Remote sensing studies of the geomorphology of Surtsey, 1987–1991

By

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INTRODUCTION AND BACKGROUND

The volcanic island of *Surtsey*, formed by explosive submarine and effusive subaerial eruptions between November 1963 and June 1967, consists of a complex combination of primary and redeposited tephra and alkaline olivine basalt lava flows in a 2.5 km^2 area (Thorarinsson, 1967; Thorarinsson et al., 1964; Fridriksson, 1975). During the past 24 years, wave and wind erosion of this subaerial mid-ocean ridge (MOR) vent complex have modified Surtsey's coastal morphology, including the deposition of a 0.5 km-long northern peninsula (*ness*) composed of tephra and rounded lava fragments derived from the southern half of the island. Detailed geomorphologic and sedimentologic mapping of the various surface units now present on Surtsey has been accomplished throughout the history of the evolving island, most recently by Calles et al. (1980) and Ingolfsson (1980). On the basis of these studies, an effort to quantify the topographic characteristics of the primary geomorphic units on the island was initiated by the *National Aeronautics and Space Administration* (NASA) and the *United States Geological Survey* (USGS) in 1987. The objective has been to directly measure the microtopographic properties of the widest range of surface types possible, with special emphasis on the pristine or dynamic types. While large-scale topographic maps of Surtsey were prepared in 1968 and 1975 (Norrman, 1980; Norrman and Erlingsson, 1991; Calles et al, 1980), and geodetic levelling surveys have been carried out (Moore, 1980), there have been no recent attempts to geodetically determine the local topography of the island. Because of the rapid rates of geomorphic processes, such as erosion and deposition, on a small, geologically isolated volcanic island such as Surtsey, it is desirable to determine the meter-scale topographic character of its surface units and landforms, and later a remeasurement of the same surfaces to further quantify volumetric change, subsidence, and process rates. In addition, precise measurements of sub-meter-scale topography of pristine geologic surfaces provides necessary data for the investigation of whether various geologic processes demonstrate fractal or self-affine behavior at a range of length-scales within the interval 0.1 m to 1 km. Thus Surtsey offers a unique opportunity to apply new remote sensing techniques to the measurement of the evolving surface "roughness" characteristics of pristine geologic surfaces within an historically well-monitored environment.

In 1987, NASA and USGS scientists and engineers initiated a multi-year project with the aim of measuring geodetically controlled topographic cross-sections of Surtsey on a biannual basis using aircraft laser altimeters. With the availability of the Global Positioning System (GPS) geodetic surveying techniques, it has become possible to position high spatial and vertical resolution topographic profiles determined by means of airborne laser altimetry (ALA) to within 10 cm (Bufton et al., 1991). GPS-tracking of aircraft, however, for the purpose of correcting for the vertical and horizontal positioning errors is in its infancy, and as the technique matures, our expectation is that annual surveys of the topography of rapidly evolving volcanic islands such as Surtsey could become routinely possible. In May of 1987, however, GPS tracking of aircraft motion was relatively untried, and this approach was attempted in parallel with previously proven methods that employed aircraft inertial navigation systems (INS), roll and pitch gyros, and vertical accelerometers. One of our colleagues, W. Krabill (NASA), has facilitated the application of GPS techniques to the problem of multi-temporal topographic monitoring of surfaces on Surtsey and elsewhere, and the new GPS-tracked ALA dataset acquired in September of 1991 provides 10–15 cm positional control on the basis of analyses conducted in the field (i.e., surveys of airfield runways).

The intent of this report is to summarize the ALA-based topographic data collected during our 1987, 1989, and 1991 remote sensing campaigns, and to highlight the preliminary results of our geologic analyses of these new forms of geomorphic data. In addition, we describe the initial results of a brief microtopographic field experiment conducted on Surtsey on 25 September 1991, as well as ancillary remote sensing data that has been acquired for the island since 1987 (Garvin and Williams, 1988). Once the 1991 ALA dataset is fully reduced and analyzed, justification for conducting future, geodetically controlled ALA overflights on a regular basis will be demonstrated.

A final objective in our topographic remote sensing studies concerns the morphometry of the vent craters, especially in comparison with craters associated with other Icelandic volcanoes. The morphometry of pristine volcanic craterforms is of interest to NASA, in part because of the commonplace occurrence of such features at various scales on all of the terrestrial planets (Venus, Mars, and the Moon). Indeed, NASA's *Magellan* mission to the planet Venus has revealed millions of volcanic edifices, many of which display summit craters reminiscent of those on Surtsey and elsewhere in Iceland (Garvin and Williams, 1990).

The format of this report is centered around examples of the data collected and a discussion of new methods for quantifying landscapes at very high spatial and vertical resolutions (i.e., finer than 1 meter in most cases). Details about the aircraft remote sensing instruments beyond those summarized in this report can be found in Bufton et al. (1991), and in Garvin and Williams (1990).

DATA ACQUIRED

In May of 1987, a NASA P-3 aircraft equipped with an airborne laser altimeter known as the *Airborne Oceanographic Lidar* (AOL) was deployed to acquire high-spatial resolution topographic cross-sections of Surtsey with sub-meter vertical control. The AOL was operated in a terrain mapping mode in this case at an altitude of 300 to 400 m above sea level (asl). The instrument utilizes a nitrogen laser transmitter together with a telescope and receiver electronics to acquire 400 pulses per second sampling of the topography along the P-3 aircraft's nadir track on the surface. The relative vertical resolution of each observation is better than 5 cm, and at an overflight altitude of 400 m the surface footprint (laser spot size on the ground) is approximately 40 cm in diameter. Thus, the topography is highly oversampled along the ground-track, because a typical P-3 aircraft velocity is 90–100 meters per second. Figure 1 illustrates four of the ALA profiles acquired on 28 May 1987 using the AOL in the NASA P-3 aircraft. GPS-tracking of the P-3 was attempted, but only the profile designated "GV305" (lowermost in Fig. 1) utilized the full benefits of GPS for vertical aircraft motion removal. The remaining three cross-sections were corrected using traditional vertical accelerometry, roll and pitch gyro, and INS techniques, and have an approximate vertical precison of better than 1 m.

Figure 1 displays four different azimuthal cross-sections of Surtsey. The profile designated "GV205" extends from west to east across the m-shaped pair of tephra rings. For each profile in this figure, four generalized topo-

