Analysis of 1966 Infrared Imagery of Surtsey, Iceland x)

by

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In August 1966 the Air Force Cambridge Research Laboratories, in cooperation with the U.S. Geological Survey, the National Energy Authority and the Infrared Physics Laboratory of the University of Michigan, undertook thermal infrared imagery surveys of selected sites in Iceland (Figure 1). Friedman, et al (1967) described the instrumentation used during these surveys and presented some preliminary results of these surveys.

This report summarizes the most important results of the study of the thermal regime of Surtsey. Included in this summary are a discussion of surface temperature and radiometric temperature observations based on ground and airborne measurements and an analysis of the effective radiance recorded by the Nimbus II satellite.

1. Ground and Airborne Surface Temperature and Radiometric Temperature Observations

Measurements of ground- and sea-surface temperatures during the Surtur I effusive eruption were made on 27 August 1966. The sea-surface temperature traverse was made from the Icelandic ship LÓÐSINN between Geirfuglasker and Surtsey (refer to Index map of Vestmannaeyjar Archipelago, Figure 2) with a Barnes IT-3 fixed-

x) This report forms a part of a paper presented at the XIVTH Gen. Assembly of the IUGG (IAV Section) in Zürich, Switzerland in October 1967 and contains excerpts from a forthcoming paper entitled, "Infrared Survey of Surtsey, Iceland", by the same authors.

field radiometer sensitive to emitted radiation in the 8-13μ wavelength region. A mean radiometric temperature of 12°C was obtained between 2 and 4 p.m. with some fluctuation during periods of rough sea. This temperature level is moderately consistent with mean sea-surface temperature records for August of 11.5°C for the Vestmannaeyjar Archipelago (Figure 3) and with the radiometric temperature range of 7-17°C derived from the Nimbus II HRIR scan-line profiles of effective radiance (Figure 10).

A diurnal maximum surface-temperature of 13°C was registered by the IT-3 for tephra surfaces (ashfall materials forming the rims of Surtur I and II). A radiometric temperature of 30°C was obtained by the same instrument integrating a trapezoidal area of several hundred square meters across the congealed lava lake and crater walls of Surtur II from a distance of more than a hundred meters. This temperature probably resulted from the integration of high temperatures due to convective venting from several large fractures and fumaroles noted on photographs and infrared images of Surtur II and lower surface temperatures of basalt scoria and lava crust. Infrared image-density variations indicate that surface temperatures within the Surtur II crater area varied from place to place during the eruptive activity in Surtur I in August 1966. A temperature of 1130-1140°C was registered for highly fluid incandescent olivine basalt lava 19-22 August, 1966 by Sigurgeirsson (1967) using a 10-m NiCr/NiAl Pyrotenax thermocouple.

Several days after the last reported explosive pulse from Jólnir's crater on 10 August 1966, Thorarinsson estimated the water temperature at the edge of the Jólnir crater lake to be 40-50°C.

These temperature points, associated with features identifiable on the infrared images, are useful in establishing a general correlation (Figure 4) relating image emulsion density and surface temperature as given in Table 1. Because of the sparse distribution of known temperature points, film processing and instrumental variations, and differences in emissivity of surface features, such a correlation can be only semiquantitative. A nonlinear relationship between the image density scale and radiometric surface temperature is indicated. There is greater image density variation per degree temperature difference at the lower end of the scale and, hence, greater reliability at the lower end of the scale. The theoretical relationship between radiant flux and radiometric surface temperature based on the Stefan-Boltzman function (Fulk and Reynolds, 1957) is given in Figure 5. These two correlation curves used with iso-density scans (Figure 6) of the imagery provide a means to estimate the areal distribution of surface temperatures useful for approximating the total hemispherical emission (Table 3) to verify the effective radiance recorded by the Nimbus II HRIR system on 22 August 1966 (Figure 10 and Table 3). Figure 9 is an isoradiance map, derived from an aerial thermal infrared image, which shows approximate radiometric surface temperatures over the entire surface of the lava flow in Surtur I on 29 August 1966. The solid black pattern indicates underflowing incandescent lava issuing from lava tubes where the irregular, lobate front of the flow has reached the sea. Of great interest are the areas of greatest cooling - at the margins of the flow and in a linear pattern in the central portion of the flow area. Decker and Peck (1967) also report that the coolest areas at Alae Lava Lake, Hawaii, were at the cooled thin margins. The cool linear central features are believed to be thick coherent slabs of helluhraun (pahoehoe) flow.

On 21 July 1967, additional surface-temperature measurements were undertaken on the surface of the 1966 flow which issued from Surtur I. YSI telethermometer and Atkins thermistor probe systems (range $< 120^{\circ}C$) were utilized as well as a Rototherm thermocouple probe (range = $100-550^{\circ}C$) in measuring temperatures in venting fumaroles and fractures. Surface temperatures ranged from ambient levels ($10-14^{\circ}C$) for tephra surfaces to more than $550^{\circ}C$ in one fracture in the floor of the Surtur I crater. This last measurement indicates that near-incandescent lava was present (July 1967) within a meter of the apalhraun flow surface.

In the area of the last sizable surface exposure of lava from Surtur II in April and May 1965 fractures parallel to the that a $\pm 2^{\circ}$ K to $\pm 4^{\circ}$ K variation in ocean surface temperature in the comparison of satellite data with actual surface temperature measurement can be expected. The approximate least-squares fit of a horizontal line on the analog scan-line trace suggests that the average ocean surface temperature of 285°K, based on effective radiance, is fairly accurate. Confirmation of the ocean surface temperature reading from Nimbus II records is provided in Figure 3. Figure 3 is admittedly a highly generalized sea surface map, but the average August sea surface temperature gives additional support to the Nimbus II data. Also most of the field of view of the HRIR detector is filled by ocean surface, hence it is contributing most of the radiant emission (see Table 2).

In conversion from radiometric temperature to true surface temperature, variations in surface emissivity of 1% can lead to an error of approximately 0.7° K (Gayevskiy, 1963). Kern (1965), in his TIROS work, found that water has an emissivity of 0.99 at ambient-temperature levels in the 8-13 micron spectral band. Daniels (1967) reported that average emissivities of basalt and tephra are on the order of 0.96 ± 0.02 for the 8-13 micron spectral band. Moreover, it is known that deviation from a plane surface in the form of surface roughness (as on the ocean surface or a lava flow) causes a higher apparent emissivity than the true emissivity of the material. Emissivities in the 3.45 to 4.07 spectral band, the 50% response points of the Nimbus II HRIR detector, are not as well known. The detector of the Nimbus HRIR system sensed radiation from a 64 km^2 segment of the earth's surface in the vicinity of Iceland. Table 2 indicates that over 96% of this transected area is ocean surface possibly having an emissivity of 0.99. Emissivity variations in the Surtsey case are thus assumed to be within the limit of observational error but are a valid subject for future investigation and could cause a reassessment of the energy values reported in this paper.

period was the time of greatest thermal emission from Surtsey in 1966. Although the pyroclastic satellite volcano, Jólnir, erupted explosively repeatedly between the time Nimbus II was placed in orbit (May, 1966) and 10 August, the thermal yield of these pyroclastic eruptions was probably not great enough for the infrared emission to rise above background levels, and no record of Jólnir's eruptive history was found on the Nimbus II infrared imagery.

