Radar Volcano Monitoring System in Iceland

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1 Introduction

Weather radars are valuable instruments in monitoring explosive volcanic eruptions. Temporal variations in the plume and ash dispersal can be monitored and thus eruption strength estimates derived. Radar reflectivity of a volcanic plume is related to the composition, concentration and size-distribution of the complex mixture of ice, water and ash as well as type, shape and orientation of the ash grains.

After the Eyjafjallajökull volcanic eruption in 2010, the radar capabilities in Iceland were greatly increased in cooperation with the International Civil Aviation Organization (ICAO). The Icelandic Meteorological Office (Veðurstofa Íslands), a government institute, now owns and operates four radars that can be utilized for volcano monitoring, see Figure 1. In addition to issuing weather forecasts and warnings of natural hazards, the institute is responsible for monitoring and conducting research on meteorology, hydrology, avalanches, glaciology, earthquakes, tectonics and volcanology.

This paper presents detailed technical information on the four radars with examples of the information acquired during previous eruptions. This expanded network of radars is expected to give valuable information on future volcanic eruptions in Iceland.

2 Radar Observations of Volcanic Eruptions in Iceland

Table 1 shows a list of explosive volcanism in Iceland since 1970. The mainly effusive eruptions of Heimaey 1973, the nine eruptions of Krafla during 1975–1984 and Fimmvörðuháls 2010 are omitted from the table. During this period Iceland has experienced 1–4 explosive eruptions per decade, with the explosive phase usually lasting from hours to a few days. The length of the Eyjafjallajökull 2010 eruption was exceptionally long.

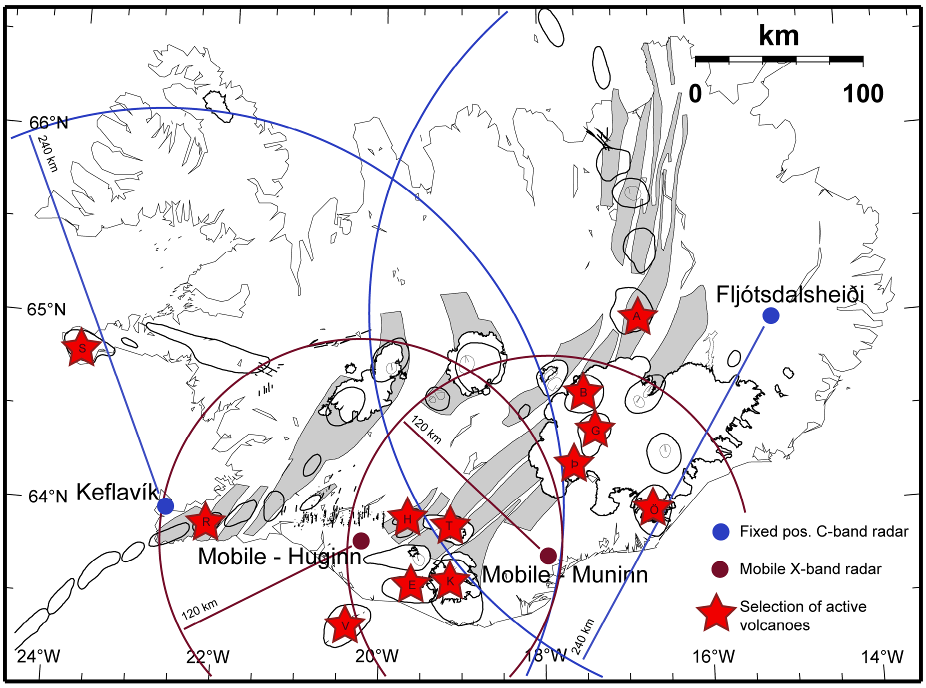

Figure 1: A selection of active volcanoes in Iceland and location of the radars.

Table 1: Recent explosive volcanic eruptions in Iceland.

Volcano	Initiation	Duration	Explosive phase
Grímsvötn	21 May 2011	8 days	8 days
Eyjafjallajökull	14 April 2010	39 days	29 days
Grímsvötn	1 Nov 2004	6 days	6 days
Hekla	26 Feb 2000	12 days	~12 hours
Grímsvötn	18 Dec 1998	10 days	10 days
Gjálp	30 Sept 1996	13 days	13 days
Hekla	17 Jan 1991	53 days	~10 hours
Grímsvötn	28 May 1983	few days	very brief
Hekla	9 April 1981	8 days	few hours
Hekla	5 May 1970	61 days	~2 hours

The volcanoes Grímsvötn, Eyjafjallajökull and Hekla are labelled G, E and H, respectively, in Figure 1. Gjálp is not shown in Figure 1, but is located between G and B (Bárðarbunga).

