MAG-GIC

Geomagnetically induced currents in Portugal mainland

PTDC/CTA-GEO/31744/2017

Final Report – Scientific Component

Prepared by: MAG-GIC Scientific Team

Coimbra, December 2022

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1. Summary

The MAG-GIC (Geomagnetically induced currents in Portugal mainland) project was funded by FCT (Fundação para a Ciência e Tecnologia) with the reference PTDC/CTA¬GEO/31744/2017 and ran from 01 October 2018 to 30 September 2022.

The main, unifying goal of this proposal was to assess, for the first time, the Space Weather hazard to power systems in Portugal mainland. This goal was achieved in the framework of WP4 (Work Package 4) in two ways, i) by producing estimates of geomagnetically induced currents (GICs) in all substations of the transmission power network operated by REN (Redes Energéticas Nacionais); ii) by assembling, testing in the laboratory, and finally installing at the Paraimo substation the first instrumental setup to measure GICs in the Portuguese power network. Parallel to this intent, and to accomplish it, the first 3D conductivity model for the whole Portugal mainland was computed in a grid of approximately 50 x 50 km of magnetotelluric (MT) soundings. This was the work developed in WP3.

Two other work packages, WP2 and WP5, dealt with more fundamental questions concerning the interpretation and modelling of sources that produce GICs. It was the case of the use of principal component analysis (PCA) to separate the solar quiet (Sq) and solar disturbed (SD) contributions to the geomagnetic field variations observed at Coimbra magnetic observatory (WP2) and the separation of different external current systems using Swarm satellite data to build a regular grid of virtual observatories (VO), using the Equivalent Source Dipole (ESD) technique and PCA on the VO generated dataset (WP5).

A further goal of this project, underlying the relevance of the geomagnetic data used in all other work packages, was the transfer of the magnetic observatory of the University Coimbra (COI) to a new site free of urban electromagnetic noise (WP1). A field campaign concluded on the viability of the S. Marcos site for the installation of a new observatory, and a report was produced.

To conclude, we highlight, as a particular feature of the MAG-GIC project, the successful participation of experts from different fields of geophysics, engineering, and mathematics, in a multidisciplinary and transdisciplinary approach.

2. The project team and collaborators

The PI, Co-PI and task leaders were Alexandra Pais (PI, WP5), Anna Morozova (Co-PI, WP2), Paulo Ribeiro (WP1), Fernando Santos/ Joana Alves Ribeiro (WP3) and Fernando Pinheiro (WP4). Joana Alves Ribeiro was the full-time Researcher in the project, and João Fernandes was responsible for the project webpage and outreach.

Besides researchers, four students were participating in the project: Cristiana Francisco (MSc student), Pedro Baltazar-Soares (MSc student, grant-holder), Rania Rebbah (MSc student, grant-holder) and Rute Santos (MSc student, grant-holder).

Two institutions, the University of Coimbra and FCiências.ID - Associação para a Investigação e Desenvolvimento, and two research units, CITEUC (Centro de Investigação da Terra e do Espaço da UC) and IDL (Instituto Dom Luiz), were initially involved in the MAG-GIC project. The Co-PI, Anna Morozova, moved from the research center CITEUC to the new Instituto de Astrofísica-UC pole in April 2021.

Two very important collaborations were established, the first one with REN (Redes Energéticas Nacionais) and the second one with LIBPhys-UC (Laboratory for Instrumentation, Biomedical Engineering and Radiation Physics) at the Physics Department of UC. The collaboration with REN was planned since the beginning, not only as a requirement to have access to fundamental data but also to get technical expert assistance all along the project. The collaboration with LIBPhys-UC, a research unit with expertise in developing electronic instrumentation for different applications, was established during the second year of the project because of the need to validate simulations with measurements and to see the obtained results more largely recognized by the scientific community.

Besides, there were several collaborations with researchers outside the project team from which we should outline:

- Collaboration with scientific consultant Dr. Diana Saturnino (LPGNantes, France) through the participation in WP 5, with a paper published and several joint communications.
- Collaboration with Jurgen Matzka (GFZ Potsdam, Head of IAGA Working Group V-OBS: Geomagnetic Observations), Katia Pinheiro (Observatório Nacional do Brazil, Co-chair of IAGA Working Group V-OBS: Geomagnetic Observations) and Marcos Vinicius (Observatório Nacional do Brazil), related to WP 1, with a joint communication at EGU2021, and a report on the viability of S. Marcos farm to host the Magnetic Observatory of Coimbra. Katia Pinheiro and Marcos Vinicius contributed strongly to the geomagnetic data analysis that led to the validation of the S. Marcos site and are presently contributing to testing the Viseu site. They were invited to Coimbra to give the Workshop 'Observatórios Magnéticos' at the Physics Department and the Geophysical and Astronomical Observatory from 5 to 8 September 2022.
- Collaboration with Marta Neres from IPMA on developing indices most adequate to describe geomagnetically induced currents (GICs) related to WP 4, with several joint communications. During the last year of the project, and due to the need to reassess the initial plan for the magnetic observatory relocation (WP 1), Marta Neres was the IPMA contact partner in a joint plan to relocate the COI magnetic observatory at an IPMA meteorological station near Viseu.

3. Work done and Deviations to the Approved Proposal

3.1 Progress report for the individual Tasks

3.1.1 WP1 - Geomagnetic data provision and transfer of COI station

The computation of GICs (WP4) has relied on the geomagnetic data as measured at the COI station at its current location in Alto da Baleia to provide for good quality time series of the two components Bx (North-South) and By (East-West) of the geomagnetic field. This goal was totally achieved, allowing to produce estimates of GICs on the power network substations during different geomagnetic storms registered at COI. The component most affected by urban noise is Bz (vertical), which is not used in those calculations.

This task most demanding and difficult goal was to plan and execute the transfer of COI station to a new site. In the following, we report on the several steps to achieve this goal and the difficulties in accomplishing it.

Magnetic surveys: Between the end of 2018 and mid-2019, magnetic surveys took place in the S. Marcos Palace farm (located in a rural area about 15 km west of Coimbra over limestone Cretaceous terrains, Fig. 1), using an Overhauser GSM-19WG magnetometer to map the horizontal and vertical gradients. As a result of these campaigns, a suitable major area was identified, located near the eastern wall of the farm, away from the palace and farm facilities (external blue line on Fig. 1), far from roads or rural paths outside the farm’s wall, thus reducing the risk of disturbances for the natural magnetic field.

Figure 1. *The S. Marcos farm (border as red line) and surveyed areas (blue lines).*

The measured low values for the magnetic gradients led us to choose this site as suitable for the future installation of the new observatory. We could select a sub-area of local lower gradients, which was surveyed using a thinner grid (5 profiles oriented approximately NNW-SSE and separated from each other by 5 m) (Fig. 2). Inside this area, two smaller areas (10x10 m, 5x5 m, about 30 m apart), intended for the installation of magnetic instruments (absolute and variometer, respectively), were surveyed following a rectangular grid of 1x1 m.

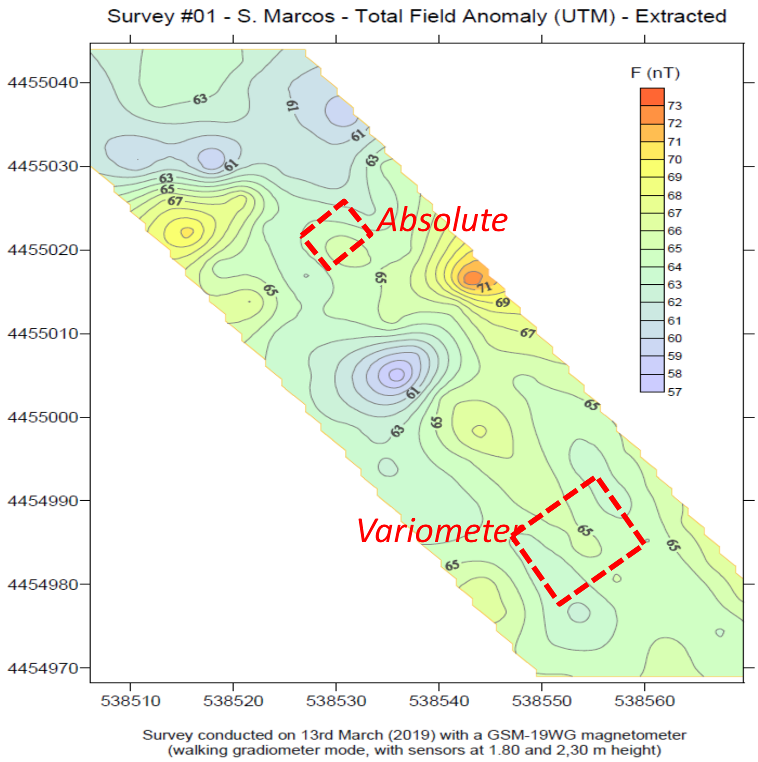

Figure 2*. Map of total field anomalies of the selected area for the installation of the new magnetic observatory in the farm of S. Marcos Palace; the red rectangles show the selection of two sub-areas for the installation of magnetic instruments.*

Electrical soundings: At the beginning of November 2019, electrical soundings were carried out to characterize the surface earth conductivity at the chosen site using Electrical Resistivity Tomography (ERT), a galvanic geophysical method that maps the electrical resistivity of the subsurface along profiles through injection of direct current into the soil. In this study, two 180 m long profiles were made with an approximate N-S orientation (see Fig. 3). Using a Syscal Pro Switch resistivimeter, the profiles were acquired according to the Wenner-Schlumberger array configuration and an electrode spacing of 5 m. Figure 3 shows the profiles and resistivity models obtained after data inversion. Characterized by global values of relatively low to high resistivity (~10-1000 Ω.m) characteristic of the studied region lithology (sandstones, marls and limestones), the models suggest a more or less “stratified” distribution of resistivity, essentially reflecting an undeformed geological stratification. The lower values of resistivity (<40 Ω.m, represented by blue colors) do probably correspond to saturated sedimentary water levels, while the higher values (300 Ω.m, reddish colors) may correspond to anthropic material since they are located at the most superficial levels of the terrain. The results obtained in the two profiles did not show important resistive bodies.

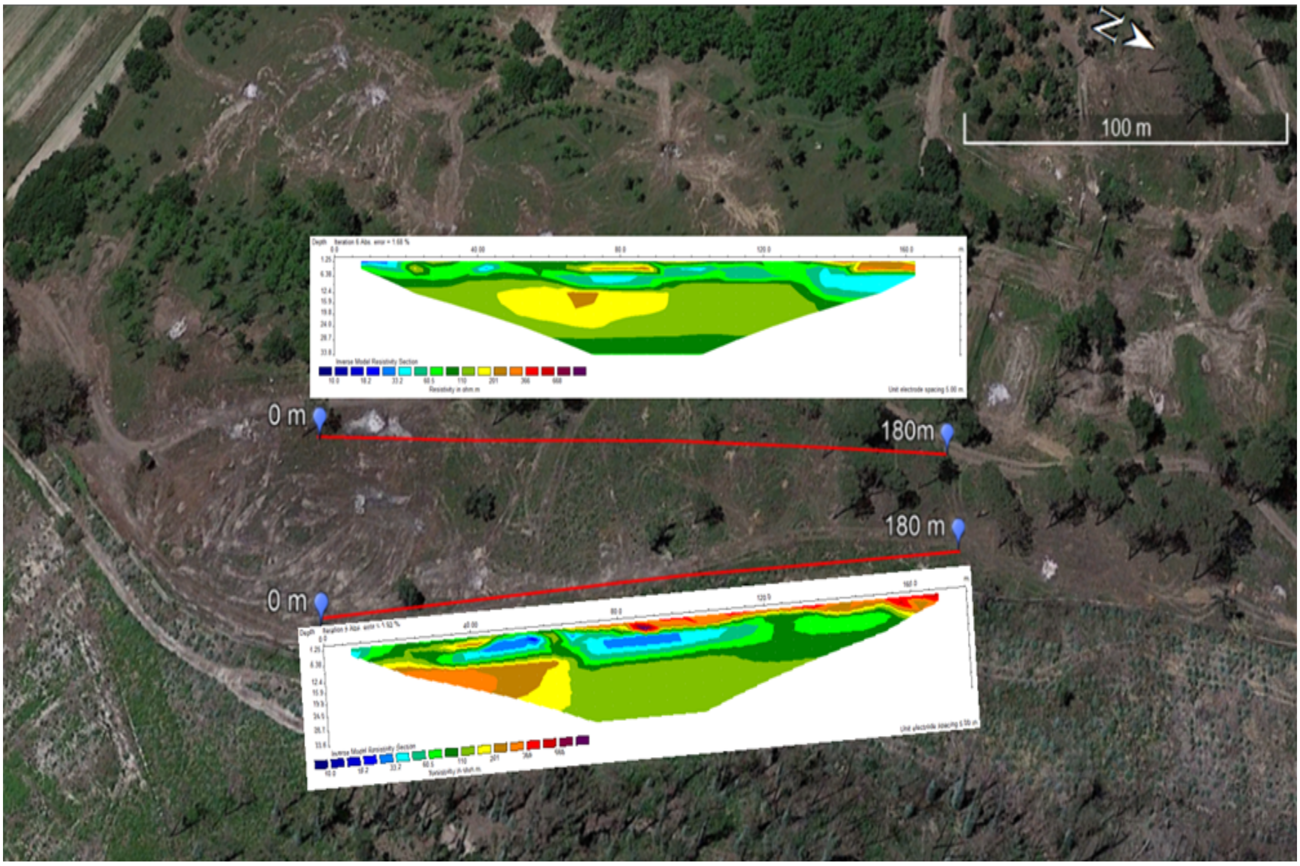

***Figure 3**. Location of the electrical profiles at Quinta de São Marcos, with the resistivity models obtained after data inversion.*

Continuous recordings (station mode): During July, September, and October 2020, a Lemi-018 triaxial magnetometer lent by IDL was installed in the centre of one of the previously selected areas for continuous recording of XYZ geomagnetic components. An anomalous signal was detected with the Lemi-018, possibly due to the instrument ageing, and a new magnetometer GEOMAG-02M was ordered to private enterprise GEOMAGNET (Ukraine) by OGAUC. Due to difficulties arisen from the Covid-19 pandemic, the magnetometer only arrived at Portugal in May 2021. The data obtained with the new GEOMAG-02M allowed to conclude that previously observed noise was associated with the malfunctioning of the Lemi-018 instrument.