The Nimbus II oscillograph record of Orbit 1315 indicates that a maximum effective radiance (N) = $10^{-0.75}$ watts/m^2 · steradian^{-1} (equivalent to a radiation of 7.13×10^{14} ergs/sec from an area of 64 km^2) was redorded by the HRIR detector, taking into account the spectral response of the system. This is equivalent to 2.94×10^{17} ergs/sec total blackbody radiation, the total energy radiated from a 64 km^2 segment of the earth's surface integrated by the Nimbus II HRIR detector assuming an emissivity of unity.

Although the spectral response and internal calibration corrections of the HRIR system are taken into account in determining the effective radiance indicated by the spike, several factors affect the accuracy of this portion of the analog profile of effective radiance: 1) sensor scan angle, 2) atmospheric absorption, emission and scattering and 3) emissivity variations of the terrestrial and ocean surface.

Order of Magnitude of Required Corrections

The nadir angle of the sensor on Orbit 1315, as the subsatellite trace passed within 275 km of Surtsey, was approximately 14° (Jack Conway, written communication 1967). This corresponds to an increase in transmission path length of 3% for a total of 1148 km instead of the orbital altitude of 1114 km. An atmospheric path increase of 3% would have little effect.

The correction for atmospheric influence would also be slight within the error of measuring the amplitude of the positive spike. Kunde (1964), Kern (1965), and Allison and Kennedy (1967) have discussed the atmospheric attenuation error and conclude flanks of serpentine pressure ridges and collapse features were convecting vapors to the atmosphere at temperatures of 40-60°C. The previous year (August 1966) these same fractures were associated with infrared image-saturation anomalies indicating convective temperatures above 100°C (Figure 6). Figure 6 does not fit the planimetric configuration of Surtsey and Jólnir due to distortion caused by an incorrect setting of the M1A1 scanner with respect to apparent ground motion.

Figures 7 and 8 are radiance profiles, lines AB and AC, showing radiant flux from different geologic (volcanologic) features. These profiles graphically portray the dynamic thermal regime of the active volcano, Surtsey, and its satellite volcano, Jólnir, at a specific point in time.

2. Effective Radiance as Recorded by the Nimbus II High Resolution Infrared Radiometer (HRIR)

Radiant emission from the Surtur I eruptive area (August-October, 1966) was of sufficient magnitude to be recorded by the HRIR system of the Nimbus II meteorological satellite. The anomaly detected by this system is visible as a minute black spot in the correct geographic position for Surtsey on the photographic record of the infrared imagery and as a sharp positive spike on Visicorder oscillograph analog profiles (showing variations in effective radiance along individual scan lines) made from records of the original spacecraft interrogation (Figure 10).

The Surtsey anomaly was first recorded on Orbit 1288, 20 August, the first orbital overpass of Iceland after the eruption began the previous morning. The anomaly is not present on imagery of previous orbits although openings in the cloud cover permitted identification of parts of southern Iceland during the nights immediately prior to 20 August. The anomaly was also identified on the following dates and orbits: 22 August, Orbit 1315; 8 September, Orbit 1546; 16 September, Orbit 1648; 20 September, Orbit 1701; and 21 September, Orbit 1774. The anomaly is definitely identifiable as late as 3 October (Orbit 1874) but becomes questionable during the latter part of October. It is significant that this

Total Hemispherical Emission Estimates from Ground Observations and Airborne Infrared Imagery

The maximum effective radiance, 7.13×10^{14} ergs/sec, as determined from the Nimbus II HRIR oscillograph record, taking into account the spectral response of the HRIR detector, is equivalent to 2.94×10^{17} ergs/sec total blackbody radiation based on the Stefan-Boltzmann function (Fulk and Reynolds, 1957). These Nimbus radiation estimates may be compared with estimates made from field observations supplemented by isodensitracer scans of airborne infrared imagery (Figure 6). The total hemispherical emission from a comparable area on the earth's surface can be estimated by dividing the resolution element of the HRIR detector (64 km^2, the area on the earth's surface transected by the cone representing the solid angle viewed by the HRIR system), into unit areas of roughly equal temperature (Figure 6). Using this method, the radiance contribution of each part may be estimated and integrated with the other parts. Temperature measurements, volcanologic observations on the island and isodensitometric analysis of the airborne imagery suggest the map units and temperatures as shown in Table 2. The area of Surtsey was 2.35 km^2 when the 19 August 1966 fissure eruption began (Thorarinsson, 1967, p. 575).

The radiation values for each map unit given in Table 2 were estimated using the following method devised by A.E. Stoddard (written communication, 1967):

If each temperature unit is assumed to radiate as a blackbody, and the HRIR detection response is taken into account, the response function ϕ_λ, may be approximated by a function which is everywhere zero except within the interval 3.45 to 4.07μ when it assumes the value one. These wavelengths are the 50% response points of the Nimbus II detector. The following approximation for each of the four temperature units is then valid:

$$\bar{N}(AT) = AT \int_{3.45}^{4.07} B(\lambda, T) d\lambda$$

where AT = the area at temperature T

$B(\lambda, T)$ = the Planck function (the amount of energy radiated in all directions from one cm^2 blackbody surface at temperature T per second and per unit wavelength interval).

$\overline{N}$ = maximum effective radiance.

Given this integral as a function of temperature and the area of each surface-temperature unit, the total energy radiated by each part within the response window of the Nimbus II detector may be calculated.

To calculate the total energy radiated from each map unit, we may substitute a function which is unity over the entire range of wavelengths

$$ET = AT \int_0^{\infty} B(\lambda, T) d\lambda$$

The advantage of using the above equation is that it gives us total radiation estimates for the eruptive volcanic area, which then can be compared to the calculated rate of thermal energy yield.

Thermal Yield of Effusive Eruption from Volumetric Outflow Observations

To give an indication of the thermal energy yield of the August 1966 fissure eruptions, we may apply the methods of Hédervári (1963) and Yokoyama (1956-57), which relate the volcanic energy to the volume of the products erupted, according to the following equation:

$$Eth = V \rho (TC + B) J$$

where Eth = thermal energy yield in ergs/sec. (assuming cooling to ambient temperature level)

V = volume of effusive lavas in cm^3/sec.

ρ = mean density of effusive lavas in g/cm^3

T = maximum temperature of the lava in ^{o}C

C = specific heat of basalt lava in cal/g ^{o}C

B = latent heat of lava in cal/g

J = 4.186×10^7 ergs/cal.

Field observations reported by Thorarinsson (1967b) and Sigurgeirsson (1967) provide us with values for V and T. Thorarinsson estimated the volumetric yield of lava to have been between 5 and 10 m^3/sec for several days after 20 August. If we assume the rate of outflow to have been 7 m^3/sec early in the morning of 22 August (02:28 UMT) at the time the subsatellite point of Nimbus II, Orbit 1315, passed almost directly across Surtsey (nadir angle of 14^{o}) we may compare the effective radiance from Surtsey, as detected by the Nimbus HRIR 1114 km above the earth's surface, with the rate of thermal energy output of the volcano.

