Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Fact-finding mission / audit: Groningen Seismic Measurements

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Executive Summary

Major issues have been reported with seismic sensors from the G and B network installed to monitor Groningen gas fields, and SodM commissioned the SED at ETH Zurich to investigate why these occurred, whether the issues are satisfactorily addressed, and to propose measures to ensure such problems do not occur again.

Since the inception of the G network in 2014 until December 2018, KNMI, who operate the seismic networks affected, provided incorrect descriptions for the surface accelerometers in the G0 network. The majority of these G0 sensors were provided with gain values that led to a reduction of ground motion of a factor of 2. The remainder were described with information leading to ground motions a factor of 2 times above the correct amplitude. At the same time as the amplitude problem was corrected in late 2018, station orientation information was changed in the network description, affecting all sensors, in particular the borehole G network sensors.

These changes were made to the network metadata information without informing stakeholders. In January 2019, a researcher outside KNMI reported the observation of significant changes to the metadata to KNMI and SodM. As these had not been announced by KNMI, there was significant concern related to transparency of operations at KNMI that has led to further investigations, including the commissioning of this report.

The subsequent analysis led to SodM requesting SED and other teams to look into a number of additional issues, including the complex ground motions that are observed across the B network, where sensors are housed in a variety of farming structures. In general, at B network stations ground motion amplitudes above a few Hertz are lower than would be expected at a free-field site, though at some sites there are amplifications in narrow bands between 10-15Hz, matching the resonant frequencies of the structures.

Various internal and independent studies indicate that the updated network information from KMNI now provides correct station descriptions for amplitudes. The modified orientations will improve the usability of the data in the long term. The impact of the incorrect metadata on the seismic network has been evaluated. There are no changes to the seismic catalogue, but shaking estimates from previous induced earthquakes based on ShakeMaps have been modified. A report on the consequences for scientific studies that were carried out using the incorrect station descriptions is being independently prepared.

It is the authors' opinion that the error with metadata has been satisfactorily identified and fixed. The metadata issues are serious and could have affected numerous scientific studies and have eroded public trust. We find that the error was an oversight caused by a lack of experience among an under-staffed network team. It is our evaluation that this was not negligence, as these types of errors can and do happen in other seismic networks (though it is rare to affect the majority of stations in a network). Although KNMI failed to adequately inform all stakeholders at the time, we find that their efforts to demonstrate the revised metadata is now correct are thorough and convincing, and that their subsequent efforts to provide transparent information on the impact of the issue go above and beyond standard network practice. Finally, we recommend that KNMI ensure that procedures to routinely check quality of their network, including metadata, are put in place.

Introduction

In February 2019 **Staatstozicht op de Mijnen** (SodM) contacted the Swiss Seismological Service (SED) at ETH Zurich to request an independent investigation into a number of issues related to seismic monitoring in the Groningen region.

The issues addressed in this report are:
- the G0 network strong motion description error
- orientation changes for all the G / B network stations
- the KNMI seismic network and seismic network operations in general
- the general quality of the B network

The scope of the work as agreed with SodM was to include
- a review of existing reports (see Bibliography)
- interviews with network managers and operators at KNMI, in particular those dealing with data management and quality control
- check and validation of the full measurement chain of the seismic network at KNMI
- a review and evaluation of the existing networks operated by KNMI, including a review of field equipment, calibration, installation, maintenance and QC procedures
- a review of the timeline of when / how errors with station metadata were spotted and reported
- an assessment of whether identified problems have been satisfactorily addressed
- suggestions on future issues to be investigated in more detail including possible improvements to QC procedures

In the preparation of this report, in addition to **SodM**, the authors were in contact with
- **KNMI** (). KNMI is the operator of the seismic network, responsible for network maintenance and health, providing open access to the data, informing authorities and public about seismicity in the Groningen region, maintaining the earth-quake catalogue, and performing basic science
- **Antea** (), the contractor who installed the network – leading the procurement of the instruments
- Independent researchers from **Witteveen and Bos** (), **FUGRO** (), **Hanze University of Applied Sciences** (), and **Seister** () who were also tasked by SodM to investigate the issues primarily related to the incorrect metadata, but extending to general questions related to network management and performance.

The authors also benefitted from reports provided by FUGRO (*FUGRO, 2019*) that included communications between stakeholders in the Netherlands and the instrument manufacturer, Kinemetrics.

Brief Network History

The development of seismic monitoring in the Groningen region, and the Seismic Network at KNMI in particular, is documented in detail in *Dost et al, 2017* and *NORSAR, 2018*. The current status of stations with data available today at KNMI can be found from the KNMI station web-service[1]. A summary of the recent network development, with focus on the strong motion monitoring at Groningen, is in Table 1. A more comprehensive list of stations can be found in *Norsar, 2018* (see in particular Table 1, Figure 2.2 and Appendix A).

Date	**Description**	**No stations**	**Configuration**	**Hardware (if relevant to this report)**
1991	Pilot borehole	1 (FSW)	4 geophones, including surface, 75m spacing	
1995	Regional network, 20km inter-station spacing	8 (ENM, ENV, HWF, VBG, VLW, WDB, ZLV, ZL2)	4 geophones, none at surface, 50m spacing	
1997	Strong motion monitoring added	5 initially, up to 17	Surface accelerometers at site of felt reports. Typically installed inside structures.	
2010	Widen aperture of network	3 (NIW, SPY, SUH)	4 geophones, none at surface, 30m spacing	
2013-2015	**B network main development (continues up to 2017)**	19	Surface accelerometers on floors inside buildings at sites of felt reports	4g +/-20V EpiSensor + 130dB Basalt
2015	**TNO network**	375	Surface accelerometers located on walls inside buildings at sites of felt reports	
2014-2016	**G network main development** – densification to 4-5km inter-station spacing	70 G[01-70][0,1,2,3,4]	Gxx0 surface strong motion; Gxx1/2/3/4 are 4 geophones with 50m spacing	2g +/-5V EpiSensor + 130dB Granite
2017	G network strong motion extension	10 G[71-80]0	Surface strong motion sensors only	2g +/-20V EpiSensor + 155dB Obsidian
2019	G network VBB borehole complement	4	Gxxx STS5 boreholes co-located with selected G stations, currently operational.	

Table 1 Summary of seismic network evolution in the Groningen region. Borehole and surface free-field strong motion **G network** developments indicated in green; strong motion **B network** developments indicated in orange; strong motion **TNO network** indicated in blue. Note TNO network data is not available to KNMI, and any accelerometric data collected prior to the B-network is not currently available from open-access KNMI data portals.

