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	Christopher Bean
Email	chris.bean@dias.ie
Host Organisation name	Dublin Institute for Advanced Studies
Project Title	Determining a new earthquake local magnitude scale for Ireland
Contract Number	2017-sc-046

Date: 15-11-2018

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

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 goal of this shortcall project was to develop a local magnitude scale for Ireland and its near offshore regions based on measurements of seismic S-wave amplitudes on seismic stations in Ireland. This project is classified under the GSI research themes No. 8 – Geophysics, and No. 11 – Geohazards and Geotechnical Engineering. Magnitude calculations are central to the routine processing of seismic events and for establishing accurate earthquake catalogs. Such catalogs can be used for the assessment of seismic hazard in the medium to long term. Seismic monitoring in Ireland is undertaken by the Irish National Seismic Network (INSN), operated at DIAS. The INSN has been using the local magnitude scale derived for the UK for magnitude calculation (Ottemoller and Sargeant, 2013). However, for a given event, discrepancies between the reported magnitudes as calculated using Irish stations compared to those using British stations indicates that perhaps seismic attenuation in Ireland is different to that of Britain. As a result, a local magnitude scale calibrated using Irish earthquakes measured on stations in Ireland is needed. This work represents the first attempt to develop a local scale for Ireland.

A local earthquake magnitude scale is essentially a tool to determine the strength of an earthquake, based on the measurement of the seismic S-wave maximum amplitude at a given station. However, as the amplitude of seismic waves decay with increasing distance, a correction to the amplitude measurement must be included that accounts for this decay. Explicitly, the local magnitude M_L is given by:

$$M_L = log(A) - Log(A_0) + S \quad (1)$$

where A is the maximum amplitude of the S-wave (measured in nm on the horizontal components of a seismic trace), $Log(A_0)$ is a distance-dependent correction term and S is a constant station correction factor. The function $Log(A_0)$ is modelled as:

$$-Log(A_0) = a\ Log(R) + b\ R + c \quad (2)$$

where R is hypocentral distance (km), a and b represent the effects of geometrical spreading and attenuation respectively, and c is a constant such that the magnitude scale can be anchored to the original scale for California, developed by Richter. Hence for any region, the local magnitude scale is characterised by the parameters a, b and c.

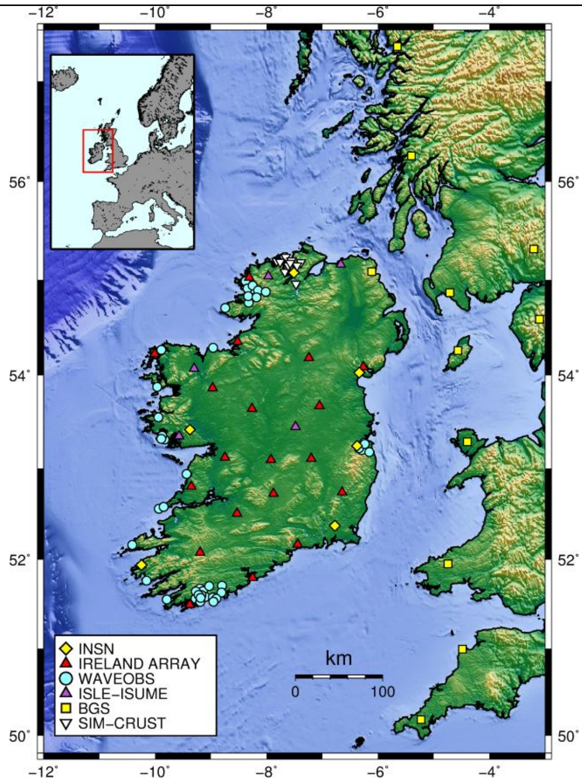

Figure 1: The distribution of seismic stations used in this study. Only the stations of the INSN and the BGS networks are permanent network stations which stream data in real-time.

Using (2) to re-write (1), we get the primary inverse problem that we solve in this project, namely:

$$a \, Log(R_{ij}) + b \, R_{ij} + c - M_{Li} + S_j = -Log(A_{ij}) \quad (3)$$

subject to the constraint 0, where *i* and *j* are the earthquake and station indices respectively, and M_{Li} is the average local magnitude for the *i*-th earthquake. The system of equations in (3) constitutes an over-determined system of linear equations and was solved using the MATLAB software package throughout this work. The resulting solution to (3) yields the earthquake magnitude scale parameters *a*, *b* and *c*, the individual earthquake magnitudes that form the input dataset and the individual station corrections.

Amplitude measurement

To generate the input for the inversion procedure, we used all located earthquakes in the INSN earthquake catalog from 2007-2017, and hence our initial dataset constituted of 222 earthquake recordings giving a total of 2,472 S-picks. Each event was manually picked using all available waveform data on Irish and British stations (Figure 1). In addition, to increase source-station path coverage of the Irish Sea, St. George's Channel and the North Channel, an additional 222 earthquakes from the British Geological Survey (BGS) catalog were picked, yielding an additional 3,781 S-picks. The maximum amplitudes (in nm) of earthquake S-waves were measured on the horizontal components of response-corrected displacement seismograms, with a Wood-Anderson simulation filter and an additional 1.5 Hz high-pass filter applied to suppress strong microseism

