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Modelling GICs in Australian Power and Pipeline Networks

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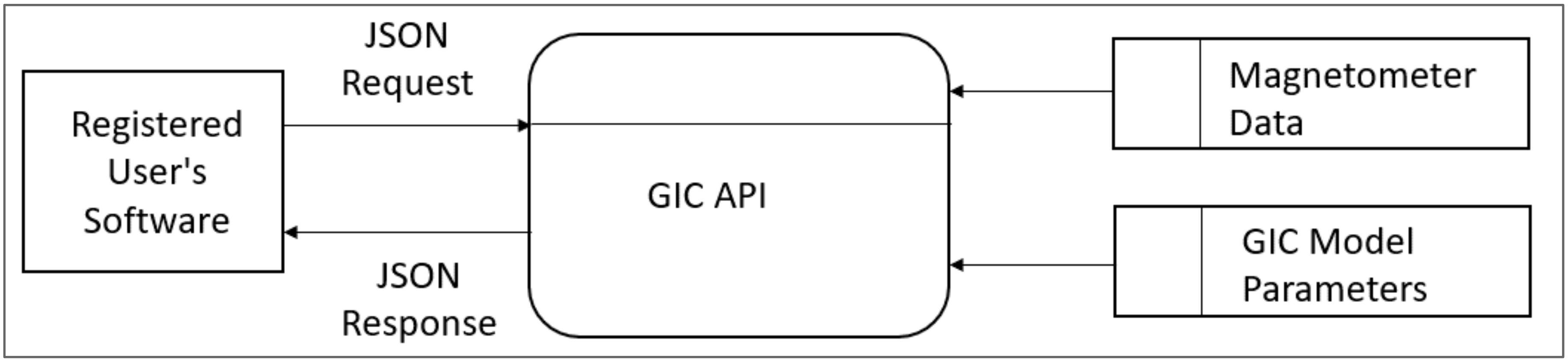
Introduction

- Geomagnetically Induced Currents (GICs) caused by space weather can impact critical infrastructure such as power network grids and pipeline networks.
- SWS is developing a new service, an Application Programming Interface (API) that provides modelled GICs on request to registered users using near real-time or historical magnetometer data. The Space Weather GIC API is currently in beta version.
- A recent study has shown that 3-D conductivity models can be used to generate better GIC estimates from geomagnetic data. 3-D models can be used to generate more realistic geoelectric field estimates for geomagnetic storm analysis, which can be used in international benchmarking of GIC impacts.

API Architecture - API Request & Response



- The GIC modelling steps include:
  a. Modelling **the induced geoelectric field** from geomagnetic field measurements.
  b. Applying the power network model to the modelled geoelectric field to calculate the **GICs** which are returned via a JSON response.
- A example request is **power-network/get-gic**. It returns a snapshot in time of the GICs flowing to/from ground at the power network's nodes.

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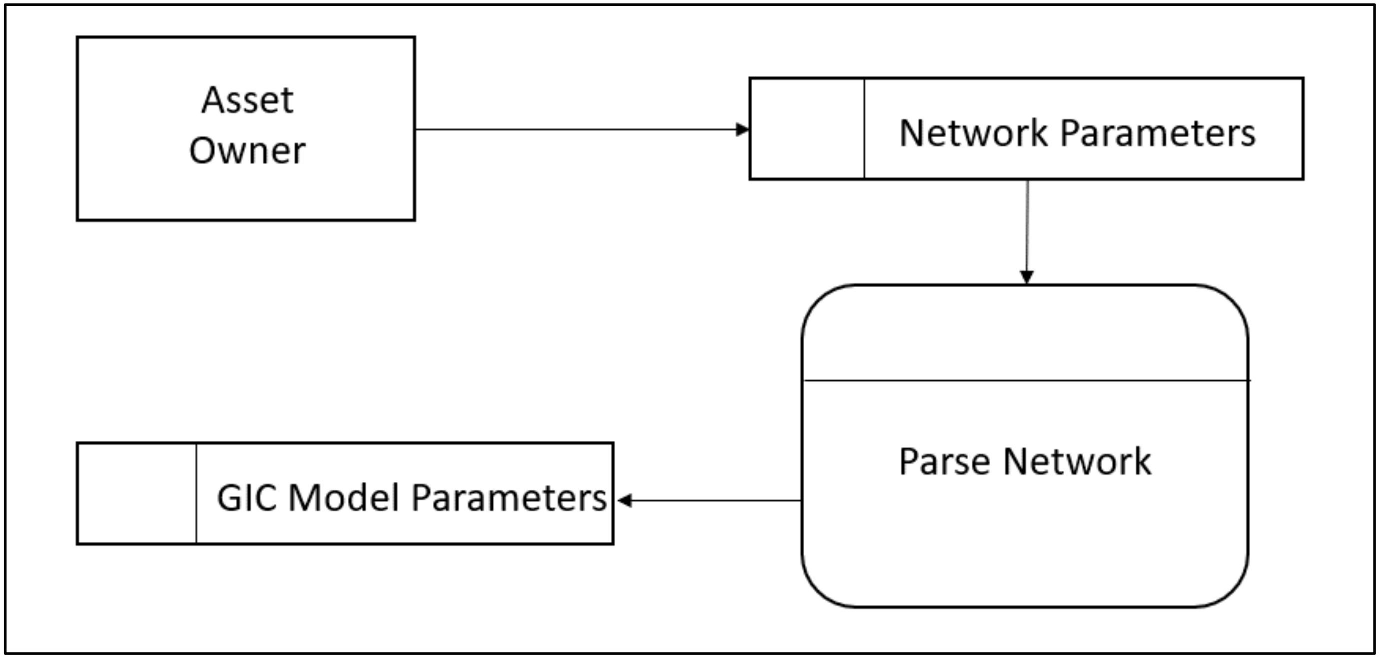
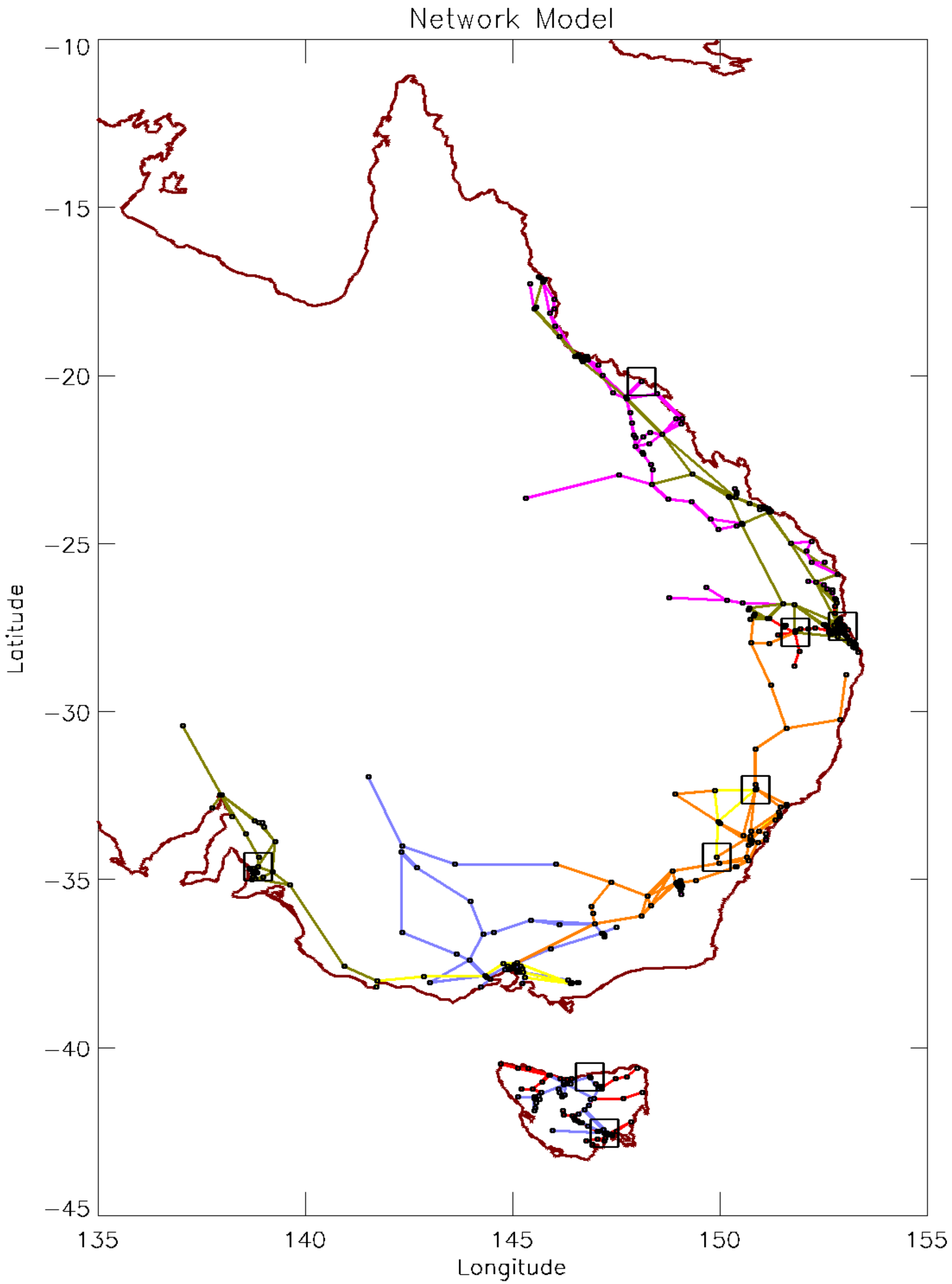
API Architecture - Network Model setup



