Ensemble Estimation of Network Parameters:

A Tool to Improve the Real-time Estimation of Geomagnetically Induced Currents in the South African Power Network

M.J. Heyns[1,2], S.I. Lotz[1], P.J. Cilliers[1], C.T. Gaunt[2]

South African Institute of Physics Conference
Stellenbosch University
4 July 2017

[1]South African National Space Agency, Space Science Directorate, Hermanus
[2]Department of Electrical Engineering, University of Cape Town

NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

Table of Contents

Where it all starts...

Orange visible light image by the Michelson Doppler Imager (MDI), green ultraviolet image by the Extreme ultraviolet Imaging Telescope (EIT), red LASCO/C2 coronagraph and blue LASCO/C3 coronagraph.

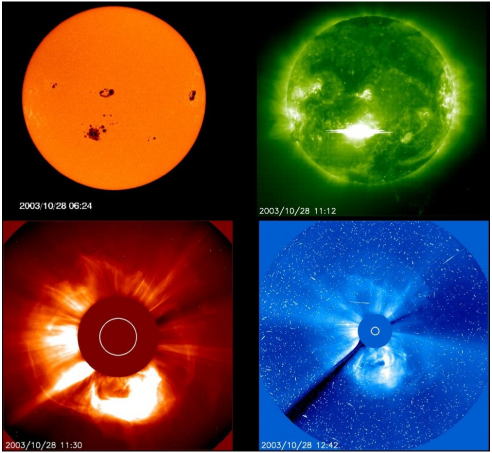
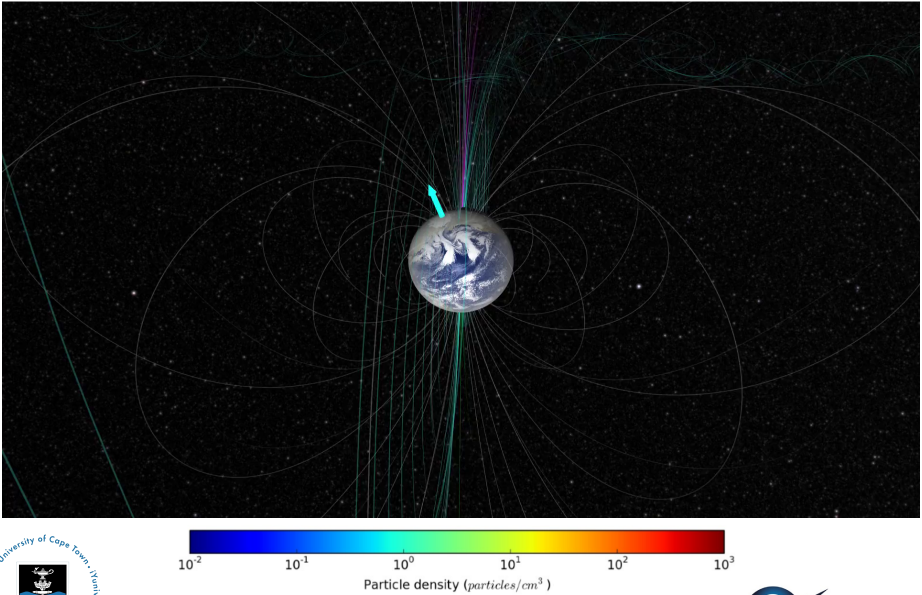


Image credit: R. O. Milligan, http://www.thesuntoday.org/ (2015)



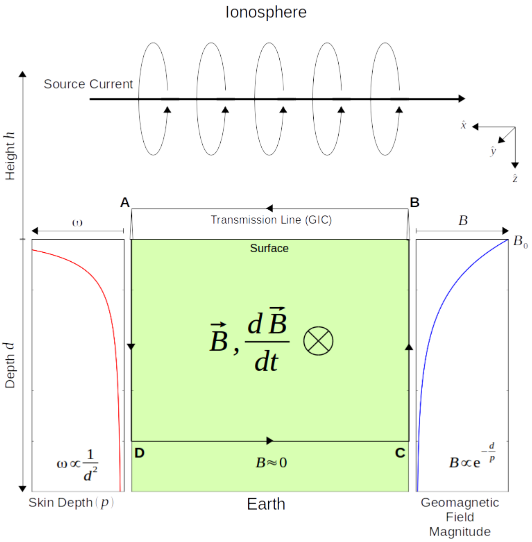
University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

SPES BONA

NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

GICs - Faraday's Law On Steroids $\oint \vec{E} \cdot \vec{dl} = -\frac{d\Phi_B}{dt} = EMF$



Where it all ends...

