Improving geomagnetic proxies for geomagnetically induced currents (GICs)

Marta Neres[1], Maria Alexandra Pais[2], Joana Ribeiro[3], Fernando Pinheiro[3], Rute Rodrigues Santos[3], and Joao Manuel Cardoso[4]

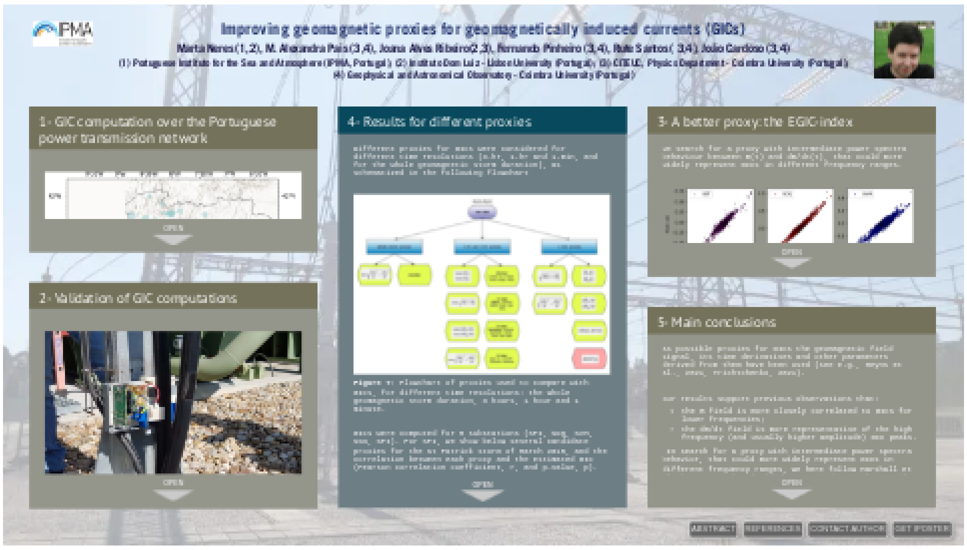
[1]IPMA - Instituto Português do Mar e da Atmosfera
[2]Department of Physics
[3]Department of Physics, CITEUC - University of Coimbra
[4]Department of Physics, LIBPhys-UC - University of Coimbra (Portugal)

November 23, 2022

Abstract

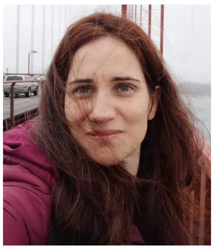
The irregular variation of geomagnetic activity, caused by the solar wind interaction with the magnetosphere/ionosphere, occurs in a wide time interval (from seconds to annual and even larger periods) and amplitude ranges (from few to hundreds of nT). Major variation events (geomagnetic storms) can cause damaging effects and important perturbations to different human activities such as satellite communications, long distance radio broadcasting, navigation, surveying, etc. Furthermore, the induction of electric currents (geomagnetically induced currents – GICs) may affect all grounded conducting networks, in particular electrical power transmission systems. Useful proxies of GIC effects are still under debate; here, we identify the pros and cons of some different candidates. The intensity of geomagnetic activity is usually characterized by geomagnetic indices, among which the 3-hourly indices Kp and local K. In this study we compare 3-hour K and 1-hour K-derived local range indices, using geomagnetic time series from the mid-latitude Coimbra observatory (COI), in Portugal. We also compute smaller time-resolution geomagnetic and GIC indices such as the geomagnetic horizontal field components and their time derivatives, horizontal field magnitude and its time derivative and the LDi/LCi indices [Cid19]. We compare the computed indices with GIC simulations in the Portuguese transmission power grid, to evaluate which of them may be used to nowcast the induced currents. We suggest as a better GIC proxy, an index obtained from geomagnetic field components filtered by convolution with the uniform conductivity Earth filter (new EGIC index). Previous studies have considered the local ground conductivity to be an important factor to determine GIC amplitudes (e.g. [Tri07] and [Rib21]). We then obtain GIC estimations for power grid substations lying at different geological regions. Acknowledgements: This study is funded by national funds through FCT (Portuguese Foundation for Science and Technology, I.P.), under the project MAG-GIC (PTDC/CTA-GEO/31744/2017). FCT is also acknowledged for support through projects UIDB/50019/2020-IDL, PTDC/CTA-GEF/1666/2020 (MN) and PTDC/CTA-GEO/031885/2017 (MN). CITEUC is funded by FCT (UIDB/00611/2020 and UIDP/00611/2020). We acknowledge the collaboration with REN (Redes Energéticas Nacionais).

Improving geomagnetic proxies for geomagnetically induced currents (GICs)



Marta Neres (1,2), M. Alexandra Pais (3,4), Joana Alves Ribeiro(2,3), Fernando Pinheiro (3,4), Rute Santos (3,5), João Cardoso (5)

(1) Portuguese Instituto for the Sea and Atmosphere (IPMA); (2) Instituto Dom Luiz - University of Lisbon; (3) Department of Physics, CITEUC - University of Coimbra; (4) Geophysical and Astronomical Observatory of the University of Coimbra; (5) Department of Physics, LIBPhys-UC - University of Coimbra (Portugal)






PRESENTED AT:

1- GIC COMPUTATION OVER THE PORTUGUESE POWER TRANSMISSION NETWORK

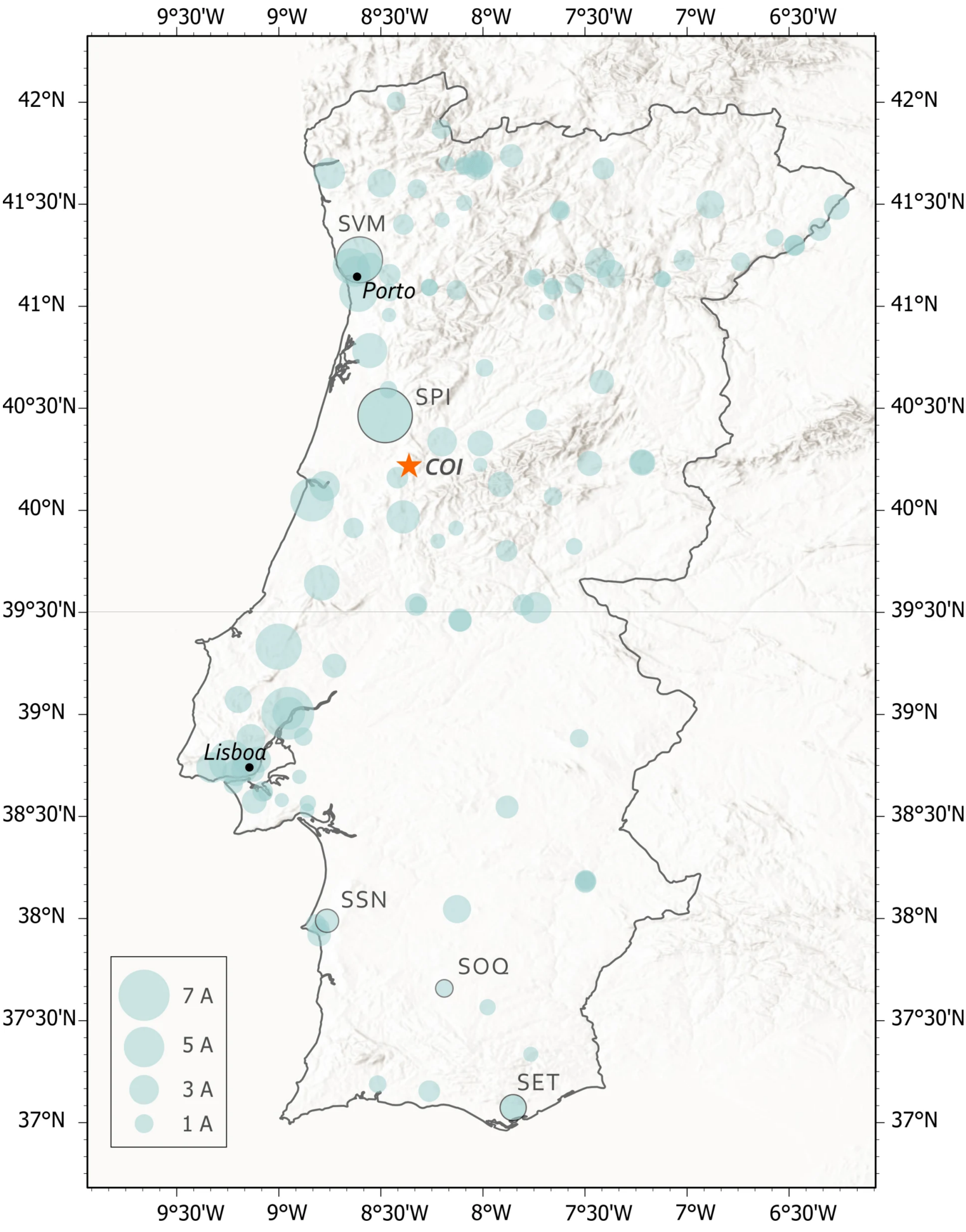


Figure 1: Map of the |GIC| maxima during the St. Patrick Day storm (2015.03.17) for substations in Portugal mainland. A dark contour highlights substations used in this study. The orange star represents the location of the Coimbra geomagnetic observatory (IAGA code COI).

In the framework of **project MAG-GIC** (*Geomagnetically induced currents in Portugal mainland*), GICs were computed in the south sector of the Portuguese power transmission network (Alves Ribeiro et al., 2021). Presently, they are being computed over the whole mainland Portugal based on:

i) geomagnetic source data B(t) from the Magnetic Observatory of Coimbra (COI)

ii) a new 3D conductivity model computed from a 50 x 50 km grid of Magnetotelluric (MT) soundings

iii) information on the topology and resistance parameters of the electric power grid, provided by REN (*Redes Energéticas Nacionais* - the national transmission operator).

The GIC estimation uses the Lehtinen & Pirjola method (1985), with an implementation adapted from GEOMAGICA (Bailey et al., 2017):

$$I = (1 + YZ)^{-1} J$$

I - GICs

YZ - power network parameters

J - electromotive forces

Figure 2: SPI, SOQ, SSN and SET substations and the power network connections to each one of them.

2- VALIDATION OF GIC COMPUTATIONS

Figure 3: Photo of the sensor installed at SPI substation, clamped around the transformer TFR6 neutral grounding cable.

In collaboration with LIBPhys-UC, an instrument for the monitorization of GICs through the use of a Hall effect sensor was assembled, calibrated, and tested in the laboratory.

On the 30th of August 2021, our first acquisition device to measure GICs was installed at one of the transformers neutral at Paraimo substation (SPI) (Figure 3), about 35 km north of Coimbra (Figure 1).

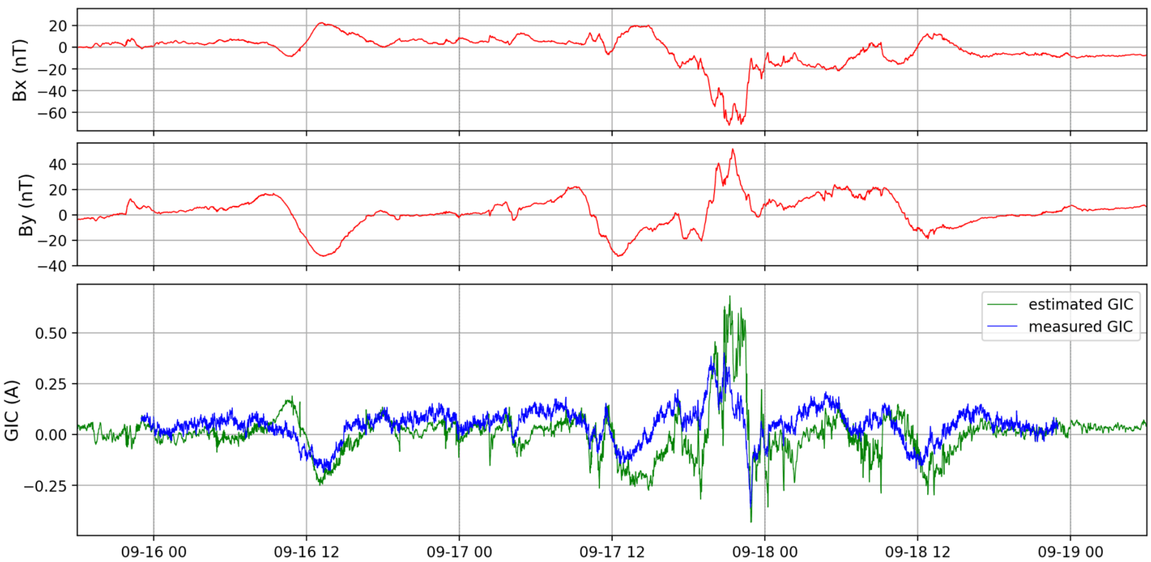


Figure 4: (top) Geomagnetic horizontal components Bx and By from COI observatory, around the 17 September 2021. (bottom) Estimated and measured GICs at the TFR6 transformer neutral during the same period.