- Asset owners provide network parameters (details of the geometry and electrical properties of the power or pipeline network) in advance.
- The network parameters are parsed to produce the GIC model parameters and matrices.
- Registered users can only access their own assets.



Australian Electricity Transmission Lines

Operating Voltages of 500, 330, 275, 220, 132, 110, 66, 33, 11 kV

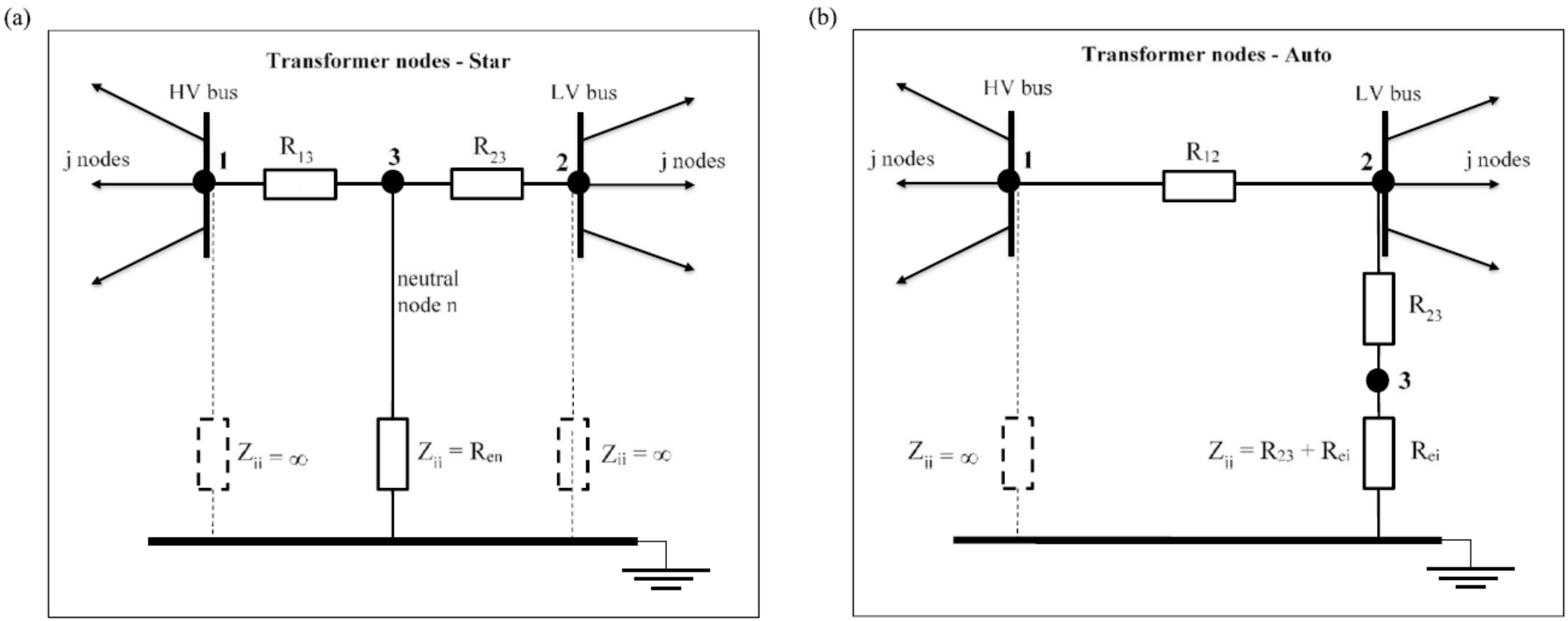
Over 2000 nodes/buses

Over 1500 branches

Over 1000 HV transformers

(Marshall et al., 2019, doi: 10.1029/2018SW002047)

Transformer connections



The model used to incorporate transformer connections for (a) star and (b) auto configuration transformers.

