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

Report

[D5.3 – Volcanic gas and river water chemistry]

Work Package:	*Long term magma tracking*
Work Package number:	*5*
Deliverable:	*Volcanic gas and river water chemistry*
Deliverable number:	*5.3*
Type of Activity:	*RTD*
Responsible activity leader:	*Andy Hooper*
Responsible participant:	*University of Leeds*
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Type of Deliverable:	*Report [X]* *Prototype [ ]*	*Demonstrator [ ]* *Other [ ]*
Dissemination level:	*Public [X]* *Prog. Participants (FP7) [ ]*	*Restricted Designated Group [ ]* *Confidential (consortium) [ ]*

Seventh Framework Programme
EC project number: 308377

Abstract

Task 5.10, *Monitoring gas emissions of volcano volatiles*, aimed at the assembling and field deployment of a permanent gas monitoring system at Hekla volcano. The system includes two scanning UV spectrometers for remote SO_2 flux measurements and a permanent MultiGAS instrument to measure in-plume carbon and sulphur species. The data from all of the instruments is telemetered to IMO. Prior to the field deployment, both types of instruments were adapted to work in the high latitude environment. Chalmers has lead the task as well as developed and installed the scanning UV instruments, UNIPA/INGV has developed and installed the MultiGAS instrument while IMO has worked with field deployment and maintenance. All three partners have worked with data evaluation, training and implementation in the central database.

Task 5.11, *Measurements of volatiles dissolved in river water*, aimed at continuous measurements of water pH and volatiles (sulfur halogens and carbon) dissolved in river waters sourced from Hekla and Katla volcanic systems. The measurements are performed by an automated system of pneumatic and spectroscopic sensors. The system has been added to an existing real-time hydrological monitoring system, which measures water temperature, conductivity and optical light absorbance. The instrument was developed by INGV-Palermo who continue to provide technical support and instrumental advice and supported by collaboration with BGS. Data from these instruments can be telemetered to the IMO. IMO has lead this task.

Contents

1 Introduction

The objective of task 5.10 is to search for precursory gas release accompanying magma ascent towards the surface. To search for and monitor such gas release at Hekla volcano, the task focusses on adapting existing gas observation instruments to use in the high-latitude conditions of Iceland. The instruments will then be permanently installed at Hekla volcano, and data will be automatically telemetered to IMO. The instruments in question are scanning UV-instruments for remote SO_2 flux measurements (DOAS) developed by Chalmers University and a MultiGas instrument for in-plume CO_2, H_2S, SO_2, and H_2O measurements developed by University of Palermo/INGV.

Volatiles released from ascending magma can become partially entrained in groundwater, some of which ends up in river systems. Task 5.11 is concerned with observations of changes in the volatile content of river water sourced from volcanic areas as a means for monitoring subsurface magma movements. Activities involve development and installation of an instrument for automatically measuring the concentration of CO_2 dissolved in groundwater, as well as water- and air temperature and conductivity.

2 Permanent gas monitoring installations at Hekla

2.1 Multi-GAS instrument

This section outlines the main improvements made to the MultiGAS (Multi-component Gas Analyzer System) instrument developed by UNIPA/INGV for use on Hekla.

The MultiGAS instrument

The MultiGAS instrument was developed by UNIPA/INGV and delivered to IMO in May 2013 where it was modified for the use on Hekla Volcano. This fully-automated instrument measures (at 0.1 Hz rate) the concentrations of major volcanic gas species (H_2O, CO_2, SO_2, H_2S,) in a volcanic gas plume, and integrates (i) an infrared spectrometer for CO_2 (Gascard II, calibration range 0 – 100000 ppmv; accuracy ±2%, resolution, 0.8 ppmv); (ii) three specific electrochemical sensors for measurement of SO_2 (CityTechnology, sensor type 3ST/F, calibration range, 0 - 50 ppmv, accuracy, ±5%, resolution, 0.1 ppmv) and H_2S (CityTechnology, sensor type 2E, calibration range, 0 – 50 ppmv, accuracy, ±5%, resolution, 0.1 ppmv); and (iii) temperature, pressure and relative humidity (Galltec sensor, measuring range, 0 – 100 % Rh, accuracy, ±2%) sensors for calculation of H_2O concentrations.

Installation site

Figure 1: MultiGAS installation, Summer of 2012

During a study of the degassing regime of Hekla Volcano in 2012 (Ilinskaya. et.al) the location with the highest emission fluxes was identified on the 1980 caldera rim at the summit of the volcano at 1490 meters. It was chosen for a temporary setup of a MultiGAS instrument (Figure 1) gathering data every 6 hours for 30 minutes. This data, collected July – September, showed that the summit of Hekla was a suitable site for MultiGAS monitoring. The high altitude and latitude of the site leads to technical challenges in installing and maintaining the station.

Installation

Figure 2: The hut after installation

The MultiGAS station on Hekla is, in principle, the same as the stations UNIPA/INGV use on Mt. Etna. Mt. Etna and Hekla share a similar climate during winter with heavy icing conditions due to fumarole steam, cold temperatures and very strong winds. This makes it very challenging to maintain a station there all year round. The main difficulty is in generating power during winter time. In late August of 2012, the temporary installation of the MultiGAS stopped working due to the wind generator falling over from icing and the inlet to the instrument got blocked by ice. It was then clear that an appropriate structure to house the instrument and keep it powered had to be developed. The solution was a small hut with a solar panel on its roof (Figure 2). The hut was built so that it could be dismantled and transported via snow scooters to the summit of Hekla, but it was instead airlifted by the aid of the Icelandic coastguard helicopter on the 20th of May 2013.

Power and environmental problems

The instrument was installed on April 10th 2013 and has mostly operated since, with power outages during the darkest winter months of January and February. The station was initially set to gather data every six hours. Data from the station was first collected manually by connecting to the station but since June 2014 an automatic software collects the data and inserts it into a database.

A recurrent problem is when the relative humidity goes above 100%. The cause of this is when the hot gas plume condenses inside the instrument. To avoid this condensation, we try to minimize the temperature difference between the instrument and the plume by the heating the instrument via a longer warmup time and a heat coil. These methods have reduced the humidity problem but it persists. Running the station more frequently, to dry the station out after condensation has entered the system, is also effective, but consumes too much power. Another approach is necessary to solve the problem, and we continue working on this.

