Observation of the effects of the subglacial volcano eruption underneath the Vatnajökull glacier in Iceland with ERS-SAR data

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Abstract

The Vatnajökull is Europe's largest glacier with an area of 8300 km² and an ice sheet up to 1000 m thick. Iceland has many periodically active volcanoes most of which are coverded by ice. The latest eruption took place between September 29 and October 13, followed by a flooding on November 5 and 6, 1996. A fissure was formed having a total length of appr. 11 km. It is surrounded by the Bárðarbunga, Hamarinn and Grímsvötn volcanoes.

Due to the remote location of the eruption and bad weather conditions only a limited observation from ground or by plane was possible. ERS-2 - and later on ERS-1 and ERS-2 - gave the unique capability to supplement the lack of information. The German Remote Sensing Data Centre acquired, processed and further analyzed the ERS data in a very short period of time and made the information available to Icelandic partners via internet. The effort was a contribution to the accepted ESA AO2-project "Monitoring of natural changes of land surface in Iceland by the use of ERS1/2 SAR data and other remote sensing systems".

Both amplitude and phase information were utilized to achieve the interpretation results. As the data were precisely orthorectified a quantitative analysis could be performed to estimate the dimensions of the fissure and the amount of melting water. The ERS data further allowed to localize possible areas effected by the expected flooding.

The presented activities proved that ERS can significantly contribute to the monitoring of volcanic eruptions and the prediction of their possible consequences.

Keywords: Volcano Eruption, Amplitude Information, Phase Information, Orthorectification

Introduction

The impact of hazardous events like the eruption of a vulcano on men and infrastructure has been increasing during the recent decades. E.g. in 1980 the eruption of Mt. St. Helens killed 57 people and caused damages of about 1.1 billion US $ (Müschen *et.al.*, 1996) and in 1985 a mudflow (lahar) resulting from the eruption of Nevado del Ruiz in Colombia killed 29,000 people (Walter, 1995).

The reason for this increasing is the growing population of the earth, forcing people to move into potentially threated regions. Therefore it is essential to observe volcano eruptions and their consequences aiming at the reduction of the event´s impact. Radar satellites give the unique capability to observe independently from daylight and cloud coverage. In addition the new technique of differential SAR interferometry add a new qualtiy of information.

During the Vatnajökull eruption the German Remote Sensing Data Centre acquired, processed and further analyzed data delivered by ERS-1 and ERS-2. The results were made available to the Icelandic partners via Internet within a very short period of time.

The work described in this paper was performed within the frame of the ESA Announcement of Opportunity project "Monitoring of natural changes of the landsurface in Island using ERS-1/2 SAR data and other remote sensing systems". It is a demonstration of the capability of ERS SAR data to monitor the event and support local authorities in their decision making.

Chronological Order of the Event

The chronological order desribed in this chapter is based on the descriptions of (Einarsson *et.al.*, 1996). Informations about the Grímsvötn lake level and the ice thickness were kindly delivered by Oddur Sigurðsson. The chronological sequence of the eruption event is described in more detail in (Müschen *et.al.*, 1996).

The Vatnajökull eruption event begun on September 30. The day before an earthquake was registered at the northern rim of Bárðarbunga caldera with continuing shock waves on September 29 and 30. On October 1 a big depression in the ice could be observed to deepen steadily. During that day several depressions were formed in a line, extending to a total length of 5-6 km each, about 2 km wide and 100 m deep.

In the early morning of Ocotber 2 the eruption melted its way through the ice. In this area the ice thickness is about 450-600 m. An eruption cloud of pyroclasts, gases and steam grew up into the troposphere to approximately 7000- 8000 m in height (derived from NOAA-AVHRR data).

Until October 8 the total visible length of the fissure on the glacier´s surface was about 6 km. In the south part the eruption broke through the ice at two spots. Between these two spots an ice bridge, approximately 400 m wide , was formed. At the north end of the visible fissure a depression, 3500 m long and 2100 m wide, arose. Meltwater flowing to the Grímsvötn caldera created a subgalcial canyon causing the covering ice to subside.

On October 12, after a few days of bad weather, a volcanic ridge on the fissure could be observed for the first time having a little crater at its north end. The crater is supposed to be the highest point of the active ridge reaching a height of 1560 m. Therefore it is 350-400 m higher then the former peak of Loki ridge.

The eruption activities ended on October 13. Nevertheless, the horizontal extension of the depression surrounding the fissure area increased significantly. It grew from 2.1 km on October 8 to 5 km on October 21. A reason could be that the area effected by the melting was much wider as previously expected and the ice was now breaking down into the cave. Additionally the glacier is flowing continously and will close the fissure again.