From Marshall et al. (2017)

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Modelling GICs

From Lehtinen and Pirjola (1985), the GICs flowing to/from ground at the network nodes, $\mathbf{I}$, are given by

$$\mathbf{I} = (\mathbf{U} + \boldsymbol{YZ})^{-1}\mathbf{J}$$

$\mathbf{I}$ is an M x 1 column matrix, where M is the number of network nodes

$\mathbf{U}$ is an M x M unit matrix

$\mathbf{Y}$ is the M x M network admittance matrix

$$Y_{ij} = -1/R_{ij} \qquad (i \neq j)$$

$$Y_{ij} = \sum_{k\neq i} 1/R_{ik} \qquad (i = j)$$

R_{ij} are the line resistances between nodes i and j (i,j = 1,…,M)

$\mathbf{Z}$ is the M x M earthing impedance matrix with diagonal elements equal to the station earthing resistances, R_{ei}

$\mathbf{J}$ is a M x 1 column matrix of the currents flowing in the perfect earthing case.

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Calculation of Matrix ***J***

$$J_i = \sum_{j=1, j\neq i}^{M} J_{ij}$$

$$J_{ij} = \frac{V_{ij}}{R_{ij}}$$

$$V_{ij} = \int_i^j \vec{E}(x,y)\, ds$$

$\vec{E}$ is the geoelectric field

V_{ij} is the electric potential field between nodes i and j.

Assuming the geoelectric field is uniform or varies linearly with distance, the integral can be simplified to

$$V_{ij} = (E_x \sin\theta_{ij} + E_y \cos\theta_{ij})\, L_{ij}$$

L_{ij} is the shortest distance between i and j for branch ij.

θ_{ij} is the azimuth of branch ij.

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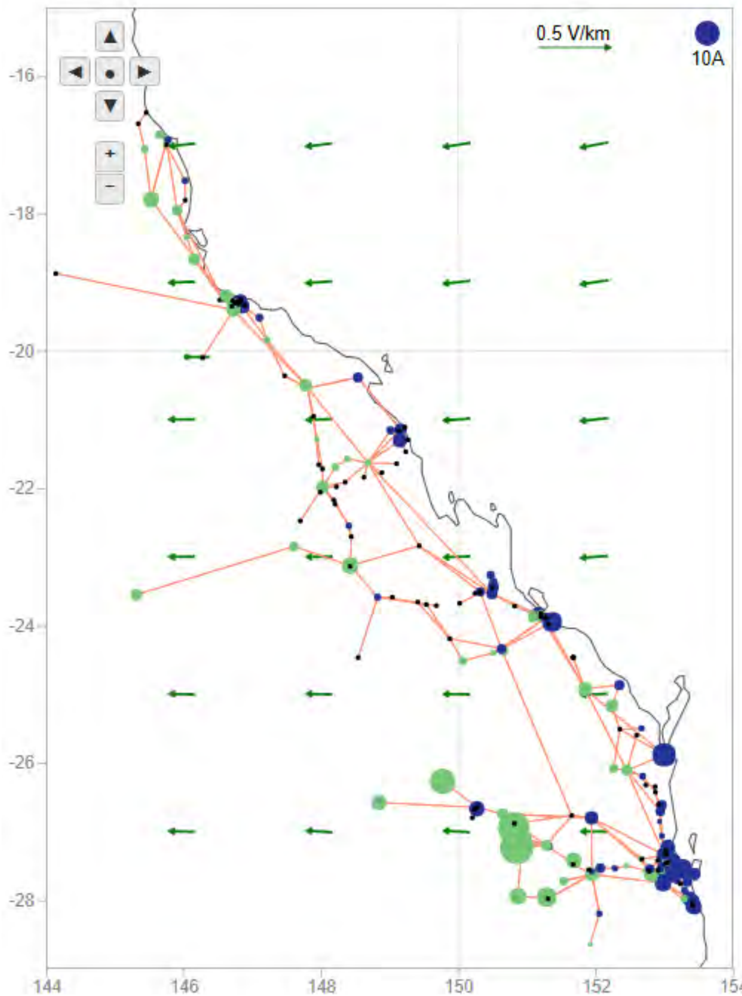
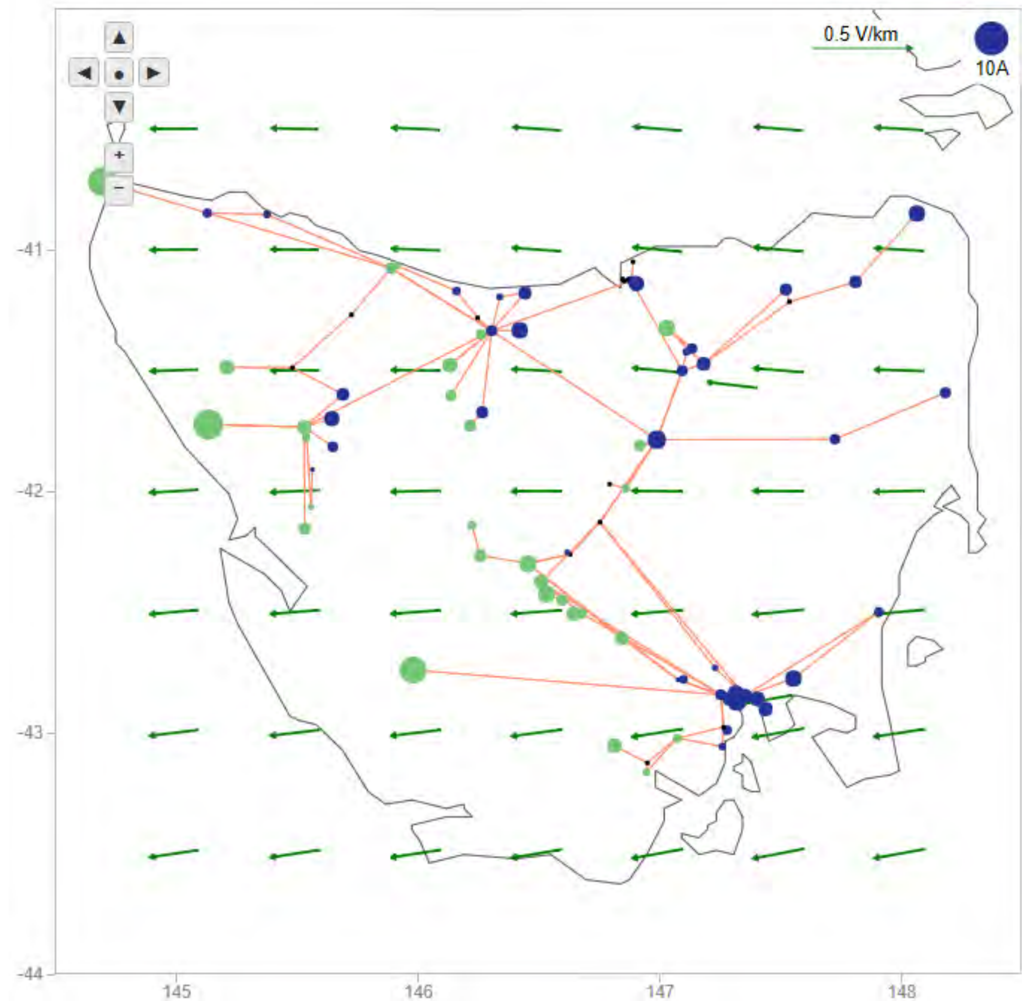
Power Network API

