Documentation for SHARP North Sea earthquake data

Dr Tom Kettlety
Department of Earth Sciences, University of Oxford
tom.kettlety@earth.ox.ac.uk

Dr Daniela Kühn
NORSAR
daniela@norsar.no

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1 Introduction

This document outlines the creation and format of the SHARP North Sea earthquake dataset. This data was generated by the SHARP Storage ACT3 project, in a collaboration between the University of Oxford, NORSAR, TU Delft, the Geological Survey of Denmark and Greenland (GEUS), the British Geological Survey (BGS), and the Royal Netherlands Meteorological Institute (KNMI).

Many details of the motivation, creation, and analysis of the data can be found in two public reports generated as a part of the above project. They can be found at the below permalinks:

1) SHARP Deliverable 2.1: Integrated earthquake locations and magnitudes plus focal mechanisms for the North Sea & construction of a velocity model (Weemstra et al., 2022). Accessed April 2025.
2) SHARP Deliverable 2.4: Updated catalog and focal mechanism database (Martuganova et al., 2024). Accessed April 2025.

Copies of these reports are also included with this dataset.

This documentation provides details of the format and labelling of the two files that make up the SHARP earthquake dataset – the earthquake bulletin and the earthquake catalogue – with additional methodological information for how the dataset was created.

2 Earthquake bulletin

The SHARP earthquake bulletin is presented in the International Seismological Centre (ISC) format ISF1.0. Information on the structure of ISF files is found on the ISC website (accessed April 2025). This data is provided in the file: `SHARP_North_Sea_Bulletin_v1.4.1.isf`.

Fortran and C codes used to read data in this format are also found on the above ISC webpage (as of April 2025). MATLAB and Python implementations for reading and writing ISF1.0 files are also included with this dataset. The ISF format breaks down the event data primarily into three "blocks" or tables. These are: the "origin block", listing the reported times, hypocentres, and associated uncertainties; the "magnitude block", listing the reported event sizes in various earthquake magnitude scales; and the "phase block", listing the reported phase arrivals for that event at seismic stations. Within the blocks, comments which house extra information can be appended to any row. In the origin block, this can include focal mechanism or moment tensor solutions.

2.1 Earthquake relocations

The primary addition to this version of the SHARP North Sea bulletin, over those described in the SHARP project reports (Weemstra et al., 2022; Martuganova et al., 2024), is the earthquake relocations. The process of relocating the earthquake origins is described in detail in both Martuganova et al. (2024) and Jerkins et al. (2025). Jerkins et al. (2025) produced an ISF1.0 bulletin of 4331 relocated events, drawn from an early version of the SHARP North Sea earthquake bulletin (described in Weemstra et al., 2022). Since then, the earthquake bulletin has undergone several rounds of event discrimination, where events reported as explosions by the local earthquake monitoring agencies have been removed. This removal process is described further in Martuganova et al. (2024), Section 1.2, and Section 2.2 of this document.

Relocations can be identified in the origin blocks of events by the modification to the "`OrigID`" code. The format of these hexadecimal codes is described in Weemstra et al. (2022) and Kettlety et al. (2024). Jerkins et al. (2025) used the prime `OrigID` to refer to the events in their relocated catalogue. When these relocations were merged into the North Sea bulletin file, the same `OrigID` was used for each event, with an "`RX`" appended onto the code, where `X` is the number of the origin in the relocated origin block. This signifies that it is a relocation from Jerkins et al. (2025). For example, for an event where the prime origin was "`A363F`", the relocations for this event are now included in the origin block with `OrigID` codes "`A363FRX`", the prime origin now having the OrigID "`A363FR1`", the second relocated origin with code "`A363FR2`", etc. The author name of these newly added origins was set to "`AEJ`".

2.1.1 Epicentre uncertainty estimate

For each event with more than two origins, an additional epicentre uncertainty estimate is included. This uncertainty estimate is found through fitting of an ellipse to the origin epicentres. This process is described in Jerkins et al. (2025), Section 4. Figure 1 shows an example of the uncertainty estimation procedure. This provides a fitted centroid latitude and longitude (i.e., the centre of the fitted ellipse), and dimensions and orientation of the uncertainty ellipse (given in terms of the axis lengths and azimuth of the major axis). This is done as an ISF standard comment, formatted in a single line. The below example is from the 1991/12/11 12:02:23 event:

```
(#New uncertainty estimate: centroid location lat: 60.7717,
lon: 5.0685, uncertainty ellipse major axis: 29.5, minor axis:
7.5, az: 98)
```

where "`lat`" refers to the centroid latitude in degrees, "`lon`" to the centroid longitude in degrees, "`major axis`" to the semi-major axis of the ellipse in kilometres, "`minor axis`" to the semi-minor axis in kilometres, and "`az`" to the azimuth (i.e., angle from north) of the ellipse major axis.