Thermocouple measurements of fresh incandescent flows by Sigurgeirsson yielded a temperature of $1140^{o}C$ for the lava. Other values for the parameters in the Eth equation for basalt are: ρ, 2.8 g/cm^3; C, 0.25 cal/g ^{o}C (at $800^{o}C$), and B, 50 cal/g. Then the total thermal yield would be:

$$Eth = 2.67 \times 10^{17} \text{ ergs/sec (or } 6370 \times 10^{6} \text{ cal/sec).}$$

Table 3 presents a summary and comparison of the thermal energy output and radiant emission from Surtsey on 22 August 1966 based on field observations, and estimates from the airborne infrared imagery and Nimbus II HRIR satellite data.

Conclusions

It may be estimated in conclusion that approximately 3.3% of the total thermal yield of the Surtur I effusive eruption was radiated into space on 22 August 1966, and that the bulk of the remaining thermal yield was dissipated by non-radiant heat transfer mechanisms to the ocean, the atmosphere, and to the terrestrial sub-surface of the island.

Acknowledgements

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Table 1

EXPLANATION

ISORADIANCE MAP ANALYSIS OF SURTSEY AND JOLNIR M1A1 INFRARED IMAGE, 19 AUGUST 1966, 1745 UMT, 4.5-5.5 MICRONS

Geologic Interpretation	[*]Δd and Map Unit	Anomaly Category	Radiometric Surface Temp. Range (°C)	Original Image Characteristics: Tone	Original Image Characteristics: Form
Sea surface; Basalt flow surface - Cool (1964-1965 flows) Tephra rims of Surtur I and II and Jólnir	0.114 - 0.456	Ambient level	10-12	Dark gray	Large areas; A few subtle gradations discernible.
Basalt flow surface of 1964-1965 flows; Jólnir lagoon water; basalt flows of 1964-1965 (Surtsey) adjacent to anomalously warm surfaces. Jólnir crater lake; basalt crust over cooling lava and subsurface lava courses of 1964-1965 flows where high conductive heat flow is associated with convective heat flow; Warm periphery of features emitting gases and steam.	0.456 - 1.368	Low and intermediate level anomalies	12-64	Medium gray to Light gray to Gray	Subtle gradations; Faint curvilinear features; Generalized diffuse areas; Many sublinear bands
Three areas: 1) area of predominately convective heat transfer from secondary fumaroles, fractures along pressure ridges and circular collapse features in area of 1965 flows, 2) primary fumaroles and gas and steam emission from scoriaceous walls of Surtur II crater and in general area of roof of northern part of subsurface lava course (1965), and 3) peripheral to image-saturation anomalies of Surtur I.	1.368 - 1.596	High temperature anomalies	64-78	Very light gray	Specific small areas; Punctuate and bleb-like features; bead-like alignments; sharp curvilinear features concentrated in three general areas.
	1.596 - 1.938		78-100	White	
Image saturation in general area of effusive incandescent flows, lava fountains and cauldron activity; intense fumarole emission and image saturation adjacent to fumaroles.	>1.938	Image saturation anomalies	100 - 1100	Bright White	Ellipsoidal area; saturation after-effect along some scan lines; blooming around some curvilinear and point sources.

[*]Δd: image density increment

TABLE 2

Radiant Emission of Surtsey and Surrounding Ocean surface
Based on Surface Temperature
22 August 1966

	AT	T°	$\bar{N}$ (AT)	ET (AT)
Map Unit (geologic feature)	Area (km^2)	T°K (average)	$AT \int_{3.45}^{4.07} B(\lambda,T)d\lambda$ ergs/sec	$AT \int_{0}^{\infty} B(\lambda,T)d\lambda$ ergs/sec
1. Incandescent lava Surtur I	.01	1120°	10.00×10^{14}	0.09×10^{17}
2. Other volcanic anomalies	.20	300°	0.02×10^{14}	0.01×10^{17}
3. Ambient Terrain (cool basalt and tephra)	2.14	286°	0.11×10^{14}	0.08×10^{17}
4. Ocean surface	61.65	248.5°	3.08×10^{14}	2.30×10^{17}
TOTAL	64.00	~ 300°	13.21×10^{14}	* 2.48×10^{17}
				** 2.94×10^{17}

* Cumulative total based on T° map units.

** Based on Stefan-Boltzmann function for blackbody radiation and blackbody equivalent temperature (300°K) derived from Nimbus data.

TABLE 3

COMPARISON OF THERMAL ENERGY OUTPUT AND RADIANT EMISSION FROM SURTSEY, 22 AUGUST 1966 AS ESTIMATED BY TWO SENSING SYSTEMS

	ENERGY UNIT ESTIMATED		REMOTE SENSING SYSTEM	ENERGY (ERGS/SEC) FROM $64KM^2$ ELLIPTICAL AREA, INCLUDING SURTSEY, INTEGRATED BY NIMBUS HRIR DETECTOR	ENERGY FROM ACTIVE VOLCANO	
					ERGS/SEC	PER CENT OF TOTAL
RADIATION	(1) Effective Radiance (N), (that portion of the radiance of the $64Km^2$ target which passes the equivalent detector filter) of the HRIR radiometer per second $\bar{N}=\int A(T)\left\{\int_{3.45}^{4.07} B(\lambda, T_{BB})d\lambda\right\}dT$ Where $A(T)$=area at temperature T $B(\lambda, T_{BB})$=Planck function	A	Nimbus II HRIR. Scan-line oscillograph record, orbit 1315, 22 August 1966 02:27:29 UMT 63°15'N, 20°45'W center point of terrestrial sweep.	7.13×10^{14}	Volcano emission alone not resolvable from Nimbus record. See below.	N/A
		B	M1A1 infrared scanner (Airborne, 5,000 feet) isodensitometric scan of imagery and surface temperature points. Emission estimated from spectral band comparable to Nimbus II HRIR system.	13.21×10^{14}	10.02×10^{14}	N/A
	(2) Total hemispherical emission ($\mathcal{E}$) (radiation emitted per second in all wavelengths assuming emissivity=1) $\mathcal{E}=\int A(T)\left\{\int_{0}^{\infty} B(\lambda,T)d\lambda\right\}dT \cong \sigma\int A(T)T^4dT$ Where $A(T)$=area of temperature T $B(\lambda,T)$=Planck function σ=Stefan-Boltzmann constant (1.354×10^{-12} cal cm^{-2} $^{o}K^{-4}$ sec^{-1})	A	Nimbus II HRIR. Scan-line oscillograph record equivalent blackbody radiation using Stefan-Boltzmann constant.	2.94×10^{17}	Volcano emission alone not resolvable from Nimbus record. See below.	N/A
		B	M1A1 infrared scanner (Airborne) isodensitometric scan of imagery and surface temperature points. Emission in all wavelengths estimated.	2.48×10^{17}	0.09×10^{17}	3.26

