European volcanological supersite in Iceland: a monitoring system and network for the future

Report

D5.2 - Moment tensor inversion and glacial seismometer performance

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Summary

This deliverable summarizes the results from two activities in WP5, 1) the development of new source inversion techniques and 2) the testing of initial seismic network operations inside the Vatnajökull ice cap, where four new stations were installed and operated during the project; two on rock outcrops (nunataks) and two directly in the ice itself. A key outcome from this work is the demonstration that it is viable to run a permanent network inside the glacier, successfully addressing issues associated with power generation and protection from snow accumulation and glacier movement.

Moment tensor inversion

In principle seismograms allow us to access two aspects of volcanic systems (i) seismic images of the volcano (ii) information about dynamic activity such as rock fracturing and sub-surface fluid movement. We use the seismic source to access information about the 2nd aspect. However we first require a means of describing the source. The first order moment tensor provides a complete description of equivalent body forces of a general seismic point source. Hence once we obtain a 'moment-tensor' solution for the source, we can interpret these equivalent forces in terms of the physical seismic source (e.g. the type of faulting that occurred to produce those forces). In practice reliable Moment Tensor solutions require that (i) we have 'good' azimuthal coverage of our seismic stations with respect to the seismic source (ii) the seismic wavefield has not been excessively distorted by wave propagation effects between the seismic source and the recording station.

Glacial seismometer performance

To improve monitoring capabilities of volcanoes beneath Vatnajökull ice cap, four new seismometers were installed inside the glacier during the FUTUREVOLC project. Two broadband instruments were installed on nunataks and two glacier broadband seismometers were developed and installed in the ice itself. The installations signify the first steps taken to expand the real-time, permanent seismic monitoring network, SIL into the glaciers of Iceland to improve the monitoring level of volcanic activity at the volcanoes in the glacier. The technical challenges needed to be overcome to enable permanent real-time operations, required testing and development of different technologies and setup in the natural environment, leading to new technologies for improved monitoring of glacier covered volcanoes.

1. Moment tensor inversion

In this deliverable the aim was to undertake Moment Tensor (MT) solutions on Long Period (LP) events recorded on the new glacier and other seismometers in the Vatnajökul area. Long Period (LP) events are usually shallow and hence are representative of near surface processes. Whilst the MT inversion software was developed (In MATLAB®) and delivered to the consortium in anticipation of obtaining LP events, to date no LP events have been detected and hence MT inversions for shallow events could not be achieved. However, as in principle the main aim of this part of the work in FutureVolc was to characterize seismic sources, we took the opportunity to refocus what was intended to be MT work on developing a novel approach to source inversions, using a much reduced number of seismic stations. This novel approach is not formal MT inversion but uses a combination of displacement and tilt recordings to invert for seismic events that are recorded in the near field (< c. 800m from the source) on as few as one station. This novel approach was in response to a limited set of data we were fortunate enough to acquire immediately adjacent to an active dyke during the Holuhraun eruption. As this is not LP MT inversion is it not reported here in D5.2 but rather it is reported in D6.5 'MT solutions and Modelling of Tremor'.

2. Glacial seismometer performance

2.1 Introduction

Seismic activity at volcanoes is often the first sign of volcanic unrest. Therefore the ability to detect and locate microearthquakes at volcanoes is one of the fundamental requirements for effective volcano monitoring. Two of the most active volcanoes in Iceland are located beneath the Vatnajökull ice cap, but at the onset of the FUTUREVOLC project, the detection level of the SIL seismic network to seismic activity in these and other volcanoes inside the glacier was rather poor and most of the volcanoes were undermonitored. The network's ability to locate earthquakes was mainly limited by the lack of instruments inside the ice cap. Therefore to improve the seismic monitoring of volcanoes in Vatnajökull, one of the objects of WP5 was to install new, permanent stations within the ice cap.

Two broadband seismic stations were installed on rock outcrops in Vatnajökull. However, only a few rock outcrops (nunataks) are accessible inside the ice cap, requiring permanent stations also to be built on the ice, where the seismic sensors were inserted directly into the ice itself. The SME partner, Güralp Systems Ltd, developed new seismometers that could be deployed directly on glaciers. Critical issues for consideration were: (i) instrument tilt, due to local melting (ii) instrument translation due to glacier movement (iii) an accurate time stamp, even if the GPS time receiver would be covered by snow for periods of time, (iv) low power consumption (v) instrument noise. The development of the new instrument represented a significant but tractable technical challenge, as did the developments needed in the station construction and location in order to ensure high up-time and real-time data access.

