Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Research Programme
- Short Calls, Final Report -

Lead Applicant Name	Joan Campanyà i Llovet
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Host Organisation name	Trinity College Dublin (TCD)
Project Title	A new digital database of Ireland´s electromagnetic fields to mitigate against Space Weather
Contract Number	2017-sc-037

Date: 15/11/2018

This report covers the period November 1st 2017 to October 31st 2018

2. (a) Project information:

Final project report (*max **2500**words, excluding figures and headings*):

(i) *Progress* of objectives and scientific/engineering targets beyond the state of the art & *methods* used

The aim of the project was to create a digital database containing new electromagnetic (EM) data that will contribute to a better understanding of the unconstrained electric fields caused by space weather events, and of the physical properties of Ireland's lithosphere. The database is named Space Weather Electromagnetic Database for Ireland (SWEMDI). The current version of the database is SWEMDI_0.0, which is in testing mode. The database will become publically available in April 2019, from the Geological Survey of Ireland, with the name SWEMDI_1.0. Further developments of the database will contain a summary report including all the updates. The databases consist of EM data from 58 long period magnetotelluric (LMT) sites, including 36 LMT sites from Rao et al. (2014), and 22 new LMT sites (Figure 1).

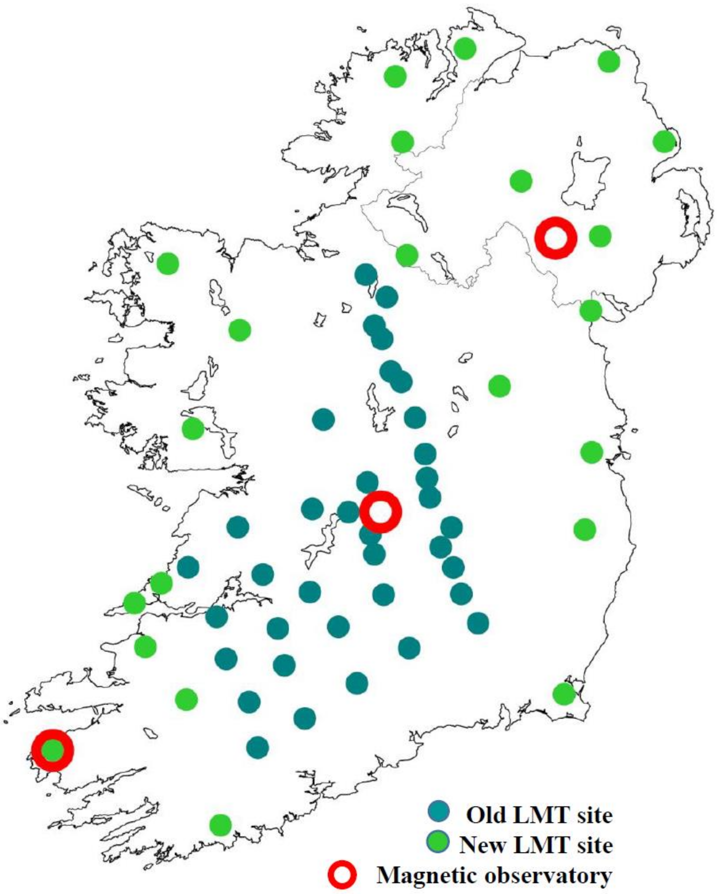

Figure 1 Map with locations of the sites related to this project. *Dark green*: Data acquired and processed in previous studies. *Clear green*: Sites either acquired or processed for first time in this project. *Red circles* show the location of the magnetic observatories in Ireland. Valentia (VAL) at the south west, Birr in mid-lands, and Armagh at the north-east of Ireland.

The database is divided in eight packages (from **P0** to **P7**):

P0_mt_sites

This package contains documents related to the project and the MT surveys and is divided in three sub-packages: P0.1_notice_land_owners contains a copy of the letter provided to the land owners that collaborate with us finding sites where to install the LMT sites, P0.2_layout_sheets contains a copy of the layout sheet for each of the new sites acquired during this project, P0.3_project_documents contain documents describing the SWEMDI project and its evaluation, and P0.4_coordinates contains a text file with the name and location, latitude and longitude, of the SWEMDI sites.

P1_time_series

This package contains electric and magnetic time series that were acquired during this project. New LMT data were acquired using LEMI-417 systems designed by Lviv Center of the Institute of Space Research, and the systems were recording a minimum of ten days in each site. The layout sheets for each site can be accessed from **P0**. Horizontal components of the electric and magnetic field, and vertical component of the magnetic field were measured, using x-component for the north-south direction, y-component for the east-west direction, and z-component for the vertical direction. Electric and magnetic sensors were oriented to magnetic north. Details about the acquisition of the old data are described in Rao et al. (2014).

Electric and magnetic time series were divided in two sub-packages containing raw and clean data, P1.1_raw_time_series and P1.2_clean_time_series, respectively. P1.1 contains time series from LEMI-417 system in ascii format. P1.2 contains clean time series that were later used to compute the EM tensor relationships. Clean time series were created by: 1) selecting segments of the raw time series that were less affected by anthropogenic noise, 2) correcting the distance between electrodes for the measured electric fields, and 3) focusing on periods between 10 s and 40000 s. **Figure 2** shows an example comparing raw and clean electric time series. A README file is included within **P1**, describing the formats and main parameters of the raw and clean time series.

