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The GEO-URBAN Project: Exploring the Geothermal Potential of Dublin City using Electromagnetic and Passive Seismic Methods

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ABSTRACT

The GEO-URBAN project aims to understand the potential of the geothermal district heating in Dublin City to respond to increasing demand for sustainable energy sources. To help elucidate the subsurface geology in the geothermal exploration effort, we perform a multi-disciplinary approach using two innovative and complementary geophysical techniques: (i) electromagnetics and (ii) passive seismics. We implement and test the feasibility of these methods to investigate the electrical conductivity and velocity variations beneath the city. The geology of Dublin City is characterised by a Carboniferous sedimentary basin separated from the Lower-palaeozoic basement by bounding faults. The depth of the basement is unclear, but presumably between 1.5 to 2 km deep. We have deployed a broadband seismic array across the city to collect a dataset of ambient noise over a 4-month period, to be used for the single station H/V analysis and the array cross-correlation interferometry. The H/V analysis results show an overall high resonance frequency peak indicating a shallow soil layer across the study area. The preliminary cross-correlation results are promising and indicate the emergence of surface waves. To test the feasibility of the electromagnetic techniques in the urban areas, we conducted a magnetotelluric experiment in Dublin City. The first data acquisition results show that the time series were heavily contaminated by Dublin City tram/railway systems and other infrastructure. We are currently developing a work strategy to apply passive and controlled-source electromagnetic techniques within the Dublin Basin.

1. INTRODUCTION

The overarching objective of the GEO-URBAN project funded by the EU GEOTHERMICA ERA-NET Co-fund is to identify and evaluate potential deep geothermal resources in Dublin City, Ireland and Vallés, Spain. The main geological challenge towards the exploration of the deep geothermal resources is acquiring an extended and full knowledge of the geological setting and properties (fractures and faults) in the Dublin Basin. The subsurface characterisation is usually achieved by using a combination of different geophysical techniques (e.g., seismic and electromagnetics) to identify water-bearing horizons and fractures.

The geology of Dublin is characterised by Lower Carboniferous basinal limestones and shale, known as Calp (Strogen and Somerville, 1984). These formations consist of dark grey massive limestones, shaley limestones with massive mudstones. The Dublin Basin spreads from Dublin coast to central Ireland showing an east-west axis, bounded by faults on its northern and southern margins (Sevastopulo and Wyse, 2009). In the Lower Carboniferous, active faulting within the basin led to the development of shallow platforms and contrasting deeper regions. The platform facies are typically clean, thickly bedded, and shale-free limestones, whereas the deeper basinal facies are thinly inter-bedded, cherty limestones and shales (Marchant and Sevastopulo, 1980). The interface between the sedimentation on the ramp and subsequent development of shelf platforms in the Dublin Basin is marked by a by layers of Waulsortian carbonate mud (Lees and Miller, 1995). The thickest developments of Waulsortian carbonate in the Dublin Basin are over 500 m thick (Strogen et al., 1996). In a previous hydrogeological study, Blake at al. (2016) identify four thermal springs discharging from Waulsortian limestone localities, which might be due to deep faults facilitating the ascent of the thermal spring waters to the surface (Blake at al.,2016).

Previous geophysical studies have been carried out within the Carboniferous Dublin Basin using the Receiver Functions (RF) method (Licciardi and Agostinetti, 2017) and the magnetotelluric method (Blake et al., 2016 and Vozar et al., *in review*). The RF study aimed at investigating the eastern margin of Dublin Basin focusing on the bounding faults that separate the Carboniferous units from the Lower Palaeozoic basement. Licciardi and Agostinetti (2017) modelled isotropic and anisotropic properties of the shallow crustal rock identifying a major sub-vertical lateral Vs contrast at the proximity of the Basin. The shallow velocity anomalies are interpreted to be the limestone of the Upper Calp which increases in terms of thickness from 700 m to 1 km from the southwest to the northeast axis of the basin. Deeper in the basin, the authors identified anisotropic layers associated with a low S velocity pattern down to 2.3 km interpreted as fluid-filled aligned cracks, which was supported by an existing 1.5 km deep sonic log borehole showing a positive and a negative jump respectively at 0.7 and 1.4 km associated with the Lower Calp limestone. An MT survey (Vozar et al., *in review*) was carried out in years 2011 and 2012, in the south-extent of the Dublin Basin crossing the Blackrock to Newcastle Fault (BNF) which juxtaposes basinal facies of the Dublin Basin and the Leinster Massif, comprising the Silurian-Devonian Leinster granite and Ordovician-Silurian metasedimentary host rocks (Figure 1, Fernandes, 2000). The 2-D and 3-D modelling imaged the BNF as a highly fractured and conductive zone down to depths of 4 km. The resistivity model delineated two enhanced conductive zones, one at 1-2 km and another 2-4 km. The deeper conductive layers are interpreted as water- or geothermal-fluid-bearing rocks.