The ellipse fitting procedure described in Jerkins et al. (2025) was extended to the complete North Sea bulletin, including events which were not relocated. This means that, unlike in Jerkins et al. (2025), some origins did not have reported epicentre uncertainties. In these cases, default uncertainties were assumed. These default uncertainty ellipse properties were based on the distribution of those found in the bulletin of Martuganova et al. (2024) and the relocated bulletin of Jerkins et al. (2025). This gave semi-major axes lengths of 10 km, semi-minor axes lengths of 5 km, and semi-major axis azimuths of 90 deg. The uncertainty ellipse procedure was conducted in the same manner as Jerkins et al. (2025), beyond the use of these default uncertainties for events with no epicentre error reported.

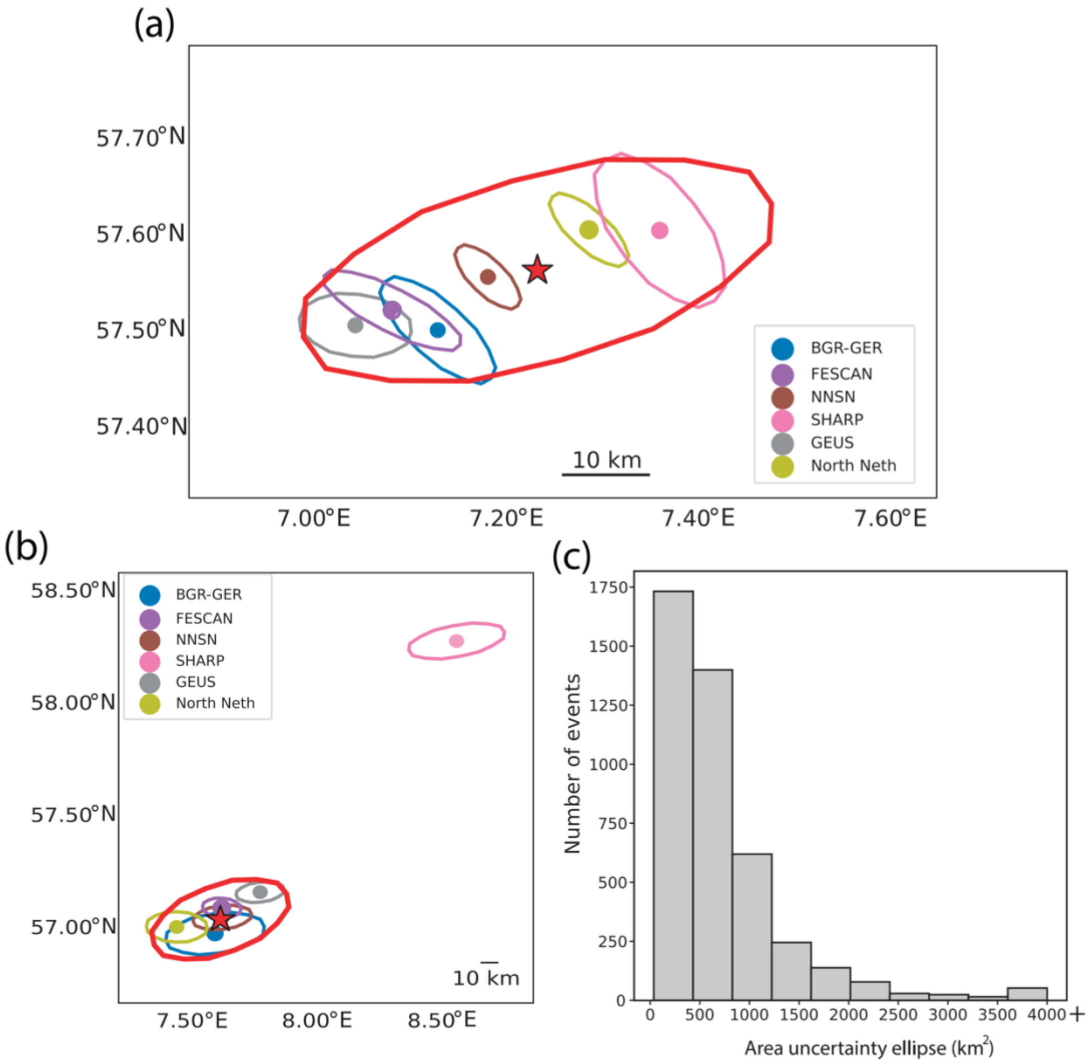

Figure 1: From Jerkins et al. (2025). (a) Locations and epicentre uncertainties derived from individual velocity models shown by filled, coloured circles, surrounded by their associated 95% confidence ellipses. New uncertainty estimate is shown by encompassing red line, with centroid epicentre represented by the red star. (b) The SHARP velocity model location is a significant outlier and is therefore excluded from the uncertainty ellipse fit. (c) Histogram illustrating distribution of relocated catalogue uncertainty ellipse areas.

This procedure does not estimate depth uncertainty. As the events, which are by and large located offshore, are primarily located using onshore recordings, accurate depth constraint is highly challenging. For events for no observations in the near-field, event depths are often fixed (denoted by the "`f`" in the origin block to the right of the depth value) in the process of inverting for the event epicentre. This inversion is done chiefly through minimisation of the travel time residual to all observed seismic stations. Fixing the event depth at several reasonable intervals, and reporting the best-fitting origin, has been found to provide more physically reasonable estimates of event hypocentre. This means that many of the reported event depths in the bulletin cannot be interpreted in the same way as the event epicentres. Thus, no new depth uncertainty is provided beyond that reported in the origin block. These depth uncertainties are either outputs from the location method used, or manually added, by the originating agency.

2.1.2 Prime event selection

The prime (i.e., the first row in the origin block) origin is selected depending on several factors, which are applied hierarchically. These are:

1) The best-fitting relocation, from Jerkins et al. (2025).
2) The origin from the European Seismic Hazard Model 2020 earthquake catalogue (Danciu et al., 2021). These origins are described further in Martuganova et al. (2024), Section 1.4.