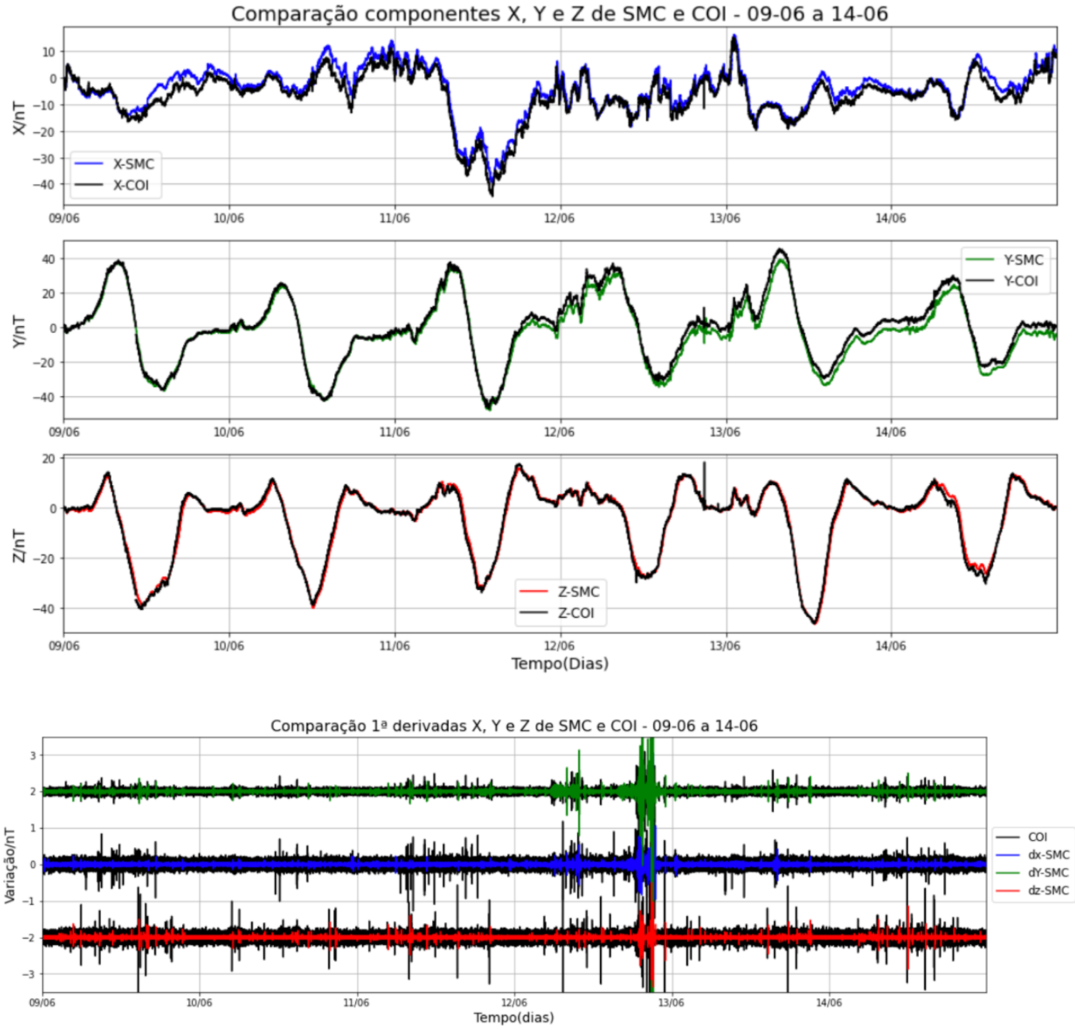

Figure 4*: Plots of the curves of X, Y and Z components (1-second sampling) at COI (XYZ) and SMC (XYZ), for the period 09-14 June 2021; Lower panel: corresponding plots for the first differences.*

Data analysis and report: In collaboration with Jurgen Matzka from GFZ Potsdam and Katia Pinheiro and Marcos Vinicius from Observatório Nacional (Brasil), the continuous data series obtained with the new GEOMAG-02M magnetometer during June-July 2021 were analysed (Fig. 4), allowing to conclude that the S. Marcos farm provided for the conditions of artificial noise isolation that are required to run a magnetic observatory. During July/August 2021, a report was written by the team and validated by Jurgen Matzka, Head of IAGA Working Group V-OBS: 'Geomagnetic Observations', who also wrote a support letter.

Main accomplishments:

- A final assessment on the viability of S. Marcos farm to install a magnetic observatory, supported by magnetic and electric geophysical surveys and the data analysis using neighboring observatories for comparison.

3.1.2 WP2 - Separation of GIC sources

The main purpose of this task was the analysis of the existing geomagnetic series to determine conditions and methods for separation of different contributions (magnetospheric, ionospheric) to the regular variations of the geomagnetic field: regular magnetospheric (so-called solar disturbed, SD, variation) and regular ionospheric (so-called solar quiet, Sq, variations).

PCA analysis: The main technique used to separate Sq and SD variations was the principal component analysis (PCA). The technique was applied to the Coimbra Geomagnetic Observatory (COI) measurements of the geomagnetic field components H, X, Y and Z between 2007 and 2017 (1 hour data). Each month was analysed separately to take care of the seasonal variability of Sq variation. The month-long series of the X, Y, Z and H elements of the geomagnetic field were analysed for all years from 2007 to 2017, both individually and combined.

Testing of the method: As the next step, we compared the PC series with Sq and SD series calculated using the standard approach: Sq is calculated as a mean daily variations for 5 international quiet days (IQD) for each of the analyzed months; SD is calculated as a difference between the mean daily variation obtained for a selected month and the corresponding Sq series. Two examples of the PC1 and PC2 series for the X element for the August and October months are shown in Figures 5 and 6, respectively, in comparison to the mean Sq and SD series.

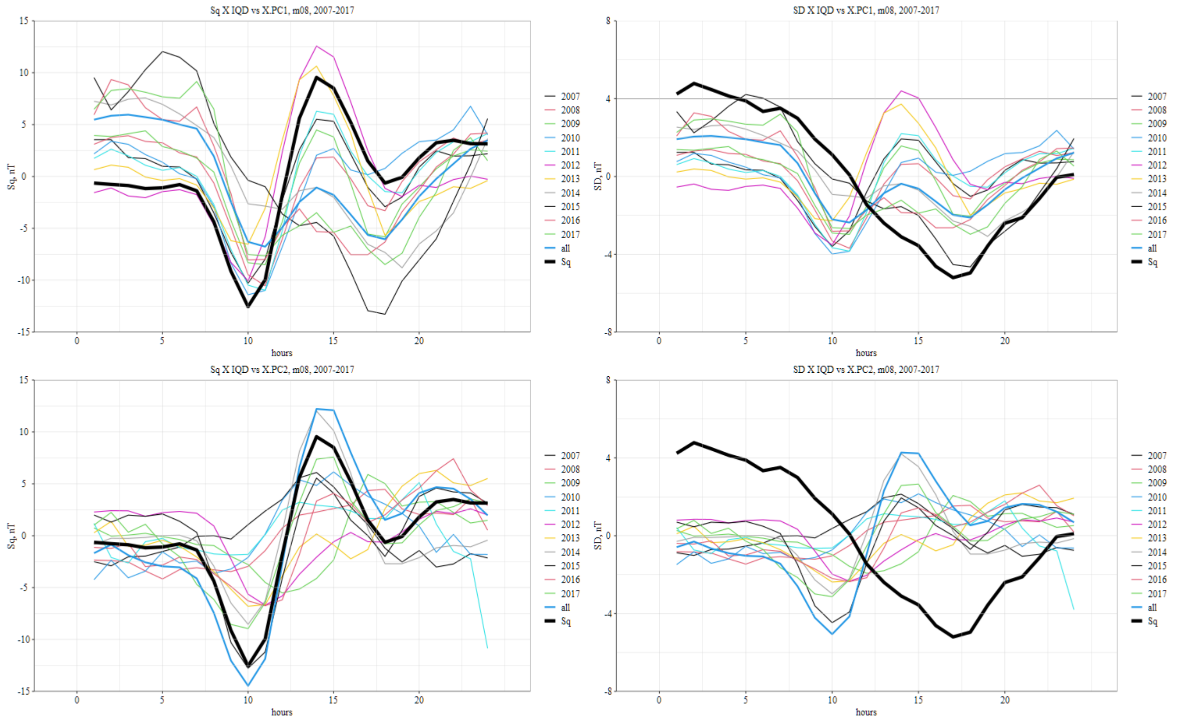

Figure 5. *Series of PC1 (top) and PC2 (bottom) for the X component of the geomagnetic field for August from 2007 to 2017 together with the mean Sq (left) and SD (right), in bold.*

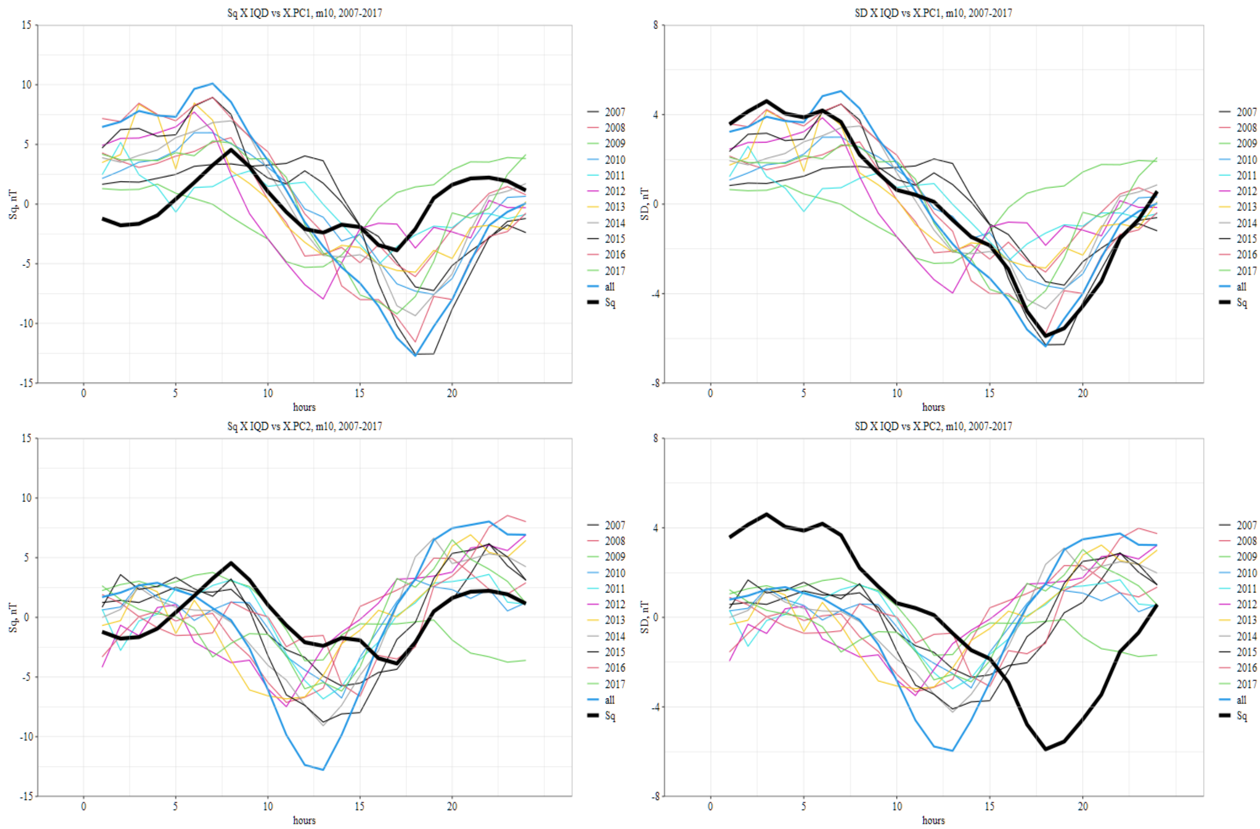

Figure 6. *Same as Figure 5, but for October.*

The comparison between PCs and Sq/SD was made through the correlation analysis confirmed by the visual analysis and through RMSE analysis to minimize the need for the (subjective) visual analysis.

The obtained results (see Figures 7 and 8) allow to conclude that for the months with a lower probability of geomagnetic storms (months near the solstices), the PC1 is more frequently identified as Sq than for the months with a higher probability for a storm (months near the equinoxes) for which PC1 is more frequently identified as SD. Consequently, for months near the solstices, PC2 is more frequently identified as SD, whereas for the months near the equinoxes, PC2 is more frequently identified as Sq.

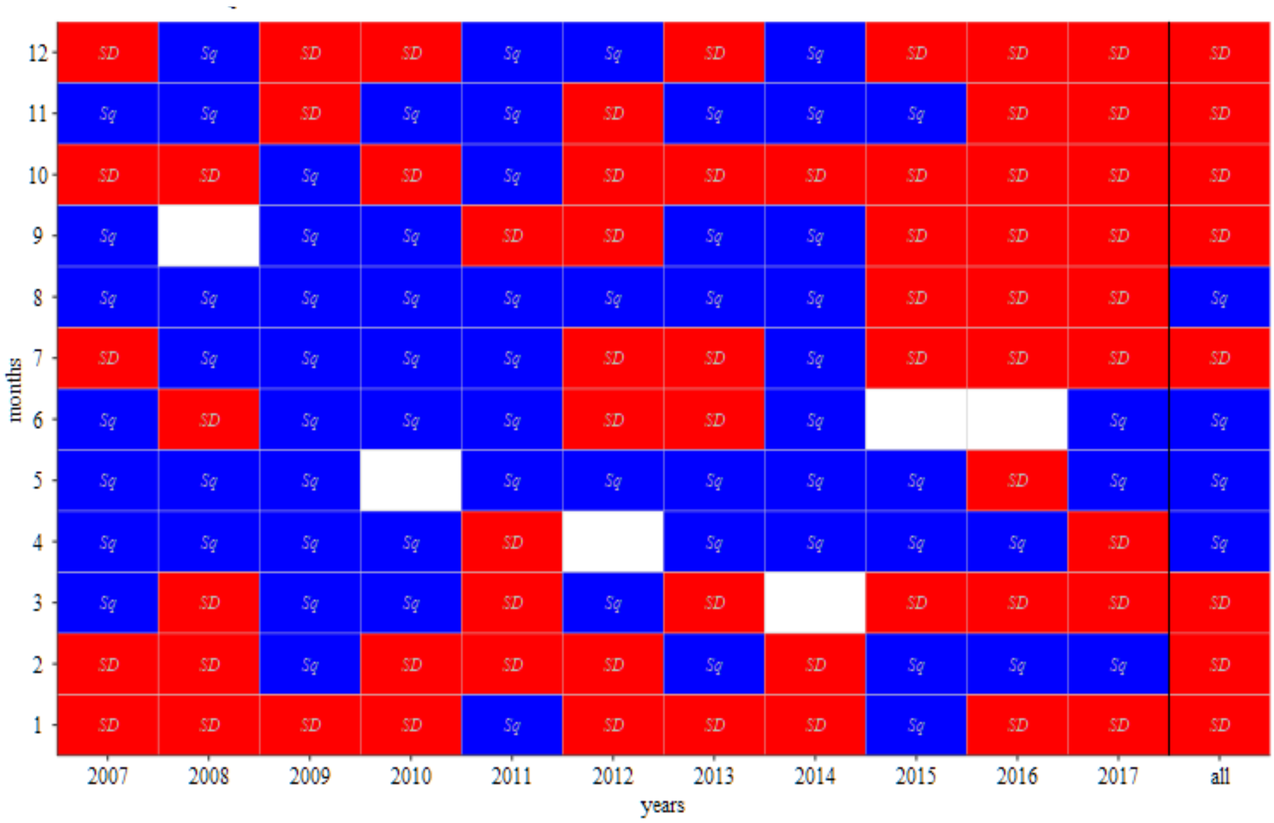

Figure 7. *Identification of PC1 of the H component as Sq or SD for different months and years.*