Despite having a wide range of available geophysical information, a clear picture of the structural setting of Dublin Basin is still missing. To enhance the knowledge of geological subsurface of Dublin City, we apply two innovative and complementary geophysical techniques: electromagnetic (EM) and passive seismic ambient noise methods which investigate the electrical resistivity and velocity structure of the subsurface. Both surveys have the objective to identify the main geological features of the Dublin Basin at different scales, such as the transitions from the overburden to the limestone and down to the metamorphic basement.

In this paper we describe the preliminary steps that we have undertaken on the implementation of the seismic and magnetotelluric surveys in Dublin City.

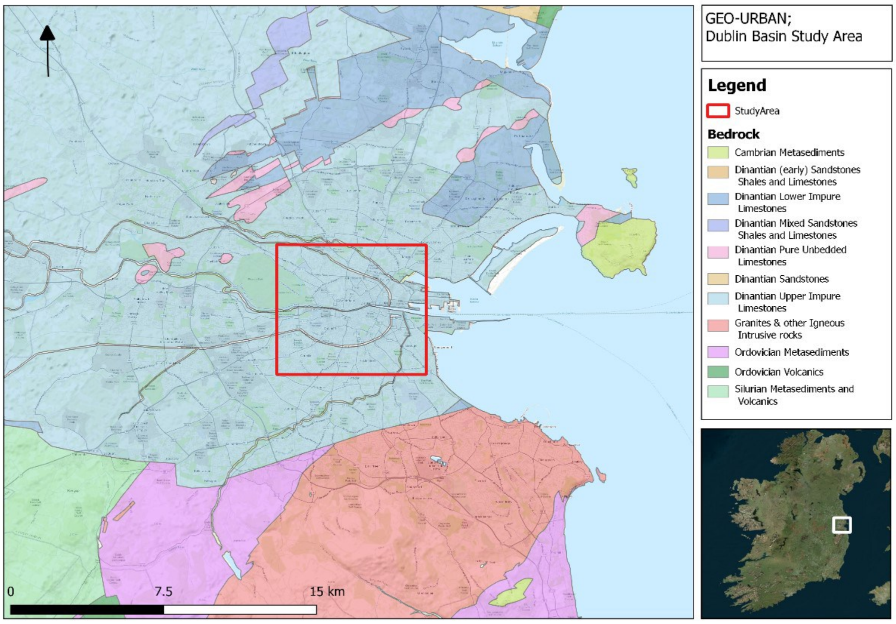

Figure 1: Geology of the Dublin basin and the study area.

2. SEISMIC SURVEY

For the seismic study, we have deployed an array of seismometers in the study area (Figure 2). From April to August 2019, we deployed 19 GURALP broadband (30 s – 100 Hz) seismometers across the urban centre of Dublin City in a 5 km by 5 km grid. The seismic array has a ~1 km interstation distance and a maximum aperture of ~7.2 km. The array is designed to target frequencies higher than ~0.5 Hz. Lower frequencies cannot be fully exploited since their wavelengths might be greater than the array aperture. The seismometers are installed indoor and in the basements of the buildings onto concrete\asphalt floors. The site locations and permissions have been provided by the Dublin City Council. The data from these stations are used for both the H\V and the cross-correlation analyses. While for the H/V analysis a few hours of data acquisition are satisfactory, the ambient noise interferometry analysis requires weeks to months of data collection which depends on the nature and consistency of the noise field. Since the data acquisition is still on-going, the preliminary analysis results are introduce here. We first analyse the frequency content of urban noise sources and afterwards we discuss the preliminary cross-correlation results and the observations on the H\V curves.