Demonstration of modelled GICs and Geoelectric Fields

Power network & modelled geoelectric field
Model time 2-Oct-2013 01:57 UT
Updated at 22-Mar-2019 05:45 UT



Power network & modelled geoelectric field
Model time 2-Oct-2013 01:57 UT
Updated at 22-Mar-2019 05:41 UT



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Comparison of Earth Conductivity Models

- A recent study has looked at modelled GICs using different conductivity models.
- Earth conductivity models:
  - Uniform half-space
  - Uniform 1-D 7-layer conductivity model
  - Variable 1-D 21-layer conductivity model
  - 3-D conductivity model

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Modelling the Geoelectric Field

Magnetotelluric (MT) Impedance Tensor

- Impedance tensor for a 3-D conductivity structure

$$\begin{bmatrix} E(\omega)_x \\ E(\omega)_y \end{bmatrix} = \begin{bmatrix} Z(\omega)_{xx} & Z(\omega)_{xy} \\ Z(\omega)_{yx} & Z(w)_{yy} \end{bmatrix} \begin{bmatrix} H(\omega)_x \\ H(\omega)_y \end{bmatrix}$$

- Impedance tensor for a 1-D conductivity structure

$$\begin{bmatrix} E(\omega)_x \\ E(\omega)_y \end{bmatrix} = \begin{bmatrix} 0 & Z(\omega) \\ -Z(\omega) & 0 \end{bmatrix} \begin{bmatrix} H(\omega)_x \\ H(\omega)_y \end{bmatrix}$$

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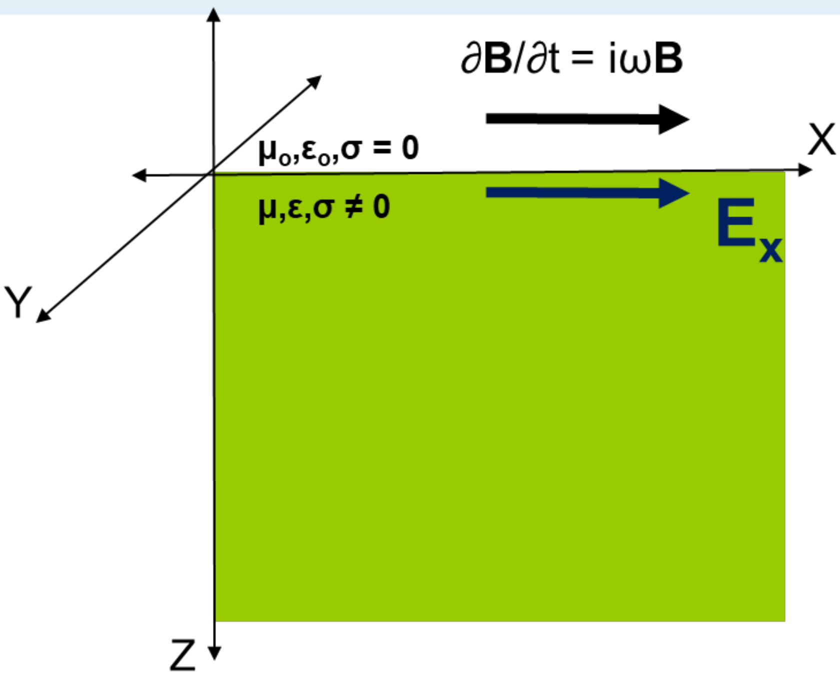
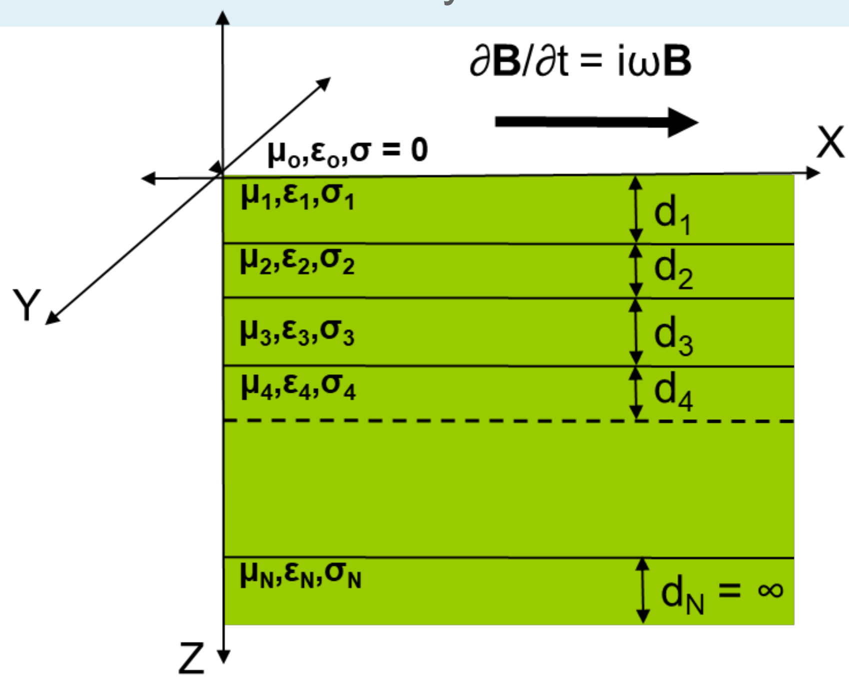
Geoelectric Field – 1-D model

Uniform Half Space



$$Z(\omega) = \sqrt{\frac{\mu_0 \omega}{\sigma}}\, e^{i\frac{\pi}{4}}$$

N-layered 1-D model



$$Z_n(\omega) = i\omega\mu\left(\frac{1 - r_n e^{-2k_n d_n}}{k_n(1 + r_n e^{-2k_n d_n})}\right)$$

$$k_n = \sqrt{i\omega\mu\sigma_n} \qquad r_n = \frac{1 - k_n \frac{Z_{n+1}}{i\omega\mu}}{1 + k_n \frac{Z_{n+1}}{i\omega\mu}}$$