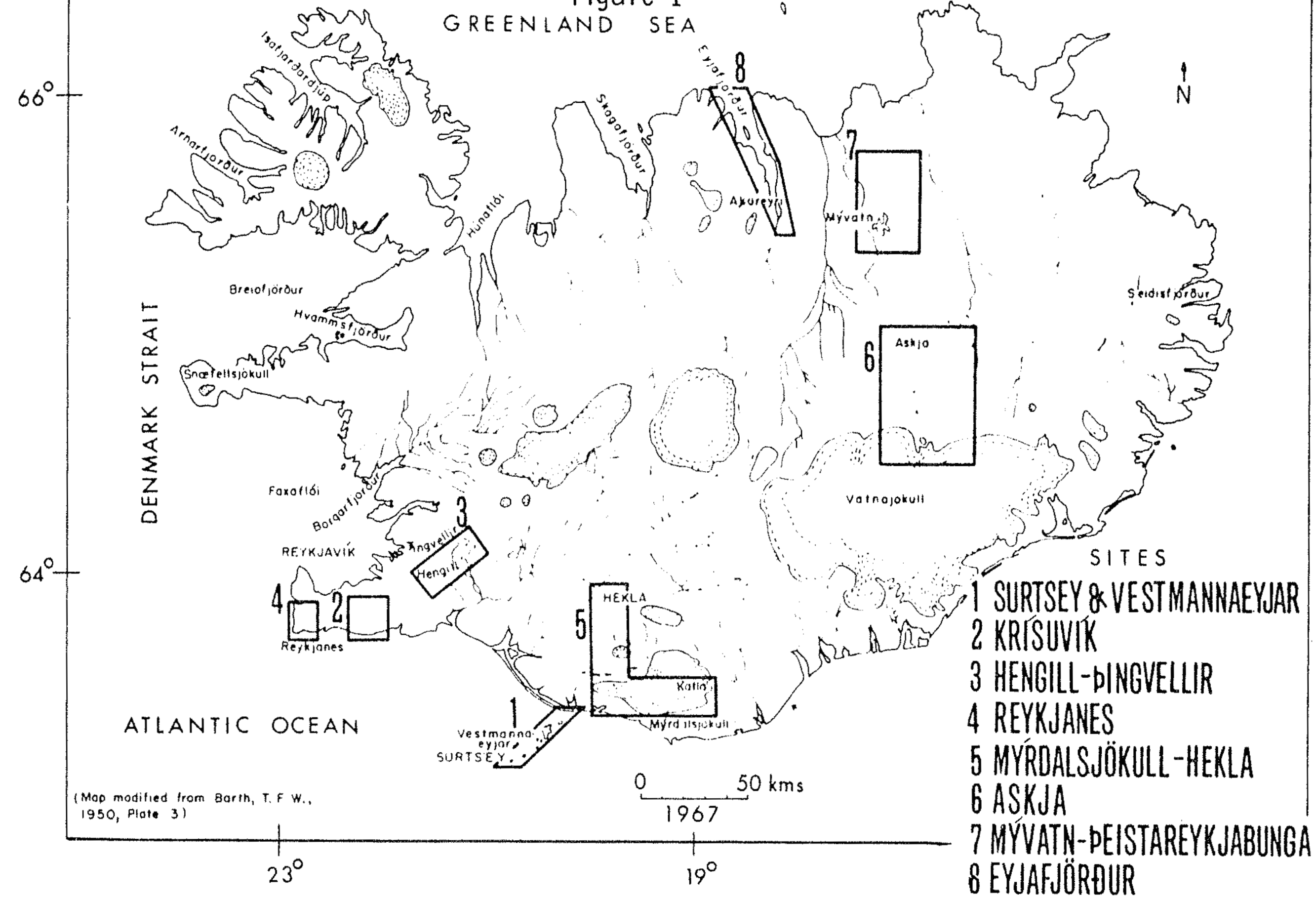
TABLE 3. (Cont.)

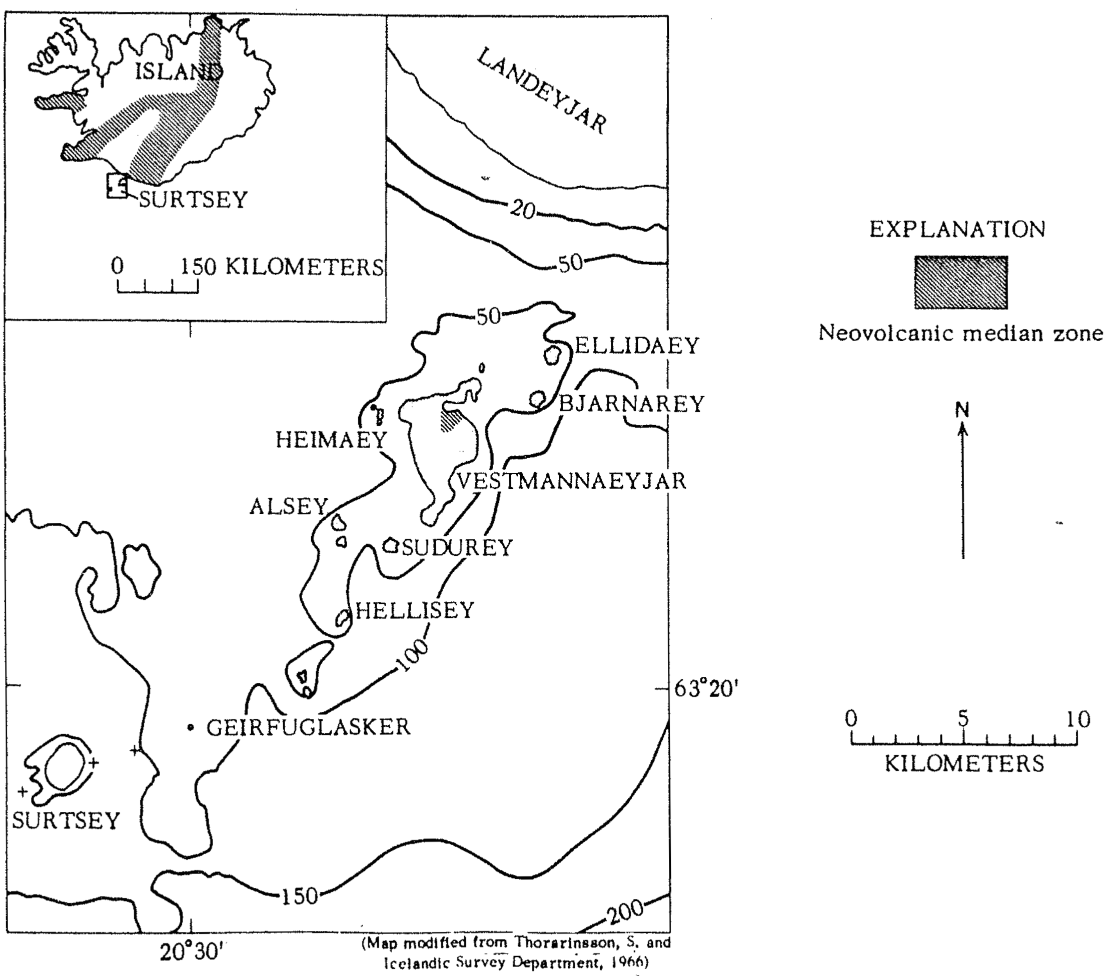
COMPARISON OF THERMAL ENERGY OUTPUT AND RADIANT EMISSION FROM SURTSEY, 22 AUGUST 1966 AS ESTIMATED BY TWO SENSING SYSTEMS