The nunatak stations were built and instrumented by IMO technicians during the first year, in summer 2013 and preparations for the glacier sites began in early 2014. Technical development of the glacial seismometers was delayed, but prototype versions were installed during winter 2014/2015. Final versions of the instruments were ready in early 2016 and one site was revived in February 2016, while the other site will be instrumented in spring.

2.2 Seismic stations on nunataks

Prior to FUTUREVOLC, two seismic stations had already been built on nunataks in Vatnajökull ice cap. The first one (*grf*) was installed in May 2001 at mount Grímsfjall on the caldera rim of Grímsvötn volcano, where the station is part of the multidisciplinary observatory at Grimsfjall. The station gets considerable support from the infrastructure at the observatory in terms of access to power and auxiliary facilities, making maintenance during the winter months and in harsh weather conditions significantly easier.

The second station (*vot*) was installed in June 2010 on the isolated nunatak Vöttur, 20 km south of Grímsvötn volcano (see Figure 1) to investigate the feasibility of running such a station on a permanent, yearly basis. The stations power system consists of (4 x 90W) solar panels and a backup battery bank, with transmission strength to communicate over a 50 km radio link to Skeiðarársandur south of the glacier. From this experiment, considerable knowledge about station operations inside the glacier was gained and with some modifications the station could be run quite reliably as a permanent station all year round. Because of its limited infrastructure, however maintenance is more difficult than at Grímsfjall.

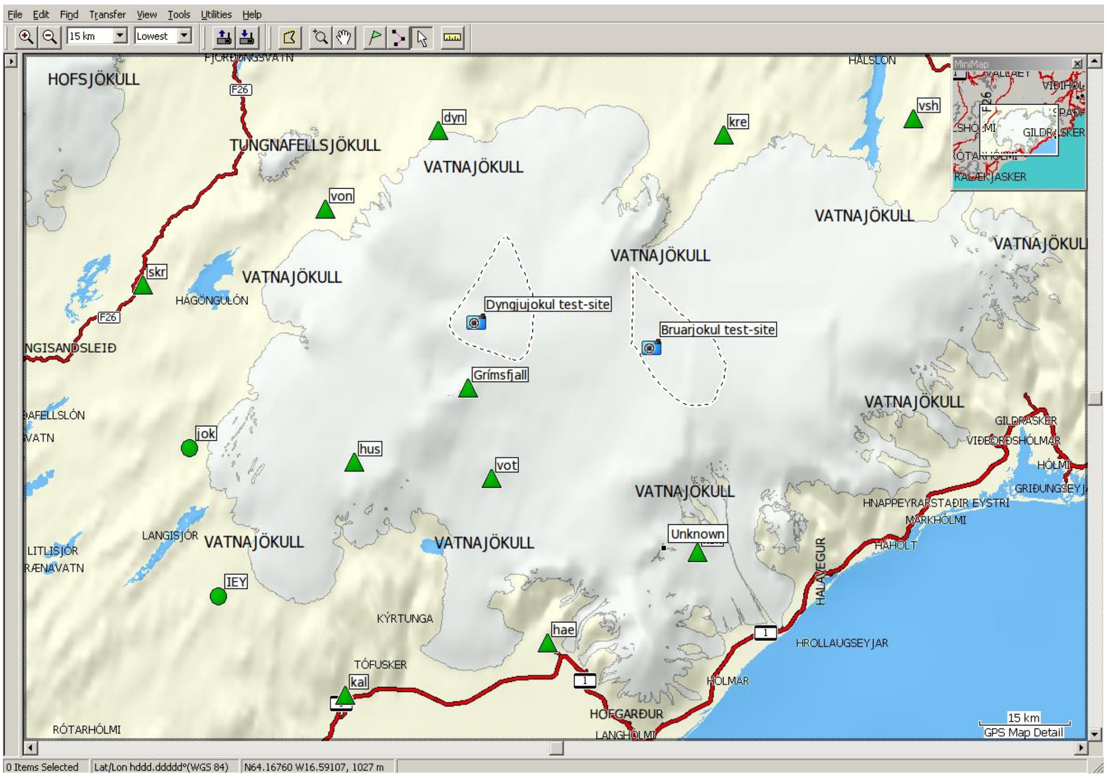

Figure 1. Map of Vatnajökull ice cap showing the locations of stations in the SIL permanent seismic network (triangles), including the FUTUREVOLC nunatak stations, hus and ksk (marked as 'unknown' on map). Locations of major volcanoes are shown with stars. The two regions for possible locations of the glacier sites are shown (dashed) and the location of the test sites within are shown with blue squares (djk on left; bjk on right).