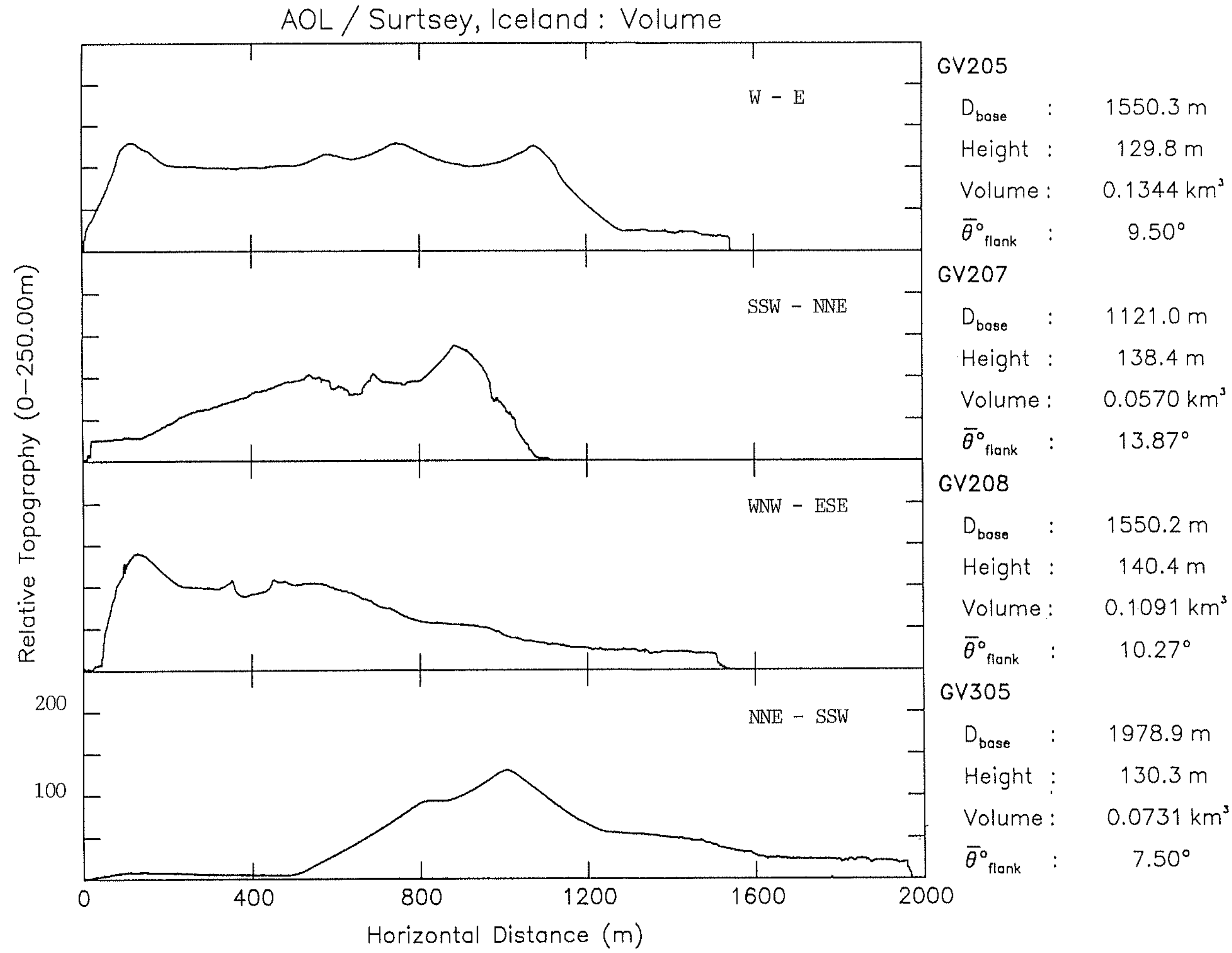

Fig. 1. Representative airborne laser altimeter topographic cross-sections of Surtsey acquired in 1987 using the AOL instrument. Spatial resolution is ~ 0.33 m, with vertical control at sub-meter levels (resolution is 5 cm point-to-point). Profile *GV205* is oriented from W to E, profile *GV207* extends from SSW to NNE across Surtur II crater, profile *GV208* traverses the island from WNW to ESE, and profile *GV305* bisects the island from NNE to SSW. Simple morphometric parameters are listed to the right of the topographic profiles. See text for details and figure 5 for location of the flight lines.

graphic parameters are given. The total length of the subaerial expression of the island is listed as *Dbase*, while the maximum height is listed under "*Height*". The above-water land volume of Surtsey is computed by numerical integration of each cross-section and listed under "*Volume*", and the average local slope of the entire cross-section is described by *∅°flank*. These parameters provide a framework for comparison of the different topographic profiles. The profile designated "GV207" extends across the Surtur II vent from SSW to NNE; profile "GV208" traverses Surtur II from from WNW to ESE; and profile "GV305" crosses the central region of the northern ness and the middle of the island from NNE to SSW. We have used these data to estimate the above water volume of materials exposed on Surtsey circa 1987 (i.e., *Volume* parameter at right of Fig. 1), and to compare these values with those for other small volcanoes within Iceland (Fig. 2). The numerical integration algorithm used in estimating the land volume from topographic profiles utilizes a straightforward "volumes of revolution" method, and as such assumes circular symmetry. As Surtsey does not display a circular perimeter, the computed volume estimates are best used as reasonable lower and upper bounds to the actual land volume.

Thorarinsson (1967), Calles et al. (1980), Jakobsson and Moore (1980), and Norrman and Erlingsson (1991) describe the apparent volume of the entire Surtsey system (submarine plus subaerial) as 1.1 to 1.2 km^3, with 60 to 70% of this volume manifested as tephra. A weighted average of the subaerial volume of Surtsey computed on the basis of the four

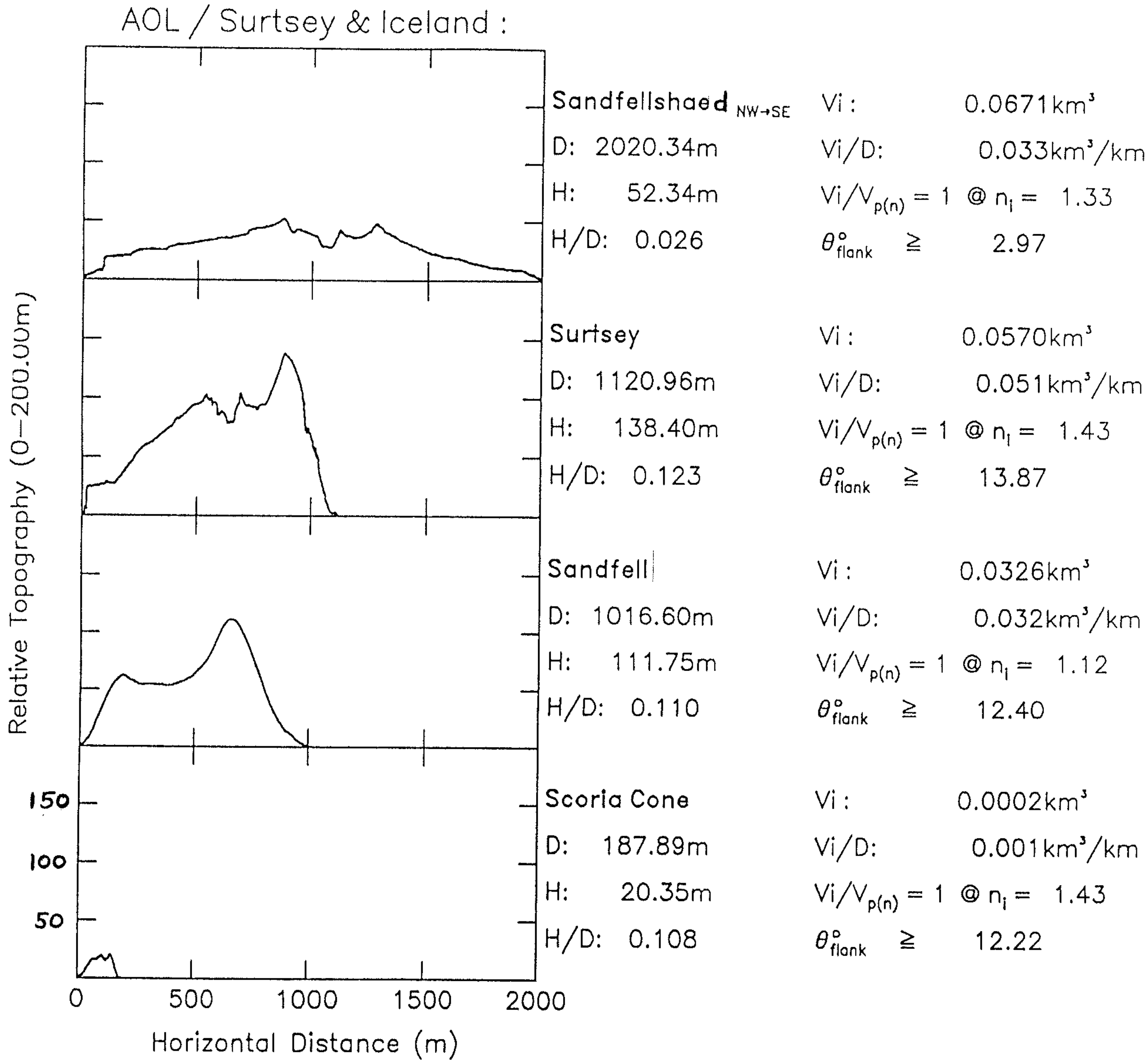

Fig. 2. Airborne laser altimeter topographic cross-sections of a representative suite of Icelandic mid-ocean-ridge volcanic landforms, including a SSW to NNE transect of Surtsey (GV207; see Fig. 1). All profiles except that for Surtsey have ~ 15 cm vertical control on the basis of GPS-tracking. All data are from the AOL instrument with 0.33 m horizontal spacing along track. Data for the Sandfellshaed lava shield, the Sandfell hyaloclastite ridge, and the Reykjanesskagi scoria cone were acquired in May of 1989, while that for Surtsey is from the May 1987 survey. Morphometric parameters listed to the right of the profiles are discussed in the text.

