TEMPEST electromagnetic transmitters with multiple loops and multistep waveforms

Andrew Sunderland
University of Western Australia
35 Stirling Highway Crawley WA Australia
andrew.sunderland@uwa.edu.au

Eric Steele
Xcalibur Multiphysics
10 Compass Road Jandakot WA Australia
eric.steele@xcaliburmp.com

SUMMARY

The vertical resolution of airborne electromagnetic systems is limited by the earliest time window and how fast the transmitter current can transition. Presented is how transmitter loop geometry and different transmitter waveforms could decrease the transmitter ramp time by up to a factor of 8.

Key words: transmitter, electromagnetic, resolution, waveforms.

INTRODUCTION

Good vertical resolution is needed for electromagnetic surveys trying to delineate structural boundaries between layers such as mapping saltwater/freshwater interfaces (Viezzoli et al, 2012). Good vertical resolution comes from early delay time measurements taken immediately after the transmitter current is switched off (Skurdal et al, 2020). However, the earth response immediately following a linear turn-off ramp is smeared out over a time scale proportional to the duration of the ramp. The vertical resolution is (Spies, 1989):

$$\text{vertical resolution in meters } = 0.55\sqrt{\frac{2\rho\Delta t}{\mu}} \qquad (1)$$

where Δt is ramp time, ρ is the resistivity of the ground, and μ is magnetic permeability.

Inductance and voltage set how fast the transmitter current can be ramped down $\Delta t = L \cdot \Delta I/V$. Excessive voltages V can overload the semiconductor switches or cause electrical arcing. Previous efforts by the industry to achieve a quick turn off time have come at a cost of lower transmitter current I and consequently reduced depth penetration. This paper presents a transmitter loop with lower inductance L and demonstrates how to replace a large current step ΔI with several smaller current steps.

MULTILOOP

Figure 1 compares a single loop transmitter with a multiloop transmitter layout using 2 parallel half loops with the same overall area. Let I_0 be defined as the current in a loop and L_0 as the inductance of a single loop. Baum (2005) showed that for a subdivided loop:

$$\text{current provided by electronics, } I = N_p I_o \qquad (2)$$

$$\text{inductance presented to electronics, } L = L_0/N_p^2 \qquad (3)$$

$$\text{ramp time, } \Delta t = LI/V = L_o I_o/(N_p V) \qquad (4)$$

The ramp time Δt is thus inversely proportional to the number of subdivided loops in parallel N_p.

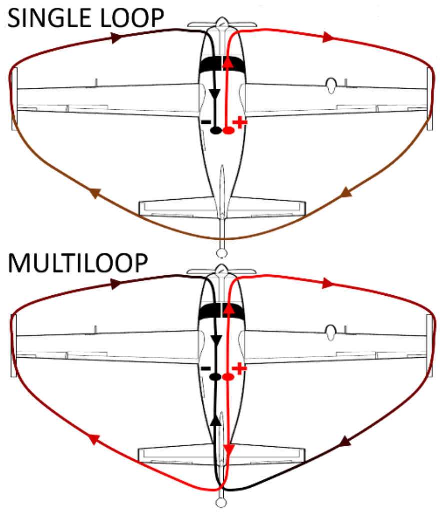

Figure 1. Single and multi-loop transmitter layouts. Current flows from + to -.

Transmitters with parallel sub-loops have previously been used in ground geophysics (Guo et al 2010), but not in airborne exploration.

MULTISTEP

Figure 2 shows multistep transmitter waveforms which have the same transmitter moment $m = NI_{rms}A$ as a square wave. Large current steps have been replaced with smaller but more frequent current steps ΔI and shorter ramp times Δt. The ramp time of a multistep waveform is:

$$\Delta t = \frac{L \cdot \Delta I}{V} = \frac{2LI_{rms}}{V\sqrt{s}} \qquad (5)$$

where s is the number of current steps per half cycle.

Fourier transforms of the multistep waveforms are presented in Figure 3. Billions of multistep waveforms were examined with a computer program and only a small number of waveforms were found to have spectra matching a square wave. The multistep waveforms shown here have amplitudes that are identical to that of a square wave and only the phases of the spectrum need to be adjusted to align with that of the perfect square wave, and whereby no noise is added.

For a system using a multistep waveform, the ground response signal can be de-convolved into to a 100% duty cycle square wave, by using this formula or similar (Legault et al, 2012):

$$V_{sq}(f) = \frac{I_{sq}(f) \cdot V(f)}{I(f)} \qquad (6)$$

where $V(f)$ is the Fourier transform of the receiver voltage, $I(f)$ is the Fourier transform of the transmitter current, $I_{sq}(f)$ is the Fourier transform of an ideal square wave transmitter current, and f is frequency. This transfomation allows a single transient decay to be presented which is easy to interpret (Lane et al, 2000). A multistep waveform with 2 steps per half cycle is currently used in TEMPEST (Lane et al, 2000).

