

THE EVOLUTION OF SEISMIC MONITORING IN THE UK AND ITS EFFECT ON THE EARTHQUAKE CATALOGUE AND GROUND MOTION DATA

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Abstract: *Amongst the many inputs used to assess seismic hazard are catalogues of earthquakes and ground motion data. Networks of seismic sensors are important in contributing to such data. In this paper the instrumental record is examined in a UK context. This began in 1963 and continues to this day. The early phases of the network were limited in terms of frequency, sensitivity and dynamic range. The ability to store raw data, as opposed to derived products like magnitude was severely limited. Initially, almost no raw data could be stored. As it became possible to store the waveforms of identified events the option of using new methodologies to re-process data became possible. Since the early 2000s a complete archive of the continuous waveform of each station has been kept, allowing new detection algorithms to be used. As dynamic range and frequency sensitivity have improved a fuller recording of ground motion at each station has been produced. This has implications for our ability to improve the early instrumental record, and for the nature of early and modern instrumental data in terms of its contribution to both the UK earthquake catalogue and ground motion data.*

The early short-period seismic monitoring network, 1969-2015

Technical specification

The on-shore seismic network used in this period was based around a very small number of Willmore mk2 sensors, until the mid-seventies when they were replaced with Willmore MK3 units, single component short-period velocity transducers with a flat response in the 2- 200Hz range. At each station the output voltage from the sensor was fed into an amplifier-modulator to be transmitted to a central hub as a frequency modulated (FM) radio signal. This required line of sight between the station and the hub unless an intermediary re-transmission station with line of sight to both hub and station was used. The need for line-of-sight transmission meant, in most cases, the distance between station and hub was less than 25km. Stations often had to be located at topographic high points, frequently in remote and inaccessible locations making installation and maintenance both challenging and expensive. Frequent maintenance of the stations was required as the extreme weather conditions they experienced often led to the directional FM antennas (Figure 1) being damaged or blown out of alignment.

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Figure 1- FM radio re-transmission station being repaired after high winds blew an aerial out of position.

Data transmission over FM had a low bandwidth and was unable to transmit the full dynamic range produced by the Willmore sensors, limiting them to around 65db when it arrived at the central hub. At the hub the data from each station would be written, as analogue data, onto reel-to-reel magnetic tapes. An MSF radio clock receiver provided a time signature for the data, also written to tape as a separate channel. The magnetic tapes were collected every few weeks and posted to the British Geological Surveys (BGS) Edinburgh office where they would be reviewed. The magnetic tapes further reduced the dynamic range of the recorded data to around 45db, as well as further limiting the frequency content to only 15-2Hz. Tapes were reviewed by humans listening to all tapes from a sub-network as audio files, played at x80 speed to bring them into the human audio range. Earthquakes would be “heard” as pops, and that section of tape could then be printed onto paper to allow the magnitude/location to be calculated and the catalogue of earthquakes to be updated. Magnetic tapes at the time were expensive and stored (by modern standards) very little data. Tapes were re-used as many times as possible. The data from significant earthquakes were often transferred to another tape (essentially an analogue recording of an analogue recording) to allow that event to be re-worked later, but this was a somewhat ad-hoc process. The modern practice of maintaining a complete continuous waveform record from each station in these early days would have been completely impractical, both from the perspectives of the cost of the tapes and the space to store them.

Some of the limitations of the equipment are shown in Figure 2. There were eight installed stations in October 1972. When a 3.5ML earthquake occurred within 50 and 150km of the station 3 stations were discovered to be faulty (EDI, ELO and EBH) and due to the limited dynamic range possible with the data transmission system all working sensors saturated. The accuracy of the calculated location/magnitude was poor, and no instrumental data on peak acceleration was possible due to the saturation. Additionally, when producing this paper, the location of station EGL could not be found in the BGS records which would be an extraordinary error in a modern network but is more understandable in the early days of the network.