ENERGY UNIT ESTIMATED		REMOTE SENSING SYSTEM	ENERGY (ERGS/SEC) FROM $64KM^2$ ELLIPTICAL AREA, INCLUDING SURTSEY, INTEGRATED BY NIMBUS HRIR DETECTOR	ENERGY FROM ACTIVE VOLCANO	
				ERGS/SEC	PER CENT OF TOTAL
TOTAL THERMAL ENERGY YIELD	Thermal energy yield (Eth) Eth=VP (TC+B) J Where V= Volumetric outflow of lava per second P= Mean density of olivine basalt lava T= Maximum temperature (^{o}K) above ambient C= Specific heat of basalt (at $800^{o}C$) B= Latent heat of lava J= Equivalent work of heat	Volcanologic ground observations of max. temperature (by thermocouple) of incandescent lava and volumetric rate of outflow. Also temperature of ocean and tephra surface.	N/A	$2.67x10^{17}$	97

SITES OF THERMAL INFRARED SURVEYS IN ICELAND — AUGUST 1966

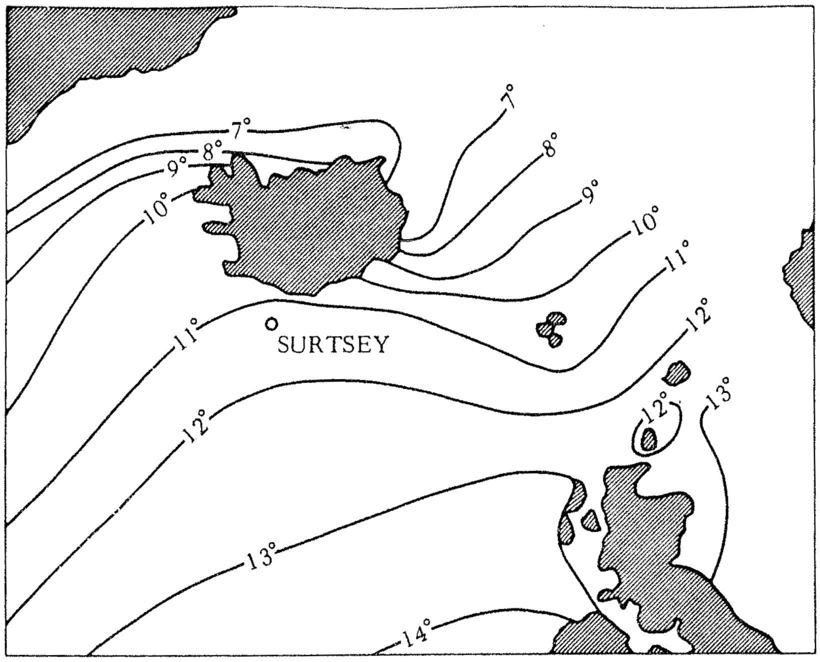
Figure 1





INDEX MAP OF VESTMANNAEYJAR ARCHIPELAGO, ICELAND

Figure 2



SOURCES	(1)	Nautisk- Meteorologisk Aabog (Copenhagen, 1898-1939)
	(2)	H. Thomsen, 1938, Zoology of Iceland, vol. 1, pt. 4, pp. 6-8, Copenhagen
CONFIRM 11.5° C SEA SURFACE TEMPERATURE NEAR SURTSEY AUGUST, 1966	(3)	S. A. Malmberg, unpublished, Sea surface temperature in Vestmannaeyjar Archipelago, August 1966; records of Marine Research Institute, Reykjavik
	(4)	Radiometric temperature traverse from Icelandic vessel Lodsinn between Geirfuglasker and Surtsey, August 23, 1966

Figure 3

AVERAGE SURFACE TEMPERATURE OF THE SEA (°C) FOR AUGUST, 1898-1939

Figure 4

INFRARED IMAGE TONAL DENSITY VS RADIOMETRIC SURFACE TEMPERATURE

SURTSEY, 8/19/66, 1745 UMT, $\lambda = 4.5 - 5.5\mu$

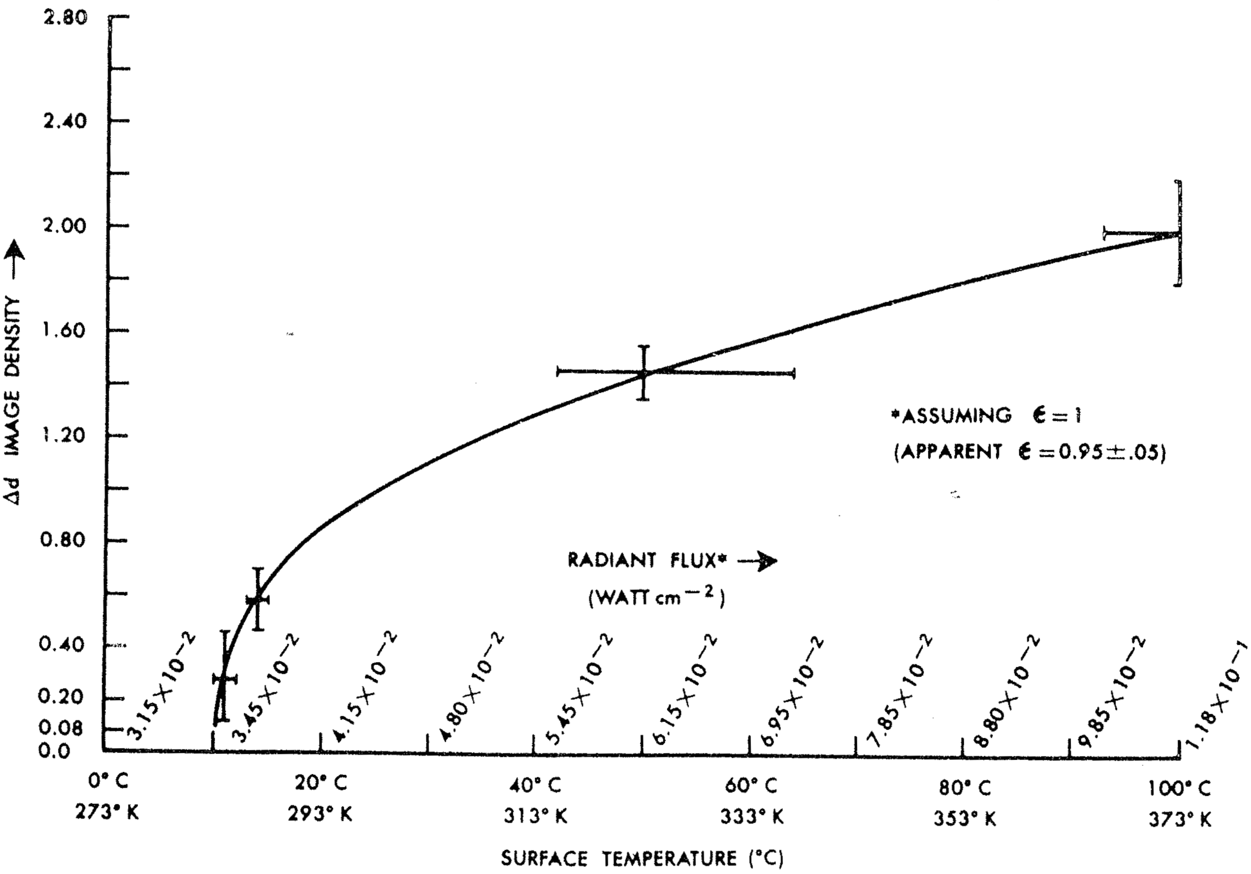
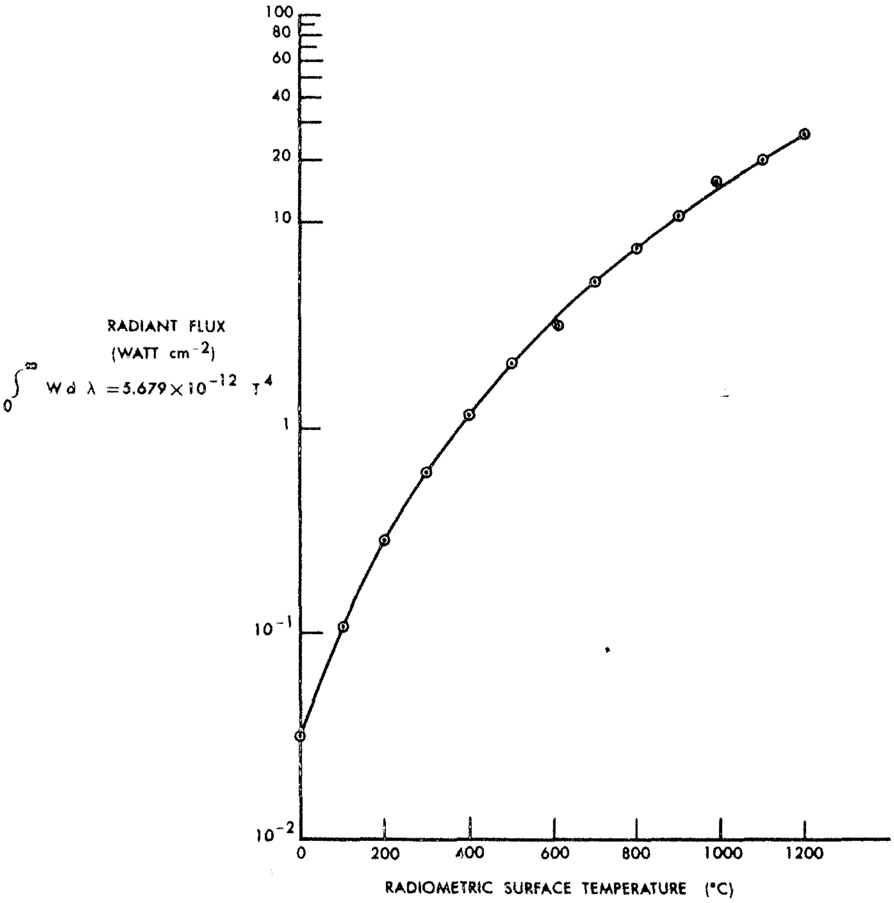