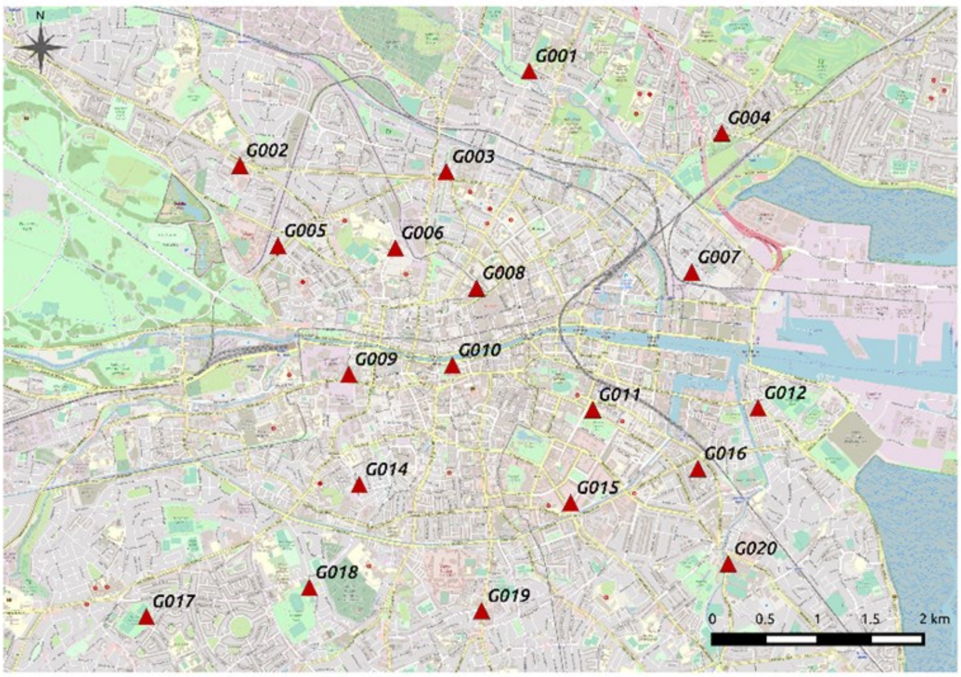

Figure 2: Seismic array deployment map in Dublin City.

2.1 Seismic Dataset and Frequency Analysis

The noise field is dominated by high-frequency signals generated by the traffic noise and any sort of anthropogenic activities occurring in the city. Figure 3 shows a smooth high-frequency background noise rich in wide-spectrum transients (such as trucks and cars) and monochromatic signals (such as ventilation systems and machinery). A clear day/night pattern can be observed in the spectrogram. The noise level increases around 5am and starts decreasing around 6pm and almost disappears during the midnight. This clearly matches with the busiest hours of a day in the city. Understanding the temporal variation of the noise enables us to target the most suitable time windows to be used for the H/V and the cross-correlation analyses. Trains and motorways might represent the most consistent and distributed noise source we could observe. However, discrimination of these signals from the localised disturbances is a challenge that needs to be tackled. Even though the noise field goes up to 40 Hz, not all the frequencies can propagate across the array since they tend to easily dissipate.