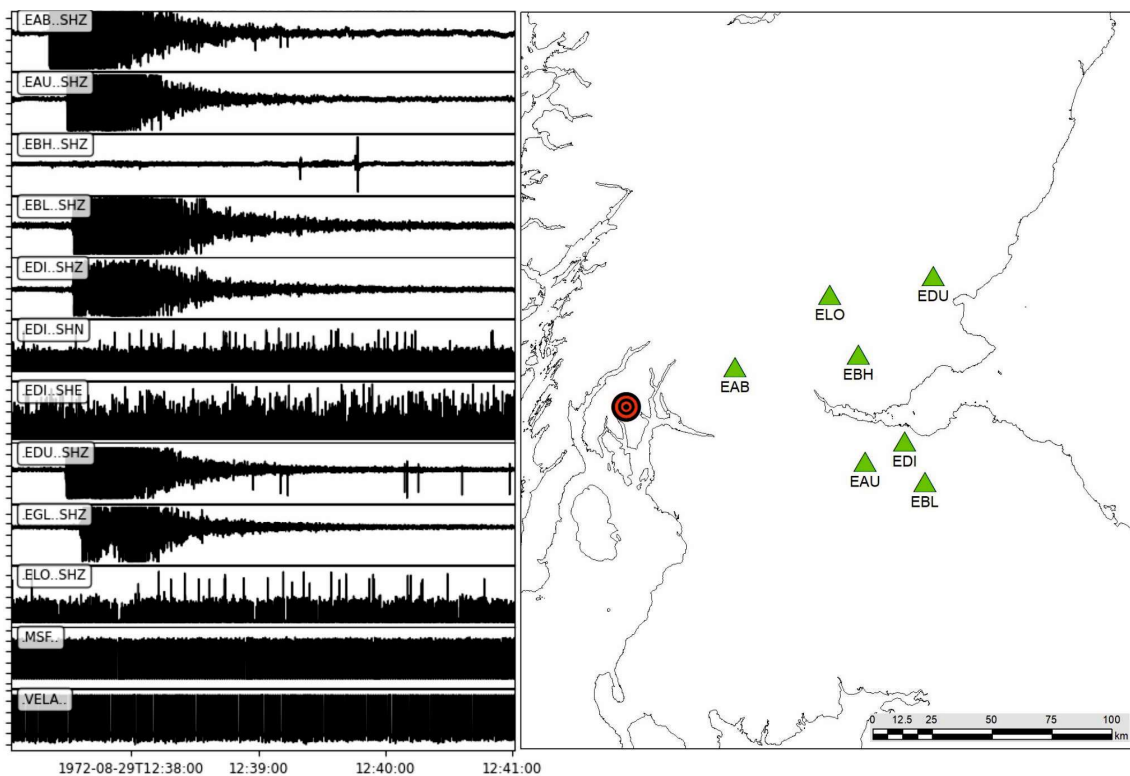


Figure 2- The 3.5ML Lochgilphead earthquake of 1972/08/29 recorded by the national network as it existed at the time. Seismic traces are on the left, except the lower two traces which were radio clock timing sources used to time stamp the incoming data. The location of the stations (green triangles) and the earthquake (red and black circle) are shown on the right-hand map.

In 1985 Integrated Services Digital Network (ISDN) lines were introduced to the UK. This, and the Asymmetric Digital Subscriber Lines (ADSL) that replaced them in the 1990s allowed a data connection to be installed at the central hub of each sub-network to allow near real-time transmission of data back to the BGS Edinburgh office. At this point the BGS moved to digitising the data at the central hub with a time stamp and recording the digital data in Edinburgh, ceasing to use magnetic tapes. This allowed the higher frequency signals to be examined (up to 50Hz) and improved the dynamic range of the data from 45db to 100db. Data was analysed electronically and stored on hard drives, although it was still only possible to keep a long-term record of only detected earthquakes, not a continuous waveform record.

Continuous waveform data only began to be saved in the 1990s, by which point the replacement of the short period network with the current broadband network had already begun.

Network development

The short period network was deployed by the BGS, and its precursor organisation the Institute of Geological Studies (IGS). The first sub-network to be deployed was Lownet (as shown in Figure 2), using Edinburgh as a central hub for seven outlying stations across Scotland's central belt. It became operational in 1969, and was part of a program to better understand seismicity within the UK, particularly in the context of high consequence engineering structures (Browitt, 1978). Subsequent sub-networks followed over the next 32 years.

