RAUNVÍSINDASTOFNUN HÁSKÓLANS
Science Institute, University of Iceland
Dunhaga 3, 107 Reykjavík

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A KINEMATIC GPS-SURVEY IN SURTSEY 1992

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Introduction

During a GPS-survey of the active plate boundary areas in South Iceland in August 1992 a GPS-receiver (Trimble 4000 SST) was brought to the Surtsey island. The main purpose of the mission was to determine accurately the position of one bench mark on the island for inclusion in the GPS network in South Iceland. This network was originally measured in 1986 to monitor crustal movements, but was remeasured and augmented in 1989 and 1992 (Foulger et al. 1987, 1993; Hackman 1991; Sturkell et al. 1993; Sigmundsson et al. 1992). This point extends considerably the width of the network, and additionally offers the possibility to monitor the continuation of the subsidence of Surtsey documented by Moore et al. (1992). During our three days stay on the island we also used the receiver to survey a number of points in the kinematic mode (Fig. 1). The purpose was twofold: To test the kinematic method of GPS-surveying under Icelandic conditions, where ionospheric disturbances are high, and to survey a few points for aerial photgraphy and mapping purposes. A new map of Surtsey in the scale of 1:5 000 based on these measurements was published in connection with the 30th anniversary of the Surtsey eruption in 1993. The GPS group was a part of an expedition of the Surtsey Research Society that visited the island on August 8 - 11, 1992.

The static survey

The Surtsey survey network was tied to an international geodetic reference system ITRF91 (International Terrestrial Reference Frame). This tie was accomplished in three steps:

1. A point on the roof of Árnagarður on the University of Iceland campus in Reykjavík was occupied continuously for a week during the IGS92 (International GPS Service) campaign in July-August 1992. A global solution of 40 stations with a world-wide distribution gave the coordinates for Árnagarður (ARNA) shown in Table 1 and 2 (Botton, 1993). The accuracies are of the order of 2 cm (H. Fagard, Institute Géographique National, Paris, pers. comm., 1993).
2. A network of about 40 GPS points in S-Iceland was measured by static GPS surveying in July-August 1992. The network includes ARNA as a fixed station, but a second reference point was established at S13 (Ísakot) by a careful tie to ARNA. The data were analyzed using the Bernese 3.3 GPS software. The method of analysis is described further by Sigmundsson (1992). This tie is considered accurate to within 1 cm.
3. Coordinates of the points S24 on Heimaey and S621 on Surtsey were determined by a static