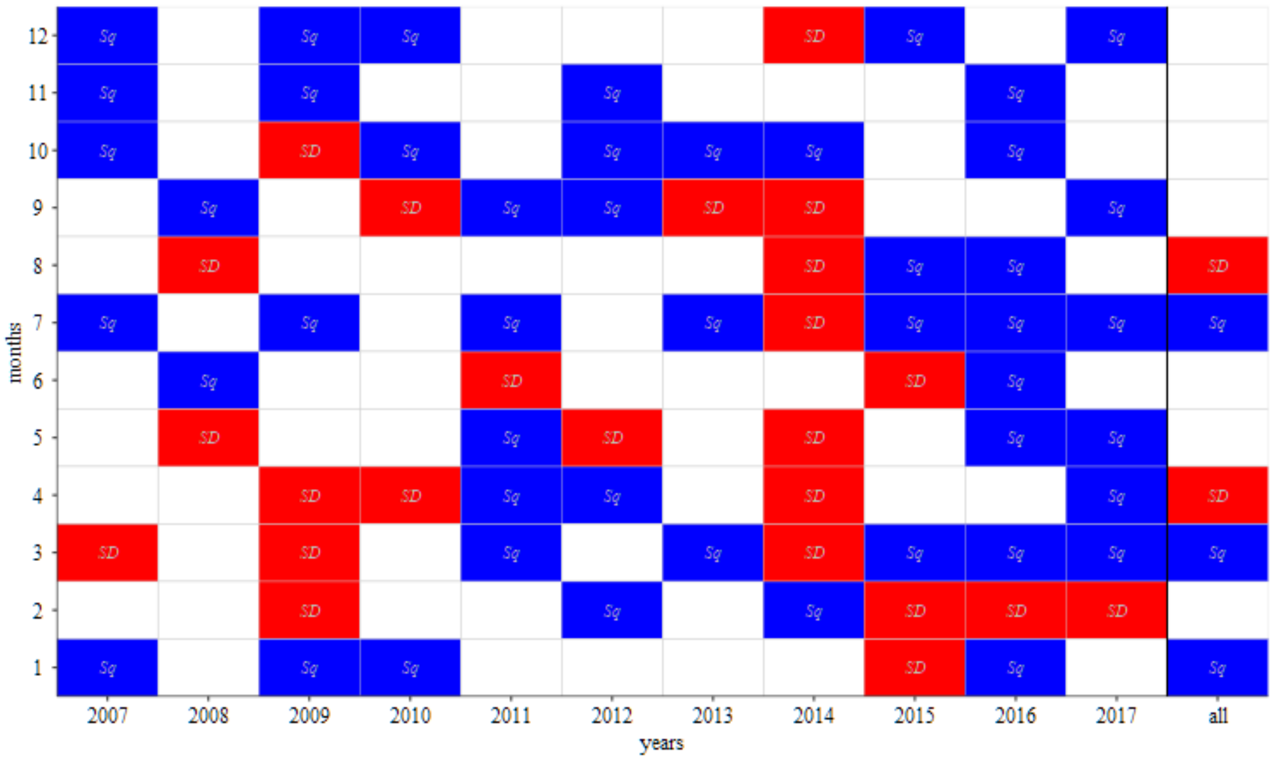

Figure 8. *Same as Figure 7 but for PC2.*

A new metric: The obtained results show that PCA can automatically extract the Sq variation from the observations of the Y and Z components of the geomagnetic field, but for the X (or H) component, the automatic extraction of the Sq variation is not possible. A complimentary analysis is then needed, using as a comparison a reference series that can be obtained from predictions of geomagnetic field models. A new metric was tested to estimate the similarity of the series, besides correlation analysis, which is the dynamic time warping (DTW) distance.

Main accomplishments:

- the PCA method for Sq extraction was proved to be reliable;
- conditions and practical recommendations for using PCA to extract Sq variation from the geomagnetic data are defined.

3.1.3 WP3 - Crustal electrical conductivity model

To produce precise GIC estimates, a realistic model of the crustal electrical conductivity is required. For better results, the model must be built based on geophysical measurements that give the distribution of the conductivity in depth and laterally. A promising model of conductivity can be built based on magnetotelluric (MT) soundings. The project could count, in the beginning, with over 150 soundings from IDL, covering mainly the south of Portugal. The idea was to acquire new MT soundings in the central and northern regions of Portugal, to have good coverage of MT soundings in the whole Portugal mainland.

MT fieldwork: The data used were obtained by compiling results of 31 MT soundings (Figure 9A, blue dots) acquired with an approximate site spacing of a 50 x 50 km grid. Eight MT soundings were carried out in the southern part of Portugal between 1997 and 2002 using an ADU03E and ADU06, both from Metronix (Almeida et al., 2005, Vieira da Silva et al., 2007, Alves Ribeiro, 2018). The most recent MT soundings (23) were conducted in different areas of Portugal mainland during the MAG-GIC project (2018-2020 period) and using the ADU07 equipment. The electric field components Ex and Ey were acquired in the N-S and E-W directions with a dipole length of about 100 m. The two horizontal magnetic field components were measured in the same direction as the electric field.

The magnetotelluric time series were processed using the MAPROS software, which is based on the robust processing technique reported in Egbert and Booker (1986).

Inversion calculation: The Modular Electromagnetic Inversion System (MODEM) was used for the 3D inversion of the MT data, which is based on a finite-difference algorithm with a nonlinear conjugate gradient (Egbert and Kelbert, 2012; Kelbert, et al., 2014).

The model grid consists of 45 x 35 x 58 cells in horizontal and vertical directions. The inner part comprises a uniform mesh of 25 x 13 x 58 cells. The central part is padded with 12 planes in which the cell sizes increase laterally by a factor of 1.3. The vertical thickness is 25 m for the first layer; the subsequent layer thickness increases successively by a factor of 1.2. A coarse 3D bathymetry of the Atlantic and Mediterranean (Amante, C., Eakins, B.W., 2009) with a fixed resistivity of 0.3 Ω.m was included as a priori information.

Several inversions were performed considering different initial resistivity models. Due to the poor quality of some impedance diagonals, only the off-diagonal of the impedance tensor was included with a 5% margin of error. The exit criteria for the inversion were RMS < 1.05 or $\lambda < 10^{-8}$ during the model updating. The final model, which had a better data fit between the observed and calculated data and a lower RMS of 1.96 %, was reached after 148 iterations.

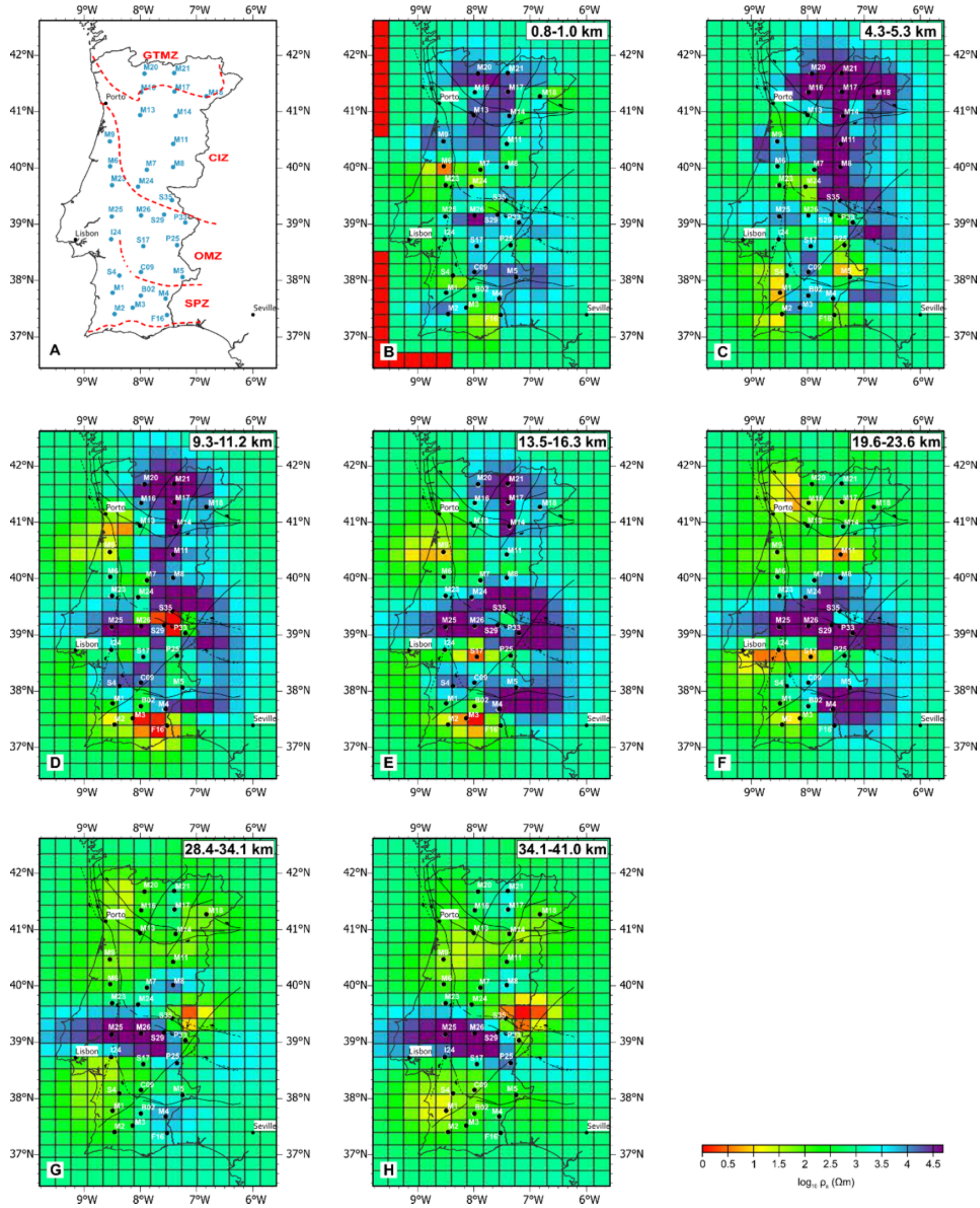

Figure 9. *A: MT sounding locations and geotectonic units (red dash line); B-H: Horizontal slices of the 3D resistivity model for Portugal mainland. Black lines represent the major thrust and faults in the studied area and black dots the location of the MT soundings. SPZ: South Portuguese Zone; OMZ: Ossa Morena Zone; CIZ: Central Iberian Zone; GTMZ: Galicia – Trás-os-Montes Zone.*

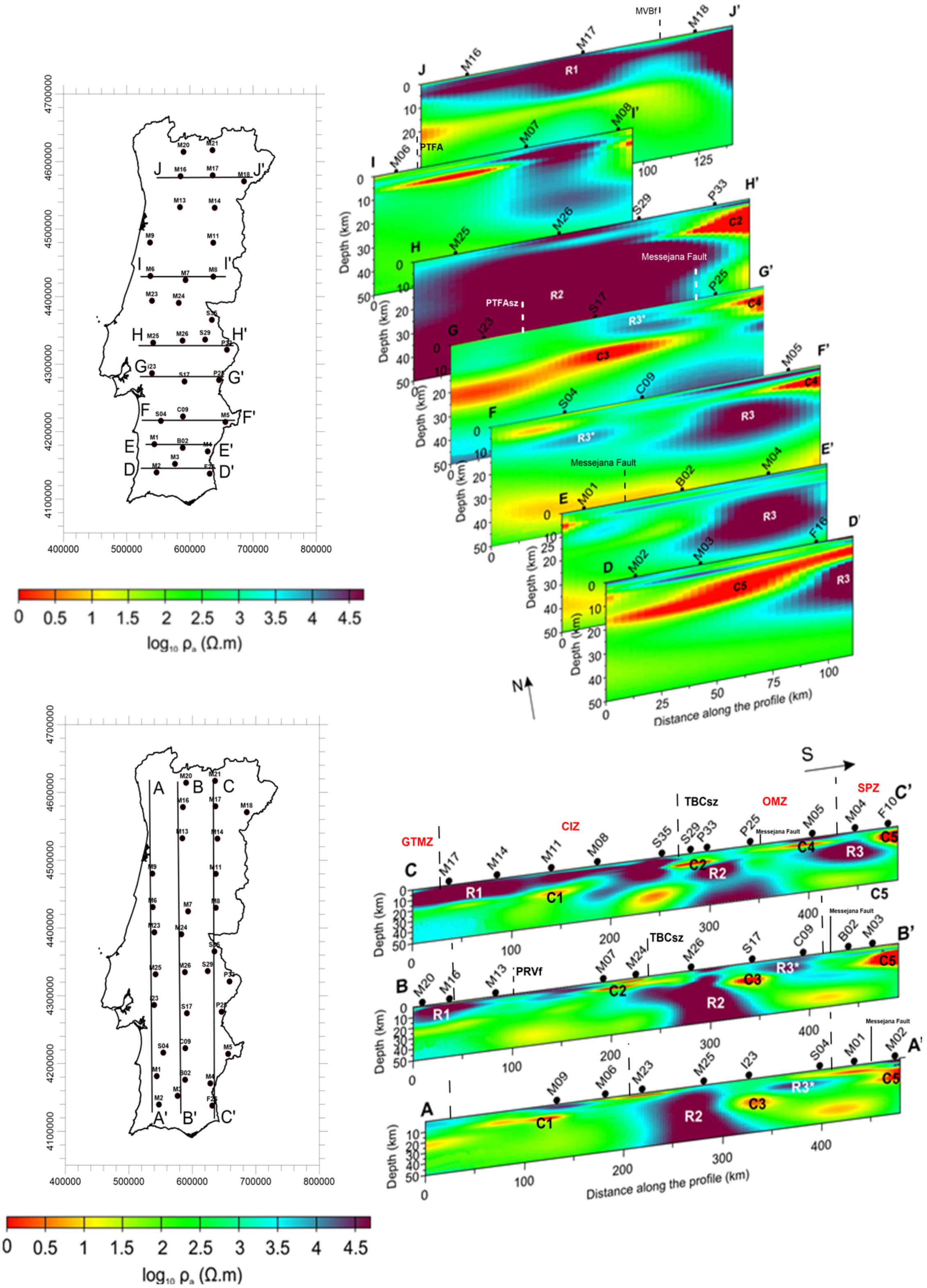

Figure 10. *Cross-sections of the 3D resistivity model for Portugal's mainland. The location of MT soundings are indicated by red points. Top - Cross-sections in W-E direction; Bottom: Cross-sections in N-S direction. The resistive and conductive anomalies are labelled with "R" and "C", respectively.*

Results: The model shows large crustal volumes with contrasting resistivity values. From analyses of Figures 9 and 10, the central and northern regions are characterized by a high resistivity crustal domain spreading in-depth (10^3-10^5 Ω.m) that correlates well with voluminous granitoid bodies and high-grade metamorphic rocks. To the West and the South, roughly corresponding to the Portuguese Western Shore and the South Portuguese Zone, respectively, the crustal resistivity tends to decrease unevenly to values between 1 and 10^3 Ω.m. Interconnected graphite in structural discontinuities, possibly forming a regional mid-crustal *décollemen*t at ≈ 13-15 km depth, were highlighted by multiple low resistivity crustal domains (1-100 Ω.m). Similarly, the model reveals a very large E-W low resistivity crustal domain in SPZ, possibly representing a deep-seated major *décollement*.

