

# **The Effect and Mitigation of Vineyard Trellising on EM38 Soil Conductivity Measurements**

**Peter James Clark**

BA (PHYSICS) Macquarie University, Australia

BSc Honours (GEOPHYSICS) University of New England, Australia

MSc (GEOPHYSICS) University of New England, Australia

A Thesis Submitted for the Degree of

Doctor of Philosophy of the University of New England

Physics & Electronics

School of Science & Technology

March, 2009.

## **Abstract**

The EM38 has a widely accepted role in precision agriculture for the efficient mapping of sub-surface apparent electrical conductivity at data densities of the order of 10 m. The resultant high-resolution maps of apparent conductivity enable agriculturists to infer soil properties such as soil moisture and salinity which aid localized crop management decisions. However, when applied to viticulture, previously published research has confirmed that the use of electromagnetic induction instruments, such as the EM38, has been flawed by the interference from the conducting wire and steel-post loops of the grapevine trellising. This has raised questions about the reliability of interpretations made from potentially flawed maps of apparent conductivity in vineyards.

In this research, a combination of component and whole trellis assembly trials confirmed that this interference was separable into two significant components: the steel trellis loops and the trellis-earth system. Furthermore, while these two effects theoretically interact, the contributions from each were found to be conceptually separable in terms of both the EM38 response and possible mitigation or data correction strategies.

An analytical expression was initially developed to predict the interference from steel conducting loops in terms of the mutual inductance from both the transmit and receive coils of the instrument to the Target Loop, the loop's self-inductance, and its electrical resistance. Increasing the complexity of the loops to reflect real trellis geometries necessitated the use of a numerical analysis program (FastHenry) to calculate the parameters of loop resistance, self-, and mutual-inductance, for substitution into the analytical expression.

Several patterns within the trellis interference were discovered in the simulated vineyard trellising and the commercial vineyard tested. These patterns led to several mitigation/correction possibilities. Future work in the trellis interference on EM38 surveys should focus on the development and refinement of the practical empirical mitigation strategies proposed, rather than further analyses of the detailed mechanism of the trellis-loop and trellis-earth eddy currents because of the difficulty to predict post-wire and post-earth resistances, as well as the complexities of the trellis-earth eddy currents.

# TABLE OF CONTENTS

|  |             |
|--|-------------|
| <b>The Effect and Mitigation of Vineyard Trellising on EM38 Soil Conductivity Measurements .....</b> | <b>i</b>    |
| <b>Abstract .....</b>  | <b>ii</b>   |
| <b>TABLE OF CONTENTS .....</b>   | <b>iii</b>  |
| <b>Abbreviations, Acronyms, Symbols and Conventions .....</b>  | <b>ix</b>   |
| <b>Certificate of Originality .....</b>  | <b>xiii</b> |
| <b>Acknowledgements .....</b>  | <b>xiv</b>  |
| <b>Chapter 1 Introduction and Review.....</b>  | <b>1</b>    |
| 1.1 Spatial Variability in Agricultural Fields and Precision Agriculture .....                       | 1           |
| 1.2 Geophysical Techniques in Agriculture.....   | 2           |
| 1.2.1 Gamma Ray Spectroscopy (GRS).....  | 3           |
| 1.2.2 Time Domain Reflectometry (TDR) .....  | 3           |
| 1.2.3 Ground Penetrating Radar (GPR) .....   | 4           |
| 1.2.4 Magnetometry .....   | 4           |
| 1.2.5 Seismic Methods .....  | 5           |
| 1.2.6 Self-Potential.....  | 5           |
| 1.2.7 Electrical Resistivity (Multi-electrode ER) .....  | 5           |
| 1.2.8 Electrical Resistivity (Capacitively Coupled ER).....  | 6           |
| 1.2.9 Electromagnetic Induction (EMI) .....  | 6           |
| 1.3 EM38 Vineyard Application .....  | 7           |
| 1.4 Vineyard Trellising Distortion of EM38 Measurements .....  | 8           |
| 1.5 Scope of the Thesis .....  | 12          |
| <b>Chapter 2 The EM38 Sensor and FastHenry Inductance Modelling Software .....</b>                   | <b>14</b>   |