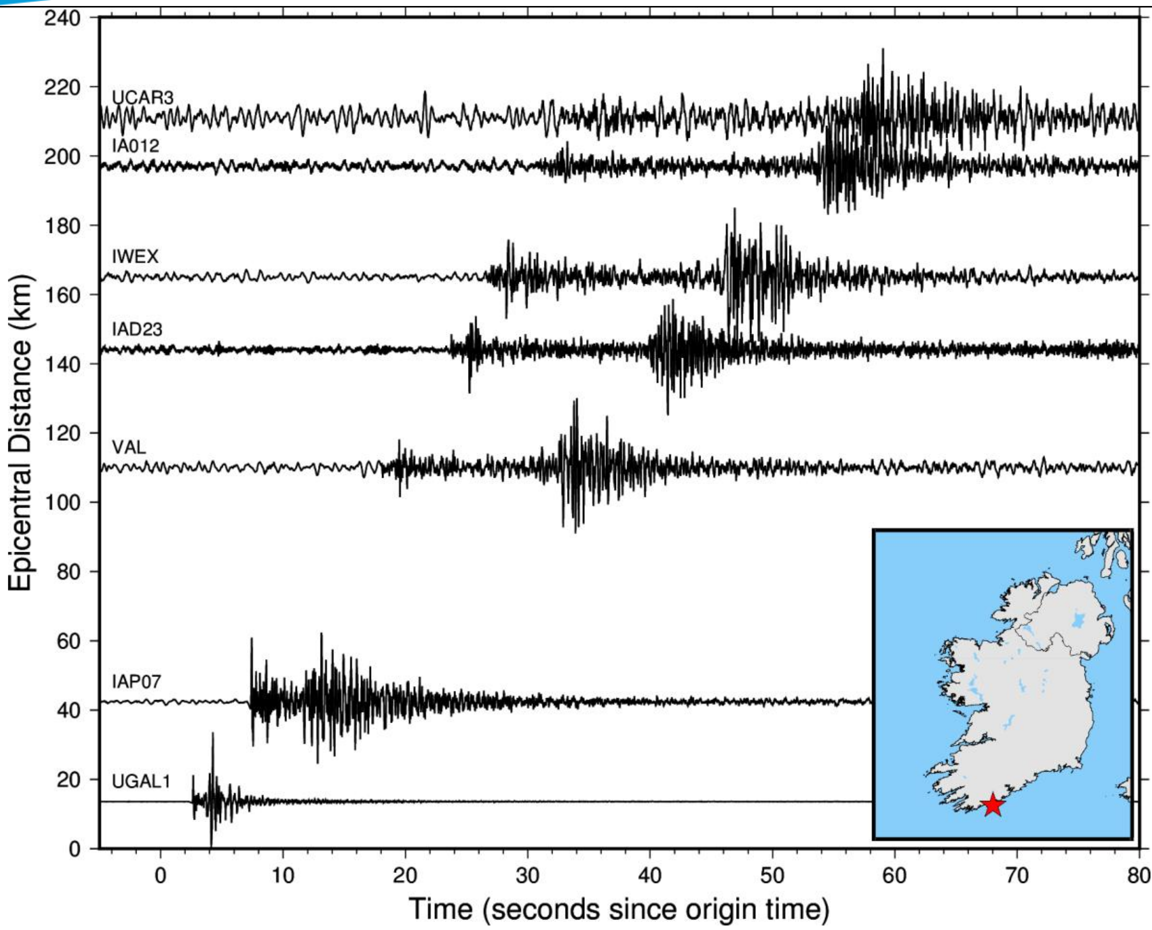

Figure 2: Seismogram of a M_L 2.2 earthquake recorded on Irish stations. This event occurred on 04-12-2013 at 07:57:29 UTC. All waveforms are filtered with the Wood-Anderson simulation filter, and an additional 1.5Hz high pass filter. The location is indicated in the lower right inset.

noise. The maximum amplitudes are then corrected for the gain of the Wood-Anderson seismograph, and also corrected for the gain of the 1.5 Hz high pass filter. The mean of the gain-corrected maximum amplitudes on the two horizontal components is taken as the amplitude reading at each station.

Testing of inversion code

Before we ran any inversions on real data, we generated synthetic measurements of amplitudes to test our inversion code. Using equation (3), for each earthquake in the INSN catalog, we determined synthetic amplitudes at each station using the reported earthquake magnitude (determined by the British magnitude scale) and the magnitude scale parameters *a*, *b* and *c* of the British magnitude scale (and by assuming each station had a station correction factor of zero). The resulting inversion of this dataset exactly reproduced the British magnitude scale, with a station correction factor of zero for each station. Hence we felt satisfied with the robustness of our inversion code.