The successful operation of Lownet led to a number of other sub-networks being deployed over the next ten years, including;

- Following public concern over long wall coal mining around Stoke on Trent the Department of Environment (DoE) funded a Midlands Sub-array.
- To quantify the seismic hazard of the North Sea for the developing Oil Industry the Department of Energy (DEn) funded sub-arrays in Orkney, Shetland and two ocean bottom stations in the North Sea.
- To monitor Geothermal energy production in Cornwall DEn supported sub-arrays in SW England.

By 1989 the BGS was operating so many sponsored sub-arrays the system was formalised into the National Earthquake Information Service (NEIS), a situation that continues to this day. Both the location of new stations and the maintenance/repair of existing stations is designed to support the needs of NEIS members. NEIS members are normally government departments, regulators and utility companies (typically Dam operators and Nuclear Licensees). As more and more subnetworks were deployed a greater area of the UK had a uniform detection capability for earthquakes. By 2000 a 2.0ML or smaller earthquake was detectable anywhere on-shore within Britain, based on 146 stations (Browitt and Walker, 2019).

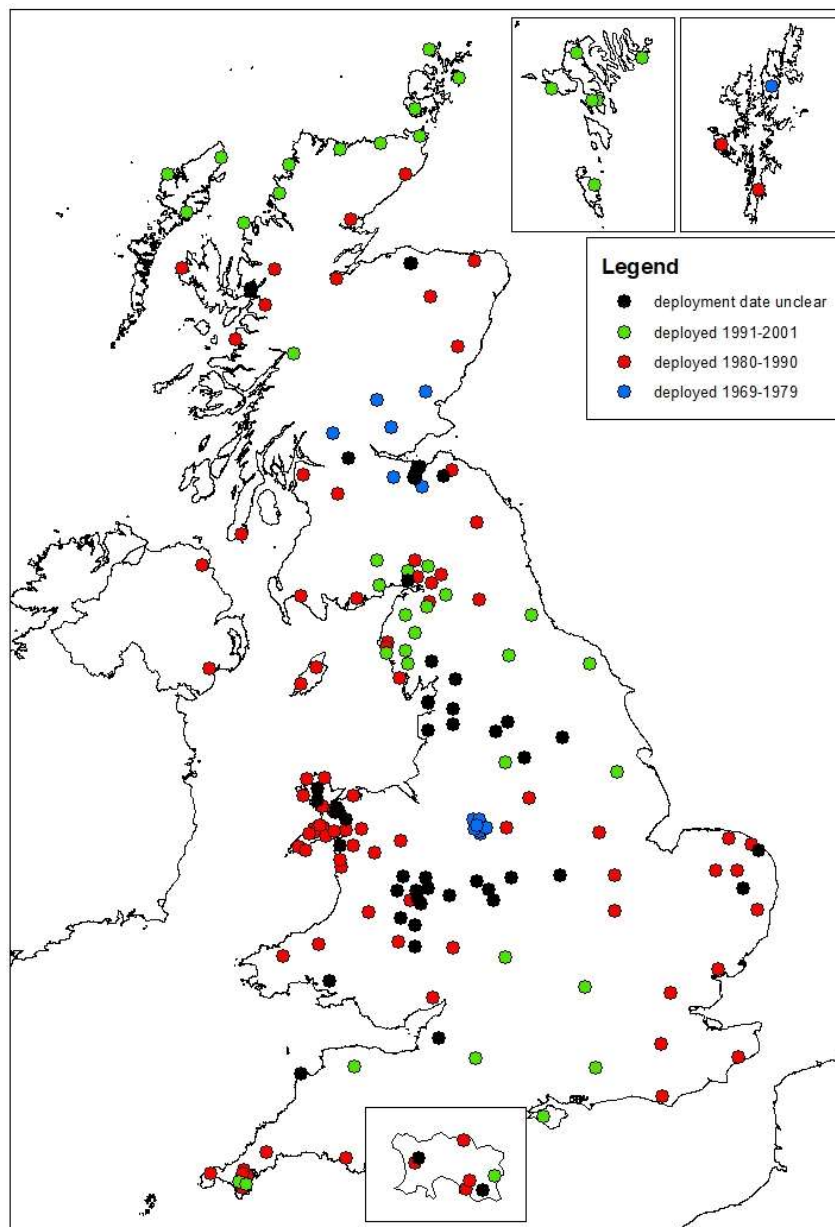


Figure 3- location of short period stations colour coded by date of deployment (where known).