3) The procedure described in Section 1.5 of Martuganova et al. (2024).

Comments indicating the prime origins (denoted as "`(#PRIME)`") from the original agency bulletins have been retained. This allows the primes selected by the origin's originating agency to be identified.

2.2 Additional explosion removal

After many candidate "explosions" (i.e., non-earthquake events) were identified in Jerkins et al. (2025), a stricter explosion removal was conducted from the bulletins generated by Weemstra et al (2022) and Martuganova et al. (2024). The following explosion removal was applied after the procedure described in Martuganova et al. (2024) was conducted.

The ISF format allows agencies to specify an "event type" in the origin block. This is expressed by a two character code: "`e`" denotes an earthquake, "`m`" denotes a mining explosion, "`h`" denotes a chemical explosion, and "`s`" denotes this event type is suspected and "`k`" if the type is known or confirmed. For example, a suspected earthquake would have an event type of "`se`", or a known chemical explosion would have an event type of "`kh`". In Martuganova et al. (2024), events were removed if *all* the origins event types in a given origin block were listed as a known or suspected explosion. If some origins were unclassified by their reporting agency, these were retained. This meant many events that could be explosions, but whose classification was uncertain, were retained in the bulletin.

In this version of the data, a stricter protocol is applied. If all the *reported* event types in the origin block of an event are suspected or known explosions, that event is removed. If any of the origins are listed as a suspected or known earthquake, that event is retained. This effectively means that origins with unclassified event types are no longer assumed to be suspected earthquakes.

From the 15,311 events in the Weemstra et al. (2022) bulletin, and the 10,644 events in the Martuganova et al. (2024) bulletin, this additional explosion removal reduced the current North Sea bulletin down to 9792 events. Despite this, the time-of-day and day-of-week of the prime origins (shown in Figure 2) indicate that many events are likely to be anthropogenic. To clean the bulletin of explosions further would require significant investigation of events in the catalogue that take place during the day (07:00 to 19:00) on weekdays (Monday to Friday) – this accounts for 6543 events, 67% of the total. Assuming a natural rate of earthquakes of ~250 events in any given hour (the approximate average rate on days between 00:00 and 06:00), or ~ 800 events a day (the approximate rate on weekends), around 5600 to 6000 events in the bulletin are likely to be natural, with the remaining ~4000 events (~40%) potentially being explosions.