Image credit: Kenn Brown & Chris Wren, Mondolithic Studios and Mondoworks (2009)

Governing Equation

GIC's can be related to the Northerly (x) and Easterly (y) components of Earth's geoelectric field via network parameters a and b,

$$GIC(t) = aE_x(t) + bE_y(t).$$

These parameters (in units of A km/V) encode the projection of the effective geoelectric field onto the network and the sum of all resistances in the induction loop, which are dominated by network resistances.

Given accurate network information, the network parameters can be determined analytically. Alternatively, empirical approaches are employed.

Ensemble Estimation of Empirical Network Parameters

Due to associated errors at each point in the GIC modelling chain, it has been observed that different empirical values of *a* and *b* may be derived for different data subsets [5-7]. To acknowledge these errors we redefine the governing equation to,

$$\Gamma(t) \approx \alpha E_x(t) + \beta E_y(t), \text{ where}$$

$$\Gamma(t) \equiv GIC(t) + GIC(t)_{err} \text{ (or the GIC as measured),}$$

$$\alpha \equiv a(1 + E_x(t)_{err}/E_x(t)) \text{ and}$$

$$\beta \equiv b(1 + E_y(t)_{err}/E_y(t)).$$

Ensemble Estimation of Empirical Network Parameters

Given a dataset consisting of n time instances,

$$\Gamma(t_0) \approx \alpha E_x(t_0) + \beta E_y(t_0),$$

$$\Gamma(t_1) \approx \alpha E_x(t_1) + \beta E_y(t_1),$$

$$\ldots$$

$$\Gamma(t_{n-1}) \approx \alpha E_x(t_{n-1}) + \beta E_y(t_{n-1}).$$

For any (t_j, t_j) pair, a set of simultaneous equations can be solved to get α and β.

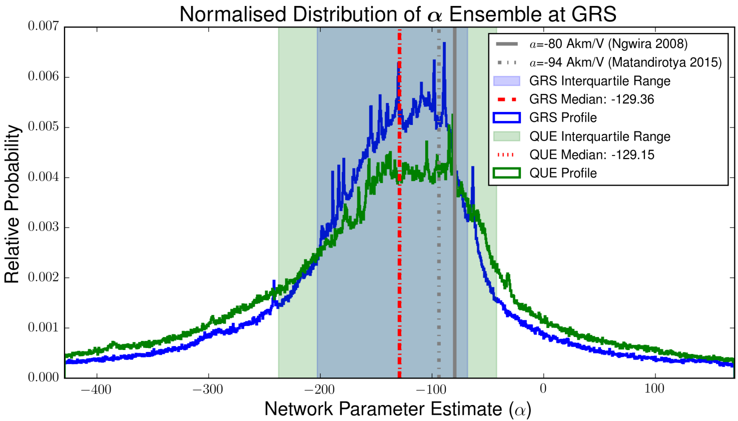
$$\begin{bmatrix} \Gamma(t_i) \\ \Gamma(t_j) \end{bmatrix} = \begin{bmatrix} E_x(t_i) & E_y(t_i) \\ E_x(t_j) & E_y(t_j) \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

Using all possible pairs results in $n(n-1)/2 \approx n^2/2$ (for large n) sets of empirical network parameter estimates.

