Precision levelling and geodetic GPS observations performed on Surtsey between 1967 and 2002

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ABSTRACT

The load on the crust from the ~ 0.8 km^3 of eruptive products of the Surtsey eruption is expected to lead to subsidence of the Surtsey island by sagging of the lithosphere, compaction of material, and slumping of the volcanic edifice. Immediately after the eruption ended in the summer of 1967 a levelling line was established across the island to monitor this expected subsidence. The line originally contained 42 benchmarks. As Surtsey is subjected to extensive erosion, in particular in the western and southern parts of the island, the western section of the line has been lost to the sea. In the year 2002 the line ended with benchmark 28. Additional benchmarks were installed 1979, 1982, 1985 and 2002, to fill in gaps in the original line and another profile was installed through the Surtur I crater. Between 1967 and 2002 levelling has been performed eleven times. One benchmark was surveyed with geodetic GPS in 1992. The benchmark was resurveyed in 2000 and 2002 and the GPS network has been extended to comprise four points. In this report we have compiled the levelling data collected on Surtsey so far. Furthermore we present coordinates for the GPS-benchmarks. Continuing subsidence of Surtsey is observed with a decaying rate. The area around the Surtur I crater is the most stable part with a subsidence rate of 0.7 cm/yr in the period 1991–2002. The largest subsidence is observed at the flanks of the island with rates up to 1.4 cm/yr. The excess rate here is most likely caused by slumping of the sides of the island.

INTRODUCTION

The new island Surtsey (Fig. 1), formed in an eruptive episode off the south coast of Iceland in 1963–1967, experiences continuous changes, from its creation during the eruption to the decline by erosion after the termination of the eruption (Jakobsson *et al.* 2000). Compaction of the island started immediately as it was formed, but during the eruption it was not possible to follow this closely. In the summer 1967, shortly after the cessation of the eruption, a levelling line was installed across the island. Repeated levelling has been performed making it possible to monitor the subsidence at Surtsey. In addition, geodetic GPS measurements were initiated on Surtsey in 1992 with the main purpose of tying the vertical displacement of the levelling line to a reference frame outside the island. Levelling has been performed on eleven occasions and geodetic GPS observation has been done three times. The geodetic measurements on Surtsey show continuing subsidence, at a decreasing rate with time. This report gives a complete record of all geodetic measurements performed on Surtsey since 1967.

THE SURTSEY ERUPTION

The eruption was detected on November 14, 1963, at the ocean surface at the southern tip of the Eastern Volcanic Zone but may have started a few days earlier (e.g. Thórarinsson *et al.* 1964, Thórarinsson 1967, Thórarinsson 1964, 1965, 1966, 1969). The water depth was 130 m but a new island, Surtsey, was formed the following day. Four craters were active on a 500 m long, SW-NE striking fissure. The activity gradually concentrated on one crater, Surtur

