

EMISAR mapping of Surtsey, Iceland

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ABSTRACT

During two measurement campaigns in 1997 and 1998, the Danish airborne Synthetic Aperture Radar (SAR) system, EMISAR, mapped a total of about 16,000 km² along the Northern and Eastern rift zones in Iceland. Although not specifically targeted, Surtsey was included in the mapping of the Eastern rift zone on August 13, 1998. The acquired SAR data have been used to generate a Digital Elevation Model (DEM) of Surtsey with a spatial resolution of 5 m and a polarimetric L-Band SAR image with a resolution of 5 m. The polarimetric SAR image shows differences in surface morphology between the geologic units on Surtsey.

INTRODUCTION

In the early 1990s, the utilization of satellite radar interferometry to measure the Earth's topography and changes of the Earth's surface became a widespread technique in geophysical research. In topographic mapping, the advantages of radar interferometry over conventional photogrammetric techniques are the rapid data collection, high vertical resolution, and the ability to collect globally consistent elevation data. Surface displacements can be measured with competitive precision, but with a much larger spatial sampling density compared to in-situ techniques. A comprehensive summary of geophysical applications of radar interferometry can be found in Massonnet & Feigl (1998).

The utilization of radar images in classification of lava units and quantitative characterization of lava surface morphology has been discussed in various papers (e.g., Dierking 1999, Campbell & Shepard 1996, Farr 1992, Gaddis 1992, van Zyl *et al.* 1990). The roughness scales typically observed on the surface of lava flows are of magnitudes to which radar sensors operating at frequency bands between C-band (wavelength about 0.05 m) and

P-band (about 0.7 m) are very sensitive. Hence, the intensity of the radar signal, which is scattered back from the flow surface to the radar sensor, is in many cases comparatively large.

A major advantage of airborne or satellite radar systems is that large areas (such as the Northern and Eastern rift zones on Iceland) can be imaged in a rather short time independent of light and cloud conditions. The ERS satellites acquire several sets of images per month and airborne systems can perform regional mapping at a much higher rate than aerial photography (2.5 km²/s for the EMISAR).

The Northern and Eastern rift zones in Iceland were mapped with the Danish airborne EMISAR system in the summers of 1997 and 1998 with a two-fold purpose. Firstly, the data were combined with radar data from the European Remote Sensing Satellites ERS-1 and ERS-2 acquired between 1991 and 1997 to study tectonic movements and inflation/deflation events of the magma chambers in the area. Secondly, polarimetric SAR images were used to study aspects of the geology in the area utilizing the fact that the radar signature is related to the

morphology of the surface (Dierking & Haack 1998).

SAR studies of terrestrial basaltic lava flows, like those in the active volcanic zones of Iceland are also useful in terms of interpreting the radar signatures of basaltic lava flows on Venus for which the only source of data are the Magellan SAR images (Johnson 1991).

Principles of SAR mapping

The EMISAR is an airborne radar system, which transmits and receives radar pulses perpendicular to the flight track. During operation the radar pulses illuminate a strip parallel to the

flight track. The width of the strip measured by the EMISAR is usually about 12 km and the altitude of the airplane during mapping is between 7 and 13 km. In a conventional radar the spatial resolution parallel to the flight direction is proportional to the antenna beam width that is smaller for long antennas and larger for short antennas. Due to the limited size of an antenna which can be mounted on an aircraft or a satellite the antenna beam is typically several degrees wide. The resolution is significantly better in the SAR system. Due to the relatively large beam width of the antenna the radar receives many pulses from a particular position on the ground as