Defining the Data

- GIC data for the Grassridge (GRS) substation is used. This data corresponds to geomagnetic storms:
  - 31 March 2001
  - **29** - 31 October 2003 (Halloween Storm) - **validation set**
- Hermanus magnetometer data is used to derive the geoelectric field (magnetotelluric method with two layered-Earth conductivity models)
  - local empirically derived 10-layer GRS profile
  - non-local 5-layer QUE profile
- To make use of relevant data, selection criteria are needed [7]:
  - $|GIC| > 0.1 \times RMS(GIC)$
  - similar selection of significant geoelectric field data (can lead to biasing)
  - ensemble estimation is robust and makes use of all possible combinations of time instances, this selection can be relaxed and varied

α Parameter Ensemble



NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

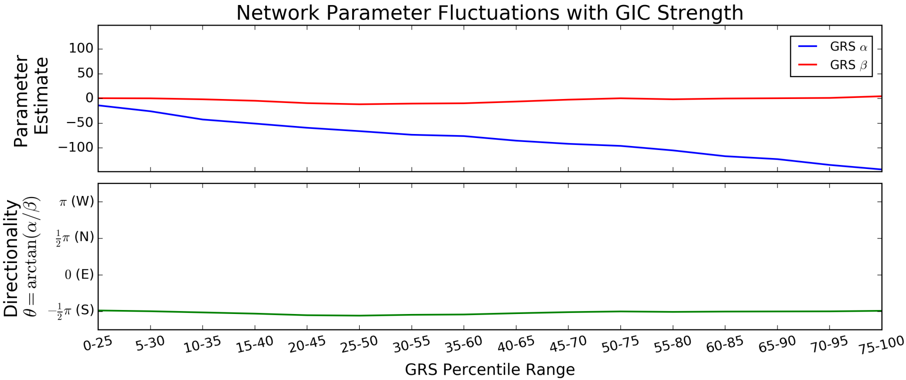
sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

Comparison with Previous Work

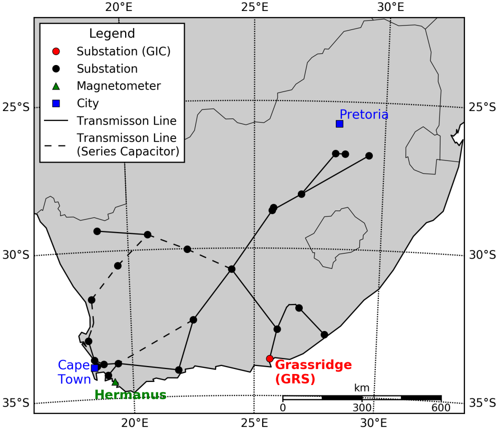
Data	RMSE [A] (ρ) 06:00-12:00	RMSE [A] (ρ) 19:00-24:00	RMSE [A] (ρ) 00:00-24:00	RE%
Ngwira Set (a=-80, b=1 A km/V)				
FEM	0.96	1.07	1.35	51
Matandirotya Set (a=-94, b=24 A km/V)				
FEM	1.38	1.11	0.98	41
Grassridge Profile (α=-129.36, β=7.90 A km/V)				
GRS	**1.42 (0.88)**	**0.54 (0.97)**	**0.86 (0.88)**	**30**
Québec Profile (α=-129.15, β=5.61 A km/V)				
QUE	1.78 (0.78)	0.81 (0.93)	1.12 (0.79)	35

Original analytical network parameters were ($a = -80, b = 15$ A km/V) [6].

Empirical Network Parameters vs. GIC Strength



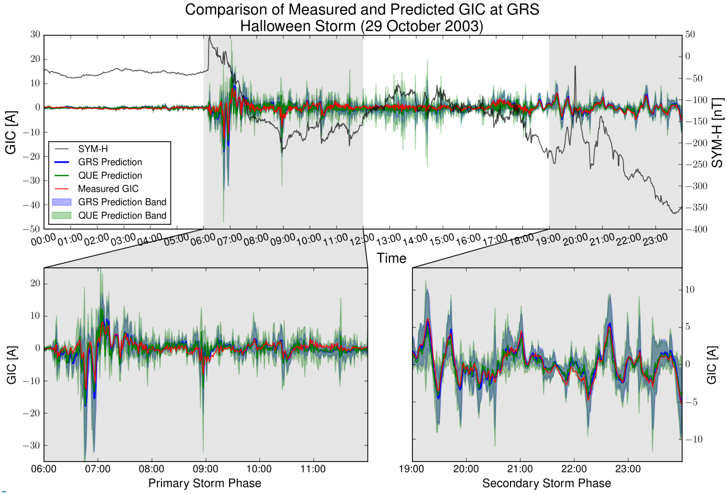
Empirical Network Parameters vs. GIC Strength