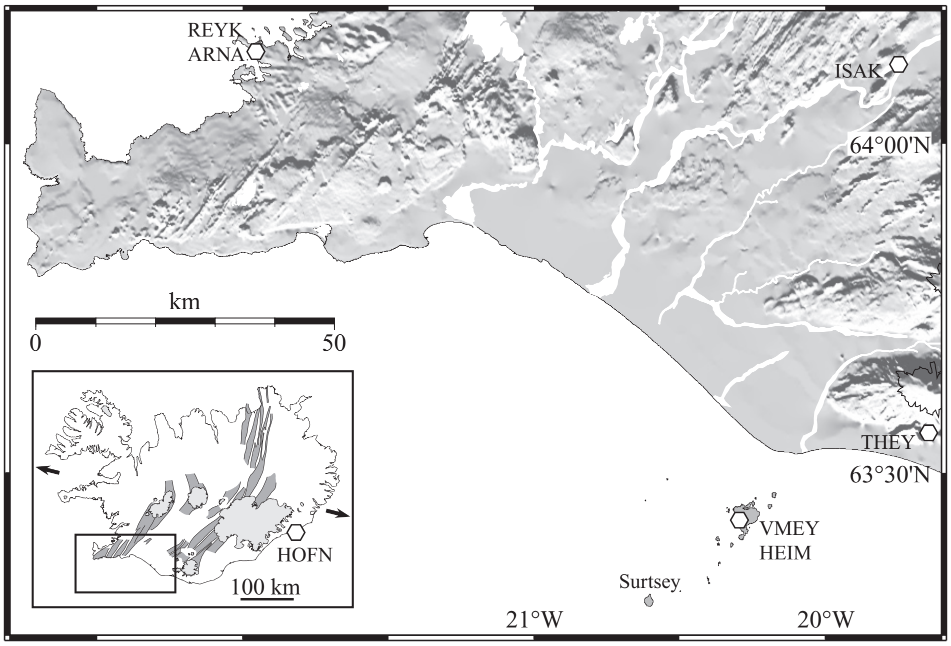

Fig. 1. Map covering the south-western part of Iceland. The hexagons show the location of the GPS points occupied as reference stations during the three geodetic GPS-surveys on Surtsey.

I, and phreato-magmatic activity continued with little changes until the end of January 1964 when it stopped temporarily. A second eruption site was active during this first phase of the eruption, about 2.5 km ENE of Surtsey, producing a submarine ridge, Surtla, almost extending to sea-level. On February 1 a new crater, Surtur II, began erupting. Phreato-magmatic activity continued until April 4, 1964. Then the magma conduit got isolated from the sea water and the activity changed into lava effusion. A lava shield was formed during a period of lava effusion that ended in the middle of May 1965. On May 23, 1965 a new submarine eruption site became active 0.6 km east of Surtsey, building an island in 5 days. The new island, Syrtlingur, had attained an area of 0.15 km^2 and height of 70 m by September 1965. This eruption site became inactive in the middle of October and the island was eroded away in a week. No eruptive activity was spotted for 2 months, but in late December 1965 an eruption began on the ocean bottom 0.8 km SW of Surtsey. The eruption built an island, Jólnir, in about a week. By July 1966 the new island had an area of 0.4 km^2 and a maximum height of 70 m. This eruption ended on August 10, 1966 and by September 20 this new island had also disappeared. On August 19, 1966 a new eruptive fissure opened up within the crater Surtur I. Three craters were active in the beginning but a few days later only one remained. Lava was erupted from this crater until June 5, 1967, building up a flat lava shield and extending the Surtsey island to the east. The eruptive fissure was temporarily extended to the north side of the island on January 1, 1967, producing a small patch of lava. The total volume of erupted material is estimated ~ 0.8 km^3 of solid rock equivalent, all of it basaltic (Jakobsson et al. 2000).

LEVELLING

The data from all the eleven levelling campaigns are given in Table 1. The original levelling line that was installed across the new island (Fig. 2) in 1967 consisted of 42 benchmarks (Tryggvason 1968) spaced approximately 50 m apart. The erosive forces of the sea have shortened this original levelling line by 14 benchmarks. Several benchmarks that are still on land are lost in the drifting sand and have been lost for years. However, some have been found again and their coordinates have now been determined by GPS measurements.

The reference point for the levelling on Surtsey was at first tied to mean sea level. A pond was located in the north part of Surtsey close to the first research hut, which was demolished in the 1980's as the sea erosion had moved the coastline close to the hut. The station HD was at the doorway in the old hut (Fig. 2). The surface of this pond was assumed to be very close to the mean sea level (Tryggvason 1968). The water level in the pond was out of phase with the predicted ocean tide and a delay of more than two hours relative to the predicted ocean tide in Heimaey was observed (Tryggvason 1968). This pond had disappeared in 1969, but, the ground water table was close to the surface and a pit was dug to observe the water table (Tryggvason 1972). The water level corrected for the ocean tide was used as the reference level for the levelling campaigns made in 1967 to 1991. In the 1979 survey Moore (1982) estimated that the average water level in the dug pit was 32±15 cm above the mean sea level. The water level in the pond and dug pits is named WP in Tables 1 & 2 and in Figure 2.

The levelling line was complemented with new points in 1979 (Moore 1982) as the sand drift on

Table 1a. Data for the levelling performed across Surtsey, including 1967 to the 2002 survey. All values are given in meters. The 1967 to 1991 surveys are referenced to the WP point. As the WP point could not be located in 2002, benchmark 621 was used as reference. The 621 benchmark is the GPS point SURS.