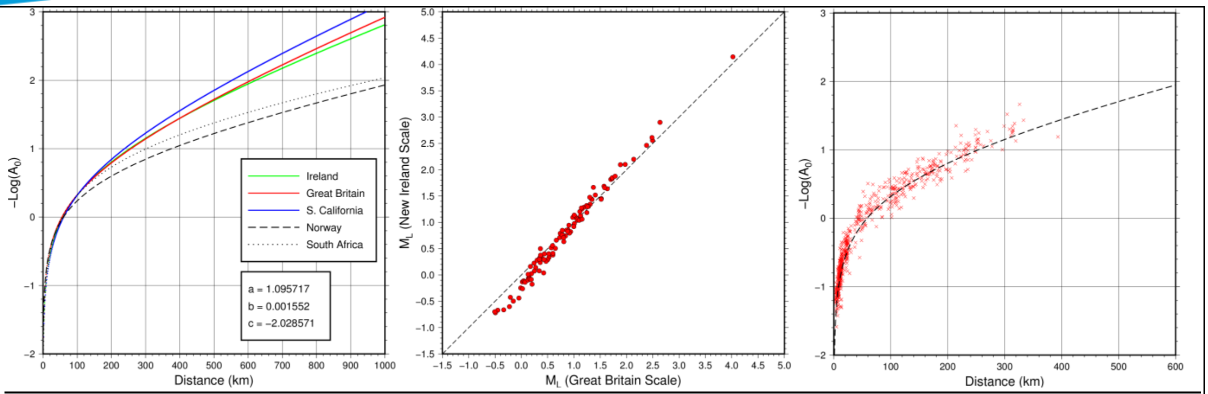

Figure 3: (Left) the results of the inversion of the INSN catalog, whereby only earthquakes whose paths cross Ireland and its near offshore are included. For comparison we have included the local magnitude scales for Britain (Ottemoller and Sargeant, 2013), southern California (Hutton and Boore, 1987), Norway (Alsaker et al, 1991) and South Africa (Saunders et al, 2013). Attenuation is similar to Britain and southern California but substantially higher than that of Norway and South Africa. (Centre) a comparison of the magnitudes of the INSN catalog earthquakes, as calculated using the currently used British scale and the new Irish scale. The black dashed line indicates a one-to-one correspondence. The new scale suggests that the British scale will result in an overestimate of Irish earthquake magnitudes for events with $M_L < 1$ and a slight underestimate of events with $M_L > 2$. (Right) The individual amplitude measurements of the input data set after correction for magnitude and station terms via Eqn (3), and the corresponding attenuation curve obtained from the inversion. Very few measurements are made at distances greater than 300km.

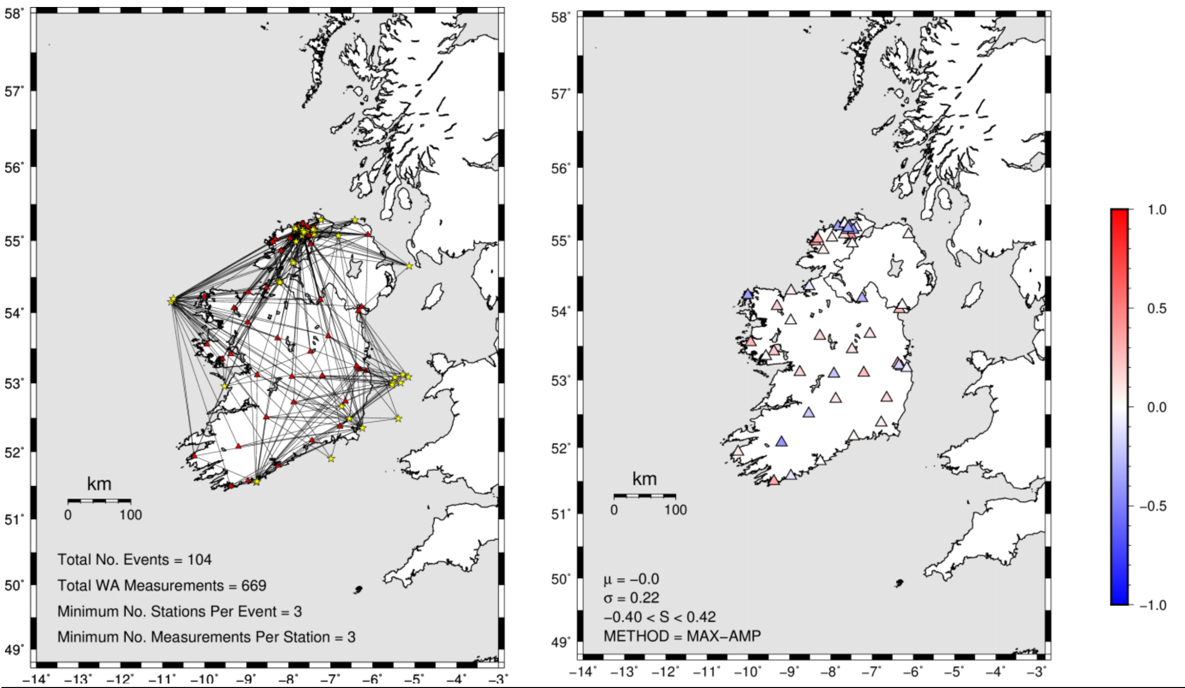

Figure 4: (Left) the distribution of travel paths between stations (red triangles) and earthquakes (yellow stars) corresponding to the scale obtained in Figure 3. (Right) the geographical variation of the station correction coefficients. Although no clear geographical trend is apparent, stations with negative correction values all belong to temporary networks, indicating that station configuration may affect the station correction value.