From 2003 onwards the short period network began to be replaced by a more modern network (see next section), but the two systems operated in parallel for several years, there were still a small number of operational short period station as late as 2018. The large number of short period stations, coupled with their relative inaccessibility, means the BGS is likely to still be removing non-operational stations for decades to come. This resulted in a brief period when there were large numbers of both operational old short period stations and new broadband stations, around

the year 2000. With so many stations the UK achieved its lowest modelled detection threshold for earthquakes (Figure 4).

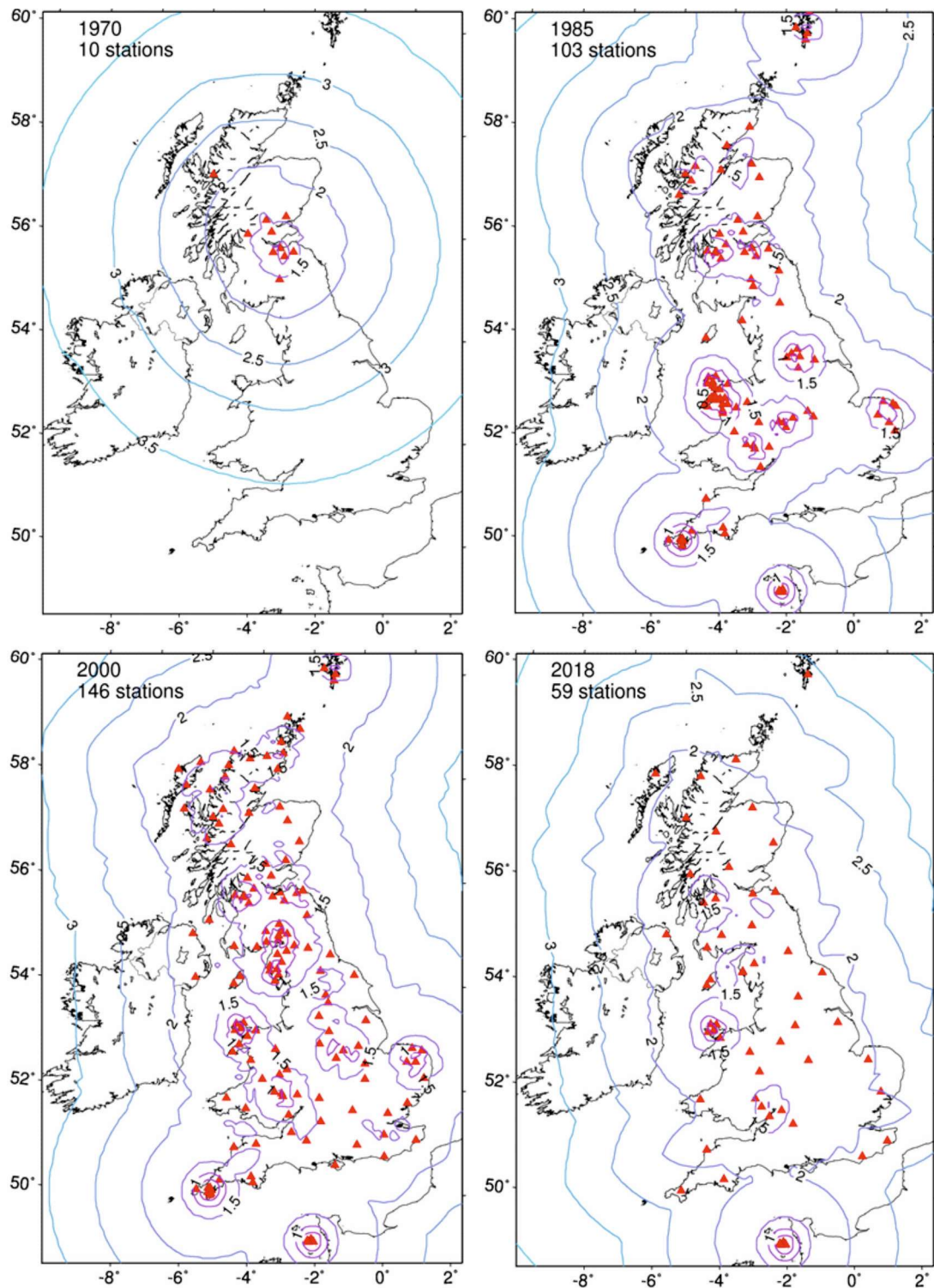


Figure 4- modelled detection capability for earthquakes in four different years. Red triangles show operational stations. Only stations operated by BGS, as the National Earthquake Information Service (NEIS), are shown. The contours show earthquake magnitudes (ML) that can be detected. Signal amplitudes must exceed the background noise level by a factor of two at four or more stations. A noise amplitude of 10 nm is assumed for all stations.

Installation of the broadband seismic network, 2003 onwards.

By the mid-nineties a number of difficulties had become apparent with the short period network. These were;

- Most stations only had a single vertical component, reducing the accuracy of earthquake location.
- The limited bandwidth and dynamic range of data meant that strong motion recordings might not be complete and might not capture the full frequency range of ground motion.
- The limited bandwidth and dynamic range also meant it could be hard to detect faults in instrumentation until they failed to record an earthquake.
- Incidences of sensors being damaged in transit were high.
- The FM radio masts were prone to damage, leading to a heavy staff burden to repair them, including a high health and safety burden to operate in such remote locations.
- Manufacture of the FM transmission system ceased in the early nineties, so a replacement solution at least for data transmission became necessary.
- The system of time stamping data using MSF radio clocks was looking increasingly inaccurate in comparison to more modern GPS based systems.

For these reasons a decision was made to completely replace the short period network with a modern, broadband network with high dynamic range. This process began in 2003 and is still ongoing today as shown in Figure 5.