GIC measurements allow validating ground resistivity and power network models. Figure 4 shows a comparison between the GIC recorded at Paraimo during the 17 September 2021 storm (Dst(min)=-64 nT) and our model estimate.

Model and observations present similar temporal variations with a Pearson correlation coefficient of 0.6. Differences may be due to imprecision in the conductivity model.

4- RESULTS FOR DIFFERENT PROXIES

Different proxies for GICs were considered for different time resolutions (3-hr, 1-hr and 1-min, and for the whole geomagnetic storm duration), as schematized in the following flowchart

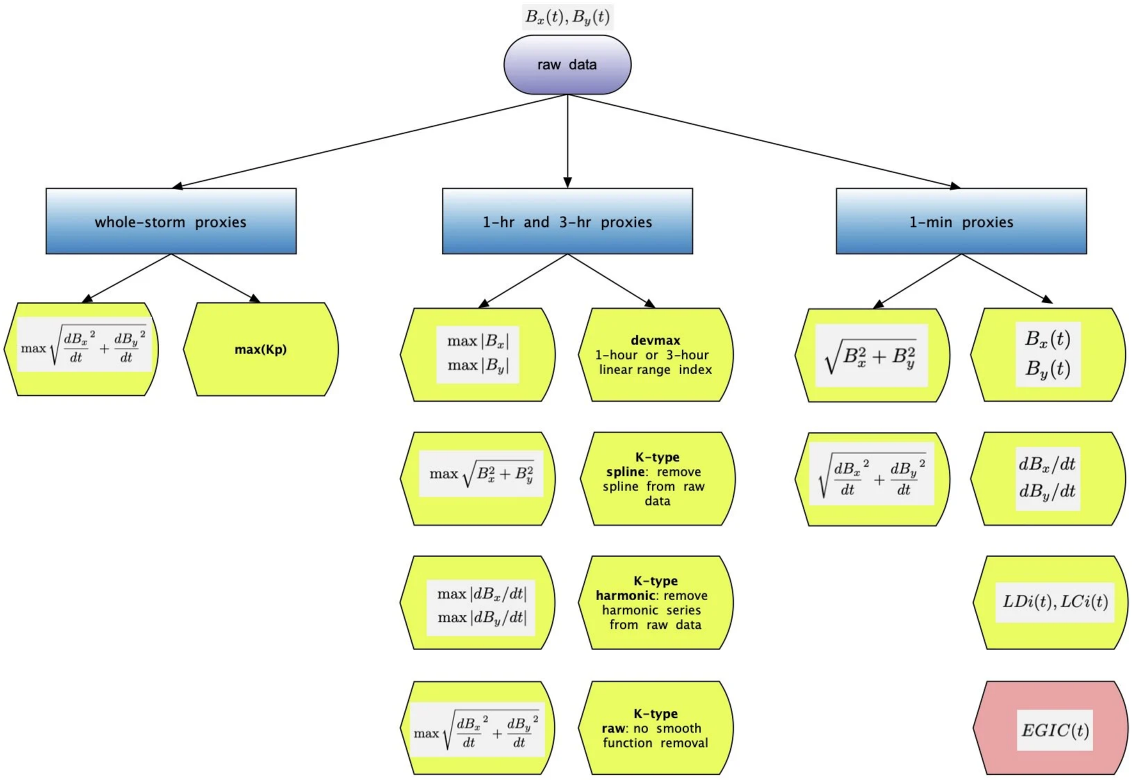


Figure 7: Flowchart of proxies used to compare with GICs, for different time resolutions: the whole geomagnetic storm duration, 3 hours, 1 hour and 1 minute.

GICs were computed for 5 substations (SPI, SOQ, SVM, SSN, SPI). For SPI, we show below several candidate proxies for the St Patrick storm of March 2015, and the correlation between each proxy and the estimated GIC (Pearson correlation coefficient, r, and p-value, p).

Whole-storm proxies

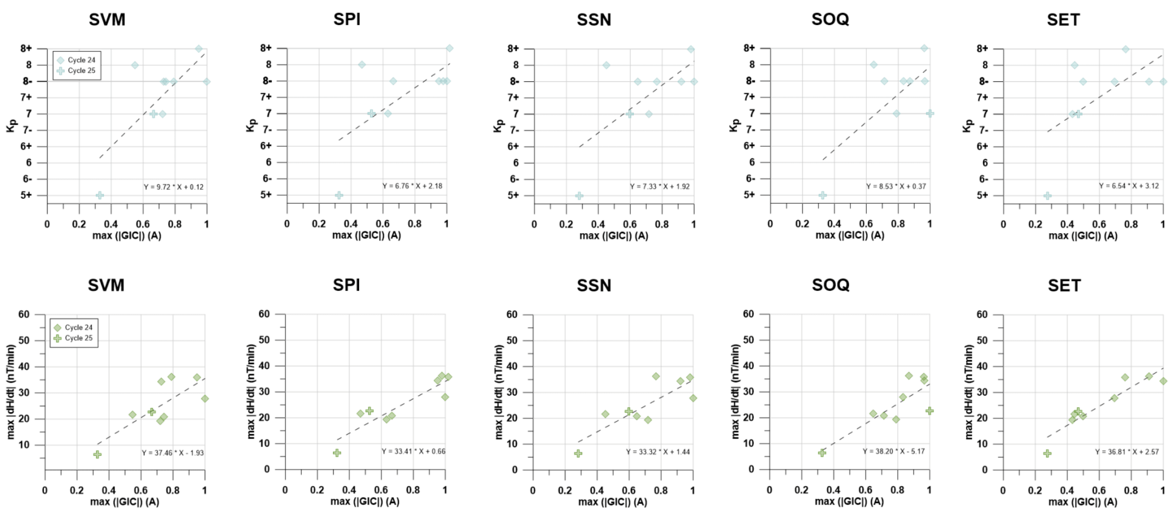


Figure 8: Scatter plots showing the correlation between whole-storm indices Kp and max(|dH/dt|), and the calculated GICs, for 9 storms (7 from Cycle 24 and 2 from Cycle 25).