The design of the infrastructure at the *vot* station set the standard for station installation on nunataks, and the two FUTUREVOLC nunatak stations in Vatnajökull where installed following this standard.

***hus* and *ksk* seismic stations**

The two nunatak stations installed under FUTUREVOLC were located at the outcrops Húsbóndi (*hus*) 30 km SW of Grímsvötn volcano and Kárasker (*ksk*) 40 km E of Grímsvötn. Both stations where installed in June 2013, with Nanometrics Trillium Compact (20 s) sensors and Centaur digitizers. A robust steel bracket was designed to hold solar panels, batteries and communication equipment. The 1-m-high bracket is bolted to the bare rock, and the battery bank and electronic equipment is installed in an aluminum box (see Figure 2), while the seismic sensor is installed in a small vault several meters away; covered by rocks at *hus*, but at *ksk*, in a shallow borehole and covered with sand to improve local noise conditions (see Figure 3).

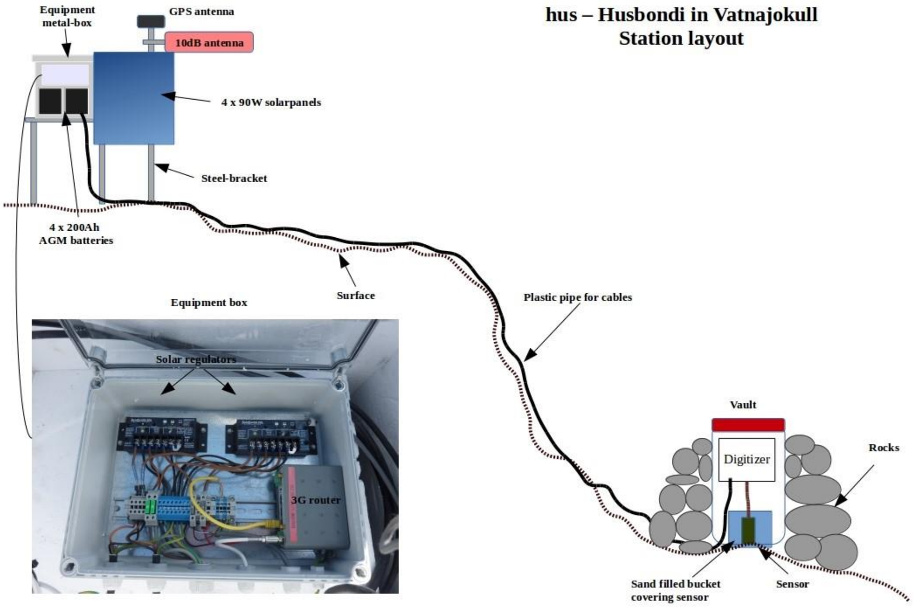

Figure 2. The layout of the setup at seismic station hus, showing: (Upper left) The raised bracket with the vertically mounted 360W solar panels, GPS and communication antenna on steel pipes mounted on the frame. The bracket carry the electronic equipment and batteries to power the station during the darkest winter months, when solar energy production is none. To prevent build-up of icing on the GPS and transmission antennae, no wire stakes are used to stabilize them. (Lower left) Inside the equipment box, showing the 3G router and regulators for the solar panels. (Lower right) The small vault containing the seismometer and digitizer.

Figure 3. Photo of the setup at station ksk. In the foreground are the solar panels mounted on the frame carrying the batteries and electronic equipment. The frame is raised to protect the equipment from surface melt water. A brown plastic cylinder covers

the transmitting antenna to protect it from icing. The brown top of the small plastic vault housing the seismometer and digitizer is seen in the background above the snowmobile.

