A SEARCH FOR NONLINEAR EFFECTS IN ELECTRICAL PROSPECTING METHODS

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ABSTRACT

Field experiments were conducted to place bounds on the nonlinear effects that may be encountered in the course of resistivity and induced polarization prospecting experiments. The experiments made use of a primary current composed of the sum of two low-frequency sinusoids, 0.02 Hz and 0.065 Hz. The current amplitudes of the two components were equal, and in all experiments each contributed a peak current density of approximately 50 nA cm^{-2} at the midpoint of the array. The potential-electrode signals were recorded digitally, both in their original form and also after subtracting a major part of the two primary components and further amplification. The entire apparatus was tested in the laboratory to ensure that no nonlinear effects could be observed with linear loads, and that simulated nonlinearities were detected.

Four field experiments were carried out. Two were on the campus of the University of British Columbia and two were at a geophysical test site in the Fraser Valley of British Columbia, where a substantial, shallow IP anomaly is known to exist. At the first site, nonlinear effects were observed to be insignificant. At the test site, substantial nonlinearities were observed in the first field experiment. The experiment was repeated after removing the common ground point to a substantial distance from both the potential electrodes, and isolating it from them. Thereafter, the nonlinearities were reduced to an insignificant level. We therefore believe that they were created by an unbalanced current through this ground electrode, but we are unable to say whether the origin was purely an electrode effect or whether it created a local current density in the ground greater than the intended value.

INTRODUCTION

Measurement of both natural and man-made electrical signals provide information about the structure of the outer parts of the earth, to depths of tens of kilometres. Studies of the electrical properties of the subsurface include measurement of the resistivity of the ground as a function of frequency and electrode configuration. From a knowledge of the apparent d.c. resistivity as a function of electrode geometry and position of the array, it is possible to infer models for the resistivity of the upper layers. The induced polarization or overvoltage phenomenon was observed in a tank containing an aqueous solution and metal particles during laboratory experiments at the Radio Frequency Laboratories of Boonton, N.J., U.S.A. in 1946. Seigel (1949) and others applied this phenomenon to the search for disseminated mineral deposits in the southwestern United States. This IP phenomenon has since been studied extensively in the laboratory and in the field (*e.g.*, Wait, 1959, 1971; Cole, 1961; Pelton *et al.*, 1978).

Fundamental to many electrical measurements in geophysics, and to their interpretation, is the assumption of linearity of response. For example, recently developed instrumenta-

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tion and interpretation techniques use measured response of the ground over a wide range of harmonically related frequencies. The results are interpreted with the assumption that the ground behaves as a linear electrical network. Similarly, the presumed equivalence of frequency domain and time domain IP assumes linearity. The likelihood of linear behaviour is increased by the low current densities used. Nevertheless, an assumption of such a fundamental nature seems to deserve careful experimental scrutiny. Moreover, should nonlinearities in nature prove to exist and be measurable, their description could provide another tool for geophysical exploration.

There are comparatively few published reports of linearity studies either in the laboratory or in the field. Ryss (1971, 1974) described a "contact method of polarization curves" in which a large current is passed through a contact between massive sulphides and the host rock. The form of the relationship between current and potential drop at the interface was used to identify different minerals. In his field tests, Ryss used a 30 kW, 250 A transmitter. Klein and Shuey (1976) have studied, through laboratory experiments, potential drops across interfaces at which electrochemical reactions take place. They concluded that it is possible by such a technique to detect sulphide minerals in the presence of graphite, and chalcopyrite in the presence of pyrite. The electrochemical reactions involved are observed only with large current densities, unlikely to be encountered in conventional surveys.

Experiments of Katsube *et al.* (1973) suggested nonlinearities at much lower current densities. His observations were made, in the laboratory, on serpentine, asbestos, pyrite, cubanite and galena, concentrating on the first and last. An undistorted sinusoidal input voltage (in the case of serpentine) or current (in case of galena) was used. The other variable, voltage or current, was observed and harmonically analysed. The apparent impedance was calculated by dividing the magnitude of the fundamental component of the voltage by the magnitude of the fundamental component of the current. For serpentine Katsube took, as an indication of nonlinearity, variation of impedance with voltage. The voltage range used was 0.3 V to 30 V, and observations were made over a frequency range of 0.1 Hz to 1000 Hz. For the galena, a distortion coefficient was defined such that its square was the sum of the squares of voltage amplitudes of harmonics two to five, divided by the square of the amplitude of the fundamental. The experiments were confirmed by nonlinear Lissajous figure techniques and double frequency analysis techniques. Katsube concluded that the serpentine became electrically nonlinear at charge densities exceeding 10^{-8} coulombs cm^{-2}, and that the galena showed nonlinear characteristics associated with two critical-charge densities at 10^{-6} and 10^{-4} coulomb cm^{-2}. Such densities could be achieved in the field.

