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

Geological Survey
Suirbhéireacht Gheolaíochta
Ireland | Éireann

Research Programme
- Short Call 2022 –
- Final Report -

Lead Applicant Name	Duygu Kiyan
Host Organisation name	Dublin Institute for Advanced Studies
Project Title	HI-RES: HIbernian Regional GeoElectrical Structure
Contract Number	2022-sc-029

This report covers the period 1st December 2020 to project end date (30/06/24)

Research Programme
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2. (a) Project information:

Final project report

Executive summary (extended abstract, e.g. for use by policy/other stakeholders):

Quantifying and de-risking the exploration for geo-resources require knowledge of the subsurface. This is true for example for both mineral and geothermal exploration. Often that knowledge is built up by local geophysical studies on areas of interest but the broad deeper context and controls for the system are often missing due to a lack of appropriate deep (e.g., >2 km) geophysical imagery. The primary goal of this project is to develop a deep (range 5-200 km) 3-D electrical conductivity model of Ireland's crust and uppermost mantle using the magnetotelluric (MT) method. Deep probing MT imaging yields information on the structure, composition and temperature of Earth's crust and upper mantle, and can detect processes associated with mineralisation and areas of high temperature and or permeability related to promising geothermal targets. It will also help better illuminate the deep geology of Ireland, particularly in the context of the mechanisms of the Caledonian and Variscan Orogenies that formed Ireland, the emplacement of its sizable granites, and the intraplate basaltic volcanism that followed the opening of the North Atlantic and created the famous Giant's Causeway and other features. MT experiments have been conducted in Ireland since 1980s. These include the Irish Magnetotelluric Profile in the late 1980s, and the Irish Magnetotelluric Lithospheric Experiment ISLE-MT in the mid-2000s. In the framework of Space Weather ElectroMagnetic Database for Ireland, long-period MT (LMT) data were acquired at over twenty stations in 2018. Since June 2019, new LMT data have been acquired at twelve stations. Hi-RES aims to complete an all-island dataset of LMT soundings by acquiring an additional 25 sites across Ireland, expanding on previous MT campaigns. The complete dataset facilitates deep geoelectrical images of Ireland's geology, allowing us to a) help constrain the locations of mineral and geothermal resources, b) interpret upper mantle temperature, hydrogen content, all of which strongly influence mantle viscosity and c) allow Space-Weather scientists to quantify geomagnetically induced currents (GICs),

that impact societal infrastructure. As part of the project, we also have developed an MT monitoring software that automates real-time processing of time series data.

(i) Results, scientific/engineering targets reached beyond the state of the art and conclusions

Long-Period MT Data Acquisition, Processing and Modelling:

The primary goal of HI-RES is to complete a nationwide dataset, to create a deep (to 200 km) island-wide 3-D electrical conductivity model of the island of Ireland's crust and uppermost mantle using the magnetotelluric (MT) method at 25 new locations across Ireland.

The Hi-RES field campaign started in December 2022 and was completed in March 2024. Long-period MT data were acquired at a total of 25 station locations across Ireland (Figure 1, green diamonds) using Ukrainian Lviv long-period called LEMI-417M instruments owned by Dublin Institute for Advanced Studies (Figure 1). With these systems time variations of orthogonal horizontal electric (Ex, Ey) and magnetic (Hx, Hy, Hz) fields were measured at the Earth's surface, and all data were stored on a flash card. While the time variations of electric fields were measured by Borin 'Stealth-2 type' Silver-Silver Chloride electrodes, variations of Earth's magnetic fields were measured using a fluxgate magnetometer. The sampling rate was 1 s and timing of the data collection was accurately determined from GPS signals. Data were collected for at a minimum of 12 days up to a maximum of 45 days (Table 1).

Table 1: Site location and recording times for each of the LMT recordings.