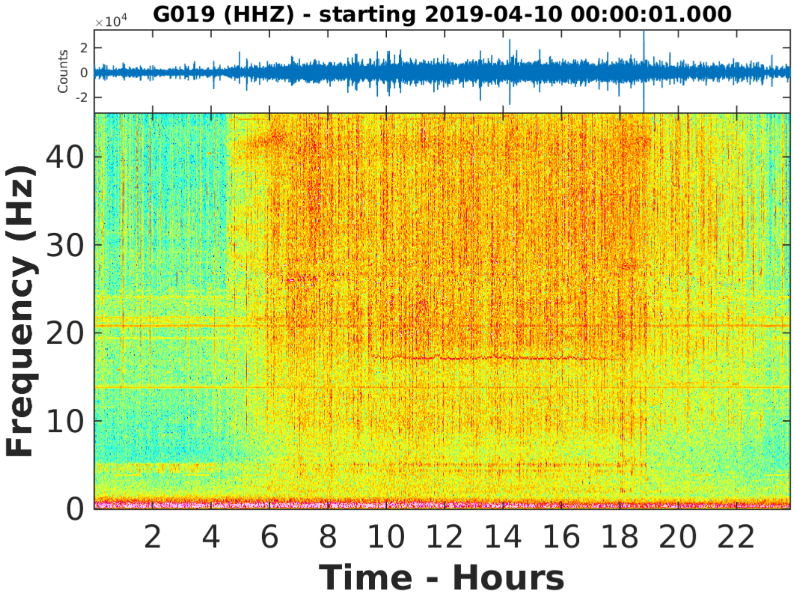

Figure 3: Twenty-four hours seismogram and spectrogram recorded at station G019.

2.2 Preliminary Cross-Correlation Computation and Surface Waves

The ambient noise interferometry aims to extract surface (or body waves) by applying the cross-correlation (CC) between two receivers. In theory, the noise sources should be homogenously distributed outside the array. In reality, however, these sources tend to be localised which could affect the cross-correlation results by adding spurious events and velocity bias. The output of the CC is a zero-lag centred cross-correlograms composed by a positive (casual) and a negative (acausal) part. For the cross-correlation processing, we followed the processing method described by Bensen et al. (2007). We first split the daily raw seismograms into 10 min segments and after detrending, and removing the mean and the instrument response, the data are filtered in 0.1-10 Hz frequency-band. In order to reduce the effect of local monochromatic noise, the spectral whitening is applied to the data. After completing the pre-processing step, the vertical component of the data is cross-correlated using MsNoise (Lecoq et al., 2014) to obtain daily cross-correlations. We then stack these CCs using the PWS method (Schimmel et Paulssen., 1997). PWS enhances the detection of coherent signals. Figure 4 shows the cross-correlation stacks for every station pair which is plotted against the interstation distance.

Since the dataset is being currently acquired, we aim to improve the signal to noise ratio (SNR) by adding more data and tuning the computation parameters. In terms of the data quality, we will select and discard the CC that do not fit the consistency criteria, e.g., the CCs that have an SNR below a given threshold will be removed and the CCs with a wavelength greater than the interstation distance between the receivers will be discarded. The next step is to extract surface waves, which are generated by the interaction of elastic waves with the free surface, from the CCs. The surface waves propagate horizontally and their amplitude and energy decay with distance and depth. The main surface wave types are Rayleigh waves (a combination of P and SV) and Love waves (a combination of P and SH). Since we are computing the vertical component of the data, Rayleigh waves are generated only. The surface waves are generally characterised by frequency dispersion that is strictly related to the elastic properties of the medium in which waves propagate through. To study the velocity dispersion, we apply the Frequency-Time ANalysis technique (FTAN) proposed by Levshin et al. (1992). Figure 5 shows the FTAN on the G011 - G018 cross-correlation pair. The Rayleigh waves have an apparent velocity of ~2.3km/s and a consistent dispersion up to 5 Hz can be observed.

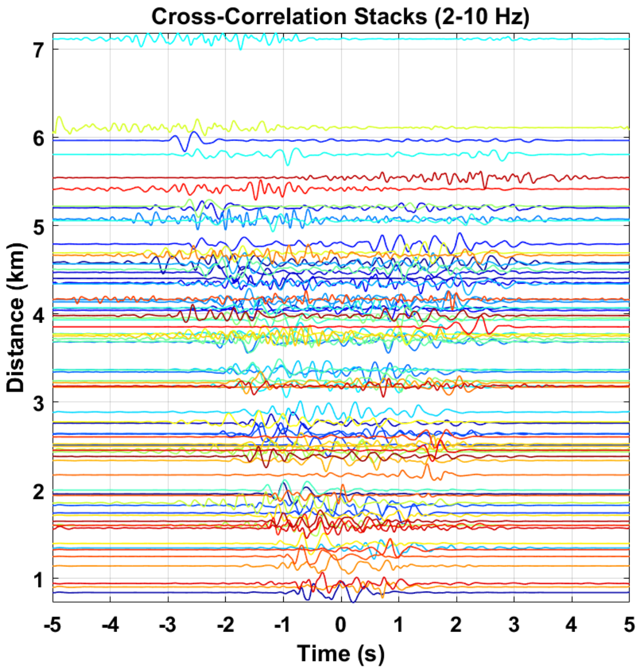

Figure 4: Cross-correlations filtered in the 2-10 Hz frequency band.