Site	1967A	1967B	1968	1969	1970	1979	1982	1985	1988	1991	2002
WP	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
601	8.7880	8.9050	8.9050	8.6090	8.5280	8.2950					
602	10.8996	11.0115	10.9983	10.6910	10.6025						
603	12.4895	12.5993		12.2636	12.1710						
604	15.4782	15.5832									
605	18.7406	18.8434	18.7995	18.4696	18.3664						
606	21.0478	21.1506	21.1037	20.7723	20.6679	20.3160	20.2100	20.0590	19.9500	20.0170	-30.4137
607	23.7212	23.8137	23.7398	23.4001	23.2908	22.8920	22.7720	22.6200	22.5140	22.5780	-27.8517
608	23.3581	23.4407	23.3378	22.9884	22.8741						
609	24.3543	24.4492	24.3739	24.0334	23.9214	23.5090	23.3970			23.2330	-27.1674
610	25.6973	25.8029	25.7742	25.4493	25.3457						
611	28.6667	28.7754	28.7499	28.4305	28.3343						-22.5233
612	30.9279	31.0358	31.0113	30.6897	30.5926		30.2300	30.1220	30.0270	30.1130	-20.2579
613	33.2649	33.3642	33.3360	33.0097	32.9115						
614	34.1049	34.2112	34.1893	33.8667	33.7723						
615	35.1394	35.2459	35.2169								
616	42.3743	42.4681	42.4285	42.0971	41.9940						-8.7601
617	43.9742	44.0339	43.8992	43.5699	43.4588						-7.2849
618	47.1692	47.2624	47.0210	46.6601	46.5523						
619	48.8669	48.9049	48.6913	48.3211	48.1996						
620	51.3190	51.4262	51.3971	51.0743	50.9791						
621	51.1409	51.2333	51.1750	50.8494	50.7541		50.4970	50.4130	50.3060	50.3910	0.0000
622	52.1904	52.2887	52.2346	51.8928	51.7902			51.4410	51.3330	51.4160	1.0359
623	52.4808	52.5728	52.4782	52.1057	51.9911			51.6250	51.5130	51.6000	1.2247
624	53.6409	53.7266	53.5830	53.1882	53.0606			52.6690	52.5580	52.6460	2.2748
625	56.3717	56.4421	56.1665	55.7002	55.5426			55.1020	54.9970	55.0810	4.7078
626	55.1859	55.2680	55.0945	54.6815	54.5441			54.0770	53.9660	54.0520	3.6750
627	46.8897	46.9858	46.8916	46.5231	46.4004			45.9180		45.8930	-4.4940
628	38.9433	39.0473	38.9879	38.6328	38.5142			38.0000	37.8690	37.9700	-12.6068
629	32.2679	32.3762	32.3373	31.9936	31.8784			31.3320	31.1860	31.2990	
630	30.9129	31.0229	30.9944	30.6573	30.5450			29.9860	29.8390	29.9430	
631	30.6739	30.7840	30.7594	30.4282	30.3215			29.7960			
632	32.1005	32.2099	32.1832	31.8525	31.7475			31.1960			
633	33.3989	33.5086	33.4820	33.1517	33.0472			32.4800			
634	33.2734	33.3819	33.3511	33.0155	32.9085						
635	37.2355	37.3432	37.3114	36.9699	36.8604						
636	33.2752	33.3811	33.3322	32.9901	32.8798						
637	31.7889	31.8949	31.8562	31.5224	31.4127						
638	30.3638	30.4712	30.4409	30.1092	30.0016						
639	26.7511	26.8596	26.8369	26.5095	26.4062						
640	22.3683	22.4780	22.4598	22.1383	22.0399						
641	20.6012	20.7121	20.7003	20.3848	20.2936						
642	15.8768	15.9931	15.9519	15.6581							

Surtsey had buried some of the original benchmarks. The levelling in 1979 tied the drill hole (SHD-1) with a water-level pit (WP). Also a new loop containing 10 benchmarks (512–520) through the Surtur I crater, and two benchmarks (510 and 511) in the beginning of the original levelling line (Fig. 2) were installed by J. G. Moore in 1982.

During the levelling in 2002 two new benchmarks (NE09 and NE10; Fig. 2) were installed in the line because benchmarks 618 and 619 were not found. To bridge the 250-m gap, two new benchmarks were installed. Also a benchmark (NE07) was installed in the centre of the helicopter landing platform and this was tied to the levelling line.