Site name	Latitude	Longitude	Data Acquisition Start	Data Acquisition End
HR01	54.7354	-8.4586	16-12-2022	04-01-2023
HR02	54.5539	-7.6991	22-05-2023	17-06-2023
HR03	54.9481	-6.9442	26-04-2023	22-05-2023
HR04	54.4302	-5.8853	27-04-2023	13-05-2023
HR05	54.5231	-6.7195	23-05-2023	23-06-2023
HR06	54.1993	-6.8156	01-06-2023	25-06-2023
HR07	53.8159	-7.4084	12-12-2022	03-01-2023
HR08	53.2269	-7.0664	28-02-2023	16-04-2023
HR09	53.1377	-6.6610	01-03-2023	31-03-2023
HR10	53.5424	-7.2476	02-02-2023	28-02-2023
HR11	53.5969	-6.6555	12-12-2022	05-01-2023
HR12	52.4605	-6.7092	13-07-2023	15-08-2023
HR13	52.1494	-7.5064	18-05-2023	05-07-2023
HR14	51.9747	-8.2103	11-07-2023	01-08-2023
HR15	52.5535	-8.7399	17-01-2024	13-02-2024
HR16	53.3385	-8.7039	03-02-2023	28-02-2023
HR17	53.6670	-9.1887	25-04-2023	24-05-2023
HR18	53.5876	-9.6093	24-05-2023	10-07-2023
HR19	54.0717	-9.1477	09-03-2023	19-04-2023
HR20	53.7201	-8.4528	15-03-2023	13-04-2023

HR21	53.8643	-6.7381	02-02-2023	28-02-2023
HR22	52.0597	-9.7399	18-01-2024	30-01-2024
HR23	54.5121	-6.3374	21-02-2024	18-03-2024
HR24	54.3388	-8.4188	18-02-2024	12-03-2024
HR25	53.2986	-8.2757	19-01-2024	12-02-2024