The maxima |GIC| correlate better with the time derivative index than with Kp.

1-hr and 3-hr proxies

K-type proxies

For the calculation of K-type indices, we tested different methods to account and then remove the smooth variation of geomagnetic components.

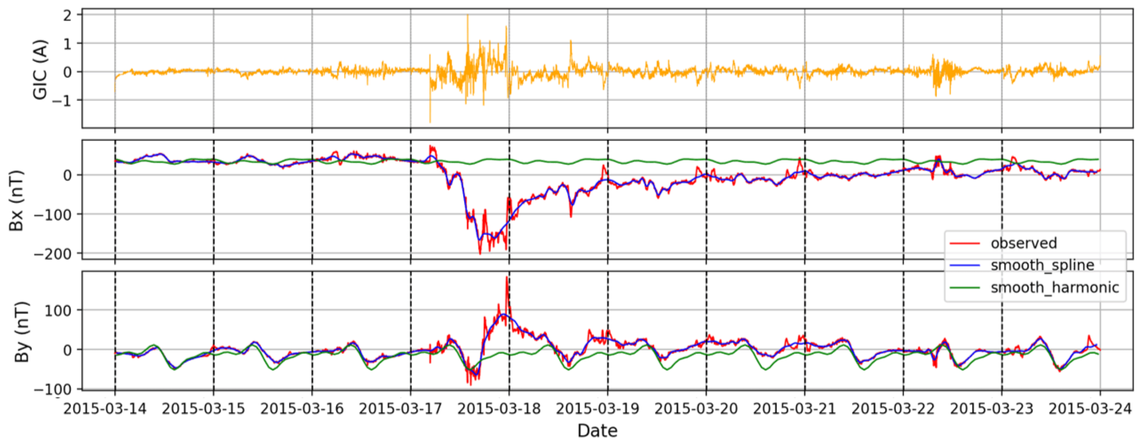


Figure 9: Computed GIC, and geomagnetic field components Bx and By for the 2015.03 storm, as measured at COI: observed (red, raw) and smoothed curve using spline fitting (blue) and harmonic series fitting (green) (Blake, 2017; Menvielle et al., 1995).

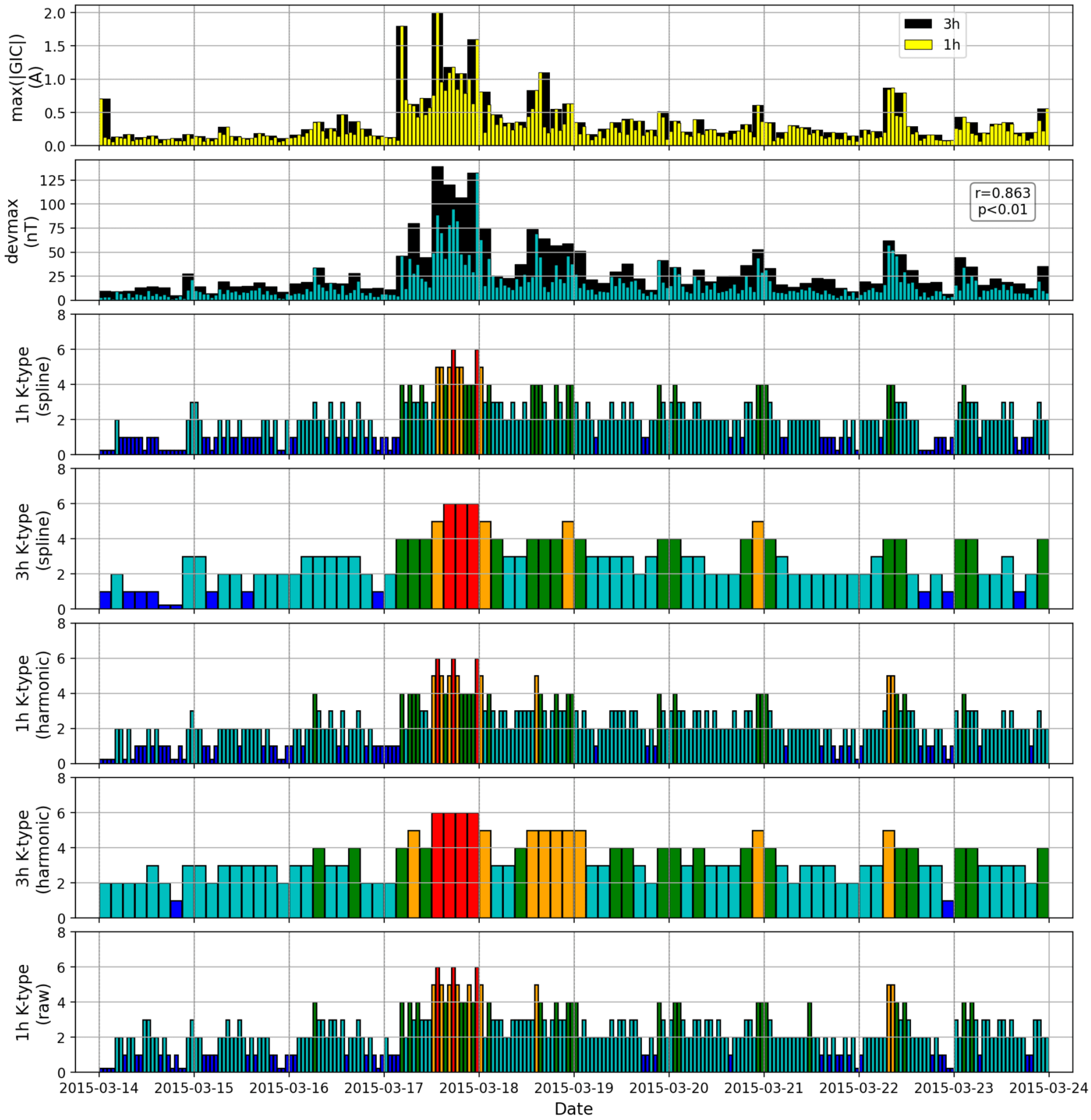


Figure 10: 1-hr and 3-hr K-type indices, for the 03.2015 storm. *devmax* is a linear index that measures the maximum range in Bx or By values during 1 hour (3 hours) interval (Trichtchenko and Boteler, 2007) (see Figure 7).