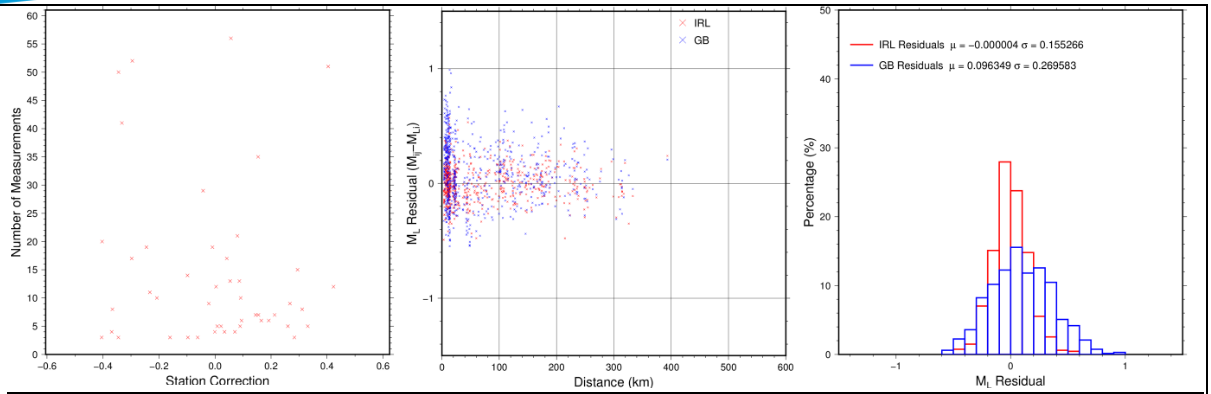

Figure 5: (Left) shows the station correction coefficients obtained through the inversion process versus the number of measurements made at each station, corresponding to the scale shown in Figure 3. No correlation exists between these two variables, indicating that the station correction coefficients are controlled by other factors. (Centre) Magnitude residuals as a function of distance for the Irish scale (red) and the British scale (blue). (Right) The distribution of magnitude residuals for the Irish scale (red) and the British scale (blue). The reduction of the standard deviation from 0.27 to 0.15 indicates that the new Irish scale is a better fitting scale than the British scale. The INSN currently uses the British scale for magnitude calculations. The differences we are finding in the magnitude values obtained using the British scale versus the new Irish scale merit the development of this new Irish scale.

Requirements on the minimum number of amplitude and distance measurements

Two simple criteria controlling the results of the inversion were (i) the minimum number of stations that contribute amplitude measurements per earthquake in order for the earthquake to be included, and (ii) the minimum number of earthquakes recorded on a station in order for the station to be included in the inversion. However, choices for these parameters were rather limited.

Criterion (i) is effectively controlling the minimum earthquake magnitude to be included in the inversion, and hence cannot be set too high, as many of the earthquakes in our data set are estimated to be $M_L < 1$. Hence we selected the value of a minimum of three stations with amplitude readings per earthquake.

Criterion (ii) cannot be set too high either, as most of the earthquakes in our data set are in Donegal or the Irish Sea. Setting this parameter too high will discard stations in the southwest, where the seismicity is lower. Hence we set this parameter to three amplitude readings per station.

Variation of the geographical distribution of earthquakes

In an attempt to determine whether regional variations exist within Ireland, we first divided Ireland into two regions, northern and southern, and performed separate inversions for these two regions. For the northern region, we included all stations above 54° N and all earthquakes above 53.5° N, and for the southern region we included all stations below 54° N and all earthquakes below 54.5° N. In each case, the earthquakes were taken from the amalgamated catalogs of the INSN and BGS. Results indicate that attenuation in Ireland is slightly lower than Britain in the northern region, while attenuation is slightly higher than Britain for the southern region, which is consistent with the findings in (Sargeant and Ottemoller, 2009), whereby regional variations in the seismic quality factor *Q* were studied for Britain. (Sargeant and Ottemoller, 2009) found that the eastern

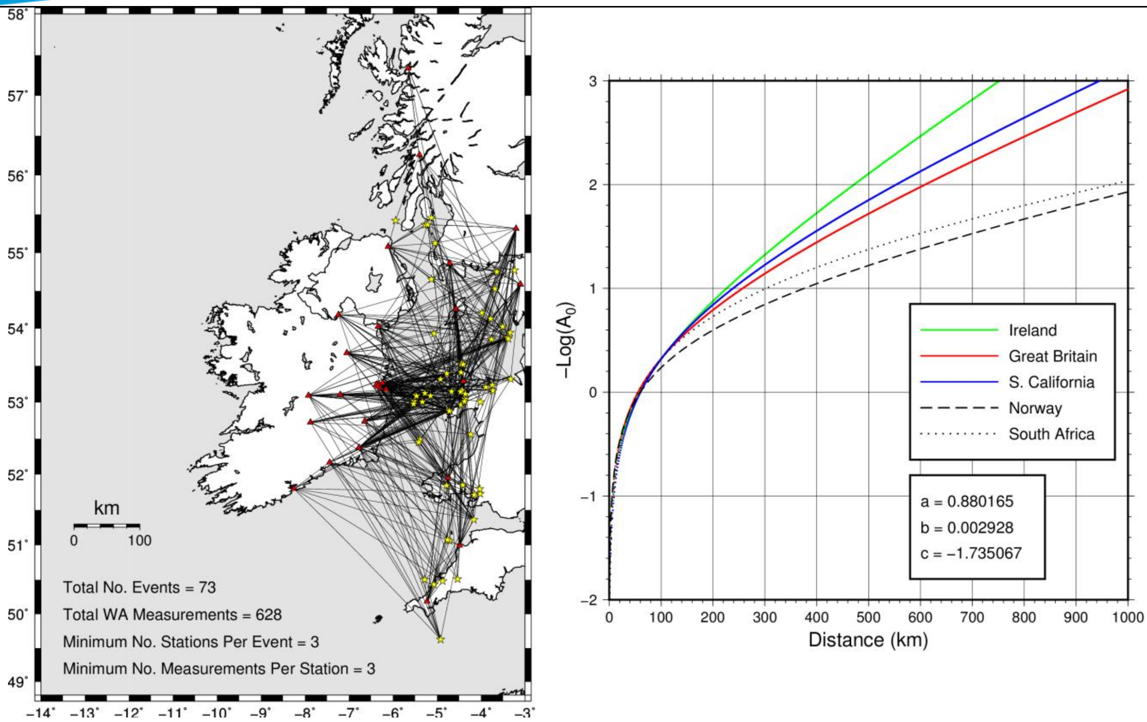

Figure 6: (Left) Coverage plot showing stations (red triangles) and earthquakes (yellow stars), where the data has been restricted to Irish Sea paths. (Right) The corresponding magnitude scale obtained for Irish Sea paths. In this case, attenuation is substantially higher than of Britain. This also contrasts greatly with the mainland Irish scale displayed in Figures 3, 4, and 5.