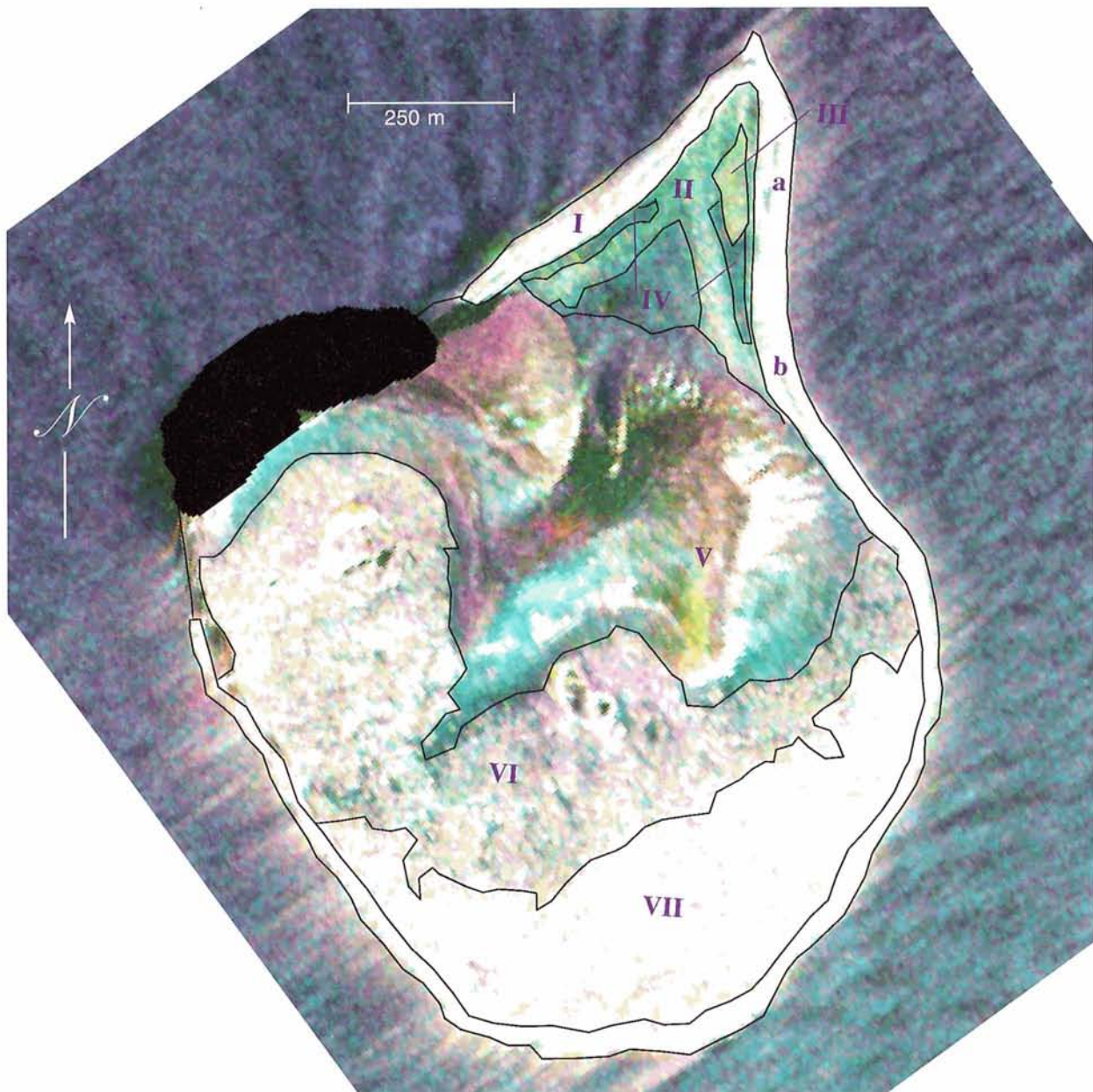


Figure 1. Polarimetric EMISAR image of Surtsey. HV-red, HH-green, and VV-blue. The units shown are described in Table 1.

the radar passes by the target. Since the radar is moving relative to the ground the time interval between consecutive pulses from a particular target is varying (Doppler shift). By combining all pulses received from a particular target and utilizing the Doppler shift information it is possible to generate images similar to those that could have been obtained with a much longer antenna or aperture (length typically in the range of kilometers) - thus the name Synthetic Aperture Radar. Moving targets will, however, not be correctly focussed by this process. For example, reflections from ocean waves are somewhat defocused (Fig. 1).

For each resolution cell on the ground the magnitude and phase of the backscattered signal is calculated for each of the frequencies and polarization used. The magnitude of the backscattered signal depends on the surface roughness and the dielectric properties of the target as well as on the target's orientation relative to the radar beam. In general, a rough surface scatters more of the signal back toward the radar than a smooth surface (unless the surface is facing the radar). In this context rough means that the surface is rough on a scale similar to the wavelength of the radar pulse. The dielectric constant determines the magnitude of the reflected and scattered signals as well as the attenuation of the signal fraction that penetrates into the medium.

The EMISAR currently includes C-band (wavelength 5 cm) and L-band (20 cm), which can be operated simultaneously. Both antennas can transmit horizontally and vertically polarized pulses and can thus be used to generate images utilizing different combinations of polarizations (polarimetric images).

Polarimetry

The color-coded polarimetric image shown here (Fig. 1) is based on three L-band EMISAR images, HH (green), VV (blue), and HV (red) where the first letter designates the polarization of the transmitted pulse and the second letter designates the polarization of the received pulse. Note that even though the transmitted pulse is either H or V, the backscattered signal from the Earth surface will in general include both polarizations. A polarization change of a fraction of the signal occurs when the scattering surface is very complex. Many vegetation types and a'a lava flows are examples of scatterers that generate a strong HV (= VH) return. For more details on polarimetric SAR see Ulaby & Elachi (1990).

Interferometry

The radar signal carries amplitude and phase information. The phase difference between two different SAR images at a given position on the

Table 1. Interpretation of radar signature and field observation. Units are outlined in Fig. 1.

