

# Laboratory Confirmation of Non-Linear Electrical Effects in Mineralised Rocks

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## **SUMMARY**

Induced Polarisation (IP) and Transient Electromagnetism (TEM) are among the most widely used ground electrical geophysics methods in Australia, being specialised in detecting conductive and chargeable targets such as sulphide deposits. A key challenge of IP & 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. As these shale deposits are undesirable targets, distinguishing by physical methods such as drilling is exhaustive on exploration resources.

Graphite-rich shales, which plague induced polarisation surveys, cannot be distinguished from sulphide mineralisation by existing electrical methods. 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. There is some evidence that shales produce a strictly linear response. This contrasts to the non-linear response of sulphide-rich rocks which generates additional signals in the frequency domain.

A laboratory-based reinvestigation into non-linear properties of sulphides has been undertaken with a view towards field application. Variable frequencies and signal strengths were used to validate the method, based initially on the processes described in White (1974). The intermodulation mixing terms produced as a response by sulphide mineralised deposits in this laboratory-based investigation may allow for electrical distinction of sulphides from non-mineralised shales and clays.

The application of a direct current (DC) bias to either signal increased the detectability of non-linear responses, allowing for a lower current density threshold for measurement. The magnitude of the non-linear signal detected provides a basis for field testing of this previously unutilised electrical property, with the eventual aim of providing a method for greatly reducing the number of drill targets barren of mineralisation.

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

## **INTRODUCTION**

The discrimination of sulphide mineralisation from other conductive and chargeable rock types has plagued mineral explorers since the rise in popularity of electrical geophysics. White (1974) proposed that it should be possible to distinguish sulphides by the non-linear semi-conducting nature of sulphide grains. He concluded that it may be possible to discriminate between minerals by the linearity of a response signal. Until now this proposal has not been successfully followed up, as it had been deemed technically infeasible to apply the technique to exploration in the field.

The potential for the discrimination of minerals through electrical geophysics is immense. Exploration for sulphide mineralisation is primarily carried out using IP which measures chargeability, or electromagnetic methods which measure conductivity. A key limitation of these methods is the variety of geological compositions which produce both a chargeable and conductive response. Specifically, sulphides and graphitic shales are within the same range for both chargeability and conductivity. The former is a highly sought spectrum of potentially economic mineralisation types, while the latter is most commonly considered to be a negative outcome. Currently the only method of discrimination between these rock types is the expensive and time-intensive process of drilling.

This paper reports an attempt to replicate the original laboratory outcomes of White (1974), in order to make a case for field testing of the method using more advanced signal transmitting and receiving technologies which are now available, when compared to those available in 1974.

The detection of semi-conducting non-linearity is through the presence of frequency “mixing terms”. These terms are generated in non-linear conductors in the presence of two non-harmonically related frequencies. The presence of these mixing terms is the key indicator that the material being tested is semi-conducting in nature. In terms of chargeable and conductive mineralisation, this method may allow for the distinction between linearly conductive graphitic shales and non-linear semi-conducting disseminated sulphides, with the potential to reduce the number of electrically identified drill targets.

## METHOD

A series of experiments were conducted to replicate the results of White (1974) and to detect the difference in conduction linearity between rock samples with high and low sulphide concentrations. The experiments were conducted at the CSIRO Lindfield site using samples provided both by Peel Mining from the Mallee Bull prospect and high-sulphide samples from Toorong Resources.



Figure 1: Sample MBDD024 attached to electrode board. Clamps ensured firm and even contact with electrodes.

The experimental setup was based on the original experiments conducted by White. Two, non-harmonically related, equal voltage amplitude sine wave signals were generated in separate oscillators, linearly combined via an operational amp summing circuit and the resultant signal used to drive a voltage controlled current source (Stanford Instruments CS 580). The output of the current source, which has an adjustable amplitude control, was then injected into the rock sample through a pair of conductive rubber coated electrodes. A voltage difference signal, measured across a second pair of rubbed coated electrodes that contacted the rock and were placed between the current pair of electrodes, was recorded by an analogue to digital converter (ADC). Voltage differencing provided some reducing of any common mode signals, e.g. mains signal pickup. The rock sample was evacuated and soaked to simulate ground conditions, coated to improve water retention, and clamped to the electrode board to ensure even contacts, as shown in Figure 1.