Today in the Groningen region, on the order of 340 borehole sensors are installed at about 80 sites. These sensors are mainly geophones, but include a small number of very broad band seismometers. From the G and B networks, between 90-100 surface accelerometers are operational. All sensors, except those in the TNO network and the pre-2013 strong motion stations, provide data continuously in real-time to KNMI for earthquake monitoring, and the data are made available openly to researchers.

[1] eg http://rdsa.knmi.nl/fdsnws/station/1/query?format=text&nodata=404&level=cha&net=NL&cha=*Z

The authors note that the accelerometers installed prior to the B network in 2013 are of a different quality, and data acquired from them are not available from KNMI websites. They are not discussed further in this report, except at the end where it is recommended that if important strong motion data was collected on them, they should be included in the data archive.

The primary goal of the B-network when it was installed was to record strong motion information within structures. Though care was taken to select a small structure if this was possible, these stations were not intended to be free-field. Sometimes a larger structure was selected, due to the fact that no alternative was found in the region. Free field sites were not considered at the time these stations were constructed due to expenses.

G-Network strong motion description error

From their inception in 2014 until December 2018, the G0 surface strong motion stations were assigned incorrect metadata description by the KNMI network.

A modern seismic station consists of a seismometer that senses ground motion. The sensor provides an analogue voltage output that is proportional to the ground motion in a manner that depends on the type of sensor. A digitizer / datalogger receives this voltage as input, 'digitizes' it into digital counts, stores it locally and transmits it to a centralized processing center.

The seismic network acquires this data in raw digital counts and makes it available for routine earthquake processing and to scientists. In order to interpret these raw counts from the digitizer, a seismic network maintains station metadata, essentially information that describes the transfer function of each of the seismometer (from ground motion to voltage) and digitizer (from voltage to counts). At KNMI, as is common practice across the majority of seismic networks operating today, the raw data is archived in miniSEED format, and the metadata as InventoryXML.

Each different seismic sensor and digitizer has a different transfer function. Most instruments, including those used in the Groningen seismic networks, also offer various different settings. For example, the EpiSensor can be set to record a maximum of 1g, 2g or 4g, and this maximum can match 5V or 20V, leading to a number of different transfer functions to map from ground motion to counts. Ideally, the seismic sensor and digitizer should carefully match so the dynamic range of the station is maximized. Also, in order to obtain the correct response, the Seismic Network must correctly track the individual settings.

Both network operators as well as scientists using the data use these metadata to interpret the raw data. Any errors in the metadata will lead to misunderstandings and errors in any product or science in which the affected sensor data is used.

As can be seen in Table 1, between 2013 and 2017, a number of different phases of network building occurred in the Netherlands.

In the first phase the B-network was installed, with 4g 20V EpiSensor acquired on a 3-channel Basalt datalogger (see for example Site BFB2 in Appendix A). The metadata for all these stations was built correctly at KNMI.

Next, the main phase of the G-network was built, consisting of 70 stations with 4 levels of borehole geophones, and a surface accelerometer. All sensors were acquired on a 16-channel Granite datalogger (see for example Site G390 in Appendix A). The free-field surface accelerometers were installed with default settings as delivered by the manufacturer, at 2g 5V**. KNMI report that rather than building the metadata from scratch using the new settings, for these strong**

motion stations, the metadata for all 70 stations was built by cloning the response from the B-network. This led to an **underestimation** of the true amplitudes of a factor of 2.

Finally, the last phase of the G-network was built, consisting of 10 stations with surface only strong motion accelerometers acquired on a 3-channel Obsidian datalogger (see for example Site G710 in Appendix A). The surface accelerometers were installed as 2g 20V**. KNMI again report that rather than building the metadata from scratch using the new settings, similarly to the strong motion G0 stations installed in the preceding main phase of network building, the metadata for all 10 stations was built by cloning the response from the B-network.** This led to an **overestimation** of the true amplitudes of a factor of 2.

The authors agree that this type of error can and indeed does often occur in a seismic network without being immediately noticed.

Detection and resolution of G-Network strong motion description error

As part of this investigation, KNMI were requested to summarise the issues around the detection and resolution of the amplitude issue. In an email response, KNMI reported the following:

> *08/2018: During the development of the new Ground Motion Model v6 (earlier called Ground Motion Prediction Equation), an inconsistency between the amplitudes of the B- and G-network is notified. KNMI is part of the team that develops the model, together with Imperial College, University of Liverpool, Virginia Tech, Deltares and NAM. It was determined that the inconsistency does not affect our reporting of earthquakes, i.e., KNMI's main task. Therefore, the cause was searched for first.*
>
> *11/2018: The cause has been found and it appeared to be a difference in gain setting between the different network. See for the methodology the separate document on amplitudes. The metadata and its corrections are discussed below.*
>
> *12/2019: The metadata is corrected and communication to the stakeholders is discussed. It was planned to inform the Ministry of Economic Affairs and Climate, SodM and stakeholders in the region of Groningen. However, due to a human error this communication was never executed.*
>
> *The methodology is described in the separate document on amplitudes (amplitudes.pdf).*
> *17/12/2018: Corrected wrong sensor response for accelerometers: the inventory data was changed for 19 B stations, 69 "initial" G stations and 10 "new" G stations. Here the exact changes for each set:*
>
> - *B accelerometers: improved the sensor description ("Episensor ES-T +-20V Differential 4g") and the sensor serial number. Sensor gain or response not modified.*
>
> - *"Initial" G accelerometers: improved the sensor description ("Episensor ES-T +-5V Differential 2g") and the sensor serial number, and modified the sensor gain from 0.5099 to 0.2549 (total gain from 213849 to 106913).*
>
> - *"New" G accelerometers: improved the sensor description ("Episensor ES-T +-20V Differential 2g") and the sensor serial number, and modified the sensor gain from 0.5099 to 1.0197 (total gain from 213849 to 427693).*

KNMI also provided a full report to the authors on the amplitudes issue (*KNMI, 2019a*). This is the document referred to in the text above.

In January 2019, a researcher outside KNMI reported significant changes to the metadata to KNMI and SodM. Since these had not been reported by KNMI, there was significant concern related to transparency and general operations at KNMI.