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|------|--|
| I. | Coastal areas in Surtsey show up as very bright areas in Fig. 1 indicating that the surface is rough on a 20 cm scale. This is in coherence with the morphology of the coastal areas. Field observations during the summer 1998 confirm that the bright areas are covered by boulders in the size range of 0.5 to a few meters in diameter. Two narrow strips covered with sand (a and b) show up as dark units within the bright unit I (Fig. 5). |
| II. | This unit represents the highest benchmarks on the northern peninsula in Surtsey. Densely distributed boulders and tree logs are observed in this area. In between the boulders and the logs we observed that eolian sand medium to coarse grained had accumulated. The darker appearance of this unit relative to unit I can be related to the smoothing effect of the sand (Fig. 5). |
| III. | A small area within the boulder field where the HH reflection is significantly stronger than the VV reflection (Fig. 2). The area in question is characterized by eolian sand, showing ripples in the range of cm to tens of cm (Fig. 5). |
| IV. | Unit 4 is the darkest of the units on the Northern peninsula. The area is covered by a thin layer of eolian sand, where occasional boulders stick out and some beach debris is scattered. The largest area is a remnant of the oldest part of the peninsula. The two smaller areas are similarly built, covered with thin layer of eolian sand and are formed in-between older boulder coasts. Common for the three areas is that they are flooded during winter time. This makes them denser and flatter than other areas covered with eolian sand like area III. |
| V. | The steep and variable slopes in the interior of the island dominate the variation in radar characteristics. The three blue areas on the crater slopes are characterized by large HH and VV backscatter. The HV channel is, however, comparatively weak which is consistent with the smooth surface of these slopes. The surface is composed of smoothly polished hyaloclastite. The reason why these areas are so bright in HH and VV is that they are facing the radar beam, which was transmitted from the SE, and thus reflect the radar pulses like a mirror back toward the plane (Fig. 6) |
| VI. | The unit is relatively dark compared to the southern part of the island. The area inside the Surtur vent and along the crater wall is almost black. This darkening of the unit is correlated with the eolian sand cover. The NW-most area is lightly brighter consistent with the less significant sand cover in Surtungur (Figs 6, 7 and 8). |
| VII. | Southward to the coast, the lava morphology plays a significantly greater role in radar signal scattering, and the image becomes brighter. In this area occasional a'a lava streams are observed. Most significant in the area are heavily fractured pahoehoe flows and shelly type pahoehoe flows. The highly fractured surfaces of these pahoehoe flows make them very rough and therefore give them radar backscattering characteristics similar to the a'a flows. Thin lava plates more or less twisted and tilted characterize shelly pahoehoe flows. The more massive pahoehoe flows show fractures due to deflation (Figs 7 and 9). |

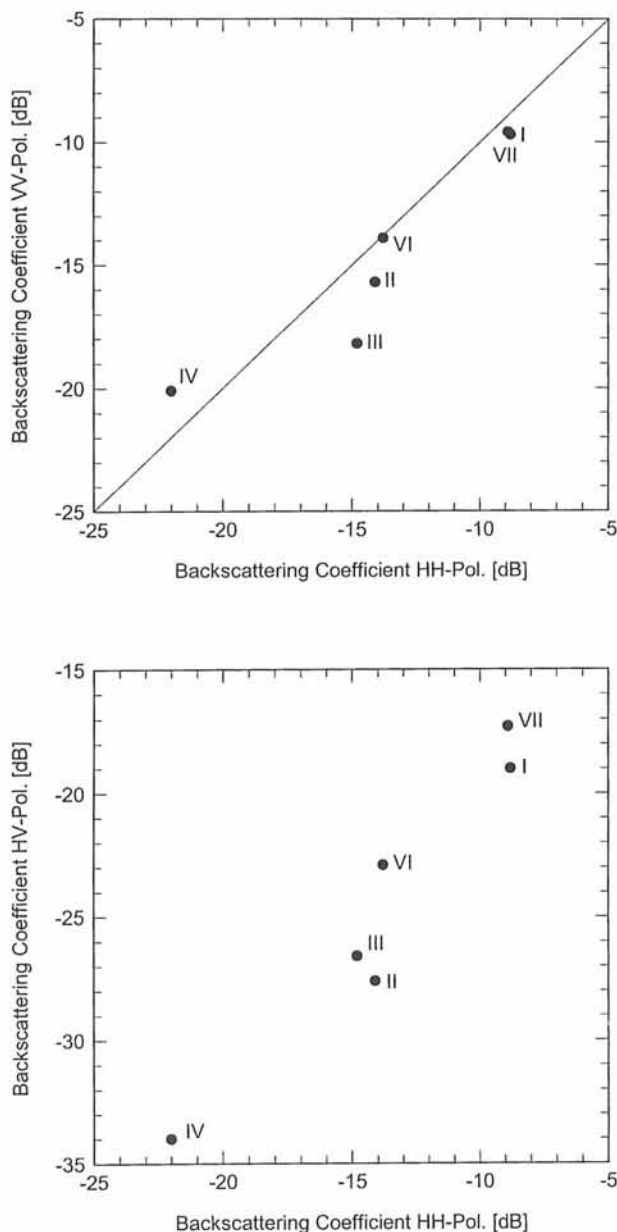


Figure 2. Characteristic backscattering coefficients of the units shown in Fig. 1. The backscattering coefficients are measures of the intensity of the received signals relative to the intensity of the transmitted signals. Units I, and VII are the brightest of all units, both in the HH and VV channel. Unit VI is darker which illustrates the smoothing effect of an increase in the areal extent and/or the thickness of the sand cover on top of the lava flows. Units II and III represent coastal morphologies. Unit III is of particular interest since it has the highest HH/VV ratio, possibly due to sand ripples perpendicular to the incoming radar pulses.

ground is a measure of the difference in distance between the particular ground element and the antenna positions at the two data takes. Images showing the phase difference of two SAR images recorded over the same area are known as interferograms. Interferograms are used for two different purposes.