H and dH/dt proxies

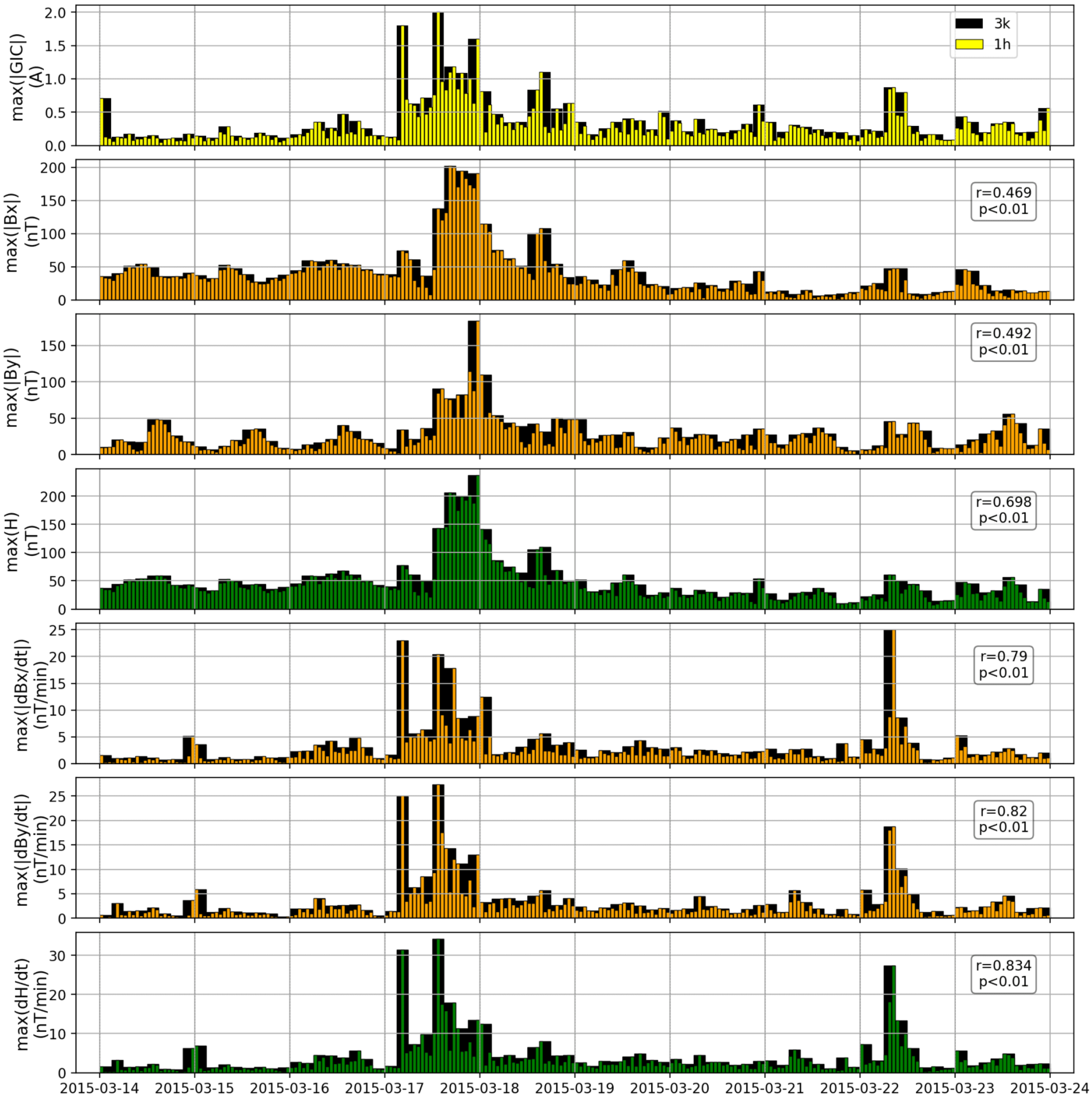


Figure 11: Correlation of |GIC| with 1-hr maximum absolute values of horizontal components (|Bx| and |By|), with their combination into H and with absolute values of time derivatives (Figure 7).