KNMI reacted by preparing documents explaining their process for understanding the problem, and demonstrating the impact of the error (*KNMI, 2019a*) In summary, in mid-2018, researchers noticed inconsistencies between B and G-network strong motion amplitudes, even though sites were close-by. These types of inter-station variations can be expected, but it is highly unusual for these to be systematic based on network type. KNMI and affiliated researchers did a careful analysis using 1) local earthquakes; and 2) key diagnostic phases from very large teleseismic earthquakes. In particular, long-period amplitudes from teleseisms can be expected to provided consistent amplitudes from across a narrow seismic array such as Groningen. Their report shows that using the original metadata, there were 3 distinct families of sensors with similar absolute amplitudes – 1) all B stations and G-boreholes; 2) 1st phase G0 strong motion (amplitudes a factor of 2 below family 1); and 3) 2nd phase G0 strong motion (amplitudes a factor of 2 above family 1). This prompted careful review of the settings provided by default in the sensor delivery by Kinemetrics, the manufacturer of both the EpiSensor and the digitizer/datalogger, where it was spotted that for each different procurement phase, 'minor' changes in delivered default instrument configuration were not accounted for in the metadata.

KNMI decided to address the problem by updating the station metadata to reflect the actual settings of the sensors in the field. The KNMI report demonstrates once these changes are made, there is no longer any systematic differences in amplitudes using the same set of tests used to identify the problem.

Further, the independent report compiled by FUGRO (*FUGRO, 2019*) using the updated metadata also confirm there are no longer any systematic amplitude offsets. In Figs. 3-4 and 3-5 of *FUGRO (2019)* spectral ratios of near-co-located strong motion sites from both the B and G networks are computed to investigate issues with the site quality of the B-network. This study shows systematic issues with site response at B-network stations, but crucially shows there is no systematic offset between B and G stations at long periods.

In a second study documented in this report, FUGRO take sensors from G0 and B stations out from the active network and test on a shake table. They find the with the corrected metadata, the amplitudes recorded on the shake table are consistent with those recorded by the seismometer.
Dost et al, 2019 document the impact on the amplitude error on various scientific studies that use the Groningen dataset.

Update of the G-Network orientations

As part of this investigation, KNMI were requested to summarise the issues around the changes made to the borehole sensor orientations. KNMI report the following:

> *16/01/2019: Corrected orientations of G and stations in Norg: the orientations of the sensors for almost all G and stations in Norg were corrected to the values deduced by KNMI research (a separate report will be provided). The deduced orientations with high error (STD) were set to the theoretical defaults (0/90). The orientations of the sensors in Twente, Grijpskerk, Anna Paulowna and Drenthe were also set to the theoretical defaults (0/90) until KNMI research provides their estimated real orientations.*

KNMI also provided a full report to the authors on the orientation issue (*KNMI, 2019b*).

Until January 2019, KNMI reported default orientation angles (dip and azimuth) for the borehole sensors in their metadata, although the channel naming convention did use orientation codes ‘1’ and ‘2’, rather than default ‘E’ (interpreted as East) and ‘N’ (interpreted as North). At the time, KNMI knew the orientations were unknown, as it was not possible to control the orientation during sensor installation. Despite the indication in the channel name, since the dip and azimuth values reflected standard orientations, it is possible that users could be confused and misinterpret the orientations.. Though it takes significant effort to provide correct orientations, and it is normal for networks to operate using these misleading orientations, it is not good practice.

At the same time that they were investigating the amplitude issue, KNMI and affiliated researchers did a careful analysis to determine the correct sensor orientation using 1) local earthquakes; 2) very large teleseismic earthquakes and 3) blasts from off-shore in the North Sea. Similar to the amplitude investigations, the long-period energy from teleseisms can be expected to provided consistent orientations across a narrow seismic array such as at Groningen. If a consistent estimate of orientation was found for each of the different source type, the updated orientation was added to the metadata. This investigation also allowed KNMI to verify the orientations of the surface accelerometers, which should generally by installed due North without complication. A handful of surface sensors were spotted to have significant errors and the orientation was also corrected in the metadata.

Why did the errors in G0 absolute gains occur?

Following discussions with Stakeholders, the authors make the following observations with respect to the amplitude gain issue:

1/ The Seismology section of KNMI has operated with a very small staff throughout the build-up and operation of the B and G networks. There are only 2 persons dedicated to seismic network operations (a seismologist and an IT technician). There are 5 scientists who also working on the data. The current 2-man operation team share all responsibility for the network, from ensuring data integrity and streaming; data quality control; station metadata; configuration of the earthquake processing software that detects and quantifies the induced seismicity from the region and allows careful manual review; alerting services; management of the earthquake catalogue; all downstream products and services, including ShakeMap; and public dissemination services. In a network of the size currently operational in the Netherlands, this is a very small staff, and there is a lot of pressure to offer the full range of services at the quality expected for this high-profile project[2]. KNMI also has a single additional person dedicated to network maintenance tasks – travelling to the field to address issues with regular maintenance, station failures and quality issues.

2/ The various stages of the seismic network buildup were realized using a complicated organizational setup that did not provide for rigorous checks / coordination. KNMI were not responsible for construction of the network, rather this was Antea. Antea received information on network targets – number of stations, vault type, suggested locations, instruments. Antea proceeded to procure the instruments from Kinemetrics, negotiate permission to install sites with landowners, prepare vaults with power and communications, and install the instruments. Antea informed KNMI when a station came on-line.

3/ At the time G-network stations began to be added, the network staff at KNMI were relatively junior and were not aware that the same seismic sensor model (EpiSensor) was being provided by same manufacturer but with different standard settings. They cloned the metadata response

[2] KNMI strongly benefits from hosting the ORFEUS Data Center, a node of EIDA (European Integrated Data Archive) – knowledge and best practice from this team has been transferred to the KNMI network staff.

of previous generations of Kinemetrics instruments from the B-network for the G0-network stations, even though the hardware settings had indeed changed.

4/ There was no requirement to test a sample instrument alongside a well-calibrated instrument, or even perform a huddle test of all instruments to check instrument quality. If this had been done, the issue would have been noticed during the installation process.

We observe that there was a lack of overall technical coordination in the procurement and installation process.

Why did the G0 amplitude error remain undetected?