ALA profiles shown in Fig. 1 is 0.11 km^3 (similar to that of profile GV208 in Fig. 1), which is only ~ 10% of that computed for the entire edifice. In order to derive this estimate, we have measured the coastal outline of the island from 1989 aerial photographs (see Fig. 5) and then we have computed the fraction of the outline that is best represented by one of our ALA-based topographic cross-sections (Fig. 1). A simple weighted average of the volumes computed from the profiles using the weightings estimated from the coastal outline yields a volume of 0.11 km^3 to within 10%. This is consistent with the classification of Surtsey as a composite submarine volcano not unlike the subglacial table mountains of the Iceland mainland (Williams et al., 1983). Therefore, only 0.033 km^3 of effusive lava materials apparently cover the tephra core of the island in the form of a carapace of geologically more resistant materials. This lava volume is within a factor of two of that typical of the smaller Icelandic lava shields (Garvin and Williams, 1990; c.f., Fig. 2); hence we suggest that it is a reasonable estimate, at least for the subaerial inventory. Furthermore erupted lava volumes in the 0.01 to 0.10 km^3 range are apparently typical of limited-duration subaerial eruptions within all of Iceland (Garvin and Williams, 1990) and at other locales on the Mid-Atlantic Ridge (e.g., the Azores), and may be related to fundamental limits on the sizes of near-surface magma storage zones in MOR geologic settings.

COMPARISON WITH TYPICAL ICELANDIC VOLCANIC LANDFORMS

It is instructive to compare representative topographic cross-sections of typical subaerial MOR volcanic landforms with Surtsey. To facilitate such comparisons, we conducted an aircraft ALA remote sensing campaign in May 1989 using the AOL sensor together with a differential GPS tracking system. As part of our remote sensing experiment, we obtained geodetic topographic profiles of a Holocene lava shield within the western part of the Reykjanes peninsula known as *Sandfellshaed*, as well as cross-sections of the *Sandfell* hyaloclastite ridge just to the NE of Sandfellshaed, and of a small scoria cone near the *Eldvarpahraun* lava flow field (Fig. 2). In Fig. 2, we compare the 1987 SSW to NNE Surtsey cross-section (designated GV207 in Fig. 1) with a NW to SE profile of the Sandfellshaed lava shield, a NW to SE (orthogonal to the long axis) profile of the Sandfell hyaloclastite ridge, and a S to N transect of a small basaltic scoria cone. From these topographic data, we have computed the aspect ratios of the volcanoes (*H/D*), the total edifice volume (*Vi*), a polynomial shape parameter $\boldsymbol{n}$ (where $\boldsymbol{n} = 1$ represents a cone, $\boldsymbol{n} = 2$ a paraboloid etc.), and the average flank slope *∅°flank*. It is clear that Surtsey demonstrates an aspect ratio that strongly reflects its construction by means of tephra accumulation as a result of hydromagmatism; the subglacial Sandfell volcano illustrates a similar aspect ratio, while that of the monogenetic lava shield Sandfellshaed is a factor of 4 to 5 lower, reflecting its origin by purely effusive activity. All four of the volcanoes illustrated in Fig. 2 are predominantly conical in cross-section, although only the orthogonal profile across the Sandfell hyaloclastite ridge is purely conical ($\boldsymbol{n} = 1.12$). There is a tendency to develop a slightly concave (down) cross-section in almost all eruptions from a central vent, so that the polynomial shape factor $\boldsymbol{n}$ tends to values such as 1.5 to 2.0 (Garvin and Williams, 1990). While Surtsey and Sandfellshaed display similar edifice volumes (*Vi*) on the basis of the ALA profiles illustrated in Fig. 2, when one compares their volume productivities, here defined as the ratio of *Vi* to a typical basal diameter *D* (*Vi/D*), Surtsey is clearly the more volumetrically productive per unit length than simple effusive lava shield volcanoes such as Sandfellshaed. Indeed, because of its volumetrically dominant core of explosive tephra, Surtsey demonstrates a relatively large *Vi/D* ratio in comparison with most small basaltic volcanoes in general.

PRIMARY VENT CRATER SURTUR II

The most developed vent crater on Surtsey is *Surtur II*, the westernmost of the primary craters on the island (Figs. 3 and 5). Surtur II is the summit crater associated with the subaerial lava shield that built the pahoehoe lava carapace over most of the western third of the island. Figure 3 is a vertical aerial photograph of Surtur II acquired using a 70 mm *Hasselblad* camera system which was operated synchronously with the acquisition of our 1991 geodetic ALA topographic profiles. This view of the crater illustrates its relatively complex formation history. The general morphology of Surtur II suggests that the crater has undergone widespread interior collapse of its onetime continuous lava lake floor, yet its rim region reflects a stage in which lavas and scoria spilled over the edge to construct a lava ridge, perhaps analagous to the lava ring features observed on the mainland of Iceland (i.e., Eldborg; see Williams et al., 1983). Smooth appearing lava terraces within Surtur II apparently represent pre-existing lava lake levels, before the drainback processes that were established once flank eruptions became more dominant in the construction of the lava shield in southwestern Surtsey.

It is apparently useful to compare the detailed topography of various end-member volcanic craters in order to investigate whether there are systematic variations in their morphometries perhaps reflective of specific growth histories or of the mechanics of formation.

Fig. 4 illustrates three simple volcanic craters, including a 1987 SSW to NNE transect of Surtur II, a typical ALA cross-section of the summit crater at Sandfellshaed, and that of the SP Mountain basaltic-andesite scoria cone in northern Arizona, USA. We display the SP Cone pit crater because it is the most canonical example of a pit within a scoria cone for which we have GPS-tracked laser altimetry data. The source of the data for the Surtsey and Sand-

Fig. 3. 70 mm *Hasselblad* vertical aerial photograph acquired on 24 May 1991 from an altitude of ~ 460 m from a NASA P-3 aircraft. The image illustrates the morphology of the Surtur II vent crater, which has an average diameter of ~ 150 m and a typical depth of 25 m.

fellshaed profiles in Fig. 4 is the AOL sensor previously described, while that for SP Cone is NASA's *Airborne Terrain Laser Altimeter System* (ATLAS) which acquired topographic profiles of Northern Arizona volcanoes in October of 1989. The spatial resolution of ATLAS is 1.5–2 m depending on sensor altitude, and the vertical resolution is 15 cm (Bufton et al., 1991).