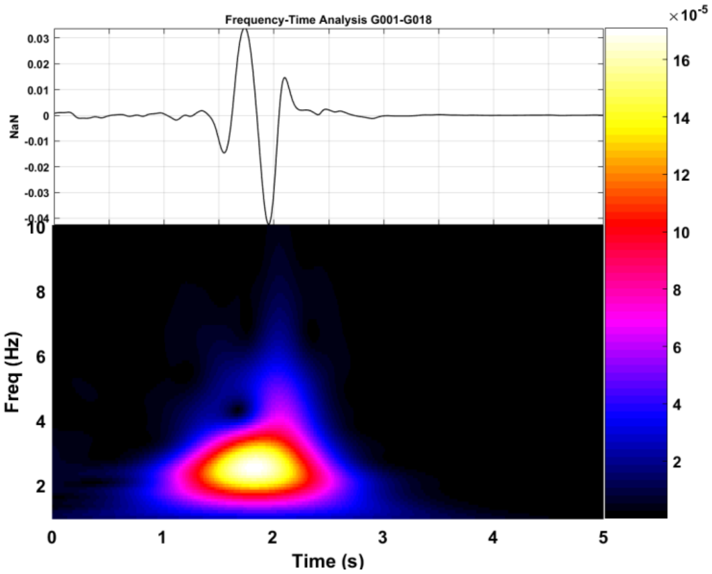

Figure 5: FTAN dispersion analysis on G011-G018 cross-correlations stack.

2.3 H\V Analysis

The H\V method is used to assess the dominant frequency of the local stratigraphy by calculating the ratio between the amplitude spectra of the horizontal (H) to vertical (V) components of the microtremor recorded at a single station. The H\V curves show the fundamental resonance peaks that are related to the contrast of impedance between the bedrock and the loose sediments. Despite the empirical validation at the support of the H\V method, there is no consensus about the physical explanation of H\V peaks. Many models and hypotheses have been formulated to investigate the role of the source and wavefield composition (Lunadei et al., 2015). Regarding the computation and interpretation, we followed the guidelines suggested by the SESAME project (2004). We process one-hour night-time recording (from 2 am to 3 am) to minimise the occurrence of nearby disturbances. Prior to the H\V calculation, we apply the following three processing steps: (1) an anti-triggering to select most stationary time windows to avoid noise transient; (2) smoothing the Fourier amplitude spectra for each time windows; and (3) quadratic mean of the horizontal components. Ultimately, we calculate the H\V ratio at the frequency interval of 0-15 Hz. Figure 6 shows the H\V curves on which the fundamental frequency peaks are identified and marked with red solid line. The frequency peaks vary from 3.7 up to 15 Hz indicating very shallow soil deposits. The next step will involve calculation of the bedrock depth by using the empirical relationship between the frequency peak and the soil thickness. This can be inferred by using the regression linear model proposed by Seht et Wohlenberg, (1999). An accurate estimation can be achieved by adjusting the regression linear model to the local geotechnical features.