During the early stage of the eruption a huge amount of ice was melted. The magma temperature was about 1200° Celsius. The meltwater mainly drained into the Grímsvötn caldera feeding a lake covered by a layer of ice approximately 50-250 m in thickness. An enormous amount of water was still pouring into the subglacial lake even after the eruption had ended. The water level increased from 1400 m before the eruption up to 1510 m at it´s highest value. Therefore the threat of a big glacial flood, or Jökulhlaup as it is called in Iceland, was given.

Jökulhlaups of the Grímsvötn lake happen periodically. All dated glacial floods began at a water level of 1430-1450 m and the water found its way slowly throughthe ice. The maximum volume of drained water was about 3.5 km³ and with a maximum rate of approximately 10.000 m³/s (Björnsson *et. al.*, 1988). This time the water reached the theoretically peak value of 1510 m. At this level the water pressure lifts the glacial ice layer in the southeastern part of the caldera causing the water to run off suddenly underneath the glacier down to the Skeiðarársandur.

The Jökulhlaup began on November 4 at 9.30 pm. A continous high frequency tremor at Grímsvötn was registered caused by the lifting and the breaking of the ice sheet. The water reached the glacier rim on November 5 at about 8:30 am causing the Skeiðarársandur rivers to rise. Three hours later the entire area of the sandur (approximately 35 km x 20 km) was flooded. The maximum rate was reached at 11 pm and was estimated at appr. 45.000 m³/s. Totally about 4 km³ of water flew into the Skeiðarársandur within 60 hours.

The flood destroyed two bridges and a section, approximately 10 km in length, of the main road circling the island. In addition it cut the main power line along the coast as well as a telecommunication cable. The river beds at Skeiðarársandur were totally changed. The road has to be redesigned and reconstructed completely. More than 100 million tons of sediments were transported directly into the ocean causing in some parts a shift of the shore line by several hundred meters.

The total amount of the damages is estimated at 31 Mio. US$ (Iceland Review, 1996). It will take at least two years to completely repair the flood damages.

Contribution of ERS-SAR Data

Iceland´s geographic location causes two major limitations in the observation ability of desaster events. It is located at 65 degrees latitude, close to the Arctic Circle. Therefore day light observation in winter is almost impossible. In addition the Golf stream passes Iceland bringing warm water into this relatively cool area. As a consequence bad weather conditions further impact the observation e.g. by airplanes.

During the recent Vatnajökull eruption a monitoring of the event was limited several times and even impossible due to dens cloud layers and the eruption cloud itself. During these days reasonable information regarding the evolution, the volume of melted ice and the length of the active fissure was not available. The preparation activities of the local authorities aiming at a minimization of the eruption's impact had to rely in these cases on estimates based on the experience of Icelandic scientists.

The established observation by airplanes and local surveying enabled a highly precise but nevertheless limited local collection of information. Data delivered by satellite systems show possibly not the same precision but allow a wider view on the event.

Orthorectification enables a qualitative and quantitative analysis of the ERS SAR data. Fortunately an ERS-1 ERS-2 data pair acquired on October 21 and 22 was highly coherent allowing even an interferometric processing.

The activities focussed on 4 areas:

- the fissure area

- the Grímsvötn caldera

- the Skeiðarársandur

- the Sylgjujökull

The Fissure Area

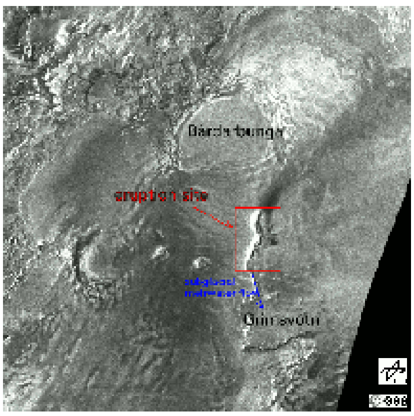

Fig. 1: Eruption Site October 6, 1996

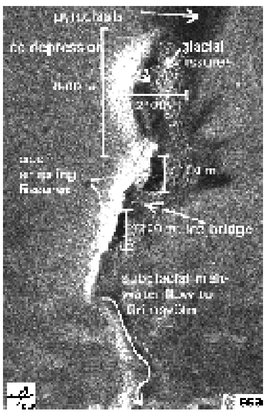

Fig. 2: Fissure Area October 6, 1996

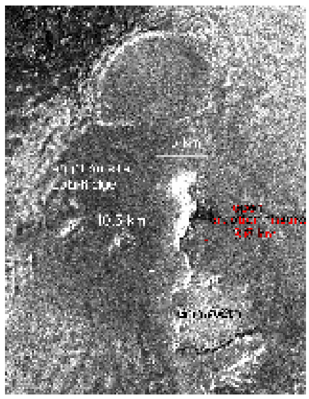

Fig. 3: Eruption Site October 21, 1996

Figure 1 shows a geocoded terrain corrected scene of ERS-2 acquired on October 6. **Figure 2** is the corresponding subimage but supplemented by annotations. At the early stage of the eruption it was not clear in which direction the water would drain, due to the fact that the eruption occured close to the watershed. The annotated subimage shows that the water drains to the south into the Grímsvötn caldera. In addition the dimension of the fissure area could be measured to estimate the amount of meltwater.