Main accomplishments:

- 23 new MT soundings, covering the central and north region of Portugal mainland in a grid ~50 x 50 km, available for future studies.
- The first 3D resistivity model for Portugal mainland using data from 31 broadband MT soundings spaced 50 x 50 km apart, from the surface to ~40 km depth.
- A contribution to a better understanding of the physical properties portraying the concealed crust in Portugal mainland, providing indirect information on its composition and structure.

3.1.4 WP4 - GIC modeling in the power grid

The computation of GICs in the national power grid was a main goal of the MAG-GIC project. The estimation of human resources was, since the beginning, larger than for other tasks. This allowed to achieve a relatively large number of significant achievements.

Collaboration with REN: The project has counted with REN support since the submission of the application through a support letter signed by Rui Marmota, Head of Department at REN. In March 2019, a Non-Disclosure Agreement was signed between the University of Coimbra and REN, to establish which information provided by REN to the project team should be kept confidential.

Right from the start of the project (October 2018), meetings with REN Engineers from Power Networks Analysis and Operational Innovation departments became regular and very important to clarify different technical issues. Several reports were produced by the team, sent to REN partners, and discussed during those meetings.

The collaboration with REN reached a higher level with the permission to install a GIC sensor prototype in a substation ~35 km from Coimbra. Finally, an undoubtedly recognition of the interest in the MAG-GIC project results by REN, was the Best Thesis Award 2021 attributed to the MSc student and MAG-GIC grant-holder Rute Santos.

REN provided the team with all the necessary information to compute GICs on the power network: location of the substations and its grounding resistance, the characterisation of the transformers at each substation (type, winding resistance for high and low voltage) and transmission line information (length and line winding resistance).

GIC calculations: The GIC's in the network were computed using the Lehtinen-Pirola method (Lehtinen & Pirola, 1985). The first evaluation of geomagnetic storm effects considered the 2015 St. Patrick's Day storm (17 March) and only the power network in the area south of Palmela/Évora (the Beta model, see Figure 10) for two main reasons: 1) the network in this region is simpler as it only has 400 kV, and 150 kV power lines; 2) a simplified 3D conductivity model could be used for this area, before the MT soundings in the centre and north of the country were complete.

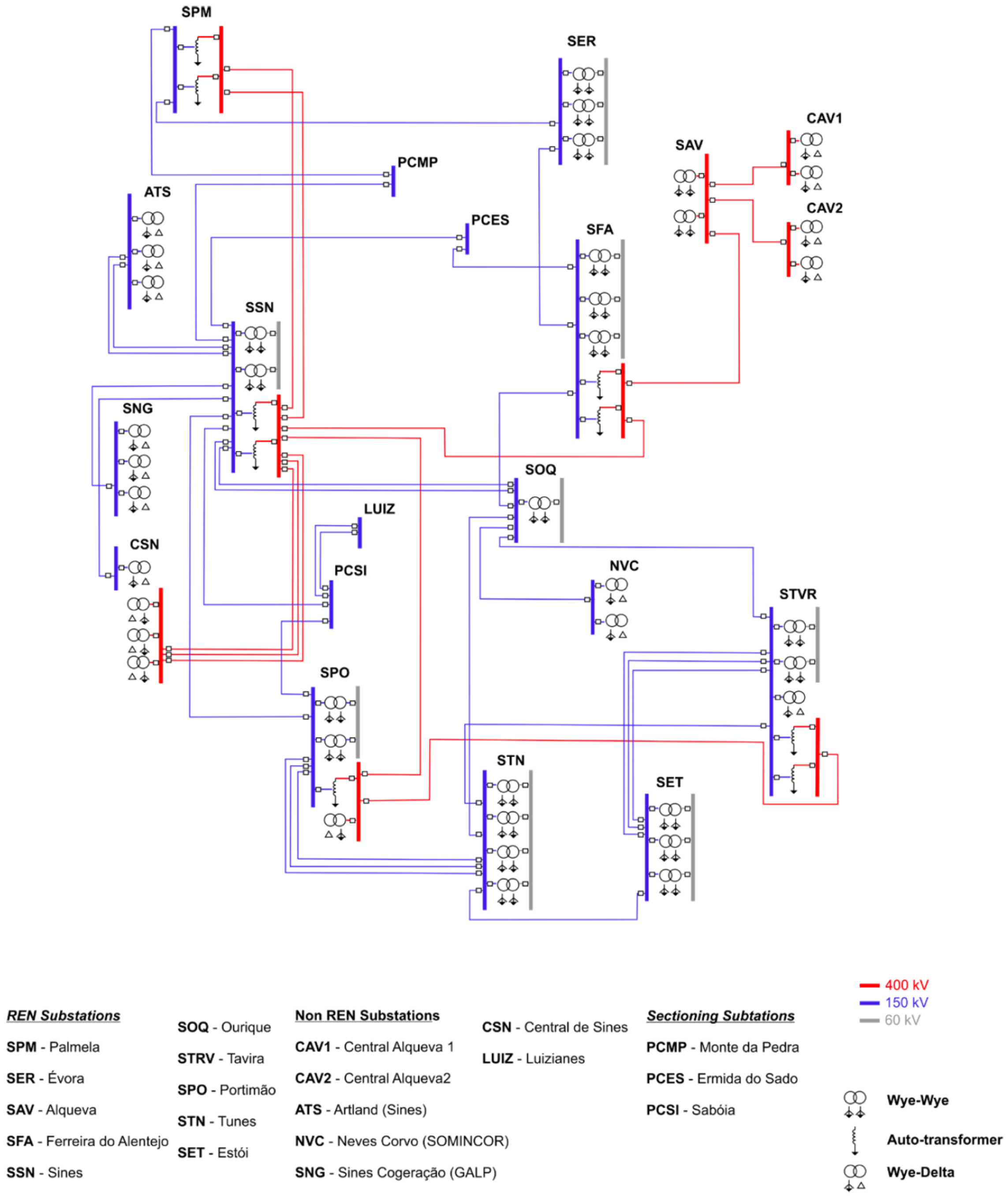

Figure 10. *Single-line diagram of the Beta network model, with information on the kind of transformers in each substation. Red and blue for the HV and LV voltage levels. In grey, voltage level of local distribution grids.*

Results showed, for the southern region, which substations were prone to larger GICs, depending on the orientation of the induced electric field (Figure 11).

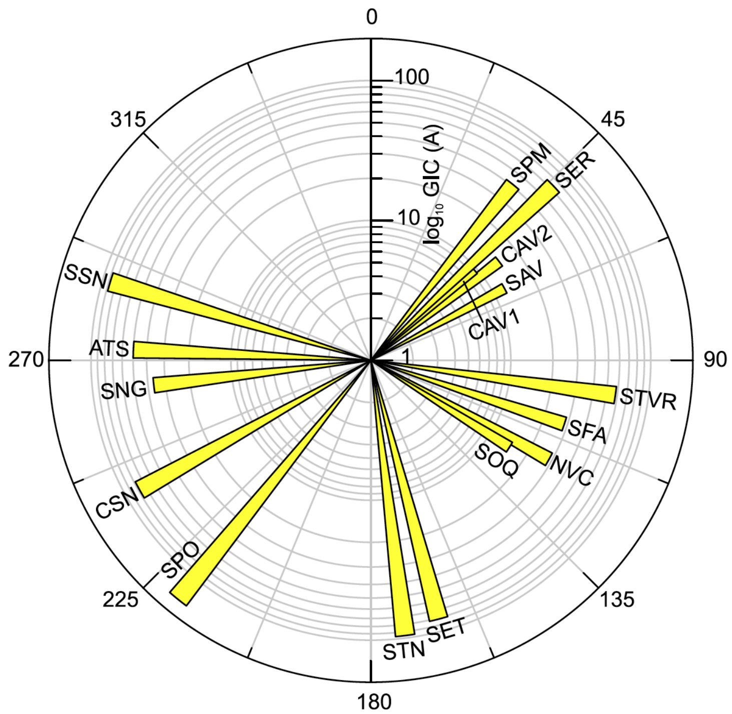

Figure 11. *Orientation, relative to north, of the uniform electric field that produces GICpeak for each substation. Length of bars represents GICpeak in a logarithmic scale.*

With a GIC model including the whole transmission power network circuit, together with a 3D conductivity model for the territory (WP3) and geomagnetic storm signals from neighboring magnetic observatories (WP1), it was possible to simulate GICs for the whole Portuguese mainland territory. The statistics of the strongest storms that took place during the solar cycle 24 was considered. As became clear from our calculations, the geotectonic environment shapes the location of power network substations which are most susceptible to GICs (Figure 12).

In the case of GICs derived from historical magnetograms, the assessment of the 31 October 1903 event (much stronger than any of the events that took place during cycle 24) shows the need for carefully digitised time-series, as the lack of high frequency information has an impact on the intensity of the computed GICs.

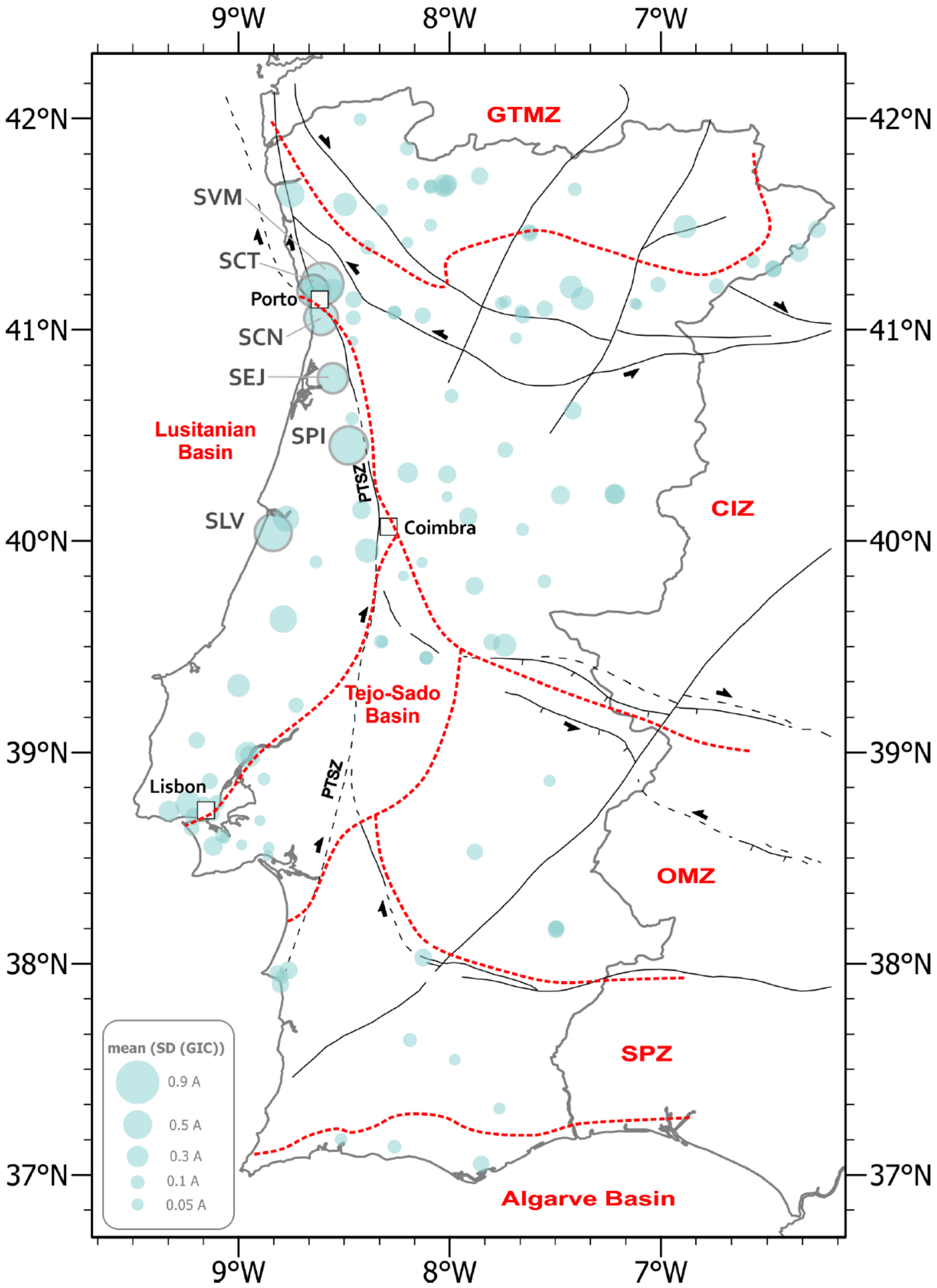

Figure 12. *Mean of SD(GIC) values, computed from the 8 most intense geomagnetic storms of cycle 24. Substations with mean (SD(GIC)) > 0.5 A are highlighted with a dark contour. Black lines represent the major thrust faults in the study region. Dashed red lines separate di erent tectonic units. Abbreviations: GTMZ - Galicia-Tr as-os-Montes zone; CIZ - Central Iberian Zone; OMZ - Ossa Morena Zone; SPZ - South Portuguese Zone; PTSZ - Porto-Tomar Shear Zone.*

GIC measurements: These GIC simulations were useful to find the substations best suited for installing GIC monitoring sensors. Based on the obtained results and the proximity to Coimbra, the substation of Paraimo (Sangalhos), at ~35 km from Coimbra, was selected.