Irish Sea Basin has higher than average attenuation (lower *Q*) than mainland Britain, while western Scotland has lower than average attenuation. However, paths through the Irish Sea make up a substantial part of the dataset for the southern region, and paths from the North Atlantic make a substantial part of the dataset for the northern region. In the development of the magnitude scale for Norway, (Alsaker et al, 1991) showed that by including offshore earthquakes in the inversion process can result in a higher attenuation law than that produced by purely continental paths.

In order to separate out the possible effects of attenuation due to the Irish Sea, we again divided our input earthquakes in two regions, western and eastern. The western group consisted of earthquakes whose paths crossed the island of Ireland and its near-offshore, while the eastern group contained paths that crossed the Irish Sea. By using land-based and near offshore paths, we obtain a very similar scale to that of mainland Britain, albeit with slightly lower attenuation. However we observe that using Irish Sea paths leads to a substantial increase in attenuation with respect to mainland Britain, which agrees qualitatively with the results obtained in (Sargeant and Ottemoller, 2009).

A detailed description of the results for the inversion of the western region, focussing on Ireland, are shown in Figures 3, 4 and 5, while Figure 6 summaries the results of the eastern region, focussing on the Irish Sea. Figures 7 and 8 summarise the results of the northern and southern regions.

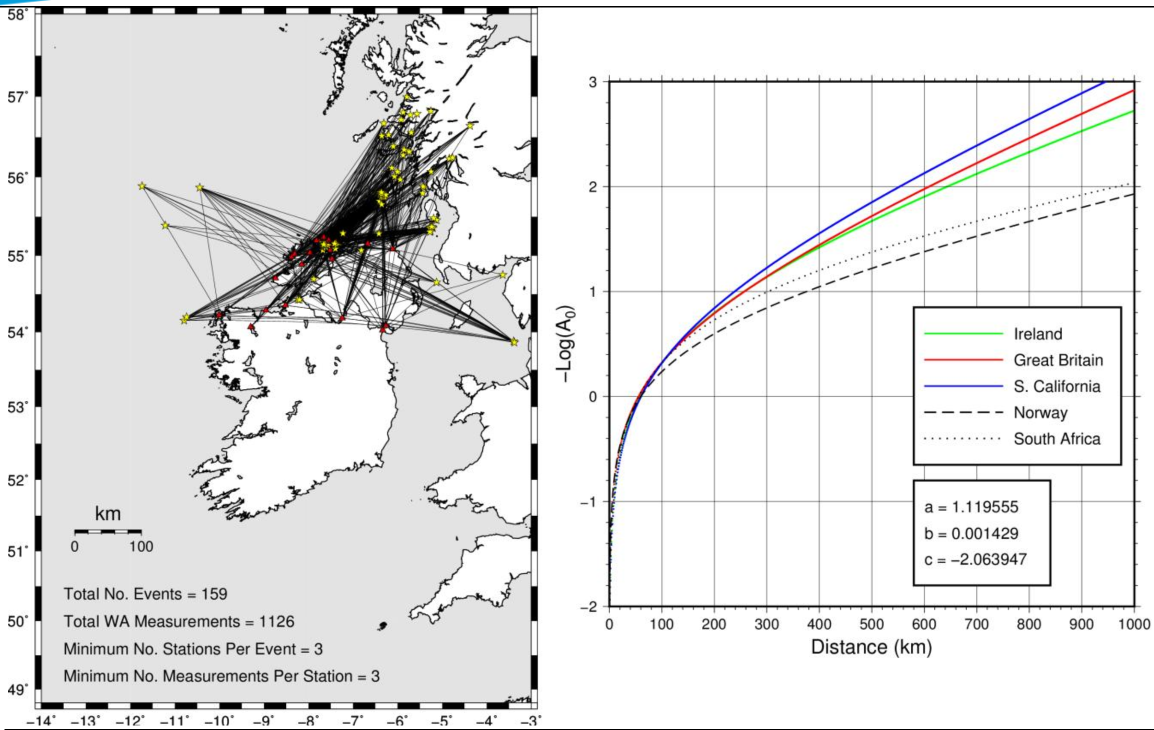

Figure 7: (Left) Coverage plot of the northern region. (Right) Attenuation in this region is slightly lower than that of mainland Britain.