The nunatak stations in Vatnajökull have been performing very well, with minor adjustments made to ensure continued operation and lower background noise at the sites. The battery backup at *hus* was enlarged to 800 Ah, as ice covers the solar panels for a longer period than at *ksk*. Communication has been stable at both sites. *hus* encountered a digitizer failure in summer 2015, which cannot be linked to the site location although cold temperatures or humidity cannot be ruled out, and *ksk* failed in November 2015 for an unknown reason at the time of writing. Overall, the two nunatak stations have been quite reliable, and could be a part of the permanent seismic monitoring network for years to come.

2.3 Seismic stations in the ice

In the past, seismic stations have been installed in the ice only for short periods of time, usually in summer, and storing the data locally. Over time, however the sensor starts to tilt due to local melting and most sensors are developed only for few degrees of tilt. The local data storage is required because communication is not available everywhere on the glacier and installing communication requires considerable effort. Snow accumulation inside the ice cap can be up to 6 m in certain locations and melting during summer can also amount to a few meters, resulting in a mass balance of up to 2 meters. To function as volcano monitoring stations, the two FUTUREVOLC glacier stations where planned as permanent installations, streaming data in near real-time for immediate analysis at IMO. This demanded significant in-depth planning and preparation.

<u>Installation and operation of test sites inside the Vatnajokull ice cap</u>

The challenge of running permanent year-round seismic stations, streaming data in real-time had not been tried before in Vatnajokull. Such operations on the moving and ever changing ice were different from the ones on nunataks, where the installations were on firm bedrock and stood out from the snow. Therefore these new installations required new solutions to be developed.

First, the site locations needed to be selected. They were based on the four following criteria:

1. To increase the sensitivity of the existing seismic network to seismic activity at the volcanoes in Vatnajökull and thus improve volcano monitoring of subglacial eruptions and subglacial floods (jökulhlaups).
2. Near an ice-divide to minimize lateral travel
3. In a location where a mobile network was readily available for communication.
4. In a location with relatively low snow accumulation.

Seismologists from the Icelandic Met. Office selected areas fulfilling the first two criteria and after discussions with glaciological experts from the University of Iceland two possible areas were identified, where all three conditions were met (see Figure 1).

Because of heavy snow accumulation on the glacier, solar panels would not be effective for power generation, and therefore an attempt would be made to use wind generators. They are however sensitive to icing and heavy winds and required testing prior to the final installations, in order to investigate whether operation of a year-round permanent station with wind-generators would be possible inside the ice cap. The worst storms usually hit the glacier in January and February, requiring the test infrastructure to be installed in the middle of winter, in time for the really bad weather. The two test-sites were selected, one at Brúarjökull (*bjk*) the other at Dyngjujökull (*djk*), and the sites implemented in late January 2014. The tests ran for the following few months. The test site at Dyngjujökull is shown on Figure 4.

At each test site, two 3-inch steel water pipes were placed in the ice, about 6 meters apart. They were installed in 2-meter-deep holes, drilled into the ice with a core-sample ice drill. The wind generator for the power production was installed on one pole, and the communication antenna, solar-panel and a web camera on the other (see Figure 4). The use of thick metal pipes, with no wire stakes minimized the accumulation of icing on the poles and attached equipment. The web camera was installed to a) test the communication link, b) monitor the wind generator and c) investigate how much load could be driven by one wind generator. Between the poles, a metal equipment box was installed just under the ice surface. The box had one 200 Ah battery, a 3G router and regulators for the solar panel and wind generator. Two types of wind generators were used; an Ampair 100 (http://www.ampair.com/wind-turbines/ampair-100) at the Brúarjökull site and an Icelandic made generator at the Dyngjujökull site. A third type, British made Aero-4F-Gen (no longer being manufactured) was installed on the same trip, to power GNSS receivers in the Eastern Skaftár-cauldron; a subglacial geothermal area just west of Grímsvötn volcano. Thus three different types of wind generators were put to the test.

Figure 4. Photo showing the installations of the test infrastructure at the Dyngjujökull test-site in January 2014. The wind generator is mounted on a steel pipe without guy-wires, to minimize icing problems. The solar panel, web camera and communication antenna are a similar pipe 6 meters away. Between them a metal box carrying the electronic equipment is buried just under the snow.