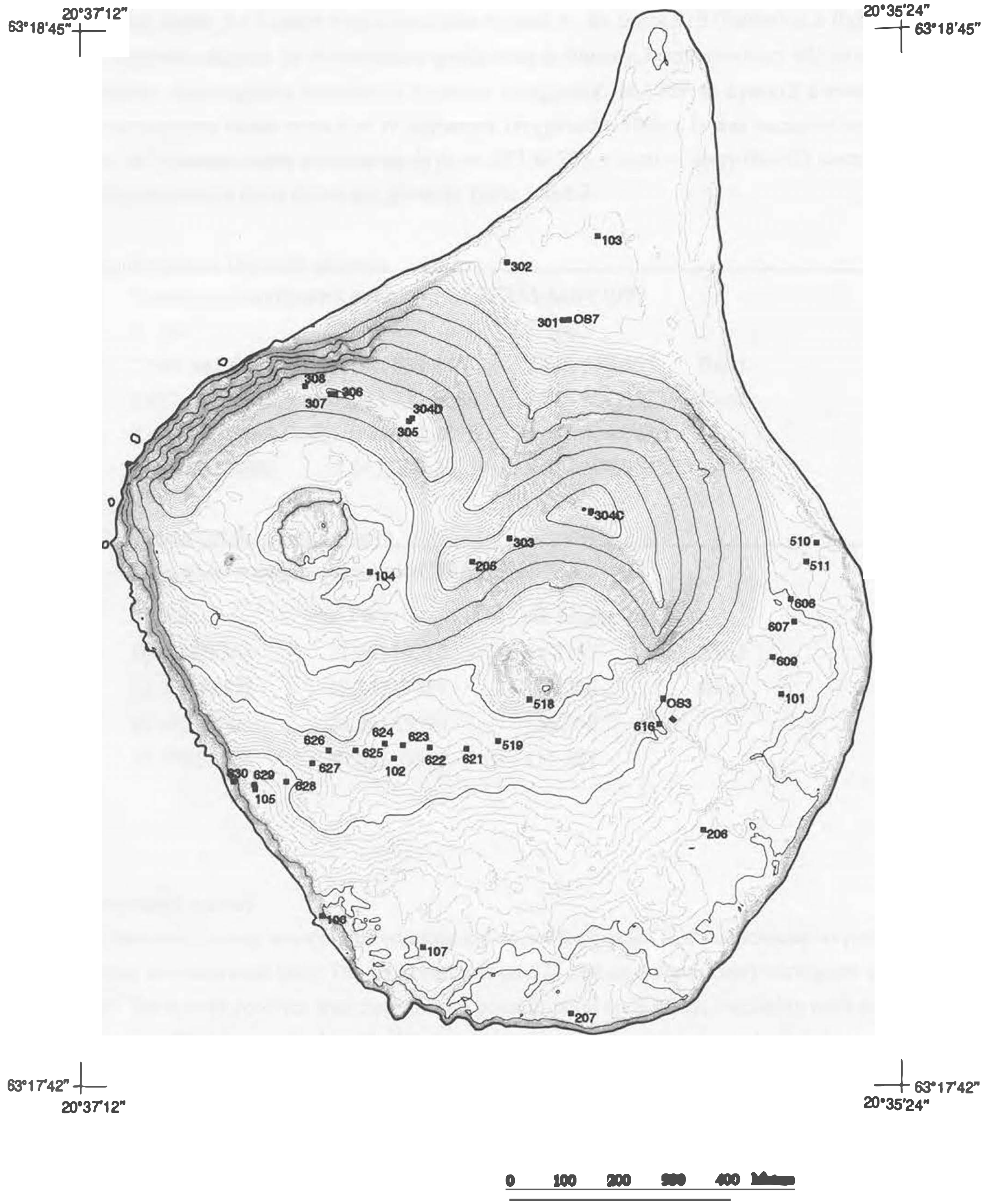

Fig. 1. *Map of Surtsey based on the 1992 kinematic GPS-survey and aerial photographs of 1993. The survey points are shown. Survey points 630 and 106 were destroyed by coastal erosion between the date of the survey in 1992 and the date of the aerial photograph in 1993. Thick elevation contours are every 20 m and thin contours every 2 m. Courtesy of Landmælingar Íslands and the Surtsey Research Society.*

GPS survey during the Surtsey expedition, with respect to the point S13 (Ísakot) as a fixed station. The point chosen for the reference positioning in Surtsey, bench mark no. 621 in the center of the island, was originally installed by Eysteinn Tryggvason in 1967, as a part of a levelling profile crossing the island from E to W (Eysteinn Tryggvason, 1968). It was occupied by the receiver for 5 measurement sessions on days no. 221 to 223, a total of more than 53 hours.

Coordinates of all these points are given in Table 1 and 2.

Table 1. Results of the static surveys
Geocentric coordinates, solution BRL3FX15-MAY1993

	X (m)	Y (m)	Z (m)	
ARNA	2 587 441.661	-1 042 831.244	5 716 573.555	fixed
S13	2 627 583.7607	- 943 252.6689	5 715 821.0133	fixed
S24	2 684 307.3169	- 990 924.4018	5 681 354.0676	
S621	2 689 701.8406	-1 011 290.2813	5 675 194.9345	

Table 2. Results of the static surveys
Ellipsoidal coordinates, solution BRL3FX15-MAY1993

	ϕ (N)	λ (W)	ell. height (m)	
ARNA	64.13900245	21.95119219	91.8157	fixed
S13	64.11932532	19.74717411	319.260	fixed
S24	63.42254065	20.26185694	166.168	
S621	63.30021571	20.60555867	115.287	

The kinematic survey

The kinematic survey was conducted using the vector from point S24 on Heimaey to point 621 on Surtsey as a reference line. The fixed receiver on S24 operated contiuously during our stay in Surtsey. The roving receiver was carried from point to point on Surtsey, beginning each session on point 621. The points are described in the Appendix and shown on a map in Fig. 1. Description of point S24 is found in Einarsson (1993). The roving antenna was placed on a 2.15 m high range pole, held vertical by hand. Each point was occupied for 2-4 minutes, and 8-16 measurements were collected. The following measurement sessions were run:

Session 2230: Points 621-519-518-616-003 003-101 003-206
Session 2231: Points 621-622-102-623-624-625-205-007-301-103-302-007-301-103-302-
-007-301-510-511-606-607-609-101-612-621
Session 2232: Points 621-626-627

Session 2233: Points 621-625-205-303-304-205-304a-305-306-307-308-205-104
Session 2240: Points 621-625-626-627-628-629-105-630-106-107-207-206-616-003
Session 2241: Points 621-622-623-624-625-626-627-628-629-628-627-626-625-624-623-622--621-519-616-612-609-607-606-511-510-511-606-607-609

Results of the kinematic survey

The program TRIMKIN provided by the Trimble manufacturer was used for the analysis of the kinematic GPS data. The program calculates point coordinates and estimates of errors. Since a number of points were occupied more than once, both within the same session and in different sessions, the consistency of the solutions can be checked in various ways. Point 621, for example, was occupied at the beginning and end of session 2231, and the solutions differ by only few centimeters. Thus session 2231 appears to be reliable. It contains point 101, which was also occupied at the end of session 2230 with similar results. Thus session 2230 also appears to be reliable. Using similar argumentation we find that session 2232 is poor, and similarly the latter part of sessions 2233 and 2240. Session 2241 is reliable. Four categories of quality of the results can be defined:

A. More than one measurement with reasonable scatter, < 20 cm.
B. One measurement, within a session that closes well, probably reliable.
C. One measurement, reliability unknown.
D. Poor result, large calculated error or scatter, should not be used for geodetic puposes.

The results of the kinematic GPS survey are given in Table 3, together with the assigned quality.

Based on our experience in Surtsey the following procedures are recommended in kinematic GPS surveying:

1. Each point should be occupied at least three times.
2. Each session should end at a previously measured point.
3. The points are conveniently occupied in loops, with each loop of about 5 points ending at a previously occupied point.

Experience elsewhere suggests that the accuracy of kinematic GPS surveying can approach that of static surveying provided that careful field procedures are applied (Jackson et al., 1990). Repeated occupation of survey points and short distance (≈ 5 km) to the reference receiver are important in this respect.

Heights above sea level

The GPS-survey determines the position of the benchmarks with respect to an Earth centered coordinate system, independent of the gravity field. The heights of points above the reference ellipsoid are therefore determined, but not the height above sea level or the geoid. One height does not transform into the other unless the geoid height is accurately known. The gradient of the geoid height may be expected to be close to 1 m per 35 km in this region, falling to the SSE

Table 3. Coordinates of points in Surtsey

Point	Latitude	Longitude	Ell. height (m)	Height a.s.l. (m)	Quality
0S3	63.30102406	-20.59841434	105.847	40.954	A
0S7	63.30728460	-20.60184337	69.046	4.153	A
101	63.30109838	-20.59410820	88.482	23.589	A
102	63.30005318	-20.60820548	116.127	51.233	B
103	63.30867183	-20.60079088	69.546	4.652	B
104	63.30311963	-20.60906984	168.789	103.896	D
105	63.29955514	-20.61326029	95.963	31.069	C
106	63.29746150	-20.61082380	88.073	23.180	C
107	63.29692467	-20.60714650	86.004	21.111	C
205	63.30328266	-20.60535727	196.739	131.846	A
206	63.29887351	-20.59694731	88.293	23.400	C
207	63.29582228	-20.60175592	87.911	23.018	C
301	63.30727666	-20.60205790	69.882	4.988	A
302	63.30824146	-20.60407912	68.949	4.055	A
303	63.30366901	-20.60399081	190.426	125.532	C
304 C	63.30411647	-20.60103766	217.041	152.147	C
304 D	63.30565857	-20.60753095	199.109	134.216	D
305	63.30561533	-21.60765022	199.170	134.277	D
306	63.30606055	-20.61032501	205.390	140.496	D
307	63.30606247	-20.61049334	205.947	141.053	D
308	63.30619772	-20.61142048	198.754	133.861	D
510	63.30358859	-20.59281478	79.602	14.709	B
511	63.30328066	-20.59320391	80.670	15.777	B
518	63.30101642	-20.60327212	132.769	67.875	B
519*	63.30034125	-20.60441224	118.464	53.571	B
606	63.30266213	-20.59376259	84.993	20.100	B
607	63.30228735	-20.59362786	87.517	22.623	B
609	63.30170268	-20.59441572	88.203	23.309	B
616	63.30061426	-20.59854897	106.429	41.536	B
621	63.30021571	-20.60555866	115.288	50.395	A
622	63.30023662	-20.60689466	116.388	51.494	B
623	63.30027474	-20.60788108	116.660	51.766	A
624	63.30030016	-20.60853687	117.614	52.721	A
625	63.30019213	-20.60960149	120.048	55.155	A
626	63.30019075	-20.61057809	119.095	54.201	A
627	63.29997855	-20.61116617	110.885	45.992	A
628	63.29968241	-20.61212946	102.925	38.031	A
629	63.29962943	-20.61328571	96.197	31.304	A
630	63.29968157	-20.61405298	94.786	29.892	C