The chosen frequencies had to be non-harmonically related to each other to allow detection of any mixing terms. The mixing frequencies are derived from the addition and subtraction of the primary frequencies and their harmonics. This is shown in Figure 2 below.

If the primary frequencies were to be harmonically related to each other, e.g. were selected to be 10Hz and 20Hz, then every possible addition and subtraction product of these two frequencies is a harmonic of the lower frequency, and so the mixing terms will be undetectable. For this experiment, the sine wave transmitters had adjustable frequencies, and several frequencies were tested to ensure the validity of the method. The testing of the rock samples and results contained herein were for primary frequencies of 47 Hz and 80 Hz. The mixing terms for non-linearity with these frequencies occurred at 33Hz and 127Hz.

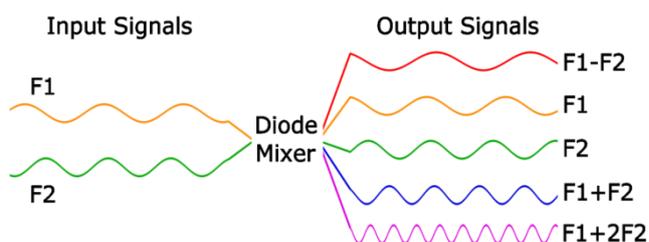


Figure 2: Heterodyne mixing products of non-linear conduction.

The application of a DC bias to the system is a key component of the BiasedHeterodynemethod. A DC bias increases the non-linearity of the response of weak semi-conductors, as outlined in White. In the presence of a bias, the amplitude of the mixing frequencies is increased without increasing the amplitude of the primary signals, so the signal-to-noise resolution is increased.

Three rock samples were used for this experiment. The first sample, designated MBDD024, was a heterogeneous sample of massive chalcopyrite. The dark grey host rock also contained disseminated sulphides. Sample two, designated 444-444-2, a siltstone containing a low percentage of disseminated sulphides. The third sample used, designated TASBW1, was a hydrothermally altered host rock containing a high percentage of disseminated sulphides. In addition to the samples, two controls were used in the same setup to ensure the validity of the method: a wire wound resistor with completely linear response profile and a diode with a highly non-linear response profile. These controls were measured at the start and end of every test to confirm that the equipment was functioning optimally and no spurious mixing terms were present.

Fast Fourier Transform (FFT) computer code was used to transform the raw time series data into the frequency domain. The signal peaks were integrated over their width to ensure that the full strength of the primary signals and the mixing terms were measured.

The laboratory equipment allowed for control of the frequency of the primary signals, their individual contributions to the current drive level and the amplitude of the DC bias applied to the rock samples. The most significant uncontrolled variable for these experiments was the resistivity of the samples.

## RESULTS

The initial testing of the setup was done using the two control samples: a wire wound resistor and a diode of similar resistance. 64 seconds of data for each sample was Fourier transformed in order for the frequency domain to be examined. In the case of the resistor, the only signal peaks were the primary frequencies of 47Hz and 80Hz, the residual, common mode, background mains power signal of 50Hz, and harmonics of all these frequencies. No mixing terms were present. Conversely, in the frequency domain of the signal recorded for the diode, all possible heterodyne frequencies for the primary signals and their harmonics were present as

high-amplitude peaks. This control test confirmed that the system was able to detect non-linearity and that no spurious mixing terms were present in the equipment.

The three rock samples were tested using 10mA peak currents. Difference signals developed across two voltage probes were recorded with a 31-bit ADC. The frequency spectrums for the three samples are shown in Figures 3 to 5.