In addition to the precision levelling performed, several control points (white paintings on rocks) were installed in 1968 and levelled for a detailed photogrammetric mapping of the island (Norrman

Table 1b. Data for the levelling performed across Surtsey, including 1979 to the 2002 survey. All values are given in meters. The 1979 to 1991 surveys are referenced to the WP point. As the WP point could not be located in 2002, benchmark 621 was used as reference.

Site	1979	1982	1985	1988	1991	2002
WP	0.0000	0.0000	0.0000	0.0000	0.0000	
510		14.7830	14.6440	14.5430	14.6180	-35.8001
511		15.8350	15.6890	15.5800	15.6530	-34.7775
512		61.9490	61.8820	61.7910	61.8770	11.5149
513		66.5630	66.4960	66.4070	66.4880	16.1256
514		70.2780	70.2100	70.1210	70.2010	19.8338
515		70.9210	70.8570	70.7670	70.8480	20.4786
516		70.7470	70.6800	70.5890	70.6700	20.3002
517		65.5100	65.4390	65.3410	65.4240	15.0473
518		67.9900	67.9200	67.8270	67.9080	17.5320
519		61.7790	61.7050	61.6040	61.6850	11.3074
520		53.7760	53.6960	53.5930	53.6770	3.2922
P-1					4.8870	
S-1	27.1570	27.0720	26.9560	26.8670	26.9550	
S-2	34.8270	34.7320	34.6320	34.5390	34.6300	-15.7358
S-3	41.1830	41.0800	40.9880	40.9020	40.9910	-9.3649
S-4	57.3390	57.2140	57.1360	57.0460	57.1340	6.7705
S-6	3.3410	3.3060				
S-7	4.1660	4.1310	4.0150	3.9150	4.0280	
SDH-1	58.7540	58.6290	58.5560	58.4590	58.5470	
SDH-2		5.6910	6.1670	6.4890		
NE07						-16.1630
NE09						-0.6930
NE10						-0.1400
ALP	10.3810					
HD	7.0570					
IS	8.7300	8.6850				
LMI	3.387					
SW	15.9050					
TW	49.4420	49.3290	49.2480	49.1570	49.2460	

1970). During the kinematic GPS-survey in Surtsey 1992 three new benchmarks were installed to complement the net of ground control points for aerial photography and mapping purposes (Einarsson *et al.* 1994).

COORDINATES FOR THE LEVELLING POINTS ON SURTSEY

The original levelling line was installed in the summer of 1967 by Tryggvason (1968), and the coordinates for the benchmarks were presented by Tryggvason (1970). In 1994 a kinematic GPS-survey was performed (Einarsson *et al.* 1994) of 14 of the originally 42 benchmarks. Twelve benchmarks (631 to 642) had been destroyed by coastal erosion in 1992. Sixteen benchmarks were not found during the 1992 survey as the drifting sand had buried them. In the 2002-survey cracks around benchmark 628 indicated that it was the next one to be lost into the sea (Figs. 2 & 3). In this survey fifteen benchmarks were found in the original Tryggvason levelling line, three in addition to what was found in 1992 as the sand continuously changes. The coordinates were measured with a hand-held GPS in 2002. The coordinates presented by Tryggvason (1970) were used to calculate the positions for the benchmark, which had not been positioned by GPS in 1992 and 2002. The coordinates from Tryggvason have the origin at benchmark 601. The GPS-survey presented by Einarsson *et al.* (1994) gave positions in longitude and latitude, which were transferred to UTM coordinates. Point 621 was chosen as the origin in both nets (the net from Tryggvason 1970, Einarsson *et al.* 1994) and the co-ordinates of point 621 were set to 0,0. Benchmark 621 was chosen to be the origin because of its central location in the line and because it is the benchmark used for geodetic GPS measurements. Thirteen points were measured both by Tryggvason (1970) and Einarsson *et al.* (1994), which were used to determine the rotation angle between the two co-ordinate sets. The average angle was 0.4° anticlockwise so the co-ordinates given by Tryggvason (1970) had to be rotated –0.4° around point 621. After the rotation