Figure 5

RADIANT FLUX VS RADIOMETRIC SURFACE TEMPERATURE



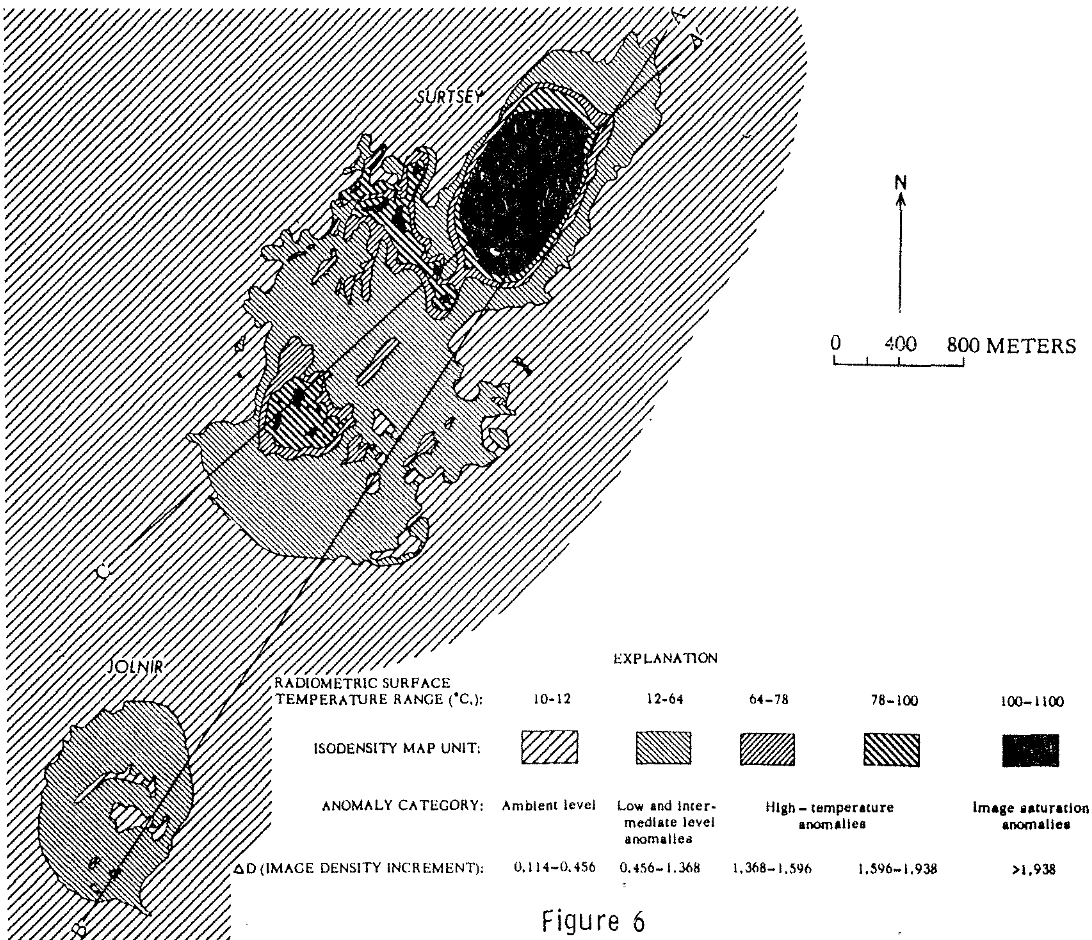


Figure 6

ISORADIANCE MAP OF SURTSEY & JOLNIR, VESTMANNAEYJAR, ICELAND

(From MIAI infrared image, 19 August 1966, 1745 UMT, 5000 Feet, 4.5-5.5 μ)