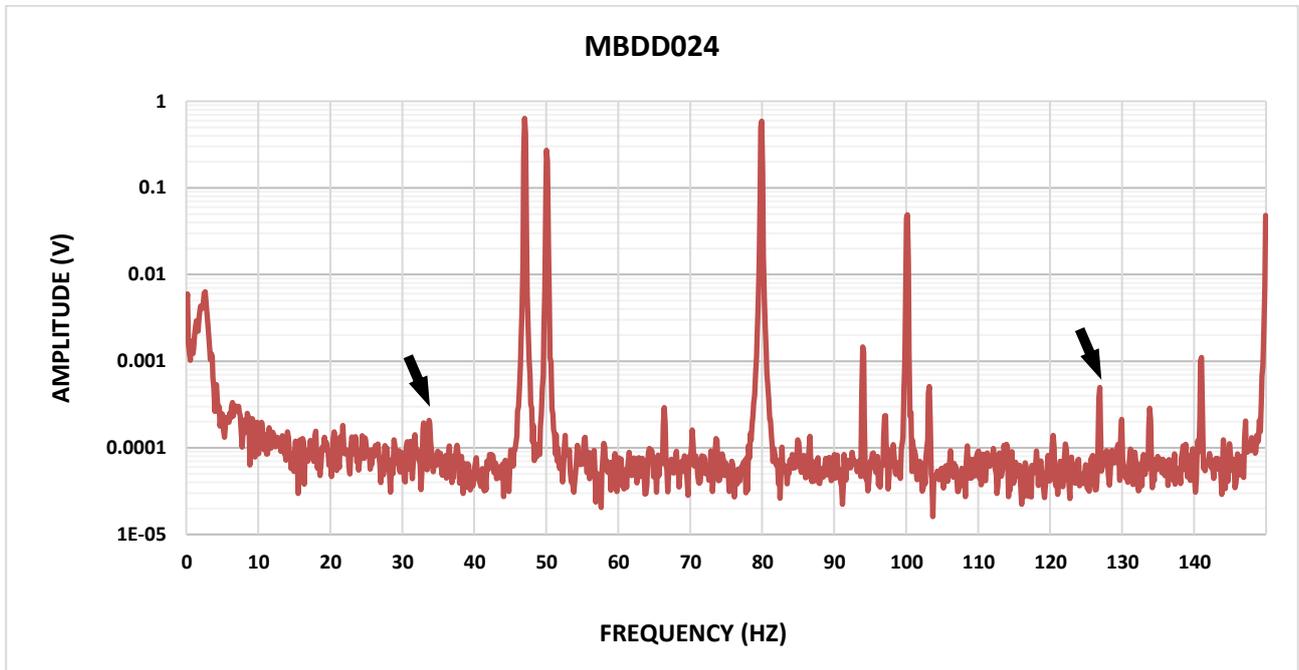


Figure 3: Frequency spectrum of sample MBDD024. Mixing terms as indicated at low amplitude indicating low sulphide concentration.