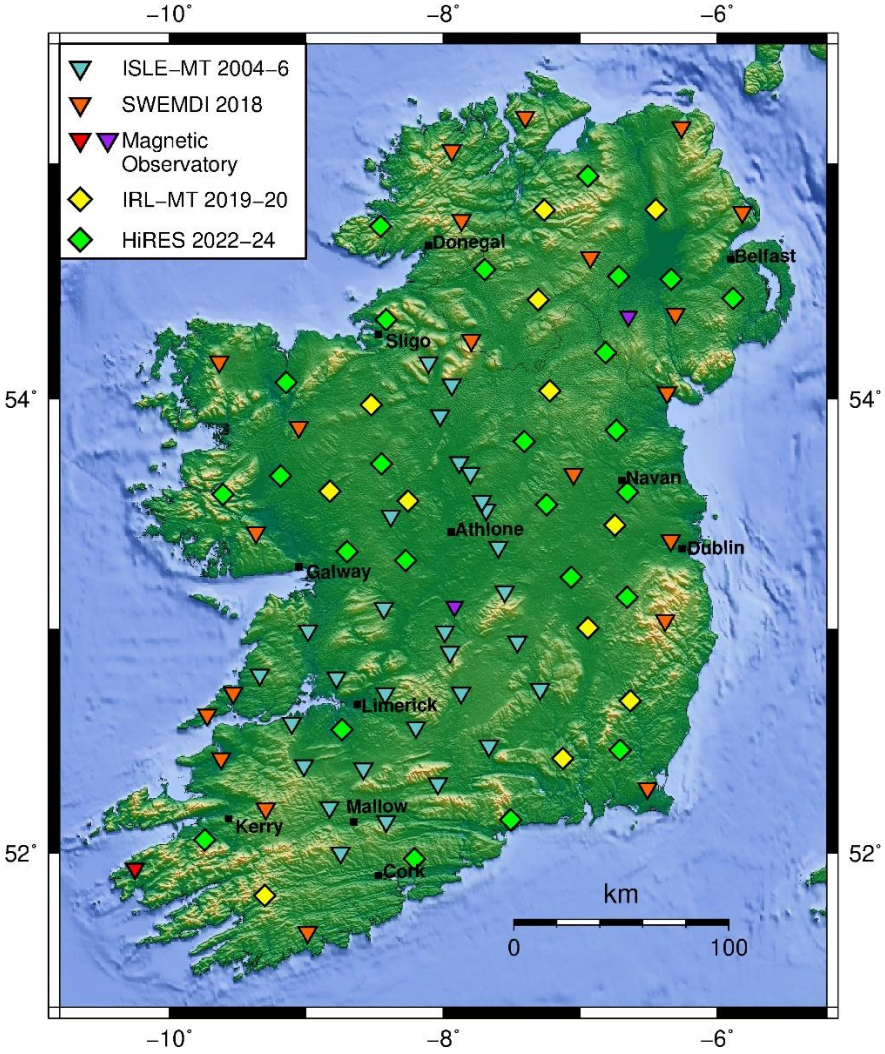

Figure 1: Location map of long-period MT (LMT) stations in Ireland. Different symbols and colours represent different LMT station networks: ISLE-MT (Rao et al., 2014), SWEMDI (Campanyà et al., 2018), IRL-LMT sites funded by DIAS and iCRAG (Kiyan et al., 2018; 2020). Hi-RES (this study) LMT stations are shown with green diamonds.

After visual inspection of the time series and removal of bad or null data, data have been processed with modern processing techniques to ensure that the most accurate and reliable MT response curves are produced to the longest period possible for each site. Two different robust remote reference methods (Chave & Thomson, 2004; Hering, 2019; Castro, 2024) have been tested to obtain optimum MT response for each LMT site and have yielded high quality apparent resistivity and phase response curves in the period range of 10 – 10,000 s for most sites (Figure 2).

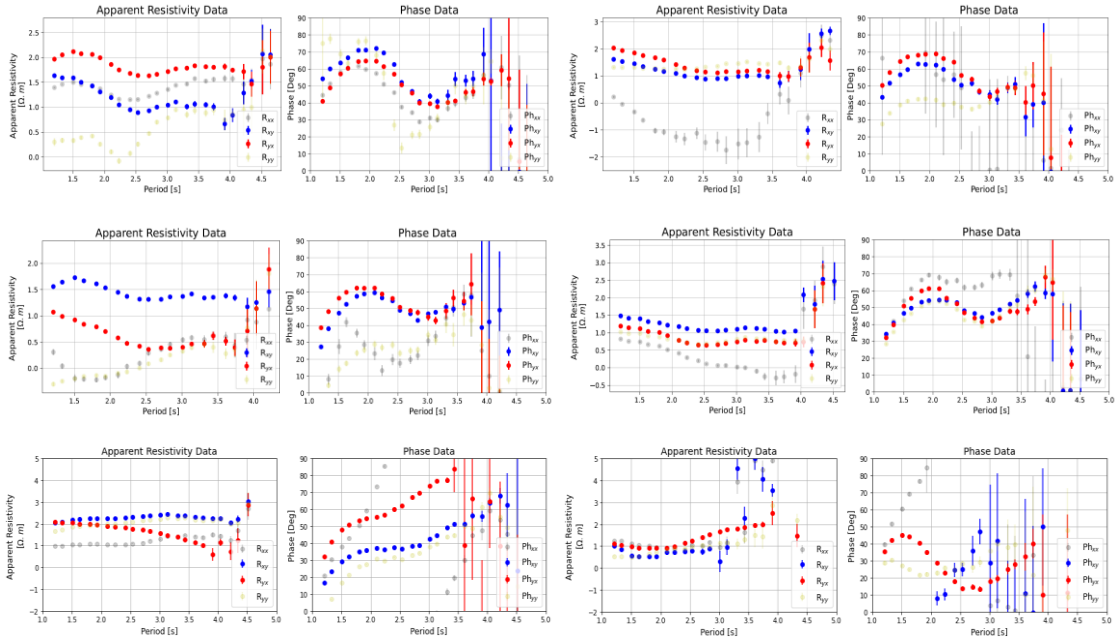

Figure 2: Example apparent resistivity and phase data curves from LMT Sites HR07 (Cavan), HR10 (Westmeath), HR11 (Meath), HR21 (Meath), HR03 (Derry) and HR04 (Down). The data have been processed with BIRRP (Chave et al., 1987, Chave and Thomson, 2004). Note that these are local data processing results.