Figure 7

RADIANCE, LINE A–B SURTSEY AND JÓLNIR 8/19/66, 1745 UMT

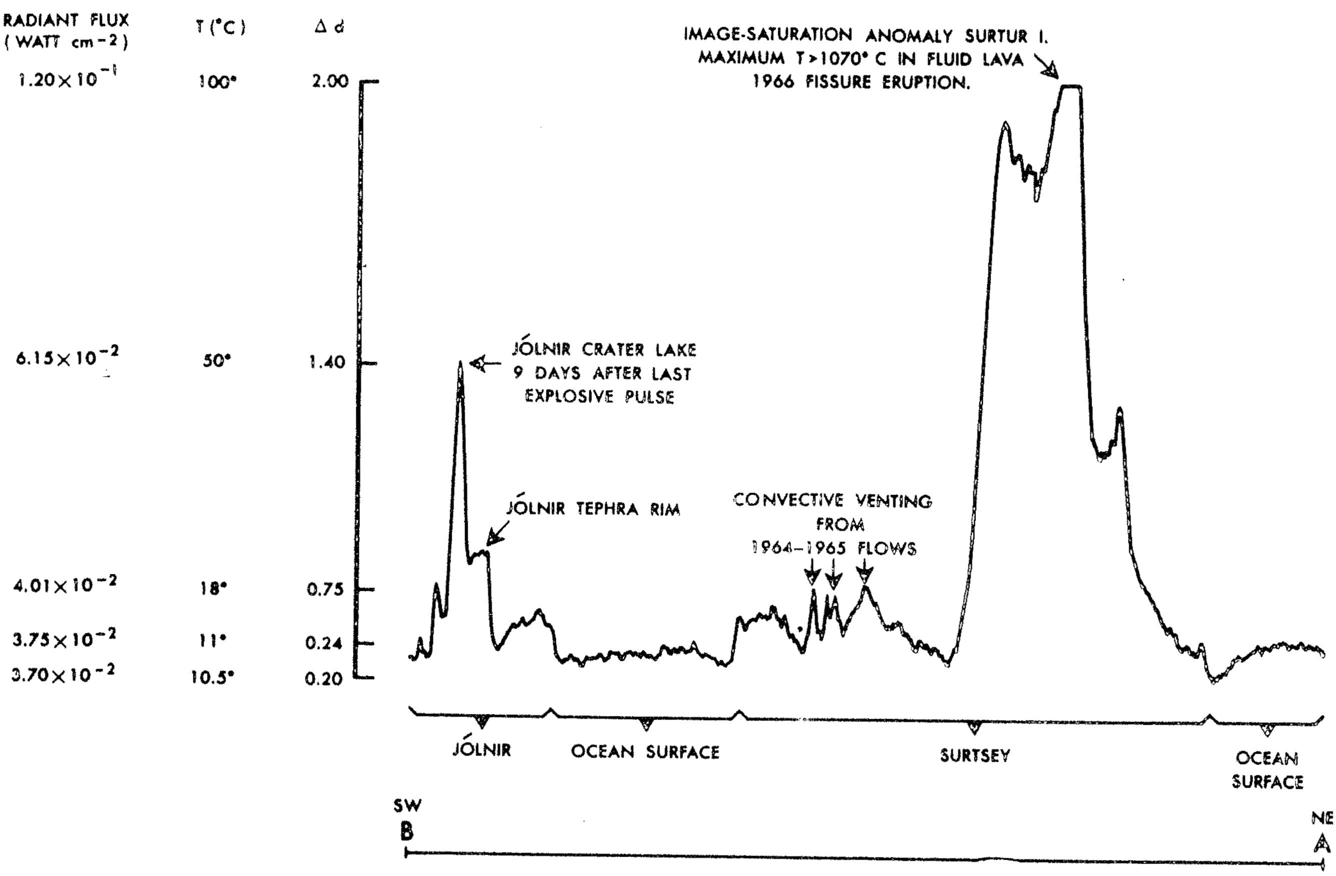
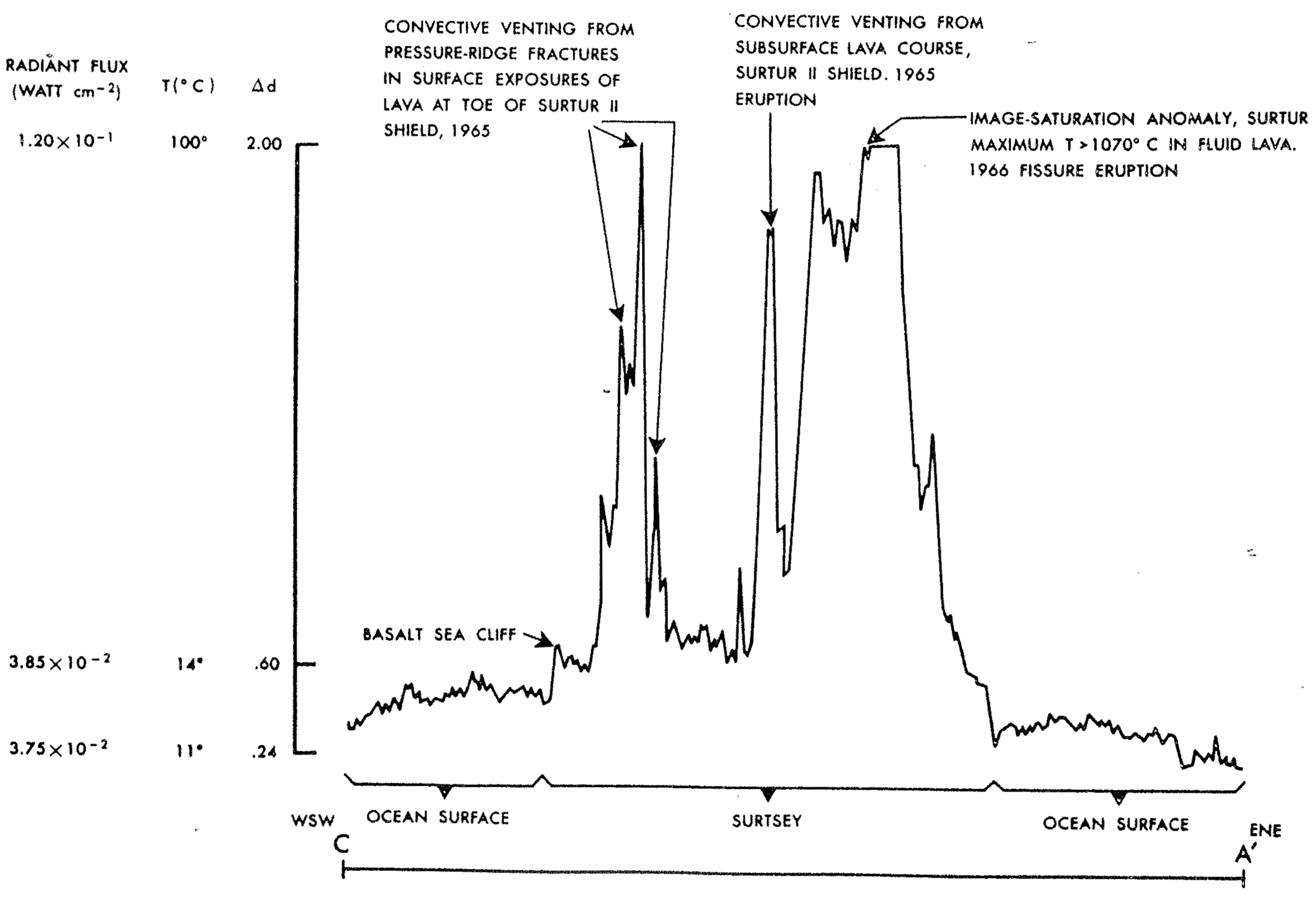