The tests went remarkably well, both sites where more or less in mobile contact the whole winter, and only lost power on few occasions during the test period. There were times, however, when the wind generators simply iced up and stopped producing power, but the ice broke off again and the generator started working. During the iced-up periods the batteries quickly discharged (see Figure 5). The load from the camera and 3G router was about 18W, considerably more load than from the operation of a seismic station, and battery backup was only 200 Ah at each site. A seismic stations uses about 5W, therefore by using larger battery backup, the iced-up periods could easily be covered.

There were also times when connection to the 3G routers was lost, more often at Brúarjökull than at Dyngjujökull. The cause for these communication failures have not been investigated thoroughly, but could be due to icing, or even problems with the base-stations of mobile network itself.

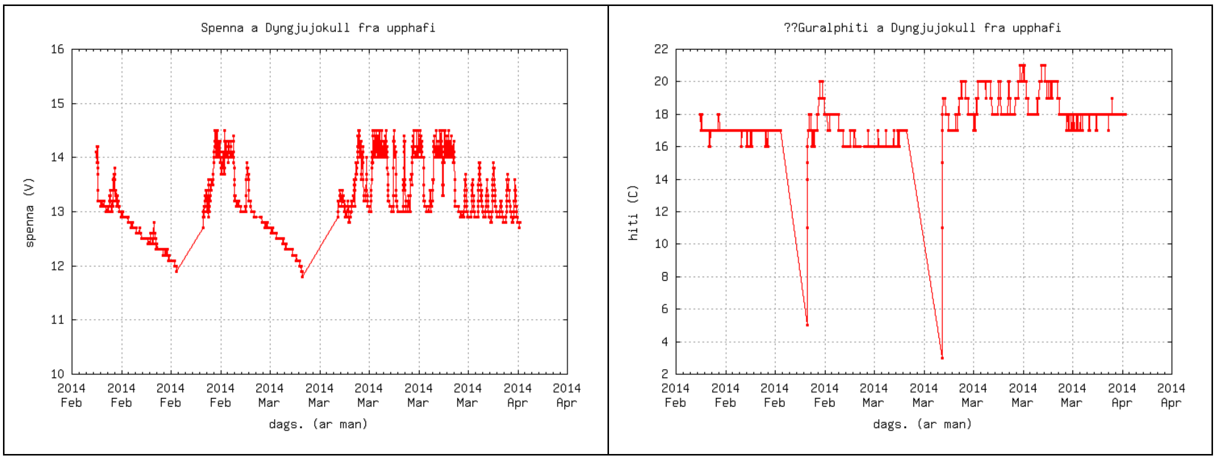

Figure 5. The Battery charge with time during the testing period (Left) and Temperature in the metal box (Right) at the test site on Dyngjujökull.

bjk **and** ***djk*** **seismic stations**

There was a significant delay in delivery of the glacier seismometers, and with the two test sites being close to being fully operationally ready at the onset of the unrest at Bárðabunga volcano in August 2014, it was decided to install temporary instruments at the sites, *djk* and *bjk*. For that purpose, two Güralp 6TD instruments where loaned by the FUTUREVOLC partners from Cambridge University. The 6TD instruments are designed for stable environments, with no tilt so the instruments quickly began to show problems. They did however work until October and they delivered invaluable data during the beginning of the unrest episode and eruption in Holuhraun.

The glacier station vaults

To make the glacier sites more resilient and to enable servicing them during winter if required, special vaults were designed for installation. To meet the winter conditions and snow accumulation at the sites, of the order of 2 - 6 meters, the vaults, which were made from pre-fabricated, double-sided plastic septic tanks were made to be 4 meters deep, bottomless and with a manhole at the end sticking out of the ice. The tanks were to be placed (upside down) in the ice, buried down about 1,5 – 2 meters. The equipment was to be mounted on the insides of the vault and the sensor installed into the ice at the bottom (see Figure 6).