1-min proxies

B and dB/dt proxies

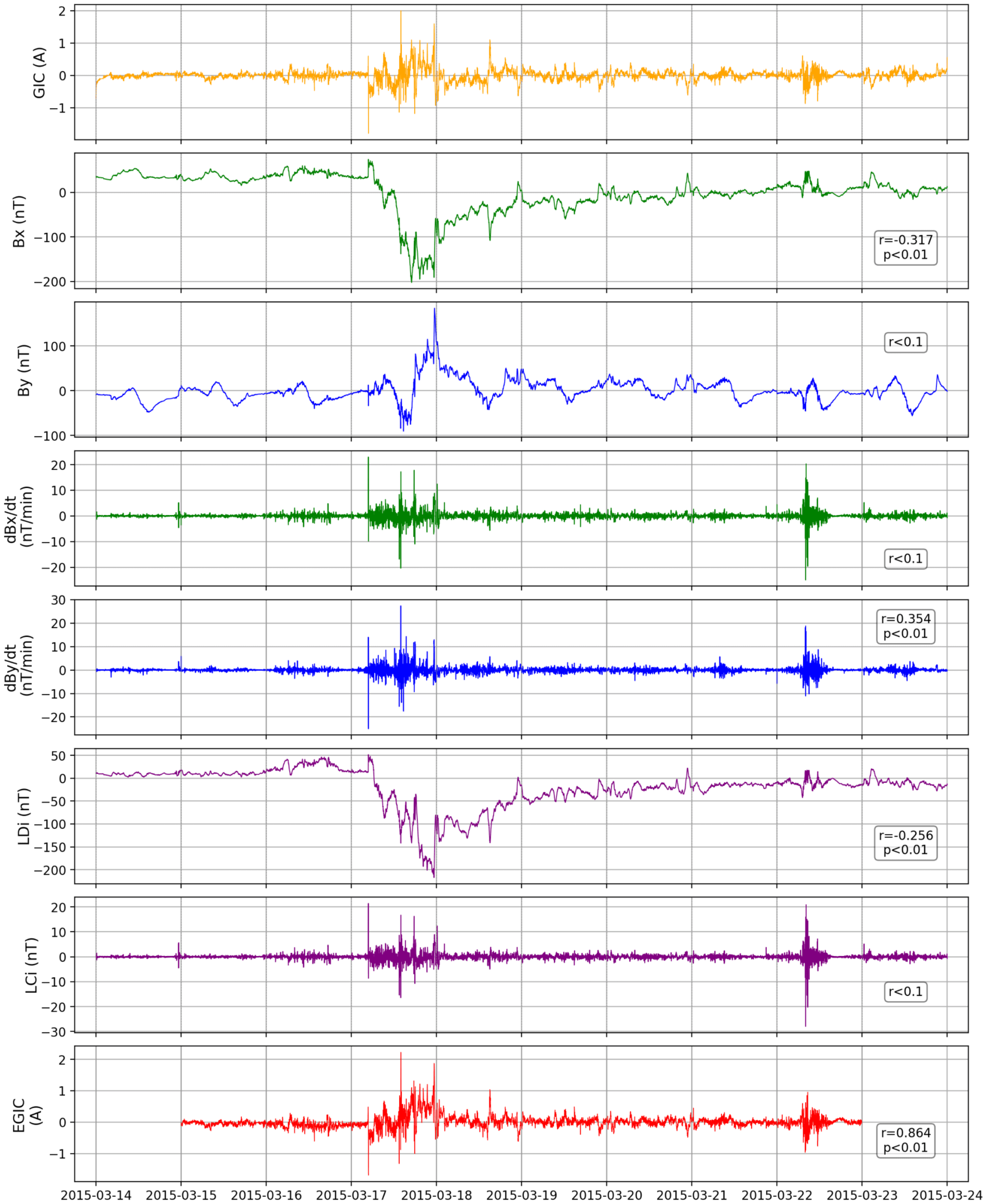


Figure 12: For the 03.2015 storm, the correlation between GIC and: (green and blue) Bx, By, and respective time derivatives; (purple) LDi and LCi indices (Cid et al., 2019); (red) the EGIC-index defined in section 3 (Figure 7).

H and dH/dt proxies

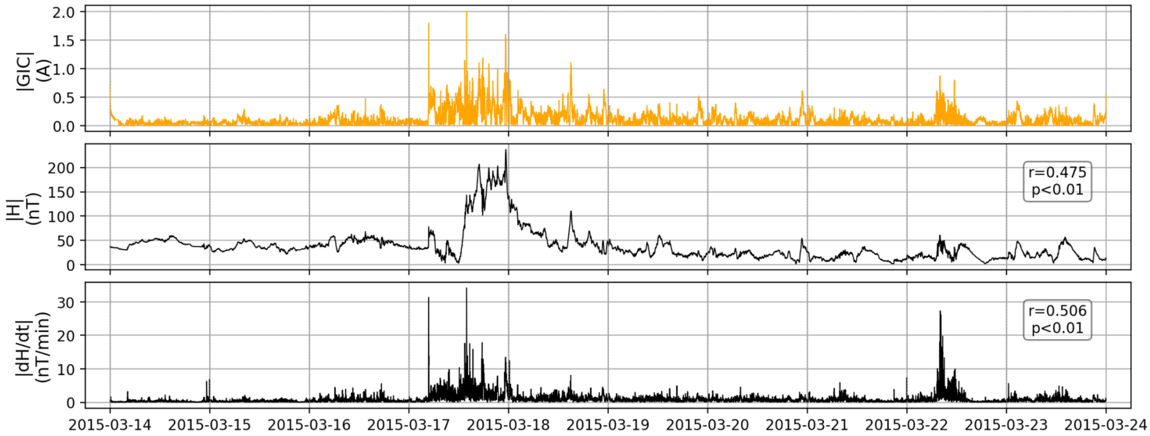


Figure 13: Correlation of |GIC| with the magnitude of the horizontal component $H = \sqrt{B_x^2 + B_y^2}$ and with the magnitude of the time derivative of $\vec{H}$

3- A BETTER PROXY: THE EGIC-INDEX

We search for a proxy with intermediate power spectra behaviour between B(t) and dB/dt(t), that could more widely represent GICs in different frequency ranges.

