Frequency and current analysis of non-linear electrical effects in mineralised rocks

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SUMMARY

Available electrical geophysical methods are specialised in detecting conductive and chargeable targets, particularly sulphide deposits. A key challenge facing Induced Polarisation (IP) and Transient Electromagnetism (TEM) methods is that often a chargeable target is not a sulphide deposit but a graphitic shale or clay formation. These shale deposits are undesirable targets, as discrimination is not able to be determined by geophysical methods but rather requires expensive physical methods such as drilling.

There is some evidence that shales produce a strictly linear electrical response, with respect to current density. This contrasts to the non-linear response of sulphide-rich rocks which generates additional signals in the frequency domain.

The effect of disseminated sulphide grains acting as a diode in the presence of two electrical signals of non-harmonically related frequencies was originally studied in the 1970s. A laboratory-based reinvestigation into non-linear electrical properties of sulphide minerals, as well as initial field trial results was undertaken. The early results of this work prompted this further study into the current and frequency dependences, in order to determine the impact these factors have on the measurement of mixing terms.

Further work on the application of a direct current (DC) bias in order to increase the detectability of non-linear responses has also been undertaken. The encouraging results will direct further field testing, with the eventual aim of providing a new method for mineral discrimination, greatly reducing the number of drill targets barren of mineralisation.

Key words: non-linear conduction, heterodyne method, sulphide exploration, laboratory study

INTRODUCTION

Induced Polarisation (IP) and Transient Electromagnetism (TEM) are among the most widely used ground electrical geophysics methods in Australia, specialising in detecting conductive and chargeable targets such as sulphide deposits. A key challenge of IP and TEM methods is that mineralogy of a chargeable target is not able to be determined; often a chargeable body is not a sulphide deposit but a graphite-rich formation of black shale or clays. These shale deposits may be false exploration targets and distinguishing by physical methods such as drilling is exhaustive on exploration resources.

Graphite-rich shales, which complicate induced polarisation surveys, cannot be easily distinguished from sulphide mineralisation by existing electrical methods. The effect of sulphide grains conducting non-linearly with respect to current density, will, in the presence of two electrical signals of non-harmonically related frequencies, produce heterodyne signals that can be detected in field surveys (White et al., 2018). This effect was originally studied in the 1970s, and there is evidence that shales produce a strictly linear response (White, 1974). This contrasts to the non-linear response of sulphide-rich rocks which generates additional signals in the frequency domain. The biased and simple heterodyne techniques therefore hold the promise of being able to distinguish between the sulphide and graphite signatures of mineralised horizons. It may also be possible by refinement of these techniques to distinguish between sulphide species.

Field techniques developed so far (White et al., 2018) consist of the galvanic transmission of two sinusoidal frequencies and the mapping of sum and difference mixing frequencies. The purpose of this study is to test, in the laboratory, the effects of varying primary frequency, current density and direct current bias on the observed secondary signals.

METHODOLOGY AND RESULTS

A variety of targeted tests with specific focus areas have been undertaken in the laboratory setting, with the aim of refining the understanding and methodology of the biased heterodyne method prior to further field testing. Tests were applied to a number of rock samples from the Kempfield Project in central NSW, which has been the main test area for field tests of the heterodyne methods. These laboratory tests were conducted to support conclusions drawn in previous work (Oertel et al., 2018) and provide further information concerning specific aspects of the method. These tests can be considered as four distinct investigations: testing of the robustness of the method, testing of rock sample responses without a DC bias, testing of rock sample responses with a DC bias, and frequency dependence.

Robustness of the Testing Procedures

A test on the linearity of the measurement system was conducted by using a wire-wound resistor as a baseline control. The aim of this control test was to confirm that no non-linearities were present in the instrumentation. In the control test there were no observable mixing terms, confirming the linearity of the measurement setup.

Tests on electrode contact area were conducted using a sample, confirmed to have high sulphide content and a high level of non-linear mixing terms, from the Que River Mine in Tasmania. Measurement of the mixing terms with differing numbers of input electrodes was undertaken to determine the effect of current density in the immediate vicinity of the electrodes. Current, voltage and frequency of the primary signals were kept constant. The amplitude of the non-linear mixing terms did not vary when changing the number of electrode pairs, implying that the current density immediately around the input electrodes probably did not impact on the response of the sample.
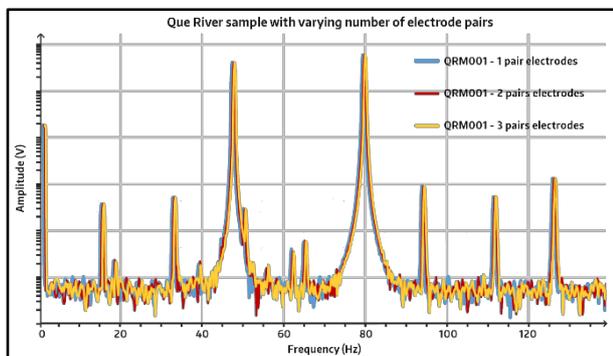
Figure 1. Response profile of Que River Mine sample with varying number of electrode pairs.