(Trichtchenko and Boteler,2002)

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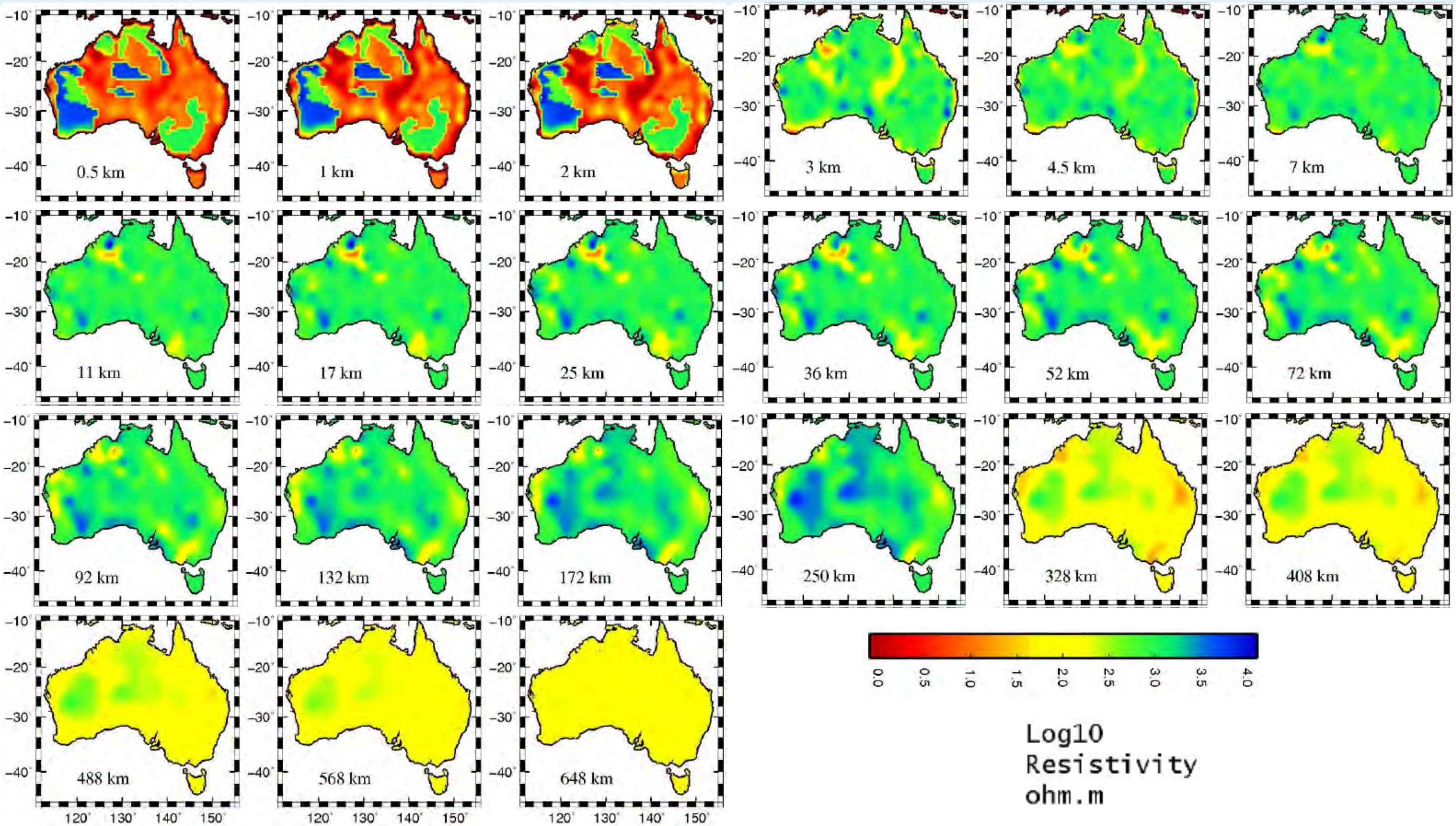
3D Conductivity Model of the Australian Region

(Marshall et al., 2019, doi: 10.1029/2018SW002047)



