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An Airborne Heterodyne Sulphide Exploration Test at Kempfield

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SUMMARY

We continue to investigate an ancillary method to Induced Polarization for sulphide exploration, using analysis to measure heterodyne effects in time-domain Airborne Electromagnetic data. We investigate how a parameter named mixabity can characterise these effects in terms of frequency content and composition, finding that with sufficiently low noise levels, heterodyne effects could theoretically be observable in time-domain AEM data.

Analysing existing AEM survey data, we earlier found no spatial correlation between known sulphide distribution and mixability. We postulated that this is because potential heterodyne effects due to sulphides were being masked by two different limitations of the survey dataset we used; firstly, variable transmitter waveform asymmetry; and secondly, the decreasing signal levels from the fixed a ground-loop transmitter resulting in increasing relative noise levels away from the transmitter. We therefore conducted a airborne Slingram EM/IP survey with the BIPTEM system to address the identified limitations of existing test data.

We present results from an airborne test at Kempfield, the test site for definitive ground tests of the heterodyne method for sulphide detection. The small mixability anomalies detected in the airborne data were not consistent with either drilled sulphides or mapped IP anomalies.

Key words: Induced Polarization Heterodyne Sulphide Airborne Electromagnetic Kempfield

INTRODUCTION

The non-linear electronic behaviour of sulphides has been well-studied in the laboratory (Shuey, 1975). Most sulphides are semiconductors, and electrical conduction between grain boundaries will usually show evidence of a directional bias, identical in concept to the physics of semiconducting p and n junctions in transistors. Recent papers (White et al., 2018; Oertel et al., 2018, Collins et al., 2022, White et al., 2023) present evidence that the known non-linear behaviour of sulphides may be detected in the field to discriminate sulphides with semiconducting grains from graphitic rocks.

The ground studies reported by White et al, used two separate injected currents at different frequencies; injected into the ground by pure sine-wave generators. Heterodyne effect detection relied on non-linear effects from frequency mixing to detect th8isa distinctive sulphide conductivity behaviour. In his talk in 2022, Steve Collins suggested that since the heterodyne effects were independent of frequency, the methodology could usefully be used in airborne electromagnetic geophysical methodology.

SULPHIDES, SEMICONDUCTORS, HETERODYNE

Sulphides are semiconductors (Shuey, 1975), and ores usually contain billions of grain boundary junctions (Figure 1). Individual grains may have different impurities and be effectively p or n "doped". In bulk, these junctions may preferentially favour current flow in one direction rather than the other, leading to asymmetric current flow and voltage responses to symmetric, alternating, background electrical fields (Figure 2).

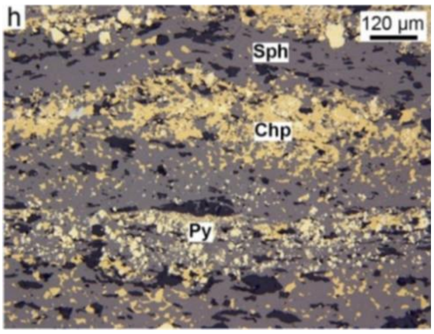

Figure 1: Example massive Sulphide structures. (Maslennikov et al, 2019)

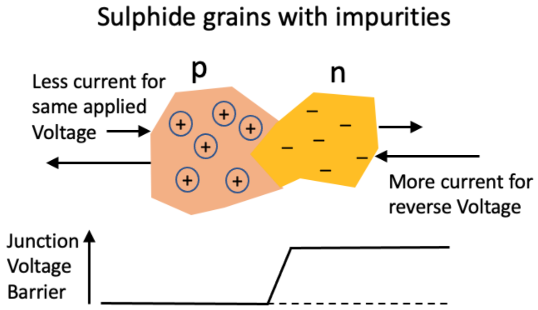

Figure 2: Semiconductor conductivity physics

The physics of semiconductor junctions has seen extensive use in radio, where the term heterodyne was used when two separate signals at different frequencies were used to create a beat. The term superheterodyne is used when frequency mixing and band-limited amplification extracts a signal at a fixed intermediate frequency. In the ground, the methodology used by White et al and Collins et al to detect non-linearities in sulphides transmits two low frequency signals into separate electrodes and looks for responses at mixed frequencies. Laboratory studies (Oertel et al, 2018, Oertel, 2019) confirm that mixed frequency signals are located when significant sulphides are present, but not otherwise (Figure 3, at end of abstract).