The first G0 strong motions stations with wrong metadata were installed 2014. All subsequent G0 stations were installed with an error, and the problem was not identified until mid-2018. It is unusual for a systematic error in metadata to go undetected for such a long time. Both seismic network operators and scientists who regularly use the data would have opportunities to detect the problem. The authors provide the following comments that can explain why the issue was not detected earlier:

- **General Comment**: the amplitude range encountered in earthquake seismology is very high. The factor of 2 error in the overall gain for the G0 stations (both too low and too high) does appear to be large, but earthquake amplitudes span very many orders of magnitude, and the magnitude scale is logarithmic. Hence, a difference between a single magnitude unit (eg the difference between a M2.5 and a M3.5 earthquake) is a factor of 10 in sensor amplitude. A factor of 2 change in sensor amplitude corresponds to a difference of 0.3 in sensor magnitude. Both magnitudes and observed intensities are built on logarithmic scales, and so the effect of a factor of 2 is not as significant as it can first appear.
- **Seismic Network Operators**: In a seismic network, one of the best ways to spot issues with data and metadata is through routine use of the data. This can be with:
  1) daily generation of seismic event locations and magnitudes for the earthquake catalogue. KMNI have adopted the convention to only use one sensor from their vertical arrays for magnitude calculation. For the G-network, only the deepest borehole G4 sensors are used in magnitude determination, surface acceerlometrs and intermediate depth geophones are not used. So the amplitude problems at the G0 sensors were not being routinely viewed by the scientists that maintain the earthquake catalogue
  2) strong motion observations for larger earthquakes – the KNMI operate a modern strong motion data portal (http://rdsa.knmi.nl/opencms/nl-rrsm/) showing all ground motions from all surface stations following any >M2.0 seismic event. This information is the input used in ShakeMaps (https://data.knmi.nl/datasets/seismic_shakemaps/1) showing the spatial distribution of ground motion during an event. Careful review of these both resources could have indicated that there were systematic problems, though this is complicated by the significant local site / source variability and trends would be hard to ascertain over a single event analysis.
- **Seismic Network Operators**: Good network practice includes routine calculation of PDFs of PSDs. In many regions, the microseismic noise can be visualized clearly between 5-15s, even for strong motion sensors with the type of high-quality instrumentation installed in B and G networks. As the amplitude of this long-period signal is very similar across wide regions and sensor depths, this signal is often used to constrain absolute amplitudes. Unfortunately, due to the soil conditions and the local anthropogenic noise, the site noise around Groningen is extremely high, and this marker is missing at Groningen.
- **Seismic Network Operators**: Good network practice should include checks on amplitude and orientation as stations are included into the network, and periodically then afterwards, eg once every 2 years. For example, using teleseismic phases, as is effectively shown in

the KNMI Amplitudes report (*KNMI, 2019a*). If this type of procedure was integrated in standard practice, the amplitude problem would likely have been spotted earlier.

- **Scientists**: the G0 and B network strong motion sensors in Groningen are located in very soft sediments. Local site amplifications at seismic frequencies are high, and are variable, sometimes with factors that are above a factor of 2 (see SEISTER report included in *FUGRO, 2019* for examples). Further, the G-network stations are located in free-field vaults, and the B-network stations are located in a variety of different farm buildings. In fact, for some scientific studies, the B-network data is not used since the site effects are considered too strong. It is to be expected that scientists looking at difference between G0 and B data can interpret the factor of 2 as a site or vault effect.
- **Scientists**: It is almost inevitable that errors in network description will creep into any network. The best way to identify errors is to provide transparent open data access with high quality tools in order to encourage usage of the data. In recent years, KNMI certainly provide such tools, but since the seismicity in the region is limited, there are only limited numbers of scientists using the data, hence problems such as incorrect gains can take longer to be identified and reported. KNMI data is no available on the various European EIDA Portals via the ORFEUS Data Center (http://orfeus-eu.org/data/eida/), providing scientists with discovery and direct access of the collected dataset. Moving forwards, these additional potential users could help provide expert feedback.

Assessment on the General Performance of KNMI Seismic Network

SodM requested that SED also provide a general evaluation of the data and operations at the KNMI seismic network. Our findings and assessment follow.

Data completeness: Table 2 provides an overview of data completeness in the KNMI continuous waveform archives, as provided by KNMI. In Appendix B, this is further broken down for each year at the station / month level. In early years, the completeness was below 90%, which is low for a seismic network unless there is an agreement to operate at this level, and likely reflects the staffing levels at the network, and the fact critical staff were junior and burdened with setting up the entire system at this time. In recent years, the network has a completeness percentage of above 90%, which is acceptable for a network managing over 100 sensors with a very small staff.

	G network		**B network**		**Total**	
	Num of stations	**Availability**	**Num of stations**	**Availability**	**Num of stations**	**Availability**
2014	*event-based data*					
2015	*full archive in cold storage*					
2016 (march-dec)	66	68.9%	16	66.2%	82	**67.6%**
2017	78	82.9%	16	79.5%	94	**81.2%**
2018	79	92.4%	16	95.4%	95	**93.9%**
2019 (jan-march)	79	89.3%	16	91.3%	95	**90.3%**
Total		**83.4%**		**83.1%**		**83.2%**

Table 2 Summary of data completeness in the KNMI data archives. Prior to March 2016, the data is not currently available with rapid access.

Data quality: Data completeness only indicates that information is available from a seismic station in an archive for a given period of time. It contains no information about whether the data is seismic, correct and of expected quality. PDFs of PSD plots are routinely produced at seismic networks in order to identify the quality of data in an archive. As part of the preparation of this report, KNMI provided PDFs or PSDs for their all their stations in their archives[3]. These images allow the following observations to be made:

- In general, the majority of G and B stations provide high quality data – for strong motion stations, the PSDs for both the G0 and B network lie near the high noise model and for the 130dB digitisers, there is a mix between site noise and digitizer noise.
- Though the main microseismic peaks at 7s and 14s are hidden underneath the high local noise in the Groningen region, a block of energy at 2s is consistently seen across the network. Since this is consistently observed at the same amplitude across all instruments, this provides added confidence that the gains across the network are now correct.
- A number of stations provide non-seismic data (eg in 2018: G050, G071, G29x) or data contaminated with noise (eg in 2018: G450, G530, BMD2, BLOP)
- A small number of strong motion sensor components have exhibited high noise for some time without being fixed or replaced, eg G680.HG2 or G530.HG2. These should be systematically checked, and broken sensors should be replaced or fixed unless this performance is deemed acceptable.
- KNMI are aware that some borehole geophones are broken, and these are buried in so cannot be fixed. Currently, these continue to stream datalogger bit noise, which provides misleading completeness statistics and requires scientists to screen these data out. Best practice would be to mark these stations as closed and cease streaming these channels / adding to the archive.