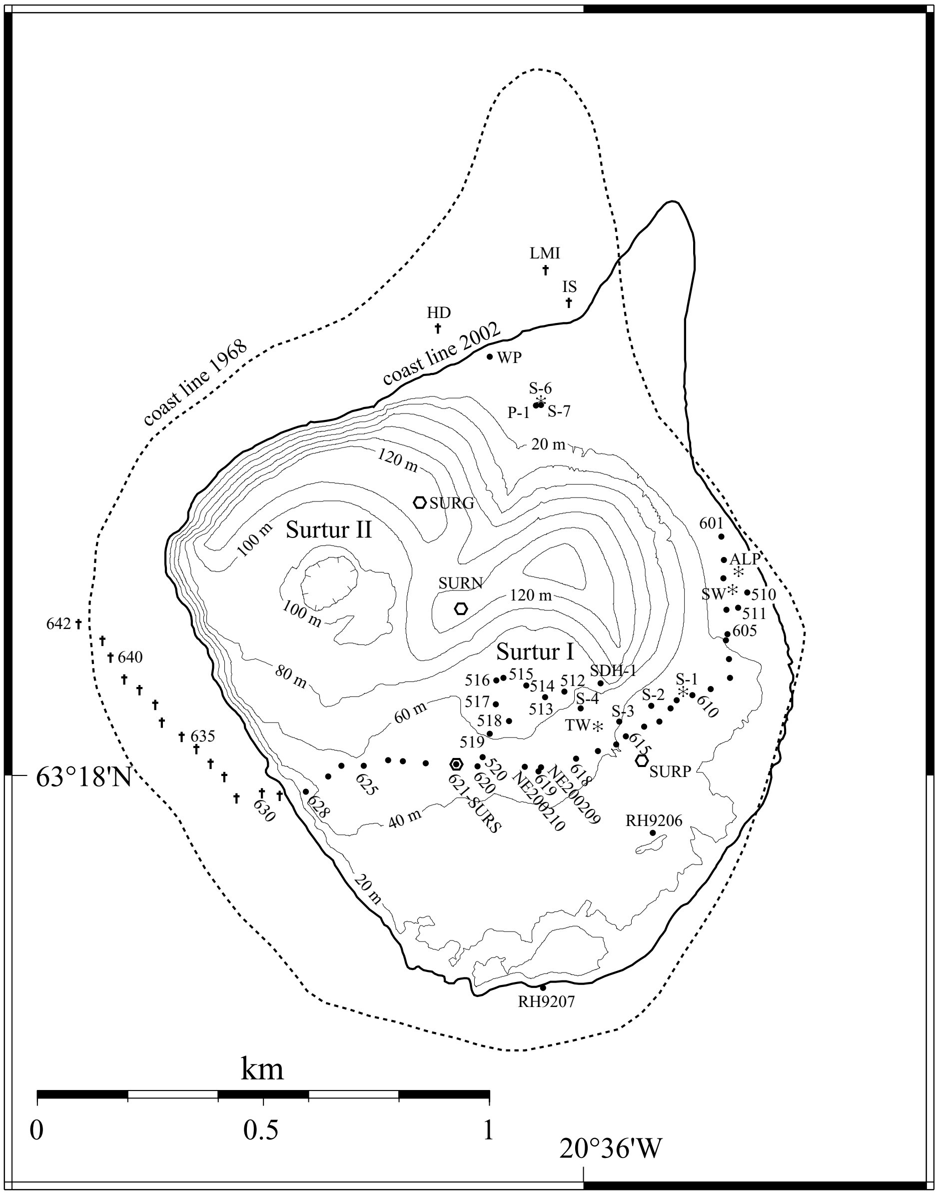

Fig. 2. Map of Surtsey with the 1968 coastline adapted from Norrman (1970) and the coastline 2002 (Sveinn Jakobsson pers. com. 2008). The benchmarks with coordinates (Table 2) are marked with filled circles. The benchmarks lost due to sea erosion are marked with crosses. The benchmark HD was located in the doorway of the first hut. Markings and benchmarks (S-1, S-6, ALP, SW and TW) not found or without any documented coordinates are marked with stars The GPS benchmarks are shown with hexagons. The levelling line is connected to the GPS measurements at BM 621 by the GPS site SURS. The topography is shown by 20 m elevation contours (Sveinn Jakobsson pers. com. 2008).