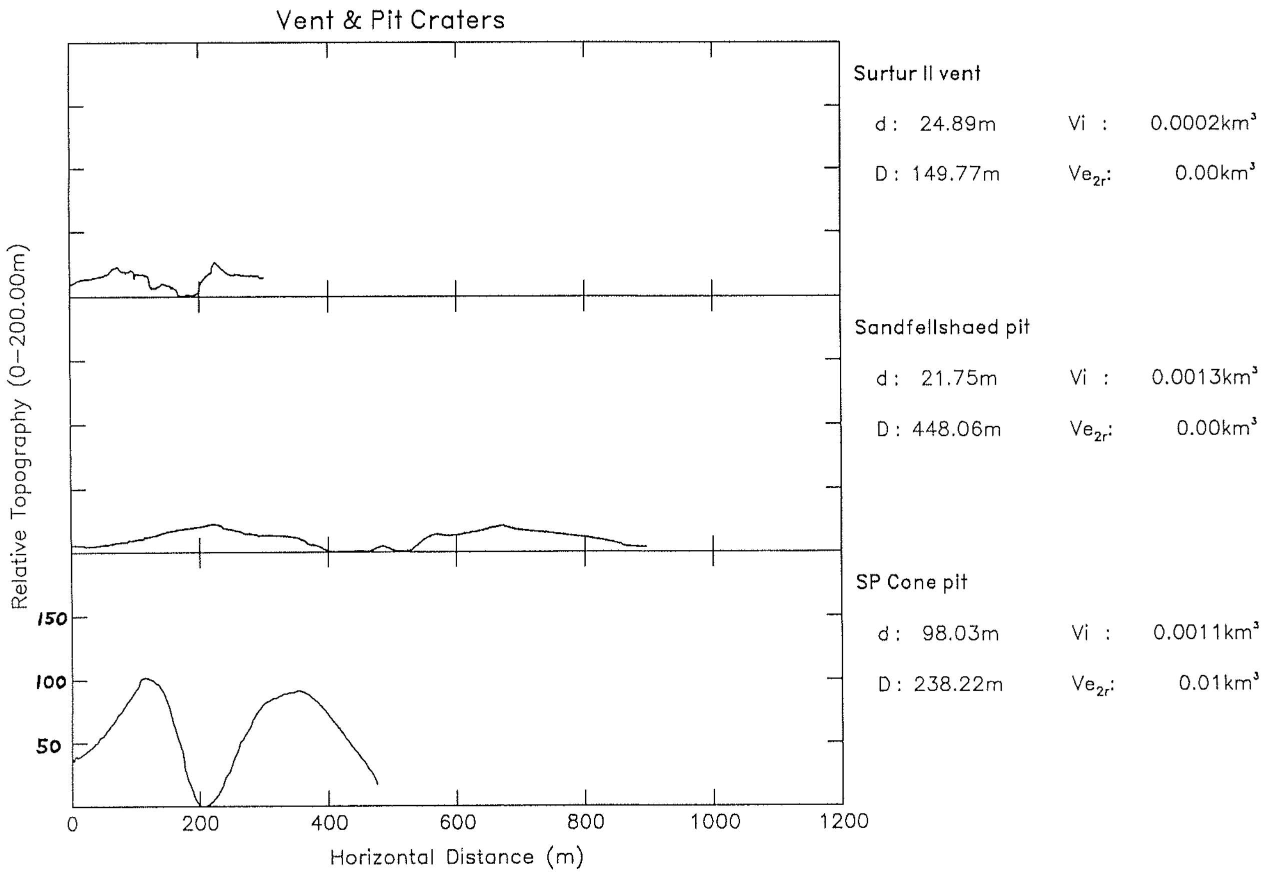

Fig. 4. Airborne laser altimeter topographic cross-sections of three volcano summit craters, including the 1987 SSW to NNE profile of Surtur II on Surtsey (top), the SW to NE profile of the Sandfellshaed lava shield summit crater acquired in 1989, and a 1989 *Airborne Terrain Laser Altimeter System* (ATLAS) profile of the *SP Mountain* basaltic-andesite scoria cone in northern Arizona, USA (with 2 m diameter footprints in contrast to the 0.33 m diameter footprints for the AOL data). All profiles display sub-meter vertical control. Simple depth *d*, basal diameter *D*, edifice volume *Vi*, and exterior volume *Ve* (within one diameter of the rim crest) geomorphic parameters are listed to the right of the profiles.

Figure 4 clearly shows the difference in appearance of the three craters. To quantify the crater shape differences, we can analyze the hypsometric properties of each crater by constructing a cumulative height frequency distribution and then computing the best-fitting power-law relationship to the height-frequency data. If N_z represents the cumulative percentage of heights greater than some height z, then we can find the parameters $\boldsymbol{k}$ and β so that:

$$N_z = \boldsymbol{k}\, z^{\beta},$$

where the exponent β indicates the slope of the hypsometric distribution. If we compute such power law relationships for Sandfellshaed, Surtur II, and the SP Cone pit, we find that:

$$N_z = 267\, z^{-0.96}$$

for Surtur II (i.e., $\boldsymbol{k} = 267$, and $\beta = -0.96$), whereas $\boldsymbol{k} = 171$ and $\beta = -0.80$ for the summit crater of the Sandfellshaed lava shield. For the SP Cone pit crater, $\boldsymbol{k} = 433$ and $\beta = -0.61$. The appreciable differences in the power-law slope values (the β's) for the three craters reflects their formation and degradation histories. The pristine Surtur II vent crater was formed by a combination of collapse (lava-lake foundering due to magma withdrawl) and extensive fire-fountaining and possibly lava spillover, while the apparently simpler Sandfellshaed summit crater was predominantly formed by collapse of a summit source vent lava lake as magma withdrew in anticipation of flank eruptions. Improved geodetic ALA topographic profiles of both Surtur II and the central portion of Surtur I were collected as part of our 1991 aircraft remote sensing campaign to Iceland and will be described later in this report.

NORTHERN NESS

As part of our data acquisition sequence in May of 1989, we acquired W to E cross-sections of the middle and northern portions of

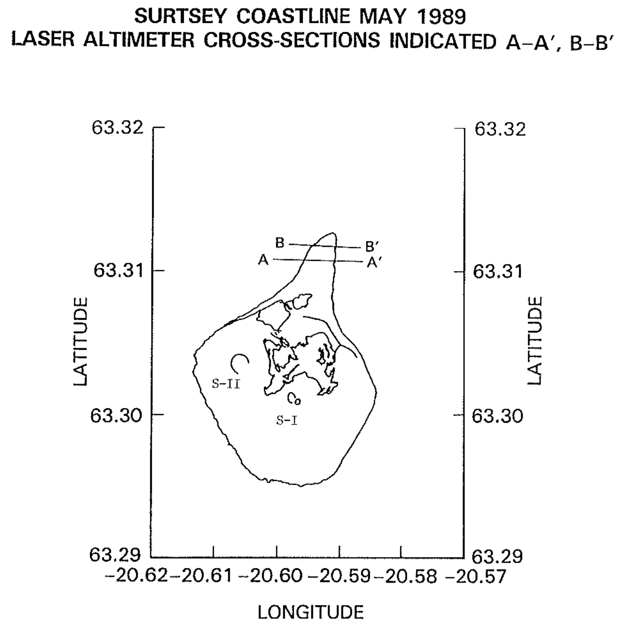

Fig 5. Outline map of Surtsey circa May 1989 illustrating the location of high-resolution topographic profiles of the northern ness acquired with the AOL system, and the other flight lines over the island described in the text.

the northern ness of Surtsey with enhanced spatial resolution. This was accomplished by operating the NASA P-3 aircraft at a flight altitude of 100 m, permitting the 400 pulses per second mode of the AOL instrument to acquire profiles with 20–25 cm horizontal sampling. Figure 5 illustrates the position of our extremely high resolution ALA profiles, acquired on 28 May 1989. In Figure 6, an E to W cross-section of the ness is shown in which the high frequency structure in the profile represents the cross-sections of individual boulders in the sub-meter-size range. In addition, it is possible to observe the nature of the wind-driven wave structure around Surtsey from the ALA data over the ocean adjacent to the island. The subtle concave character of the central, interior portion of the ness is apparent, in part a consequence of the deposition and erosion cycle in this part of the Surtsey system (Norrman, 1980; Moore, 1980; Norrman and Erlingsson, 1991). Our field experiment of 1991 confirmed that the 0.5 to 1.0 m scale berms seen in the ALA topography of the northern ness are wave-transported boulder berms derived from the eroding lava flows of the SW part of Surtsey.

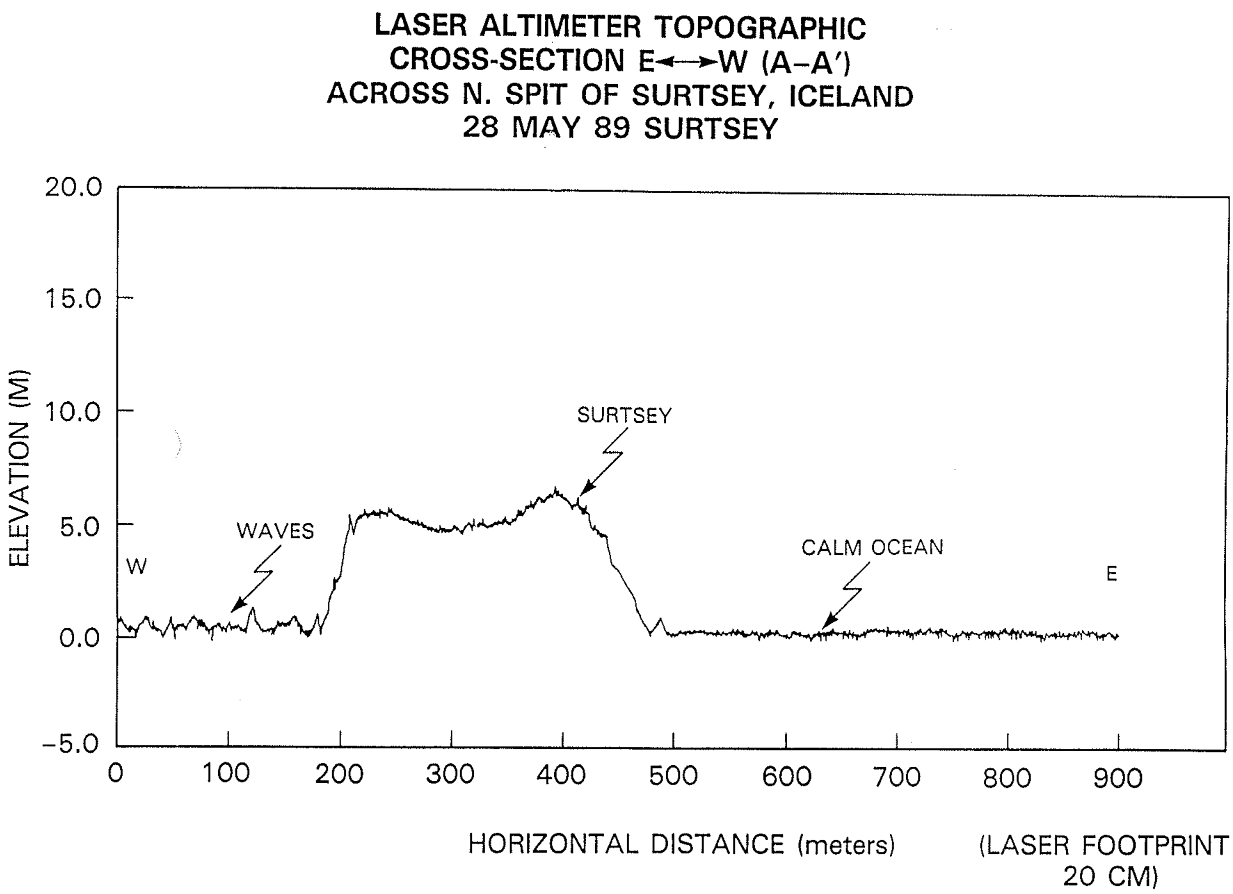

Fig. 6. East to west topographic profile across the northern ness of Surtsey acquired with the AOL instrument in May of 1989. This profile sampled the topography of the ness with ~ 20 cm spatial resolution. The "bumps" that can be observed across the ness represent boulders in the sub-meter-size range.