If the two images are recorded from identical

or nearly identical tracks but at different times the phase difference represent displacements of the Earth's surface. Displacements down to 1-2 cm may be detected using C-band SAR images. SAR interferometry is used to study inflation/deflation of the surface, tectonic movements, glacier motion etc. Until now, this has mainly been done using satellite data since the satellite tracks are smoother than airplane tracks and can be determined with greater accuracy than the tracks followed by an airplane during two consecutive flights.

Alternatively, if the images are recorded at the same time, but with a slight vertical offset, the difference in the distance between ground element and the antennas is due to the difference in viewing angle. Knowing the distance to the target and the difference between the two antennas, it is possible to calculate the elevation of the target. This technique is used to generate Digital Elevation Models. For more details on SAR interferometry see Madsen & Zebker (1998).

RESULTS

Figs 1-3 show the results from the polarimetric and interferometric analysis of the data. During the measurement the radar illuminated Surtsey from SE (126°) while the airplane was flying toward the NE. The area below the high cliffs along the NW-shore in Figs 1 and 3 was in the radar shadow and was therefore not mapped.

Polarimetry

We have visually classified the surface features on Surtsey into seven major radar units (Table 1). Each unit has a characteristic radar signature due to its particular surface characteristics and morphology. The vegetation on Surtsey is densest in the southern part of the island where large spots of grass have developed. Radar polarimetry can in many cases be used to detect and distinguish different vegetation covers (Ulaby & Elachi 1990, Skriver *et al.* 1999). The low vegetation on Surtsey is too sparse to show up clearly in the L-band polarimetric image. It could possibly be detected using C-band polarimetry because of the shorter wavelength. Although C-band data were also recorded over Surtsey it is not possible to generate a C-band polarimetric image since only vertically polarized pulses were used in the interferometric measurement mode. In Table 1, the field characteristics of the radar units are briefly described and related to the observed radar signatures.