Sensor metadata - amplitudes: *KNMI, 2019a* documents a systematic approach to identify and resolve the problems with sensor amplitudes. It is clear this problem began appearing in 2014, and should have been noticed before 2018. But the analysis presented in *KNMI, 2019a* and elsewhere in this report does convincingly demonstrate the problems are well understood and are now fixed.

Sensor metadata - orientation: *KNMI, 2019b* documents a systematic approach to measure sensor orientations and add them to sensor metadata. This effort goes above and beyond what is normal for a seismic network, but considering the fact that deep sensors dominate the stations in the Netherlands, it is considered a minimum requirement. It is a valid criticism to state sensor-specific sensor orientations should have been made available in the station metadata information, for both network managers and for external researchers, before 2019.

Data processing: KNMI use the SeisComP3 software suite for their seismic data management and processing. This is the current standard for seismic networks. KNMI operate an effective and appropriate service to review automatic detections and provide manual reviewed solutions to the public in an appropriate timeline. These procedures also been positively reviewed in the *NORSAR, 2018* report.

Data access: KNMI provide earthquake information to the public using their own web infrastructure. The breath and content provided is extremely impressive. Much of the portals and underlying software and tools they provide adopt solutions widely used in the European seismic monitoring community, reflecting the close collaboration with the ORFEUS Data Center. Following large earthquakes, ground motion data is available using USGS-style ShakeMaps .knmi.nl tasets/seismic_shakemaps/1). Station information, waveform data and earthquake catalogues are available using standard FDSN webservices at .knmi.nl/fdsnws/, and an interactive data access portal provides access to event-based ground motions .knmi.nl/ and continuous ground motions .knmi.nl/). QC information follows EIDA standards using wfcatalogue.

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[3] There are thousands of these images, so they cannot reasonably be added to this document. KNMI can provide these to interested parties, though currently they are not available on-line.

Transparency to scientists: KNMI have operated and continue to operate a seismic network using very high standard with modern tools for data management, earthquake detection and quantification, and data dissemination. It is clear the widespread interest in operations at the KNMI mean there is a spotlight is on transparency with any changes to the network operation and information dissemination. KNMI start from a strong place but non-standard tools would be recommended here, including making the following available on-line:

- Completeness and PSD information
- A log of any changes in metadata

The fact that, in reaction to the recognition of concerns that the errors in sensor gains have eroded public trust, they already provide before / after results from Peak Ground Motion estimates and ShakeMaps, demonstrates a commitment to transparency. At the main page on the data access portal at knmi.nl there is an announcement that there were inventory changes in December 2018, and a document providing before / after ShakeMaps showing the impact of the changes in the metadata are also linked. ShakeMaps are the product most obviously affected by the metadata error.

Comments and Suggestions for Improvements in Seismic Monitoring at Groningen

In summary, the SED find that the KNMI were not negligent in providing incorrect metadata for some time. The errors were in general difficult to spot. The KNMI operate a sophisticated and modern, high quality seismic network operation. In response to the problems, KNMI provided reports documenting they have identified the initial errors and now provide correct metadata that are serious, sufficient and convincing.

The SED also provide the following comments on the existing seismic network operations and give suggestions for improvements.

Seismic Network Stations:
Site visits were made to select B and G sites (see Appendix A) and the *FUGRO, 2019* report provide further insight into the quality of the data recorded at stations in the networks operated by KNMI. The hardware installed at the networks is excellent, Kinemetrics has a well-earned reputation for providing community-leading sensors and dataloggers with performance that consistently meets advertised specifications with excellent quality and reliability. The instrumentation selected is appropriate for the site conditions.

The G-network is state-of-the-art, free-field and provides excellent data for researchers.

The B-network has issues related to the site conditions that are noted in the FUGRO report and the Site Visit: 1) the sensors are located in different farming structures, that are observed to have an impact on the recorded data. Subsequent scientific analysis should take these effects into account; 2) the rooms the sensors are located in are not currently controlled and additional loose material can be placed beside or even above the sensors. In the event of strong shaking, it is likely there will be local disturbances which will be recorded by the sensor and these spurious motions will be erroneously interpreted. A review of the quality of the B-network that addresses both these issues is appropriate. If this network is to be of optimal scientific value, we would recommend either 1) **relocation of the stations**: the stations should be moved to near-by free-field sites within seismic vaults similar to those at the G0 network; or 2) **improvement in understanding and site protection of the existing stations:** the existing sites, that can be heavily influenced by site-structure interaction, should all be fully characterized in terms of their frequency response, and this information should be made available to scientists via KNMI as they access the data. Further, the furniture surrounding the sensors themselves should be reviewed with a focus on ensuring clean seismic records during strong shaking, and systematic site visits should be implemented. The authors note that this second option has significant benefits as future studies using the already collected datasets can be improved if the site response is well characterized, and there is significant benefit for maintaining seismic sensors at one place over long periods of time, as the site conditions are not varying between events / epochs.

Future Network Extensions:
If there are further extensions to the network planned, there should be improved coordination between KNMI and any team selected to build the network. Pre-installation testing should include verification of the final sensor setup for deployment to the field alongside known seismic sensors, eg at KNMI; as well as huddle tests for all equipment before deployment. Calibration sheets from the manufacturer for all sensors should be archived at KNMI. It should be ensured the equipment is set up to provide the maximum possible dynamic range. KNMI should establish and implement integration tests once new stations are installed, that includes checks on amplitudes.

Access to TNO stations:
A more complete view of the impact of the on-going and past seismic events at Groningen could be facilitated by making the stations from the TNO network publicly available, ideally through the KNMI data portal. The TNO network comprises strong motion sensors deployed on walls inside structures, so the effects of the non-free-field locations will be even more significant than for the B-network. Nevertheless, open access to earthquake recordings these stations, especially if this is combined with understanding of the actual impact of the site / structure conditions, will lead to better understanding of the seismic hazard.

Access to pre-2013 strong motion data
KNMI operated a set of strong motion stations with significantly poorer data quality than todays' network from 1995 up to 2013, when the B-network was started. The stations were often temporary with numerous issues - station dynamic range was low, GPS timing was sometimes missing, site quality was poor (inside structures) and stations only operated in triggered rather than continuous mode. Nevertheless, if significant events were recorded, this data should be secured in standard forms and made available to scientists.