Empirical Network Parameters vs. GIC Strength

Québec Profile	RMSE [A] (ρ) 06:00-12:00	19:00-24:00	00:00-24:00	RE%
Static Parameters	1.78 (0.78)	0.81 (0.93)	1.12 (0.79)	35
Dynamic Parameters	**1.75 (0.82)**	**0.72 (0.94)**	**1.05 (0.82)**	**36**
Extreme Parameters	1.97 (0.79)	0.78 (0.93)	1.21 (0.79)	36

Prediction Band (Quantifying the Uncertainties)



Concluding Remarks

1. Empirical network parameters outperform analytical network parameters - amongst these the ensemble approach comes out on top.
2. Errors in the modelling chain are ultimately absorbed into the network parameters - taking the resulting spread into account can result in a prediction band which quantifies uncertainty.
3. Empirical network parameters are not constant!

Ultimately, we want to develop real-time predictive models that can provide input for utility mitigation strategies.

Bibliography

[1] T. Bridgman
Comparative Magnetospheres: A Carrington-Class CME.
NASA Scientific Visualisation Studio, https://svs.gsfc.nasa.gov/4189, 2015. (Date accessed: 19/06/2017)

[2] C. T. Gaunt and G. Coetzee
Transformer failures in regions incorrectly considered to have low GIC-risk.
IEEE Lausanne Power Tech, April:807–812, 2007.

[3] E. J. Oughton, A. Skelton, R. B. Horne, A. W. P. Thomson and C. T. Gaunt
Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure.
Space Weather, 2017.

[4] A. Viljanen and R. Pirjola
Geomagnetically induced currents in the Finnish high-voltage power system.
Surveys in Geophysics, 15(4):383–408, 1994.

[5] M, Wik, A. Viljanen, R. Pirjola, A. Pulkkinen, P. Wintoft and H. Lundstedt
Calculation of geomagnetically induced currents in the 400 kV power grid in southern Sweden.
Space Weather, 6(7), 2008.

[6] C. M. Ngwira, A. Pulkkinen, L. McKinnell and P. J. Cilliers
Improved modelling of geomagnetically induced currents in the South African power network.
Space Weather, 6(11), 2008.

[7] E. Matandirotya, P. J. Cilliers and R. R. van Zyl
Modelling geomagnetically induced currents in the South African power transmission network using the finite element method.
Space Weather, 13(3):185–195, 2015.

Questions?

Modelling Metrics

Root Mean Square:

$$RMS = \sqrt{\Sigma_{i=1}^{n} GIC(t_i)^2 / n}$$

Root Mean Square Error:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(GIC_{obs}(t_i) - GIC_{mod}(t_i))^2}{n}}$$

Relative Error:

$$RE = \frac{GIC_{obs} - GIC_{mod}}{GIC_{obs}}$$

Keeping in line with previous work, the median RE for $|GIC| > 1$ A is considered and the result is shown as a percentage [7].

WSA-ENLIL Modelling of St. Patrick's Day Storm

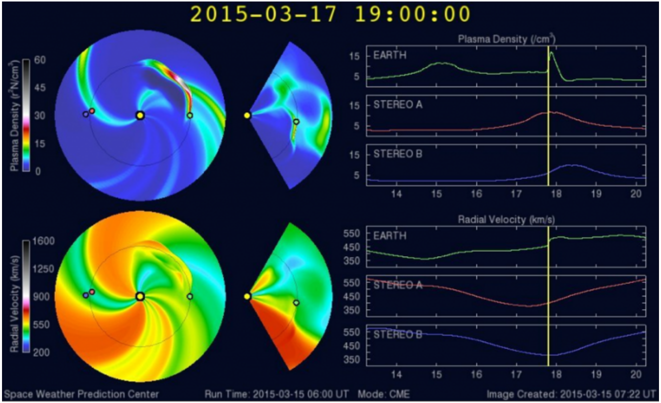


Image credit: http://www.swpc.noaa.gov/ (2015)