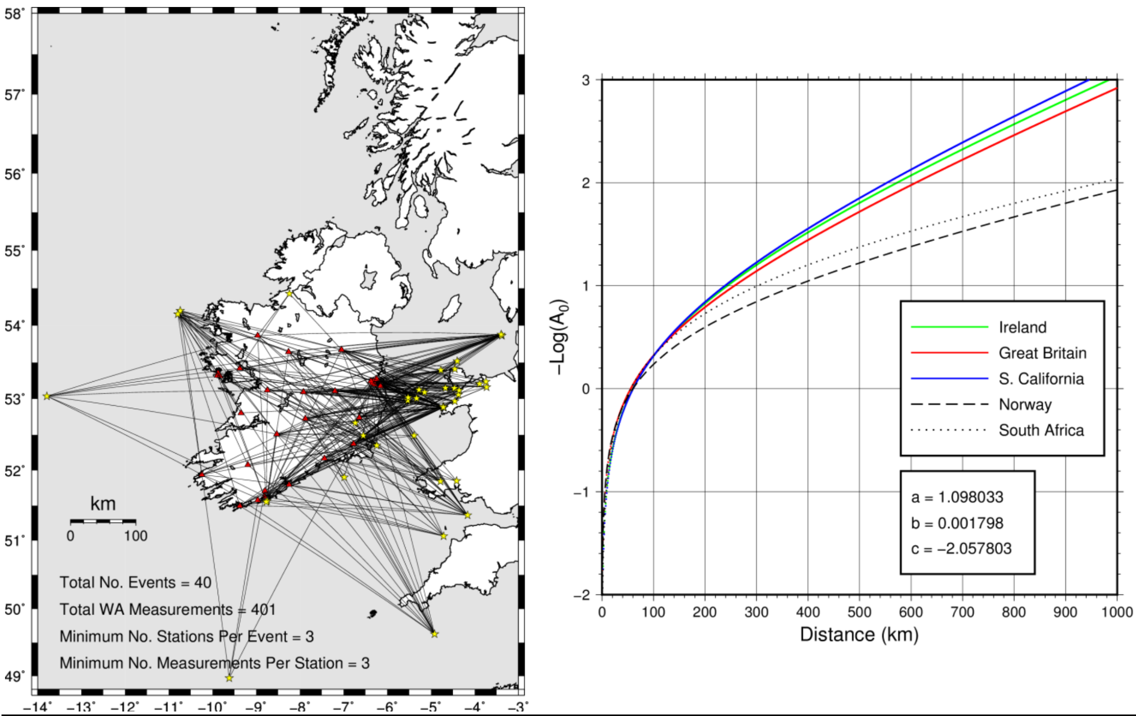

Figure 8: (Left) Coverage plot of the southern region. (Right) Attenuation in this region is slightly higher than that of mainland Britain.

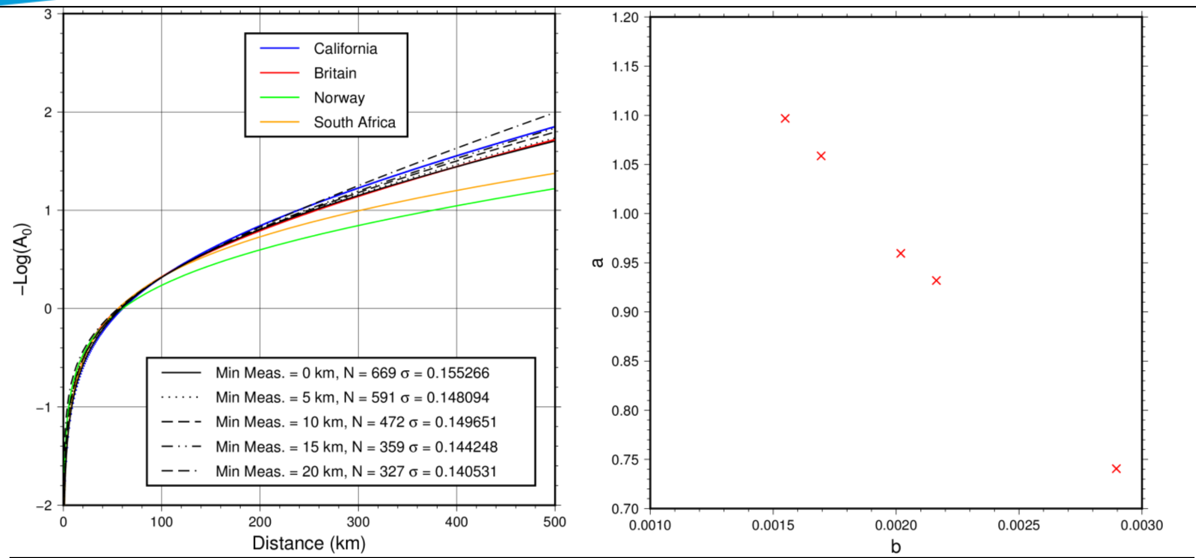

Figure 9: (Left) shows the results of multiple inversions where the minimum distance at which measurements are included is varied. (Right) The linear dependence between the parameters *a* and *b* as the minimum distance is varied. As the minimum distance is increased, *a* decreases while *b* increases.

Requirement on the minimum epicentral distance

Another parameter which was free to vary was the minimum epicentral distance at which station amplitude measurements were to be included in the inversion process. By increasing this distance, we are rejecting amplitude measurements made at nearby stations. Our results show that the effect of this was to decrease the magnitude scale parameter *a* and to increase the parameter *b*, shown in Figure 9. Previous studies have also shown similar trade-off between *a* and *b* (Bakun and Joyner, 1984; Bobbio et al, 2009; Chovanova and Kristek, 2018).

As the magnitude scale parameter *a* represents geometrical spreading of S-waves, we would expect values of *a* close to unity to be obtained in the inversion process. Hence we also constrained the parameter *a = 1* for a given dataset. This now resulted in a trade-off between the parameters *b* and *c*, whereby we observed the same negative correlation as in the case of *a* and *b* when the minimum epicentral distance threshold was varied.