Fig. 3. Levelling performed in 2002, with the invar rod at benchmark 628. This is probably the last picture of that benchmark as the ground is cracked and the sea erosion will consume it.

Table 2. Measured and calculated coordinates for all benchmarks found and with reported coordinates. The prefix PE indicates that the coordinates (±1m) originate from Einarsson et al. (1994), the HG prefix indicates coordinates (±3m) obtained in 2002, and the remanding are coordinates (±1m) ET/ES calculated (marked ET/ES) from Tryggvason (1970). These coordinates are only for locating the points and should not be used for geodetic purposes.

Site	Longitude	Latitude	Origin
601	-20.59396	63.30470	ET/ES
602	-20.59384	63.30423	ET/ES
603	-20.59386	63.30388	ET/ES
604	-20.59374	63.30326	ET/ES
605	-20.59370	63.30278	ET/ES
606	-20.59376	63.30266	PE
607	-20.59363	63.30229	PE
608	-20.59359	63.30192	ET/ES
609	-20.59442	63.30170	PE
610	-20.59522	63.30158	ET/ES
611	-20.59591	63.30148	ET/ES
612	-20.59617	63.30132	ET/ES
613	-20.59668	63.30106	ET/ES
614	-20.59734	63.30096	ET/ES
615	-20.59798	63.30076	ET/ES
616	-20.59855	63.30061	PE
617	-20.59936	63.30048	ET/ES
618	-20.60032	63.30033	ET/ES
619	-20.60196	63.30008	ET/ES
620	-20.60462	63.30018	ET/ES
621	-20.60556	63.30022	PE
622	-20.60689	63.30024	PE
623	-20.60788	63.30027	PE
624	-20.60854	63.30030	PE
625	-20.60960	63.30019	PE
626	-20.61058	63.30019	PE
627	-20.61117	63.29998	PE
628	-20.61213	63.29968	PE
629	-20.61329	63.29963	PE
630	-20.61407	63.29969	ET/ES
631	-20.61518	63.29959	ET/ES
632	-20.61571	63.30001	ET/ES
633	-20.61632	63.30027	ET/ES
634	-20.61693	63.30056	ET/ES
635	-20.61757	63.30080	ET/ES
636	-20.61844	63.30108	ET/ES
637	-20.61874	63.30143	ET/ES
638	-20.61943	63.30172	ET/ES
639	-20.62010	63.30193	ET/ES
640	-20.62068	63.30236	ET/ES
641	-20.62104	63.30269	ET/ES
642	-20.62209	63.30302	ET/ES
642	-20.62209	63.30302	ET/ES
510	-20.59283	63.30360	HG
511	-20.59322	63.30330	HG
512	-20.60081	63.30165	HG
513	-20.60167	63.30154	HG
514	-20.60250	63.30177	HG
515	-20.60348	63.30192	HG
516	-20.60380	63.30187	HG
517	-20.60381	63.30140	HG
518	-20.60325	63.30107	HG
519	-20.60409	63.30082	HG
520	-20.60441	63.30036	HG
WP	-20.60408	63.30824	PE
P-1	-20.60206	63.30728	PE
S-2	-20.59702	63.30137	HG
S-3	-20.59843	63.30106	HG
S-4	-20.60011	63.30132	HG
S-7	-20.60184	63.30728	PE
RH9205	-20.60536	63.30328	PE
RH9206	-20.59695	63.29887	PE
RH9207	-20.60176	63.29582	PE
NE09	-20.60184	63.30016	HG
NE10	-20.60256	63.30017	HG

Table 3. Description of lost stations from Moore (1982).

Site	Notes
ALP	Base of bent aluminium peg (not found recently)
HD	Threshold in the doorway of the old hut (destroyed)
IS	Iron stake in a small tuff hill, which is eroded today (destroyed)
LMI	Iron stake north of the former small tuff hill (destroyed)
SW	White painted square with a yellow inner circle (not found recently)
TW	White triangle painted on the lava (not found recently)
SDH-2	The top of pipe at the WP site (not found recently)

the difference between co-ordinate pairs from the two sets was 1 meter or less. Finally the generated UTM co-ordinates for the "missing" points were transferred to longitude and latitude form and are presented together with the positions given by Einarsson *et al.* (1994) in Table 2.