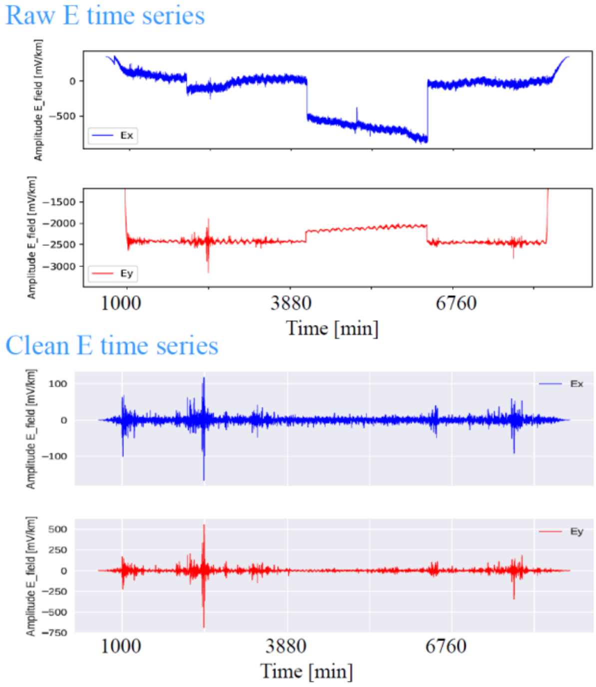

Figure 2 Example of Raw and Clean electric time series from SWEMDI database. Blue for the x-component of the electric field, north-south direction, and red for the y-component of the electric field, east-west direction.

P2_em_tensor_relationships

EM tensor relationships contains information about the electrical resistivity properties of the subsurface geology, and can be used to model the geoelectric fields at the Earth's surface caused by geomagnetic storms, and to image the electrical resistivity values of the subsurface geology. Four distinct tensor relationships are included in this package: 1) the MT impedance tensor (***Z***), 2) the geomagnetic transfer function (***T***), the quasi-MT impedance tensor (***Z'***), and the interstation horizontal magnetic transfer function (***H***). The MT impedance tensor (***Z***) describes the linear relationship between the measured horizontal components of the electric (E_x, E_y) and magnetic (H_x, H_y) fields. The geomagnetic transfer function (***T***) describes the linear relationship between the vertical component of the magnetic field (H_z) and the horizontal components of the magnetic field (H_x, H_y). The inter-station horizontal magnetic transfer function (***H***) describes the linear relationship between the measured horizontal magnetic field at one site (H_x^1, H_y^1) and the horizontal magnetic field measured at a different site (H_x^2, H_y^2). Finally, the quasi MT impedance tensor (***Z'***) describes the linear relationship between the measured horizontal electric field at one site (E_x^1, E_y^1) and the horizontal magnetic field measured at a different site (H_x^2, H_y^2). This package (**P2**) is divided in three sub-packages (P2.1_ZT, P2.2_Z', and P2.3_H). The EM tensor relationships are currently in .edi and .j formats. More detail about this formats can be check in the following link (http://www.complete-mt-solutions.com/mtnet/docs/).

The EM tensor relationships were computed using clean data (P1.2) using BIRRP algorithm (Chave and Thompson, 2004). Remote reference (RR) (Gamble et al., 1979a,b) and ELICIT (Campanyà et al., 2014) routines were performed when processing the data in order to avoid the effects of local noise and to improve the statistics. RR and ELICIT were performed using the INTERMAGNET (www.intermagnet.org) magnetic fields from Hartland (HAD), Eskdalemuir, Chambon la Foret (CLF), Valentia (VAL), and Ebre (EBR) magnetic observatories, and magnetic data from Birr and Armagh magnetic observatories (Figure 3). The interstation transfer functions were computed using magnetics from CLF as reference site, performing RR with the other magnetic observatories. The EM tensors were modified to be oriented to true north instead of magnetic north. Figure 4 shows an example of the computed tensor relationships. From the 36 sites from previous studies 27 sites were selected as having higher quality data, and the other 9 sites were discarded (discarded folder in P2.1).