Thick icing can occur in winter, which blocks the solar panel from charging and then the batteries drain (Figure 3). The station can be maintained by a visit, bringing fresh batteries or charging them with a generator. In March 2015 the station was restarted and a new solar panel strategy was implemented. The solar panel that was initially installed (Figure 2 and 3) broke from the heavy icing. Two new flexible and larger panels were installed (Figure 4). The Battery bank has also been increased to 720 Ah (started with 480Ah) to extend the time the station can stay alive without charging.

The new panels were also chosen as they do not contain any metal surface and they are only 3mm thick, making them less likely to get iced up. As the hut is always warm from the heat of the emissions, these panels are more likely to melt the ice at an earlier stage than the previous panel did. The newer panels are also stronger and will withstand much heavier icing without breaking.

Figure 3: Icing after 3 days in spring conditions

Figure 4: The Hekla hut after its 2015 maintenance visit.

Data processing and evaluation.

Data has been gathered every six hours for the past two and a half years with periods of down time. The raw, unprocessed data is stored in an online database. The data is then processed manually on a regular basis. Since installation, the calculated gas ratios have stayed relatively constant, with a large variance, dominated by CO_2 with little sulfur (Figure 5 and 6). Typical, high CO_2 concentrations are around 40000 ppm. This has a very high variance, influenced greatly by the winds.

Quantitative models of gas-water-rock interactions (Ilyinskaya et al) demonstrate that these CO_2-rich (and S-poor) compositions measured at Hekla are justified by high levels of scrubbing of magmatic volatiles into the volcano's groundwater system. This observation implies limited (but still detectable) transfer of magmatic volatiles inside Hekla volcano, during its current decadal-long dormancy period.