In the framework of the MSc thesis work of Rute Santos, co-supervised by João Cardoso from LIBPhys-UC, a GIC measuring system was designed and assembled with the collaboration of LIBPhys-UC. The instrumental setup consists of a Hall effect current sensor LEM HOP 1000-SB with a manufacturer's sensitivity 4 mV/A, and a Raspberry Pi 4 Model B platform with a high resolution 24-bit digitizer board (Waveshare AD/DA). The system comprises a mobile internet router. Data is stored in the local database and can be accessed through a remote connection. Laboratory tests revealed a true sensitivity of 4.25 mV/A, a current o set of -0.39 A at constant (ambient) temperature and a noise standard deviation of 0.056 A. On August 30^{th}, the GIC measuring system was installed at the Paraimo substation with the support of the REN local team (Figure 13).

***Figure 13**. GIC instrumentation system for measuring GICs, installed at Paraimo substation. The system consists of two boxes: one with power sources (bottom photo), the other around the transformer neutral cable and the Hall effect sensor inside (two top photos).*

The comparison between the GIC recorded at Paraimo during the 17th September 2021 storm (Dst(min)=-64 nT) and the GIC model estimate, revealed similar temporal variations with a Pearson correlation coefficient of 0.60. This value increases to 0.67 if most high frequencies (poorly resolved due to sensor limitations) and most low frequencies (poorly resolved due to limitations in the conductivity model at deep layers) have been removed (Figure 14).

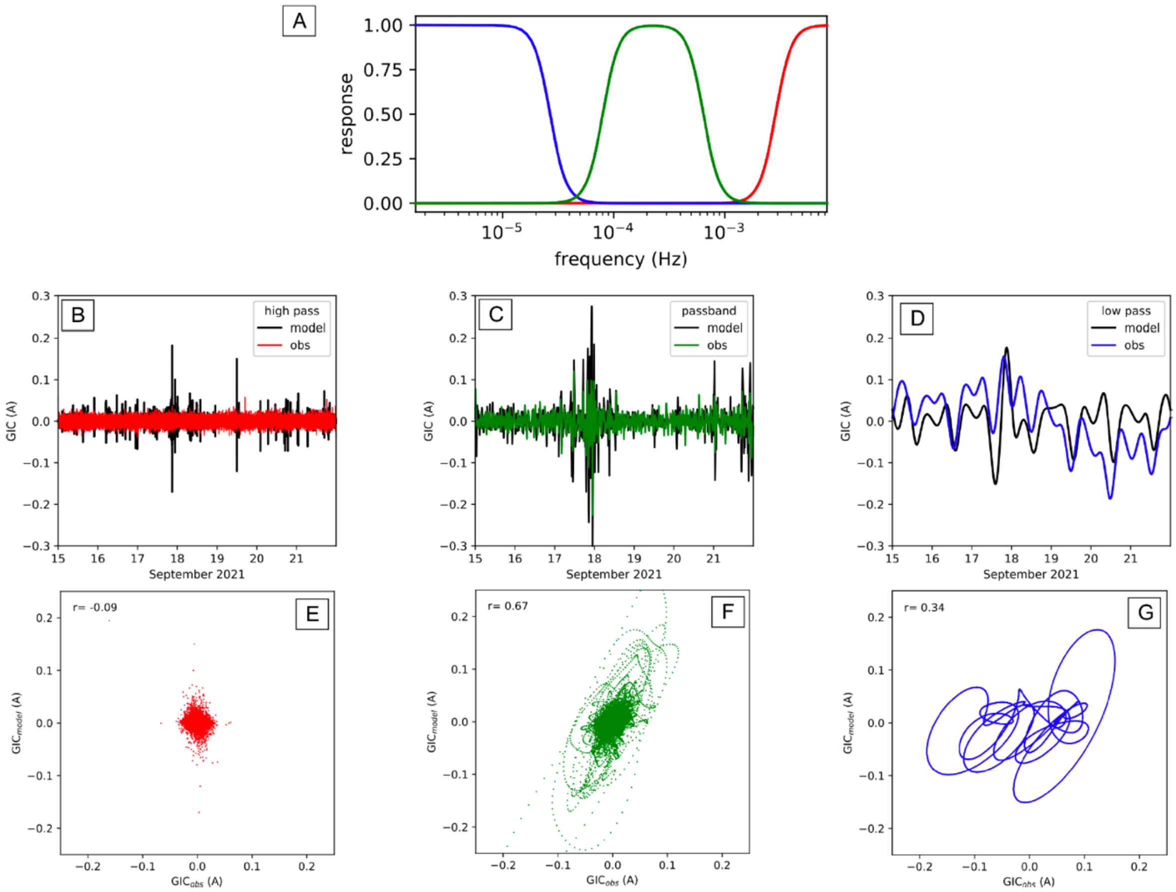

Figure 14. *The geomagnetic storm of 17th September 2021, at Paraimo. Comparison between observed and simulated GIC signals in different frequency bands, after using a high-pass (B, E), band-pass (C, F) and low-pass (D, G) Butterworth filters (A).*

The effect of shield wires: A further accomplishment in this task was the derivation of an equivalent circuit model to add the effect of shield wires in the computation of GICs (Figure 15). In transmission power networks and during geomagnetic storms, shield wires can carry induced currents in the same way as phase conductors but are not usually considered in the study of the impact of geoelectric phenomena in power systems. Our study made it clearer the influence of shield wires on GICs in power systems, both through the effect of added electrical resistances and through the additional contribution of electromotive forces induced along these lines.

As shown, differences can be relevant in relatively short transmission lines with only some tens of towers, as some of the lines in the Portuguese network.

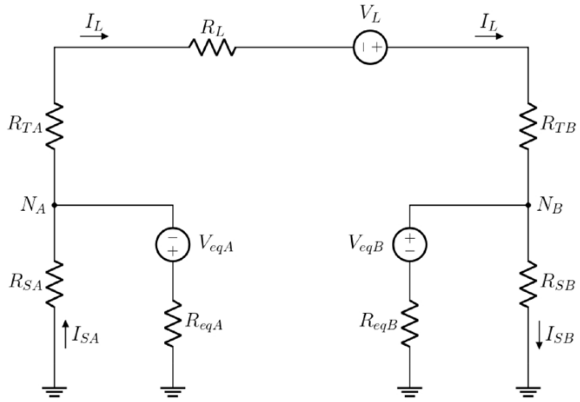

Figure 15. *Equivalent circuit model considering the resistance and the induced voltage sources along shield wires. Analytical Expressions for R_{eq} and V_{eq} were derived.*

Errors in GIC estimations: Sources of errors in the computation of GICs include the conductivity model used, the power lines path, the source of geomagnetic data, grounding resistances uncertainties and the presence of shield wires. We obtained estimations for errors due to uncertainties in the conductivity model and in some circuit parameters, amounting to 50% and 20%, respectively (Figure 16).

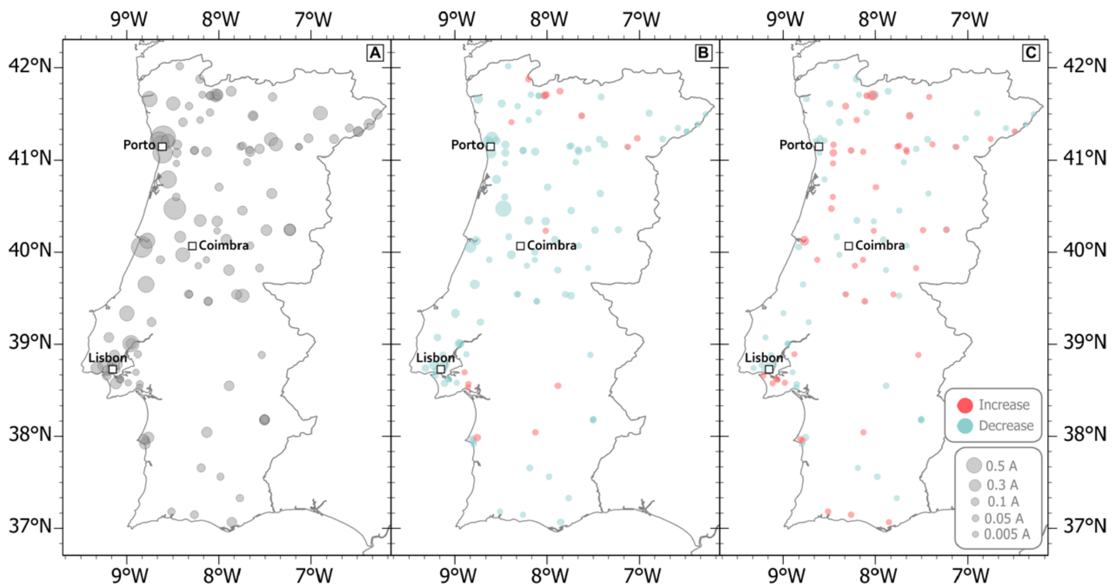

***Figure 16**. For the geomagnetic storm of 17th March 2015, (A) the distribution of GIC in the power network, and differences in GIC when replacing (B) the conductivity model; (C) the standard grounding resistance.*

Main accomplishments:

- A new GIC model for the whole Portuguese territory was possible by combining a power grid model for the entire territory (Kappa network) and a new 3D conductivity model inverted from a 50 X 50 km coverage with MT soundings (output of WP3).
- For the strongest events of solar cyle 24, it was concluded that during this period GIC intensities should correspond at best to low risk exposure levels for transformers in the power network.
- The development (assembly, calibration and testing) of an instrument for the monitorization of GICs through the use of a Hall effect sensor. This instrument was installed at the Paraimo transformer substation located in the vicinity of Coimbra by the end of August 2021.
- Analytical derivation of the influence of shield wires in the power network and first estimations including the effect of electromotive forces along these lines.
- Evidence for the influence of the geotectonic environment in shaping the location of power network substations most susceptible to GICs.

3.1.5 WP5 - Ionospheric equivalent currents for GIC sources

This task was initially planned to extract a spatial structure of driving currents from ground data analysis, using simultaneous time series from the network of observatories in Iberia and applying the Spherical Elementary Current System method. However, due to different factors explained in section 3.2, this task evolved differently, although keeping as a main goal the separation of different source contributions in the external geomagnetic signal.

Virtual observatory series from Swarm data: We have computed geomagnetic field series at a dense and homogeneous grid of Virtual Observatories (VO) using the Equivalent Source Dipole (ESD) technique (Saturnino et al., 2018) (Figure 17). The VO series have 30-day resolution and are computed from an extended Swarm dataset, covering all geomagnetic activity levels between January 2014 and December 2019.

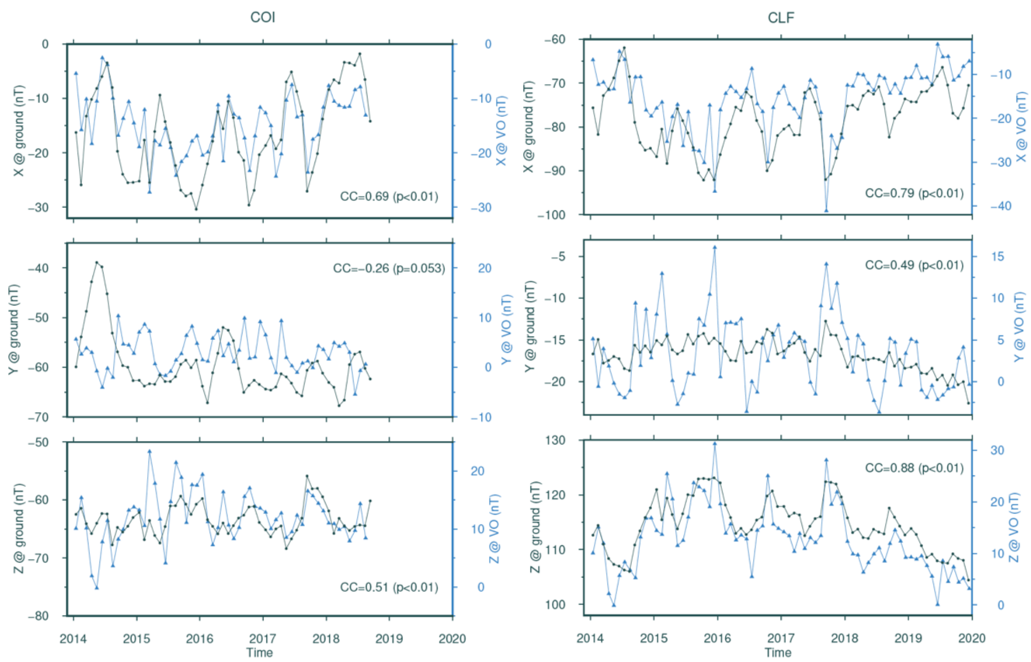

Figure 17. *30-day resolution time series for geomagnetic field components (X, Y, Z) at COI (40.03 N, 8.43 W) and CLF (47.83 N, 2.26 E) observatories (grey) and at corresponding VOs at 500 km altitude (blue). For COI observatory, the series was interrupted at 2018.7, due to damages caused by hurricane Leslie at the variometers' house. Also shown inside each frame, the correlation coeffcient (CC) between curves, and the corresponding p-value.*

We outlined the limitations in time resolution of the computed models as being intrinsic to the satellite coverage, with the presence of a spurious 4.5-month oscillation due to non-homogeneous Local Time coverage by the Swarm satellites. We have identified the 2017-2018 period as the best period to obtain higher time resolution (Figure 18). These results contribute to highlight the importance of on-Earth magnetic observatories as the COI observatory, where the time resolution limitations are purely instrumental.