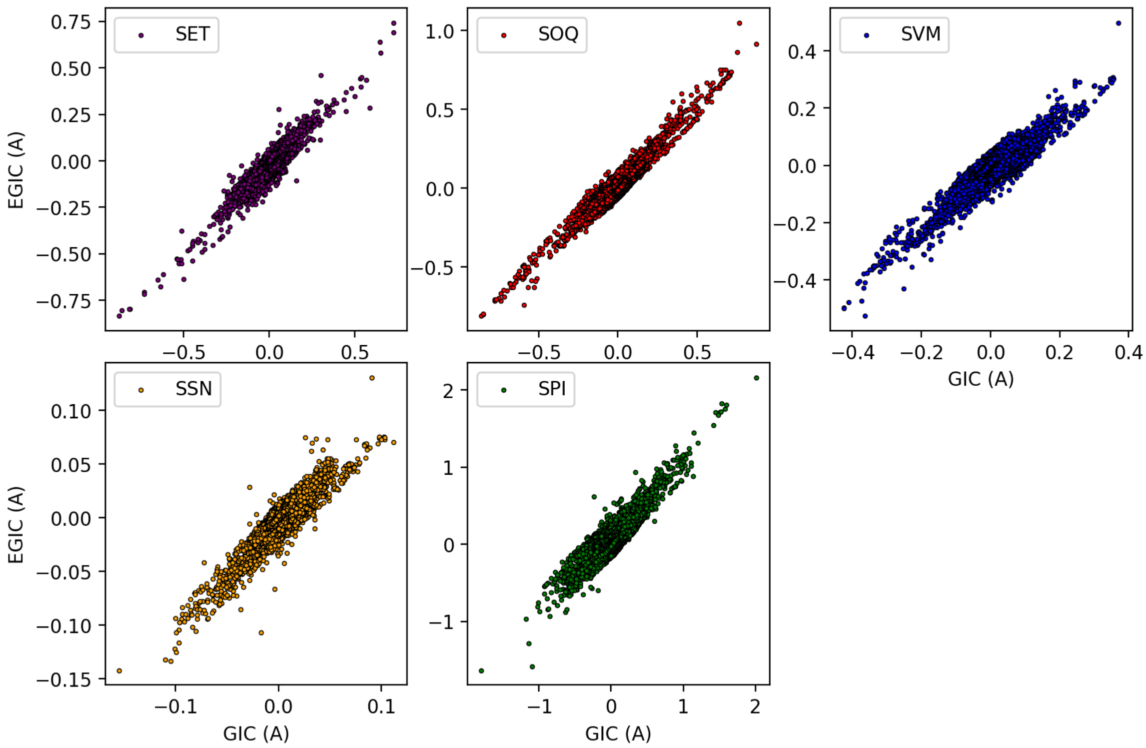


Figure 5: Scatter plots showing the correlation between the *EGIC*-index and the calculated GIC at different substations, during the 2015.03 storm.

Marshall et al. (2010, 2011) proposed two GIC indices computed from the two components of the geomagnetic storm horizontal field signal $\vec{H} = B_x\,\hat{i} + B_y\,\hat{j}$

transformed with the filter of a uniform conductivity (ρ = 1000 Ω.m) solid Earth.

Here, we call that signal $\vec{E}_{pseudo}$, since it is physically an induced electric field (e.g., Cagniard, 1953):

$$\vec{E}_{pseudo} = \frac{1}{\sqrt{\pi\,\mu_0}}\hat{k} \wedge \int_0^{\infty} \frac{1}{\sqrt{\tau}} \frac{d\vec{H}(t-\tau)}{d\tau}\,d\tau$$

and search for the best combination of its two components $E_{pseudo,x}$ and $E_{pseudo,y}$in the sense of fitting more closely the GIC. We call that proxy ***EGIC***:

$$EGIC = A\,E_{pseudo,x} + B\,E_{pseudo,y}$$

and compute the parameters ***A*** and ***B*** using the least-squares method. As can be seen in Figure 5, the EGIC-index then computed shows a very high correlation with simulated GICs.

	A	B	σ_A	σ_B
SPI	20751.4	55524.8	2252.9	4423.5
SVM	3321.7	−17640.4	644.5	1299.7
SSN	614.8	−4628.2	156.9	394.2
SOQ	−22020.5	26581.6	949.5	1399.2
SET	−20131.7	−9433.7	408.8	1107.5

Table 1: ***A*** and ***B*** parameters for each of the 5 studied substations, based on geomagnetic data of 4 storms: 2012.03, 2013.09, 2015.03, 2021.11

The EGIC-index curves for each substation during the 2015 St Patrick storm, computed using parameters in Table 1, are shown below.

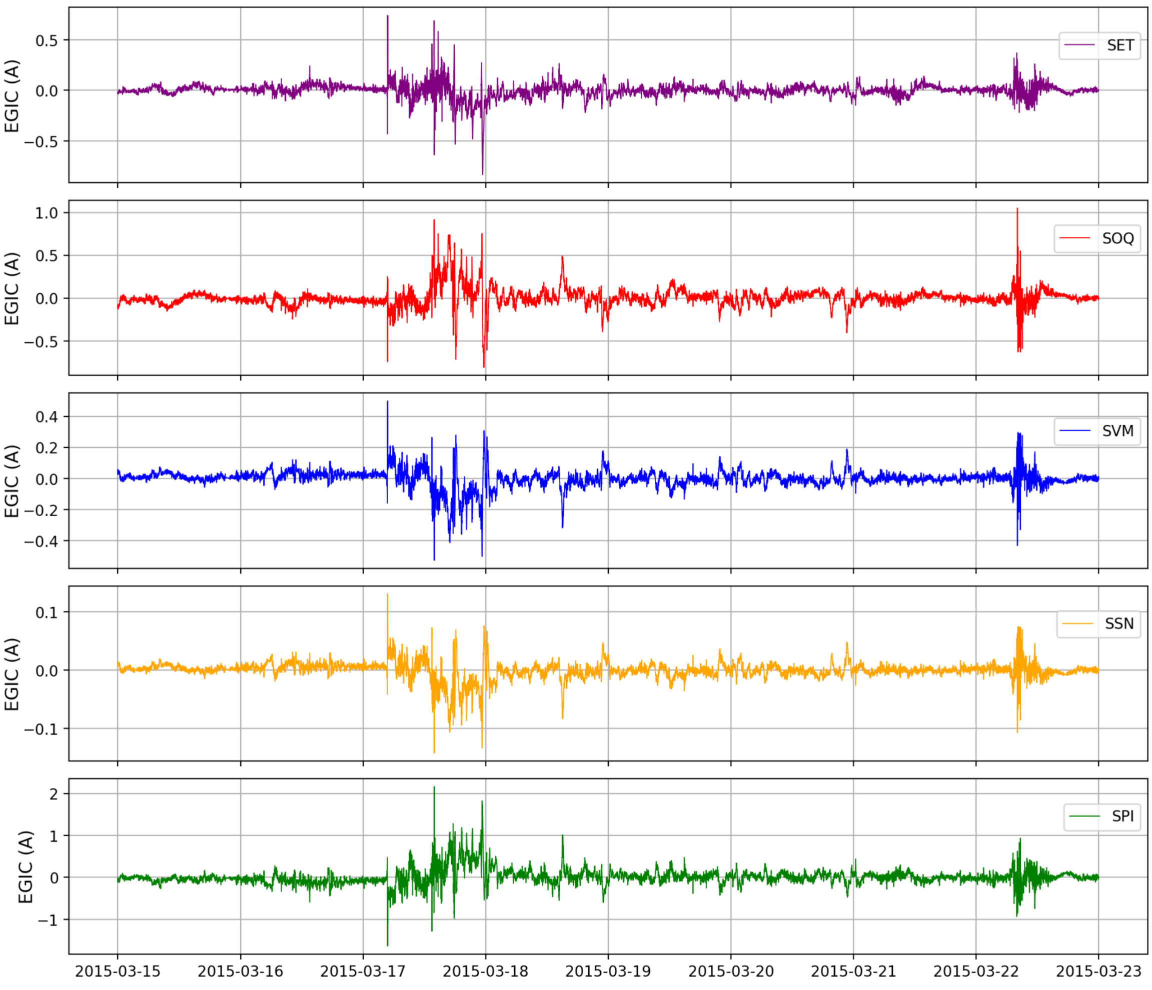


Figure 6: ***EGIC*** index calculated for 5 substations for the period 15-22 March 2015 (St. Patrick's storm, 2015.03).