Figure 3 shows the same area as figure 1, but acquired 15 days later by ERS-1. Based on this data set the progressing extension of the glacial area directly affected by the eruption could be monitored. The melt water estimates were further improved. The amount of melt water being dammed up into the fissure area was estimated to 0.5-0.7 km³.

Grímsvötn Caldera

The area affected by uplifting of the Grímsvötn ice sheet was mapped in the data set shown in **figure 3** supported by the interferogram (**figure 4**). The z-component could be derived from a 3D volume model of the Grímsvötn caldera (**figure 5**). "Additional information concerning the subglacial relief, the ice thickness and the ratio of ice overburden pressure to subglacial water pressure were derived from (Björnsson, 1988). This informations lead us to a volume of 3.3-3.7 km³ of water in the caldera giving a total amount of approximately 4 km³ (caldera plus fissure area).

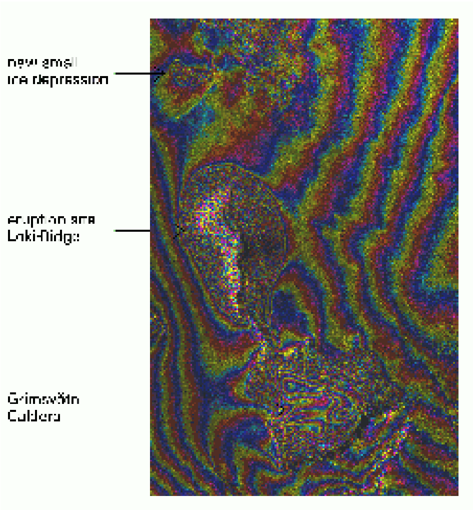

Fig. 4: Interferogram of Eruption Site

Fig. 5: 3D Model of Grímsvötn Caldera

Figure 4 shows a subset of the interferogram produced from the ERS-1/2 tandem pair acquired on October 21 and 22. Each phase cycle corresponds to a difference in altitude of approximately 75 m. But displacements on ground of about 2.8 cm cause a complete phase cycle as well. Topographic fringes can be seperated from fringes induced by movemements by either using a digital elevation model or another coherent interferomteric data set.

Three main phenomena are visible in this subset:

- In the centre the fissure area appears as a pear shaped region, indicating that big displacements are still ongoing distroying the local coherence completely.

- South of the fissure tight swirls indicate the Grímsvötn caldera. The ice sheet is lifted due to the rising water level. In addition as the ice sheet is uplifted it is tilted and stressed as well. In those areas were it is contacting the surrounding solid ice fractures, compressions and crevasses are formed.

- North of the fissure area a beginning depression can be noticed. It was detected the first time in this data set and a few days later confirmed by aireal observation. The subsidance is estimated to 10-15 cm in this 24 hours time span based on the number of fringes. A reason for the depression could be that another smaller eruption took place in this area.