|                  |   |           |
|------------------|---|-----------|
| 2.1              | Introduction .....  | 14        |
| 2.2              | Definition of Conductivity .....  | 14        |
| 2.3              | Conductivity Surveying.....   | 15        |
| 2.4              | Deducing Soil Properties from Soil Conductivity .....   | 17        |
| 2.5              | Electromagnetic Induction (EMI).....  | 18        |
| 2.6              | Electromagnetic Induction (EMI) Theory.....   | 18        |
| 2.7              | EMI Depth Function .....  | 21        |
| 2.8              | EMI Theory for a Horizontally Layered Earth.....  | 23        |
| 2.9              | The EM38 Soil Conductivity Meter .....  | 24        |
| 2.10             | EM38 Accuracy, Calibration, Zeroing and Drift.....  | 25        |
| 2.11             | Inductance Estimations with FastHenry.....  | 28        |
| 2.12             | Conclusion.....   | 32        |
| <b>Chapter 3</b> | <b>EM38 Response to Simple Conducting Loops.....</b>  | <b>33</b> |
| 3.1              | Introduction .....  | 33        |
| 3.2              | Magnetic Field of the EM38 Transmitter.....   | 33        |
| 3.3              | Mutual Inductance between Two Distant Coplanar Loops.....                                       | 35        |
| 3.3.1            | The Magnetic Field of a Dipole .....  | 36        |
| 3.3.2            | Mutual Induction Definition .....   | 37        |
| 3.3.3            | Mutual Induction Approximation for Initial Testing .....  | 37        |
| 3.4              | Relative EM38 Response to a Distant Horizontal, Coplanar Loop.....                              | 38        |
| 3.4.1            | Materials and Methods: Relative EM38 Response to Distant<br>Coplanar Loops with Distance .....  | 39        |
| 3.4.2            | Results and Discussion: Relative EM38 Response to Distant<br>Coplanar Loops with Distance ..... | 42        |
| 3.5              | Relative EM38 Response to Distant Coplanar Loops of Different<br>Size .....                     | 45        |

|   |   |           |
|---|---|-----------|
| 3.5.1   | Materials and Methods: Relative EM38 Response to Distant Coplanar Loops of Different Size.....  | 47        |
| 3.5.2   | Results and Discussion: Relative EM38 Response to Distant Coplanar Loops of Different Size..... | 47        |
| 3.6   | Absolute EM38 Response to Distant Horizontal, Coplanar Loops .....                              | 49        |
| 3.7   | Conclusion.....   | 52        |
| <b>Chapter 4 EM38 Response to Components of an All-Steel Vine</b> |   |           |
| <b>Trellis</b>  | .....   | <b>54</b> |
| 4.1   | Introduction .....  | 54        |
| 4.2   | EM38 Response from Gripfast Steel Posts .....   | 56        |
| 4.2.1   | Materials and Methods: EM38 Response to Gripfast Posts .....                                    | 58        |
| 4.2.2   | Results and Discussion: EM38 Response to Gripfast Posts.....                                    | 59        |
| 4.2.3   | Materials and Methods: Impact of Gripfast Post-Earth Interaction on EM38 Response .....         | 60        |
| 4.2.4   | Results and Discussion: Impact of Gripfast Post-Earth Interaction on EM38 Response .....        | 61        |
| 4.3   | EM38 Response to a Single Steel Trellis Wire .....  | 65        |
| 4.3.1   | Materials and Methods: EM38 Response to a Single Trellis Wire .....                             | 66        |
| 4.3.2   | Results and Discussion: EM38 Response to a Single Trellis Wire .....                            | 67        |
| 4.4   | EM38 Response to a Vertical Trellis Loop (Unearthed) .....                                      | 68        |
| 4.4.1   | Materials and Methods: EM38 Response to a Vertical Loop of Trellis Wire (Unearthed).....        | 68        |
| 4.4.2   | Results and Discussion: EM38 Response to a Vertical Loop of Trellis Wire (Unearthed).....       | 70        |
| 4.5   | EM38 Response to Individual Steel Trellis Panel Loops.....                                      | 72        |