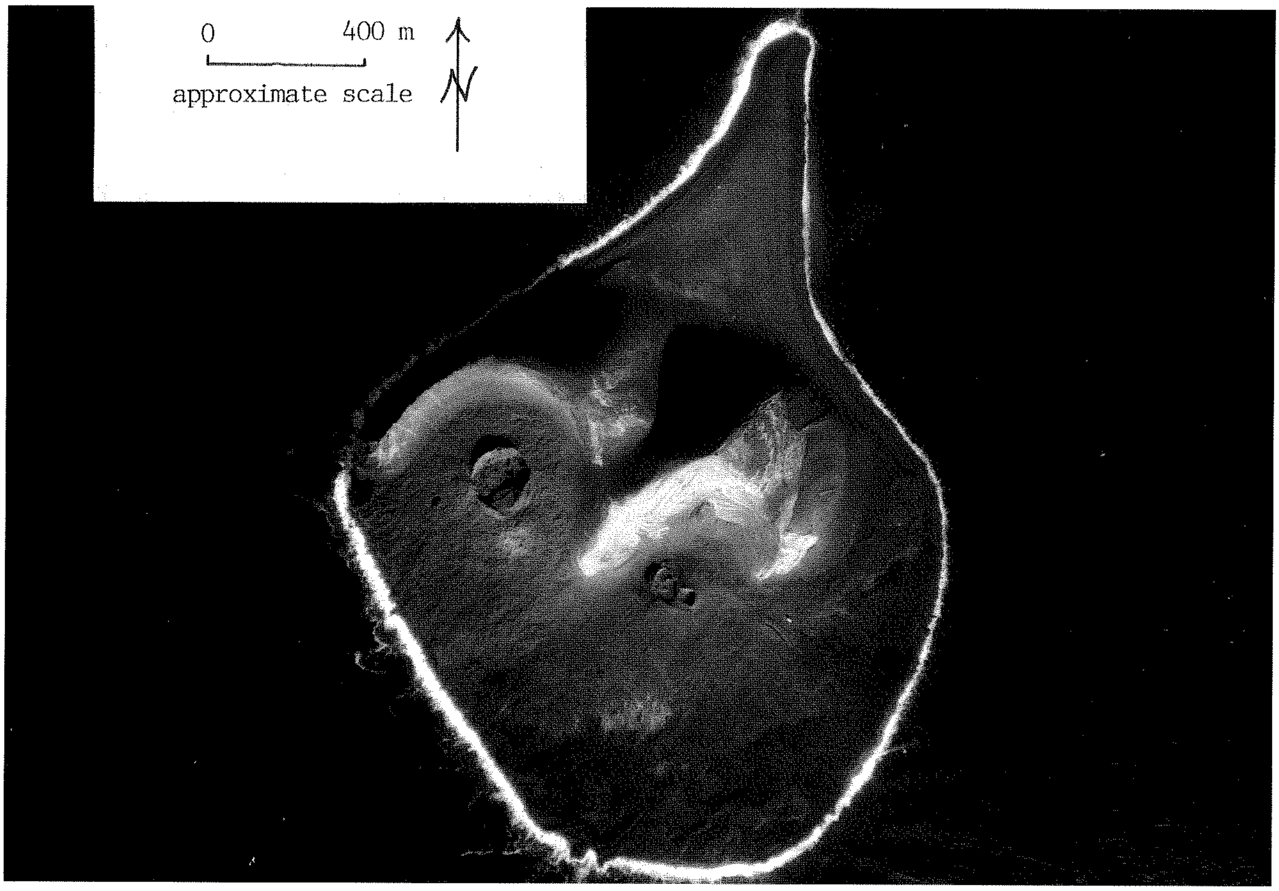

Fig. 7. 70 mm *Hasselblad* vertical aerial photograph of Surtsey acquired on 23 May 1991 from the NASA P-3 aircraft operating at ~ 3.3 km altitude (10,000 feet asl). This image was acquired at 11:30 local time (UT).

The topographic remote sensing data collected in 1987 and 1989 provided us with a mechanism for quantifying the microtopography of the more significant geomorphic units and volcanic features on the island. In 1991, we returned to Iceland to conduct a topographic remote sensing mission in which our objective was to measure the sub-meter scale topography of all the major units on Surtsey, but also to do so in a manner so that repeat overflights in later years can be carried out to quantify microtopographic changes, if any. All of the data collected in the 1991 topographic remote sensing campaign was required to have associated GPS-determined positional information at the 10 cm level. This entailed the use of multiple GPS receivers within the aircraft and GPS control of the autopilot (i.e., to facilitate reflying the same transect to within 10 m on the ground of the initial overpass). Topographic monitoring with geodetic-levels of accuracy for the most dynamic regions of Surtsey is our long-range objective, and the 1991 project was intended to provide baseline data for the purpose of comparisons with future datasets.

1991 FLIGHT AND FIELD MISSION

Figure 7 illustrates Surtsey as seen from a NASA P-3 aircraft on 23 September 1991. The 70 mm *Hasselblad* vertical aerial photograph is one of a series of overlapping frames acquired in order to document our ALA datasets. The photograph illustrated in Fig. 7 was taken by photographic engineer W. Lazenby (NASA) from an altitude of 3300 m asl at approximately 11:30 local time.

Figure 8 illustrates a "raw" laser altimeter profile (from S to N) of the middle region of Surtsey, acquired by the ATLAS sensor with a horizontal sampling resolution of 1.7 m and a vertical resolution of better than 15 cm. All of the profiles displayed in this report from our 1991 mission to Surtsey are not yet corrected for aircraft motion using the simultaneously acquired differential-GPS tracking data, but first-order roll-and-pitch variations have been removed, in some cases. Our calculations suggest that "raw" ATLAS data has a vertical integrity of 1–3 meters over a length scale of ~ 1 km. In Fig. 8, and all other preliminary 1991 ALA datasets, the horizontal axis is in units of

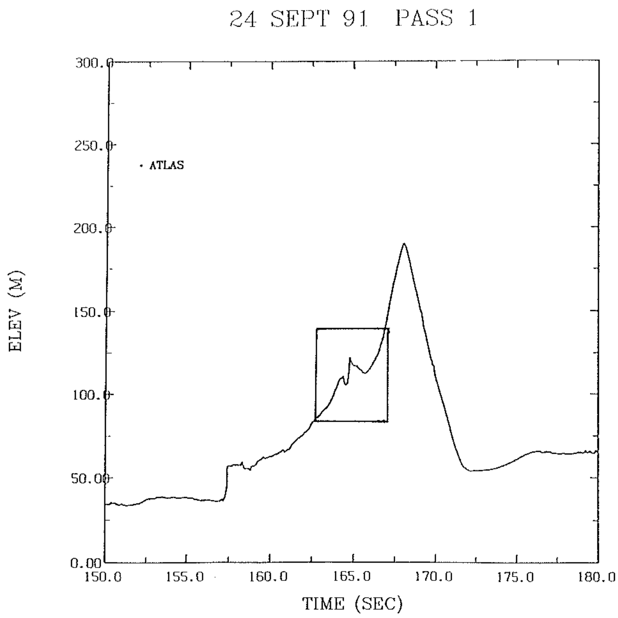

Fig. 8. Uncorrected ATLAS laser altimeter profile across Surtsey from S to N acquired on 24 May 1991 at 330 m elevation. The ATLAS instrument has a spatial resolution of about 1.7 m from this altitude, with a vertical resolution of better than 15 cm. Surtur I can be observed in this profile. Aircraft motion has not been removed from these preliminary data (i.e., GPS trajectories with which to correct the data are still forthcoming for all of our 1991 data). The horizontal axis is in units of time (seconds), and can be converted to horizontal distance using the observation that the NASA P-3 aircraft had an average forward velocity of 90 meters per second (i.e., 1 sec corresponds to 90 m along the ground).