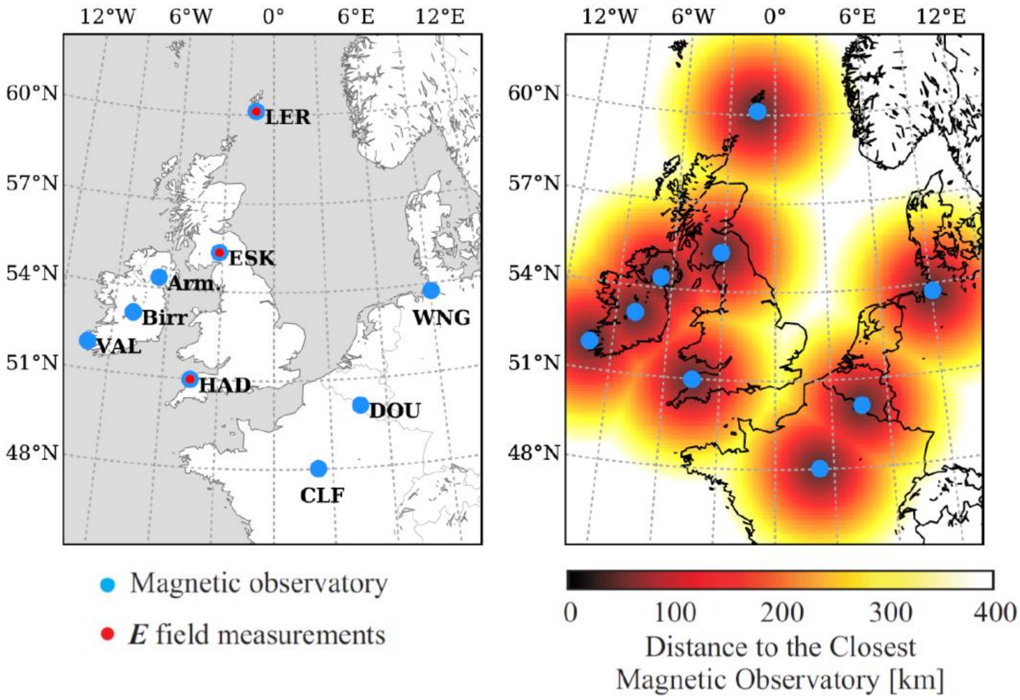

Figure 3 Left: Magnetic (blue circle) and electric (red circle) observatories close to Ireland. VAL, HAD, ESK, LER, CLF, DOU, and WNG are part of INTERMAGNET network. Bir and Arm are part of the MagIE Irish network. Right: Map showing the distance of any location in Ireland and the UK to the closest magnetic observatory.

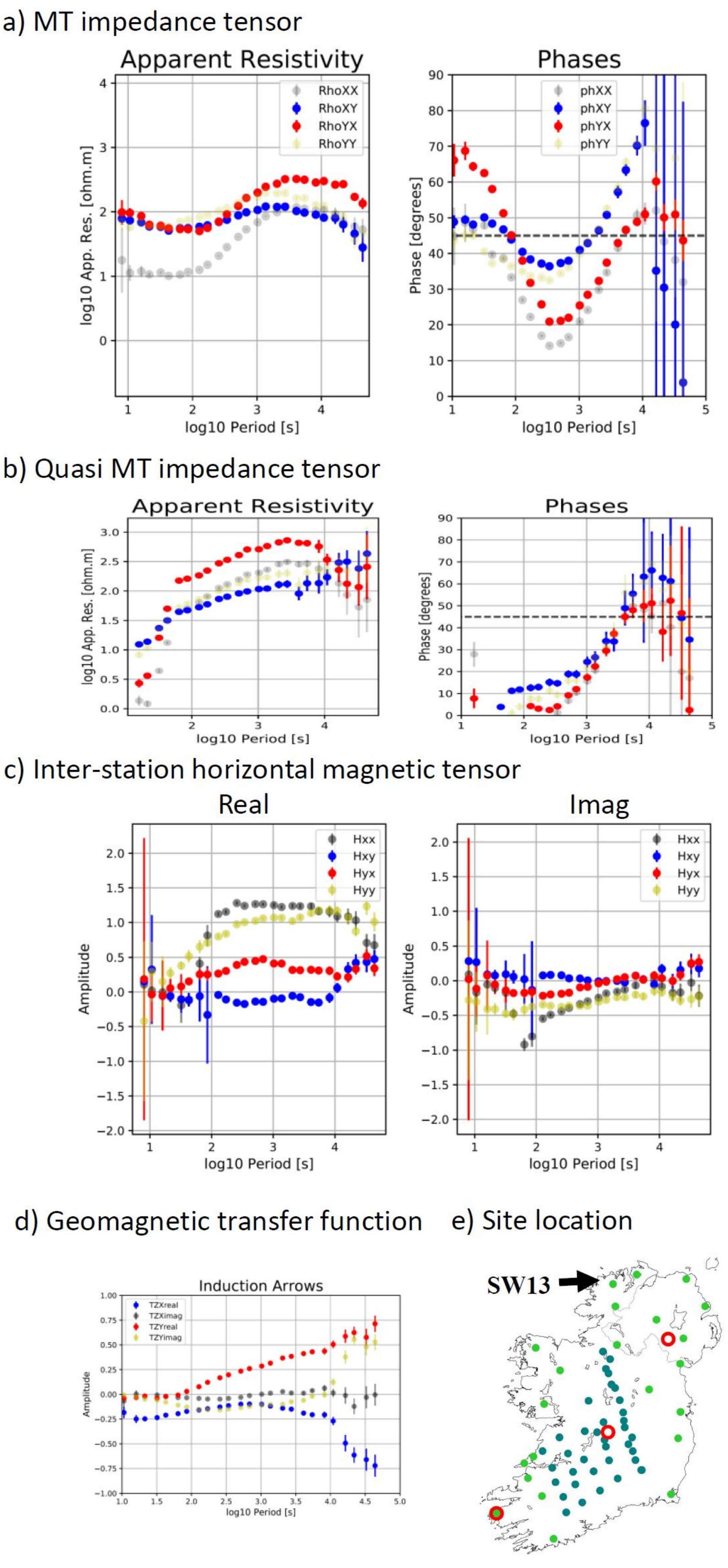

Figure 4 Computed tensor relationships for sites SW13. a) MT impedance tensor, showing apparent resistivity and phase values, b) quasi MT impedance tensor, showing apparent resistivity and phase values, and c) Interstation horizontal magnetic tensor, d) Geomagnetic transfer function, and e) site location.

Note that periods between 100 s and 10000 s seems to have better quality data than either shorter or larger periods, in particular for the inter-station transfer functions.

The tensor relationships were evaluated following different approaches with the aim of providing a prior analysis about the electrical resistivity properties of Ireland's lithosphere (Figures 5, and 6). Longer periods are related to greater depths.