The 3-D inversions are currently being performed employing the parallelised nonlinear conjugate gradient algorithm of ModEM3DMT (Egbert and Kelbert, 2012; Kelbert et al., 2014). The 3-D inversions will be run with full impedance tensor elements and vertical magnetic transfer functions. The impedance tensor data will be decimated to 14 periods per site with regular distribution for periods from 10 s to 18,000 s. Data from 10 s to 5623 s (12 periods) are used for the vertical magnetic transfer functions. In total, 89 and 86 sites are being used in the inversion process for the impedance tensor data and the vertical transfer functions, respectively. The 3-D mesh consists of 136 × 120 × 103 cells in the north-south, east-west, and vertical directions, respectively. The centre of the mesh comprised a uniform mesh of 96 × 80 × 103 cells, with a horizontal cell size of 5 km x 5 km. 3-D inversions are currently being performed and the resulting 3-D electrical conductivity models of Ireland will be presented by October 2024.

Software Development:

Advances in magnetotelluric (MT) instrumentation now enable continuous real-time data transmission from MT stations to a local server for storage, processing, and analysis. This advancement facilitates the detection of changes in the electrical conductivity of the subsurface, making it an ideal tool for long term, MT monitoring. The EM group at DIAS acquired several Phoenix MTU-5C systems co-funded by SFI, GSI and SEAI under the framework of the SFI Research Infrastructure Call 2022. As part of the Hi-RES project, we have developed an MT monitoring software for this unique national infrastructure. LiveMT (Figure 3) is an advanced suite for magnetotelluric processing and "real-time" monitoring, developed in MATLAB. It is based on the robust multivariate

errors-in-variables (RMEV) estimator method by Egbert (1997) and has been further extended and adapted by Hering (2019) and Castro (2024).
In LiveMT the data are segmented into frequency-oriented time windows and transformed into the spectral domain. A recursive multivariate linear regression (rMVLR) is performed, using local site channels as observations and remote reference site channels as predictors (if available). This allows for the calculation of the spectral density matrix (SDM) and the noise covariance matrix (NCM) is derived from the regression residuals. Statistical MT parameters, along with an eigenvalue index (EVind), enable the rejection of segments with low SNR or those contaminated with coherent noise.

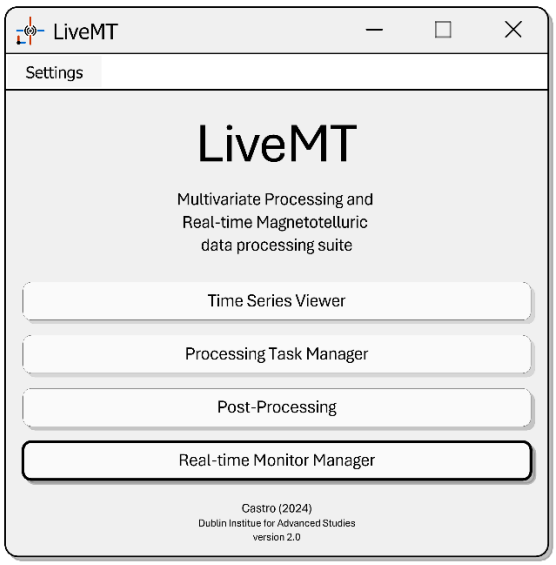

Figure 3: LiveMT Main Screen and Modules

Currently, LiveMT is capable of processing time series from broad-band Phoenix Geophysics MTU5/MTU5-A (.ts), MTU5-C/MTU8-A (.td_**) and long-period LEMI 417 (.b**), and LEMI 424 (*.txt).

(ii) Project Implementation (milestones, deliverables, project management)
This project is divided into seven work packages (WP) as detailed below.