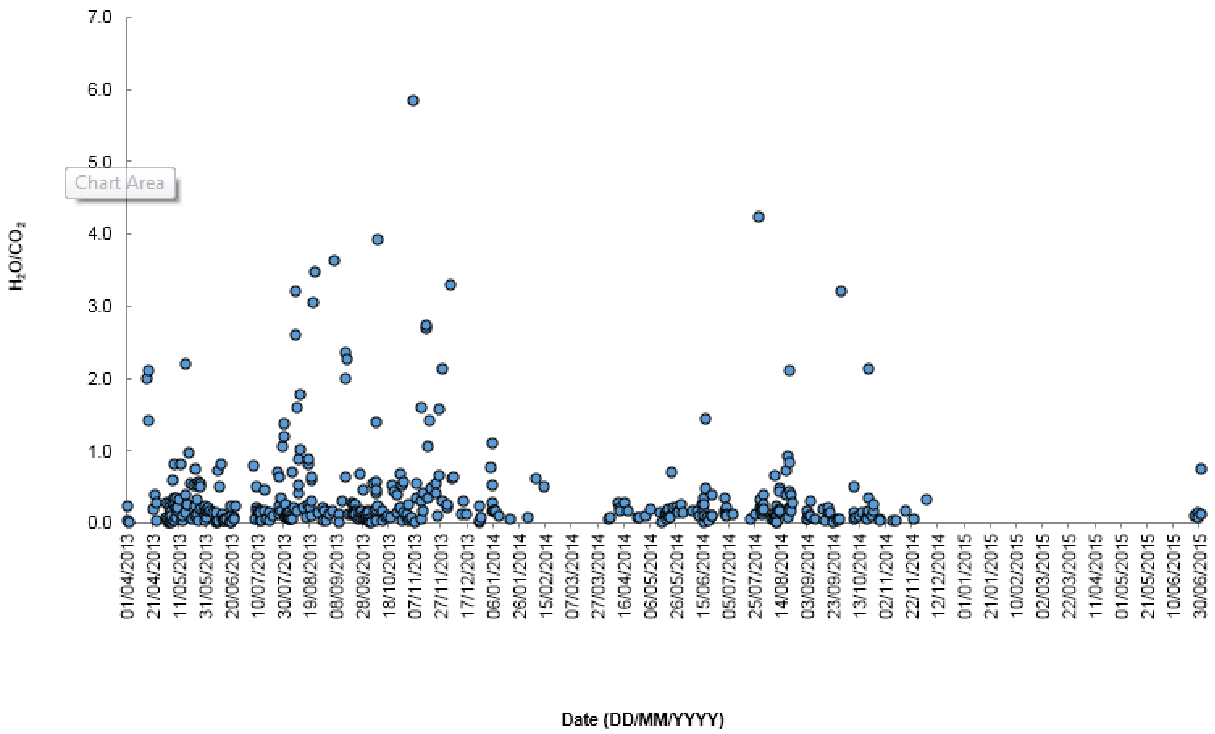

Figure 5: Hekla MultiGAS H_2O/CO_2 ratios

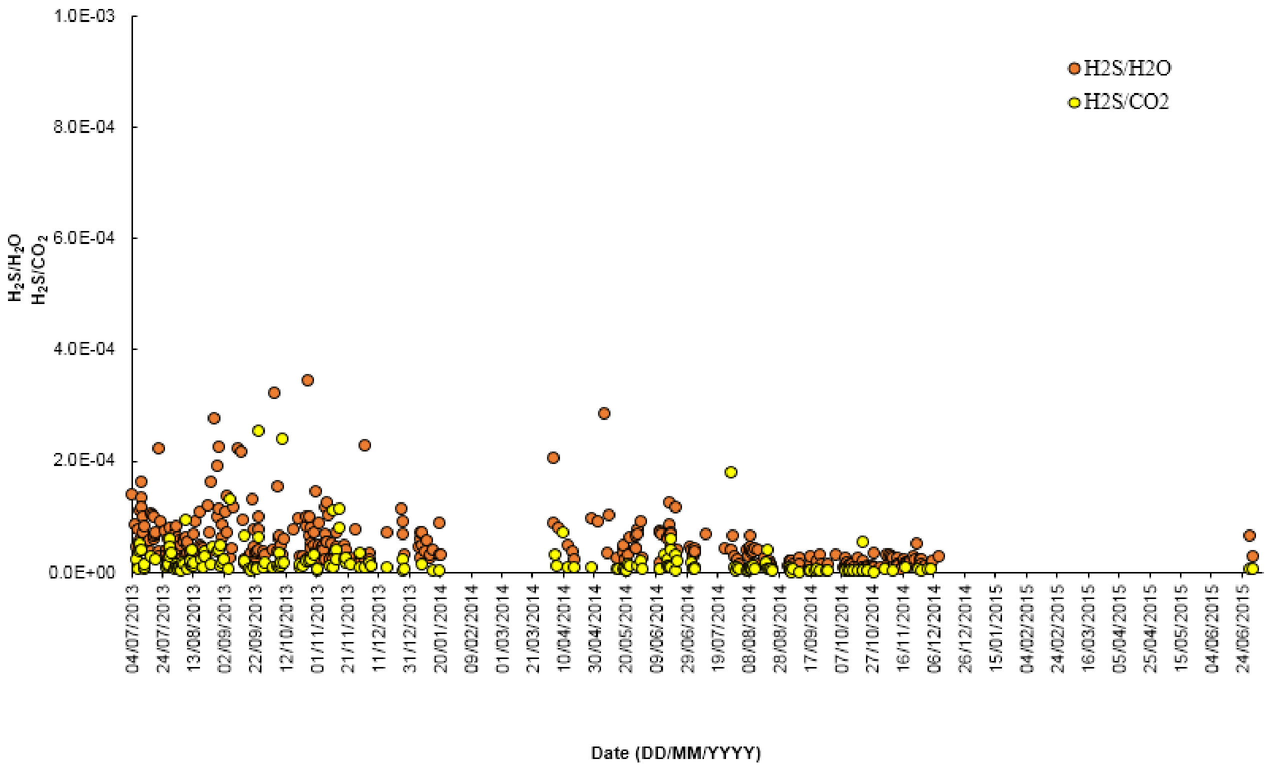

Figure 6: Hekla MultiGAS H_2S/H_2O and H_2S/CO_2 ratios

2.2 Scanning mini-DOAS instruments

This section describes the modifications made on the NOVAC Scanning DOAS instruments to make them better suited for high latitude conditions, and the stationary installation of two of these instruments on Hekla volcano. Two modes of operation are facilitated; normal flux measurements providing emission estimates with 5 minutes time resolution and fast sensitive slant column measurements indicating the onset of gas emission without quantifying the emission rate (Section 2.3).

The standard NOVAC version I Scanning DOAS instrument

The basic mini-DOAS system consists of a pointing telescope fiber-coupled to a spectrograph. Ultraviolet light from the Sun, scattered from aerosols and molecules in the atmosphere, is collected by means of a telescope. Light is transferred from the telescope to the spectrometer using an optical quartz fiber. The spectra are analyzed using Differential Optical Absorption Spectroscopy (DOAS) and the slant column of various gases in the plume is derived.

In the Scanning mini-DOAS the telescope is attached to a scanning device consisting of a mirror attached to a computer-controlled stepper-motor, providing a means to scan the field-of view of the instrument over 180^o, see Figure 7.

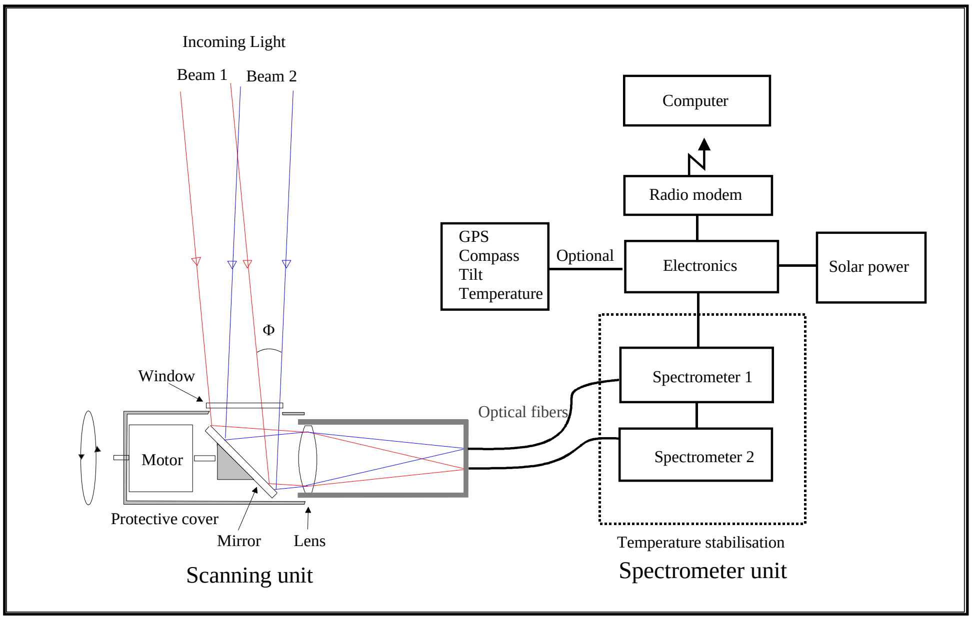

Figure 7. Schematic view of the optical layout of the Dual-Beam scanning mini-DOAS instrument. The mirror and the protective cover are rotated around the optical axis of the telescope, thereby scanning the field-of-view of the instrument in a plane perpendicular to the optical axis (and also perpendicular to the plume propagation direction).

In a typical measurement the instrument is located under the plume, and scans are made, from horizon to horizon, in a plane perpendicular to the wind-direction. After geometrical corrections the total number of SO_2 molecules in a cross-section of the plume can be determined and after multiplication with the wind speed the emission in kgs^{-1} may be derived. Typically a 3 seconds integration time is used, with 3.6^{o} angular resolution, providing a full emission measurement every 5-10 minutes. In a modification of the scanner the scan is following a conical surface with 60^{o} opening angle and with apex at the scanner. With this modification a larger span of wind directions can be covered with each instrument [Galle *et al* 2010].

Modifications made to adapt the NOVAC version 1 instrument to high latitude conditions

The NOVAC version I instruments has proven to work well under low- and mid-latitudes and today 84 instruments are running on 30 volcanoes worldwide. However, we so far only have limited experience on running these instruments at higher latitudes. Two major problems may be anticipated:

1. Low UV light conditions. During summer the days are long at high latitudes, but the Solar Zenith Angle is relatively high which reduces the UV-component of the scattered Sunlight. In addition the higher stratospheric ozone levels in the polar vortex further reduces the UV light. During winter the high Solar Zenith Angle and short daylight duration minimizes the hours available for measurements.

2. The harsh weather conditions, especially the freezing/thawing conditions during spring and fall causes problems with external moving parts, as the rotating hood of the standard NOVAC version I system.

Thus two major developments has been made; change to a more UV-sensitive spectrometer and modification of the scanning device to avoid external moving parts.