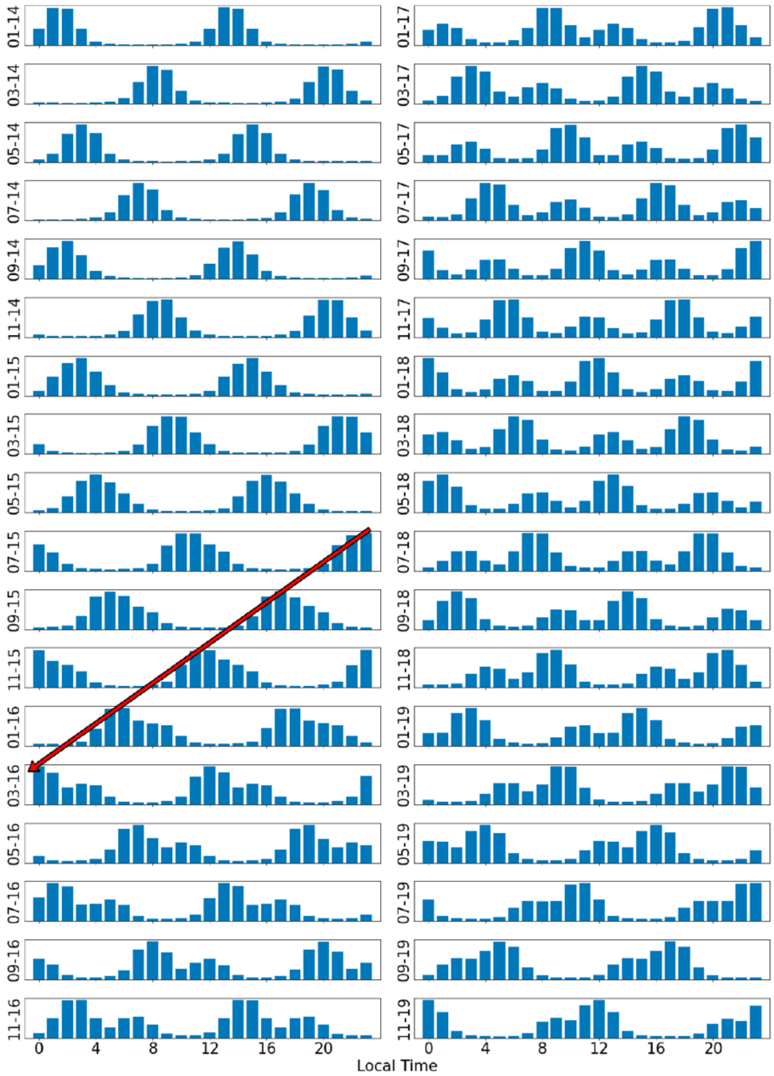

Figure 18. *Local time drift of Swarm satellites A+B+C. Variation in time of local time distribution of the whole set of satellite measurements used in the calculation of VO series, during the 2014 to 2019 period (only 1 out of 2 epochs is plotted, with 1 epoch corresponding to a 30-day period). Straight red line shows the retrograde drift of a certain group of sampled LT values. As can be seen, during the 2017-2018 period the Swarm sampling is more even in Local Times.*

External geomagnetic signal in satellite data: We have separated contributions from different external sources in the magnetic field signal measured at satellite altitude, using Principal Component Analysis applied to the geomagnetic field series at VOs.

Our results display a resolved principal mode (PC2) of annual periodicity and approximately zonal quadrupolar radial pattern, reminiscent of results from a previous similar study (Domingos et al., 2019. It brings to light another principal mode (PC1), with dipolar geometry and time variation following very closely the Dst geomagnetic activity index (Figure 19).

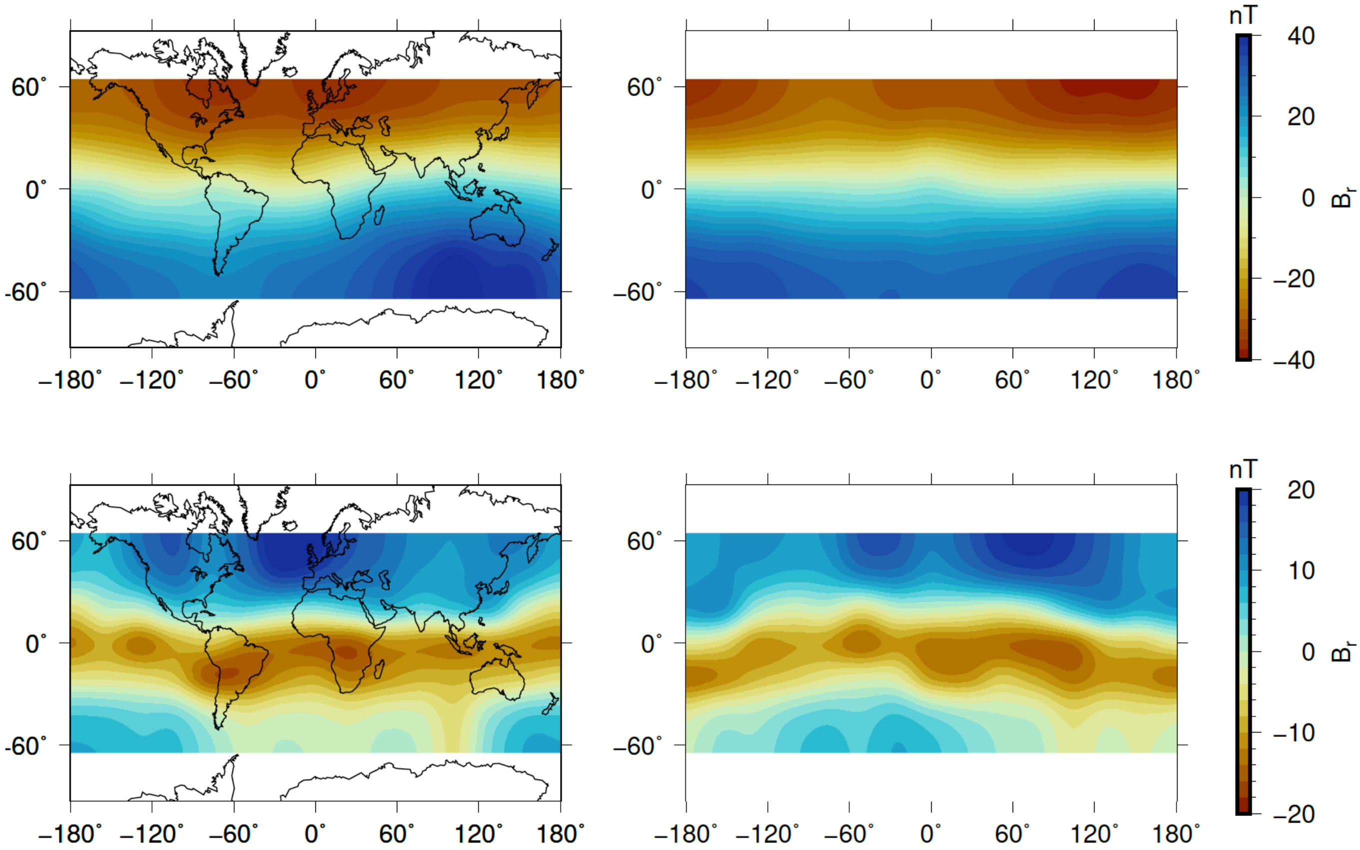

Figure 19. *Spatial structures for the radial component of the first two PCA modes, both in the geographic (left) and centered dipole (right) frames. Top: PC1; Bottom: PC2.*

We resort to the CM6 model and different geomagnetic activity proxies and precursors in order to identify sources for these two main modes. We find that the quadrupolar mode can be interpreted as the seasonal variation of ionospheric conductivity due to daily solar ionization and the dipolar mode can be the expression of the ring current dynamics, both at the 30-day time resolution.

Once these modes have been identified using the whole set of VOs, we could isolate their effect along the time for different VOs separately (see Figure 20):

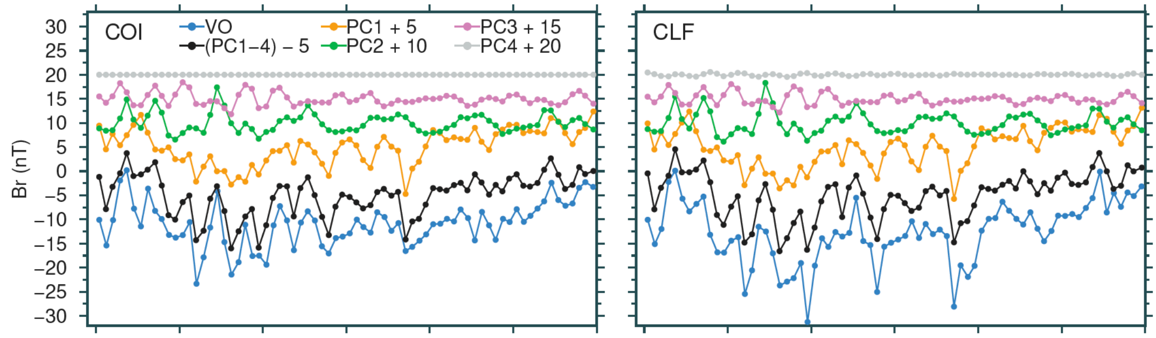

Figure 20. *Radial component of VO series and corresponding contributions from the first four PCA modes, at 500 km above the two magnetic observatories COI and CLF. PC1 is for the ring current contribution, PC2 is for the Summer/Winter oscillation of the global ionospheric current system, PC3 and PC4 show semiannual oscillation possibly associated with the ionospheric current vortices and their driving by DE3 nonmigrating tides.*

Modulation by nonmigrating tides: We also discuss a third and fourth modes, possibly related to the semi-annual oscillation of solar quiet current vortices and the ionospheric dynamo modulation by nonmigrating DE3 tidal wave. We retrieve the longitudinal distribution of convective cloud formation regions in South America, Africa, Southeast Asia, and the central Pacific sectors, condensation at these regions being a possible driving source for DE3 (e.g. Oberheide et al., 2015). A semiannual variability has been associated with this structure, with amplification close to equinoxes (e.g. Pedatella et al., 2011), as we also observe in our results. To clarify if the effect of nonmigrating DE3 tidal wave could be retrieved in VO series from Swarm data, we repeated PCA calculations for the 2017-2018 period when the Swarm sampling is more even in Local Time. Mode 3 does now clearly show the four-peaked longitudinal structure, with peaks located at longitudes of about 5°, 115°, 200° and 280° (see Figure 20).

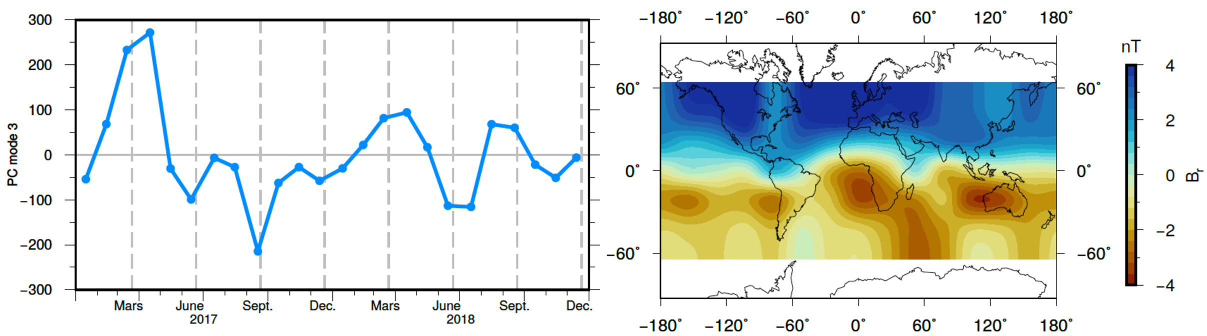

Figure 20. *For the 2-year period 2017-2018, the PCA mode 3 (PC on the left, EOF on the right), showing equinoctial amplification of a nearly equatorial four-peaked structure. Vertical lines on the left mark equinoxes and solstices.*

Dissemination: The study on different external current systems using Swarm satellite mission, in the framework of the collaboration with consultant scientist Diana Saturnino from LPGNantes (France), was published in the Journal of Geophysical Research – Space Physics.

A set of 30-days resolution series was computed for a grid of points at 500 km above the Earth surface and made available at the open repository Zenodo.

Main accomplishments:

- 30-days resolution time series for a grid of points at 500 km above the Earth surface and made available at the open repository Zenodo.
- PCA tools recover the main external modes contributing to geomagnetic satellite data.
- We highlight the presence of a nearly equatorial wavenumber-4 structure that peaks at the equinoxes, possibly related to lower atmosphere-ionosphere coupling due to tidal winds, which should be taken into account in comprehensive models of the geomagnetic field.

3.1.6 Outreach

The dissemination of results obtained in the MAG-GIC Project, at the scientific level, was done in the framework of each different task coordinated by the corresponding leaders.

A web page dedicated to the Project is available at: https://www.uc.pt/en/org/maggic. The web page contains information on the Project's goal and team, as well as links to the electronic versions of the presentations at different meetings and seminars.

Besides, the team participated in several initiatives for the public in general, where the work carried out in the MAG-GIC project has been explained.

1. Morozova, A., Rebbah, R., P. Ribeiro, Pais M. A., The solar quiet variation observed near the vortex focus: effect of the geomagnetic activity and vortex dynamics on the Sq extraction, Dia da Investigação no Departamento de Física, UC, 26 May, 2021, Coimbra

2. Santos, R., Cardoso, J., Pais, M.A., Silva, M., Alves Ribeiro, J. and Pinheiro, F.J.G., “Shield Wires effect on GICs in power networks and design of an instrument to monitor GICs”. Oral flash presentation and poster. Dia da Investigação no Departamento de Física, UC, 26 May, 2021, Coimbra.
3. Alves Ribeiro, J., Pinheiro, F. J.G., Baltazar-Soares, P., Monteiro Santos, F.A., Pais, M. A., “The impact of the Earth subsurface on GICs estimation”. Dia da Investigação no Departamento de Física, UC, 26 May, 2021, Coimbra.
4. Alves Ribeiro, J.. Space Weather and GICs hazard mitigation. Encontro Ciência 2021, June 2021.
5. Alves Ribeiro, J., Pinheiro, F., Santos, R. "Tartarugas e o campo magnético", Noite Europeia dos Investigadores, September 2021.
6. Pinheiro, F., Alves Ribeiro, J., Santos, R. “Magnetismo em Coimbra”, September 2021.
7. Pais, A. ”Acender uma lâmpada com o campo geomagnético? É possível!” Academia Júnior de Ciências, Universidade da Beira Interior, October 2021.
8. Pais, A. Interview for “Antena 2 Ciência”, November 2021.
9. MAG-GIC Team. Video “Efeitos da Meteorologia Espacial na rede elétrica”, promoted by FCTUC (https://youtu.be/CFfOZTm6AVs). The video can also be found subtitled in english (https://youtu.be/yweoDsrOuEQ).
10. MAG-GIC Team. Video “GIC measuring system in Paraimo” https://www.youtube.com/watch?v=w76KH7edsuM
11. MAG-GIC Team. Press-release from the University of Coimbra named “Cientistas da FCTUC estudam o impacto das tempestades solares na rede elétrica de Portugal”, 25th October 2021 (https://www.uc.pt/fctuc/article?key=a-32fd0e7aae).
    The press-release had an impact of more than 50 news in local, national and international social media (https://drive.google.com/drive/u/1/folders/1KwHJuWqQxmz2r0rt26gE5lCIbynF4sZr)
12. Pinheiro, F., Alves Ribeiro, J., Santos, R., Silva, M., Cardoso, J., Pais, M. A. “GIC measuring: combine the useful with the fundamental”. Dia da Investigação no Departamento de Física, UC, 27 April 2022, Coimbra.
13. Pinheiro, F., Santos, R. and Pais, M.A. , "Magnetómetros e o Campo Magnético", European Researchers’ Night, September 2022.