All the eruptions listed in Table 1 since 1991 were monitored by the Keflavík radar. Additionally, the Grímsvötn 2011 eruption was monitored by an X-band mobile radar, temporarily on loan from the Italian Civil Protection Authorities.

It is important to monitor variations in height of volcanic plumes. Ash dispersion models linked to numerical weather prediction models require height information to forecast the advection and distribution of ash. Furthermore, the eruption rate can be related to the plume height, e.g. Mastin et al. (2009)

$$H = 2000\,\dot{V}^{0.241} \tag{1}$$

where H is height of plume above the volcano (m) and $\dot{V}$ is the dense rock equivalent volumetric eruption rate (m^3/s).

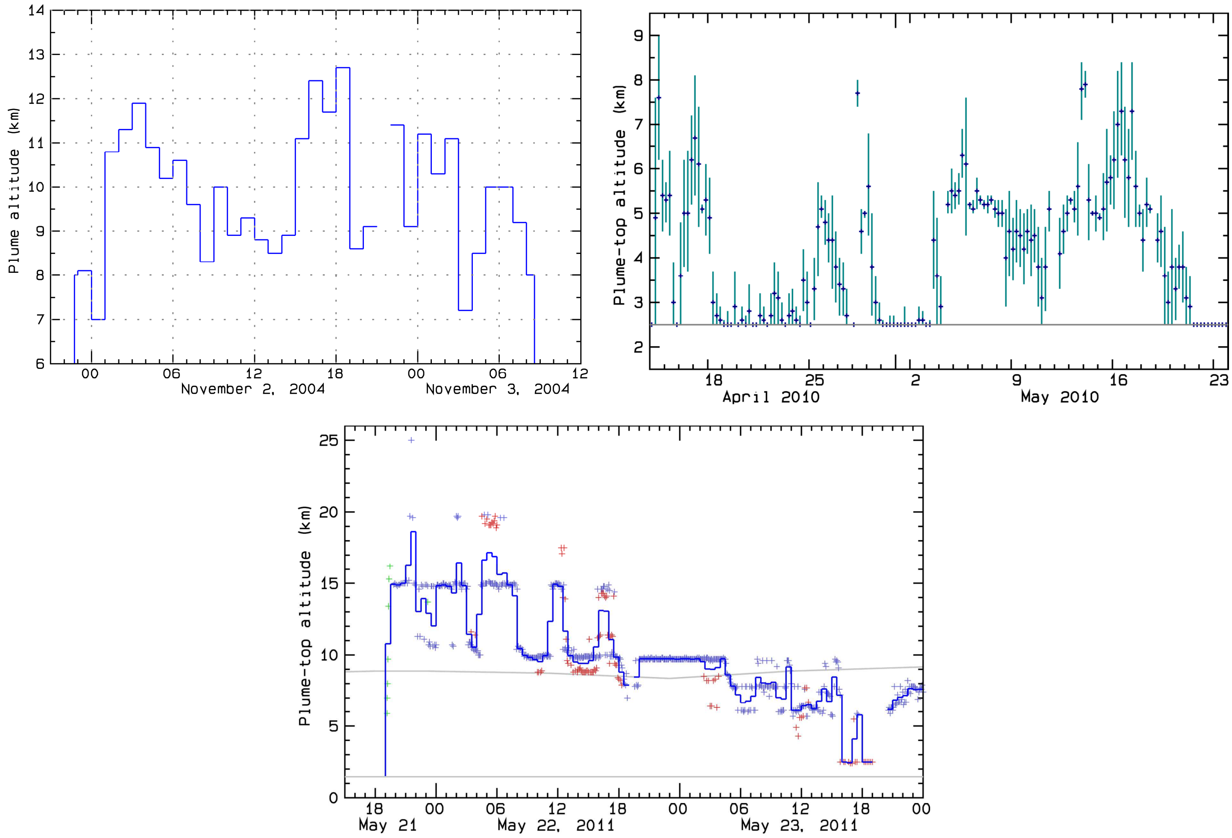

Figure 2: Plume-top altitude during the Grímsvötn 2004, Eyjafjallajökull 2010 and Grímsvötn 2011 volcanic eruptions.