Replacing the S2000 spectrometer with the Maya2000 Pro spectrometer

The standard spectrometer used in the NOVAC stations is the S2000 from OceanOptics Inc. In order to better handle the situation with less light, a new spectrometer with higher sensitivity to UV light has been tested. The new spectrometer is the Ocean Optics Maya2000 Pro, which has considerably better sensitivity to UV light.

In order to compare the Maya2000 Pro spectrometer with the S2000 spectrometer two conical scanner systems were set up in parallel, one with the S2000 and one with the Maya. To get a clear reference of SO_2 in order to simulate a flux and validate the detection limit, a quartz gas-cell containing approximately 100 ppmm of SO_2 were placed on top of each scanner. The data was then processed according to the normal NOVAC Program evaluation procedure. The evaluated flux was now of course constant and without interest, while the calculated error gives a realistic measure of the quality of the measurement.

Data was collected between March 7 and March 11 2013, and the result is shown in Figure 8. The weather during these days was relatively good with mostly clear sky. The sunrise and sunset in

Gothenburg at March 9 was 06:45 and 18:00, respectively. During those conditions we see that the Maya spectrometer was able to produce measurements with a column error below 20 ppmm within 20 minutes after sunrise and until 20 minutes before sunset, while the same numbers for the S2000 spectrometer is above two hours at each end. Also noticeable is the considerably lower error of the Maya2000 spectrometer during the whole day

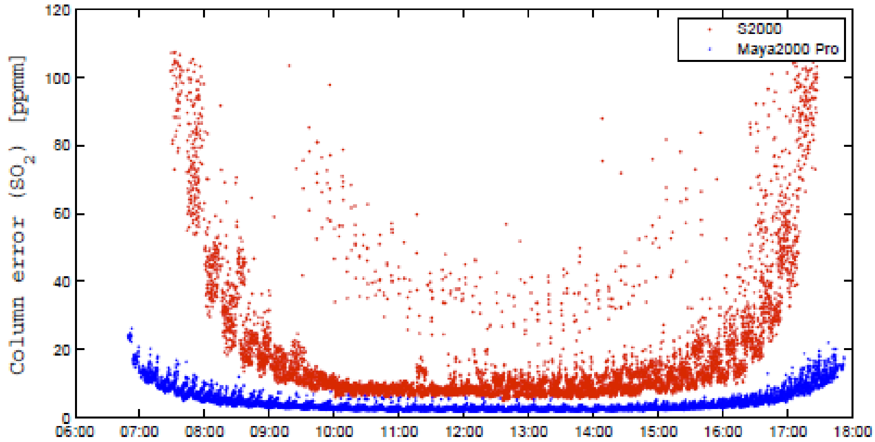

Figure 8: Diurnal variation of column error in the estimation of SO_2 for the S2000 and the Maya between March 7 and March 11, 2013.

While the Maya2000 Pro spectrometer has a higher sensitivity to UV light, the exposure time used in measurements is still calculated for the peak of the collected spectrum rather than the level of saturation in the UV region. Thus, the calculated exposure time may not necessarily follow this improved sensitivity. However, it is still interesting to compare the calculated exposure times for the Maya2000 and the S2000 spectrometers as the exposure time is one of the major limitations to faster measurements and higher temporal resolution. It is also interesting to see at which time of the day an exposure time of 1000 ms is reached, as it is used as the maximum exposure time at most NOVAC stations.

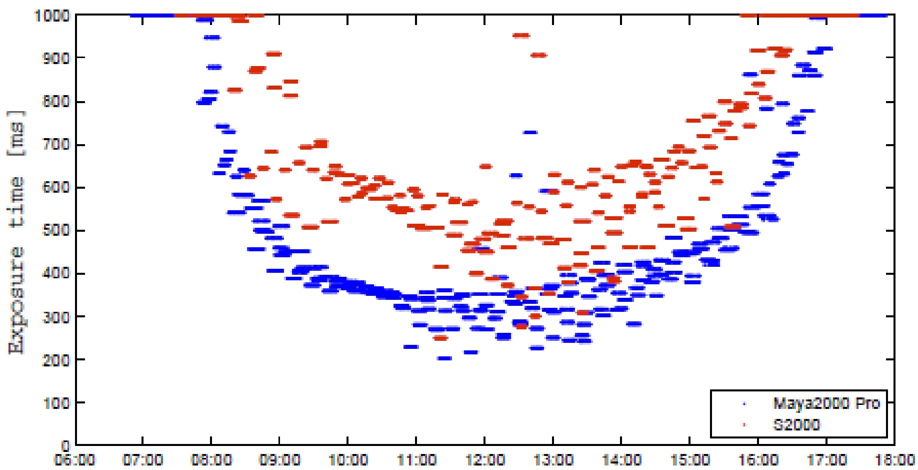

Figure 9 Diurnal variation of calculated exposure time for the S2000 and the Maya between March 7 and March 11, 2013.

As seen in Figure 9 the calculated exposure time from the same dataset is lower for the Maya2000 compared to the calculated exposure time for the S2000 spectrometer at basically all times during the day. For measurements where both exposure times drop below 1000 ms, the calculated exposure time of the Maya spectrometer is typically 200-300 ms lower compared to the S2000. Worth noting is that the calculated exposure time of the Maya spectrometer goes below 1000 ms approximately 45 minutes earlier in the morning and reaches 1000 ms approximately 45 minutes later than the S2000 spectrometer.

These studies was made in Gothenburg, at about 57^{o} N, in March. It is expected that the advantages demonstrated in Figure 8 and Figure 9 will be even more pronounced at higher latitudes as the sunrise and sunset are more prolonged in time at higher latitudes.

Replace rotating hood with a quartz cylinder

In order to protect the telescope, the motor and the mirror in the scanning mini-DOAS instrument, they are covered by a hood with a small quartz window. As the mirror, and thus the viewing angle, is rotating during the scan, the hood with the quartz window also needs to rotate and it is therefore attached to the motor. There are a number of both potential and real problems with this setup, namely;

- Since the hood has to rotate the total moment of inertia is higher. As a result, the stepping motor will need a longer time to complete a full step in order to avoid damage and misalignment. This will effectively constrain on how fast a scan can be done, lowering the temporal resolution.

- Moving parts increases the risk of parts getting stuck or events that otherwise result in breakdown. The scanner case needs to have enough margins to be able to rotate in spite of dust, dirt, ice or small misalignments.