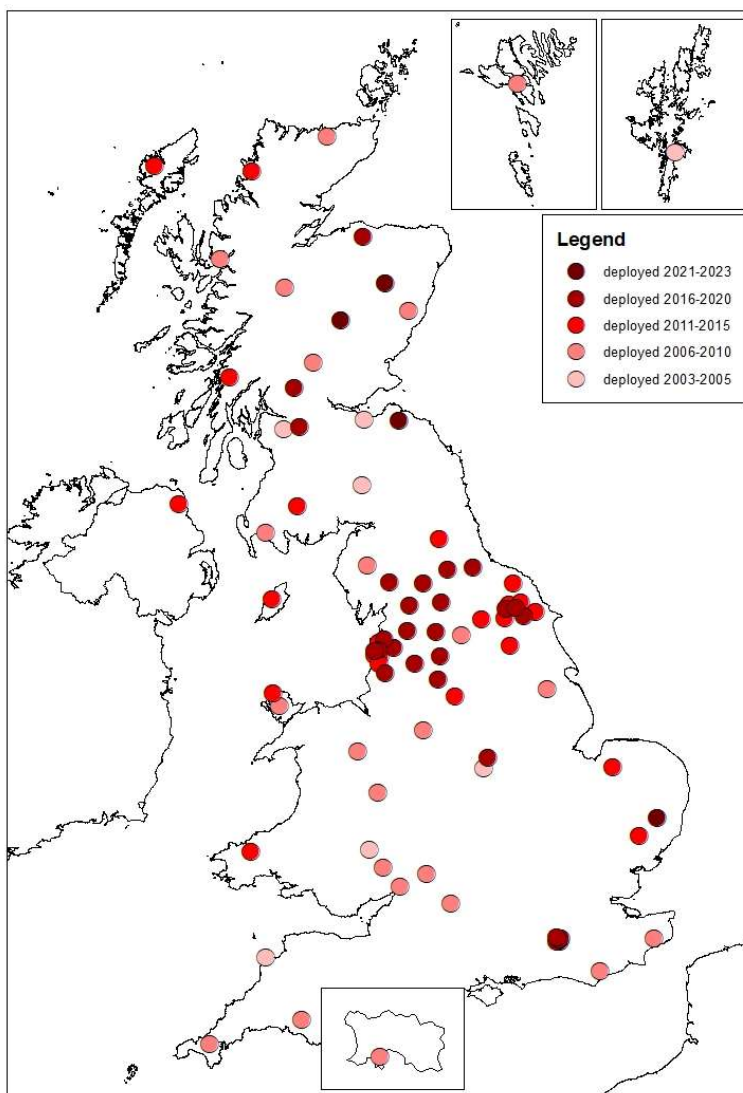


Figure 5- location of Broadband stations colour coded by date of deployment

From 2003 to 2014 deployed broadband stations were intended to be in a location permanently, to ensure not just the ability to detect and locate earthquakes but also to provide continuity of ground motion recordings, partly in support of hazard calculations. Early broadband stations were deployed in the location of the central hubs of the short period sub-networks, which typically already had some form of data link. This was quickly found to be less than optimal, due to the higher performance of the sensors. Many of these locations had high levels of anthropogenic seismic noise. This couldn't be detected on the old short period systems, but with the new systems was both highly visible and limited the value of the data. New selection criteria placed the sensors as far as practicable from sources of seismic noise, such as roads, power lines etc. in line with international guidelines (e.g. Bormann, 2000). Data transfer was continuous using a mixture of ADSL lines, Satellite and 3G/4G. The higher performance of the sensors also meant that far more care had to be taken in the construction of the seismic vaults housing the equipment. Seismic vault design was initially based on a United States Geological Survey (USGS) design (McMillan, 2002). This was gradually modified in light of UK conditions, mainly to reduce the use of concrete to allow its installation in less accessible locations.

Permanent stations mostly use sensor with a flat response of either 50Hz to 120s (Guralp CMG-3Ts) or 35Hz to 240s (Nanometrics Trilliums) although there are a small number of stations with 50Hz-360s Guralp 3Ts or 200Hz to 120s Guralp radian borehole sensors. Additionally, from the 2010s onwards Guralp ESPCs were used in temporary deployments, and Guralp Radians were used in borehole deployments. This was partly due to these sensors being able to record higher frequency signals more accurately as well as having very low internal noise levels. This was required for studies of weak near earthquakes, such as those associated with induced seismicity, which are more dominated by higher frequency ground motion (e.g. Ackerley, 2012). In comparison to the old short period sensors the modern network enabled both higher and lower frequency signals to be recorded (Figure 6), and because the modern equipment had a lower noise floor than the old network weaker events were resolvable.