5- MAIN CONCLUSIONS

As possible proxies for GICs the geomagnetic field signal, its time derivatives and other parameters derived from them have been used (see e.g., Heyns et al., 2021, Trichtchenko, 2021).

Our results support previous observations that:

- the B field is more closely correlated to GICs for lower frequencies;
- the dB/dt field is more representative of the high frequency (and usually higher amplitude) GIC peaks.

In search for a proxy with intermediate power spectra behavior, that could more widely represent GICs in different frequency ranges, we here follow Marshall et al. (2010, 2011) and add the EGIC-index to the set of proxies to compare with our simulated GICs.

Our main conclusions follow:

1. At the level of the whole-storm duration, dH/dt is a better proxy for GICs than Kp
2. For 3-hr and 1-hr time resolutions, K-type indices miss detecting GICs due to Sudden Storm Commencements (SSC)
3. The dH/dt index performs quite well at 1-hr and 3-hr time resolution
4. At higher resolution (1-min), a combination of different components of B and dB/dt come into play to explain the GIC signal
5. The EGIC-index, a linear combination of the two components of the Epseudo induced field, is clearly the best proxy at 1-min time resolution.
6. For each substation, parameters A and B fitted to simulations not only allow to quickly estimate local GICs but can also be used to improve the local conductivity models.

ABSTRACT

The irregular variation of geomagnetic activity, caused by the solar wind interaction with the magnetosphere/ionosphere, occurs in a wide time interval (from seconds to annual and even larger periods) and amplitude ranges (from few to hundreds of nT). Major variation events (geomagnetic storms) can cause damaging effects and important perturbations to different human activities such as satellite communications, long distance radio broadcasting, navigation, surveying, etc. Furthermore, the induction of electric currents (geomagnetically induced currents – GICs) may affect all grounded conducting networks, in particular electrical power transmission systems.

Useful proxies of GIC effects are still under debate; here, we identify the pros and cons of some different candidates. The intensity of geomagnetic activity is usually characterized by geomagnetic indices, among which the 3-hourly indices Kp and local K. In this study we compare 3-hour K and 1-hour K-derived local range indices, using geomagnetic time series from the mid-latitude Coimbra observatory (COI), in Portugal. We also compute smaller time-resolution geomagnetic and GIC indices such as the geomagnetic horizontal field components and their time derivatives, horizontal field magnitude and its time derivative and the LDi/LCi indices [Cid19].

We compare the computed indices with GIC simulations in the Portuguese transmission power grid, to evaluate which of them may be used to nowcast the induced currents. We suggest as a better GIC proxy, an index obtained from geomagnetic field components filtered by convolution with the uniform conductivity Earth filter (new EGIC index). Previous studies have considered the local ground conductivity to be an important factor to determine GIC amplitudes (e.g. [Tri07] and [Rib21]). We then obtain GIC estimations for power grid substations lying at different geological regions.

Acknowledgements:

This study is funded by national funds through FCT (Portuguese Foundation for Science and Technology, I.P.), under the project MAG-GIC (PTDC/CTA-GEO/31744/2017). FCT is also acknowledged for support through projects UIDB/50019/2020-IDL, PTDC/CTA-GEF/1666/2020 (MN) and PTDC/CTA-GEO/031885/2017 (MN). CITEUC is funded by FCT (UIDB/00611/2020 and UIDP/00611/2020). We acknowledge the collaboration with REN (Redes Energéticas Nacionais).

REFERENCES

- Alves Ribeiro, Joana, Fernando JG Pinheiro, and Pais, Maria Alexandra (2021). "First Estimations of Geomagnetically Induced Currents in the South of Portugal." Space Weather 19.1: e2020SW002546.
- Blake, Seán (2017). "Modelling and monitoring geomagnetically induced currents in Ireland". Diss. Trinity College Dublin, Ireland.
- Bailey, Rachel L., et al 2017. "Modelling geomagnetically induced currents in midlatitude Central Europe using a thin-sheet approach." Annales Geophysicae. Vol. 35. No. 3. Copernicus GmbH.
- Cagniard, Louis (1953). "Basic theory of the magneto-telluric method of geophysical prospecting." *Geophysics* 18.3: 605-635.
- Cid, C., Guerrero, A., Saiz, E., Halford, A. J., & Kellerman, A. C. (2019). "Developing the LDi and LCi geomagnetic indices, an example of application of the AULs framework". Space Weather, 18, e2019SW002171. https://doi.org/10.1029/2019SW002171
- Heyns, M. J., S. I. Lotz, and C. T. Gaunt (2021). "Geomagnetic Pulsations Driving Geomagnetically Induced Currents." Space Weather 19.2: e2020SW002557.
- Lehtinen, M., & Pirjola, R. (1985). "Currents produced in earthed conductor networks by geomagnetically-induced electric fields". Annales geophysicae (1983), 3, 479–484.
- Marshall, R. A., C. L. Waters, and M. D. Sciffer (2010). "Spectral analysis of pipe-to-soil potentials with variations of the Earth's magnetic field in the Australian region." Space Weather 8.5.
- Marshall, R. A., et al (2011). "A preliminary risk assessment of the Australian region power network to space weather." Space Weather 9.10.
- Menvielle, M., et al (1995). "Computer production of K indices: review and comparison of methods." Geophysical Journal International 123.3: 866-88
- Trichtchenko, Larisa (2021). "Frequency considerations in GIC applications." Space Weather 19.8: e2020SW002694.
- Trichtchenko, L., and D. H. Boteler (2007). "Effects of recent geomagnetic storms on power systems." 2007 7th International Symposium on Electromagnetic Compatibility and Electromagnetic Ecology. IEEE.
- FMI method of K-index calculation: http://isgi.unistra.fr/softwares.php (http://isgi.unistra.fr/softwares.php)
- Sean Blake's method for K-index calculation: https://github.com/TerminusEst/k_index_calculator (https://github.com/TerminusEst/k_index_calculator)