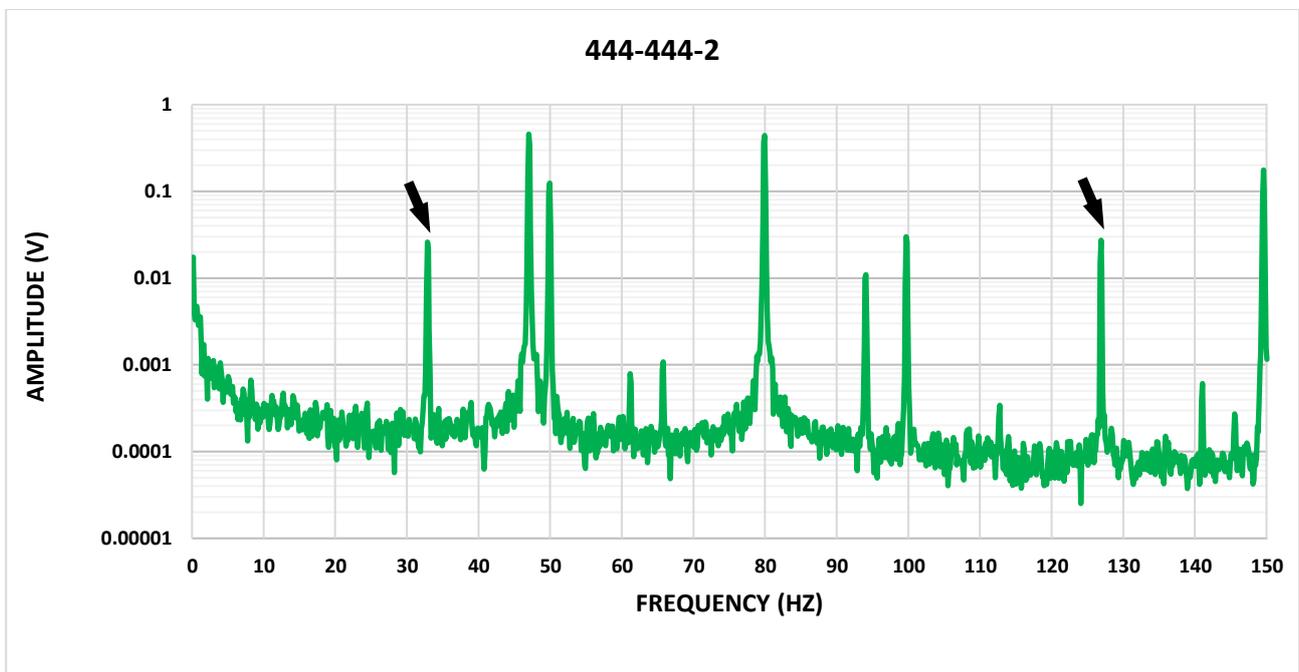


Figure 4: Frequency spectrum of sample 444-444-2. Mixing terms are indicated showing a high concentration of sulphides.

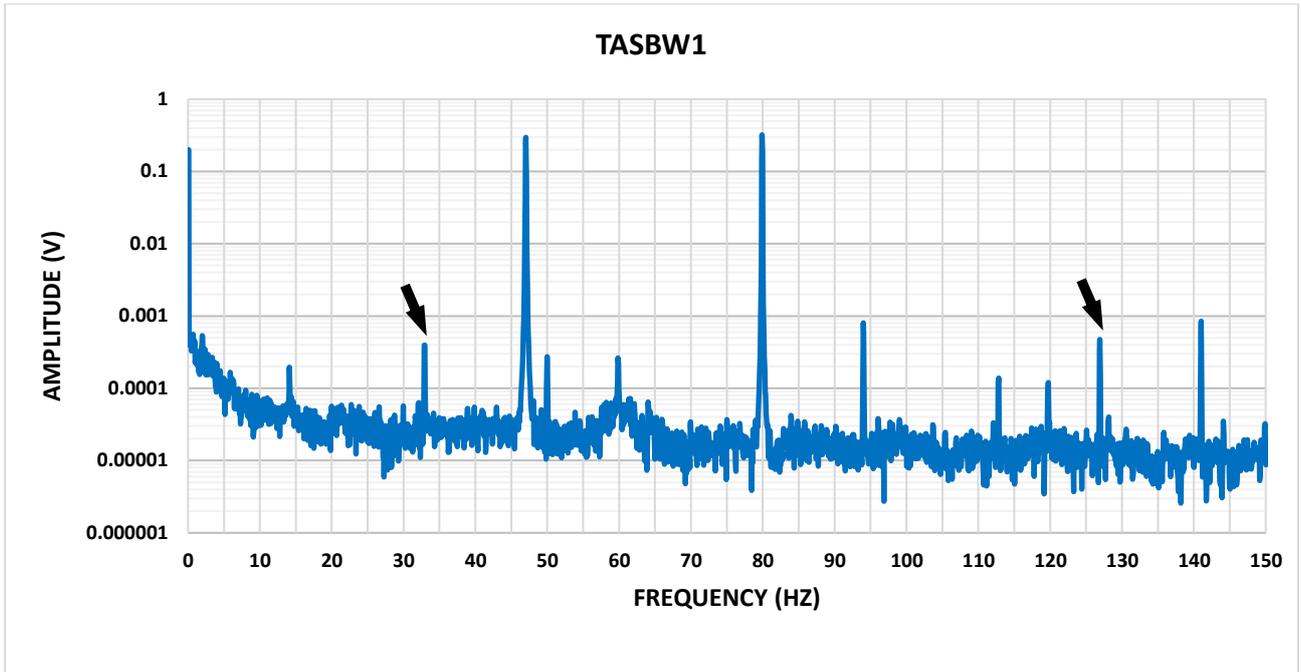


Figure 5: Frequency spectrum of sample TASBW1. Mixing terms are indicated showing a moderate concentration of sulphides.