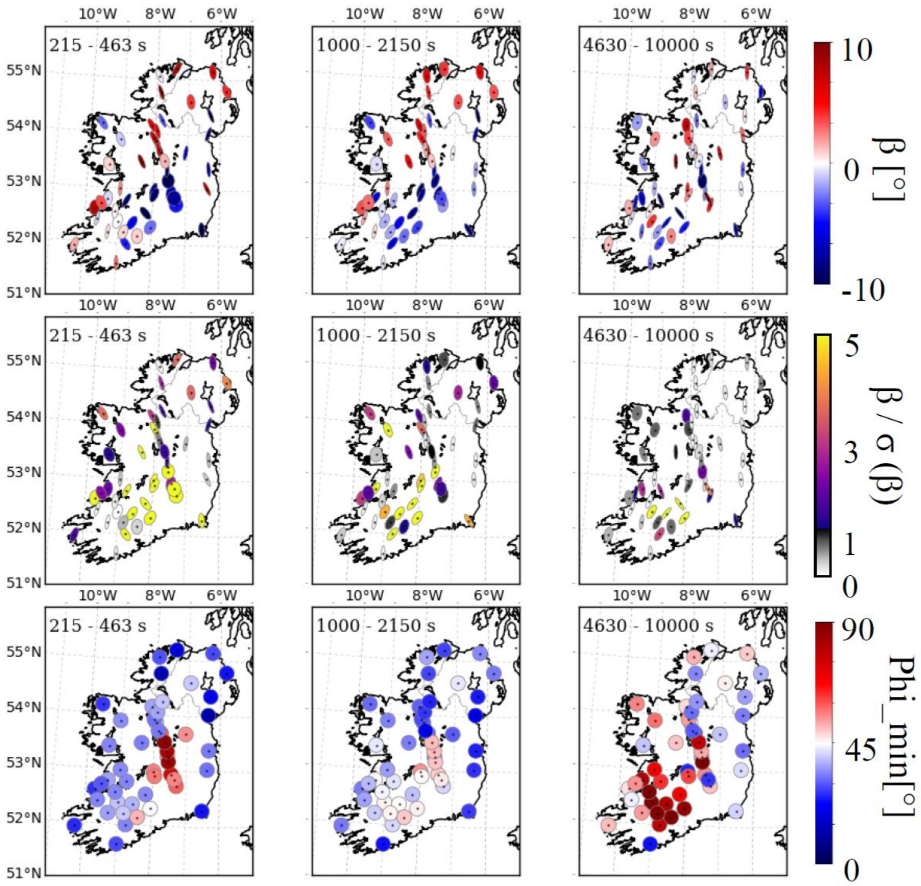

Figure 5 **Top**: Phase tensor analysis (Caldwell et al., 2004) showing the value of beta angle (colour). Large absolute values are associated with a 3D environment. **Middle**: Phase tensor analysis showing the value of beta divided by the error at constraining beta (standard deviation). Values larger than one suggest the influence of a 3D environment. **Bottom**: Minimum angle of the phase tensor. Blue colours are associated with an increase in resistivity and red colours with a decrease in resistivity.

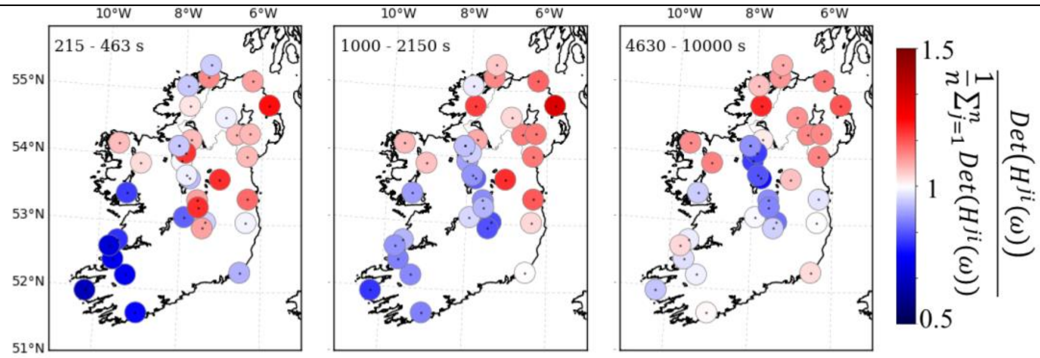

Figure 6 Determinant of the **H** tensor divided by the average of the **H** tensors in Ireland. Red colours are related to low electrical resistivity values of the subsurface geology and blue colours to high electrical resistivity values of the subsurface geology.

Galvanic distortion was not corrected for the ***Z*** and ***Z’*** tensors in SWEMDI_0.0, but a galvanic distortion analysis will be included in SWEMDI_1.0.

P3_3d_em_model_irelands_lithosphere

This package contains: 1) the starting model used for the inversion process, 2) a preliminary 3-D electrical resistivity model of Ireland’s lithosphere, 3) the input data used for the inversion process, and 4) model responses. A README file is included describing the properties and formats of the models and data files. The MT impedance tensors from P2.1 were used as inputs to constrain the electrical resistivity values of the subsurface geology. In SWEMDI_1.0 we will also present models obtained by combining several tensor relationships, from P2.1 to P2.4.

A 3-D mesh was created to model Ireland’s lithosphere, including the coastal effects (Figure 7). The mesh extends laterally from ~-2400 km to ~2400 km in the north-south and east-west directions and to a depth of ~1300km. The green cells have the values of 100 Ω·m and can be modified during the inversion, and red cells represent the Irish Sea and the Atlantic Ocean and are fixed to 0.3 Ω·m. In total, the mesh consists of 136 x 120 x 103 cells in the north-south, east-west and vertical directions, respectively. The centre of the mesh comprised a uniform mesh of 96 x 80 x 103 cells, with a horizontal cell size of 5 km x 5 km. The lateral extends of the padding cells, 20 planes in each of the north, south, east and west directions, increased by a factor of 1.25. In the vertical direction, the cell thickness is of 7.5 m and the subsequent layer thicknesses are increased by a factor of 1.1.