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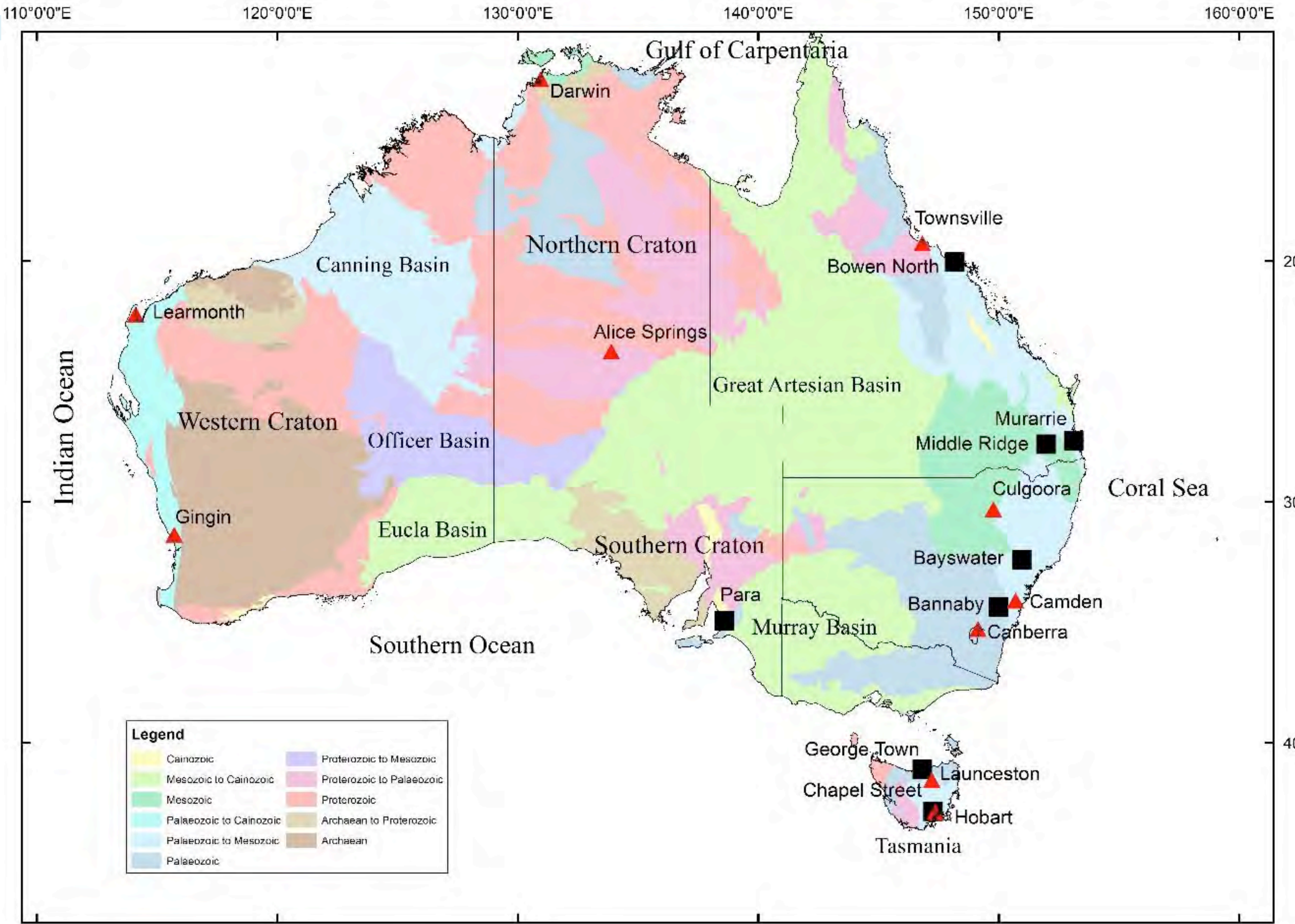
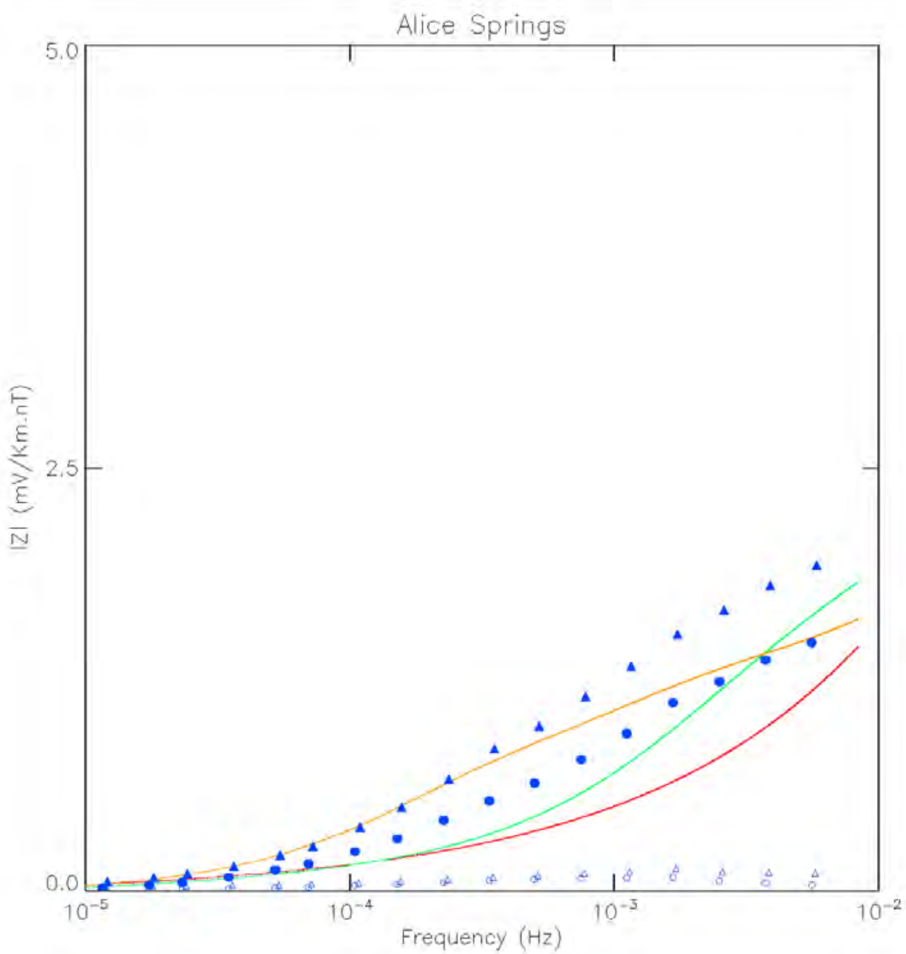
Magnetometer Network

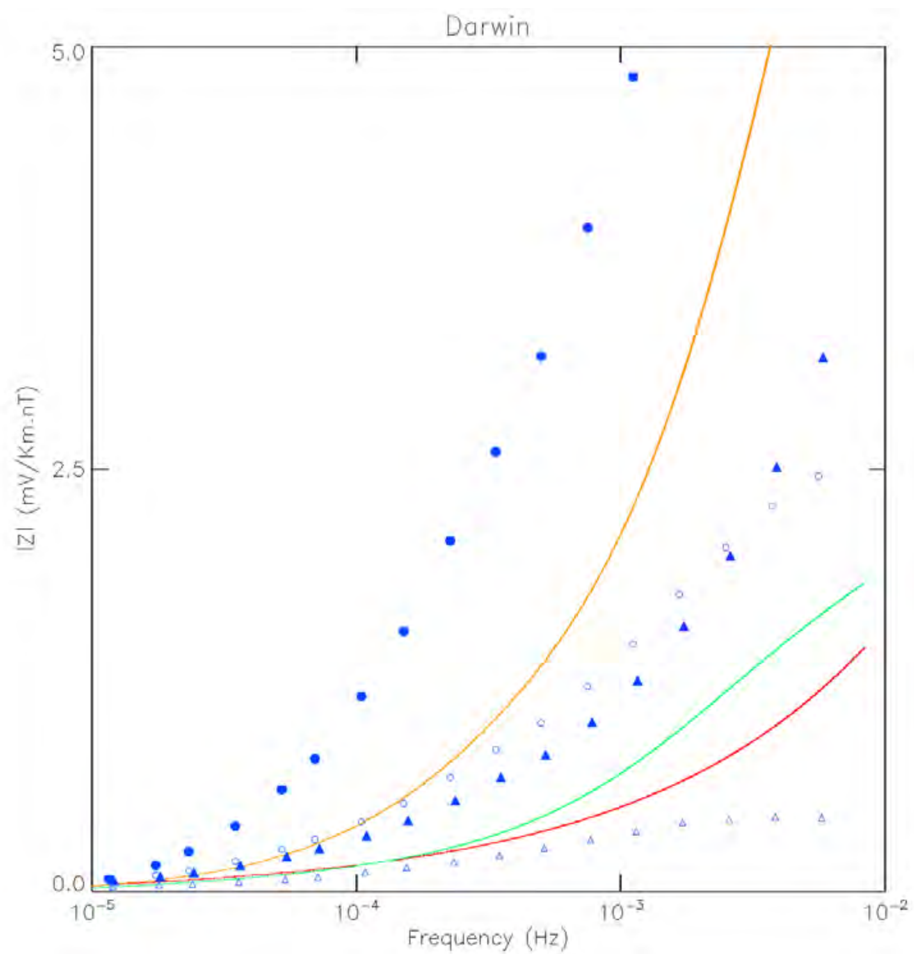
(Marshall et al., 2019, doi: 10.1029/2018SW002047)