ACE Measurements of St. Patrick's Day Storm

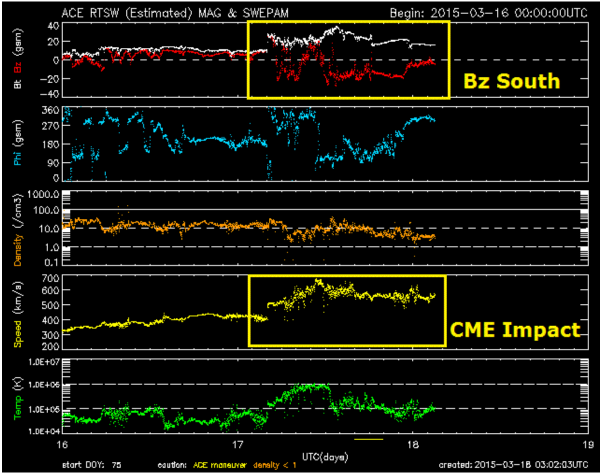
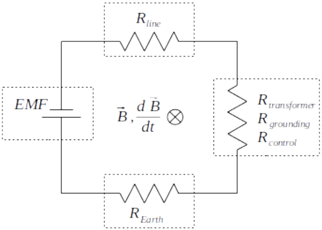


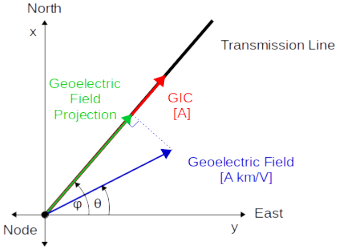
Image credit: http://www.solarham.net/ (2015)

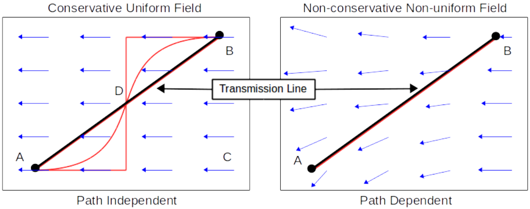
NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

Further GIC Theory



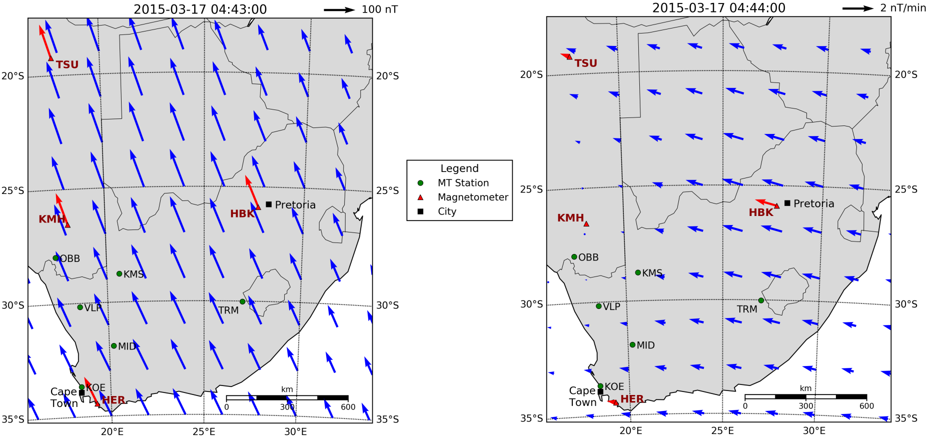




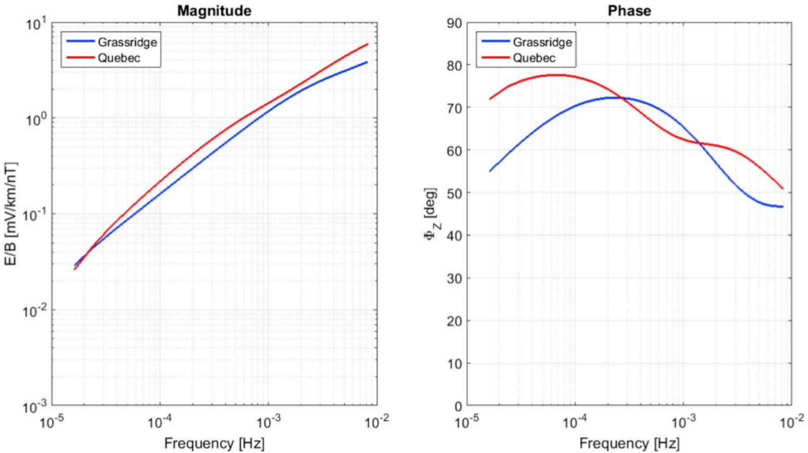
NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