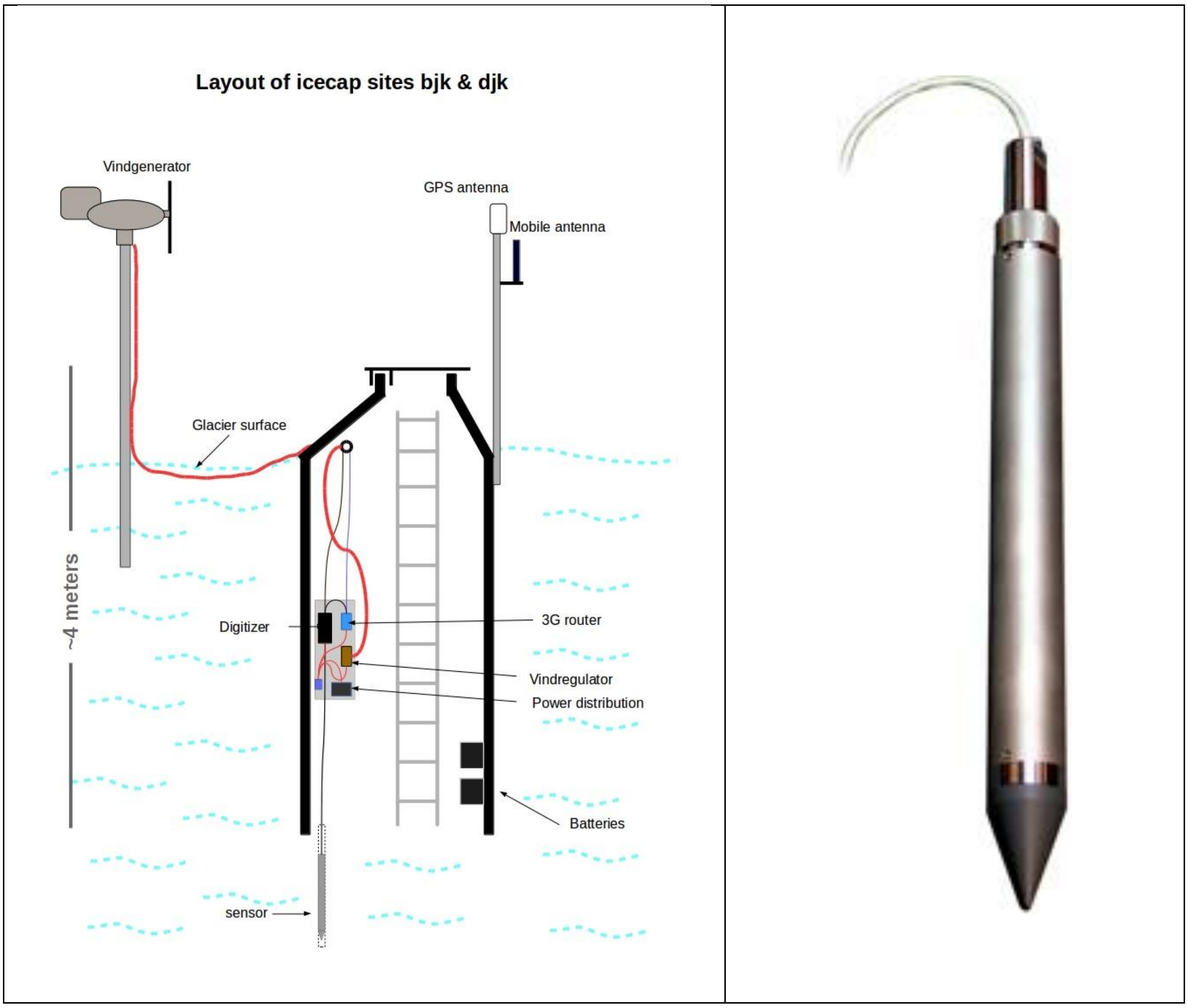

Figure 6. (Left) A schematic figure of the layout at the two glacier sites, bjk and djk. The vault is 4 m deep and buried into the ice. The equipment is mounted on the inside of the vault and the seismometers is placed in the ice below. (Right) The Güralp "flute" seismometer.

Due to the snow accumulation at the glacier sites, the tank has to be lifted at least twice a year, by ~2 meters up and out of the snow, to prevent it from being totally lost into the glacier. A hot-steam ice drill can be used to heat up the inside of the double-layered plastic tank, until it loosens from the ice. Two farm jacks can then be used to lift the tank. The same goes for the steel-pipes holding the wind generator and the antennae; the hot-steam ice drill can be used to warm up the steel-pipe from the inside so the pipe can be lifted out of the snow. New wires are then installed. The seismometer will also need to be raised at regular, but longer intervals. The hot-steam drill can be put around the cable at the top to melt the ice around it, enabling the raising of the instrument. The cable may have to be replaced after such maneuvers.