Figure 8

RADIANCE, LINE A′–C SURTSEY 8/19/66, 1745 UMT



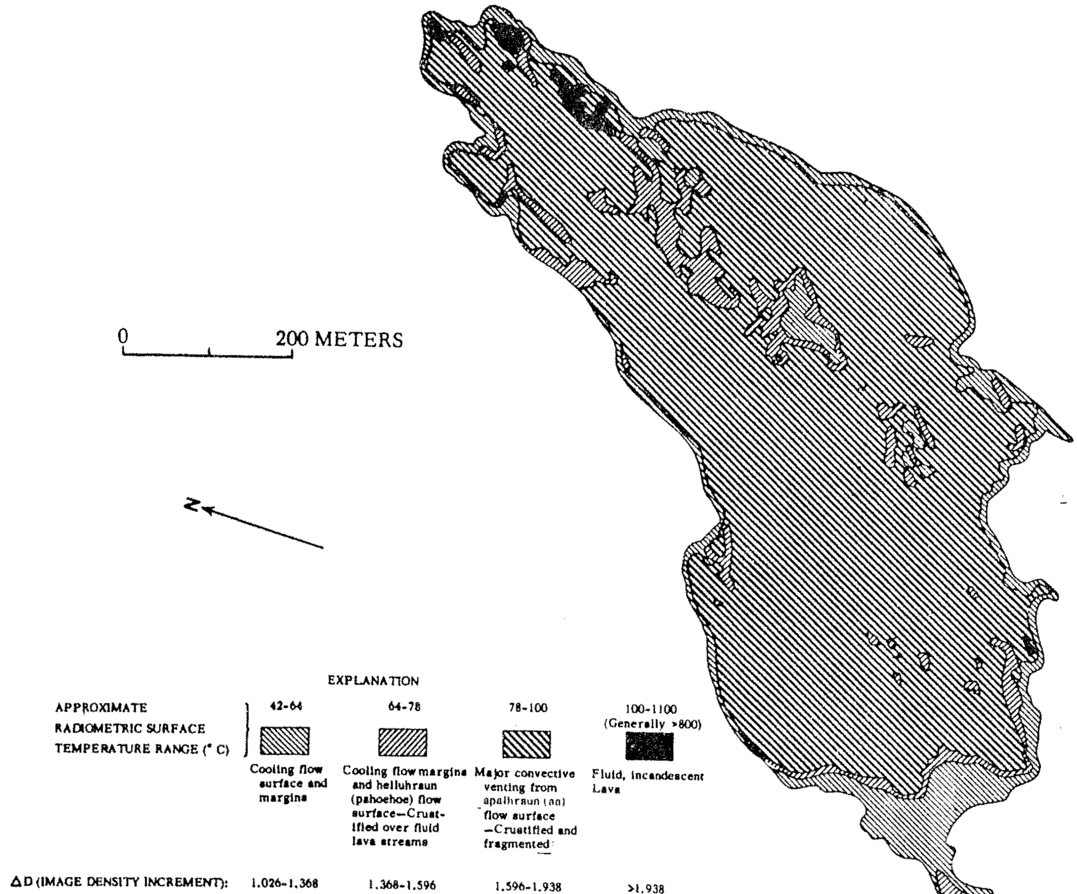


Figure 9

ISORADIANCE MAP OF LAVA FLOW FROM SURTUR I, SURTSEY, ICELAND
(From MIAI infrared image, 29 August 1966, 1721 UMT, 2500 Feet, 4.5-5.5 μ)

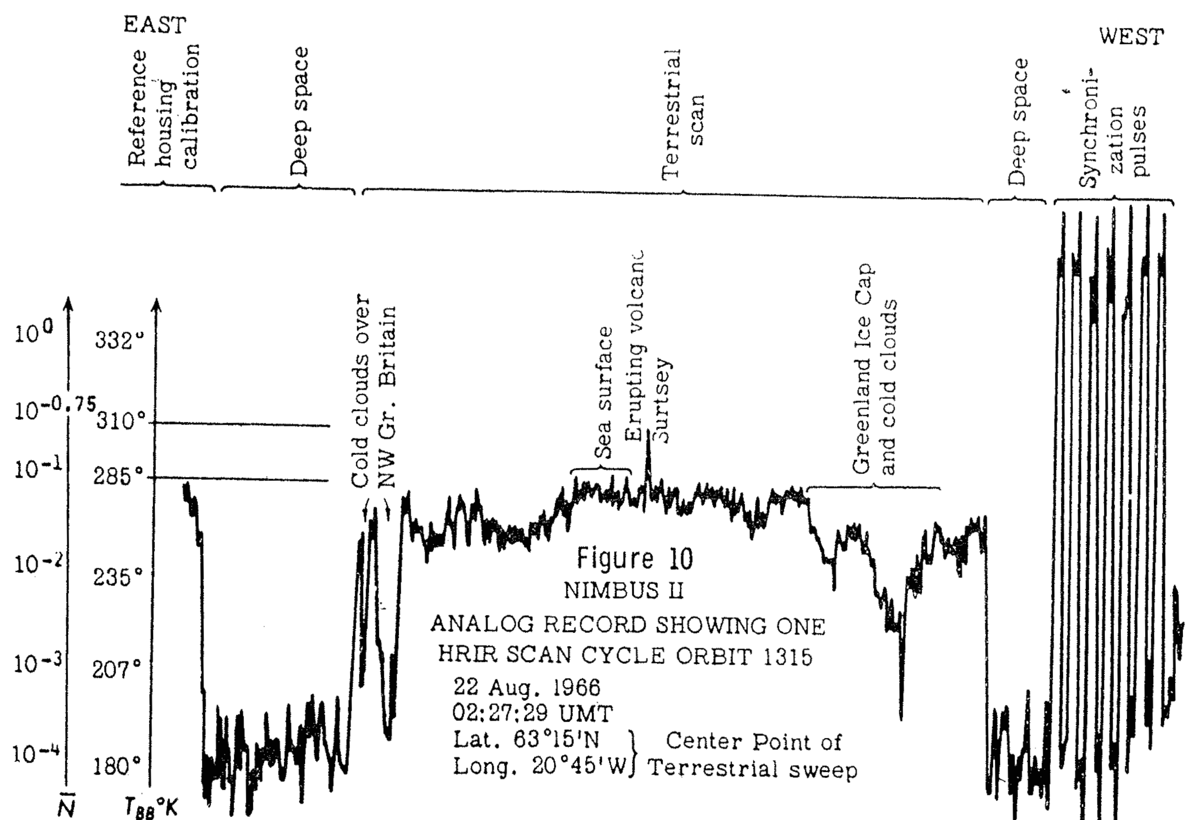


Figure 10
NIMBUS II
ANALOG RECORD SHOWING ONE HRIR SCAN CYCLE ORBIT 1315
22 Aug. 1966
02:27:29 UMT
Lat. 63°15'N, Long. 20°45'W } Center Point of Terrestrial sweep

$$\text{Effective radiance, } \bar{N} \text{ (watts/m}^2\cdot\text{ster)} = \int_0^\infty B_\lambda (T_{BB})\, \phi_\lambda\, d_\lambda$$

Where B_λ = Planck function T_{BB} = Equivalent blackbody Temperature in °K ϕ_λ = Effective spectral response (about 3.4 to 4.1 μ)