* This is probably point 520 of Moore et al. (1992).

(Torge, 1989). Over the width of the Surtsey island a maximum change of 6 cm in geoid height is expected.

No independent height measurements to sea level were done in connection with our GPS survey. We rely on the study of Moore et al. (1992) to connect our GPS height determinations to sea level. They find that the whole levelling network has been subsiding with respect to sea level, a total of 0.8-1.3 m from August 1967 to August 1991. The subsidence is rapid during the first years, but slows down considerably with time and is only about 1-2 cm per year during the last decade. The last 3 surveys, 1985, 1988 and 1991, for instance, show very little change in the height of benchmark 606. It is 20.0 m above the water level in a pit dug near the coast, which in turn was estimated to be 0.1 m above mean sea level. We therefore choose benchmark 606 as a reference for our hights, and define its hight as 20.1 m. Heights of other points are found by adding to this value the ellipsoidal height differences determined by our GPS survey (Table 3). This is equivalent to assuming a flat geoid height in this region. A maximum error introduced by this assumption is 6 cm.

Comparisons with levelling results

An independent check on the accuracy of the kinematic results is provided by the set of 18 common points between the levelling survey of 1991 by Moore et al. (1992) and our kinematic survey. A histogram of the differences in height between the two methods is shown in Fig. 2. For 7 out of the 18 points the difference is less than 2 cm. The largest difference is 18.9 cm for point 519. The RMS value for the whole set of points is 7 cm, and is improved to 6 cm if only quality A points are included.

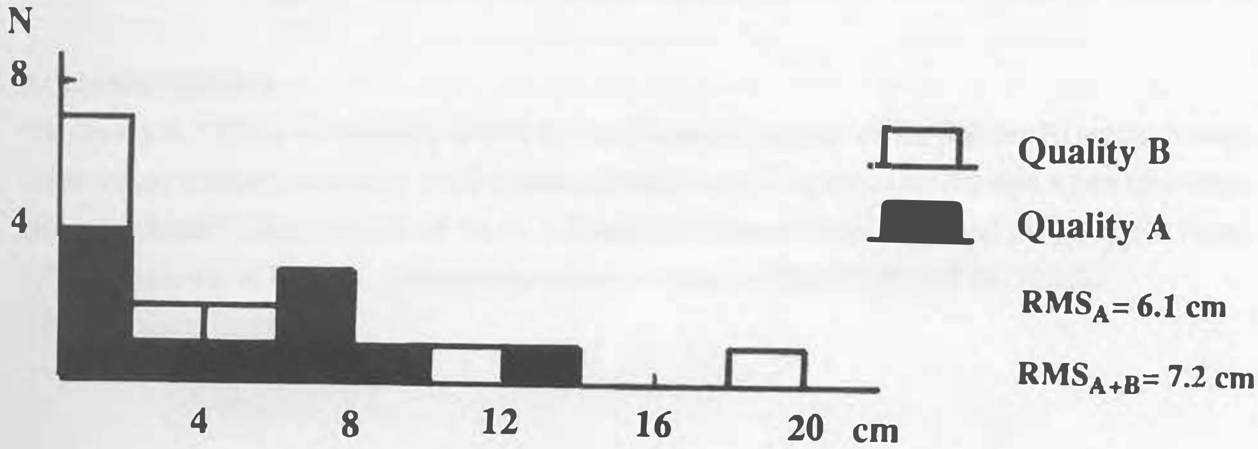

Fig. 2. *Histogram of differences between heights determined by conventional leveling (Moore et al., 1992) and kinematic GPS surveying.*