This work presents co-ordinates for all benchmarks except three, which might surface in the future as the windblown sand is ever shifting. Those are benchmarks S-1, S-6 and ALP. They are indicated in Figure 2 with stars, as their position is not well known.

In the 1979 survey (Moore 1982) only a few of the original benchmarks were found (Table 1), and the drill-hole elevation was determined relative to a five days average of the water level in the pit (WP in Fig. 2). In this survey several new benchmarks were installed and other markers with less long-term stability were also used. Most of these are lost forever but the two stations that were painted on lava might be re-discovered (Table 3).

GPS MEASUREMENTS

Three campaigns with geodetic GPS measurements have been performed on Surtsey, in 1992,

Table 4. The sites surveyed in the 1992 Surtsey GPS campaign.

Site	Start	End	Receiver	Antenna	Slant height [m]
SURS	221	222	Trimble 4000 SST	TRM 14532.00	1.247
HEIM/0S24	221	222	Trimble 4000 SST	TRM 14532.00	1.142
ISAK/0S13	213	229	Trimble 4000 SST	TRM 14532.00	1.025
ARNA	205	216	Trimble 4000 SST	TRM 14532.00	1.059

Table 5. The sites surveyed in the 2000 Surtsey GPS campaign.

Site	Start	End	Receiver	Antenna	Slant height [m]
SURS	195	197	Trimble 4000 SSI	TRM 33429.20	0.931
SURN	197	198	Trimble 4000 SSI	TRM 33429.20	0.987

Table 6. The sites surveyed in the 2002 Surtsey GPS campaign.

Site	Start	End	Receiver	Antenna	Slant height [m]
SURS	228	230	Trimble 4000 SSI	TRM 33429.20	1.032
SURN	228	230	Trimble 4000 SSI	TRM 33429.20	1.038
SURG	230	231	Trimble 4000 SSI	TRM 33429.20	1.028
SURP	230	231	Trimble 4000 SSI	TRM 33429.20	0.995

2000 and 2002. In the 1992 survey kinematic GPS was also carried out at a number of points, see Einarsson *et al.* (1994). Geographic descriptions of the GPS points are given by Ólafsdóttir *et al.* (2003), who also include a complete list of the major campaigns in which some of the GPS measurements on Surtsey were included. In the first GPS-measurements, in 1992, only benchmark number 621 was occupied, now called SURS and it was re-measured in the year 2000. A new GPS-point was measured on benchmark RH9205 named SURN and it is situated in palagonite tuff in the saddle between the two main peaks (Fig. 2). During the 2002 survey SURS and SURN were re-occupied and two new points were added, one in palagonite tuff on the crest of the western mountain, called SURG, with the inscription NE08 (Fig. 4), and a second in the centre of the helicopter platform (SURP, inscription NE07). The purpose of a GPS-point in the helicopter platform is mainly for aerial photography as the concrete plate makes an excellent aerial marker.

Fig. 4. Measurements of the GPS station SURG.

In Tables 4–6 we list the measured sites for each campaign, the start and end day (UTC days), receiver type, antenna type and the slant antenna height. Naming conventions of receiver and antenna type are according to the manufacturer. The original GPS point SURS (benchmark 621) has three different names throughout time: In 1992 it was called S621, in 2000 SURM and in 2002 SURS.

GPS DATA PROCESSING

GPS-data were processed with the Bernese GPS software package (Beutler *et al.* 2000), versions 3.5, 4.0 and 4.2. The data were collected at 15-second intervals during three 8 hours sessions at each site during the 1992 and 2000 campaigns and in the 2002 campaigns the session length was 24 hours. The processing procedure is described by Sturkell *et al.* (2003). Geocentric coordinates for the points in the three different surveys are presented in Tables 8–10.

A slight matter of complication arises from the choice of reference stations for the Surtsey campaigns. In 1992 station ISAK was intended as the reference station, in 2000 REYK was intended as the reference station and ISAK not observed simultaneously, and in 2002 both ISAK and REYK were running during the Surtsey campaign as parts of the continuous GPS network in Iceland (Geirs-

Table 7. Tie coordinates between ARNA and REYK (after Hreinsdóttir 1999, p. 59).

Station name	x(m)	y(m)	z(m)
REYK	2587384.501	–1043033.496	5716563.974
ARNA	2587441.511	–1042831.287	5716573.510

Table 8. Geocentric coordinates for the Surtsey sites in 1992 (campaign SUD92).