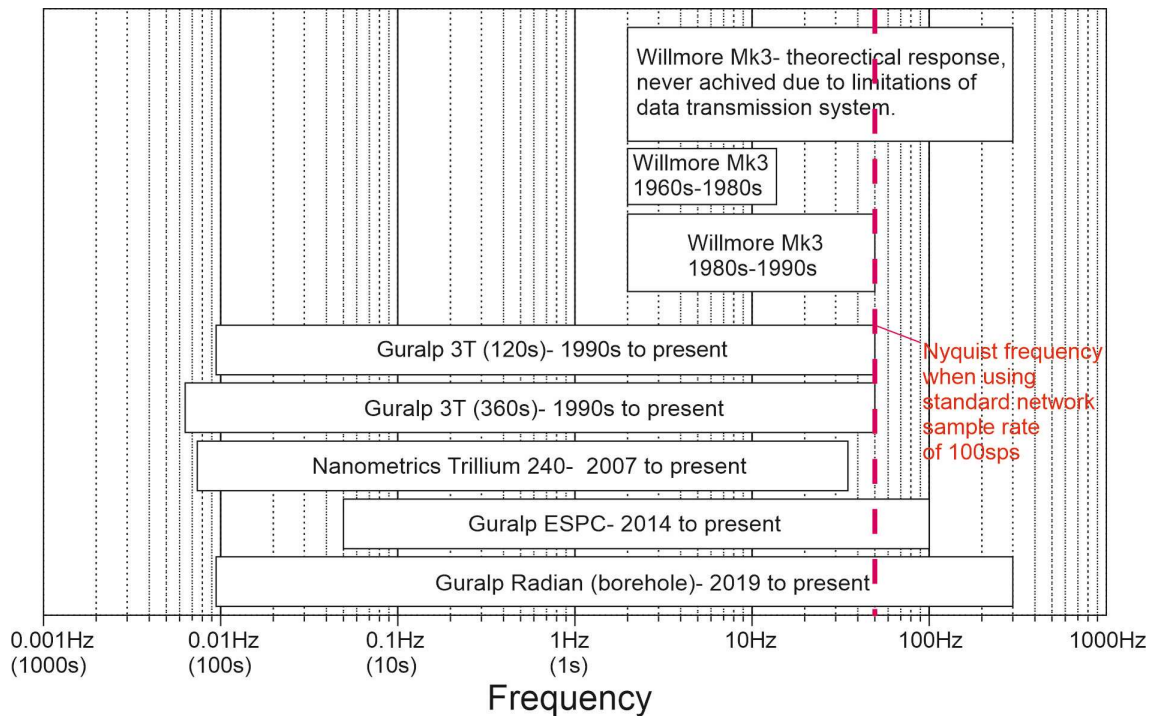


Figure 6- Diagram showing the different sensors used (past and present) across the BGS network showing the frequency range over which they can accurately record ground movement.

These new broadband sensors were able to record much weaker ground motion over a wider frequency range than previous short period network. This can mean they “saturate” during strong ground motion, providing an incomplete record of ground movement. Because of the potential importance of strong motion records in UK hazard analysis (for instance Goda, 2013) this is mitigated by the co-location of strong motion sensors at many permanent stations.

The desire for the stations to be permanent in nature and to generate high quality data can mean protracted negotiations are required with the landowner, as does the provision of new mains power and data links. To maximise data quality BGS has installed up to 1000s of meters of cable to connect the data and low voltage DC power link to the seismic vault with the nearest source of mains power and the data upload link.

The majority of permanent stations stream data in real time at 100 samples a second to the BGS data centres. A small number of stations use sample rates between 200 and 500sps, generally to allow detection of small earthquakes with high frequency content.

Whilst the installation of permanent broadband stations continues to this day, with the most recent being station BEDF (Suffolk) in 2022, from 2014 onwards temporary Broadband stations started to be deployed. Such temporary stations were used for a number of reasons including;

- Testing possible locations for new permanent stations, where 3-4 temporary stations are typically located in an area for 6-12 months with the best one being converted into a permanent station.
- Carrying out specific short term commercial work- for instance establish a baseline of natural seismicity in Yorkshire and Lancashire on behalf of the (then) Department of Business, Energy and Industrial Strategy (BEIS).
- Providing an improved detection capability above the normal to investigate a specific event, for instance the five stations deployed West of Gatwick airport to investigate the Newdigate earthquake swarm in 2019 (Hicks, 2019). Such stations are typically in place for 2 to 5 years.

It is typically far quicker to locate and install temporary stations. All use solar panels for power and provide real time data via the 3G/4G network. One of the advantages of using temporary broadband stations is that should their data prove to be of good quality, or their location particularly beneficial, they can be made permanent. The sensors used in temporary stations (Guralp ESPCs) are not quite as broadband as those used in permanent stations, having flat responses from 100Hz- 60s. However, they are both cheaper and have more tolerance to tilt (potentially important in temporary seismic vaults) than the sensors used in permanent stations.

As with the development of the short period network the location and installation dates of the short period network has been driven to a large extent by the members of the customer group that funds much of the seismic network. Stations in North and South Wales are associated with nuclear facilities in those location. Good uniform coverage of Scotland is due to the membership of several Scottish utility companies in the consortium. The most recently deployed station, BEDF in Suffolk, is located due to its proximity to both Sizewell and Bradwell.

The deployment of the broadband network coincided with advances in digital data storage, both in terms of cost and capacity. The entire continuous waveform from all stations in permanently archived.