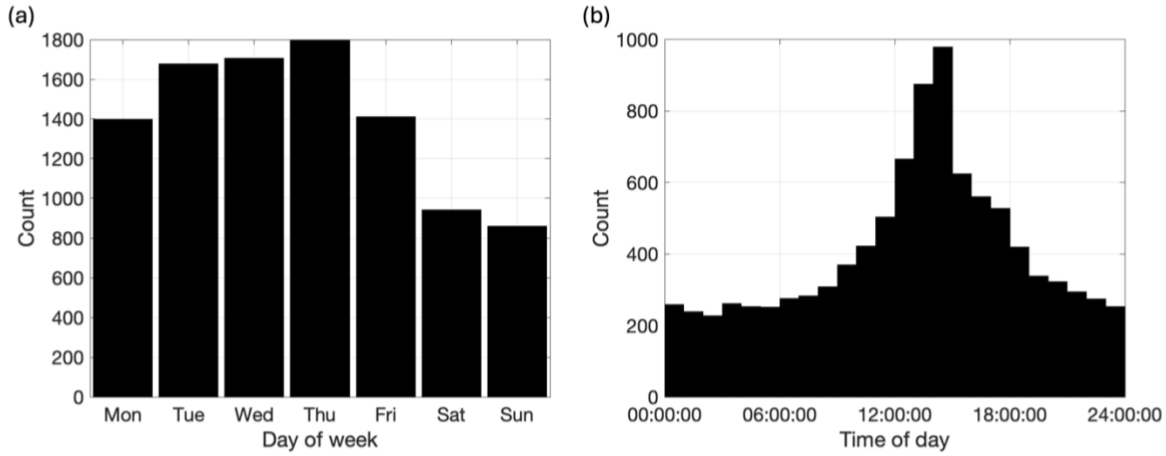

Figure 2: (a) Day-of-week and (b) time-of-day histograms for the prime origins in the current SHARP North Sea bulletin. In (b), the time-of-day histogram bin width has been set to 1 hour.

2.3 Additional moment magnitudes

Goertz-Allmann et al. (2024) calculated stress drops for a focussed subset of the events located in the Horda Platform region. During this, spectral ratios for the chosen events were computed, which simultaneously provide the origin time, location, and long period spectral level of the event. See Goertz-Allmann et al. (2024) for a detailed description of the spectral data processing. The latter was used to compute new moment magnitudes for the subset, which have been included in this version of the North Sea bulletin.

These moment magnitudes are added to the magnitude blocks of their associated events. The two datasets (the event ISF bulletin and the new magnitude computations) were merged using the time of the prime origin and the event epicentre. Events within 180 seconds and 0.25 degrees latitude and longitude were resolved as being the same events, and the new moment magnitude was added to the event's magnitude block. The new SHARP magnitude was given the associated `OrigID` of the prime origin, and an author name of "`NOR_BGA`". An example additional magnitude report for the 2008/05/29 07:23:26 event is given below:

```
Magnitude  Err Nsta Author      OrigID
Mw     2.5          NOR_BGA    71B99R1
```

2.4 Additional focal mechanisms

Weemstra et al. (2022) and Martuganova et al. (2024) created a catalogue of high-quality focal mechanisms available from several sources. Moreover, Martuganova et al. (2024) recomputed moment tensors for several large events and supplied a few newly computed moment tensors for events for which no mechanism could be extracted from the considered sources, at least not with sufficient quality. Moment tensors were decomposed according to the Frobenius norm (Silver and Jordan, 1982) and double couple parts of both recomputed and newly computed mechanisms were added as focal mechanisms to this focal mechanism catalogue. The revised catalogue is presented in detail in Martuganova et al. (2024).

FMs from this revised catalogue were added to the earthquake bulletin as comments in the origin block using the Fault Plane Solution Origin Comment format of ISF1.0 (ISF webpage, accessed April 2025).

The Martuganova et al. (2024) FM catalogue lists the `OrigID` of the event, which was used to associate the two datasets (the bulletin and the FM catalogue). Of the 76 events in the FM catalogue, 72 are matched with events still in the bulletin after explosion removal. The four events in the FM catalogue (with magnitudes between M_L 2 and 4) that are not present in the bulletin were each marked by many contributing agencies as suspected mining and chemical explosions. Detailed investigation into these suspected explosions with earthquake FMs fell outside the scope of this reanalysis.