Station name	x (m)	y (m)	z (m)
ISAK	2627583.7742	–943252.6850	5715821.0363
ARNA	2587441.6610	–1042831.2440	5716573.5550
0S24	2684307.3194	–990924.4230	5681354.0879
SURS	2689701.8356	–1011290.2930	5675194.9495

Table 9. Geocentric coordinates for the Surtsey sites in 2000 (campaign SURT00).

Station name	x (m)	y (m)	z (m)
HOFN	2679690.2241	–727951.2181	5722789.1977
REYK	2587384.6616	–1043033.4437	5716564.0364
SURS	2689701.8852	–1011290.1472	5675194.8866
SURN	2689453.8128	–1011186.0329	5675421.3052
THEY	2681807.1338	–957239.1215	5688292.0480
VMEY	2683329.9906	–992250.9465	5681548.1928

Table 10. Geocentric co-ordinates for the Surtsey sites in 2002 (campaign SURT02).

Station name	x (m)	y (m)	z (m)
ISAK	2627583.7742	–943252.6850	5715821.0363
HOFN	2679690.2241	–727951.2181	5722789.1977
REYK	2587384.5923	–1043033.4748	5716563.9524
SURS	2689701.8430	–1011290.1442	5675194.7997
SURN	2689453.7723	–1011186.0243	5675421.2133
THEY	2681807.0966	–957239.1163	5688291.9778
VMEY	2683329.9532	–992250.9413	5681548.1164
SURG	2689228.7345	–1011198.5186	5675527.3505
SURP	2689831.5096	–1010904.3236	5675183.9268

son *et al.* 2006). Ultimately we would like to have a single reference station for all the campaigns. To achieve this goal we note that in 1992 station ISAK was observed between days 213 and 229 and station ARNA was observed between days 205 and 216 (Table 4). Therefore, we can make ties between ARNA and ISAK and effectively use ARNA as the reference site for the 1992 survey. In 1998 a tie was made between ARNA and REYK (Hreinsdóttir 1999; Table 7) and this tie we use to effectively have the 1992 results referred to the REYK station. Therefore, we can compare the reuslts from 1992, 2000 and 2002 as if the same reference station, REYK, had been used for all campaigns. The REYK station is known to follow well the movements of the North-American plate and it is subsiding by a rate of about 3 mm/yr in a global reference frame (Sella *et al.* 2002, Geirsson *et al.* 2006). It is therefore straightforward to obtain the absolute horizontal and vertical motions of the Surtsey points. For future reference we recommend that the continuous GPS station on Heimaey (VMEY) will be used as a reference site. VMEY was included in the processing of the 2000 and 2002 data.

CONCLUSIONS

The vertical displacement signal gives most information on the processes that are currently active on Surtsey. A levelling dataset, extending back to 1967, and the later GPS data are compiled and gives good opportunity to unravel the different processes currently active on the island. The GPS data improve the possibility to tie the vertical displacements to a reference frame outside the island and thus reduce the uncertainties in the absolute height determinations.

The data presented here are used to assess different processes responsible for vertical displacements in Surtsey in particular during the 1991–2002 period (Sturkell *et al.* 2009). The main conclusions are the following: Surtsey subsided rapidly during the first 10–15 years and later with a decaying rate. This decay was confirmed by GPS during 1992 to 2002. In the period 1992–2000 the rate was approximately 1 cm/yr, and for the 2000–2002 period approximately 0.5 cm/yr. The deformation processes currently active on Surtsey are compaction of the volcanogenic material, slumping of the flanks of the island, lithosphere sagging due to load of the erupted material and possible compaction of the seabed sediments. Palagonitization of the tephra causes consolidation by growth of secondary minerals and thereby counteracts the compaction. During the first years, thermal contraction of the lava fields may have contributed to the subsidence signal, but probably decayed away in less than 20 years. Between 1991–2002 largest amount of subsidence is observed (15 cm in 11 years) along the sides of the tuff cones where the lava overlays the delta and the central part of the island has subsided by 8–10 cm during the same period.

Because of the current magnitude of the vertical deformation signal and its decay with time, we suggest that in the future the GPS sites and the levelling line be reoccupied at 5–10 year intervals.

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