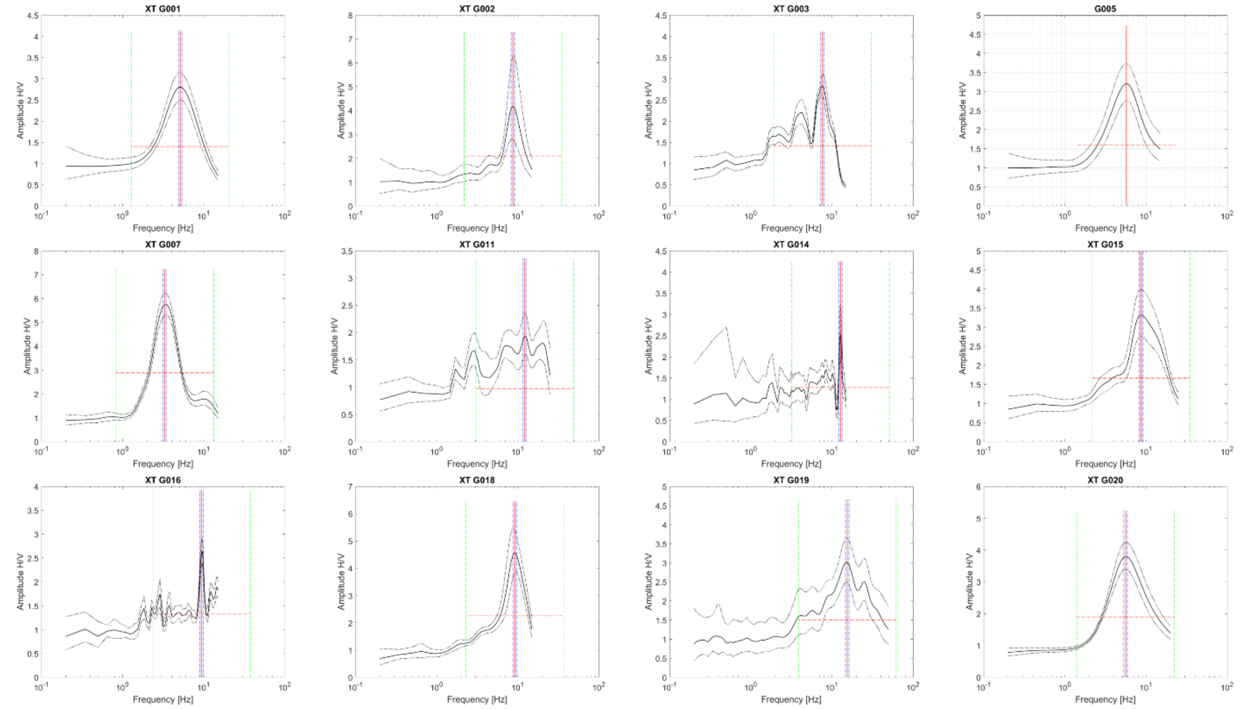

Figure 6: H\V curves calculated at thirteen stations. The red line indicates the fundamental resonance frequency.

3. ELECTROMAGNETIC SURVEY

The second and third geophysical techniques applied in the project are electromagnetic methods, namely, magnetotellurics (MT) and controlled-source electromagnetics (CSEM). The natural-source MT method utilises natural variations in electromagnetic energy to infer the electrical conductivity (or its inverse resistivity) properties of rocks within the Earth. The first MT data acquisition was undertaken in the Merrion Square Park in Dublin City centre (Figure 7) using Phoenix Geophysics equipment, namely MTU-5A recording boxes and MTC-50 induction coils. Magnetic time-series data were simultaneously recorded at a remote reference site (electrically quiet area) about 45 km away. At the site, the two horizontal, perpendicular magnetic field components were recorded, as well as the vertical magnetic field component. The two horizontal, perpendicular electric field components were measured using non-polarising Pb–PbCl (lead–lead chloride) electrodes laid out in a cross with a dipole length of 60 m. This first data acquisition has highlighted some issues with anthropogenic noise in the urban area. The MT time-series, particularly the electric fields, were heavily contaminated and distorted due to electromagnetic noise from Dublin City tram /railway systems and other infrastructure. Since Dublin City is underlain by resistive Viséan limestone, one can anticipate that noise signals permeate over a large area. The next step will involve new controlled-source audiomagnetotellurics (CSAMT) data acquisition in the city centre during the winter of 2019/January 2020 to overcome severe cultural noise contamination.