One reason for choosing a non-zero minimum epicentral distance threshold at which to include amplitudes is to minimise the effect of hypocentral location errors in the inversion results. The depth of an earthquake is usually the least well constrained parameter obtained in the location process. Errors in depth can cause significant overall changes to the hypocentral distance when the epicentral distance is of the same order as the depth. By setting a minimum threshold and neglecting close-by stations we attempt to reduce this error.

Examination of magnitude residuals

To determine whether a new magnitude scale was a better fitting scale than that of the British magnitude scale, we computed the residuals between the magnitudes found by the inversion and the network average magnitude for each earthquake computed using the amplitude and distance measurements at each station. We compared the distribution of residuals obtained using the new scale with the corresponding distribution of residuals obtained using the British scale. For each inversion that was performed on the input data, we consistently obtained a better fitting magnitude scale than the British scale currently in use by the INSN, as the distribution of residuals using the Irish scale always had a smaller standard deviation compared to that of the British scale. This has also been found for other local magnitude calibration studies (Ottemoller and Sargeant, 2013). This is most likely due to the use of station correction coefficients in the inversion.

The largest residuals obtained by the British scale occur when the epicentral distance is small (less than 10 km), whereas the magnitude scales obtained in our inversions did not show much variation with epicentral distance. In particular, we did not observe any unusually large residuals produced by the Irish scale ($\Delta M > 1$) at very small epicentral distances, and these residuals do not appear to have a positive or negative bias, in contrast with the scenario encountered in (Butcher et al, 2017).

Choosing a scale for the INSN

The vast majority of the events recorded by the INSN each are quarry blasts from quarries based in Ireland. The minimum distance at which quarry blasts are recorded at INSN stations is approximately 3km, and hence the scale adopted by the INSN needs to accommodate this. Hence, we would recommend using the magnitude scale calibrated from land-based and near offshore paths with no restriction on the minimum distance at which amplitude measurements can be made.

The values of the magnitude scale parameters for this scale are:

$$a = 1.095717$$
$$b = 0.001552$$
$$c = -2.028571.$$

The INSN uses the software SeisComP3 for its real-time detection, location and magnitude estimation for local events. Implementation of a customised local magnitude scale based on amplitude measurements on horizontal components is straightforward. In addition, SeisComP3 also estimates magnitudes based on amplitude measurements from *vertical* components (MLv). In Figure 10, we show the relationship between measured amplitudes on horizontal components and vertical components. As the amplitudes on horizontal components are higher than those on the vertical component, we would expect lower magnitudes to be reported using this measure. However, the module implementing vertical component magnitude estimation can also be customised in SeisComP3. Hence it remains a simple task to rerun our inversion using only vertical component measurements to obtain the corresponding vertical component magnitude scale, which can then be implemented in SeisComP3.

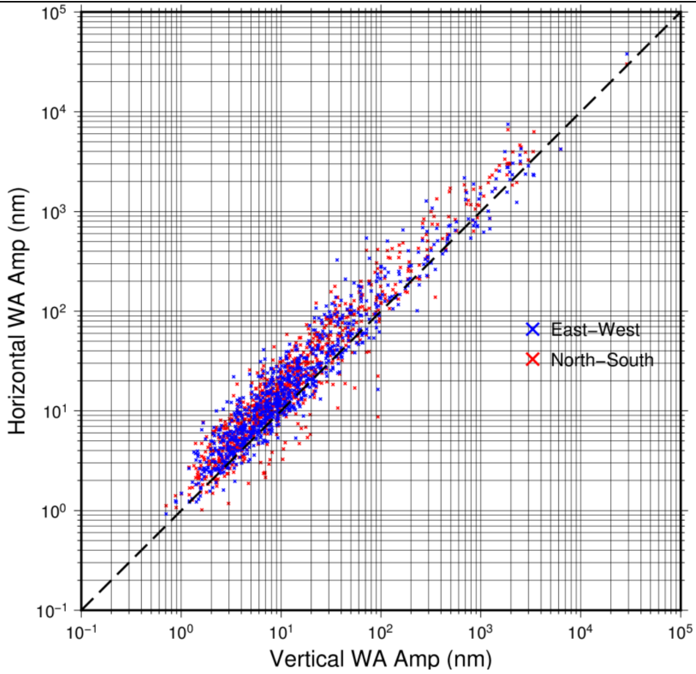

Figure 10: The relationship between horizontal and vertical component amplitudes, measured on Wood-Anderson (WA) simulation filtered traces for this study. On average, amplitudes are larger on the horizontal components than on the vertical components. From Eqn(1), using vertical components for amplitude measurement will result in smaller computed magnitudes (where the magnitude scale has been calibrated using horizontal components).

Estimate of the seismic quality factor for Ireland

Using the value of $b = 0.001552$, we can obtain an estimate for the seismic quality factor Q. From (Havskov and Ottemoller, 2010), Q is given by:

$$Q = \log_{10}(e)\, \pi\, f\, (v\, b)^{-1} \quad (4)$$

where e and π are mathematical constants, f is frequency and v is the S-wave speed. For purposes of comparison with Britain, we choose $f = 1$ Hz, and assuming $v = 3.5$ km s $^{-1}$, we obtain a value of Q(1 Hz) = 251. This compares with a value of Q(1 Hz) = 266 obtained in (Sargeant and Ottemoller, 2009).