WP-1 (Acquisition of MT time series) (completed): Long-period MT data acquisition was completed at 25 stations (Figure 1, green diamonds). The data acquisition and QC of the acquired data were led by the co-applicant Colin Hogg. Students and researchers from DIAS Geophysics and Astronomy and Astrophysics Sections, namely Oscar Avila Vargas, John Malone-Leigh, Tao Ye, Meysam Rezaeifar and Emma Chambers, were involved in the fieldwork programme.
Lead: Colin Hogg
Contributors: Colin Hogg, DIAS Geophysics and Astronomy Astrophysics Students and Researchers and Duygu Kiyan
Key deliverables: MT time series from 25 stations

WP-2 (Processing of MT time series) (completed): Estimations of the frequency-dependent MT transfer functions at 25 stations have been carried out using BIRRP

(Chave et al., 1987). The results from BIRRP have been compared against the results from a new processing code, called FFproc (Hering 2019, Castro 2024).
Lead: Duygu Kiyan
Contributors: Cesar Castro and Colin Hogg
Key deliverables: MT transfer functions from 25 stations

WP-3 (Digital database update) (on-going): Digital products (i.e., MT time-series, transfer functions and the 3-D MT model) will be added to the SWEMDI database hosted by GSI. This will require specific formatting/conversion to be applied to the data.
Lead: Duygu Kiyan
Contributors: Colin Hogg and the Space Weather Group (SWG) (PG: Peter Gallagher, JML: John Malone-Leigh, JC: Joan Campanyà)
Key deliverables: An updated MT database for Ireland

WP-4 (HI-RES 3-D MT Model) (on-going): 3-D modelling and inversion of the resulting data are performed using the Modular system for Electromagnetic inversion software (ModEM; Egbert and Kelbert 2012; Kelbert et al., 2014). Prior to the modelling of the field data, synthetic checkerboard tests with station locations that represent the current actual Hi-RES station locations have been performed to better understand the sensitivity of the station network used to the subsurface structures.
Lead: Duygu Kiyan
Contributors: Cesar Castro
Key deliverables: A model of the electrical conductivity structure of the crust and the uppermost mantle beneath Ireland

WP-5 (Magnetometer Network of Ireland (completed): Following the processing, analysis for anthropogenic noise and modelling of the data from the SE and NW of Ireland, one new node is planned to be added to the existing network. 3 new potential locations have been identified: Sligo, Connemara, and South Wicklow.
Lead: Peter Gallagher
Contributors: Duygu Kiyan, SWG, Colin Hogg
Key deliverables: Identification of new locations for the Magnetometer Network of Ireland.

WP-6 (Near real-time processing code) (completed): An MT data processing and real-time monitoring suite to enhance the software capabilities compatible with the MASTER (Magnetotelluric Acquisition Systems for Terrestrial Earth Research) MT infrastructure.
Lead: Cesar Castro
Contributors: Duygu Kiyan, Colin Hogg
Key deliverables: A magnetotelluric processing and "real-time" monitoring suite

WP-7 (Dissemination of research): Two poster presentations on the Hi-RES project were given at the European Geosciences Union 2023 in Vienna, Austria, 24-28 April 2023 and at the GSI Geoscience Conference on 7 November 2024.
WP-6 will be presented at the 26th Electromagnetic Induction Workshop in Beppu, Japan, 7-13 September 2024. Abstract has been accepted for the workshop. Title: LiveMT: an automated suite for real-time magnetotelluric monitoring.

(iii) Outputs to date (this should include the location of datasets generated, as per GSI and NORF requirements)

- A copy of raw MT time-series from 25 stations are available on DIAS data repositories.
- Processed MT transfer functions from 25 stations are available on DIAS data repositories.
- LiveMT software and LiveMT Manual, hosted in DIAS.
- **(On-going)** Hi-RES 3-D MT Model