Figure 2 shows three time-series of the plume-top altitude in km a.s.l. obtained by radars during volcanic eruptions in Iceland in the past ten years. During the Grímsvötn 2004 eruption the plume was observed by the Keflavík C-band weather radar every 5 min at a distance of 257 km. The plume was not visible by the radar when below about 6 km a.s.l. due to orographic blockage and curvature of the Earth. The graph shows variations in 1 hour averages of the echo-top altitude during 39 hours of the initial and most powerful phase of the eruption, 1–3 Nov 2004. Monitoring data from this eruption is described by Vogfjörd et al. (2005). The most powerful phase when the plume was visible by the radar lasted for 34 hours, and during this period the plume-top height varied between 7 and 14 km a.s.l.

The Eyjafjallajökull eruption lasted 39 days, 14 April – 23 May 2010. The altitudes were determined from radar scans every 5 min from the Keflavík C-band weather radar at a distance of 153 km. The graph shows a time series of a mean and a standard deviation every 6 hours of the radar determined echo-top level. The plume was not visible when below about 3 km because of orographic blockage and curvature of the Earth. This data series is described in detail by Arason et al. (2011).

The graph from the Grímsvötn 2011 eruption shows 57 hours of the initial and most powerful phase of the eruption, 21–23 May 2011. The gray line at about 9 km represents the height of the tropopause in Iceland and the lower line the height of the volcano. The blue crosses are heights derived from the Keflavík radar every 5 min, 257 km from the volcano and the red crosses heights from the mobile X-band radar, 75 km from the volcano. Green crosses are height estimates from photographs during the initial rise of the plume. The curve shows 30 min averages of the available data. This data is described in detail by Petersen et al. (2012). The eruption was powerful, but of a short duration, delivering material into the stratosphere. The ash was not as fine-grained as during the Eyjafjallajökull eruption and wind speeds were lower, so most of the ash was deposited locally.

3 Expansion of the Radar Network after 2010

The Keflavík radar was installed in 1991 and for twenty years it was the only available weather radar in Iceland. This radar has been used to monitor seven eruptions: Hekla in 1991 (Larsen et al., 1992), Gjálp in 1996, Grímsvötn in 1998, Hekla in 2000 (Lacasse et al., 2004), Grímsvötn in 2004 (Vogfjörd et al., 2005), Eyjafjallajökull in 2010 (Arason et al., 2011) and Grímsvötn in 2011 (Petersen et al., 2012). In 2011 the institute had a mobile X-band radar (Selex - Meteor 50DX) on loan from the Italian Civil Protection, and it was able to monitor the Grímsvötn 2011 eruption (Petersen et al., 2012).

The fine-grained silicic ash of the Eyjafjallajökull 2010 eruption and its advection into the crowded airspace of Europe caused major disruption of flights. This led to the greatest aerial shutdown since World War II and affected over ten million passengers worldwide. Following the Eyjafjallajökull eruption, the International Civil Aviation Organization was instrumental in financing a significant expansion of the radar system in Iceland for the purpose of monitoring future eruptions. A fixed position 250 kW doppler C-band weather radar was installed in April 2012 at Fljótsdalsheiði, E-Iceland, and in June 2012 and February 2013 the institute received two mobile 65 kW dual-polarization doppler X-band radars. Tables 2–4 show detailed technical information on the radars.

The Icelandic Meteorological Office is the owner of the four radars, operates and maintains them and is responsible for issuing warnings to the public as well as to aviation authorities. The institute has also been designated as the Icelandic Volcano Observatory, monitoring collecting, disseminating and distributing various volcanological warnings and data.

Figure 3 shows photos of the Keflavík radar, the initial rising plume of the Grímsvötn 2011 eruption and one of the new mobile X-band radars, of type Selex Gematronik Meteor 50DX, towed by a specially adapted truck for off road driving. The figure shows the initial Grímsvötn eruption plume as seen from Skeiðarársandur, 50 km south of the volcano about 20 min after the initiation of the eruption. Altitude scale at the distance of Grímsvötn (Gr) is shown on the left. The tropopause (Tr) at this time was at about 8.9 km a.s.l.

Figure 3: The Keflavík C-band weather radar, the initial rising plume of the Grímsvötn 2011 eruption and a mobile X-band radar. Photos Þórður Arason, Bolli Valgarðsson and Geirfinnur S. Sigurðsson.

Table 2: Keflavík C-band weather radar, technical information.