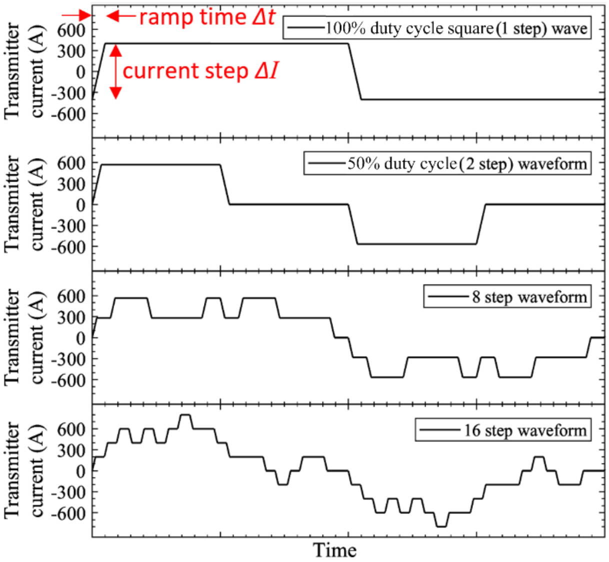

Figure 2. Multistep transmitter waveforms with identical rms currents I_{rms} and ramp rates $\partial I/\partial t$. The higher order waveforms have more steps per half period, smaller current steps ΔI, and smaller ramp times Δt.

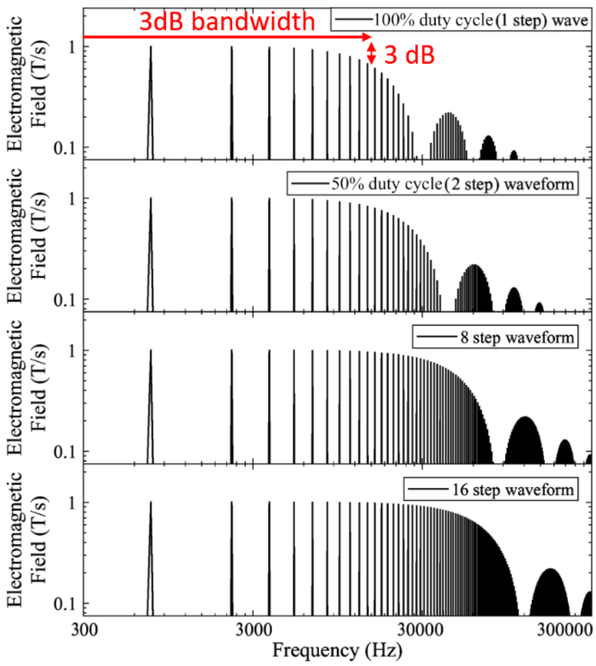

Figure 3. Fourier transforms of the waveforms shown in figure 2. The waveforms shown here are comprised of only odd harmonics of equal amplitude, up to a bandwidth of the transmitter. The higher order waveforms have a wider 3dB bandwidth due to shorter ramp times.

IMPROVED MAPPING

Combining multistep $s = 16$ current steps (Equation 5) with multiloop $N_p = 2$ (Equation 4) could decrease the ramp time by a factor of 8:

$$\Delta t \propto \frac{1}{N_p\sqrt{s}} \tag{9}$$

Electromagnetic waves diffuse downward as per the square root of time, depth $d = \sqrt{(2t\rho/\mu)}$. Figure 4 shows the mapping capability of an electromagnetic system which is limited by its earliest and latest time t windows. A system with 8 times lower ramp time will have √8 better vertical resolution (Spies, 1989).

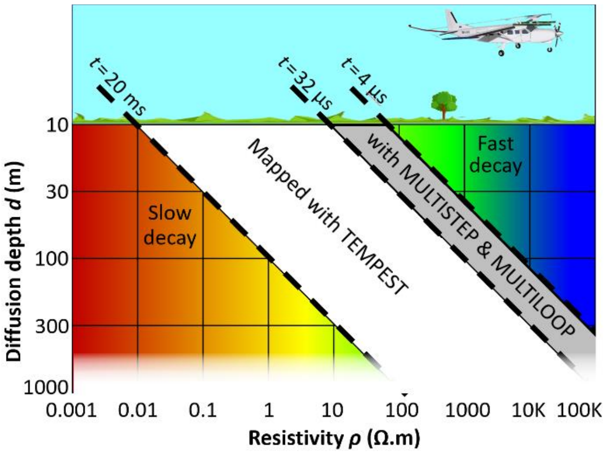

Figure 4. The minimum depth (vertical resolution) and maximum depth of a typical airborne electromagnetic system depends on the earliest and latest time windows and varies with the resistivity of the ground. The grey parallelogram shows the additional shallow and resistive geology that might be mapped with multistep and multiloop.

CONCLUSIONS

Multiloop geometry and multistep waveforms could potentially decrease the transmitter ramp time by a factor of 8. However, to make meaningful measurements of the earth response at early delay times may also require compensating the large primary field and snubbing any high frequency ringing in the transmitter electronics. An electromagnetic system with these improvements could have up to √8 better vertical resolution.

Combining a high transmitter moment and a quick transmitter ramp in a single waveform, could also give better vertical resolution at depth.

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