In October 2014 the new vault was installed at the *djk* site and the infrastructure, except for the seismometers installed. At the same time necessary supplies were transported to *bjk*. In November same year Güralp Systems delivered prototypes of the glacier seismometers, one of which was quickly installed at the *djk* site. Because of the increasing activities related to the Holuhraun eruption, however, and very bad winter weather, the *bjk* site was not installed until January 2015.

The new *bjk* stations operational for a few months, until the seismometer failed, while the new *djk* station remained operational until early October 2015. In the end only the vertical component was working, but the station managed to capture the first few days of the long-awaited subglacial flood (jökulhlaup) draining from the Eastern Skaftár cauldron.

After both glacier instruments had failed, they were sent back to Güralp for repair and upgrade to the initially planned design. Upgraded instruments were returned in January 2016 and one of them installed at the *djk* the following month. The *bjk* site will be instrumented in spring.

At the time of writing the sites are going through their second winter. The winter of 2014/2015 was a very stormy with heavy snow accumulation. Such that when the *djk* station infrastructure that was installed in October 2014 it stood approximately 2 meters out of the snow, but was 3 meters under the snow in June 2015. The spring and summer where cold so that in August 2015 the vault was still under 2 meters of snow. At that time, both stations where dug out of the snow and lifted. Both stations had the same treatment in January/February 2016.

The glacier seismometer design

Güralp Systems Ltd. had the task of delivering seismic equipment for the experiment, for which they planned to use their 30 s "Flute" borehole-instrument along with a low power CD24 digitizer.

The design included the instrument being housed in a 'flute' casing (see Figure 6). Instrument tilt would be addressed using a tilt correction mass-centering motor. The sensor would continuously monitors its position and make a correction when a pre-defined threshold was exceeded. In addition, mass positions would be stored on the instrument for offline, post processing and analysis. The instruments were to be tested in simulated conditions, in Güralp's labs, prior to installation.

In the event of loss of a GPS signal and absence of GPS time, an accurate time stamp depends on an accurate 'internal' clock. Clock accuracy is largely controlled by temperature fluctuations. Prior to installation the temperature sensitivity of the real time clock would be determined. Temperature would then be monitored at the instrument in the field and a lookup table used to correct time for drift.

Power consumption of the initial prototype version of the flute seismometer was 0.5W. Plans were to reduce the consumption to 0.1W by employing technology from Güralp's low power Ocean Bottom System. Digitizers, clock and GPS were expected to add a further 0.7W.

Initial tests indicated that instrument self-noise was be below the USGS New Low Noise Model (Peterson 1993) from ~10 s to 8 Hz (see Figure 7). The initial prototype glacier instruments did not contain the electronics required to monitor orientation and tilt. With the final version of the instruments being just recently delivered, their performance testing, except that of the manufacturer, has been limited. Assuming the new instruments will continue to operate for considerable time, testing will continue. Loss of GPS signal has not been a major problem, so the clock accuracy has not been put to the test.