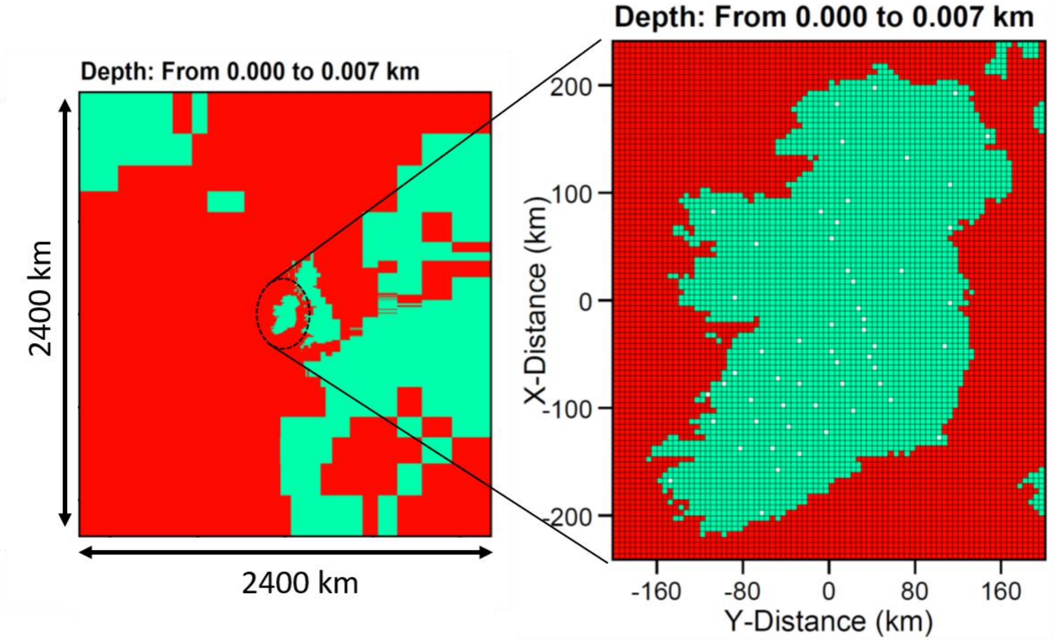

Figure 7 Plan view of the 3-D mesh designed for modelling Ireland's lithosphere. The green cells have the values of 100 Ω·m and can be modified during the inversion, and red cells represent the Irish Sea and the Atlantic Ocean and are fixed to 0.3 Ω·m.

The LMT data acquired in this project covers the period range of 10 – 20,000 s with good data quality. These data, together with the legacy MT dataset (Rao et al., 2014) were decimated to 14 periods per site with regular distribution for periods from 10 s to ~18,000 s. In total, 54 sites were used in the inversion process. The 3-D inversion was run with full impedance tensor elements (Z_{xx}, Z_{xy}, Z_{yx}, and Z_{yy}). Error floors were set to an absolute value of 5% of $(Z_{xy} \times Z_{yx})^{1/2}$. The ModEM code (Egbert and Kelbert, 2012; Kelbert, 2014) was used for the inversion process to obtain the preliminary electrical resistivity model of Ireland's lithosphere (Figure 8 and Figure 9).

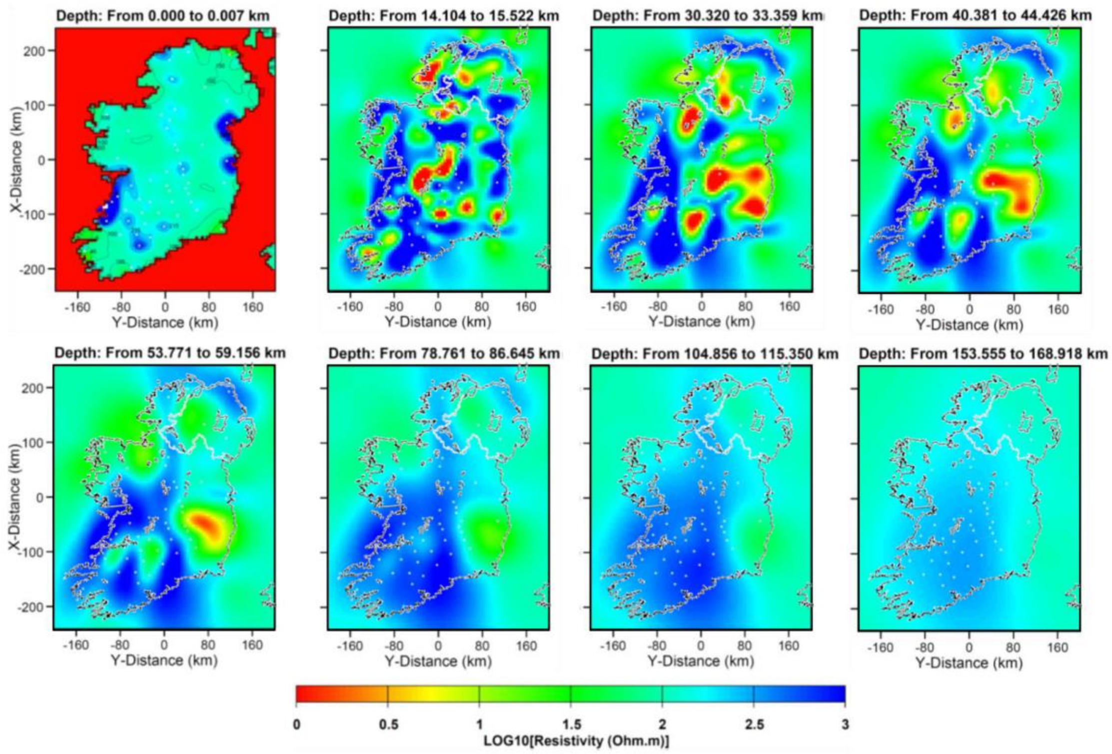

Figure 8 Horizontal slices of the preliminary 3-D electrical resistivity model showing regional electrical resistivity distribution at various depths.