Sulphides have frequency-dependent conductivities usually modelled with the Cole-Cole equation. When this behaviour is combined with the effect of junction non-linearities, some of the mixed frequency responses are reduced in amplitude (Figure 4). The largest secondary amplitudes (at 10 and 100 Hz) mixed from the source frequencies being 55 and 45 Hz are somewhat affected by including a Cole-Cole response as well as the heterodyne mixing, but still remain the optimum search targets from a frequency analysis for the presence of heterodyne effects.

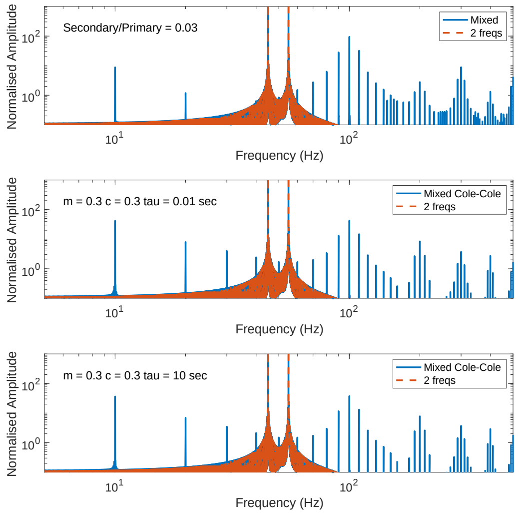

Figure 4: Relative amplitude modulations of the 'pure' mixed frequencies (top) are modified if Cole-Cole IP effects are also present. Source frequencies of 45 and 55 Hz in this simulation.

HETERODYNE EFFECTS IN TIME DOMAIN

Collins et al (2020) suggested that the lab and ground survey concepts could be extended to AEM as they are frequency independent at local grain level. To do so on existing data, we investigated what the time domain equivalent to the mixing in a superheterodyne response might be.

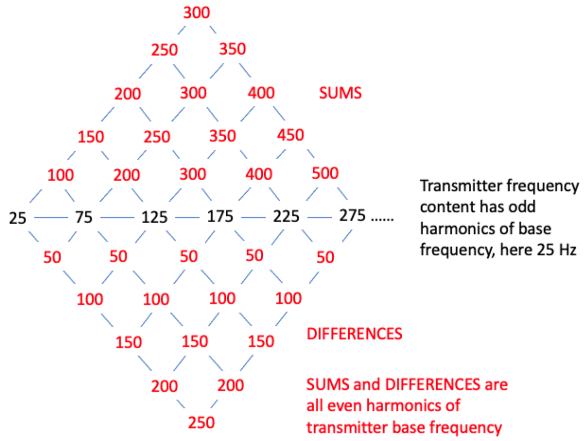

Figure 5: Mixed additive and subtractive frequencies from non-linear response to a 25 Hz repetitive waveform. The heterodyne frequencies in this case are all harmonics of the 50Hz powerline frequency, and as such not a useful detection frequency in Australia.

Taking the Fourier transform of 25 Hz base frequency data shows that the waveform consists only of odd harmonics of the base frequency, i.e. 25, 75, 125, 175 … Hz. In an fft, there is an upper limit to the odd harmonics just less than the Nyquist (sampling) frequency. A non-linear process is expected to produce new frequencies at the sums/differences of the transmitter waveform's odd harmonics. Figure 5 shows that all the simple sums and differences lie at the even harmonics of the transmitter base frequency. More convoluted differences such as f3 = (2f2 – f1) lie on odd harmonics. It was clear to us that in Australia, 50 Hz and its harmonics are undesirable frequencies to look for small effects, so ubiquitous 25 Hz airborne AEM data unless located far from infrastructure was likely to be of limited value. We therefore looked for some 12.5 Hz data. Note that as implemented in frequency domain, the mixing frequencies are not harmonics of either of the primary frequencies.