Location	64°01.54' N, 22°38.11' W (SW-Iceland, fixed position)
Type	Ericsson UBS 103 04 radar system
Operational since	January 1991; doppler since April 2010
Operating frequency	5.61 GHz, C-band
Wavelength	5.3 cm
Peak transmitted power	250 kW
Maximum range	480 km
TX type	Magnetron
RX type	Analog
Polarization	Linear horizontal
Signal Processor	UFC 108 14/8
Data managing software	Rainbow®5
Reflector diameter	4.2 m
Height of antenna	47 m above sea level
Pulse duration	0.58±0.05 μs (doppler); 2.0±0.2 μs (reflectivity)
Pulse repetition frequency	900/1200 Hz (0.6 μs); 250±2 Hz (2 μs)
Half-power beam width	0.9°
Range resolution	1 km (doppler); 2 km (reflectivity) (typical)
Actual gain of antenna	44.9 dB
Minimum detectable signal	−114 dBm (0.6 μs); −109 dBm (2 μs)
Scanning speed	1 − 6 rpm; 3 rpm (typical)
Elevation angles reflectivity scans	0.5°, 0.9°, 1.3°, 2.4°, 3.5°, 4.5°, 6.0°, 8.0°, 10.0°, 15.0°, 25.0° & 40.0° (typical)
Elevation angles doppler scans	0.5°, 1.3°, 2.4°, 5.0°, 7.0°, 10.0°, 15.0°, 20.0° & 30.0° (typical)
Reflectivity threshold (echo top)	−20 dBZ (typical)

Table 3: Fljótsdalsheiði C-band weather radar, technical information.

Location	65°01.68' N, 15°02.29' W (E-Iceland, fixed position)
Type	EEC SWR-250C(F)
Operational since	May 2012
Operating frequency	5.52 GHz, C-band
Wavelength	5.4 cm
Peak transmitted power	250 kW
Maximum range	480 km
TX type	Magnetron
RX type	Digital
Polarization	Linear horizontal
Signal Processor	IQ2
Data managing software	EDGE V5.5
Reflector diameter	4.25 m
Height of antenna	698 m above sea level
Pulse duration	0.8 μs & 2 μs
Pulse repetition frequency	250 − 934 Hz (0.8 μs); 250 − 300 Hz (2 μs)
Half-power beam width	1°
Range resolution	0.016 − 2.000 km; 0.25 − 0.50 km (typical)
Azimuthal resolution	0.2° − 1.2°; 0.4° (typical)
Minimum gain of antenna	44 dB
Minimum detectable signal	−115 dBm (0.8 μs); −117 dBm (2 μs)
Angle position accuracy	< 0.1°
Scanning speed	1 − 6 rpm; 2 rpm (typical)
Elevation angles reflectivity scans	0.7°, 1.8°, 3.1°, 4.6°, 6.3°, 8.3°, 10.6°, 13.2°, 16.2°, 19.7°, 23.8°, 28.4°, 33.8° & 40.0° (typical)
Reflectivity threshold (echo top)	−20 dBZ (typical)

Table 4: Huginn and Muninn mobile X-band weather radars, technical information.

Location	mobile
Type	Selex Gematronik Meteor 50DX
Gross weight	3500 kg
Operational since	Hu: June 2012 / Mu: February 2013
Operating frequency	Hu: 9.375 GHz / Mu: 9.355 GHz, X-band
Wavelength	3.2 cm
Peak transmitted power	65 kW
Maximum range	120 km
TX type	Magnetron
RX type	Digital
Polarization	Horizontal and vertical
Signal Processor	GDRX
Data managing software	Rainbow®5
Antenna type	XDP15, parabolic, prime focus reflector
Reflector diameter	1.88 m
Height of antenna	3 m above ground
Pulse duration	0.5 µs, 1 µs & 2 µs
Pulse repetition frequency	250 − 2000 Hz
Half-power beam width	1.25°
Minimum gain of antenna	42.4 dB
Minimum detectable signal	Hu: H&V: −117 dBm; Mu: H/V: −117/−119 dBm
Range resolution	0.03 − 2.00 km; 0.1 km (typical)
Azimuthal resolution	1° (typical)
Angle position accuracy	< 0.1°
Scanning speed	1 − 6 rpm; 3 rpm (typical)
Elevation angles reflectivity scans	0.7°, 1.8°, 3.1°, 4.6°, 6.3°, 8.3°, 10.6°, 13.2°, 16.2°, 19.7°, 23.8°, 28.4°, 33.8° & 40.0° (typical)
Reflectivity threshold (echo top)	−20 dBZ (typical)

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