14. Santos, R., "Sabias que a Atividade Solar pode ser detetada na Rede Elétrica?". SoapBox Science Coimbra; 23 November 2022; Coimbra.

4. Publications, meetings and other output indicators

4.1 Publications:

4.1.1 Submitted articles

1. Morozova, A. & Rebbah, R., Principal component analysis as a tool to extract Sq variation from the geomagnetic field observations: conditions of applicability. MethodsX (under revision, to be published in 2023, see Appendix)

2. Baltazar-Soares, P., Martínez-Moreno, F. J., Alves Ribeiro, J., Monteiro Santos, F. A., Ribeiro, P., Pais, M. A., Mateus, A., Pous, J., Crustal Imaging of Portugal Mainland Using Magnetotelluric Data, submitted to Earth and Space Science in November 2022 (see Appendix)

3. Ribeiro, J.A., Pinheiro, F.J.G., Pais, M.A., Santos, R., Cardoso. J., Baltazar-Soares, P. & Monteiro Santos, F., Towards more accurate GIC estimations in the Portuguese power network, submitted to Space Weather in December 2022 (see Appendix)

4.1.2 Published articles

1. Hayakawa, H., Ribeiro, P., Vaquero, J. M., Gallego, M. C., Knipp, D. J., Mekhaldi, F., Bhaskar, A., Oliveira, D. M., Notsu, Y., Carrasco, V. M. S. (2020). The Extreme Space Weather Event in 1903 October/November: An Outburst from the Quiet Sun. The Astrophysical Journal Letters, 897 (1), L10. https://doi.org/10.3847/2041-8213/ab6a18

2. Morozova, A. L., Ribeiro, P., Pais, M. A. (2021). Homogenization of the historical series from the Coimbra Magnetic Observatory, Portugal. Earth Syst. Sci. Data, 13 (2), 809–825. https://doi.org/10.5194/essd-13-809-2021

3. Alves Ribeiro, J., Pinheiro, F. J. G., & Pais, M. A. (2021). First estimations of geomagnetically induced currents in the South of Portugal. Space Weather, 19 (1), e2020SW002546. https://doi.org/10.1029/2020SW002546.

4. Hayakawa, H., Hattori, K., Pevtsov, A. A., Ebihara, Y., Shea, M. A., McCracken, K. G., Daglis, I. A., Bhaskar, A., Ribeiro, P., Knipp D. J. (2021). The Intensity and Evolution of the Extreme Solar and Geomagnetic Storms in 1938 January. The Astrophysical Journal, 909(2), 197. https://doi.org/10.3847/1538-4357/abc427.

5. Castillo, Y., Pais, M.A., Fernandes, J., Ribeiro, P., Morozova, A. L. & Pinheiro, F. J. G. (2021). Relating 27-Day Averages of Solar, Interplanetary Medium Parameters, and Geomagnetic Activity Proxies in Solar Cycle 24. Solar Physics, 296(7), 1-23. https://doi.org/10.1007/s11207-021-01856-8.

6. Morozova, A.L., Rebbah, R., and Ribeiro, P. (2021). Datasets of the solar quiet (Sq) and solar disturbed (SD) variations of the geomagnetic field at the Coimbra Magnetic Observatory (COI) obtained by different methods. Data in Brief, 37, 107174. https://doi.org/10.1016/j.dib.2021.107174.

7. Saturnino, D., Pais, M. A., & Domingos, J. (2021). The signature of geomagnetic field external drivers in Virtual Observatory 30-day means derived from Swarm data. Journal of Geophysical Research: Space Physics, 126 (10), e2021JA029579. https://doi.org/10.1029/2021JA029579

8. Santos, R., Pais, M.A., Alves-Ribeiro,J., Cardoso, J., Perro, L., Santos, A. (2022). Effect of shield wires on GICs: Equivalent resistance and induced voltage sources. International Journal of Electrical Power & Energy Systems, 143, 108487. https://doi.org/10.1016/j.ijepes.2022.108487

4.1.3 Chapters in Books:

1. Pinheiro, F.; Ribeiro, J.; Pais, M.A.; Ribeiro, P.; Morozova, A.; Santos, F.; Fernandes, F.; Francisco, C. (2020). From geomagnetic observations at COI to GICs in the Portuguese power system network. In I. Abrantes, P. M. Callapez, G. P. Correia, E. Gomes, B. Lopes, F. C., Lopes, E. Pires, & A. Rola (Eds.). Uma visão holística da Terra e do Espaço nas suas vertentes naturais e humanas. Homenagem à Professora Celeste Romualdo Gomes. Coimbra: CITEUC - Centro de Investigação da Terra e do Espaço da Universidade de Coimbra, https://doi.org/10.5281/zenodo.4409274

4.1.4 Other publications (extended abstracts, proceedings, supplements, ArXiv, …):

2. Morozova, A.L., Rebbah, R., & Ribeiro, P. (2020). Datasets of the solar quiet (Sq) and solar disturbed (SD) variations of the geomagnetic field at the Coimbra Magnetic Observatory (COI) obtained by different methods, arXiv:2103.13899 [physics.geo-ph], https://arxiv.org/abs/2103.13899

3. Morozova, A. L., Ribeiro, P. & Pais, M. A. (2020). Homogenization of the historical series from the Coimbra Magnetic Observatory, Portugal. Earth System Science Data Discussions, https://essd.copernicus.org/preprints/essd-2020-317/, https://doi: 10.5194/essd-2020-317

4. Morozova, A., Rebbah, R. & Pais, M. (2020). The solar quiet variation observed near the vortex focus: effect of the geomagnetic activity and vortex dynamics on the Sq extraction, Earth and Space Science Open Archive, 22. https://doi.org/10.1002/essoar.10504878.1

5. Morozova, A. L. and Ribeiro, P. & Pais, M. A. (2021). Homogenization of the historical series from the Coimbra Magnetic Observatory, Portugal. Earth System Science Data, 13, 809–825, https://doi: 10.5194/essd-13-809-2021-supplement

6. Morozova, A.L. & Rebbah, R. (2021) Comparison of the solar variations of the geomagnetic field at the Coimbra Magnetic Observatory (COI) obtained by different methods: effect of the solar and geomagnetic activity, arXiv:2104.00391 [physics.geo-ph], https://arxiv.org/abs/2104.00391

7. Saturnino, D., Pais, M. A. & Domingos, J. (2021). The signature of geomagnetic field external drivers in Swarm data. Earth and Space Science Open Archive, pp27, doi:10.1002/essoar.10507234.1, https://doi.org/10.1002/essoar.10507234.1

8. Morozova, A. & Rebbah, R. (2021). Principal component analysis as a tool to extract Sq variation from the geomagnetic field observations: conditions of applicability. ArXiv, arXiv:2112.01827, https://arxiv.org/abs/2112.01827

9. Neres, M., Pais, M. A., Ribeiro, J., Pinheiro, F., Santos, R., Cardoso, J. (2021). Improving geomagnetic proxies for geomagnetically induced currents (GICs). Authorea. December 09, 2021. https://www.authorea.com/doi/full/10.1002/essoar.10509320.1

10. Santos, R., Pais, M.A., Cardoso, J., Alves-Ribeiro, J., Pinheiro, F.J.G. (2022). Effect of Shield Wires on GICs, https://doi.org/10.1002/essoar.10510536.2

4.2 Published Datasets:

1. Morozova, A., Ribeiro, P. and Pais, M. A. (2020). Homogenized monthly datasets of all geomagnetic components of Coimbra observatory for the time period 1866-2015, (version 2) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.4308036.

2. Ribeiro, P., Pais, M. A. and Morozova, A. L. (2020). Monthly values of absolutely measured geomagnetic components (D, I, H, Z, F) of Coimbra observatory in the period 1866-2015, (version 2) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.4308022.

3. Saturnino, D., Pais, M. A., & Domingos, J. (2021). Virtual Observatories (VO-ESD) time series in Geocentric and Centred-Dipole frames, (version_1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.4515779

4. Morozova, Anna; Rebbah, Rania; Ribeiro, Paulo (2021). Datasets of the solar quiet (Sq) and solar disturbed (SD) variations of the geomagnetic field at a midlatitudinal station in Europe obtained by different methods, Mendeley Data, V1. http://dx.doi.org/10.17632/jcmdrm5f5x.1

5. Santos, Rute, Alves Ribeiro, Joana, Pinheiro, Fernando J. G., Cardoso, João, & Pais, Maria Alexandra. (2022). Simulation and Observation of GICs in the Portuguese power network SPI substation [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7446370

6. Baltazar-Soares, Pedro, Martínez-Moreno, Francisco José, Alves Ribeiro, Joana, Monteiro Santos, Fernando, Ribeiro, Paulo, Pais, Maria Alexandra, Mateus, António & Pous, Jaume (2022). Crustal Imaging of Portugal Mainland Using Magnetotelluric data [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7147543

7. Alves Ribeiro, Joana, Pinheiro, Fernando J. G., Pais, Maria Alexandra, Santos, Rute, & Cardoso, João. (2022). Geomagnetic Induced Currents (GICs) estimations for Portugal mainland - Top 8 geomagnetic storms of solar cycle 24 [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7443212

4.3 Thesis:

The project had a significant contribution for young researchers training. Three MSc students were attributed grants: Pedro Baltazar-Soares, Rania Rebbah and Rute Santos. Due to difficulties and delays brought by COVID-19, there was a decision to extend each grant for six months each at the expense of a PhD grant for 18 months, as initially planned. The three young researchers were kept as team members until the end of the project. There was a further young researcher working with the team during her Master thesis, Cristiana Francisco. Overall, three MSc theses were produced:

1. Pedro Baltazar-Soares; Combining ERT, TDEM, and FDEM in shallow geophysical investigation; Msc thesis in Ciências Geofísicas (Geofísica Interna), Universidade de Lisboa, Faculdade de Ciências, supervisor: Fernando Acácio Monteiro dos Santos; University of Lisbon, 2019. http://hdl.handle.net/10451/42091

2. Cristiana Francisco; Preliminary study of the sensitivity to geomagnetic storms of the power network substations in Portugal south region; Msc thesis in Astrophysics and Space Instrumentation, supervisors: Maria Alexandra Pais; Fernando Gutierrez Pinheiro; University of Coimbra, July 2020. http://hdl.handle.net/10316/92484

3. Rute Santos; *Development of instrumentation for measuring Geomagnetically Induced Currents (GICs) and effect of shield wires on GIC simulations*. MSc thesis in Physics Engineering, specialization in Instrumentation. Supervisors: Maria Alexandra Pais and João Cardoso. University of Coimbra, October 2021. http://hdl.handle.net/10316/98060

4.4 Awards:

The national recognition of the relevance and interest of the MAG-GIC project, came also with two awards granted to the former MAG-GIC grant-holder student Rute Santos, for her contribution to GIC measurement and modelling, as well as for her good communication of results.

1. **Best oral presentation Award**: Rute Santos, for the oral presentation "Geomagnetically Induced Currents in Portugal mainland". Magnetism in Portugal 2022- Young Researchers; September 12th, 2022; University of Porto.

2. **Best Thesis Award, cash prize of €25,000**: Rute Santos, for the MSc thesis "Development of instrumentation for measuring Geomagnetically Induced Currents (GICs) and effect of shield wires on GIC simulations". November 2022. https://www.ren.pt/en-GB/media/comunicados/detalhe/masters_thesis_of_student_from_university_of_coimbra_wins_ren_award_2

4.5 Models:

1. Alves Ribeiro et al. (2020) Beta model: Power network model to the south of Palmela
2. Alves Ribeiro et al. (2021) Delta model: Power network model to the south of Lisbon
3. Alves Ribeiro et al. (2021) Kappa model: Power network model for the whole mainland Portugal
4. Baltazar-Soares et al. (2021) B-S model: 3D Conductivity model for mainland Portugal
5. Alves Ribeiro et al. (2021) GIC model for Portugal mainland

4.6 Computational Applications:

1. Santos et al. (2022) Implementation of shield wire effect on the GIC model

4.7 Prototypes:

1. GIC sensor installed at Paraimo substation

4.8 Communications:

4.8.1 International scientific meetings:

1. Pinheiro, F., Santos, F., Pais, M. A., Morozova, A., Ribeiro, P., Castillo, Y., Francisco, C., Fernandes, J., Miranda, M. (2019). Scanning the crust with magnetospheric currents. In *European Geoscience Union Annual Assembly* 2019, Vienna, Austria (7-12 April 2019), interactive PICO presentation. https://figshare.com/articles/egu2019_pinheiro_etal_final_pdf/8862278/1

2. Ribeiro, P., Cruz, J., Pinheiro, F. G., Pais, M. A., Neres, M. (2019). Observatórios e estações geomagnéticas de Portugal: entre tradição e modernidade. In *MAGIBER XI*, Condeixa (4-7 September, 2019) https://www.uc.pt/en/org/maggic/Ribeiro2019

3. Pinheiro, F., Ribeiro, J. A., Santos, F., Pais, M. A., Morozova, A., Ribeiro, P., Castillo, Y., Francisco, C., Fernandes, J. (2019) Geomagnetic induced currents in Southwest Portugal; poster presented in *16th European Space Weather Week (ESWW*), Liège (Belgium); 18-22 Nov., https://www.uc.pt/en/org/maggic/ESWW_pinheiro

4. Cardoso, J., Silva, M, Pinheiro, F., Pais, M. A. (2019) Standalone Geomagnetically Induced Current Data Logger in Substation Transformers with Open-Loop Hall-Effect Based Sensors, poster presented in *16th ESWW*, Liège (Belgium); 18-22 Nov., https://www.uc.pt/en/org/maggic/ESWW_cardoso

5. Saturnino, D., Pais, M. A., Domingos, J., Pinheiro, F. (2019) The signature of external drivers from Swarm satellite data; poster presented in *16th ESWW*, Liège (Belgium); 18-22 Nov., https://www.uc.pt/en/org/maggic/ESWW_saturnino

6. Morozova, A., Rebbah, R., & Pais, M. A. (2020). Separation of the daily quiet variation from the geomagnetic field observations with the principal component analysis. In *EGU General Assembly Conference Abstracts* (pp. 3423), https://doi.org/10.5194/egusphere-egu2020-3423