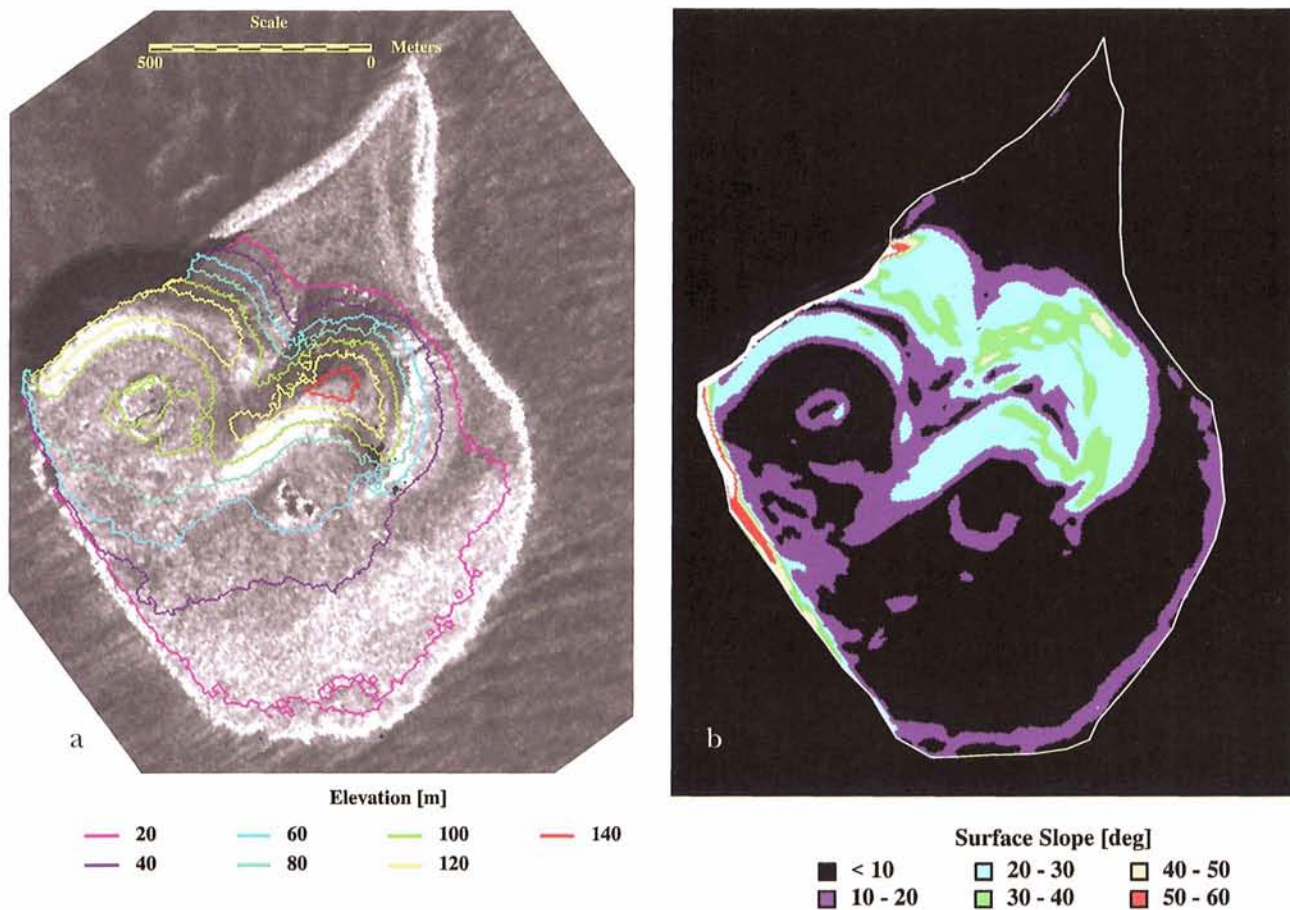


Figure 3. a) Digital Elevation Model of Surtsey superimposed on a C-band intensity image. Contour lines are shown for each 20 m starting with 20 m in red. The height accuracy is about 1 m. b) Slopes calculated on the basis of the DEM shown in 3a. The grey area is an artifact caused by the radar shadow. North is up.

Comparison of the polarimetric image with the geologic map

The polarimetric images reflect variations of certain surface characteristics of Surtsey. The radar signature is sensitive to variations in small-scale roughness of the lava flows, thickness and humidity of sand covers, boulder size along the shore line and surface slope relative to the incoming radar signal. These surface characteristics are not necessarily correlated with differences in rock type, mineralogy, or age as shown in the geologic map. Two lava flows of different age may for example have similar surface morphologies and may therefore not be discriminated in the polarimetric image. The polarimetric image may, however, show differences in surface morphology within single units shown in the geologic map. A problem in the interpretation of the radar signatures is the occurrence of variable, partly steep slopes on parts of the island. Variations in signature caused by changes in radar incidence angle are not easily separated

from variations due to changes in surface morphology.

The geologic map (Jakobsson 2000) is divided into 9 different units, three types of coastal sediments, three lava flow units and three other types of volcanic units. The two types of beach sediments are readily distinguished in the polarimetric image. The large boulders (Unit 1) have sizes closer to the radar wavelength and are therefore characterized by a very strong backscattered signal. Narrow bands (~20 m wide) of smaller scale coastal sediments (a and b in unit I) NE of Austurbunki clearly show up in the polarimetric image as darker bands. One of these bands is indicated on the geologic map, the other is not (but can be identified in aerial photography).

The spatter cones are not easily distinguished as coherent units in the polarimetric image because of their irregular topography. The rough surface of the spatter is likely to give it radar characteristics similar to that of the lava