Data products of the network, and their availability for research.

The primary product of the network has always been a catalogue of earthquakes detected. This can currently be accessed direct from the BGS's website;

<https://quakes.bgs.ac.uk/earthquakes/dataSearch.html>

Events are also archived with the International Seismological Centre (ISC). Macro seismic data has also been collected by the BGS since the earliest days of the network, at first via cut-out and post adverts published in local newspapers until that was overtaken by electronic means. At present access to the macro seismic database is only by request to the BGS, partly due to issues around GDPR.

With technological advances it became possible to supplement the catalogue of earthquakes with waveform data. Initially this was only of key events, but with time this become a continues record of waveform data from all stations. Today, all data being generated from BGS stations can be downloaded directly from its ftp server (scheduled for replacement) at <ftp://seiswav.bgs.ac.uk>.

The data from some, but not all, stations is also archived with both IRIS (<https://ds.iris.edu/ds/nodes/dmc/>) and Orfeus (<https://www.orfeus-eu.org/data/odc/>). Direct access to seismic data via a website, whether the BGS's, IRIS's or Orfeus's is still only for comparatively recent waveform data. Older data is only available via request to BGS.

Summary and Conclusions

There have, unsurprisingly, been some significant changes to instrumental seismic monitoring in the UK since 1983. These can be divided into the following phases;

- Early 1960s: data limited in terms of frequency sensitivity and dynamic range. Very limited ability to store data meaning only a few event files remain. Long time delays (weeks) between an earthquake occurring and analysts getting the data
- 1994-2003 Marginal improvement in frequency sensitivity, increased capacity to store at least the detected events as recorded on each station. Near real time transfer of data from stations allowing rapid notification of earthquakes.
- 2003-present: Modern broadband sensors, archive of full waveform, not just event files.

The dates given above are deliberately imprecise. One of the difficulties in quantifying changes in the national monitoring capability is that it happens very slowly. Both the short period network and the (still incomplete) broadband network took decades to deploy. Improvements in telemetry or data storage will often only spread across the network slowly, on a station-by-station basis. It is, essentially, a constantly evolving entity and an obvious conclusion is it cannot easily be divided into distinct phases, in terms of data quality type.

This evolution of the network over time has several implications for its use in seismic hazard research;

- Where there is no waveform data saved from stations the earthquake catalogue of those events has to be taken on trust. It cannot be re-analysed or examined. Unless someone thought to write down derived parameters, like PGA, at each station for an earthquake, they are now lost. Advances in processing methodology, for instance recent improvements in the calculation of local magnitude (Luckett, 2019), cannot be applied without the waveform data.
- Where only event waveform data is recorded it should be remembered that those are the events as identified by the BGS at the time. Where complete continuous waveform data is archived new automated detection systems can be used to find previously missed earthquakes. Modern machine learning methodology offers the tantalising possibility of finding orders of magnitude more small events in a catalogue (Zhu, 2022), if there is the continuous data to do so.
- Technological advances since 1963 have led to wider frequency of ground motion being recorded with better timing accuracy. Prior to the 1990s ground motions with frequencies below 2Hz could not be accurately recorded limiting our data set of spectral accelerations. The improved timing provided by GPS over MSF radio clocks has resulted in better magnitude/location calculations, and hence a better catalogue of seismicity for the UK.

It should be noted that not all changes have been entirely positive. One of the drivers behind moving from the short period network to the modern broadband one was to lower operational costs. Today the smallest detectable earthquake across UK is broadly similar to what it was under the full extent of the short period network. That is achieved with fewer stations, and only a fifth of the staff required to run the short period network. Fewer stations achieve a similar detection capability through their improved performance but make it less likely there is a ground motion recording near the epicentre. Without a near station there is large uncertainty both as to the depth of the earthquake and the maximum ground motion it will have caused.

Finally, there can be an assumption that national monitoring has always aimed to achieve a uniform coverage across the UK. Such an assumption is wrong. The location and maintenance of stations has been heavily dominated by the make up of a consortium of governmental bodies, regulators and utility companies whose assets the network is optimised for.

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