(iv) Impact

- Relevance/application to GSI programmes, where applicable

- The broad range of outputs of this research complements the principal goals of the latest GSI Research Roadmap: (a) This national dataset allows us to create a nationwide 3-D geoelectrical model of the island of Ireland will make an impact by increasing the geological understanding of the subsurface (b) this dataset will aid the understanding and development of Ireland's natural resources (geothermal energy and mineral systems).
  One primary example is the DIG project (Derisking Ireland's Geothermal energy potential: grant number 19/RDD/522, www.dig-geothermal.ie) by SEAI and GSI. DIG focusses on decarbonising Ireland's energy system into the future, a key component of National Prioritisation areas (2018-2023) 'Decarbonising the Energy System. The island-scale research aspect of DIG uses Rayleigh and Love surface waves specifically to determine the lithospheric structure, with crustal geometry (Chambers et al., 2023). This new MT data and data products will greatly enhance the imaging of regional-scale structures at depth especially in areas where regional geotherms are poorly constrained. The local-scale research component of DIG is an MT survey focussing on imaging a localised warm-spring resource in County Cork (in the south of the island). These additional data will provide unique insights into the deeper geology feeding this localised geothermal resource and possibly identify analogous anomalies relating to this deeper system (O'Reilly et al., 2021; Kiyan et al., 2022).
  Second example is the DIAS-iCRAG project entitled 'Multiphysics Joint Inversion of the Irish Lithosphere' (Molodtsov et al., 2024), which aims at developing a coherent multi parameter geophysical model of the Irish lithosphere. Hi-RES MT data will be added to the existing MT database and will be jointly inverted with seismic first-arrival traveltime tomography (FATT) using quarry blasts as sources and gravity data for the whole Ireland. These developed all-Ireland geophysical models will be used as the initial models for multi-method imaging of the Leinster Granite funded by the GSI Short Calls Programme 2024 (grant no: 2024-sc-015).
- A previously funded (grant number: 2017-sc-037) GSI Short-Call project (SWEMDI), created a digital database of Ireland's electromagnetic fields to mitigate against Space Weather. Digital data from HI-RES will add significant

value to this database, and in doing so yield additional data for Space Weather research.

- Other impacts (these should be medium-long term impacts, not the project outputs)

- Software development for the new MASTER MT instrumentation will allow creating the ability for near real-time electrical conductivity change monitoring, as the instrumentation allows remote data transfer. 4-D geophysical imaging for physical property change monitoring is becoming ever more important. This new toolkit will allow the DIAS EM Group to increase capacity and leverage greater collaboration potential, particularly on an EU level to progress ongoing work on volcano imaging and monitoring (e.g., Hekla Volcano, Iceland, Kiyan et al., 2021) and geothermal fields elsewhere in the world further internationalising our research.

References:

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magnetotelluric imaging. AGU Fall Meeting 2018, GP31D-0739, Washington D.C., USA, 10-14 December.

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Molodtsov, D., Kiyan, D., Bean, C., (2024). 3D joint inversion of regional magnetotelluric, seismic, gravity and magnetic datasets to image lithospheric structure of Ireland, EGU General Assembly, 14–19 Apr 2024 April, Vienna, Austria.

Publications:

[Poster presentation] **Kiyan, D., Hogg, C.,** Campanyà, J., Bean, C. J., Fullea, J., Blake, S. P., Malone-Leigh, J., **Gallagher, P. T.,** Rath, V., Jones, A. G. and Scanlon, R.: 3-D Magnetotelluric Assessment of the Geo-resources Potential of the Irish Crust. EGU General Assembly 2023, Vienna, Austria, 24–28 April 2023, EGU23-16297, https://doi.org/10.5194/egusphere-egu23 16297, 2023.

[Poster presentation] **Kiyan, D., Hogg, C., Gallagher, P.T.,** Malone-Leigh, J. and Campanyà, J.: HiRES - Hibernian Regional GeoElectrical Structure, 2023. GSI Geoscience Conference 2023, 7 November, Dublin, Ireland.

[Seminar] **Kiyan, D.**: Probing the Lithosphere with Magnetotellurics. Mantle Group, 28 May 2024, hosted by DIAS Geophysics.

[Poster presentation - accepted] **Castro, C., Hogg, C., Kiyan, D.,** Moorkamp, M. and Hill, G: LiveMT: An Automated suite for real-time Magnetotelluric monitoring. 26th Electromagnetic Induction Workshop, 7-13 September 2024, Beppu, Japan.

3. Supplemental information/datasets

Recording time windows of the Long-Period MT Sites during the HiRES field survey