- The abovementioned margins doesn't allow for the case to be sealed, which will let acid rain and acidic particles to enter the cavity and corrode both the mirror as well as the lenses and filter in the telescope.

To address the problems mentioned above, a new scanner prototype has been developed. Rather than having a small quartz window, the entire rotating hood is instead replaced by a static quartz cylinder that gives the telescope sky vision without having to rotate. Benefits of this setup are; lower moment of inertia, better sealing properties and no external moving parts. The new scanner prototype can be seen alongside the old (conical) scanner in Figure 10.

Figure 10: The standard conical scanner with a rotating hood and a small quartz window can be seen to the left and the prototype scanner with a non-rotating quartz window can be seen to the right.

Installation of modified Scanning DOAS instruments on Hekla volcano

At the start of the project, a first version of the Scanning DOAS system was already installed at two sites near Hekla, at Rauðaskál NE of the volcano and at Feðgar NW of it. During the first year a prototype of the instrument, adapted to Icelandic conditions was developed and tested and a first version of this system installed at the two sites in March 2013. This installation involved an upgrade of the spectrometers. In June 2013 a second upgrade was made, where the scanner was replaced by the modified version, using only internal moving parts. At the same time the field of view (FOV) of the systems was changed to rectangular. On this visit data transfer issues were also discussed. The software for data evaluation was installed on an IMO computer and the first training on the use of the evaluation software was conducted.

In Figure 11 is shown the location of the two sites Fedgar and Raudaskal, as well as two additional potential sites (MJSK and BRSK) having some existing infrastructure. Also seen is the approximate coverage of the conical scanning and the prevailing wind direction. Data is sent using FTP to a hub located at Burfell about 5 km north of Hekla.

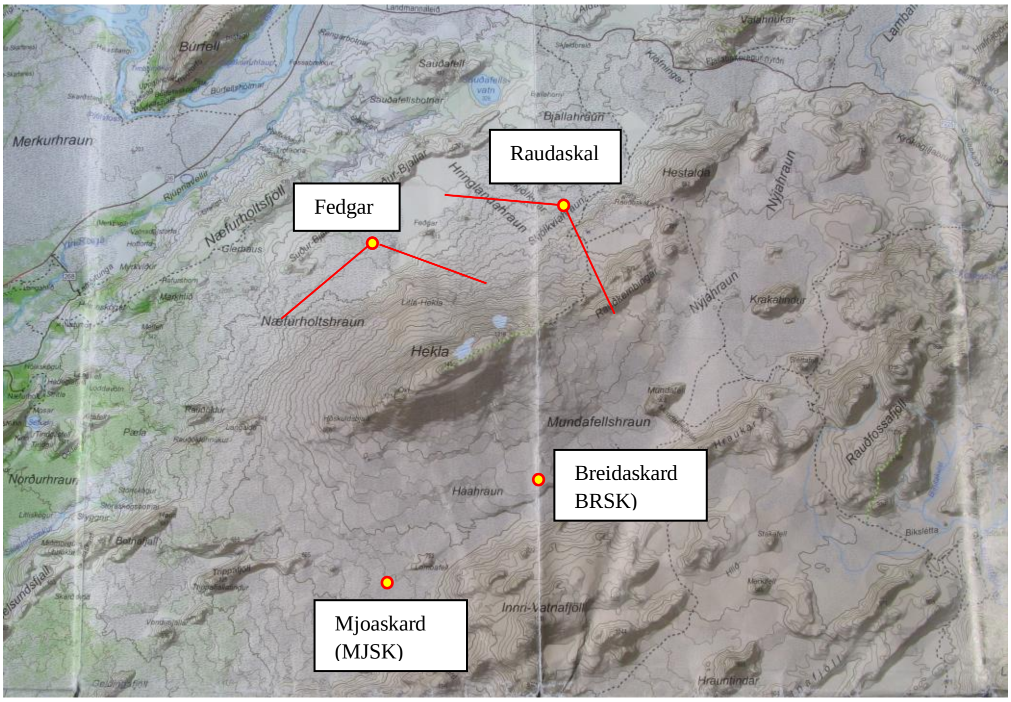

Figure 11. Map showing the location of the 2 Scan-DOAS sites Raudaskal and Fedgar. Also shown are the 2 potential future sites Mjoaskard and Breidaskard.

In Figure 12 is shown photos of the 2 installations. The electronics, embedded computer and spectrometer are located in a Pelicase inside the larger aluminum box, and the optical scanning unit as well as the telemetry antenna is mounted on a 5 cm diameter pole secured by wires bolted to the rock. Both ScanDOAS stations are powered by wind generators and a 100Ah lead battery.

Figure 12. Photoes of the 2 ScanDOAS installations at Hekla. The left Photo shows the Raudaskal site with Hekla in the background, while the right photo shows the Fedgar site.

Unfortunately no gas emissions have been detected from Hekla during the project. However, an identical instrument, with the above mentioned modifications for high latitude, was tested during a field campaign in Alaska in July-September 2013. This campaign offered a possibility to test the instrument under realistic conditions, a high latitude location with a degassing volcano. The instrument was installed at the Martin volcano (N 58.16642°, W 115.35380°, alt 1727 m), about 3 km north of the crater and data was downloaded from a base camp site about 14 km away using FreeWave FGR2-PE-U 900 MHz transceivers. An example of a scan made with this instrument, yielding 76.5 ton/day SO_2 is shown in Figure 13.