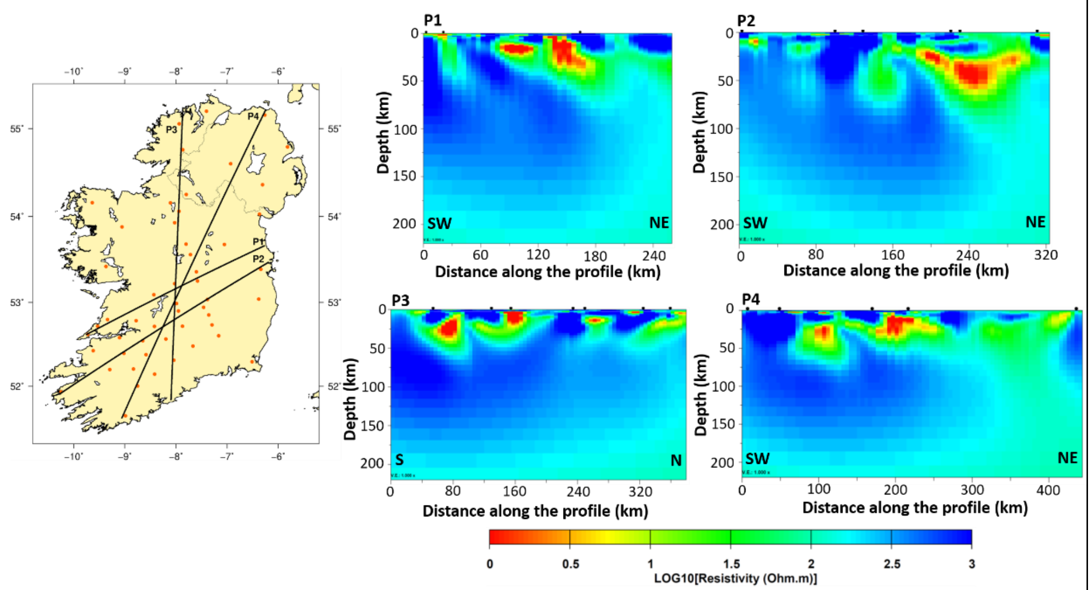

Figure 9 Two-dimensional profiles extracted from the preliminary 3-D electrical resistivity model (**Figure 8**). Profile locations derived are shown on the left-hand-side.

The presented resistivity model converged to an RMS of 2.76 after 176 hours of computation using one node on the Kay cluster of the Irish Centre of High Performance Computing (ICHEC, www.ichec.ie). We are currently testing the nested mesh approach implemented in ModEM (described and first applied to real data by Meqbel et al. 2014). This approach will reduce the required computational time for inversion runs.

P4_geoelectric_fields

This package contains modelled electric and magnetic field variations in Ireland during geomagnetic storms (Figure 10). The electric field variations were modelled using the approaches presented by Campanya et al. (under review) using electromagnetic tensor relationships from **P.2**. The magnetic field variations were measured by magnetic observatories in Ireland, the UK, and France, and interpolated to the SWEMDI sites using spherical elementary current systems (SECS) (Amm and Viljanen, 1999). More examples of EM fields in Ireland will be added in SWEMDI_1.0.

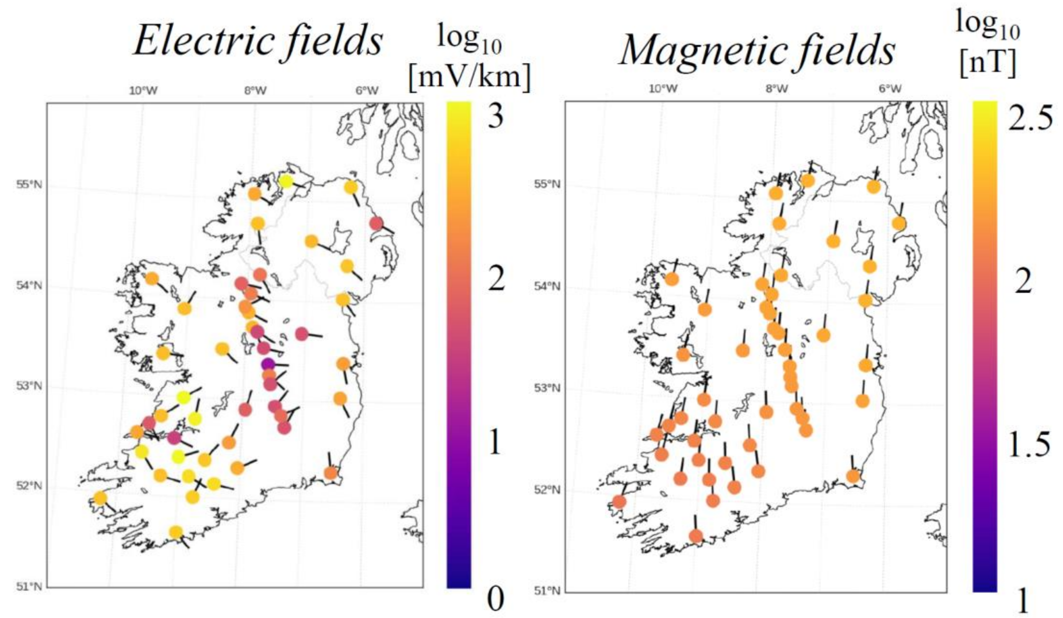

Figure 10 Electric and magnetic fields in Ireland during the 22-23/06/2015 geomagnetic storm at 18:36 UTC. The colour of the circle indicate the intensity of the fields, and the unit arrows the direction of the fields. The magnetic field variations are mostly dominated by the geomagnetic source, being quite homogeneous all over Ireland for the presented example. However, the electric field variations are mainly controlled by the electrical resistivity values of Ireland's lithosphere, showing a more complex behaviour than the magnetic field variations because of the complex Irish geology.