In all three samples, the frequency peaks were clearly visible at the primary frequencies of 47 Hz and 80 Hz, as well as the additional peaks at 50 Hz, and the harmonics of the primary frequencies. The mixing term frequencies at 33 Hz and 127 Hz are indicated with arrows in the Figures 3 to 5 above. It can be seen that the peaks are present in all three samples. As all three samples contained sulphide minerals in differing proportions, these results when compared to that of linear wire wound resistor, confirmed the existence of non-linear mixing effect in these rocks. The sample MBDD024, which contained sulphide minerals in a much lower proportion to the other samples, had significantly lower amplitude of mixing terms compared with the other two samples, suggesting that the higher proportion of sulphides correlated to a greater amplitude of the mixing terms.

Sample	Ratio without Bias	Ratio with Bias
MBDD024	0.34	0.65
444-444-2	22.6	57.1
TASBW1	0.64	1.55

Table 1: Comparison of mixing ratio with and without bias.  

$$\frac{((V_{33}+V_{127}) * 1000)}{(V_{80}+V_{47})}$$

The amplitude of the heterodyne frequency was normalised to that of the primary frequency, and the resulting ratio was compared for the three samples with and without the presence of a DC bias. The presence of a DC bias in the system increased the amplitude of the mixing terms without increasing the amplitude of the primary frequencies. A comparison of the mixing terms for each sample with and without the application of a bias is shown in Table 1

In an environment where the signal to noise ratio is comparable to the ratio of the mixing terms to the primary signal, the increase in mixing term amplitude caused by the DC bias may be instrumental in identifying the presence of the heterodyne frequencies and therefore the presence of semiconducting sulphide grains.

## DISCUSSION

The results of this study are comparable to those by White. Rock samples containing sulphide mineralisation clearly exhibit the anticipated non-linear conductive response. The study showed that the higher the proportion of semiconducting sulphide minerals, the higher the ratio of the mixing terms to the primary signals. This directly supports the original work by White and warrants further investigation into potential applications of this method for mineral exploration by conducting a field trial.

Some difficulties in conducting these laboratory tests had to be overcome to provide confidence in the reported results. The possible presence of the generation of spurious mixing signals from within our equipment was a constant concern, which warranted daily testing of the controls of the wire wound resistor and the diode. For sample MBDD024, which had with the lowest amplitude of the mixing terms, the noise floor of the transmitters and the ADC was close to the amplitude of the mixing terms, making resolution at lower current densities unfeasible. The rock samples used were also heterogeneous and displayed zonation, which affected the repeatability of the experiment. Experiments were repeated many times in order to validate the final conclusion of our results. Other samples were tested, however in some cases where the resistivity of the sample was high; the input impedance of the equipment being used became an issue. Spurious terms were generated as a result. Further work is needed to refine this method for a wider range of sample resistances.

The results warrant a significant amount of further study. There is potential for improving the method through the development of specialised equipment. Field testing of the method for geophysical exploration is needed, with early tests being outlined in White et. al 2018 (this volume). Further experimentation using additional samples is ongoing.

## **CONCLUSIONS**

The experimental results of this laboratory study indicate that non-linear mixing of two, non-harmonically related, transmitter signal frequencies should be viable as a new electrical technique for geophysical exploration. The potential for this technique for detecting non-linear conduction has exciting implications for the future development of electrical geophysics. Mineral discrimination by electrical methods between sulphides and graphitic shales, previously indistinguishable by geophysical methods, may be possible through the detection of frequency mixing in semi-conducting sulphide grains. The application of a DC bias to the system may further increase the detectability of the mixing frequencies.

Further work is needed, with a greater selection of samples, to further constrain the parameters for discrimination. Field testing of the method is needed to develop this technique as an entirely new method of geophysical exploration.

This study has determined that, as first shown by White (1974), it may be possible to detect non-linear conduction in sulphide bearing rocks and use this to discriminate between mineral accumulations with similar conductivity and chargeability based on the semiconducting non-linear response of sulphides present in the rock.

## **REFERENCES**

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