White (1974) made laboratory measurements that were similar in method to that reported in this paper, but he observed a much smaller number of harmonic terms. St.-Amant (1976) also conducted experiments in an attempt to observe significant nonlinear electrical effects in rocks. These experiments gave essentially negative results. The commercial value of nonlinearities, if they can be measured, has also been recognized. A patent by Weiss and Massé (1954) discusses the essential phenomena and suggests experimental procedures that might be used to make the necessary observations.

Since the above experiments must be regarded as inconclusive, and because they are primarily laboratory experiments, our experiment was designed as a field experiment that would contribute evidence about the nature and magnitude of electrical nonlinearities in the ground.

Experimental Arrangement

Current to the ground was supplied from two *KEPCO* BOP-500 Power Supplies connected as voltage-to-current transducers. The control signal to the power supplies came from a summing amplifier, the inputs of which were driven by *Wavetec* function generators, operating in a sinusoidal mode. We found negligible harmonics in the oscillators, and no intermodulation distortion produced by the summing amplifier. The two power supplies, driven in antiphase, were connected in series, and the midpoint was grounded at the middle of the array. The currents were balanced so that this common ground connection carried a current less than 10 μA. In some of our experiments the ground electrode was also used as a ground point for the potential measuring circuit, and in others the two circuits were electrically separated.

The levels of the two individual current sinusoids were set at 60 mA peak-to-peak, and were made equal. This value resulted in a total current well below the capabilities of the power supplies used, so that no nonlinearity from these supplies was expected or observed. The frequencies used were 0.02 Hz and 0.065 Hz.

We chose to use electronic summation to combine the two sinusoids, rather than duplicate current electrodes. Each procedure has an advantage. The advantage of using a single set of current electrodes is that the experiment can be simulated easily with linear resistors, either in the laboratory or in the field, to test the apparatus. Extensive laboratory and field tests were carried out in this manner, and we observed neither harmonics nor intermodulation coupling terms. Therefore we are confident that the apparatus itself does not produce nonlinearities, unless the nonlinearities are produced in the electrodes themselves. The test with linear resistors does not include a test of the potential or current electrodes. With nonlinear loads, involving diodes or tungsten filaments, the apparatus clearly detected the nonlinearities.

Since the current drive was rather small in comparison with many conventional IP Surveys, we placed the current electrodes only eight metres apart in the field test. This spacing provided a current density of approximately 100 nA cm^{-2} at a point midway between the current electrodes, which seemed to be a reasonable simulation of conventional IP experiments.

The potential field was monitored with a pair of copper/copper sulphate electrodes connected to a differential amplifier with an input impedance of 100 MΩ. The signal from the potential electrodes was amplified to between ± 2 and ± 8 volts, digitized and recorded on magnetic tape. It was also fed into a summing amplifier, the other input of which was obtained from the input to the power supplies by attenuation and phase shifting. This enabled the cancellation of a large proportion of the fundamental components, and the further amplification of the harmonics and the intermodulation terms. At least 97 percent of the two primary signals was removed and the remaining signal amplified another 25 times. This, too was recorded on magnetic tape. The nulling procedure was monitored by using a *Brush* two-channel chart recorder.

The digital tapes were analysed harmonically by means of a fast Fourier transform program on the IBM 370/168 computer of the Computing Centre of the University of British Columbia. To achieve a good spectral resolution, 24 periods of the lowest frequencies (0.02 Hz) were recorded and analysed. This fixed the observation time at 20 minutes.

The tape-recording and digitizing system was made available by Dr. R. M. Clowes. It is normally used for marine seismic data collection, and consists of an eight-channel A/D converter, a buffer formator and a *Kennedy* nine-track digital tape recorder. This system produces tapes in a format to be read by the IBM Computing System.

Three channels of data were recorded: the input to the power supplies, the amplified output from the potential electrodes, and the amplified signal from the nulling circuits. The latter two of these signals were passed through low-pass filters to remove all components with frequency above the Nyquist frequency of the digitizer.