Continued collaboration with ORFEUS Data Center (ODC):
ODC .orfeus-eu. is the key node of the European Integrated Data Archive (.orfeus-eu. and is housed at KNMI. Through ODC, KNMI data is openly shared with seismologists across the world, an advantage as data usage implicitly provides a form of quality control. Further, best practice, quality control, data management and dissemination tools are generated and deployed by ODC and have subsequently been adopted by KNMI. The seismic network at KNMI benefits from their close relationship with ODC and this should continue to be nurtured.

KNMI network management, monitoring and QC procedures:

- **improve quality control in general**: KNMI should make PSDs available routinely. They should define and implement procedures to systematically check data amplitudes and orientations that include assigning clear responsibilities and timelines. It is also important to establish procedures to manage broken and noisy stations. It appears some sensors have exhibited high noise for some time without being fixed, eg G680.HG2 or G530.HG2.
- **communication with stakeholders**: KNMI management should establish a clear set of procedures for informing the public / authorities / scientists if any modifications are made to network configuration and / or metadata. This includes providing persistent information about these changes at key websites.
- **consider enlarging the seismic network staff**: primary focus should be on increasing the size of the team managing quality control and data processing.
- **more carefully separate roles between KNMI and NAM**: it was not clear to the author what roles are shared for network maintenance between KNMI and NAM – clearly the KNMI maintenance staff is currently too small, so the KNMI role can only be limited, and mandatory tasks such as ensuring regular firmware updates for hardware or identifying, diagnosing and fixing

broken and noisy sensors are challenging to manage. Since the network maintenance itself is expected to be maintained by KNMI staff, with some outsourcing, it should be reflected how this should be managed as the network ages in the future. In their review of this document, KNMI provided the following comment in response to this point: "the Network maintenance is only done by KNMI, since the borehole stations are owned by KNMI. NAM has no role in maintenance, except that they pay for material expenses. KNMI has additional money from the ministry of Economic Affairs and Climate Policy to deal with maintenance and this task is outsourced within the KNMI at the department of operational observations. This last department is presently understaffed."

- **maximise the dynamic range of strong motions stations**: once the amplitude issues were identified, KNMI chose the appropriate technical solution that immediately corrects the metadata for the past and moving forward, by modifying the metadata. In the long run though, it is important to review whether the current settings actually maximise the dynamic range in the field. This will require KNMI to decide a standard peak acceleration across the network (2g is likely appropriate), and work with the manufacturer to ensure the strong motion accelerometer voltage output uses the full range of the digitizer input (most likely not currently the case for the Granite datalogger, so affecting a large number of G0 sensors). This will require site visits to most stations to change hardware settings (ie the jumpers on the internal EpiSensor boards).

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Appendix A – Station Site Visits.

On Tuesday, 16 April, KNMI facilitated site visits to 3 stations near Groningen, on the southern edge of the network. A typical B-network site was checked, as was a standard borehole G-station (where strong motion setting was initially a factor of 2 too small) and a standard surface accelerometer only G- station (where strong motion setting was initially a factor of 2 too high). A map showing the locations of the 3 stations is below.

B Network : BFB2 (Froombosch2)

Hardware: EpiSensor + Basalt
Vault: very large Farming shed
Observations: sensor placed in corner of shed in a small room
Sensor well installed, but vault conditions are not optimal. Note this station is also described in the FUGRO report, photos therein indicate quite different conditions to those observed during this site visit.
1/ *general site selection* – the sensor is located in a large farming unit ~30m x 15m footprint, ~5m tall brick building with heavy roofing material. It is far from a free-field site, and the amplifications (and deamplifications) arising from the site would need to be taken into account in scientific study using this data.
2/ *current vault conditions* – the sensor is located in the corner of the farm building, in a small room that is now full with farming and family equipment. The sensor is protected using an upturned plastic case. One top of the sensor, inside an identical box is the digitizer, electronics and communications units, all loosely packed inside. During any sort of strong shaking, toppling of a number of items is likely, that will be recorded by the sensor and would be erroneously attributed to the earthquake itself.

Station BFB2 Photos. Left: Barn, with sensor located in corner in center of photo. Middle: view of small room, sensor is behind brick wall to left. Right: sensor located underneath the blue box for protection.

G Network: G390/1/2/3/4 (Woudbloemsloot)

Hardware: EpiSensor + Granite, plus 4 borehole geophones.
Vault: free-field
Observations: Strong motion sensor well installed in free-field site, far from busy roads. About as optimal a site as can be found in the region.

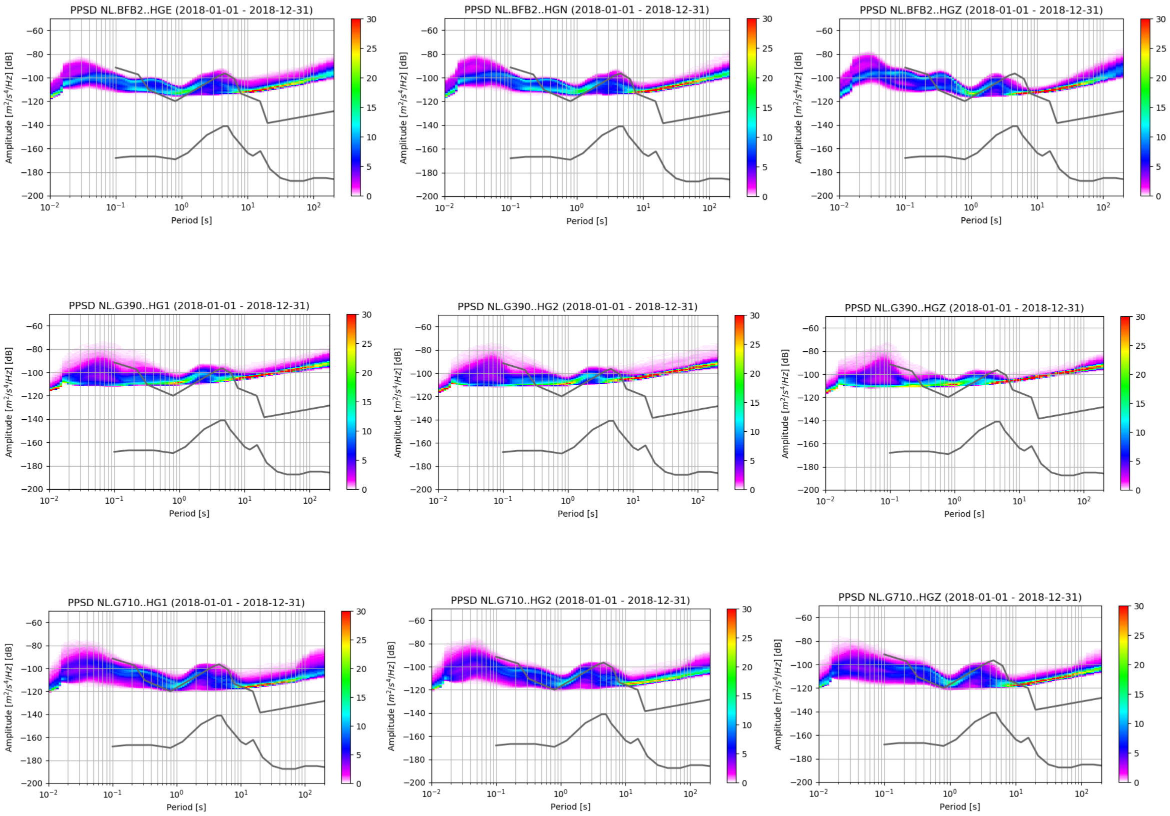
Station G39 Photos. Left: Overview of site. New VBB borehole accessory box is in foreground, G39 box in background ~30m distant. Middle: Inside G39 box, showing 14 channel Granite datalogger. Right: strong motion sensor located underneath the datalogger.