Geoid height

The static GPS measurement of point 621 gives a height above the WGS84 ellipsoid of 115.288 m. According to Moore et al. (1992) the point was 50.491 m above mean sea level in 1991.

Assuming that mean sea level is a good approximation of the geoid in this area we get a geoid hight of 64.8 m.

This value may be compared to the gravimetric geoid determined for the Iceland region by Torge (1989). Interpolation in his map of geoid heights gives a value of 65.8 m for Surtsey. His reference ellipsoid is the 1980 International (a = 6 378 137 m, f = 1:298.257). The difference between the WGS84 and the 1980 International ellipsoids is very small, of the order of millimeters. The difference between the hight of the gravitationally derived geoid and our GPS determination is thus 1 m. This difference is satisfactory in light of the uncertainty of 0.5-1 m given by Torge (1989) for the gravimetric geoid and the fact that the mean sea level deviates from the geoid, typically by a few tens of cm but sometimes more than a meter (Pugh, 1987).

Conclusions

1. Kinematic GPS-surveying is an efficient method for locating points in a limited area for mapping purposes. Standard deviation of the order of a few centimeters in horizontal positioning and 5-10 cm in vertical positioning can easily be obtained. A network of 25 points was measured in two days by three men under difficult conditions. Considerably higher efficiency could have been achieved.
2. The method also has application in crustal deformation studies, where higher accuracy is required. More rigorous field methodology must then be exercised. Points have to be occupied several times within the same session and the roving antenna should be placed on a centered tripod. The high efficiency of the method is valuable in areas where large displacements are expected and where a large number of points in a limited area are needed, such as in epicentral areas of large earthquakes and around active rifts.
3. The height of the geoid above the WGS84 reference ellipsoid in Surtsey (point 621) is 64.8 m.

Acknowledgements

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APPENDIX: Point descriptions

No.	Lat.	Lon.	Height	
	Approximate coordinates			
	d m s	d m s	m a.s.l.	

Points installed by Eysteinn Tryggvason in 1967

No.	Lat.	Lon.	Height	Description
606	63 18 12	20 35 39	20.1	Bolt set in lava inside a painted circle, about 370 m ENE of the hut, 100 m from the cliff on the east coast.
607	63 18 08	20 35 38	22.6	Bolt in lava inside a painted circle, about 350 m NE of the hut.
609	63 18 06	20 35 40	23.3	Bolt in lava inside a painted circle, about 280 m NE of the hut.
612	63 18 05	20 35 46	30.2	Bolt in lava inside a painted patch, about 170 m NE of the hut.
616	63 18 02	20 35 57	41.5	On the E edge of the lava channel immediately W of the hut.
621	63 18 01	20 36 20	50.4	About 350 m W of the hut, on a flat patch of lava. Marked by a cairn and a painted square.
622	63 18 00	20 36 23	51.5	Bolt in flat lava, about 400 m W of the hut.
623	63 18 02	20 36 30	51.8	Bolt in lava, about 470 m W of the hut. Painted circle around the bolt.
624	63 18 01	20 36 30	52.7	Bolt in lava, inside a faint, painted circle, about 500 m W of the hut.
625	63 18 00	20 36 32	55.2	Bolt in lava, inside a painted circle, about 550 m W of the hut.
626	63 17 59	20 36 40	54.2	Bolt in lava, inside a painted circle, about 600 m W of the hut.
627	63 17 58	20 36 42	46.0	Bolt in lava, inside a painted circle, about 640 m W of the hut. May be buried in sand, but arrows are painted on nearby outcrops.
628	63 17 58	20 36 44	38.0	Bolt in lava, inside a faint, painted circle, about 690 m W of the hut.
629	63 17 57	20 36 49	31.3	Bolt in lava, inside a painted circle, about 740 m W of the hut.
630	63 17 59	20 36 49	29.9	Bolt in lava, about 780 m W of the hut. The point was 2 m from the edge of the sea cliff on the western shore, surrounded by cracks in 1992. It disappeared during the following winter due to erosion (see Fig.1).