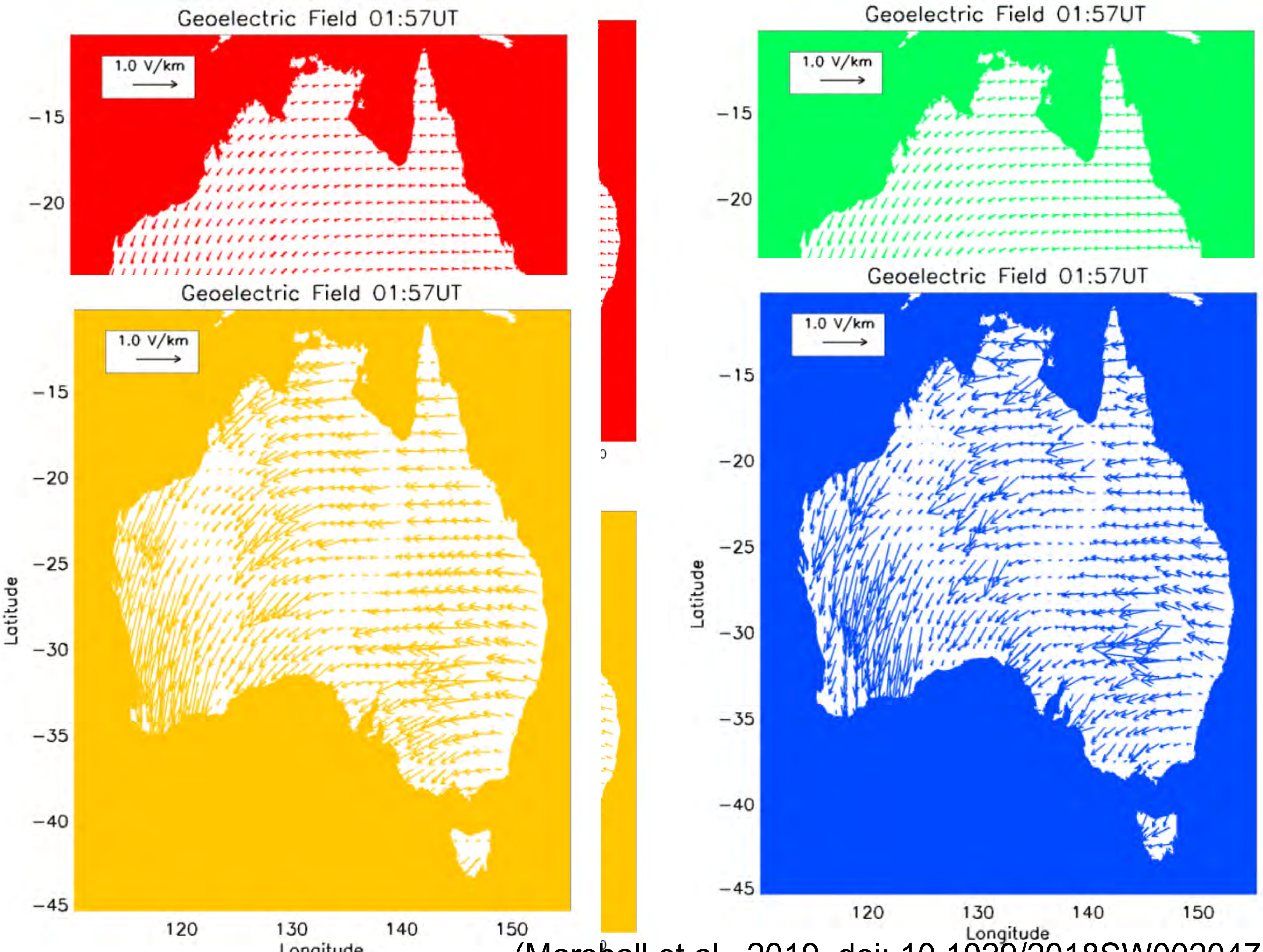


Comparison of the impedance amplitude for different conductivity models

(Marshall et al., 2019, doi: 10.1029/2018SW002047)







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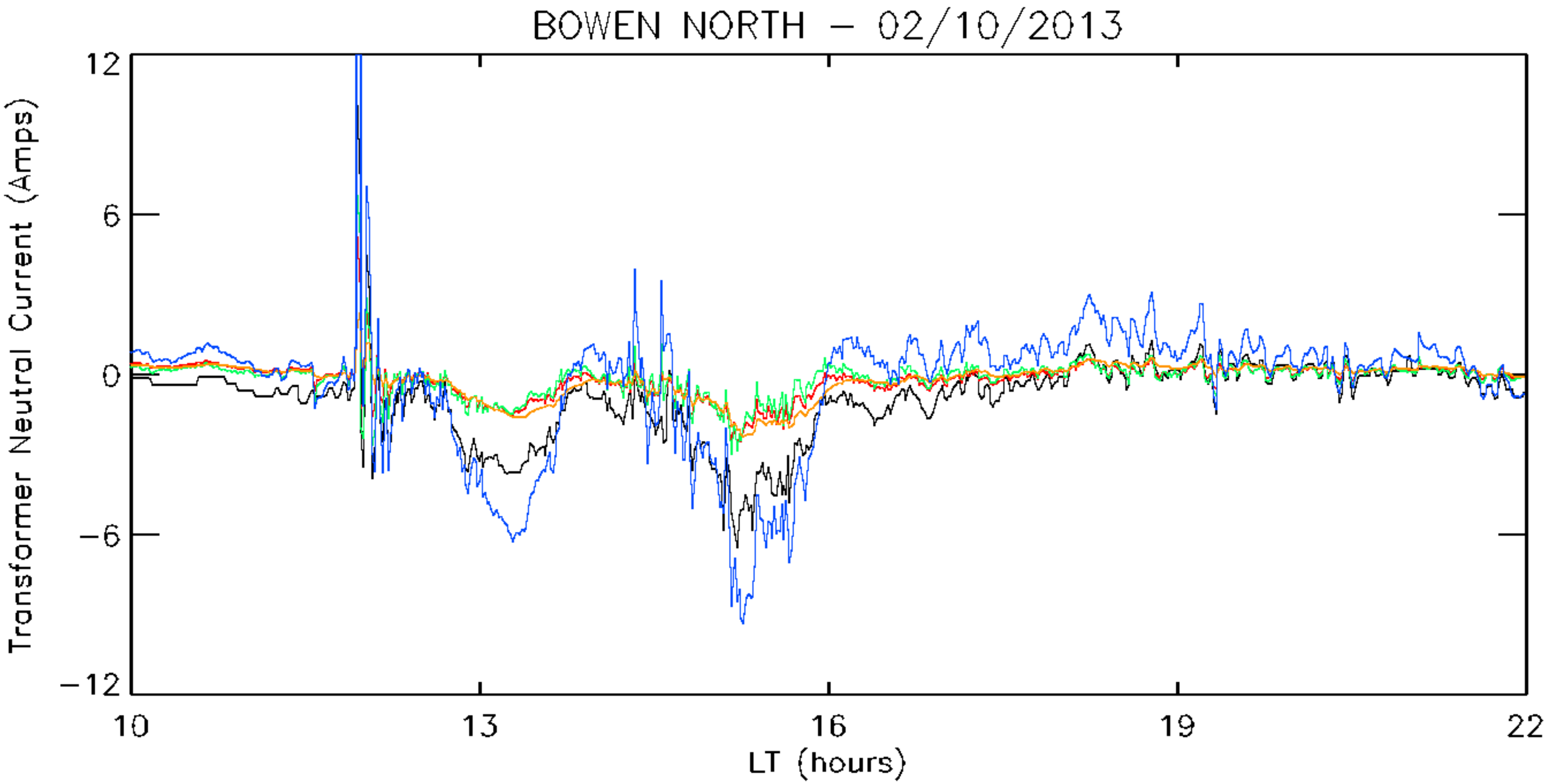
Modelled vs Measured GICs