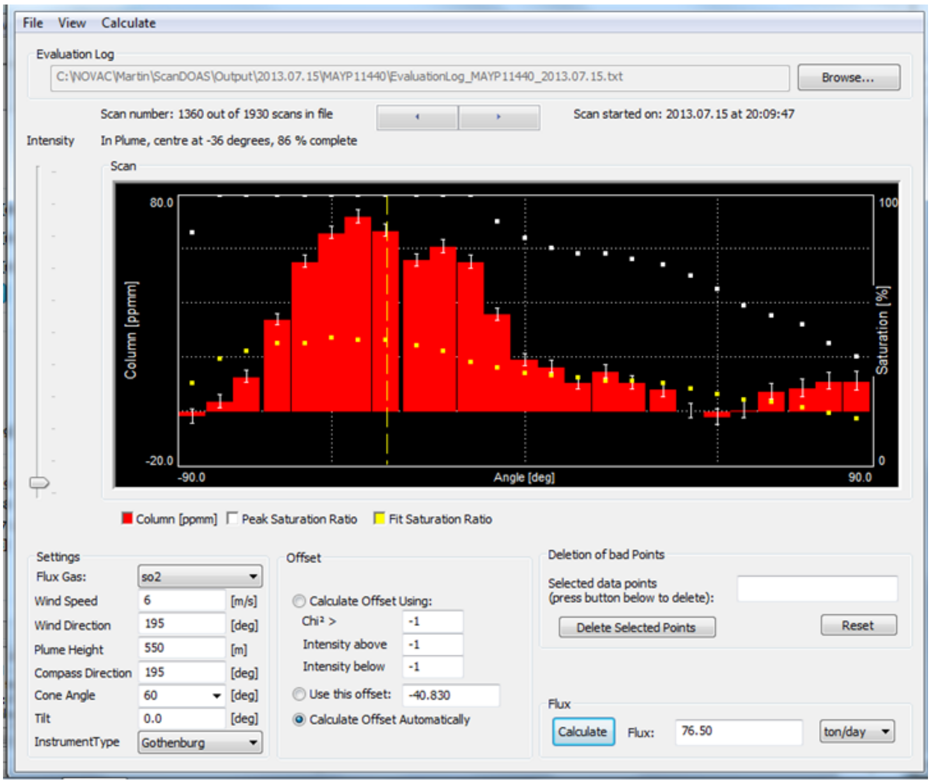

Figure 13 . Example of a measurement made by the Scanning DOAS instrument at Martin volcano on 15 July 2013. The red columns represent the vertical columns of SO_2 in a scan from one horizon to the other. The scan started at 12.09 and the SO_2 flux was evaluated to 76.5 ton/day. White and yellow dots show spectrum max intensity and fit interval intensity respective. The white bars indicate spectral evaluation error.

2.3 Fast response mini-DOAS instrument

As it is possible that the onset of SO_2 gas emission may be an early indicator of increased activity at Hekla volcano it was decided that an alternative mode of operation of the instrument, that can provide measurements of SO_2 integrated over specific areas with high sensitivity and time resolution but without quantifying the emission, should be implemented. Thus, an additional Scan-DOAS system was operated in an alternative mode where it is constantly measuring the slant column of SO_2 in a fixed direction with the purpose of simply detecting the presence of SO_2.

In this mode of operation, the instrument has a rectangular FOV covering 0.5° × 7.2°. A first test of this mode of operation was made in Alaska in July 2013, and Figure 14 shows the detection limit for SO_2 as a function of time on a day with moderate cloud cover. It can be seen that between 09.00 and 19.00 a detection limit below 5 ppmm is achieved. Note that Solar noon occur at 14.00 in Alaska.

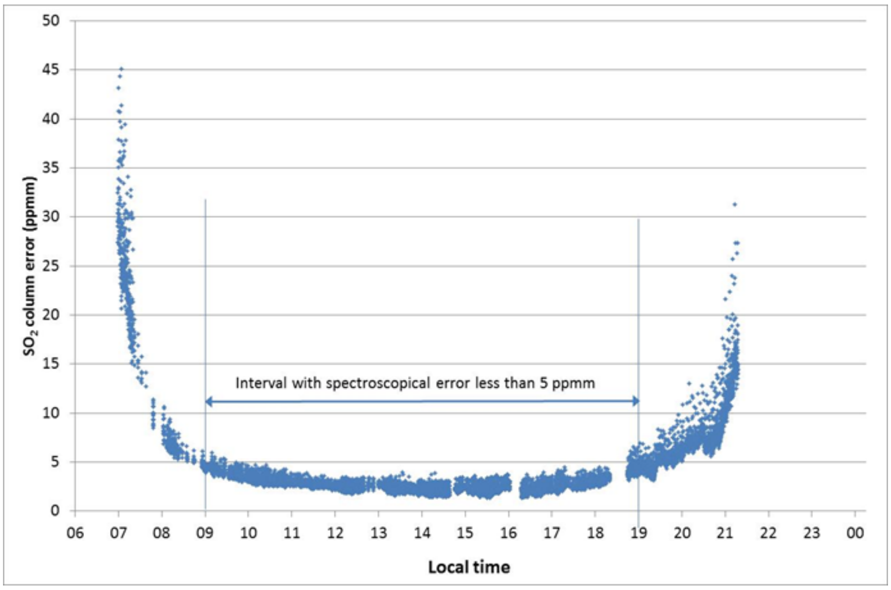

Figure 14. The error in the spectral evaluation plotted against time of day for the measurements at Martin volcano on 15 July 2013. Between 09.00 and 19.00 the error is less than 5 ppmm.

The system was installed at Rauðaskál, co-located with the stationary Scanning DOAS system, in connection with the First Annual meeting in September 2013. The instrument integrates all SO_2 molecules along a rectangular FOV located just above the rim of the volcano as seen in Figure 15. Data is collected with a time resolution of 10 seconds and is downloaded in near real time to IMO via a hub at Búrfell, located 5 km north of Hekla. As the prevailing wind direction at Hekla is from southwest it can be expected that a possible SO_2 plume is intersected along a considerable distance, yielding a very good sensitivity to the presence of SO_2. As an example, if the plume is intersected over 1 km we will be able to detect concentrations as low as 5 ppb if the weather conditions are favourable. Development of a software routine for automatic real-time download and display of data was implemented at IMO in summer 2014.

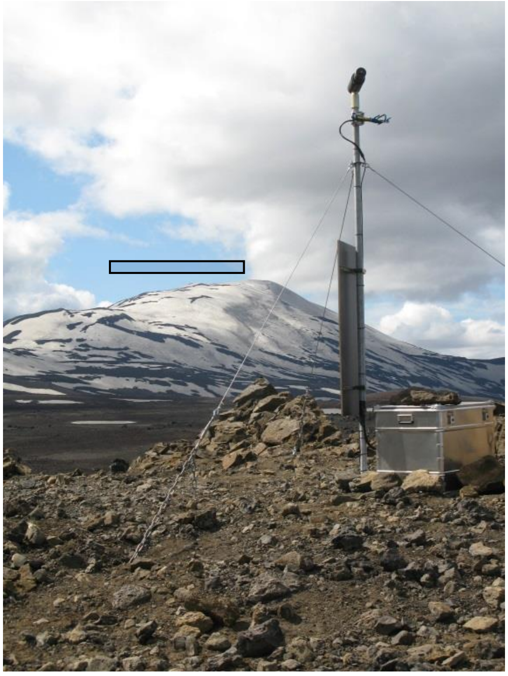

Figure 15. Hekla viewed from the Rauðaskál site. A rectangle representing the Field of View of the Fast Response mini-DOAS system is shown over the rim of Hekla.