7. Alves Ribeiro, J., Pais, M. A., J. G. Pinheiro, F., Monteiro Santos, F. A., and Soares, P. (2020) MAG-GIC: Geomagnetically Induced Currents risk hazard in the Portuguese power network, in *EGU General Assembly 2020*, Online, 4–8 May 2020, EGU2020-1002, https://meetingorganizer.copernicus.org/EGU2020/EGU2020-1002.html

8. Pinheiro, F., Alves Ribeiro, J., Morozova, A., Monteiro Santos, F., Baltazar-Soares, P., Ribeiro, P., Fernandes, J., Pais, M. A. (2020). On extreme GIC values affecting the Portuguese power grid. In *European Space Weather Symposium (ESWS2020),* online, 4-6 November 2020, Abstract Book and Programme. http://esws2020.iopconfs.org/QV88

9. Rebbah, R. & Morozova, A. (2020). Principal component analysis to separate different ionospheric and magnetospheric contributions to the geomagnetic field variations. In *European Space Weather Symposium (ESWS2020)*, online, 4-6 November 2020, Abstract Book and Programme http://quickviews.iopconfs.org/1003402

10. Alves Ribeiro, J., Baltazar-Soares, P., Pinheiro, F. J. G., Santos, R., Monteiro Santos, F., Pais, M. A., Cardoso, J. (2020) Geomagnetically Induced Currents in the portuguese power network (GP014-0004). In *AGU Fall Meeting*, online, 1-17 December 2020. https://ui.adsabs.harvard.edu/abs/2020AGUFMGP0140004R

11. Baltazar-Soares, P., Martinez Moreno, F. J., Alves Ribeiro, J., Monteiro Santos, F., Ribeiro, P., Pinheiro, F. J. G., Pais, M. A. (2020) Electrical crust of Portugal mainland (GP002-0019). In *AGU Fall Meeting*, online, 1-17 December 2020. https://ui.adsabs.harvard.edu/abs/2020AGUFMGP0020019B

12. Morozova, A. L., Rebbah, R & Pais, M. A. (2020). The solar quiet variation observed near the vortex focus: effect of the geomagnetic activity and vortex dynamics on the Sq extraction (SA015-0005). In *AGU Fall Meeting*, online, 1-17 December 2020. https://ui.adsabs.harvard.edu/abs/2020AGUFMSA0150005M

13. Baltazar-Soares, P., Martinez Moreno, F., Alves Ribeiro, J., Monteiro Santos, F., Pais, M.A. and Ribeiro, P. (2021). Crustal Characterization of Portugal's mainland based on Magnetotelluric measurements. In EGU, online, 1 April - 1 June 2021. In *EGU General Assembly Conference Abstracts* (pp. EGU21-15690). https://meetingorganizer.copernicus.org/EGU21/EGU21-15690.html

14. Pais, M.A., Ribeiro, P., Pinheiro, K., Vinicius, M. and Matzka, J. (2021). Geophysical study of viability for a new geomagnetic observatory at São Marcos (Portugal). In EGU, online, 1 April - 1 June 2021. In *EGU General Assembly Conference Abstracts* (pp. EGU21-12312). https://meetingorganizer.copernicus.org/EGU21/EGU21-12312.html

15. Santos, R., Cardoso, J., Pais, M.A., Silva, M., Alves Ribeiro, J. and Pinheiro, F.J. (2021). Shield wires effect on GICs in Portuguese power network and design of an instrument to monitor GICs in the transformer neutrals. In EGU, online, 1 April - 1 June 2021. In *EGU General Assembly Conference Abstracts* (pp. EGU21-14663). https://meetingorganizer.copernicus.org/EGU21/EGU21-14663.html

16. Saturnino, D., Pais, M.A., Domingos, J. and Pinheiro, F.J. (2021). Altitude dependence of geomagnetic external fields using Swarm and ground observatories data. EGU, online, 1 April - 1 June 2021. In *EGU General Assembly Conference Abstracts* (pp. EGU21-13239). https://meetingorganizer.copernicus.org/EGU21/EGU21-13239.html

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29. Santos, R., Pais, M.A., Pinheiro, F.J.G., Cardoso, J., Alves Ribeiro, J. (2022). Influence of shield wires in GIC simulation: application to the Portuguese transmission network. In *European*

Space Weather Week, Zagreb (Croatia), 24-28 October 2022. https://www.stce.be/esww2022/program/session_details.php?nr=P4#

30. Pinheiro, F.J.G., Alves-Ribeiro, J., Pais, M.A., Santos, R., Cardoso, J., Baltazar-Soares, P., Monteiro Santos, F.A. (2022). GICs na rede elétrica de alta tensão de Portugal Continental. In *10a Assemblea Hispano Portuguesa de Geodesia y Geofísisca*, Toledo (Spain), 28th November - 1st December. https://congreso.ign.es/AsambleaHPGG-theme/resources/docs/Programa_detallado_ingles.pdf

4.8.2 National scientific meetings:

1. F. Pinheiro et al. (2019). Space Weather and Society: CITEUC´s contribution. In Encontro Ciencia 2019, Lisbon (8-10 July 2019) https://www.uc.pt/en/org/maggic/Pinheiro2019a

2. Alves Ribeiro, J., Pais, M.A., Pinheiro, F.J.G. (2021). Space Weather and GIC hazard mitigation. In Encontro Ciência 21, 28-30 June 2021.

3. Pais, M.A., Alves Ribeiro, J., Pinheiro, F.J.G., Baltazar-Soares, P., Monteiro Santos, F.A., Santos, R., Cardoso, J., Ribeiro, P., Francisco, C., Morozoca, A., Rebbah, R., Fernandes, J. Miranda, M. (2022). Project MAG-GIC: Geomagnetic Induced Currents in Portugal Mainland. presented at Redes Energéticas de Portugal S.A. (Lisbon), 20th of April 2022.

4. Pinheiro, F.J.G., Alves Ribeiro, J., Santos, R., Silva, M., Cardoso, J., Pais, M.A. (2022). GIC measuring: combine the useful with the fundamental. Poster presented at Dia da Investigação do DF; April 27th, 2022; University of Coimbra.

5. Santos, R., Pais, M.A., Alves Ribeiro, J., Pinheiro, F.J.G., Cardoso, J. (2022). Geomagnetically Induced Currents aggregate Industry and Science. In FISICA 2022 - 23rd National Physics Conference and 32nd Iberian Meeting for Physics Teaching at the Faculty of Sciences, 7-10 September, University of Porto.

6. Santos, R., Pais, M.A., Cardoso, J., Alves Ribeiro, J., Pinheiro, F.J.G. (2022). Geomagnetically Induced Currents in Portugal mainland. Magnetism in Portugal 2022- Young Researchers; 12-13 September 2022; University of Porto.

4.9 Scientific Meetings and Conferences

4.9.1 Scientific Meeting Organization

1. Miquel Torta, "Geomagnetically induced currents by solar storms: how we model and measure them" in Café com Física, UC, Dep. Física, 16 October, 2019. https://indico.lip.pt/event/626/

2. Diana Saturnino, LPGNantes, 'Measuring the ever-changing geomagnetic field', Café com Física, UC, Departamento de Física , 5 February 2020. (https://indico.lip.pt/event/689/)

3. Diana Saturnino, LPGNantes, 'Introduction to VirES for Swarm and available Swarm data products', 'hands-on' activity at Observatório Geofísico e Astronómico, 7 de fevereiro, 2020.

4. Workshop 'Observatórios Magnéticos', Departamento de Física da FCTUC, 5-8 September 2022 (11 participants)
   - 05 September 2022, 14:30 – "Geomagnetic field observations and applications in studies of the Earth's core, mantle and ionosphere", by Katia Pinheiro
   - 06 to 08 September 2022, 10:00 to 12:00 + 14:00 to 17:00 – 'hands-on' course on "Geomagnetic data analysis and processing", by Marcos Vinicius + Katia Pinheiro
   - 09 September 2022, 10:00 – visit to the Magnetic Observatory of Coimbra, guided by Paulo Ribeiro

4.9.2 Chair of conference sessions

1. Pais, M. A., Co-convenor in Session "EMRP2: Measuring space weather condition with geomagnetic data", EGU General Assembly 2022, Vienna, Austria & Online, 23–27 May

2. Alves Ribeiro, J., Co-convenor in Session "CD8 - Measuring and modeling geoelectric fields for GIC studies". 18th European Space Weather Week, 24-28 October 2022, Zagreb, Croatia.

4.9.3 Participation in Scientific Committees

1. Pais, M. A., member of the Scientific Committee of *X Assembleia Luso-Espanhola de Geodesia e Geofísica*, section Geomagnetism and Aeronomy, Toledo, Espanha, 28 novembro-1 dezembro 2022. https://congreso.ign.es/pt

4.10 Reports:

1. Alves Ribeiro, J., Pais, M. A., Pinheiro, F. (2019). Relatório de avanço dos trabalhos de cálculo de GICs na rede da REN; October 2019.

2. MAG-GIC team (2019). First year report of project MAG-GIC; October 2019.

3. Baltazar-Soares, P. (IDL), Ribeiro, P. (OGAUC) (2019). Relatório de Prospecção Geofísica efectuada na Quinta do Palácio de São Marcos (Coimbra); November 2019.

4. Alves Ribeiro, Pais, M. A., Pinheiro, F. (2020). Influence of shield wires on GIC currents -- a case study. Report sent to REN; February de 2020.

5. Alves Ribeiro, J.; Pais, M.A.; Pinheiro, F. (2020). Influence of LPM.ER shield wires on GIC currents a case study; report to REN; May 2020.

6. Santos, R. R., Pais, M. A., Cardoso, J. R., Ribeiro, J. A., Pinheiro, F. (2020). Shield wires and GICs: influence of equivalent voltage sources along the shield wires due to induced geoelectric fields; report to REN; October 2020.

7. MAG-GIC team (2020). Second year report of project MAG-GIC; October 2020.

8. Rebbah, R. (2020). Final report of grant DPA-20-090 from 02 February 2020 to October 2020; October 2020.

9. Santos, R. (2020). Final report of grant DPA-20-091 from 02 February 2020 to October 2020; October 2020.

10. Santos, R., Pais, M.A., Cardoso, J., Alves Ribeiro, J. and Pinheiro, F. (2020). Shield wires and GICs: influence of equivalent voltage sources along the shield wires due to induced geoelectric fields.
11. Report sent to REN; November 2020

12. Rebbah, R. (2020). Separation of the different ionospheric and magnetospheric contributions to the geomagnetic field Variations. Report at Space Weather, Space Weathering and Space Debris Summer School; November 2020

13. Santos, R., Pais, M.A., Cardoso, J., Alves Ribeiro, J. and Pinheiro, F. (2021). Effect of shield wires on GICs: ladder circuit model to derive equivalent resistances and equivalent induced voltage sources. Report sent to REN; March 2021

14. Santos. R., Cardoso. J. R., Silva, M., Pais, M.A. (2021). Specifications of the GIC Measurement Instrument. Report sent to REN; April 2021

15. Paulo Ribeiro & Maria Alexandra Pais (2021). Transferência do Observatório Magnético de Coimbra; Estudos geofísicos na quinta do Palácio de S. Marcos, 41p; Setembro 2021

16. MAG-GIC team (2021). Third year report of project MAG-GIC; November 2021.

4.11 Meetings and seminars:

11.10.2018, Maria Alexandra Pais, "Correntes induzidas pelo campo geomagnético no território português", seminar at REN, Lisboa. https://www.uc.pt/en/org/maggic/Apresentacao

Meetings with REN engineers to discuss the work progress were organized by REN and MAG-GIC team members, on 11-10-2028, 13-12-2018, 27-05-2019 and 30-09-2019. Participants: M. A. Pais, J. Ribeiro, F. Pinheiro, F. Santos, P. Ribeiro (MAG-GIC) and Pedro Carola, Susana Ludovino, André Santos, Luís Perro, Inês Santos (REN).

During the first year (2018-2019), regular meetings involving part, or all team members took place monthly.

01.02.2019, Cristiana Francisco, “Current Systems in the Earth’s Magnetosphere” at UC, Dep. Física, Seminar I from the MSc in Astrophysics and Instrumentation for Space, supervised by M. A. Pais and F. Pinheiro

27.03.2019, Anna Morozova, “Separation of different ionospheric and magnetospheric contributions to the geomagnetic field variations” in Café com Física, UC, Dep. Física, https://indico.lip.pt/event/551/

14.05.2019, Anna Morozova, “Separation of different ionospheric and magnetospheric contributions to the geomagnetic field variations”, Univ. Alcalá de Henares, Spain. https://www.uc.pt/en/org/maggic/Moroz2

24.10.2019, Fernando Pinheiro, "Project MAG-GIC: Geomagnetically induced currents in Portugal mainland", SWE-MED Portugal Workshop, Coimbra. https://www.uc.pt/en/org/maggic/SWE

24.03.2020, Anna Morozova, "Solar quiet variations of the geomagnetic field: the origin and methods to separate it from the measurements", MAG-GIC team seminar

04.09.2020, Rania Rebbah, “Separation of different ionospheric and magnetospheric contributions to the geomagnetic field variations- overview”. Student seminar at “Space Weather, Space Weathering and Space Debris Summer School”, University of Coimbra

01.10.2020, Rania Rebbah, “Separation of different ionospheric and magnetospheric contributions to the geomagnetic field variations-preliminary results”. Presentation at the “Space Weather, Space Weathering and Space Debris Summer School”, University of Coimbra.

07.11.2020, Rania Rebbah, “Principal component analysis to separate different ionospheric and magnetospheric contributions to the geomagnetic field variations-Results”, presentation at the Space Weather, Space Weathering and Space Debris Summer School, with the participation of PTspace, OGAUC, University of Coimbra

04.12.2020, Joana Alves Ribeiro, “First estimations of geomagnetically induced currents in the South of Portugal”, MAG-GIC team seminar, online

23.02.2021, Pedro Soares, “Crustal Characterization of Portugal's mainland based on Magnetotelluric measurements”, MAG-GIC team seminar, online

30.03.2021, Rute Santos, “Shield wires effect on GICs in Portuguese power network”, MAG-GIC team seminar, online

MAG-GIC team meetings on 09.11.2020, 14.05.2021.

Meetings with REN engineers to discuss the work progress were organized by REN and MAG-GIC team members, on 09.12.2020, 05.04.2021, 04.05.2021, 30.08.2021, 02.11.2021. Participants: M. A. Pais, J. Ribeiro, F. Pinheiro, Rute Santos (MAG-GIC) and André Santos, Luís Perro, Inês Santos, susana Ludovino (REN).

20.04.2022, Maria Alexandra Pais, “Projeto MAG-GIC: Correntes induzidas pelo campo geomagnético no território português”, seminar in REN Workshop, online.

5. Distribution of outputs over time and different items