Bowen North



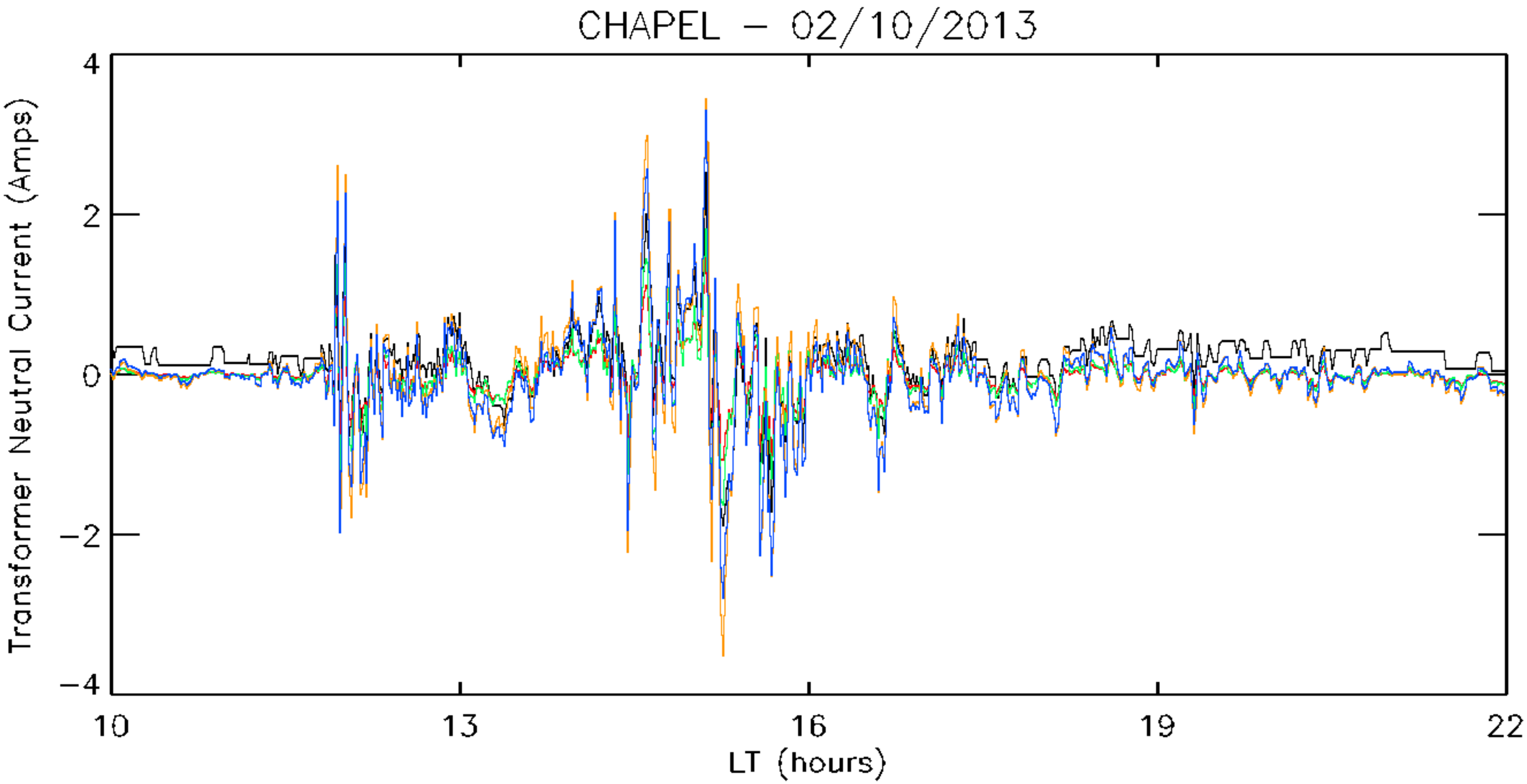
(Marshall et al., 2019, doi: 10.1029/2018SW002047)

Black – Transformer Neutral

Red – Uniform half-space   Green – Uniform 1-D   Orange – Variable 1-D   Blue – 3-D

Modelled vs Measured GICs

Chapel



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Black – Transformer Neutral

Red – Uniform half-space Green – Uniform 1-D Orange – Variable 1-D Blue – 3-D

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Summary

- Two recent developments in the GIC work at SWS:
  1. A new service that provides estimates of the impacts of GICs on power and pipeline networks via an API for registered users, using either near real-time or historical magnetometer data.
  2. Improved models for calculating geoelectric fields based on 3-D conductivity models of the Australian region (see Wang et al., 2016), which will lead to improved GIC estimates in coastal areas and areas with large conductivity anomalies, such as Western Australia.
- 3-D conductivity models can be used to generate more realistic geoelectric field estimates for geomagnetic storm analysis, which can be used in international benchmarking of GIC impacts.

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  - Geoscience Australia,
  - University of Newcastle Space Physics Group,
  - Australian Government Antarctic Division,
  - International Center for Space Weather Science and Education, Japan.
- Power network and GIC monitoring data used in this study were provided by Powerlink, Energex, Ergon, TasNetworks, TransGrid, ElectraNet, AusNet Services, and AEMO.

Thank you…

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