SECS Interpolation of Geomagnetic Field



Conductivity Profiles

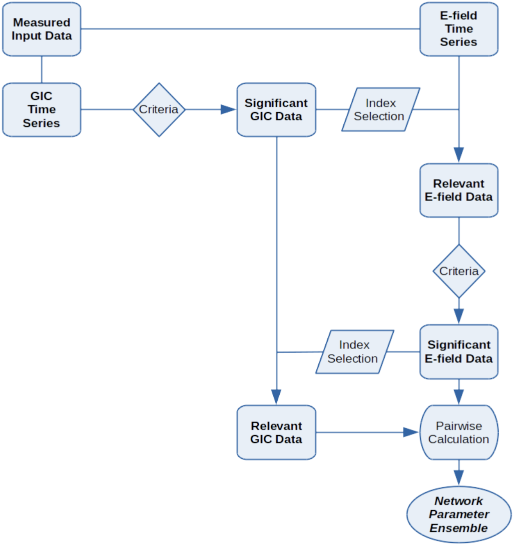


S. I. Lotz, M. J. Heyns and P. J. Cilliers
Regression-based forecast model of induced geoelectric field.
Space Weathers, 15(1):180–191, 2017.

NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

SANSA SOUTH AFRICAN NATIONAL SPACE AGENCY

Flow of Method

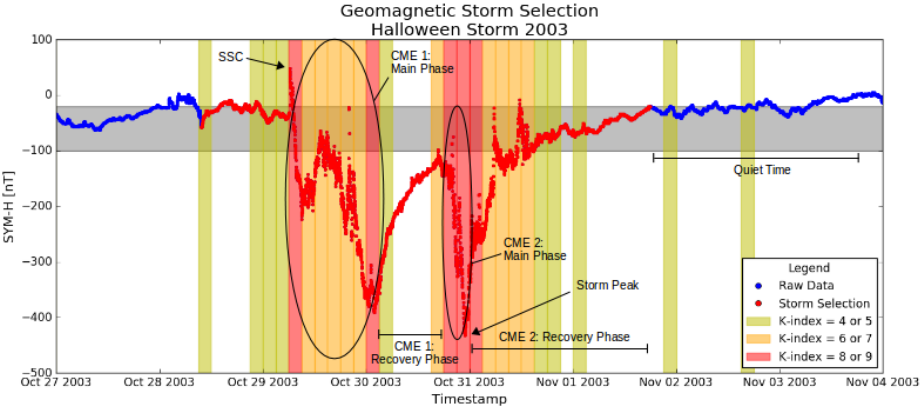


University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

Storm Selection - Halloween Storm

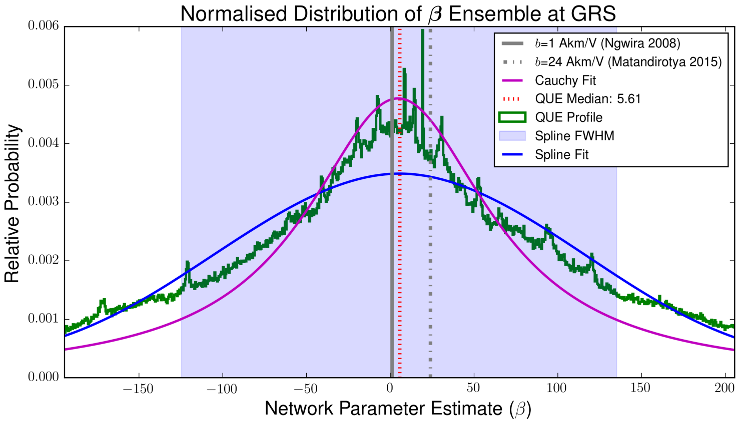


University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