Also with this instrument no significant SO_2 emissions from Hekla have been seen during the project duration. However, on 4 September 2014 the Fast Response system detected SO_2, see Figure 16. This gas was however coming from the Holuhraun fissure eruption located about 140 km east of Hekla, but demonstrates the ability of the instrument to detect SO_2 over Hekla volcano.

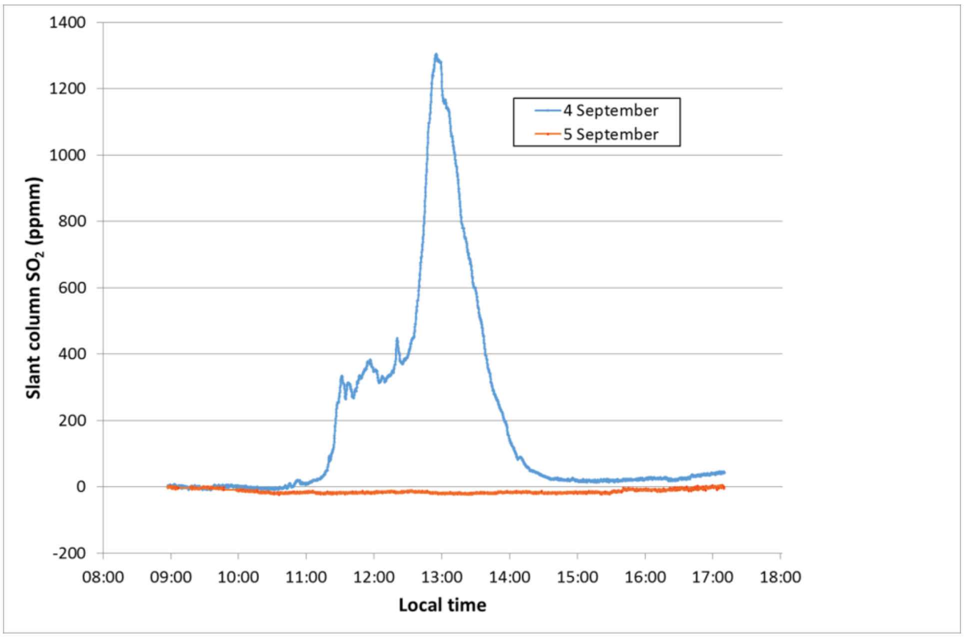

Figure 16. Time series of SO_2 slant columns measured over Hekla volcano with the Fast Response mini-DOAS instrument. The significant peak in SO_2 on 4 September originates from Holuhraun fissure eruption. Also shown is data from 5 September, representing a day without gas.

3 Measurements of gas emissions from river water

This section outlines the efforts made to measure dissolved gases in the waters of the volcanoes Hekla and Katla. As the environmental conditions differ substantially two different techniques were used. For Hekla a relatively new type of instrument developed at INGV-Palermo in 2008 was installed in two of Hekla's outlet streams. For Katla a different approach was used as the relevant technology to measure the dissolved gasses in river water in a continuous monitoring fashion was not available during the main course of the project. To measure the dissolved gases a portable MultiGAS (see D7.6 section 2.1) was used when the gases had the chance to escape the water due to turbulent water flow.

3.1 The spring water station.

In 2008 a new instrument was developed by INGV-Palermo that measures the dissolved CO_2 as well as conductivity and temperature in fresh spring water (De Gregorio et al., 2011). This type of station does not have yet have a particular name. The instrument has been tested both in the lab and in the field. One station is currently monitoring the dissolved CO_2 in a drainage gallery of the flank of Etna and one is installed at Hekla.

Function:

The instrument is constructed of a probe containing a conductivity/temperature sensor and a coiled, PTFE membrane tube that allows dissolved gas to enter from the water. The PTFE tube is connected to a silicone tube which connects to a pump, when the pump is switched on the gas from the PTFE tube is transported through the pump to an infrared gas analyser (IRGA).

The dissolved CO_2 gas defuses through the PTFE membrane until the partial pressure of the gas has reached an equilibrium on both sides of the tube. It takes 3 hours for the partial pressure of the gas outside of the PTFE tube to reach an equilibrium with the gas inside, thus measurements can only be taken every 3 hours. Figure 17 shows a schematic of the instrument itself.

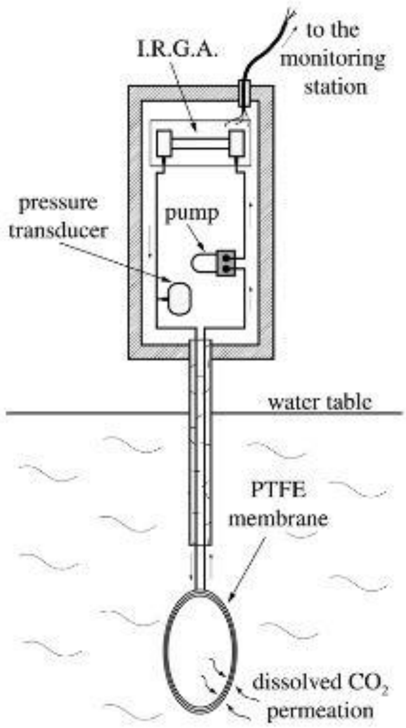

Figure 17: Schematic of the instrument

Installation in Iceland:

A groundwater monitoring station was first setup in Iceland in July 2013 with the participation of colleagues from IMO, INGV-Palermo and BGS. The station was installed in a small spring that flows into Selsundslækur. This spring is historically known for being affected greatly by Hekla, with spring water levels decreasing prior to eruptions. The station as seen in Figure 18 was running from July - September 2013, when larvae blocked the PTFE tube.

After the station stopped running and before it was reinstalled, bi-monthly water samples were collected and analysed for CO_2, conductivity, and pH. In 2014, improvements were made and the station operated from June - October.

Figure 18: Station at Selsund in August 2013

In 2015, the Selsund station was reinstalled on June 20, but had a problem with its electronic board in August . The station is now being sent back to INGV to be tested and repaired. A second station was installed in Rangárbotnar and this station has been operating since June 23 2015 (Figure 19).