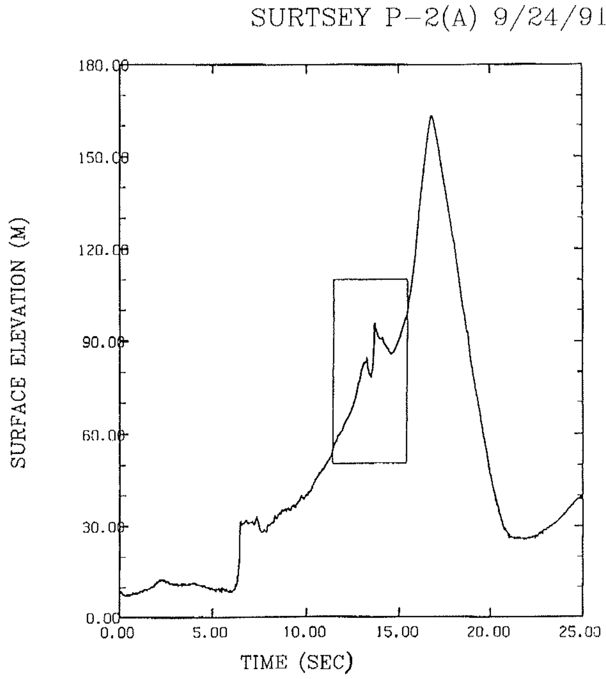

Fig. 10. South to north topographic cross-section of Surtsey acquired with the AOL sensor on 24 May 1991 from an altitude of 330 m. These data are uncorrected for aircraft motion. The AOL sampled the topography of Surtsey at 900 pulses per second in its 1991 configuration, which corresponds to a measurement every 10 cm along the ground-track. The inset box highlights the topography of Surtur I. These data have approximately 15 times greater horizontal sampling resolution than the ATLAS data illustrated in Figs. 8 and 9. The start of the pass was at 11:41:35 UT.

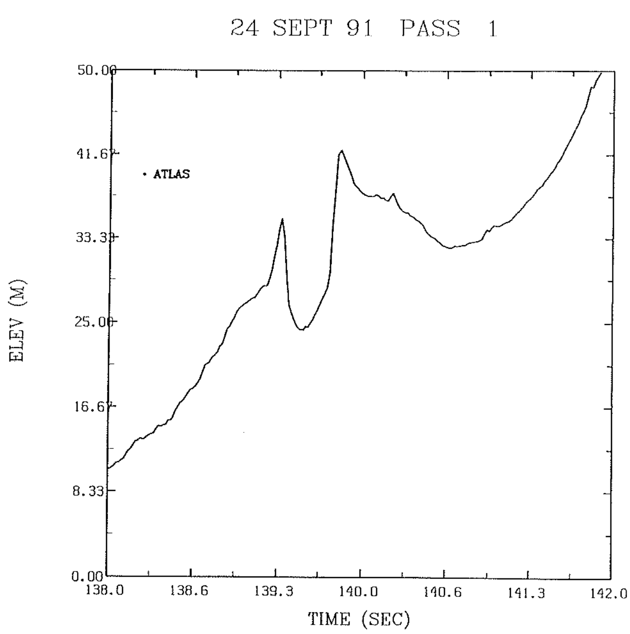

Fig. 9. Enlargement of a section of the topographic cross-section shown in Fig. 8 which illustrates the topographic structure of the *Surtur I* vent crater. One second corresponds to ~ 90 m on the surface in this and all other profiles from the 1991 remote sensing campaign.

time (seconds), where 1 second represents approximately 90 m. Figure 8 demonstrates that Surtsey is dominated by two indurated tephra rings (Jakobsson, 1972) which form a crude m-shaped outline across the middle portion of the island. A closeup ATLAS view of a S to N cross-section of Surtur I is illustrated in fig. 9. The largest crater in Surtur I is apparently more than 10 m deep and only tens of meters in width.

Figure 10 shows the S to N cross-section of Surtsey acquired by means of the AOL instrument operating at 900 pulses per second at 330 m aircraft altitude (i.e., one 30 cm diameter laser footprint spatially positioned every 10 cm along track). An inset box highlights the region around Surtur I, and Figure 11 shows a closeup of the vent crater. The high frequency structure in the floor of Surtur I represents a lava terrace which sits above the eolian drift sand that fills the crater's interior. Contrasting Figures 9 and 11 illustrates the effect of increasing the spatial resolution in topographic profile data by a factor of 10, from ~ 1.7 m

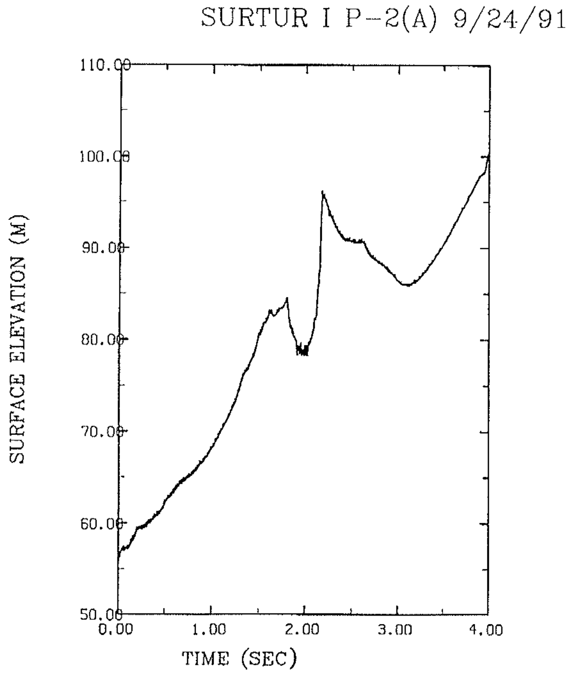

Fig. 11. Enlargement of section of topographic cross-section shown in box in Fig. 10 highlighting the *Surtur I* vent crater at high spatial resolution. Compare with the lower spatial resolution view (1.7 m) from the ATLAS sensor shown in Fig. 9. One second on the horizontal axis corresponds to 90 m. The start of the pass was at 11:41:46.5 UT.

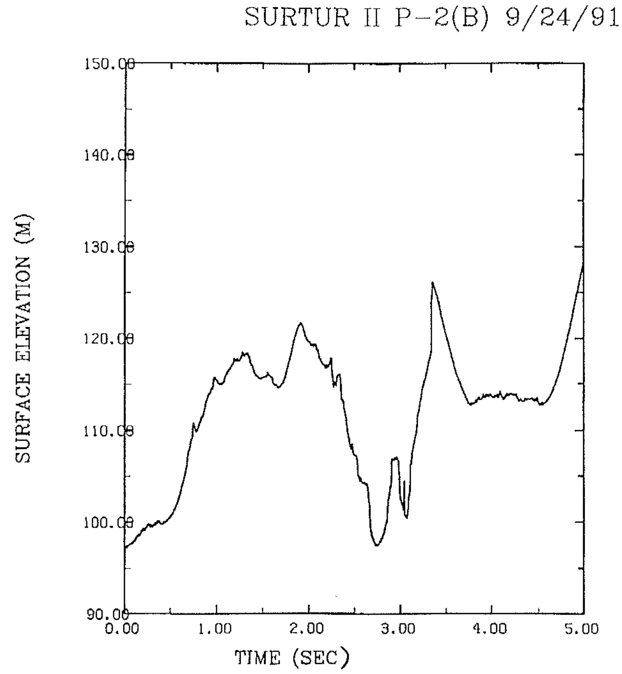

Fig. 13. Enlargement of region shown in the inset in Fig. 12. The clearly-defined depression is the pristine *Surtur II* vent crater. One second represents 90 m on the surface. The start of the pass was at 11:57:31.5 UT.