Field Experiments

A total of four field measurements were carried out, two on the lawn in front of the Geophysics Building on the campus of the University of British Columbia, and two at the Seneca mine on the north side of the Fraser River, about 65 km east of the city of Vancouver, Canada (Pearson, 1973). For the first site, no IP anomaly was known to exist, and therefore the site constituted a reasonable control location. The Seneca site is a shallow, volcanogenic deposit, associated with a pronounced, shallow IP anomaly. This latter site has been used as a geophysical test site by the British Columbia Geophysical Society.

For the experiments on the lawn at the University of British Columbia, the ground resistivity was observed to be approximately 550 Ωm. No harmonics or intermodulation coupling terms were observed in the recordings. Knowing that the drive current had a peak value of 60 mA, and that the separation between the two current electrodes was 8 m, the primary electrode current at a near-surface point at the centre of the array can be calculated to be 120 nA cm^{-2}, and is independent of the resistivity of the ground provided it is reasonably homogeneous and isotropic. The potential electrodes were positioned centrally along the line of the current electrodes, and were separated by 1 m.

Because it was important to know that the procedure could detect nonlinearities, an artificial nonlinearity was introduced in this control experiment. This was accomplished with two additional electrodes, displaced one metre from the potential electrodes in a direction at right angles to the array. Two diodes were connected in parallel across the additional electrodes, one anode being connected to each electrode. (That is, the arrangement was symmetrical.) The diodes can be represented as secondary current sources. Because of the nonlinear characteristics of semiconductor (silicon) diodes, the diode current will contain harmonics and intermodulation terms. The peak current was not measured, but can be estimated as follows. Knowing the ground resistivity and the electrode configuration, the potential difference (in the absence of diodes) between the diode electrodes is calculated to be 0.61 V. A reasonable estimate for the contact resistance of the diode electrodes is approximately 500 Ω for one, or 1000 Ω for the pair. Thus the diodes are driven by a 'power supply' of 0.61 V, open circuit, and internal resistance 1000 Ω. The voltage-current characteristic of such a supply was superimposed on the nonlinear voltage-current forward characteristic of the diode. The peak diode current and voltage correspond to the intersection of the two characteristics. These were found to be 150 μA and 0.42 V. The diode contributed at the midpoint of the array a peak current perturbation of about 1.7 nA cm^{-2}, or less than two percent of the primary current. Even over this relatively low current range, the diode characteristic is quite nonlinear, and it is not surprising that the experiment yielded substantial harmonic and intermodulation terms (Fig. 1, Table 1).

The principal uncertainty in the above calculation of the diode current is the contact resistance of the diode electrodes. It is not likely to be much smaller than the value used. If it was ten times our estimate, then the diode current would have been only one-third of our estimated value.