The FM comment is appended to the associated `OrigID` listed in the FM catalogue. An example of a FM comment for the 1995/06/20 21:22:14 event is given below:

```
(#FAULT_PLANE Typ Strike   Dip    Rake  NP  NS Plane Author    )
(#                110.44 85.08   37.73               NAO       )
(+                338.10 63.20  -30.90                         )
```

2.5 Event type corrections

The final processing step for the SHARP bulletin file corrected the "event type" field. Due to an error in retrieving the origin data from the ISC using a python-based method, event types for all origins retrieved from the ISC database we're all set as being the same the event type listed for the origin with "ISC" as the author. This meant that many event types were incorrect in previous iterations of the bulletin and needed to be corrected.

To get corrected event types, a new bulletin file was generated using the ISC's "inactive bulletin search" service. This uses the same polygon search area as was used in the creation of the SHARP bulletin, as described in Weemstra et al. (2022). A search algorithm based on finding exact matches to origin time, latitude and longitude, and origin author was used to find matching origins from one bulletin to the next. Of the 47,012 origins in the current North Sea bulletin, 11,041 are from the original ISC database search. Of these 11,041, 801 origins are unmatched with equivalents in the new ISC bulletin search data using the developed algorithm. Only 12 of these 801 origins have equivalent origins in the new ISC data with time differences of less than 100 s. Each of these 12 was reviewed manually to ensure the lack of match was not a fault of the algorithm. It was found that there just are no equivalent origins, and thus it is likely that they have since been delisted from the ISC database for some reason, sometime between now and when the original ISC data was pulled during the SHARP project (i.e., June 2022). The other 789 origins with large time gaps with any origin in the new ISC data correspond to events that in the SHARP bulletin, but not the ISC. These are likely smaller events from some seismic agencies that are not in the ISC database, or events located close to the boundary of the polygon (see Weemstra et al., 2022, for treatments of events close to the boundary).

Origins in the SHARP bulletin matched with the new ISC bulletin have their event type entries corrected. Unmatched origins have their event type's removed, to ensure the accuracy of the event classification.

3 Earthquake catalogue

The earthquake catalogue – consisting of a single time, location, associated uncertainties, and magnitudes of various types – is generated using the data provided in the earthquake bulletin (`SHARP_North_Sea_Bulletin_v1.4.1.isf`). The above sections list how the data in the earthquake bulletin was produced. This catalogue data is provided in comma-separated variable (CSV) format in the file: `SHARP_North_Sea_Catalogue_v1.4.1.csv`.

Catalogue data are primarily reported from the prime origins of the events in the bulletin (selection of which is described in Section 2.1.2). Location uncertainties are reported in two ways: the prime origin's reported uncertainties; and the uncertainty estimate from the procedure described in Section 2.1.1. Magnitudes are reported using the method described in Martuganova et al. (2024), Section 1.5.

3.1 Column descriptions

The CSV data is organised into columns, in the following order. Descriptions of each of the column's data are given below, with parameter units given if appropriate:

- `str`: UTC string of prime origin time.
- `lat`: prime origin latitude in degrees.
- `lon`: prime origin longitude in degrees.
- `depth`: prime origin depth in kilometres.
- `smaj`: prime origin epicentre error ellipse semi-major axis length in kilometres.
- `smin`: prime origin epicentre error ellipse semi-minor axis length in kilometres.
- `azi`: prime origin epicentre error ellipse semi-major axis azimuth in degrees.
- `dz`: prime origin depth error in kilometres.
- `lat_fit`: centroid latitude of ellipse fit to origins in degrees.
- `lon_fit`: centroid longitude of ellipse fit to origins in degrees.
- `smaj_fit`: semi-major axis length of ellipse fit to origins in kilometres.
- `smin_fit`: semi-minor axis length of ellipse fit to origins in kilometres.
- `azi_fit`: semi-major axis azimuth of ellipse fit to origins in degrees.
- `ML`: local magnitude of prime origin, or if not present, median ML of magnitudes reported.
- `Mw`: moment magnitude of prime origin, or if not present, median Mw of magnitudes reported.
- `Mb`: body wave magnitude of prime origin, or if not present, median Mb of magnitudes reported.
- `Md`: duration magnitude of prime origin, or if not present, median Md of magnitudes reported.
- `Ms`: surface-wave magnitude of prime origin, or if not present, median Ms of magnitudes reported.
- `Mc`: coda-wave magnitude of prime origin, or if not present, median Mc of magnitudes reported.

- `OrigID`: unique hexadecimal code for the origin as used in the `SHARP_North_Sea_Bulletin.isf` file.
- `catID`: name of the agency from which the origin's data was collected/derived. Found from the value of the `OrigID`, as described in Weemstra et al. (2022), Section 4.3.

4 References

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