|        |  |    |
|--------|--|----|
| 4.5.1  | Materials and Methods: EM38 Response to Individual Steel Trellis Panel Loops.....                          | 73 |
| 4.5.2  | Results and Discussion: EM38 Response to Individual Steel Trellis Panel Loops.....                         | 75 |
| 4.6    | Mid-Panel EM38 Response to Multiple Loops in a Single Trellis Panel .....                                  | 80 |
| 4.6.1  | Using FastHenry to Predict EM38 Response to Multiple Loops in a Single Trellis Panel.....                  | 80 |
| 4.6.2  | Materials and Methods: Mid-Panel EM38 Response to Multiple Steel Trellis Panel Loops.....                  | 84 |
| 4.6.3  | Results and Discussion: Mid-Panel EM38 Response to Multiple Steel Trellis Panel Loops.....                 | 85 |
| 4.7    | EM38 Response with Distance from a Multiple Wire Trellis Panel .....                                       | 88 |
| 4.7.1  | Materials and Methods: Mid-Loop EM38 Response with Sensor-Loop Distance from a Multiple Wire Trellis.....  | 88 |
| 4.7.2  | Results and Discussion: Mid-Loop EM38 Response with Sensor-Loop Distance from a Multiple Wire Trellis..... | 89 |
| 4.8    | EM38 Response to a Trellis Panel Edge .....  | 90 |
| 4.8.1  | Materials and Methods: EM38 Response to a Trellis Panel Edge .....   | 91 |
| 4.8.2  | Results and Discussion: EM38 Response to a Trellis Panel Edge .....  | 92 |
| 4.9    | EM38 Response from a Single, Grounded Wire Loop .....  | 94 |
| 4.9.1  | Materials and Methods: EM38 Response from a Single Grounded Wire .....                                     | 94 |
| 4.9.2  | Results and Discussion: EM38 Response from a Single Grounded Wire .....                                    | 96 |
| 4.10   | EM38 Response from a Multi-Grounded Wire .....   | 98 |
| 4.10.1 | Materials and Methods: Multi-Grounded Wire .....   | 98 |

|                  |  |            |
|------------------|--|------------|
| 4.10.2           | Results and Discussion: Multi-Grounded Trellis.....                                    | 100        |
| 4.11             | Importance of the Post-Earth Resistance .....  | 104        |
| 4.12             | Conclusions .....  | 105        |
| <b>Chapter 5</b> | <b>The EM38 Response to Multi-Row Trellises.....</b>                                   | <b>108</b> |
| 5.1              | Introduction .....   | 108        |
| 5.1.1            | Kirby Test Site: Survey Procedure and Data Processing .....                            | 109        |
| 5.2              | Kirby Test Site: EM38 Survey Repeatability Result .....                                | 111        |
| 5.3              | Kirby Test Site: EM38 Bare Earth and Dripper Wire Survey.....                          | 113        |
| 5.4              | Kirby Test Site: EM38 All Wire Survey.....   | 116        |
| 5.5              | Comparison of the Trellis Minus Ground Loop Data with<br>FastHenry Predictions.....    | 120        |
| 5.5.1            | Materials and Methods: Modelled Response using FastHenry<br>Estimated Parameters.....  | 120        |
| 5.5.2            | Results and Discussion: Modelled Response using FastHenry<br>Estimated Parameters..... | 121        |
| 5.6              | Correcting the All-Steel Interference of the Trellis .....                             | 124        |
| 5.7              | Correcting for the Earthing Interference of the Trellis .....                          | 126        |
| 5.8              | Conclusion.....  | 130        |
| <b>Chapter 6</b> | <b>Correcting EM38 Survey Data for a Commercial<br/>Vineyard .....</b>                 | <b>133</b> |
| 6.1              | Introduction .....   | 133        |
| 6.1.1            | Peterson’s Commercial Vineyard (Test Site) .....                                       | 134        |
| 6.2              | EM38 Background Response to an Insulated Trellis.....                                  | 137        |
| 6.2.1            | Materials and Methods: Background Response to an<br>Insulated Trellis .....            | 137        |
| 6.2.2            | Results and Discussion: Background Response to an<br>Insulated Trellis .....           | 140        |