G Network : G710 (Onnen)

Hardware: EpiSensor + Obsidian
Vault: free-field
Observations: Strong motion sensor well installed in free-field site, on the side of a relatively rarely-used road.

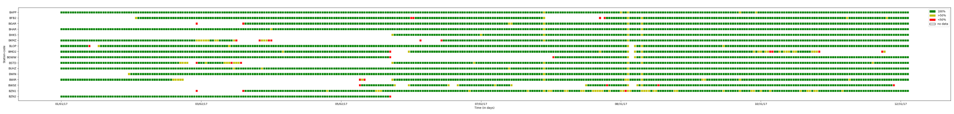
Station G710 Photos. Left: Overview of site. Right: Inside G710 box, showing 3 channel Obsidian datalogger, strong motion sensor located underneath the datalogger as at G39.

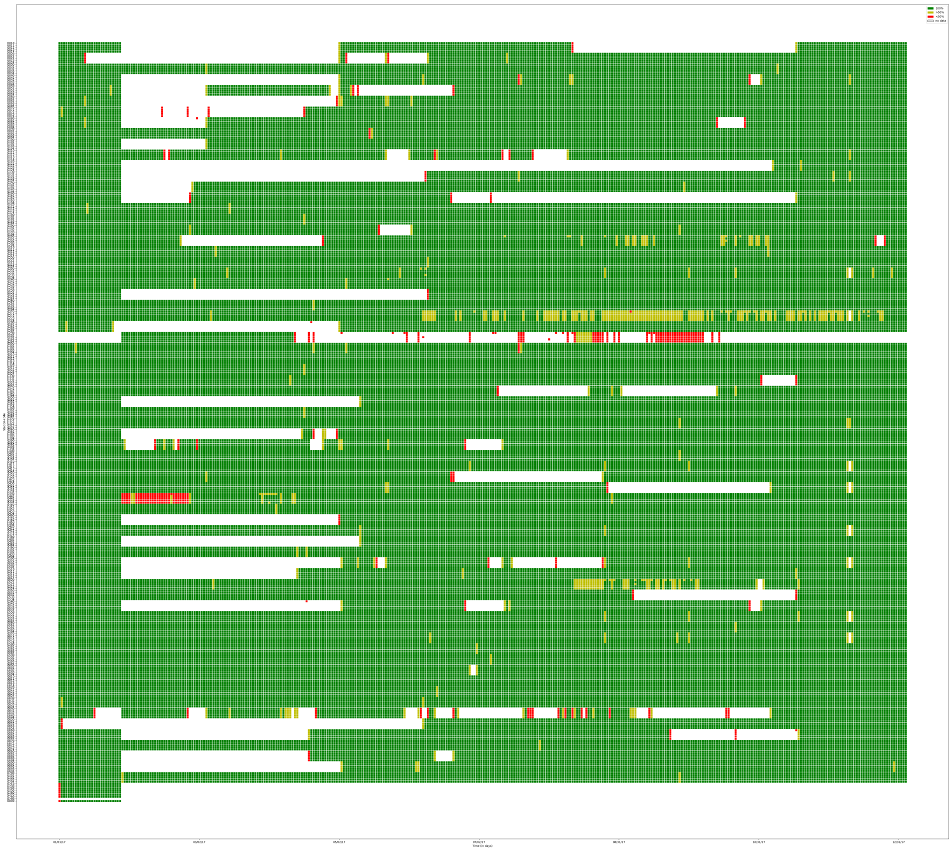
Comparison of PSDs for strong motion sensors at all 3 sites.