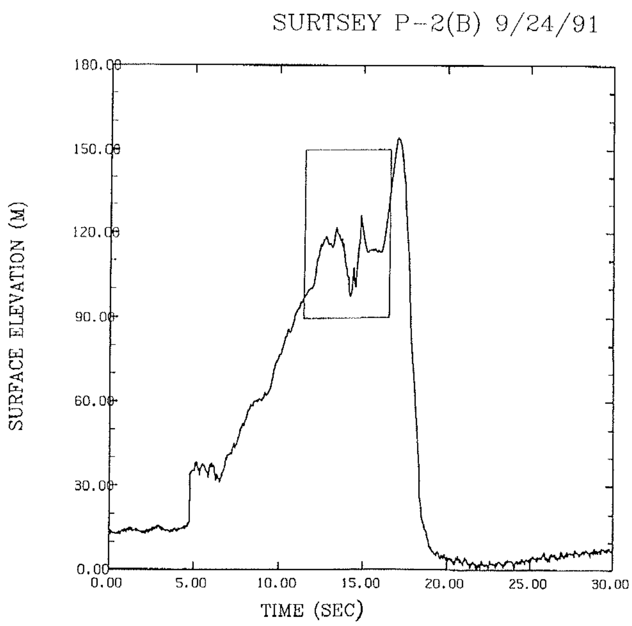

Fig. 12. Topographic cross-section of Surtsey acquired in a SSE to NNW direction using the AOL sensor on 24 May 1991 from an altitude of 330 m. Horizontal resolution is ~ 10 cm. The inset box highlights the Surtur II vent crater. The start of the pass was at 11:57:20 UT.

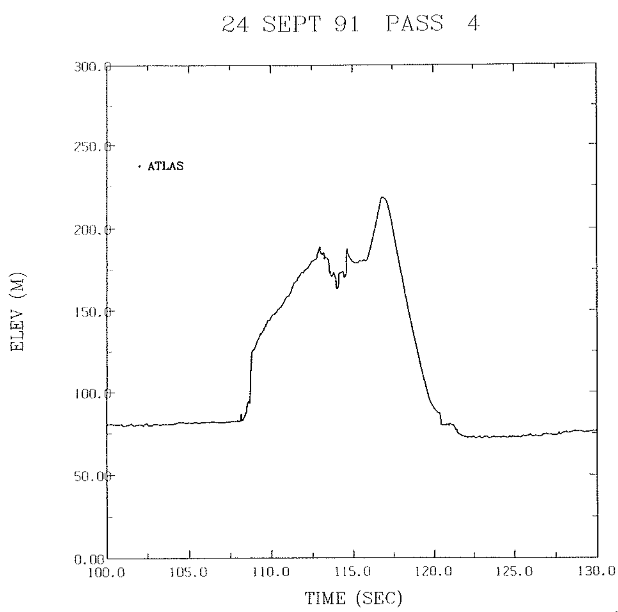

Fig. 14. Topographic cross-section of Surtsey in a SSW to NNE direction acquired on 24 May 1991 using the ATLAS sensor operating at 460 m elevation from a NASA P-3 aircraft. One second corresponds to 90 m along the surface. The ATLAS data have a horizontal resolution of ~ 1.7 m and a vertical resolution of better than 15 cm. Compare with the AOL profile shown in Fig. 12.

(Fig. 9) to ~ 0.10 m (Fig. 11) for the Surtur I vent crater.

As part of our 1991 mission, we acquired data in two different azimuths across the Surtur II vent crater, including that highlighted in Figures 12 and 13. These two Figures illustrate how the AOL sensor measured the detailed topography of the Surtur II vent at a sam-

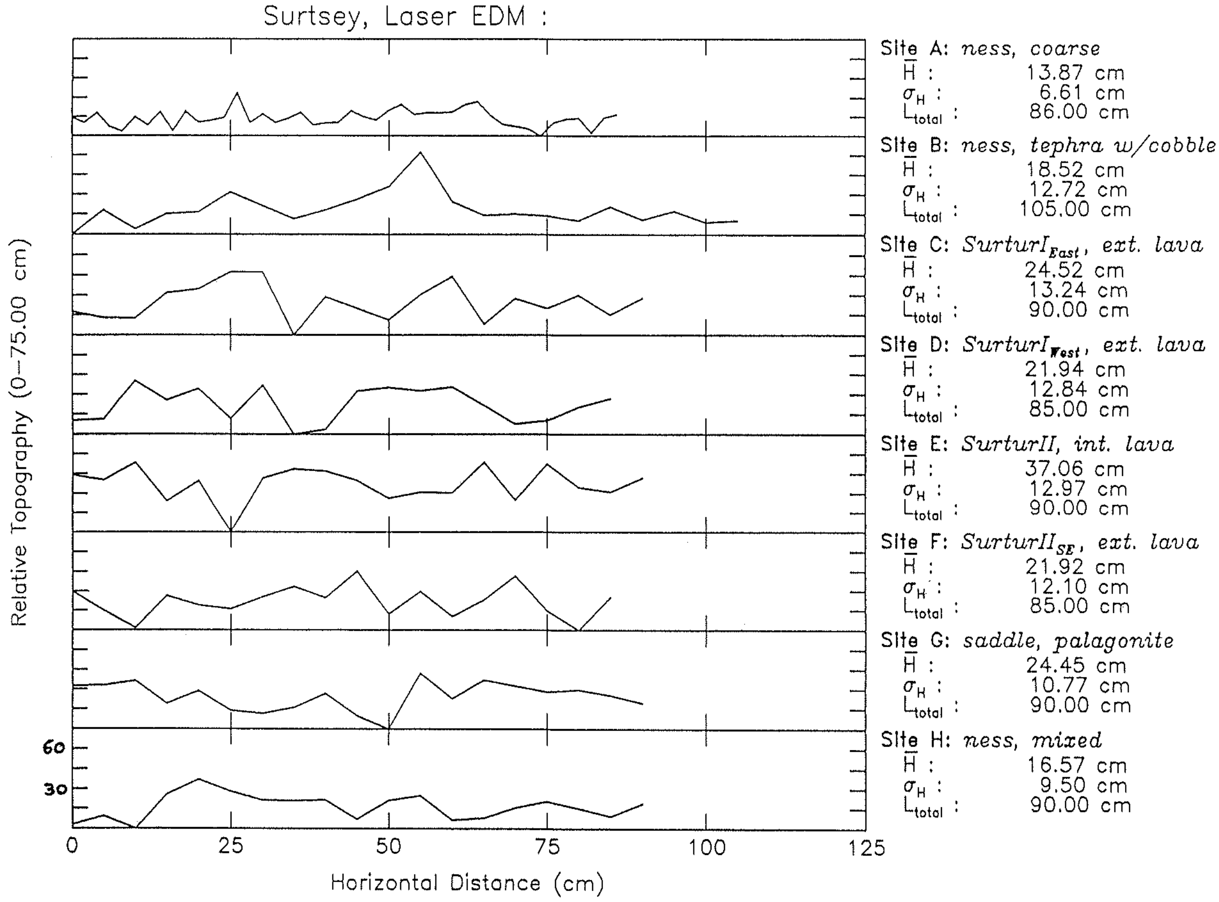

Fig. 15. Field-measured microtopographic profiles acquired on Surtsey using a laser electronic distance measuring device (Cubic Precision „*Red Dot*") with 4 mm vertical precision. Data were collected on 25 May 1991 for 8 sites on Surtsey. See text for further details. Profile at Site A (ness, coarse sand) produced from measurements spaced at 2 cm intervals; measurements for other sites (B through H) were acquired with 5 cm sampling intervals.

pling interval of 10 cm. Indeed, Fig. 13 shows a closeup of the tens of cm scale vertical structure of a 150 m diameter craterform, with a depth in excess of 25 m. Figure 14 illustrates another topographic profile of Surtsey acquired by the ATLAS sensor at 55 pulses per second (i.e., 1.7 m horizontal sampling along track). This profile (Fig. 14) crossed Surtur II from the SSW to NNE. These 1991 data should provide a unique set of ground-control points for features on Surtsey, because each profile has its own associated differential GPS tracking file to permit removal of aircraft vertical motion to 10 cm levels.

1991 SURTSEY FIELD SURVEYS

On 25 September 1991, the senior author and three other individuals (see acknowledgements) visited Surtsey for ~ 6 hours for the purpose of making direct measurements of the 2–5 cm scale microtopography of representative geomorphic surfaces. Our method for making the required measurements in so short a time centered around a hand-held laser distance measurement device known as a "*Red Dot*" (manufactured by Cubic Precision; see acknowledgements), together with a pair of tripods on which we mounted a 1.4 meter-long reference bar. We calibrated the "*Red Dot*" system under several conditions (inside and outside) and found that for smooth surfaces it yielded reproducible results at the 4 mm level. Therefore we decided to translate the "*Red Dot*" instrument either 2 or 5 cm along a graduated and levelled reference bar supported by a pair of tripods in order to construct a profile of the surface microtopography. Our objective was to acquire as many 1 meter long microterrain profiles as possible, with either 2 cm or 5 cm sampling along each meter-long traverse. Due to winds that averaged over 30 knots (~ 15 meters per second), additional sources of error in our "*Red Dot*" measurements are likely, at least at the 1–2 mm level.