In the simple case of a 50% duty-cycle square wave current, a perfect p-n junction inhomogeneity appears as a reduction in amplitude on one half of a secondary in-phase with the primary B field. Taking the fft of this modified response for a 12.5 Hz base (Figure 6) leads to a very interesting result. When phase information is included, half of the predicted even harmonics are not evident. The primary field is evident at 12.5, 37.5, 62.5, 97.5 … Hz, and the heterodyne effects are seen at 25, 75, 125, 175 … Hz. This is a set of odd harmonics of the first even harmonic of the base frequency, called even-odd harmonics later in the paper.

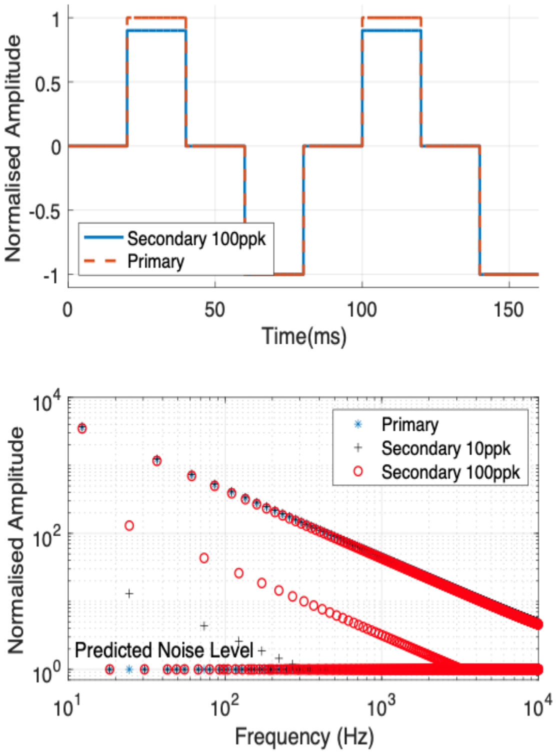

Figure 6: (Top) Plot of time domain 50% duty cycle with 12.5 Hz base frequency. A non-linear secondary B field of amplitude 10% (100 parts per thousand) of the primary field is plotted and reduces the observed field on the positive transmitter cycle. (Between harmonics at 25, 75, 125, 175 … Hz These signals do not compete with the powerline harmonics and should be detectable in data if (a)

superheterodyne effects exist and (b) the noise level is low enough.

FIELD TEST

During testing of the BIPTEM system at Kempfield, we had the opportunity to use the acquired data to measure mixability over 4 profiles. Similarly to the ground field results of Collins et al (2023), our airborne data did not show any evidence of significant mixability effects. While small variations (between 0.3 and 0.5 ppk above background are seen, these did not correspond to sulphides in the initial analysis,. Whose intrinsic mixabilities were in the 10 to 100 ppk range.

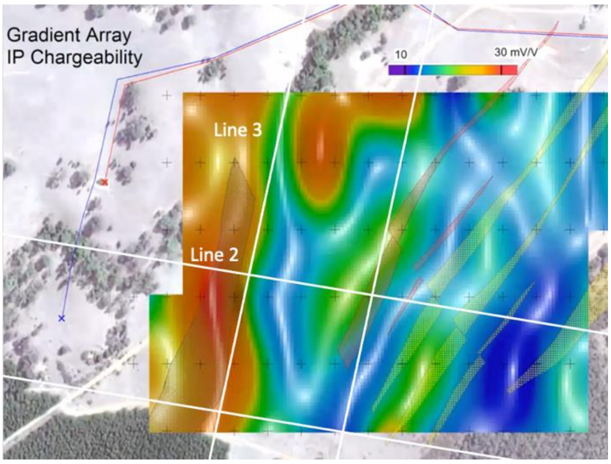

Figure 7: Gradient Array IP (Collins et al., 2022) with location of BITTEM flightlines 2 and 3.

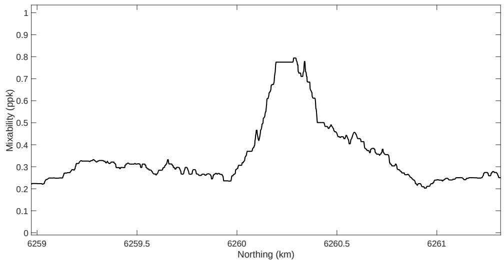

Figure 8. Mixability of the 25 Hz signal on Line 3 at Kempfield. All measured values are less than 1 part per thousand and do not correspond to IP responses or drilled sulphides.