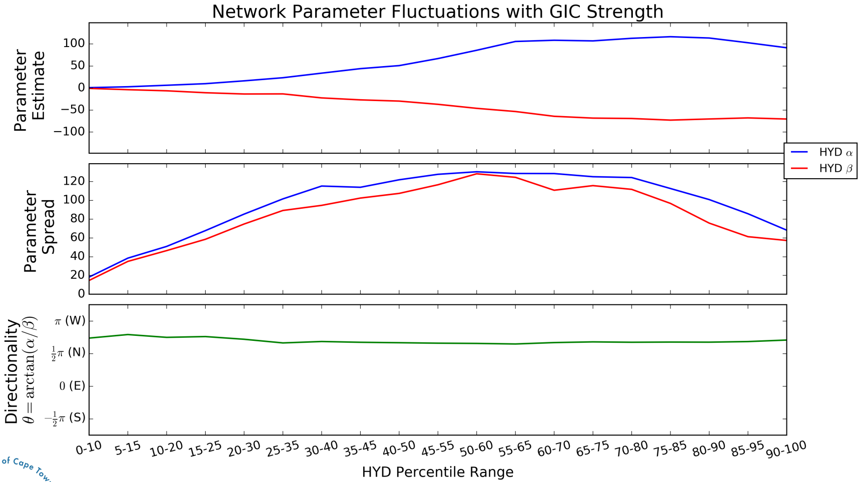
β Parameter Ensemble



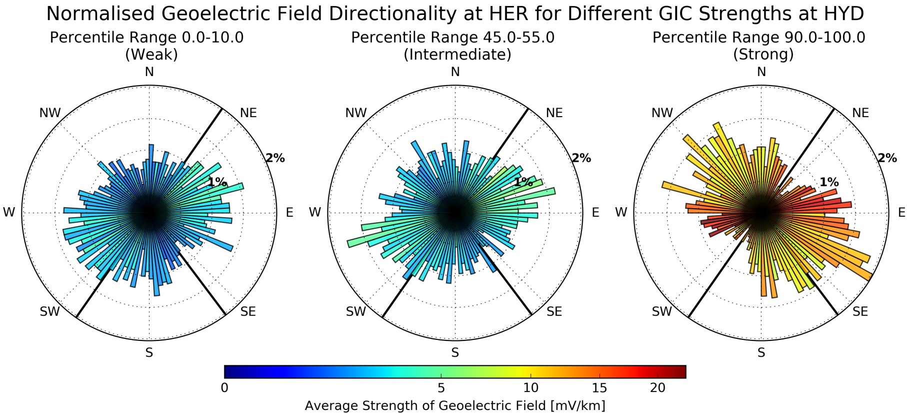
NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

Results - Hydra



Geoelectric Field Directionality with GIC Strength

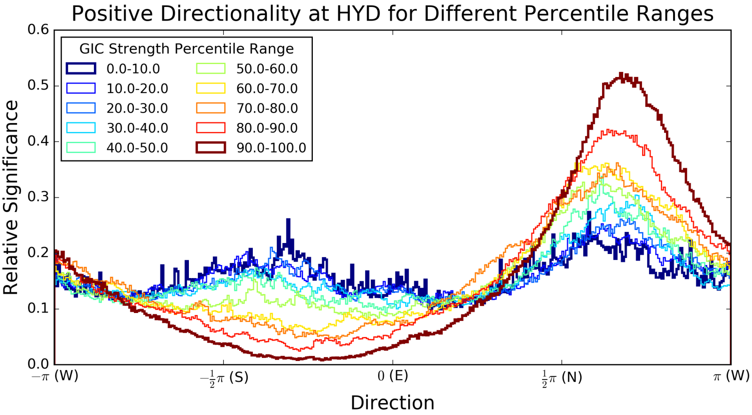


University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

Network Parameter Directionality with GIC Strength



University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

SPES BONA

NASSP NATIONAL ASTROPHYSICS AND SPACE SCIENCE PROGRAMME

sansa SOUTH AFRICAN NATIONAL SPACE AGENCY

Dynamic Network Parameter Estimation