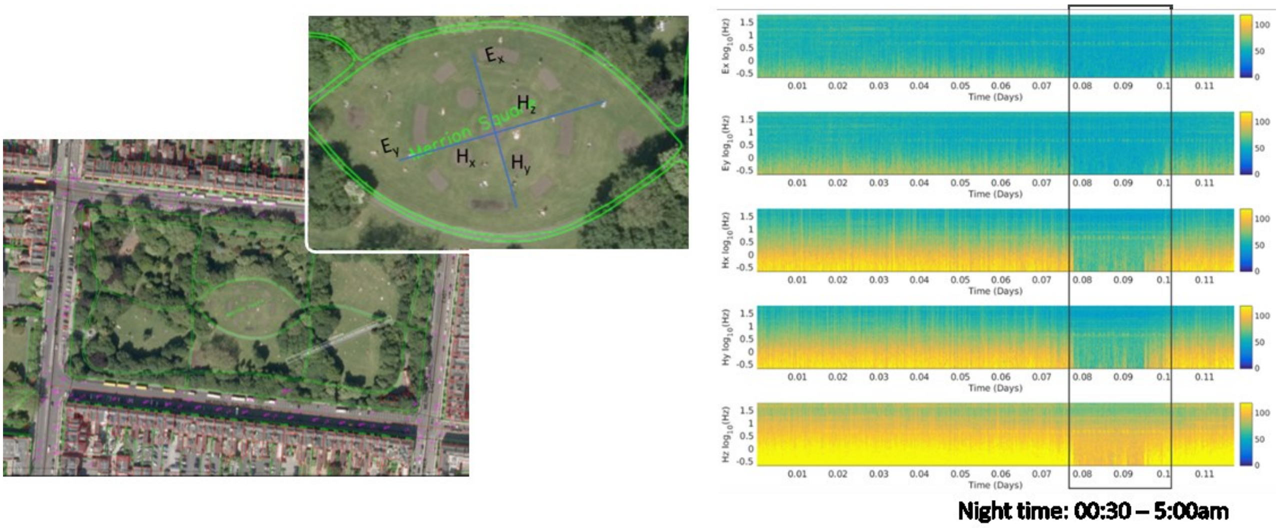

Figure 7: MT station set-up (left panel) and the estimated spectrograms for the electromagnetic field (right panel).

Prior to data acquisition in Dublin city, electrical resistivity measurements using Phoenix Geophysics CSAMT instrument will be performed in the highly urbanised Dublin suburb, Newcastle, which is approximately 15 km away from the city centre and located at the south-east extent of the Dublin basin. The Newcastle area has already been investigated using multi-geophysical methods (e.g., natural-source AMT and MT (Vozar et al., *in review*)) between the years of 2009 and 2012 with an aim of the development of geothermal energy. Most importantly, information on rock properties and geophysical parameters from two deep (approximately 1.4

km) boreholes is available. The Newcastle area will therefore be an excellent test bed for the CSAMT data acquisition. Depending on the results from robust processing and dimensionality analysis, data will be inverted with 1-D and 2-D codes. The inverted models will then be compared with the existing MT models and borehole information. Preliminary results of the surveys in Newcastle and Dublin City centre will be presented.

4. CONCLUSIONS

We present the preliminary geophysical observations in Dublin City. The ambient noise cross-correlation analysis shows the emergence of the surface waves although the further data processing steps are required to fully exploit the potential of the urban noise sources. The H/V analysis identifies reliable and clear resonance frequency peaks indicating a thin soil layer below the City. Since the MT time series were heavily contaminated by the anthropogenic noise in Dublin City, a reliable and interpretable MT impedance and geomagnetic transfer function could not be obtained yet.

5. AKNOLEDGEMENTS

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REFERENCES

Aki, K., and Richards, P.G.: Quantitative seismology, Sausalito, Calif: University Science Books, (2002).

Behm, M., Leahy, G.M., and Snieder, R.: Retrieval of local surface wave velocities from traffic noise - an example from the La Barge basin (Wyoming), Geophysical Prospecting, 62(2), (2014), 223-243.

Bensen, G.D., Ritzwoller, M.H., Barmin, M.P., Levshin, A.L., Lin, F., Moschetti, M.P., and Yang, Y.: Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, Geophysical Journal International, (2007).

Blake, S., Henry, T., Muller, M. R., Jones, A. G., Moore, J. P., Murray, J., Rath, V.: Understanding hydrothermal circulation patterns at a low-enthalpy thermal spring using audio-magnetotelluric data: A case study from Ireland, Journal of Applied Geophysics, (2016).