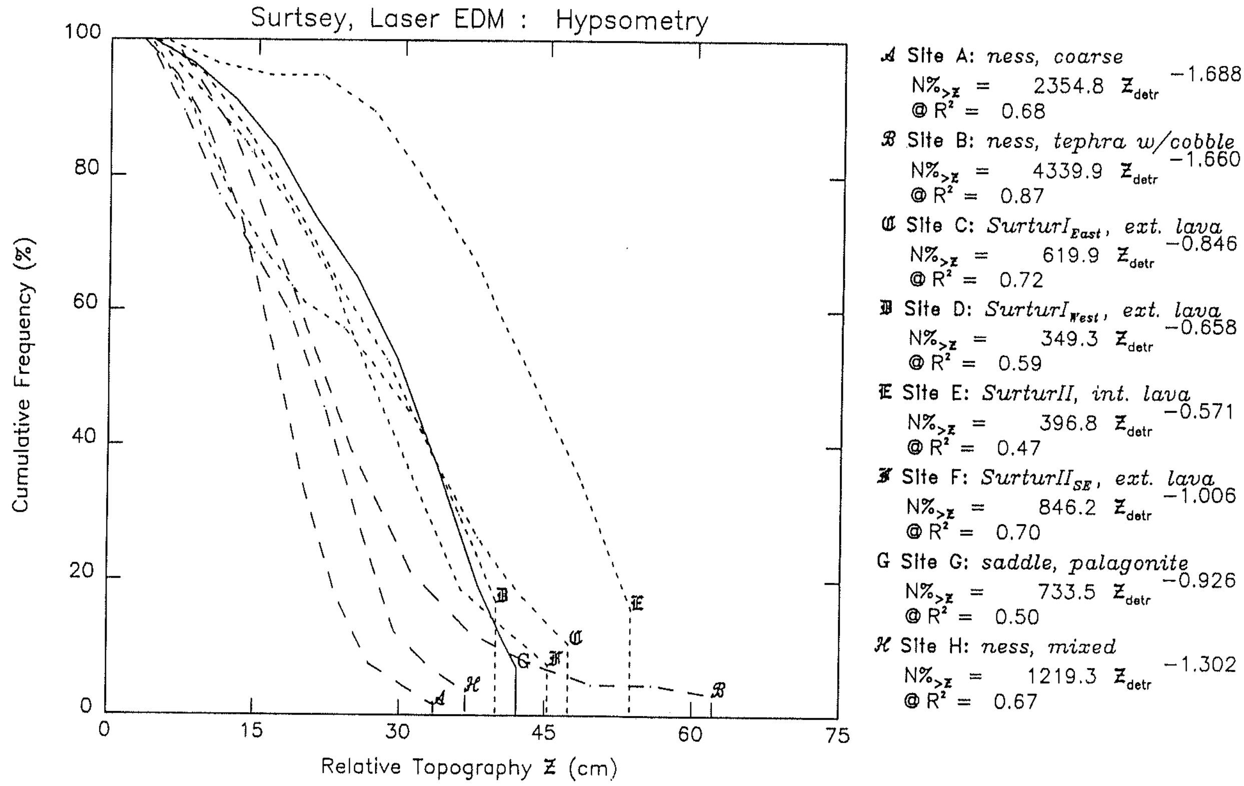

Fig. 16. Hypsometric distributions for the field survey site microtopographic profiles illustrated in Fig. 15. Sites A, B, and H are on the *ness* and are denoted with dashed curves, while sites C–F are lava surfaces and these are denoted with dotted curves. The solid curve (G) represents the one palagonitized tephra site (saddle area of the dual tephra rings). Those power-laws which best fit the actual data plotted in this figure are listed at the right. See text for additional details.

Figure 15 illustrates the 8 microterrain profiles acquired with the "*Red Dot*" sensor on 25 September 1991. The 8 sample sites ranged from poorly-sorted coarse eolian deposited tephra on the ness to various examples of slabby or platey lavas adjacent to and within the two vent craters. The text for sites A through H listed to the right of the actual data in Fig. 15 summarize the mean relative elevation (*H*), the standard deviation of local elevation (*sigma*), and the total length of the profile. Except for the initial site (A) within the poorly consolidated surficial materials of the ness, we used a sampling increment (***dx***) of 5 cm. For site A on the ness, we investigated the merits of a 2 cm ***dx***, but found that instrument stability in the gusty winds made observations difficult for longer than 10 minutes. These field data will serve as the basis for assessing whether our ALA topography data adequately sample the most significant wavelengths of topography necessary to understand the geomorphic evolution of a natural surface. In Figure 16, a family of hypsometric curves derived from the cumulative distribution of cm-scale elevations which can be computed from the topographic profiles shown in Fig. 15 is illustrated. In this plot, the solid curve represents our one test site (G) in palagonitized tephra (in the saddle region between the two tephra rings), the finely stippled curves denote lava sites, and the dash pattern denotes those sites on the ness. From the data plotted in Fig. 16, it appears that the relict lava lake slab pahoehoe (*helluhraun*) lava surface at site E is anomalous, and the power-law exponent in the fit to the raw hypsometric data is statistically distinct from all the other sites at a 95% level of confidence. To the right of the curves plotted in Fig. 16 is the best-fitting power law to the cumulative height frequency distribution (hypsometric distribution) for each site. These relationships are listed in the form of equations with two free parameters, $\boldsymbol{k}$ and β.

If N_z is the cumulative frequency (%) of local, relative elevations larger than a given elevation $\boldsymbol{z}$, then the hypsometric power law is given by:

$$N_z = \boldsymbol{k}\, \boldsymbol{z}^{\beta},$$

with a correlation coefficient of R^2. Thus, sites A and B located within the same general vicinity of the ness display very similar power-law statistics. The hypsometric power law exponent values (β's) apparently reflect some degree of formation process control on cm-scale topography at meter length scales. Thus, β values for the lava flow surfaces range from -0.57 to -1.00, while those for the ness sites vary from -1.3 to -1.7. The indurated palagonite site (saddle site G) appears to statistically resemble the lava flow sites in terms of its β value (-0.93), yet this similarity may be more a function of the mechanical strength or competency of the target. We have not fully interpreted the significance of these field microterrain data for Surtsey, but we did learn that 6 hours on a 2.4 km^2 island is not sufficient time to measure the entire suite of surfaces that exist on the island.

SUMMARY

In this report we have summarized the highlights of an ongoing NASA/USGS investigation of the topographic characteristics of a geomorphically active, yet pristine MOR volcanic island. Geodetic microtopography profiles from aircraft remote sensing data acquisition missions have been acquired in 1987, 1989, and most recently in September of 1991. We have demonstrated the unique morphometries of various terrain types on Surtsey, and are now in the process of reducing and analyzing the hundreds of megabytes of aircraft laser altimeter data (AOL and ATLAS), as well as the associated data from our GPS receivers acquired during our September 1991 aircraft remote sensing campaign. Results of our ALA and *in situ* field topographic surveys of Surtsey attest to the uniqueness of several of its surfaces, including the main vent crater Surtur II and the palagonitized tephra.

From the four directional profiles illustrated in Figure 1, the subaerial expression of the MOR volcanic edifice that represents Surtsey as a whole is best approximated by an asymmetric ridge with a cross-section that approaches a paraboloid in an E-W direction, but is more conical in a N-S orientation, not unlike Hekla (Williams et al., 1983). The surface area of the island as of May 1987, as computed from a weighted numerical integration of the four profiles shown in Fig. 1, is less than 2.43 km^2, and the aspect ratio (Height to basal Diameter ratio, H/D) of Surtsey apparently averages 0.09, with a range from 0.066 to 0.12. Mean local slopes are 20° to 24° depending on orientation, with large variances (10°–16°). The normalized mean height of the island is approximately 44 m (± 2 m), on the basis of the mean volume-to-surface area ratio. We believe that these data represent the meter-scale topographic character of Surtsey, and that they serve as the basis for comparison with other MOR volcanoes.

Ground surveys of the cm-scale topography of small segments (100 cm) of typical surfaces clearly demonstrate that differences in local topography reflect formation and degradational histories. Our objective is to return to Surtsey for additional field surveys, perhaps utilizing differential GPS surveying techniques for measuring extremely local topography ($<$ 10 cm scale). The ALA topographic data collected for Surtsey can be used to assist scientists who will be investigating newly acquired (June 1991) airborne imaging radar (SAR) and multispectral imaging spectroscopy data; these uniques datasets were collected for Surtsey in June of 1991, but await reduction at the time of this writing.

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