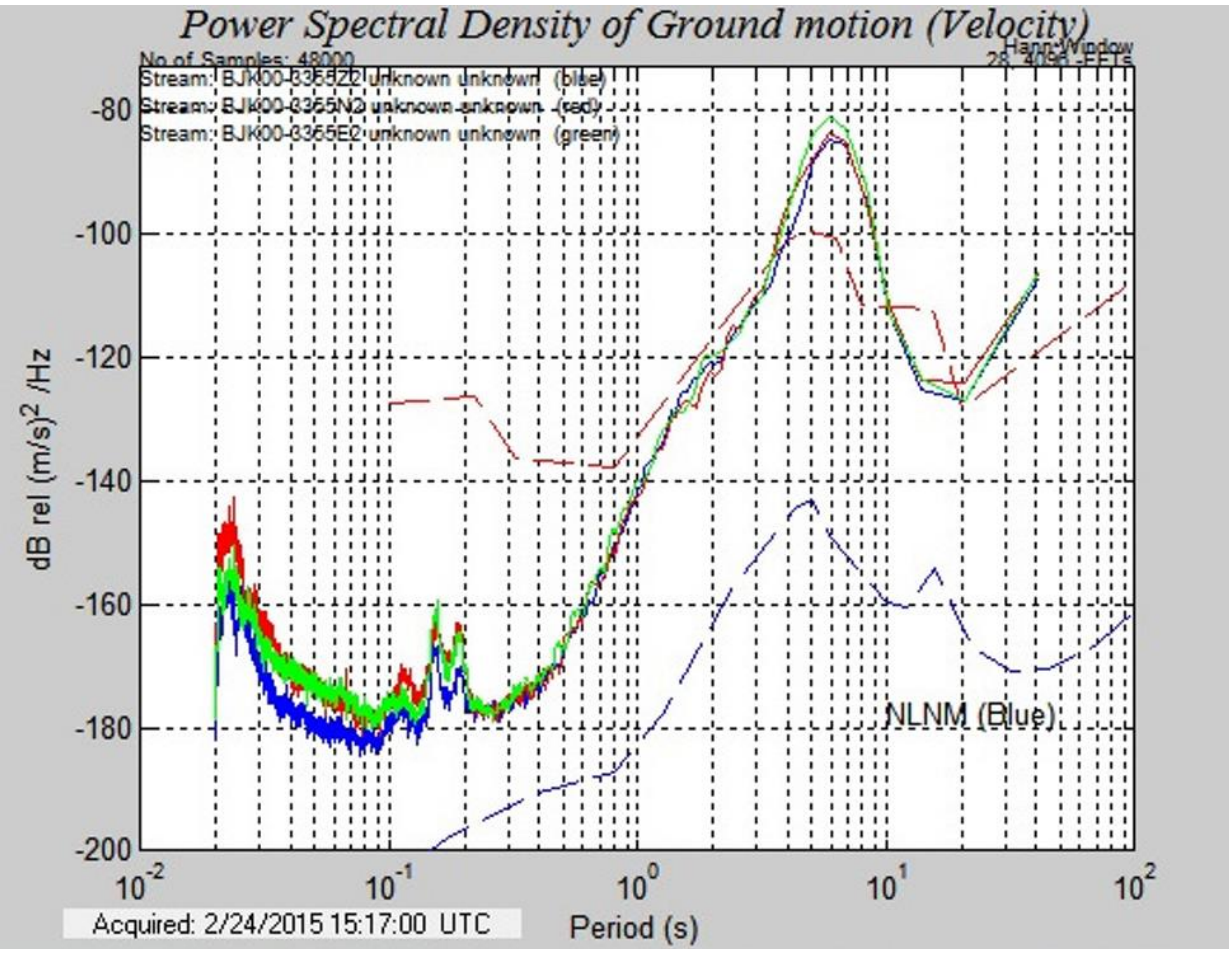

Figure 7. Noise test at Glacier Seismometer station bjk. The instrument self-noise was below the USGS New Low Noise Model (Peterson 1993) from ~10 s to 8 Hz (see Figure 1 for station location)

2.4 Conclusions

The two FUTUREVOLC nunatak stations have had a fairly reliable operation. However one digitizer (at *hus*) failed after 2 years of operation and the other station (at *ksk*) functioned without problems for 30 months.

So far most of the problems have been with the Güralp seismic equipment. The sensors have been quite unstable and as these where only prototypes, full functionality was missing, thus preventing remote troubleshooting. In January 2016 Güralp sent the final version of the digitizer and a unit holding a magnetometer and tilt meter that fits in-line with the sensor and reports the bearing and tilt of the sensor, as well as the temperature. This information has been very valuable for determining what is causing problems at the site, whether it is tilt or temperature, or something else? Since installation in February 2016, cold seems to be the biggest problem at *djk*. As the sensor is installed in ice close to the surface, the temperature of the instrument has been as low as -16° C. Even though the instrument is rated for -20° C the cold seems to have a disturbing effect on the self-noise of the sensor. In late February the sensor was installed in a layer of sand, as an attempt to isolate it a bit better. Further experiments will be ongoing, and advice sought from Güralp Systems. Communication and power generation has been going very well. A few occasions of bad communication to *bjk* have occurred, but *djk* has been in very good connection. Lack of power has never been a problem, the wind generator and 400 Ah of backup batteries have proven to be sufficient to keep the stations running.

Assuming that problems with the glacier sensors will be solved, we have demonstrated through this FUTUREVOLC work that permanent online stations can be run successfully in the glacier on a yearly basis. At least two visits are needed every year to lift the instrumentation out of the snow, and experience is being acquired regarding the best methods to do the lifting. On a calm winter’s day with a two person team, only 5 – 6 hours per person are needed at each site to complete the job.