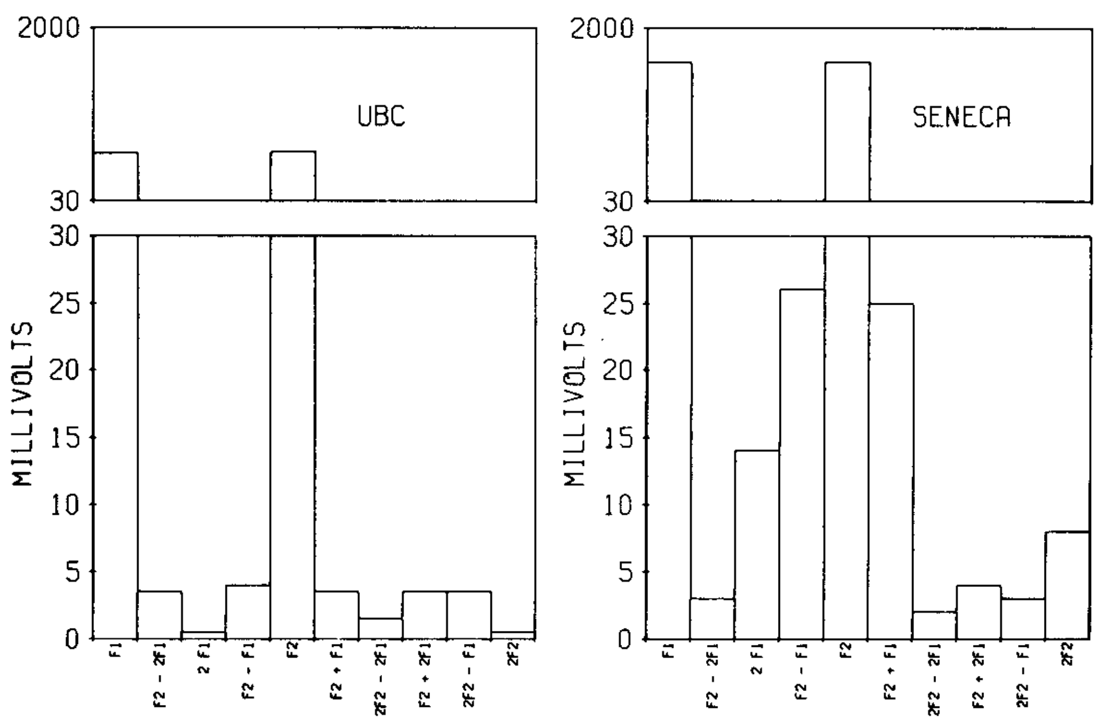

Fig. 1. A comparison of the nonlinear effects observed in two of the four field experiments. In the case of the campus experiment, the nonlinearity was induced by the use of diodes. In the case of the Seneca experiment, the cause of the nonlinearity is unknown, but it might be attributable to non-negligible electrode current.

Two field experiments were carried out at Seneca. The first exhibited harmonics and intermodulation terms of substantial magnitude. The contrast with the reference experiments at the University of British Columbia was quite dramatic. In fact, the nonlinearities seemed to be substantially greater than those observed when diodes were used to force nonlinearity of the campus site. The results are summarized in Table 1.

We set about trying to determine whether the nonlinear effects were truly a natural phenomenon or were an artifact of the experimental arrangement. In addition to the results reported here, there had been several other observations made at Seneca at which the potential electrodes were positioned differently. The results were similar, but suggested that the nonlinearites became greater when the potential electrodes were positioned closer to the common reference electrode. As mentioned already, this electrode served as both the common point of the two power supplies and the reference point of the potential measurements. Although care was taken to keep the supplies balanced so that current through this electrode was very small (less than 10 μA), even a small unbalanced current could result in local current densities in the region of the electrode that are much greater than that produced by the primary electrode array.

To examine this point further, a second field experiment was carried out at Seneca. This time the potential and current electrodes were kept quite separate, and the common point of the power supplies was grounded at a point relatively remote from the potential electrodes. In this experiment we observed (Table 1) negligible nonlinearities, as was the case in the reference experiment. Therefore, we suppose that the nonlinearities observed in the first Seneca experiment resulted from non-negligible current through the common power-supply electrode. We are not able to say whether the nonlinearities observed resulted from the small current flowing through the electrochemical cell (a copper / copper sulphate porous pot electrode) or from a higher current density producing local nonlinear electrical responses in the ground near the common electrode. The first possibility seems the more likely.

Conclusion

This experiment was an essentially negative one in that we failed to show that nonlinearities could be induced in the ground in an experiment representative of typical IP prospecting experiments. We consider it a useful result because the level of detection of nonlinearities seems to be much lower than obtained in experiments previously reported. The greater

HZ	COMPONENT	UBC DIODE	UBC NO DIODE	SENECA EXPT 1	SENECA EXPT 2
0.020	f1	575 mv	564 mv	1600 mv	1600 mv
0.025	f2 - 2 f1	3.5		3	
0.040	2 f1	0.5	*	14	
0.045	f2 - f1	4.0	*	26	0.2
0.060	3 f1	*		1	
0.065	f2	587	587	1600	1600
0.085	f2 + f1	3.5		25	0.2
0.090	2 f2 - 2 f1	1.5		2	
0.105	f2 + 2 f1	3.5	0.5	4	0.1
0.110	2 f2 - f1	3.5	0.5	3	
0.130	2 f2	0.5		8	0.1
0.135	3 f2 - 3 f1	1.5			
0.150	2 f2 + f1	3.5	0.5	5	
0.155	3 f2 - 2 f1	1.0		1	
0.170	2 f2 + 2 f1	1.5		2	
0.175	3 f2 - f1	1.0			
0.190	2 f2 + 3 f1	0.5			
0.195	3 f2	*	1	0.2	

*Clearly seen but not measurable.

Table 1. A summary of the frequency components observed in the four principal field experiments.

sensitivity of the arrangement used, combined with the negative results obtained, provides a much stronger foundation for the analysis of IP experiments on the basis of linear theory.