|                   |   |            |
|-------------------|---|------------|
| <b>Chapter 7</b>  | <b>Project Review, Conclusion and Recommendations .....</b>                     | <b>152</b> |
| 7.1               | Project Review .....  | 152        |
| 7.2               | Mitigation and Correction Strategies .....                                      | 155        |
| 7.2.1             | Strategy: Insulate the Trellis .....  | 155        |
| 7.2.2             | Strategy: Manual Measurement along the Trellis Rows .....                       | 156        |
| 7.2.3             | Strategy: Measurement along the Inter-trellis Lanes (with Calibration) .....    | 157        |
| 7.2.4             | Strategy: Measurement along the Inter-trellis Lanes (without Calibration) ..... | 158        |
| 7.3               | Scope for Further Work.....   | 159        |
| <b>References</b> | <b>.....</b>  | <b>161</b> |
| <b>Appendix A</b> | <b>. The EM38 History and Model Designations.....</b>                           | <b>167</b> |



## Abbreviations, Acronyms, Symbols and Conventions

| Variable,<br>Unit or<br>Symbol | Definition or Meaning                                       | Units  |
|--------------------------------|---|--|
| $\alpha$                       | Shape parameter (aspect ratio for rectangles)               | Unit-less  |
| $a$                            | Electrode spacing   | m  |
| $A$                            | Area  | m <sup>2</sup>                                       |
| A                              | Amperes   | Amperes  |
| $B$                            | Magnetic flux density (magnetic induction, vector quantity) | T≡kg s <sup>-2</sup> A <sup>-1</sup>                 |
| cm                             | Centimetres   | 10 <sup>-2</sup> m                                   |
| $\sigma$                       | Electrical Conductivity (≡EC)                               | S≡Siemens  |
| Δ                              | Delta (implies change in value of)                          | Not applic.  |
| $d$                            | Incremental change  | Not applic.  |
| $EC_a$                         | Apparent Electrical Conductivity                            | S≡Siemens  |
| $EC_e$                         | Electrical Conductivity of Extracted soil sample            | S≡Siemens  |
| ER                             | Soil Electrical Resistivity                                 | Ω-m  |
| $\phi$                         | Depth response function                                     | Not applic.  |
| $\Phi$                         | Magnetic flux   | Vs≡kg m <sup>2</sup> s <sup>-2</sup> A <sup>-1</sup> |
| $f$                            | Frequency   | s <sup>-1</sup>                                      |
| $H$                            | Magnetic field (vector)                                     | Am <sup>-1</sup>                                     |
| Hr                             | Hour  | s  |
| $H_s$                          | Secondary magnetic field (vector)                           | Am <sup>-1</sup>                                     |
| $H_0$                          | Primary magnetic field from Loop 0 (vector)                 | Am <sup>-1</sup>                                     |
| $i$                            | Imaginary part of a complex number ( $i^2 \equiv -1$ )      | Unit-less  |
| $I$                            | Current, electrical   | A  |

|            |  |   |
|------------|--|---|
| $I_Q$      | Current in Quadrature phase  | A   |
| Km         | Kilometre  | m   |
| $\ell$     | Length of a cylinder   | m   |
| $L$        | Self-inductance  | $H \equiv VA^{-1} \equiv kgm^2s^{-2}A^{-2}$ |
| L          | Litre  | $m^3$                                       |
| $\mu$      | Magnetic permeability  | $kgm^{-2}A^{-2}$                            |
| $\mu_0$    | Magnetic permeability in vacuum i.e. free space<br>( $4\pi \times 10^{-7}$ ) | $kgm^{-2}A^{-2}$                            |
| $\mu_r$    | Relative magnetic permeability   | dimensionless                               |
| m          | Metres (but as a prefix means milli: $10^{-3}$ )                             | m   |
| $m$        | Dipole moment (vector quantity)  | $Im^2$                                      |
| $M$        | Mutual inductance  | $H \equiv VA^{-1} \equiv kgm^2s^{-2}A^{-2}$ |
| mm         | Millimetres  | m   |
| $N$        | Number of turns of a coil (of wire)  | integer                                     |
| $\pi$      | Pi   | constant                                    |
| $\rho$     | Resistivity (reciprocal of conductivity)                                     | $\Omega m$                                  |
| $R_H$      | Horizontal depth response function (cumulative)                              | $\Omega mm^{-1}$                            |
| $R_V$      | Vertical depth response function (cumulative)                                | $\Omega mm^{-1}$                            |
| $r_x$      | Cross-sectional radius   | m   |
| $r$        | Loop radius  | m   |
| $R$        | Resistance, electrical (Reciprocal of conductance)                           | $\Omega$                                    |
| $R$        | Radial Vector  |   |
| s          | Seconds  |   |
| $s$        | Spacing or separation  | m   |
| $s_1, s_2$ | Spacing or separation to Loop 1 and Loop 2<br>(respectively)                 | m   |