P5_conferences_and_publications

This package contains participations in conferences and publications related to the SWEMDI database. The README file within this package contains the related references.

P6_reports

This package contains the two interim reports and the final report submitted to the Geological Survey of Ireland related to this project.

P7_scripts

This package contains scripts that can be used to read and plot the products of the database. Each script contains, within the name, the package to which is related. All the provided scripts are in python. A README file is present in this folder specifying the requirements of the scripts. This package is currently under development and will be updated in SWEMDI_1.0 facilitating the access to the database to the possible users.

(ii) Implementation (please include any issues with timelines, milestones, management etc. or deviations from the original implementation plan)

The implementation of the project is described below, in relation to the work packages from the original Gantt Chart (Figure 11) and the executed Gantt Chart (Figure 12).

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
WP1 (EM Time Series)												
Task 1.1 Fieldwork 1 (1.5 week)	RA+D+T											
Taks 1.2 Fieldwork 2 (1 week)		RA + T										
Task 1.3 Fieldwork 3 (1 week)			RA + D									
Task 1.4 Fieldwork 4 (1 week)				RA + D								
Task 1.5 Fieldwork 5 (1.5 week)					RA + T							
Task 1.6 Cleaning Time Series		RA	RA	RA	RA							
WP2 (Processing EM Time Series)												
Task 2.1 Compute MT Tensors		RA + D	RA + D	RA + D	RA + D	D						
Task 2.2 Compute ITF		RA + T	RA + T	RA + T	RA + T	T						
WP3 (3-D Modelling)												
Task 3.1 3-D Modelling							T + D	T + D	T + D			
WP4 (Digital Database) *												
Task 4.1 Time Series						T + D						
Task 4.2 Tensors						T + D						
Task 4.3 3-D Models										T + D		
WP5 (Dissemination of Research)												
Task 5.1 Pub. Space-Weather										T	T	T
Task 5.2 Int. Conference							D					
Task 5.3 Final Report											T + D	T + D
Task 5.4 GSI Meeting												T + D

RA = Research Assistant
T = Trinity College Dublin
D = Dublin Institute for Advanced Studies

Task
Task / Milestone

* Will be made publically available six months after the end of the project.

Figure 11 Original Gantt Chart of the project with work packages, tasks, timelines, and milestones. RA: Research Assistant; T = Trinity College Dublin (Lead Applicant and Co-applicant), and D = Dublin Institute for Advanced Studies (Co-applicant)

	Nov 1	Dec 2	Jan 3	Feb 4	Mar 5	Apr 6	May 7	June 8	July 9	Aug 10	Sep 11	Oct - Nov 12
WP1 (EM Time Series)												
Task 1.1 Fieldwork 1	RA+D+T											
Taks 1.2 Fieldwork 2		RA+T+D	RA+T+D									
Task 1.3 Fieldwork 3				RA+T+D	RA+T+D							
Task 1.4 Fieldwork 4						T + D	T + D	T + D				
Task 1.5 Fieldwork 5									T + D	T + D	T + D	
Task 1.6 Cleaning Time Series		RA	RA		RA			T			T	
WP2 (Processing EM Time Series)												
Task 2.1 Compute MT Tensors		RA	RA	RA	RA			T			T	
Task 2.2 Compute ITF						T		T			T	
WP3 (3-D Modelling)												
Task 3.1 3-D Modelling									D	D	D	D
WP4 (Digital Database) *												
Task 4.1 Time Series											T	
Task 4.2 Tensors											T	
Task 4.3 3-D Models												T + D
WP5 (Dissemination of Research)												
Task 5.1 Pub. Space-Weather										T	T	T
Task 5.2.1 Int. Conference										T + D		T + D **
Task 5.2.2 National Conference				T + D								T + D
Task 5.3 Final Report												T + D
Task 5.4 GSI Meeting												T + D

RA = Research Assistant
T = Trinity College Dublin
D = Dublin Institute for Advanced Studies

Task
Task / Milestone

* Will be made publically available six months after the end of the project.
** Results will be presented at a conference in December

Figure 12 Executed Gantt Chart with packages, tasks, timelines and milestones. RA: Research Assistant; T = Trinity College Dublin (Lead Applicant and Co-applicant), and D = Dublin Institute for Advanced Studies (Co-applicant).

Data acquisition (WP1)
All the tasks were completed. The timings were modified from the original plan because of bad weather conditions in winter, and because some of the equipment needed to be repaired during the development of the project.

Processing EM time series (WP2)
Local and inter-station tensor relationships for all the sites acquired during this project were computed. Inter-station transfer functions for some of the sites from previous studies were also computed, when possible. Because of the delay in the data acquisition, the processing of the data was completed in September 2018 instead of April 2018.

3-D Modelling (WP3)
A preliminary model constraining the electrical resistivity values of Ireland's lithosphere was computed using the MT impedance tensors. Further modelling, including inter-station transfer functions and the geomagnetic tensor will be performed and included in SWEMDI_1.0.