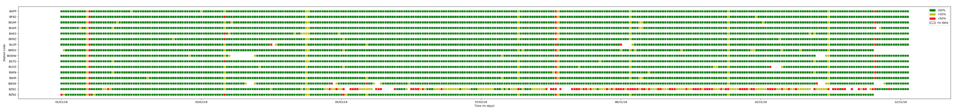


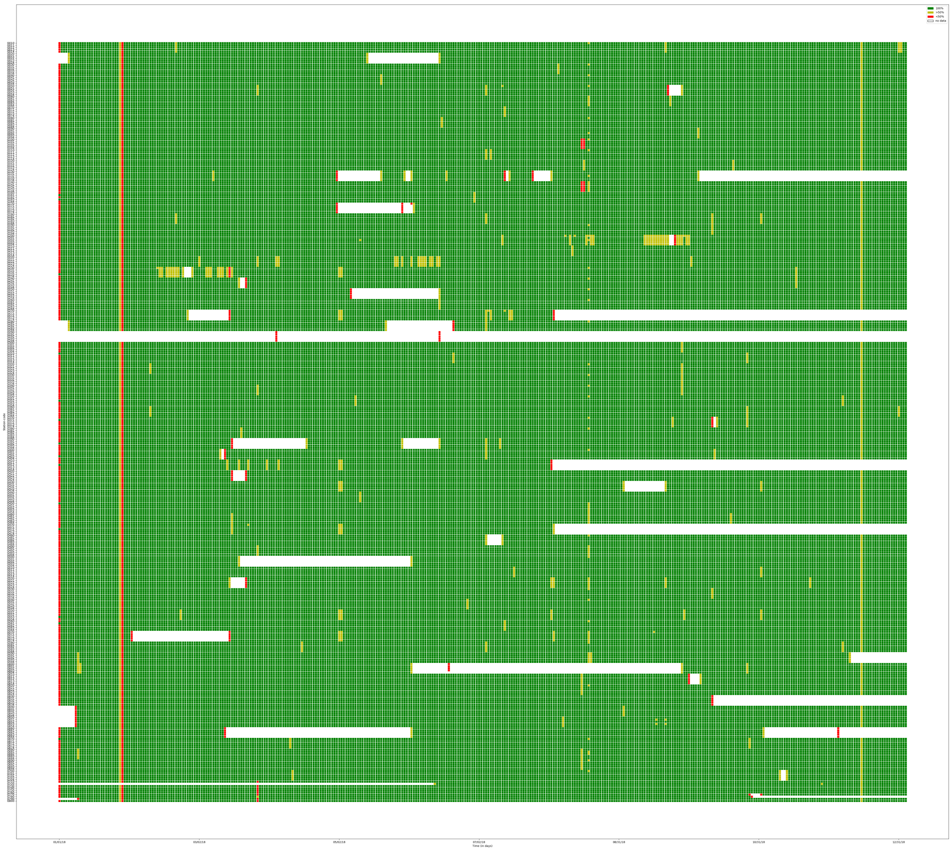
Power Spectral Density plots for 3 visited stations for entire 2018. Top: BFB2; Middle: G390; Bottom G710. Left middle and right are 1, 2 and Vertical components respectively. Note at 2s, all sensors have a similar amplitude peak, suggesting stations have similar gains. Variation at high frequency are due to differences in site quality. G390 is quietest, and is generally recording -110dB, the limitation of the 130dB datalogger recording 4g, and possible also a mismatched 5V EpiSensor output. Though the other stations have higher noise variation reflecting higher anthropogenic noise, the better quality datalogger at G710 and the optimally match hardware at GFB2 allow data to be recorded down to -120dB.

Appendix B – KNMI network completeness images from 2016-2019










BAPP
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BGAR
BHAR
BHKS
BKMZ
BLOP
BMD2
BOWW
BSTD
BUHZ
BWIN
BWIR
BWSE
BZN1
BZN2
Station-code
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>50%
<50%
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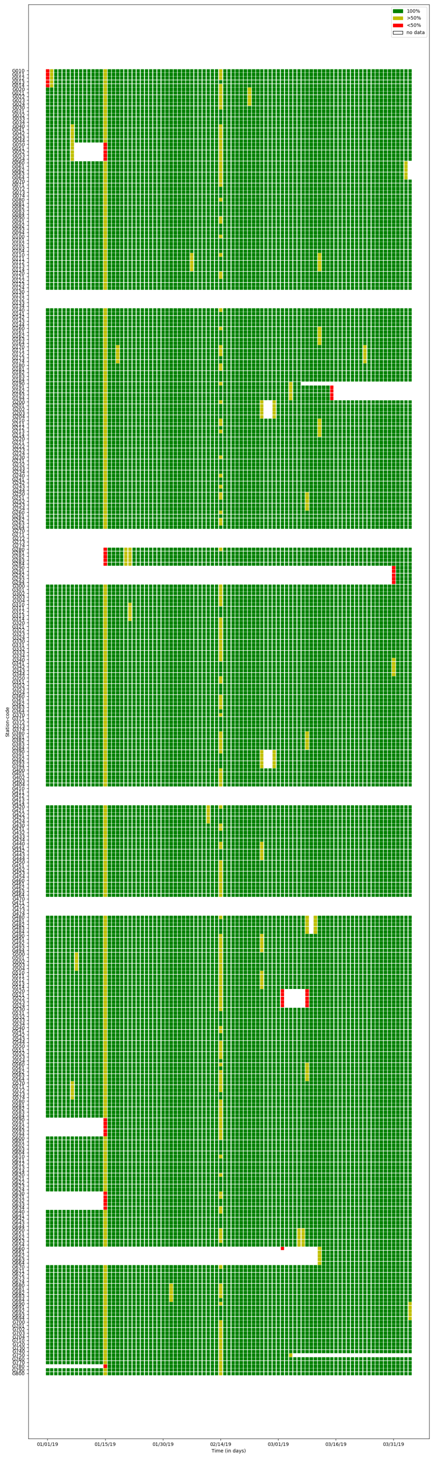
01/30/19
02/14/19
03/01/19
03/16/19
03/31/19
Time (in days)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<50%
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01/15/19
01/30/19
02/14/19
03/01/19
03/16/19
03/31/19
Time (in days)

Appendix C – Comments from KNMI and Responses

Comments on "Fact-finding mission/audit: Groningen Seismic Measurements"

This report clearly describes the findings of the recent audit on the Groningen seismic network. It is well written and clearly addresses the problems encountered in the network.

A few remarks on the text:
In the Executive summary it is mentioned at line 20 that the B station network the "ground motion amplitudes above a few Hz are lower than expected". This raises the question what this expectation was. The B-network was installed with the main aim to record strong motion information in the region in structures and was never intended to be a free field recording, although care was taken to select a small structure if this was possible. Sometimes a larger structure was selected, due to the fact that no alternative was found in the region. There was no financial possibility to construct free field sites at the time these stations were constructed.

Response by authors: The sentence in the Executive Summary is revised to better explain the observations. Further, the comment that B-network was intended to monitor the structural response is added in the introduction.

Table 1 corrections:
In 1991 station FSW was installed with 4 levels, not 5. Later a surface sensor was temporarily added
In 1995 8 boreholes were added to FSW. The boreholes lacking in this overview are VLW (Vlagtwedde) and VBG (Venebrugge)
2014-2016 densification to 4-5 km inter-station spacing
2019: there are 4 VBB borehole sensors installed and they are operational

Response by authors: Table 1 is modified, adding all these corrections

p6. "Until January 2019…" The channel naming of the horizontal channels was deliberately chosen to be HG1 and HG2, indicating that there was an uncertain orientation. So, we did not report default orientations.

Response by authors: the paragraph is amended to include the fact KNMI naming convention was correct though the azimuth / dip values were default.

p11. Network maintenance is only done by KNMI, since the borehole stations are owned by KNMI. NAM has no role in maintenance, except that they pay for material expenses. KNMI has additional money from the ministry of Economic Affairs and Climate Policy to deal with maintenance and this task is outsourced within the KNMI at the department of operational observations. This last department is presently understaffed.

Response by authors: this text is added at the appropriate place in the text.