|          |   |                                  |
|----------|---|----------------------------------|
| S        | Siemens, a unit of conductance                        | ( $\equiv \Omega^{-1}$ )         |
| <i>S</i> | Surface   |                                  |
| <i>t</i> | Time  | s                                |
| <i>V</i> | Voltage & EM38 Response value in Vertical dipole mode |                                  |
| V        | Volts   | $\text{JA}^{-1}\text{s}^{-1}$    |
| $V_B$    | Background EM38 Response value (Vertical dipole mode) |                                  |
| $V_{BE}$ | Bare-Earth EM38 Response value (Vertical dipole mode) |                                  |
| $V_Q$    | Quadrature EM38 Response value (Vertical dipole mode) |                                  |
| $\Omega$ | Ohms, unit of resistance, electrical                  | $\text{VA}^{-1}$                 |
| $\xi$    | Electro-motive force                                  | $\text{V} \equiv \text{WA}^{-1}$ |
| $\omega$ | Angular frequency                                     | $\text{s}^{-1}$                  |
| <i>z</i> | Depth   | m                                |
| <i>Z</i> | Complex impedance, electrical                         | $\Omega$                         |

| <b>Acronym<br/>or<br/>Abbreviation</b> | <b>Meaning</b>                            |
|--|---|
| BE                                     | Bare-earth                                |
| CD                                     | Coefficient of Determination, statistical |
| CW                                     | Cordon Wire                               |
| conn.                                  | Connected                                 |
| corr.                                  | Corrected                                 |
| dGPS                                   | Differential GPS                          |
| DW                                     | Dripper Wire                              |

|           |                                     |
|-----------|-------------------------------------|
| <i>EC</i> | Electrical Conductivity             |
| EMI       | Electro-Magnetic Induction          |
| F1        | Foliage wire 1 (lower foliage wire) |
| F2        | Foliage wire 2 (upper foliage wire) |
| GPR       | Ground Penetrating Radar            |
| GPS       | Global Positioning System           |
| GRS       | Gamma Ray Spectroscopy              |
| GW        | Grab Wire                           |
| insul.    | Insulated                           |
| N         | Northing                            |
| ppt       | Parts per thousand                  |
| Rx        | Receiver                            |
| TDR       | Time Domain Reflectometry           |
| Tx        | Transmitter                         |
| UNE       | The University of New England       |

## **Certificate of Originality**

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification.

I certify that any help received in preparing this thesis, and all sources used, have been acknowledged in this thesis.



**Peter James Clark**

**Armidale,**

**March 2009.**

# Acknowledgements

I would like to express my sincere thanks to my supervisor Associate Professor David Lamb (School of Science and Technology, UNE) for his enthusiasm, inspiration, hard work, and ‘hands-off’ approach. Thanks are also due to Ron Bradbury for initiating my involvement in the project, technical guidance throughout the research process, and ‘attention-to detail’ proof reading.

I would also like to thank G-tek Australia Pty Ltd for use of their geophysical software package: Geosoft oasis montaj, and Peterson’s Winery, Armidale, for permitting me unfettered access to their vineyard.

Finally, thank you to my wife, Jane, for her intellectual and emotional support.