The experimental results also suggest a reason to be cautious when making some electrical measurements of the ground. Assuming that our interpretation is correct, that the nonlinearity observed in the First Seneca experiment resulted from a small current flow through an electrode, then one must accept that such nonlinearities could be produced near the electrodes of many electrical prospecting experiments. The magnitude of the effect observed at Seneca is much too small to affect most conventional interpretations, but such nonlinearities could affect interpretations of a more sophisticated type. This conclusion is the same whether the nonlinearity was confined solely to the electrode or was induced in the ground materials.

As is the case for most negative experiments, this research leaves many questions unanswered. We are troubled by several such questions. If the nonlinearity observed at Seneca was induced by current in the reference electrode, why was it not observed during the reference experiment on the university campus? The same porous-pot electrode was used, and the experimental procedures were the same as far as we could tell. Were we lucky enough to have achieved near-perfect balance of the power supplies during the campus experiment, or do the results suggest that, after all, it is some property of the ground that contributed to the anomaly? It should be remembered that a properly constructed porous pot is supposed to approach chemical reversibility and to be otherwise well behaved, at least at small currents. Another point of interest is the very great difference in the *characters* of the nonlinearities observed on the campus with the diodes and in the first Seneca experiment. These effects are compared in Figure 1. The latter experiment uncovered proportionally higher sum and difference terms, and higher first harmonics. The diode arrangement used on the campus was essentially symmetrical with respect to current direction. The character of the Seneca nonlinearity suggests an assymetry, but we cannot offer a plausible mechanism.

Finally, we suggest that it is worth while to carry out further studies to search for nonlinear electrical behaviour of earth materials. The experiments described here were quite sensitive, but the experimental arrangement was quite cumbersome. An arrangement that is more appropriate for extensive data collection in the field could be used to make valuable extensions of our study. Modern technology provides the means to increase the sensitivity of such measurements further. It is to be expected that, at some level, true nonlinearities can be observed for earth materials. Whether they can have value as a prospecting tool is still a matter for speculation.

References

Cole, R. H., 1961, Theories of dielectric polarization and relaxation: Progress in Dielectrics 3: New York, J. Wiley and Sons.

Katsube, T. J., Ahern, R. H. and Collett, L. S., 1973, Electrical nonlinear phenomena in rocks: Geophysics, v. 38, p. 106-124.

Klein, J. D. and Shuey, R. T., 1976, A laboratory investigation of the complex impedance of mineral-electrolyte interfaces: (abstract) Geophysics, v. 41, p. 360.

Pearson, D. E., 1973, Harrison, Lucky Jim, *in* Geology, Exploration and Mining in British Columbia: British Columbia Dept. of Mines and Petroleum Resources, p. 125-128.

Pelton, W. H., Ward, S. H., Hallof, P. G., Sill, W. R. and Nelson, P. H., 1978, Mineralization discrimination and removal of induction coupling with multi-frequency IP: Geophysics, v. 43, p. 588-603.

Ryss, Yu. S., 1974, Utilization of the contact technique of polarization curves in the prospecting for ore deposits and the evaluation of ore occurrences. Exploration Geophysics in the U.S.S.R. at the beginning of the 70's: Subsurface Geophysics, p. 375-380. NADRA Publishers, Moscow.

———, 1971, Contact method of polarization curves, *in* Volosyuk, G. K. and Safronov, N. I., *eds.*, Borehole Mining Geophysics: Vses. Nauchno-Issled. Inst. Metod. Tekh. Razv., Leningrad, 535p.

St.-Amant, M., 1976, Les paramêtres de la conduction electrique non linaire des roches: M.S. Thesis, Department de Génie Mineral (Géologie), Ecole Polytechnique, Université de Montréal, Canada.

Seigel, H. O., 1949, Theoretical and experimental investigation into the application of the phenomenon of overvoltage to geophysical prospecting: Ph.D. Thesis, Department of Electrical Engineering, University of Toronto, Canada.

Wait, J. R., (ed.), 1971, Electromagnetic probing in geophysics: Boulder, Colorado, The Golem Press, 391p.

______, 1959. Overvoltage research and its geophysical applications: New York, Pergamon Press, 158p.

Weiss, O. and Massé, L., 1954, Electrical method and apparatus for geological exploration: United States Patent Office 2,690,537, 9p.

White, R. M. S., 1974, A study of nonlinear effects in mineralized rocks: M.Sc. Thesis, Macquarie University, New South Wales, Australia.