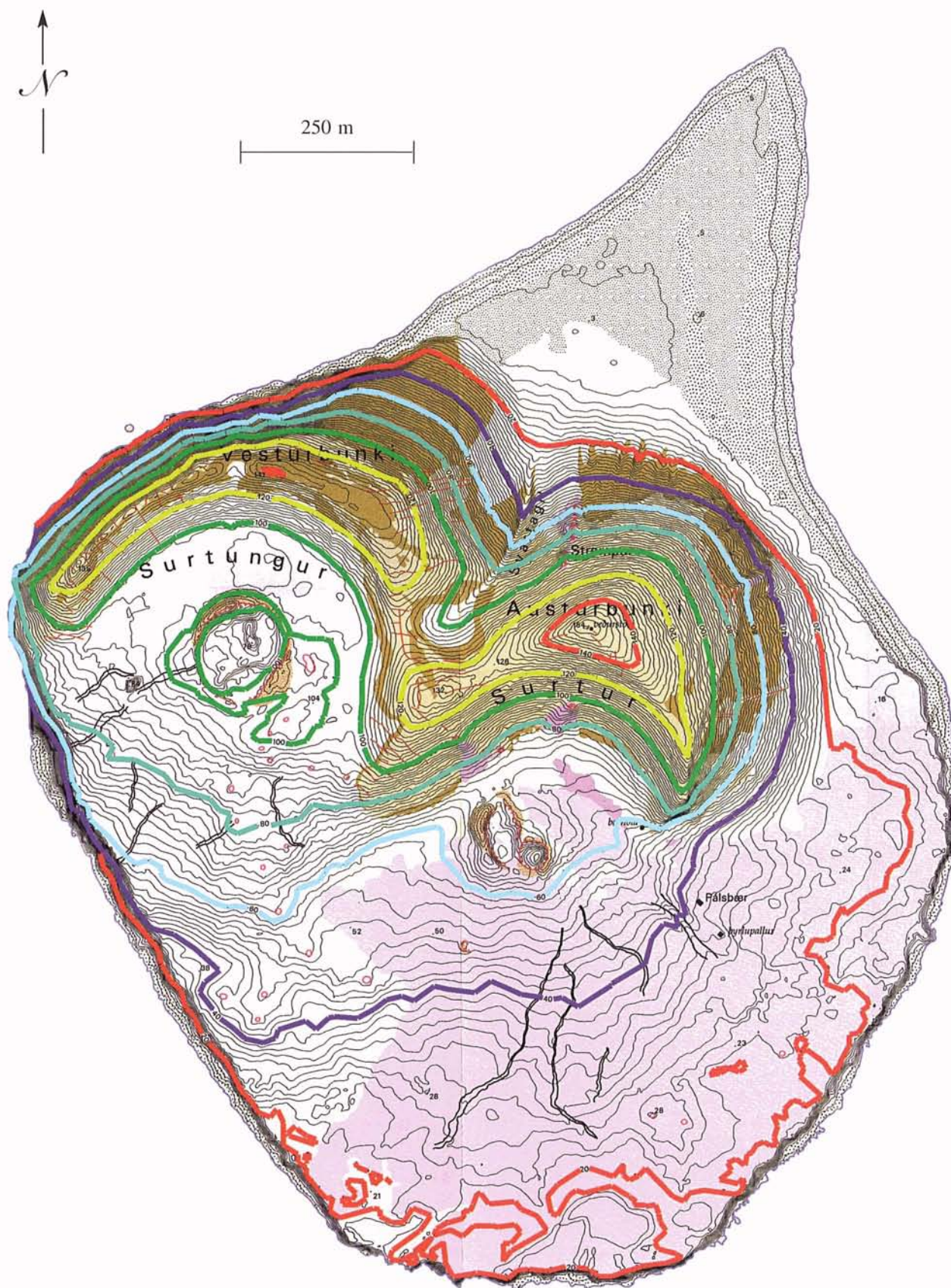


Figure 4. Geologic map of Surtsey (Jakobsson 2000) with the contour lines corresponding to Fig. 3a highlighted and color-coded using the color scheme of Fig. 3a.

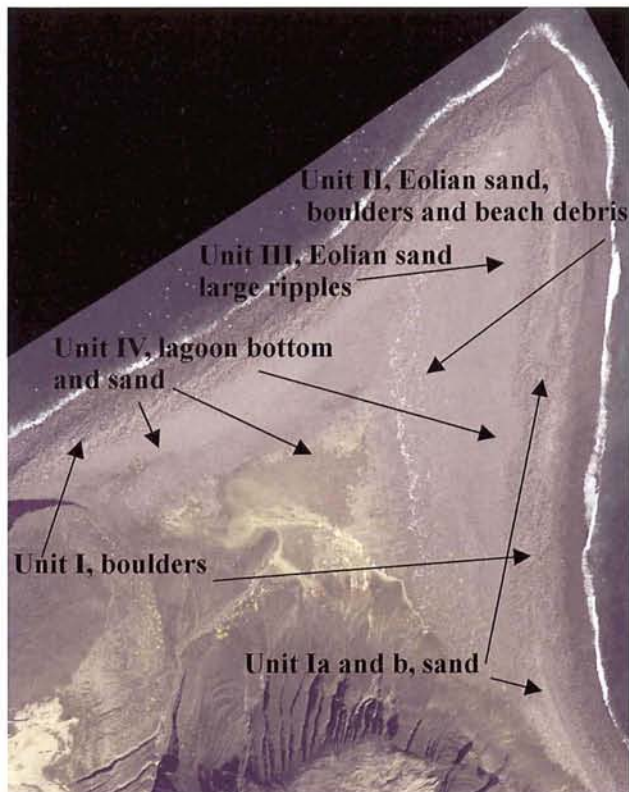


Figure 5. Aerial photograph of the northern tail of Surtsey. The figure shows the four different units that can be distinguished on the tail.

flows. The palagonite tuff and tephra units in the terrain of variable, partly steep surface slopes cannot be distinguished in the polarimetric image, either. It is, however, likely that the similar grain size and surface morphology of these two geologic units also would make it difficult to discriminate them even in areas with modest slope.

The lava type in the three different lava units is mainly shelly pahoehoe with occasional a'a streams. Since both of these types have very rough surfaces and thus high backscattering coefficients they are very difficult to distinguish in the polarimetric image. In general, however, pahoehoe and a'a are easily distinguished in radar images since pahoehoe flows normally have very smooth surfaces.