All samples used for testing were evacuated and stored immersed in water. The samples were removed from the container and excess water was wiped off before being placed on the measurement array. Testing was undertaken on the response of a sample immediately after being removed from the water and subsequently while remaining on the array for a period of half an hour. The absolute value of the mixing terms was stable for these tests, as shown in Figure 1. However, with a constant current source, the value of the primary signals increased as the rock dried, due to the increasing rock resistivity. Thus, the normalised mixing ratio (mixability), which is the mixing term amplitude (x1000) divided by the average primary signal, may be inaccurate for tests on laboratory samples. This parameter has been used in these tests but for future laboratory tests, which do not involve comparisons between samples, the raw mixing amplitudes may be more appropriate. For testing which involves comparison of different samples, it is necessary to normalise by the primary signals to allow for the different resistivities of the samples. If a normalised value such as mixability is calculated, then it is important to check for consistency of surface moisture in the samples to allow for the resistivity of the sample.

Frequency Dependence Testing

Following laboratory tests of the heterodyne methods in Oertel et al. (2018) and field tests in White et al. (2018), where

different primary frequencies were used, thorough testing was undertaken to determine whether the heterodyne mixing terms were subject to frequency dependence. Testing on samples from Que River and Kempfield with primary frequencies ranging from 47 to 480 Hz revealed little or no consistent frequency dependence in the amplitude of the mixing terms.

This finding is critical for future field tests, as it allows equipment to be designed without uncertainty around optimal frequency of the primary signals.

No attempts were made in this study to determine the phase of the secondary signals relative to the primary inputs. This will be the subject of future tests as the relative phases of the detected signals may contain information relevant to the discrimination of different types of linear or non-linear conduction and hence leading possibly to mineral species discrimination.

Tests on Samples without Bias

The sulphide-rich sample from Que River was cut into three pieces, and the non-linear response of each was measured and analysed. The results of measuring the three samples are shown in Table 1 below. Despite the three pieces being cut from the same sample, the strength of the primary signals, mixing terms and resultant mixing ratio varies significantly. This is quite indicative that heterogeneity on the small scale of the samples used in these tests can cause a large variance in the data. This is a common feature of laboratory tests of field geophysical techniques

Table 1. Response of Que River Mine sample with varying primary signal amplitudes.

F1 (47 Hz)	F2 (80 Hz)	M1 (33 Hz)	M2 (127 Hz)
2.9E-02	2.9E-02	2.2E-05	5.6E-05
2.9E-02	1.4E-02	1.4E-05	3.2E-05
2.9E-02	7.1E-03	8.2E-06	1.7E-05
1.4E-02	2.9E-02	1.2E-05	3.2E-05
1.4E-02	1.4E-02	7.7E-06	1.9E-05
1.4E-02	7.1E-03	5.4E-06	1.1E-05
7.1E-03	2.9E-02	6.9E-06	1.8E-05
7.1E-03	1.4E-02	4.5E-06	1.1E-05
7.1E-03	7.1E-03	3.3E-06	7.0E-06

A Que River sample was tested to determine the effect of the relative amplitudes of the two primary signals. The lowering of either primary signal decreased the amplitude of mixing terms as expected. The resulting mixability values, however, appeared to depend on the total primary signal even after normalisation. Table 1 shows the sum and difference mixabilities for a range of ratios of primary signal. It is clear that there is still some dependence on the total primary signal even after normalisation. The measured mixabilities depended on the total signal but were relatively unaffected by the proportion of one primary relative to the other. Since the mixing effects are a product of non-linear conduction, this is not surprising, but the result does have significance for both laboratory and field testing. In the laboratory, the results are dependent on the current density, making them somewhat questionable, given that the current densities are several orders of magnitude greater than would be experienced in the field. In the field, it may be necessary to ensure that the current densities are relatively uniform over the area of the survey. On

the positive side, the dependence of the effects on the current density may mean that more information may be gathered in the field by surveying with a range of transmitter currents. At this stage, the relevance of the effects of current density are unknown.

Tests on Samples with Bias

The mixability parameters for a range of drill core samples from the Kempfield prospect were measured to determine whether a DC bias would strongly affect the generated heterodyne signals. Six drill core samples with varying sulphide content were tested with a wide range of DC bias. For two of the samples, the primary currents were also attenuated by a factor of 10 (from 0.8 mA to 0.08 mA) to examine whether bias effects were different at different primary signal strengths.