Points installed by J. Moore

0S3	63 18 06	20 36 01	41.0	Point S3 of Moore. Rusted nail in lava, inside a painted circle, about 40 m NE from the hut.
0S7	63 18 27	20 36 08	4.2	Point S7 of Moore. Rusted nail in a small patch of lava at the N foot of the palagonite mountain. The point is almost buried in sand, but arrows are painted on surrounding outcrop.
510	63 18 13	20 35 33	14.7	Rusted nail in lava, inside a painted circle. About 400 m NE of the hut, 18 m from the edge of the lava at the coast.
511	63 18 11	20 35 35	15.8	Rusted nail in lava, inside a painted square, about 40 m SW of point 510.
518	63 18 05	20 36 12	67.9	Rusted nail inside a painted circle, at the south edge of the eastern cone within the Surtur I crater, 220 m W of the hut.
519	63 18 02	20 36 14	53.6	Rusted nail driven into the lava, 270 m W of the hut, north of a small crater. (This is probably point 520 of Moore et al., 1992)

Points installed in 1992

205	63 18 13	20 36 19	131.8	Brass bolt and a plate set in palagonite, inside a painted square, on the central peak in the saddle between the two main peaks. Inscription RH 92 05.
206	63 17 56	20 35 49	23.4	Brass bolt and a plate in pahoehoe lava, about 300 m S of the hut. Inscription RH 92 06. Painted square.
207	63 17 44	20 36 04	23.0	Brass bolt and a plate, inside a painted square, about 30 m from the edge of the sea cliff on the southern shore. Inscription RH 92 07.

Points, permanent but without numbers

103	63 18 31	20 36 02	4.7	A steel rod driven into the loose material on the middle of the northern ness. The top of the rod stands 15 cm out of the sand. Marked for aerial photography by a three-armed star of driftwood and rocks.
301	63 18 27	20 36 07	5.0	Point Pl of Moore. Rusted nail in a small lava outcrop on the N part of the island, about 10 m W of point S7.
302	63 18 30	20 36 15	4.1	A pipe with a cap sticking 1.73 m out of the sand, near the site of the old hut on the northern ness. This pipe was used for water level measurements by Moore et al.(1992).

303	63 18 13	20 36 16	125.5	Steel rod, sticking 1.11 m out of the palagonite in the saddle E of the middle peak and W of the eastern peak.
305	63 18 21	20 36 26	134.3	Rusted steel rod, sticking 56 cm out of the loose surface material, screw in the end. Near the eastern end of the crest of the western mountain, about 7 m from point 304.
306	63 18 22	20 36 35	140.5	Rusted steel pipe with a cap, on the crest of the western mountain.
307	63 18 22	20 36 35	141.1	Steel rod, 45 cm high, in a small cairn. On the crest of the western mountain, about 8 m from point 306.

Points, painted only, or marked for aerial photography

101	63 18 08	20 35 39	23.6	Painted square on lava, about 200 m E of the hut.
102	63 18 00	20 36 29	51.2	Painted square, near point no. 623.
304 C	63 18 16	20 36 03	152.1	Painted square on the helicopter pad on the eastern peak.
304 D	63 18 21	20 36 26	134.2	Canvas bag, near the eastern end of the crest of the western mountain.
308	63 18 23	20 36 41	133.9	Point marked for aerial photography, in the saddle at the crest of the western mountain.
104	63 18 12	20 36 34		Painted square on lava, east of the large lava crater of Surtur II.
105	63 17 58	20 36 47	31.1	Painted square on lava, about 750 m W of the hut, 7 m from point 629.
106	63 17 51	20 36 37	23.2	Painted square on pahoehoe lava just south of a a-a lava tongue, about 5 from the edge of the sea cliff on the western shore in 1992. Disappeared during the following winter due to erosion (see Fig.1).
107	63 17 48	20 36 24	21.1	Painted square on lava in southern part of the island, south of the sea gull colony, north of a large sink hole area.