The EMISAR DEM

The digital elevation model and the slope map shown in Fig. 3 are based on two images recorded with the EMISAR's two C-band antennas. The C-band antennas are mounted on the side of the airplane with a vertical spacing of 1.05 m. The elevation contours are superimposed on a greyscale image showing the intensity of the received C-band pulses. The EMISAR DEM was found to closely resemble the elevation data in the geologi-

cal map (Jakobsson 2000). The elevations in the EMISAR DEM are relative to the mean of the sea surface but seem to reveal a slight offset relative to the elevations of Jakobsson (2000). Since it was difficult to identify a set of reference points in the C-band magnitude image for estimating the offset between the two DEMs, we lack a quantitative number but the offset is approximately 2 m (with the EMISAR elevation numbers being higher than those of Jakobsson 2000). Part of the offset could be due to low tides during the EMISAR mapping. In an interferometric measurement campaign specifically targeted on Surtsey, one can put out radar reflector targets close to the existing GPS stations on Surtsey and thus make it possible to tie the two DEMs together.

In some areas with poor signal to noise ratios such as on the slopes that are facing away from the radar the height accuracy of the EMISAR DEM is deteriorated. This effect may be seen on the N-side of Austurbunki, in particular on the yellow 120 m contour, which reveals high frequency variations. We were able to derive smoother contour lines resembling Jakobsson (2000) in this area by applying a 3x3 median filter to the data (thus reducing the spatial resolution). In other areas with good signal to noise ratio such as the southern lava fields the height accuracy is about 1 m.

An estimate of the volume of Surtsey (above sea level) can be calculated from the EMISAR

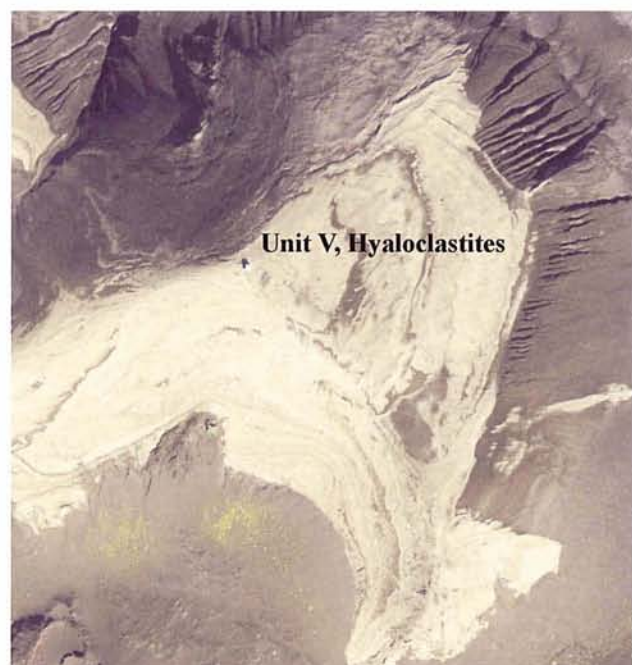


Figure 6. Aerial photograph of the Austurbunki hyaloclastites. The two units marked V and VI can be easily distinguished.

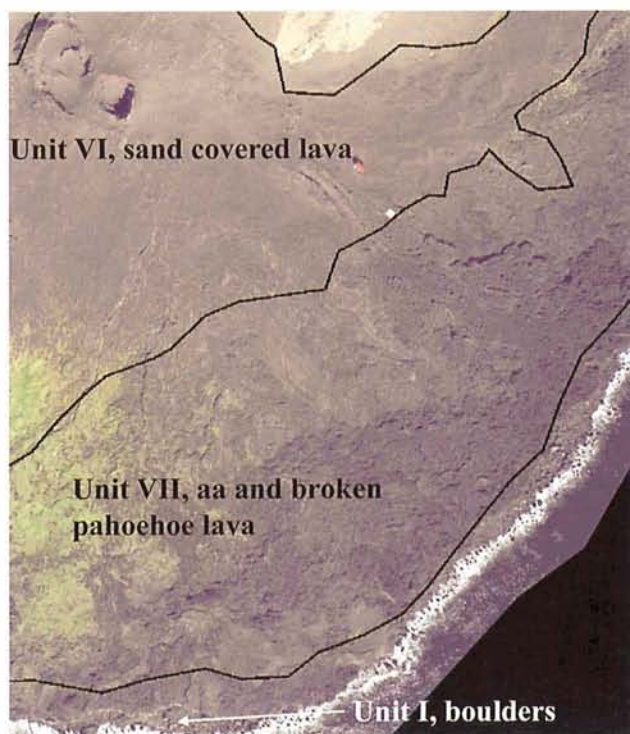


Figure 7. Aerial photograph of the southern most part of Surtsey. The units marked VI and VII are shown on this photograph. The main difference between the two units is the infilling of eolian sand in unit VI. The pahoehoe lavas within unit VII gain their roughness due to inflation and deflation of the surface during formation. Also, note that the width of unit I is larger than the true width seen in the aerial photograph. This is probably due to a combination of the lower resolution of the radar image and a slight broadening of the very strong backscattered signal from the coastal cliffs, boulders and waves along the coast. Multiple reflections from the boulders and vertical cliffs also contribute as these have a longer ray path and thus plot inland of the coast.