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Uski, M. and A. Tuppurainen (1996). A New Local Magnitude Scale for the Finnish Seismic Network, *Tectonophysics*, 261, pp. 23-37.

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

A pre-doctoral scholar, James Grannell, was hired for the duration of one year, starting on the 1st Nov 2017. The original lead applicant and P.I. for this shortcall project, Dr. Pierre Arroucau, was offered a permanent position at EDF France in December 2017. As a result, Prof. Chris Bean assumed the role of P.I. after the departure of Dr. Arroucau.

As the project developed, we decided to shift our focus from determining a multi-segmented magnitude scale (whereby the parameters can vary with distance, as originally proposed in task no. 6 of the deliverables) to investigate thoroughly the sources of variation between inversions. Hence we spent more time than expected in the completion of task no. 3 of the deliverables (local magnitude scale and quality factor for Ireland). However, the resulting time spent at this task gave us confidence in the robustness of our results, and illustrated the sharp regional variation in attenuation seen in the Irish Sea. This aspect was not expected at the beginning of the project.

Attempts were made to construct a multi-segmented model (whereby the scale parameters can vary with distance). However, the behaviour of the individual magnitude residuals did not improve upon those derived from the single-segment approach in Eqn(3). The inclusion of station correction factors in the single-segment magnitude scale appears to have negated the need for a multi-segmented approach. As a result of this and the additional time spent investigating the sources of variation, we were not able to fully pursue the multi-segmented magnitude scale model construction, as well as the Bayesian implementation for determining the distance at which the various segments of the scale should apply (task no. 6 of the deliverables).

We did investigate the possibility of determining a frequency-dependent quality factor $Q(f)$, given by

$$Q(f) = Q_0 f^{\,n} \quad (5).$$

Following the method of (Uski and Tuppurainen, 1996), this resulted in a frequency dependent power law given by:

$$Q(f) = Q_0 f^{n} = 177 f^{0.89} \quad (6).$$

When the expression in (6) is compared to that of Britain, $Q(f) = 266 f^{0.53}$ (Sargeant and Ottemoller, 2009), we see that the frequency dependence obtained in (6) is much stronger than that of Britain, and gives rise unrealistically high values of *Q* at higher frequencies. Hence we do not feel confident in the result obtained in (6). An *Lg* tomography of Ireland would provide a more robust estimation of the frequency-dependent quality factor for Ireland. However such a study was beyond the scope of this shortcall project.

As the journal article summarising the results of this project is still in preparation, task no. 9 of the deliverables (article submission) will be expected to be completed in the near-future.

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

- We have assembled a large database of 4,674 P- and 6,253 S-picks of local earthquakes spanning the period 2007-2017 with a corresponding waveform database.
- Software for the processing of waveforms, input data selection, inversion and analysis of results is now available to the INSN for future projects, or indeed to update the local magnitude scale as new data are recorded.
- Our results show that the magnitude scale recommended for adoption by the INSN is a better fitting scale than the British scale, currently used by INSN.
- Our results can be easily implemented in SeisComp3, the software used by the INSN for real-time local seismic monitoring.
- We have produced the first estimate of the seismic quality factor for Ireland.
- The regional variations in attenuation we have observed indicate the possible need for an island-wide seismic attenuation study, with possible implications for broad scale geothermal potential mapping.
- Our preliminary findings were presented at the Irish Geological Research Meeting (IGRM) in Cork, Feb 2018, whereas the findings in this report were presented at the European Seismological Commission (ESC) Meeting in Malta, September 2018 and also at the Geoscience Meeting in Dublin, November 2018.
- We aim to publish the results obtained in this project in an international journal.

Task No.	Deliverable description	Planned delivery (as per proposal)	Date of delivery
1	Sg/Lg maximum amplitude measurements	Month 2	Month 2
2	Local magnitude scale linear inversion code	Month 3	Month 4
3	Local magnitude scale and quality factor for Ireland	Month 4	Month 4 (preliminary scale) Month 10 (final scale)
4	Presentation of results at the IGRM conference	Month 5	Month 4
5	Mid-term report	Month 6	Month 5 and Month 9 (reporting periods differed from original plan)
6	Bayesian inversion code for local magnitude scale determination	Month 8	Attempted, but not fully investigated due to time constraints
7	Updated local magnitude scale for Ireland	Month 9	Month 10
8	Presentation of results at the ESC meeting	Month 11	Month 11
9	Article Submission	Month 12	In preparation
10	Final Report (including financial report)	Month 12	Month 12

Publications to date: *Please use format below and provide a copy of the presentation*

[Conference Presentation - Poster] Grannell, J. R.; Arroucau, P.; Lebedev, S.; Mollhoff, M.; Bean, C. (2018) A Magnitude Scale for Ireland and its Offshore Regions *ESC General Assembly 2018,* Valletta, Malta, 6-SEP-18

[Conference Presentation - Poster] Grannell, J. R.; Arroucau, P.; Lebedev, S.; Mollhoff, M.; Bean, C. (2018) Seismic Discrimination between Earthquakes and Quarry Blasts in Ireland, *IGRM 2018, Cork*, 28-FEB-18

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

Poster Presentation: Grannell, J. R.; Arroucau, P.; Lebedev, S.; Mollhoff, M.; Bean, C. (2018) A Magnitude Scale for Ireland and its Offshore Regions.

Poster Presentation: Grannell, J. R.; Arroucau, P.; Lebedev, S.; Mollhoff, M.; Bean, C. (2018) Seismic Discrimination between Earthquakes and Quarry Blasts in Ireland.

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).