Skeiðarársandur

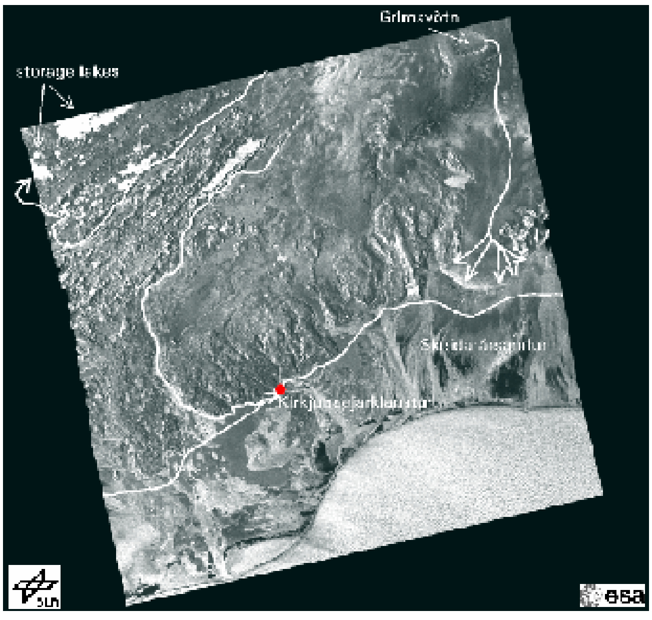

Fig. 6: Sandur Area on October 8, 1996

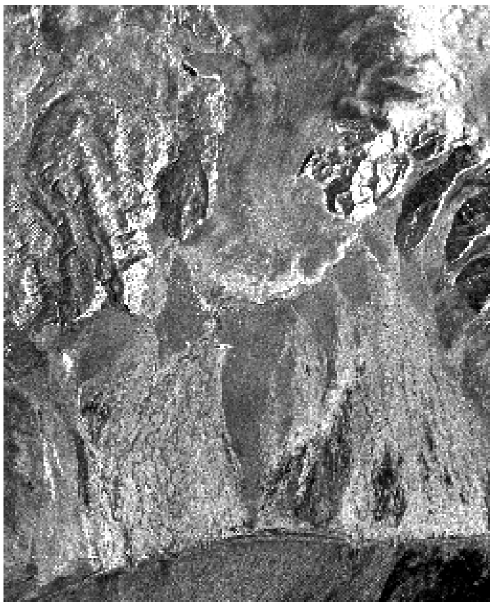

Fig. 7: Sandur Area on November 7, 1996

Figure 6 shows the sandur area with normal level of draining water. In the ERS-2 scene acquired on November 7 (**figure 7**) the parts affected by the jökulhlaup can be identified easily. The higher reflectancy of flooded areas are mainly caused by ice blocks and rocks being spread all over the sandur plane.

Sylgjujökull

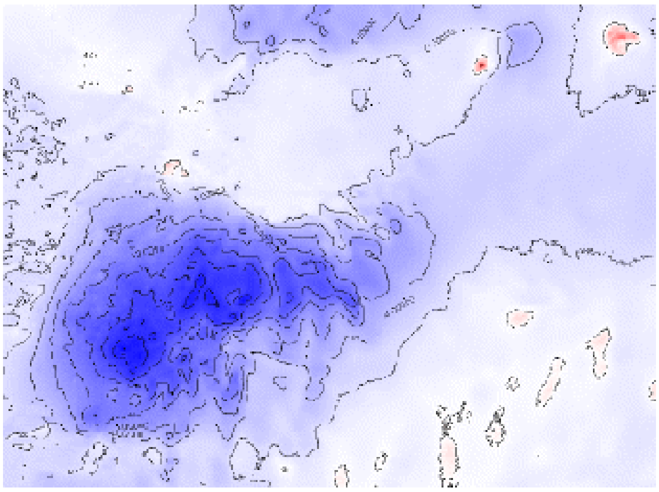

Fig. 8: Displacement Map of Sylgjujökull

One interesting phenomena of the Vatnajökull is a sudden sliding of a single glacier tongues. This local event can be seen at many of the outlet glaciers every few decades when the glacier rim is shifted up to several kilometers into it's forefield. One explanation for these glacier surges is the relatively low slope of the outlet glaciers. Falling snow is acculmulated, forming ice but without being able to flow down constantly. Reaching a certain height or ice pressure the accumulated ice is surging down the glacier within a very short period of time (up to several months). The Sylgjujökull was surging through almost the entire year of 1996. The tandem data set October 21 and 22 fortunately was covering this area as well.

Figure 8 shows the result of a differential interferometric processing. Here topographic fringes were removed by considering a digital elevation model. The image is stored in slant range geometry. Blue colors indicate areas of increasing range distance while red means decreasing range. The displacement rate was determined to up to 12 cm per day (dark blue).

This image shows the results of recent developments. It shall be further analyzed jointly with the Icelandic partners in the project by comparing the results to in situ measurements. A major benefit of interpreting interferometricaly processed ERS SAR data is the simultaneous observation of the entire glacier. The stage of surge´s development can be completely determined. The availability of more tandem pairs enabels even a further detailed analysis.

Conclusions

The capability of ERS-SAR data for supporting local authorities as well as science institutions in observing the subglacial eruption and it´s effects could be demonstrated successfully. In particular the eruption and the aereas affected could be determined precisely. An attempted for the meltwater volume estimation was performed. The orthorectified ERS SAR data allow a detailed mapping of the flooded areas and those parts of the sea shore being drastically shifted.

The interferometric processing broadens further the capability of SAR data for delivering valuable informations. A new depression was detected the first time in the ERS tandem pair of October 21 and 22. The determination of displacements, in this case the calculation of the ice flow velocity at glacier surges could be demonstrated and will be further investigated.

The availability of ERS tandem data is a special benefit for the investigations. At this time of the year snow and rainfall reduces drastically the coherence of 35 day repeat pass data hampering interferometrical investigations.

Acknowledgements

We like to thank all the partners in the project for their support. Especially we appreciated the critical and fruitful discussions with Sigurjon Jonsson from Icelandic Geodetic Survey.

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