DEM. Since a small but very high fraction of the island is in the radar shadow the calculated volume is slightly lower than the actual volume. We estimate that the current volume of Surtsey above sea level as seen by the radar was 0.075 km^3 . The volume in the radar shadow was of the order of 0.002 km^3 and the true 1998 volume therefore $\sim 0.077 \text{ km}^3$. The mapped area of the island was 1.40 km^2 , which excludes about 0.03 km^2 in the radar shadow. The total area based on the EMISAR data was therefore 1.43 km^2 or 0.05 km^2 less than the estimate of Jakobsson (2000).

The DEM determined for Surtsey could be used to correct ERS 1/2 interferometric images for topography. Interferometric images could be of interest because of the large variation in subsidence rate which has been observed across Surtsey (Moore *et al.* 1992). Corrected ERS interferograms may provide information on deformation of Surtsey after 1991 when the ERS satellites came into operation.

CONCLUSIONS

A polarimetric SAR image, a digital elevation model, and a slope map of Surtsey have been produced based on SAR data recorded on August 13, 1998. The digital elevation model closely resembles the elevation data from the Geological map of Surtsey (Jakobsson 2000). The DEM has been used to calculate an area and volume above sea level of Surtsey of 1.43 km^2 and 0.077 km^3 .

The polarimetric images can be used to dis-



Figure 8. An overview over unit VI. The lavas are mostly filled with eolian sand derived from the volcanic ash formed in the Surtsey eruption. Stick for scale about 0.5 m high.



Figure 9. Overview of the pahoehoe lavas forming unit VII. The lavas are heavily fractured and tilted, although their original surface is smooth. Man for scale.

criminate between lava flows with varying degrees of roughness and/or sediment cover, and areas with different boulder size along the coast. These differences are correlated with field observations from the summer of 1998 and with the most recent geological map of Surtsey (Jakobsson 2000).

Radar mapping specifically targeted at Surtsey could be performed at much higher spatial resolution (down to 75 cm by 1.5 m for C- and L-band using the EMISAR system) than the resolution obtained in the regional mapping setup used here. The regional setup used in the 1998 mapping only allows us to study the large-scale features of Surtsey.

ACKNOWLEDGEMENTS

The Danish National Research Foundation supported this work. Freysteinn Sigmundsson and Sveinn P. Jakobsson are thanked for constructive reviews that helped to improve the paper significantly.

References

- Campbell, B.A. & M.K. Shepard 1996. Lava flow surface roughness and depolarized radar scattering. *J. Geophys. Res.*, 101, E8: 18941-18951.
- Dierking, W. 1999. Quantitative roughness characterization of geological surfaces and implications for radar remote sensing. *IEEE Trans. Geosci. Remote Sensing*, 37(5): 2397-2412.
- Dierking W. & H. Haack 1998. L-band polarimetric SAR signatures of lava flows in the northern volcanic zone, Iceland. *Proceedings of the International Geoscience and Remote Sensing Symposium IGARSS'98*, Vol 3, IEEE Catalog #98CH36174: pp. 1339-1341, Seattle, USA.
- Farr, T.G. 1992. Microtopographic evolution of lava flows at Cima volcanic field, Mojave Desert, California. *J. Geophys. Res.* 97, B11: 15171-15179.
- Gaddis, L.R. 1992. Lava flow characterization at Pisgah volcanic field, California, with multiparameter imaging radar. *Geol. Soc. Am. Bull.* 104: 695-703.
- Johnson, W.T.K. 1991. Magellan imaging radar mission to Venus. *IEEE, proceedings* (ISSN 0018-9219) 79: 777-790.
- Jakobsson, S.P. 2000. Geological map of Surtsey, scale 1:5000. Icelandic Institute of Natural History and Surtsey Research Society, Reykjavik.
- Madsen, S.N. & H.A. Zebker 1998. Imaging radar interferometry. In F.M. Henderson & A.J. Lewis (eds), *Principles & Application of imaging radar. Manual of remote sensing*, third edition, Vol 2, John Wiley & Sons, Inc., pp. 359-380.
- Massonnet, D. & K.L. Feigl 1998. Radar interferometry and its application to changes in the earth's surface. *Rev. Geophys.* 36(4): 441-500.
- Moore, J.G., S.P. Jakobsson & J. Hólmjárn 1992. Subsidence of Surtsey volcano, 1967-1991. *Bull. Volcanol.* 55: 17-24.
- Skriver, H., M.T. Svendsen, & A.G. Thomsen 1999. Multitemporal C- and L-band polarimetric signatures of crops", *IEEE Trans. Geosci. Rem. Sens.* 37(5): 2413-2429.
- Ulaby, F.T. & C. Elachi (eds) 1990. *Radar polarimetry for geoscience applications*. Artech House, Inc. 364 pp.
- van Zyl, J.J., H. A. Zebker, & C. Elachi 1990. Polarimetric SAR applications. In F.T. Ulaby & C. Elachi (eds). *Radar polarimetry for geoscience applications*, Artech House, Norwood, MA, 364 pp.