Figure 19: The station at Rangárbotnar during the installation in June 2015.

The data.

The instrument gives one reading every three hours. The data can be automatically downloaded and integrated into an IMO database or it can be downloaded manually. Right now it is being downloaded manually so that a collaborator at INGV Palermo can optimize the acquisition interval.

This data has shown some changes in the dissolved CO_2 in the groundwater system of Hekla (Figure 20) so a general interest is to keep this going. The Selsund station will be reinstalled once the problem with the electronic board has been identified.

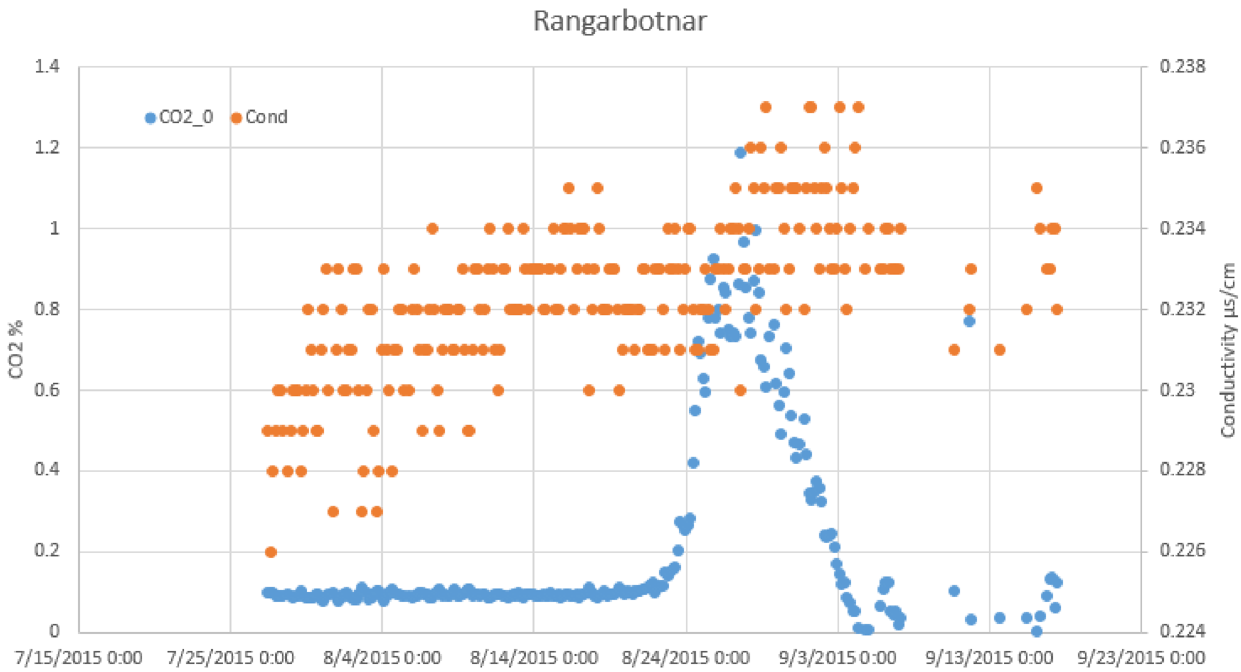

Figure 20: Data from the Rangárbotnar station showing changes in the dissolved CO_2.

3.2 Using a Portable MultiGAS to measure airborne gases from a Jökulhlaup

The system used at Hekla is ill-suited to monitor dissolved gases in sediment-rich glacial rivers. We hope that future developments will enable us to adapt this system to use at Katla. We were able to measure the composition of gases from Katla during a jökulhlaup using a portable version (not permanently installed) of the MultiGAS. The portable MultiGAS is fully described in D7.6 section 2.1. Katla has subglacial geothermal systems where gases are scrubbed by and stored in melt water. During jökulhlaups, gases that have been dissolved in the water can escape during turbulent flow. These gases can be measured using the MultiGAS.

The Jökulhlaup at Jökulsá á Sólheimasandi.

The MultiGAS was setup on the 8th of July 2014 at the mouth of the glacier in the area of the outburst (Figure 22). The instrument was on site for one week, gathering data hourly for the first day and then every 3 hours. Data was sent via a telemetry link to IMO. The MultiGAS measurements of the concentrations of potentially toxic gases were provided to the Icelandic civil protection, and were used to help decide how long access to the affected area close to the river should be restricted. These measurements also provide the first dataset of airborne gases from a geothermal system of Katla volcano. The MultiGAS showed high gas concentrations at the beginning of the flood, followed by a daily decline until background air concentrations were measured (Figure 21). The data shows high CO_2/H_2S, CO_2/H_2 and H_2/H_2S ratios. The CO_2/S_{TOT} ratios ranged from 60 at the start of the measurements to 300 at the end of the event. These CO_2/S_{TOT} ratios fit with the range of values observed in geothermal systems of Iceland. It was not possible to correlate H_2O with the other gases, and we suspect that H_2O ratios will not be meaningful during jökulhlaup gas monitoring. The concentration of SO_2 was much lower than that of H_2S which is consistent with the flood being of geothermal origin.

Figure 22: The MultiGAS by flood site in 2014.

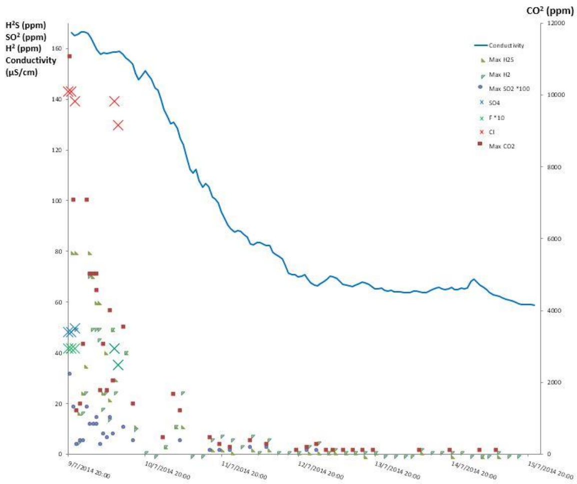

Figure 21: Atmospheric gas and river chemistry data showing an overall decline over time (note that F is multiplied by 10 and SO_2 by 100).

This work will form the basis of a master thesis to be submitted in 2016 by Baldur Bergsson.

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