Dziewonski, A., Bloch, S., and Landisman, M.: A technique for the analysis of transient seismic signals, Bull. Seismol. Soc. Am., 59, (1969), 427–444.

Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations - measurements, processing and interpretations, SESAME European research project, deliverable D23.12, (2005).

Lecocq, T., Caudron, C., and Brenguier, F.: MSNoise, a Python Package for Monitoring Seismic Velocity Changes Using Ambient Seismic Noise, Seismological Research Letters, (2014).

Lees, A., and Miller, J.: Waulsortian Banks. In: Monty, C.L.V., Bosence, D.W.J., Bridges, P.H., Pratt, B.R. (Eds.): Carbonate Mud-Mounds: their Origin and Evolution, Special Publication of the International Association of Sedimentologists 23. Blackwell Science, Oxford, (1995), 191-271.

Levshin, A., Pisarenko, V., and Pogrebinsky, G.: On a frequency-time analysis of oscillations, Ann. Geophys. 28 (2), (1972), 211-218.

Licciardi, A., and Piana Agostinetti, N.: Sedimentary basin exploration with receiver functions: Seismic structure and anisotropy of the Dublin Basin (Ireland), Geophysics, (2017).

Lunedei E., and Malischewsky P.: A Review and Some New Issues on the Theory of the H/V Technique for Ambient Vibrations. In: Ansal A. (eds) Perspectives on European Earthquake Engineering and Seismology. Geotechnical, Geological and Earthquake Engineering, 39, (2015).

Marchant, T.R., and Sevastopulo, G.D.: The Calp of the Dublin district, J. Earth Sci. Roy. Dublin Soc. 5, (1980) 195-203.

Nogoshi, M., and Igarashi, T.: On the amplitude characteristics of microtremor (part 2) (in Japanese with English abstract), Journal of seismological Society of Japan, 24, (1971) 26-40.

Nakamura, Y.: Method for dynamic characteristics estimation of subsurface using microtremor on the ground surface, Quarterly Report of RTRI (Railway Technical Research Institute) (Japan), (1989).

Parolai, S., Bormann, P., and Milkereit, C: New relationships between Vs, thickness of the sediments and resonance frequency calculated by means of H/V spectral ratio of seismic noise for the Cologne area (Germany), Bull. Seismol. Soc. Am., 92, (2002), 2521-2527.

Schimmel, M., and Paulssen, H.: Noise reduction and detection of weak, coherent signals through phase-weighted stacks, Geophysical Journal International, 130, (1997), 497-505.

Sevastopulo, G., and P. Wyse Jackson: Carboniferous: Mississippian (Tournaisian and Visean), in The Geology of Ireland, 2nd ed.: Dunedin Academic Press, (2009), 215-268.

Seht, M. I. V, & Wohlenberg, J.: Microtremor Measurements Used to Map Thickness of Soft Sediments, Bull. Seismol. Soc. Am., (1999).

Strogen, P., Somerville, I. D., Pickard, N. A. H., Jones, G. L., and Fleming, M.: Controls on ramp, platform and basinal sedimentation in the Dinantian of the Dublin Basin and Shannon Trough, Ireland, Geological Society, London, Special Publications, (1996).

Strogen, P., and Somerville, I.D.: The stratigraphy of the Upper Palaeozoic Rocks of the Lyons Hill Area, Count Kildare: Irish J. Earth Sci., 6, (1984), 155-173.

Tsai, V.C.: The relationship between noise correlation and the Green's function in the presence of degeneracy and the absence of equipartition. Geophysical Journal International, (2010).

Vozar, J., Jones, A.G., Campanya, J., Yeomans, C., Muller, M.R., and Pasquali. R.: A geothermal aquifer in the dilatation zones on the southern margin of the Dublin Basin (in review), (2019).

Wapenaar, K: Retrieving the elastodynamic Green's function of an arbitrary inhomogeneous medium by cross correlation, Physical Review Letters, 93, (2004).

Wapenaar, K., and Fokkema, J.: Green's function representations for seismic interferometry, Geophysics, (2006).