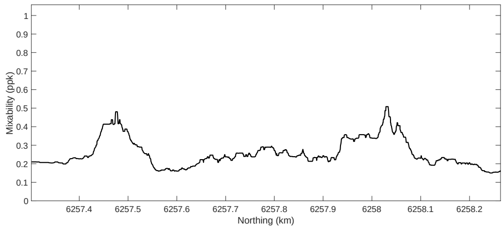

Figure 9. Mixability of the 25 Hz signal on Line 2 at Kempfield shows lower amplitude than on Line 3.

CONCLUSIONS

Mixability (a measure of non-linearity in electrical response) clearly occurs in Kempfield drill-core samples, but measurements using streamed airborne data did not show any useful characterisation of known sulphides or mapped IP effects.

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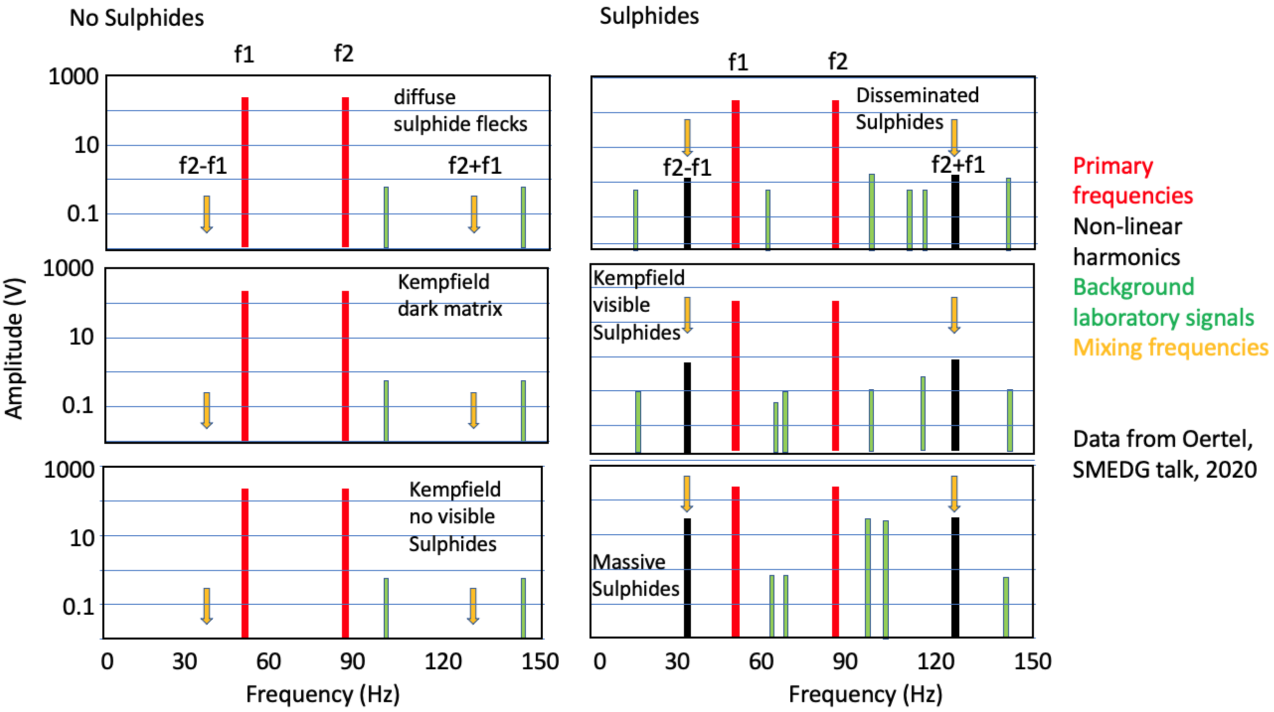

Data from Oertel, SMEDG talk, 2020

Figure 3. Figure 3: Laboratory testing of cores by Oertel (2020) shows that significant mixing responses at the difference and sum of the two source frequencies inly occur when significant sulphides are present. Note that the vertical logarithmic scale has 5 decades so covers a 100,000 to 1 amplitude range. Mixability values between 10 and 100 ppk (parts per thousand) were seen in sulphides.