Unfortunately, the experimental setup only allowed relatively large increments for the bias signal which resulted in bias current densities far higher than would be obtained in the field, and ambiguous results. These tests will need to be repeated in a more sophisticated, low noise environment using both primary and bias currents orders of magnitude lower than was possible for these tests.

Despite these problems, some relevant information was obtained from these tests. In particular, the dependence of the mixability on sulphide content, as found previously by Oertel et al. (2018), was confirmed. The strong dependence of the measured mixability on the current density, as determined in the tests without bias, was also confirmed. The general rise in the mixability values with increasing DC bias was suggested by these tests, but this was not conclusively proven. Further laboratory and/or field tests will be required to conclusively determine the effect of a DC bias on the heterodyne signals.

Figure 2 shows the results of the bias testing for a representative sample (Sample 95) from Kempfield with low sulphide content.
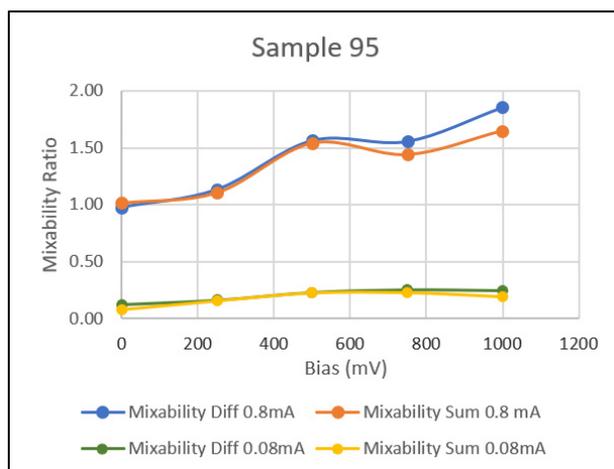

Figure 2. Plot of positive and negative mixability ratios for sample 95 with primary frequencies transmitted at 0.8 mA and 0.08 mA.

As can be seen from these data, there is a general increase in the mixability parameter with increasing DC bias but at low primary signals; this result is not conclusive. The effect on the mixability parameter of reducing the primary current is immediately apparent, with mixabilities for the lower primary

current being an order of magnitude lower than for the higher current. Interestingly, for this sample, the drop in mixability is proportional to the drop in current density. This suggests that at the current densities used in a field environment, the mixability values may be of a very low magnitude. It is not clear whether this is a general principle. Although field tests by White et al. (2018) indicate that mixability is readily measurable despite the low current densities in the earth.

Results show that at relatively low current densities the bias has little effect in some samples. At higher currents the bias has the effect of increasing the heterodyne signals. It may be that some parameter of the electrical conduction within the samples reaches a linear / non-linear limit at higher currents. This may be an exotic non-linear effect or possibly even non-linearities in the IP polarisation in these samples. It is not clear whether these observations are relevant at the low current densities observed in a real field environment. Further testing will require significantly lower current densities, which in these tests, are four orders of magnitude greater than would be expected in a field situation. Such testing will require a very low noise environment (shielding), as was done by White (1974).

CONCLUSIONS

We have undertaken these tests not only out of scientific interest, but because we wish to develop and apply the biased and simple heterodyne methods as possible discriminatory tools in sulphide mineral exploration. These tests were designed to further constrain the factors, determining the style and magnitude of responses we may detect in the field.

The greatest challenge for our controlled tests has been that the current densities that are feasible to use on small samples are several orders of magnitude greater than would be attainable in field operation. Also, the non-uniform nature of the rocks which are used in laboratory tests may be unrepresentative of what would be obtained when the secondary signals are averaged over large volumes in the field. The samples used for these tests are heterogeneous at the scale of tests and can be subject to highly variable effects from current channelling, uneven drying, contact resistance and crystal structure. By taking small samples as analogues for larger in-situ units, the laboratory setting exacerbates these effects.

While we have made progress in constraining some of the controls, such as the independence of the response from the frequency and the effect of increasing the surface area of the electrodes, detailed investigation of the complex interaction between the controlling parameters for this method will require considerable future effort and ultimately may not be possible in laboratory tests. Sample heterogeneity and current densities used in the laboratory tests may be incomparable to a field setting, due to the problems of replicating field conditions in small samples. However, laboratory tests have generated some understanding as to the parameters that are relevant to field testing. In particular, the apparent independence of the secondary mixing signals from the frequency of the primary signals is an important result for practical field operations.

The heterodyne methods have the potential to provide new insight in geophysical exploration, and to further develop as a new geophysical tool in mineral exploration. However, testing

may need to progress on the scale of the true mineral exploration setting, that is, in a field environment.

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