 1 and 10 cph. The regional EW telluric field was obtained by comparing two records of U_R at GSB and WAI [Eq. (7)]

On the other hand, the observed phase jump at WAI (Fig. 7) supports the assumption (1). Turning back to this more likely model, the mean regional EW telluric field $\bar{E}_E(t)$ between the sites WAI and GSB was calculated using Eq. (7), with $d=47.4$ km. Because no significant D-correlated part was found in ΔU_R,

$$\bar{E}_E(f)=\bar{Z}_{yx}(f)\, H(f) \tag{9}$$

suffices to describe the relation between the telluric and magnetic field components.

For further analysis both impedance estimates from Eqs. (8) and (9) are expressed by the apparent depth $z^*(f)$ and resistivity $\rho^*(f)$, which are estimates of the true resistivity-depth distribution. The conversion formulae (Schmucker, 1979) take into account the phase, ϕ, of the impedance Z and are given in Eq. (10):

$$z^* = \mathrm{Re}\{Z(i\omega)^{-1}\}$$

$$\rho^* = \begin{cases} 2Z^2(\omega\mu_0)^{-1}\cos^2\phi & (\phi \geqq 45°) \\ \tfrac{1}{2}Z^2(\omega\mu_0)^{-1}\sin^{-2}\phi & (\phi \leqq 45°). \end{cases} \quad (10)$$

Reasonable results were obtained only for the time period of the pipe elongation and are plotted in Fig. 9 for frequencies of 1–10 cpd. A significant increase in the apparent resistivity from 20–60 Ωm with decreasing depth between 100 and 110 km is followed by a depth range of rather stable apparent resistivity of 50–60 Ωm up to an apparent depth of 60 km.

An attempt was made to compare the regional with the local telluric field at GSB. Since the transfer functions between $\bar{E}_E$ and E_E proved to be frequency-dependent, it was not possible to remove the local telluric field distortion. Nevertheless, the use of pipe-to-soil potentials of well-insulated pipelines for the purpose of long-distance magnetotellurics yields reliable estimates of the apparent resistivity-depth distribution. The method, therefore, seems to be of interest for further investigation.

Acknowledgements. We express our gratitude to the Ruhrgas AG, especially Mr. W. v. Baeckmann and Mr. W. Prinz, for their kind support during the investigation and for theoretical discussions, as well as to Dr. H. Voelker from the Geophysical Institute, Göttingen. Special thanks are due to Prof. U. Schmucker for kindly reading the manuscript.

References

Campbell, W.H.: Observation of electric currents in the Alaska oil pipeline resulting from auroral electrojet current sources, Geophys. J.R. Astron. Soc. **61**, 437–449, 1980

Schmucker, U.: Erdmagnetische Variationen und die elektrische Leitfähigkeit in tieferen Schichten der Erde, Sitzungsberichte der Braunschweigischen Wissenschaftlichen Gesellschaft (Hg. K.H. Olsen), Sonderheft 4: Beiträge zur Geowissenschaft, 1979

Siebert, M.: Maßzahlen der erdmagnetischen Aktivität, in Handbuch der Physik (Hg. S. Flügge), Band XLIX/3, Springer-Verlag, Berlin, 1971

Smart, A.: The trans Alaska pipeline – potential measurements and telluric current, IEEE Trans. on Ind. Appl., Vol. I8–18, No. 5, Sep./Oct. 1982

v. Baeckmann, W., Schwenk, W.: Handbuch des kathodischen Korrosionsschutzes, Verlag Chemie, Weinheim, 1980

Received February 13, 1984
Accepted March 22, 1984