Digital database (WP4)
The digital database was created the last month of the project, because of the issues at acquiring the data. The database is currently in testing mode (SWEMDI_0.0), and will be publically available in April 2019 with the name SWEMDI_1.0. If more changes are performed in the database after April 2019, the version of the database will be updated and a file will be added detailing the changes from the previous version.

Dissemination (WP5)
This work package was achieved as expected from the initial plan.

(iii) Outputs (please provide a short description *and* complete the table below)

The main outputs of the project are:

1. Digital database
2. Space Weather publication
3. Participation in an international conference
4. GSI Final Report

1) The digital database is currently in testing mode (SWEMDI_0.0). Between now and April 2019 we will optimize the database and update it with new results, such as an updated 3-D model of Ireland's lithosphere, and the analysis of galvanic distortion of the MT impedance tensor. A provisional link to the database is added in the supplementary material.

2) There is a manuscript in preparation quantifying geoelectric hazards in Ireland during geomagnetic storms, in which the SWEMDI database plays a primary role. The manuscript will be submitted for publication before the database is made publically available. In addition, the SWEMDI database was already mentioned in two publications in the space weather AGU journal (Blake et al., 2018; Campanyà et al., under review) mentioning that the SWEMDI database will provide valuable information for the study and understanding of space weather effects in Ireland, and that will contribute to mitigate space weather effects in ground based infrastructures.

3) The SWEMDI database has been presented in national (Irish Geological Research Meeting 2018, Geoscience Meeting 2018), and international (Electromagnetic Workshop 2018, and American Geophysical Union 2018) conferences. A copy of the posters and presentations are attached to this report, included in the database (**P5**), and uploaded in Research Gate (https://www.researchgate.net/profile/Joan_Campanya_i_Llovet) and in Figshare (https://figshare.com/authors/Joan_Campanya/3806170).

4) GSI final report as presented here. When SWEMDI_1.0 is made publically available to the public we will update the current report.

References

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Blake, S.P.; Gallagher, P.T.; Campanyà, J.; Hogg, C.; Beggan, C.; Thomson, A.W.P.; Richardson, G.S.; Bell, D., 2018. A Detailed Model of the Irish High Voltage Power Network for Simulating GICs. Space Weather, https://doi.org/10.1029/2018SW001926.

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Task No.	**Deliverable description**	**Planned delivery (as per proposal)**	**Date of delivery**
Task 4.1	Digital database: electric and magnetic time series	April 2018	September 2018
Task 4.2	Digital database: Tensor relationships	April 2018	September 2018
Task 4.3	Digital database: 3-D electrical resistivity model	August 2018	October 2018
Task 5.1	Publication in peer-reviewed international journal	November 2018	Paper in preparation
Task 5.2	Participation in International conferences	Between May and October 2018	August 2018 (EMIW) December 2018 (AGU)
Task 5.3	GSI Final Report	November 2018	November 2018

Publications to date:

National and international conferences

Campanyà, J.; Gallagher,P.T.; Blake,S.P.; Hogg,H.; Scanlon, R.; Jackson, D.; Gibbs, M.; Beggan, C.; Richardson, G.S.; Reay,D.; Raine, R.; Kiyan, D.; Fullea, J.; Rath,V. (2018) SWEMDI: Space Weather Electromagnetic Database for Ireland Irish Geological Research Meeting (IGRM2018), Cork, Ireland, 25th of February 2018 (oral).

Campanyà, J.; Gallagher, P.T.; Blake, S.P.; Hogg, H.; Scanlon, R.; Jackson, D.; Gibbs, M.; Reay, D.; Kiyan, D.; Fullea, J.; Rath, V. (2018). SWEMDI: Space Weather Electromagnetic Database for Ireland. Electromagnetic Induction Workshop, Helsingør, Denmark, 12-19 August 2018 (poster).

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Kiyan, D.; Campanyà, J.; Fullea, J.; Hogg, C.; Blake, S.P.; Rath, V.; Gallagher, P.T.; and Scanlon R. (2018). Electrical conductivity distribution of the lithosphere in Ireland revealed by magnetotelluric imaging. American Geophysical Union, Washington D.C., USA, 10-14 December 2018 (poster).

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Blake, S.P.; Gallagher, P.T.; Campanyà, J.; Hogg, C.; Beggan, C.; Thomson, A.W.P.; Richardson, G.S.; Bell, D., 2018. A Detailed Model of the Irish High Voltage Power Network for Simulating GICs. Space Weather, https://doi.org/10.1029/2018SW001926. A copy of the manuscript is available under request.

Campanyà, J.; Gallagher, P.T.; Blake, S.P.; Gibbs, M.; Jackson, D.; Beggan, C.D.; Richardson, G.S.; Hogg, C. Modelling Geoelectric Fields in Ireland and the UK for Space Weather applications (Under review). A copy of the manuscript is available under request.

4. Data/outputs submitted with final report *(please list the documents, presentations, datasets etc. submitted with this report)*

a. Presentation at the Irish Geological Research Meeting (IGRM)
b. Poster at the Electromagnetic workshop (EMIW)
c. Poster at the Geoscience meeting 2018: Meeting the challenges
d. Presentation at the Geoscience meeting 2018: Meeting the challenges
e. Abstract submitted to American Geophysical Union Fall Meeting that will take place in December 2018
f. Link to SWEMDI_0.0 database (supplementary material)

SUPPLEMENTARY MATERIAL

(This section will be included in your published report unless otherwise instructed. If you have a published report, publication, etc. you may include it here).

Data will be made available online via the GSI data service. In the interim, to request the data from this project, please contact research@gsi.ie