Working Report 2008-19

Precise Levelling Campaigns at Olkiluoto in 2006 – 2007

Pekka Lehmuskoski

April 2008

POSIVA OY
Olkiluoto
FI-27160 EURAJOKI, FINLAND
Tel +358-2-8372 31
Fax +358-2-8372 3709

Working Report 2008-19

Precise Levelling Campaigns at Olkiluoto in 2006 – 2007

Pekka Lehmuskoski
Finnish Geodetic Institute

April 2008

Precise levelling campaigns at Olkiluoto in 2006-2007

ABSTRACT

The GPS observation network of Olkiluoto was constructed in 1994 for monitoring crustal deformations in the investigation area. To fulfil a better vertical control of the GPS network, precise levellings were started in the area in autumn 2003. The GPS network was first connected at Lapijoki to the precise levelling network of Finland to control the vertical movements of the whole island of Olkiluoto. Then the GPS network was levelled. It consisted of the reserve marks of eight GPS pillars and five levelling bench marks, two of which constituted the nodal bench mark pair.

The second precise levelling campaign on the area was carried out in autumn 2005. Now only the GPS network added with the antenna platforms of nine GPS pillars were levelled. Compared to the other points, the elevation difference of two reserve mark pairs had changed significantly during two years, about one millimetre. The reason may be the blasting of the rock in the neighbourhood of these points and deformation of the rock after the blasting.

Inspired by the observed elevation changes in 2005, micro loops were established and levelled onto the ONKALO and the VLJ Repository in autumn 2006. The micro loops consisted of seven and five bench marks the mean interval being about 300 metres.

The campaign in autumn 2007 consisted of the levellings of all measured and undestroyed points of the earlier campaigns. The most interesting results were: 1) Compared to the mean theoretical land uplift the nodal bench mark 03216 near the crossing of Olkiluodontie and Satamatie had risen in four years 2.6 mm more than the nodal bench mark of Lapijoki and 1.9 mm of this occurred within the 0.8 mm long interval which separates the island and the continent. 2) During four years the northern part of the island had risen about one millimetre more than the middle part, where the before mentioned 03216 is located. 3) The elevation differences between the bench marks of the ONKALO micro loop were changed even one millimetre during one year. In the place where the land uplift gradient was most significant, the change was 0.5 mm within a bench mark interval of a little more than one hundred metres.

According to the plan the line from Lapijoki to Olkiluoto will be levelled every fourth year, GPS network every second year and the mini networks every year. The latest observations prove that the levelling frequency of the bench mark interval separating the island and the continent should be increased.

Keywords: Deformation of bedrock, precise levelling, vertical control.

Tarkkavaaituskampanjat Olkiluodossa vuosina 2006-2007

TIIVISTELMÄ

Olkiluodon GPS-verkko perustettiin vuonna 1994 kallioperän liikkeiden seuraamiseksi tutkimusalueella. Tarkkavaaitukset alueella aloitettiin syksyllä 2003 paremman korkeuskontrollin saavuttamiseksi. Ensin GPS-verkko liitettiin Suomen tarkkavaaitusverkkoon Lapijoella koko Olkiluodon saaren mahdollisen vertikaalisen liikkumisen seuraamiseksi. Sitten vaaittiin verkko, joka käsitti kahdeksan GPS-pilarin varamerkit ja viisi tarkkavaaituskiintopistettä, joista kaksi muodosti solmupisteparin.

Toinen tarkkavaaituskampanja tutkimusalueella suoritettiin syksyllä 2005. Tällöin vaaittiin vain GPS-verkko, johon oli edellisestä kampanjasta lisätty yhdeksän GPS-pilarin antennijalustat. Kahden varamerkkiparin korkeusero muihin pisteisiin nähden oli kahdessa vuodessa muuttunut merkittävästi, yhden millimetrin. Syynä saattoivat olla esimerkiksi kallion räjäytystyöt kyseisten pisteiden läheisyydessä sekä räjäytysten jälkeinen kallioperän uudelleen muotoutuminen.

Korkeuseroissa vuonna 2005 havaittujen muutosten innoittamana syksyllä 2006 perustettiin ja vaaittiin ONKALON ja VLJ-luolan yläpuolelle seitsemän ja viiden pisteen minisilmukat, joiden keskimääräinen pisteväli oli noin 300 metriä.

Syksyn 2007 kampanja käsitti Lapijoelta lähtien kaikissa aikaisemmissa kampanjoissa mitattujen tuhoutumattomien pisteiden vaaitukset. Mielenkiintoisimmat tulokset olivat: 1) Keskimääräiseen teoreettiseen maannousuun nähden solmupiste 03216 Olkiluodontien ja Satamatien risteyksen lähistöllä oli noussut neljässä vuodessa 2.6 mm enemmän kuin Lapijoen solmupiste. Tästä 1.9 mm tapahtui 0.8 km:n kiintopistevälillä, johon sisältyi saaren ja mantereen erottava salmi. 2) Saaren pohjoisosa oli neljässä vuodessa noussut noin millimetrin enemmän kuin keskiosa, jossa em. 03216 sijaitsee. 3) ONKALON mikrosilmukan kiintopisteiden väliset korkeuserot olivat yhdessä vuodessa muuttuneet jopa millimetrin. Suurimman maannousugradientin kohdalla muutos oli 0.5 mm runsaan sadan metrin kiintopistevälillä.

Suunnitelman mukaan tulevaisuudessa Lapijoelta Olkiluotoon vaaitaan joka neljäs vuosi, GPS-verkko joka toinen vuosi ja miniverkot joka vuosi. Viimeisimmät havainnot osoittavat, että saaren ja mantereen erottavan kiintopistevälin vaaitustiheyttä tulisi lisätä.

Avainsanat: Kallioperän deformaatio, tarkkavaaitus, korkeuskontrolli.

TABLE OF CONTENTS

1 INTRODUCTION

Repeated GPS observations in the investigation area of Posiva Oy at Olkiluoto have been continued for twelve years *(Ahola et al. 2007)*. However, the accuracy of GPS determinations in the vertical direction is worse than in the horizontal direction. To monitor also the vertical movements of the GPS points as accurately as possible, the precise levellings on the area were decided to begin in autumn 2003. Originally the period of the levellings between the Olkiluoto island and the continent was decided to be four years and the levellings of the GPS network two years. However, because of the interesting results of the campaign in autumn 2005, new levelling loops were established and levelled onto the ONKALO and VLJ Repository in autumn 2006. The levelling period of these micro loops was decided to be one year. This report treats of the campaigns in autumns 2006 and 2007 and the comparison with the campaigns in 2003 *(Lehmuskoski 2004)* and in 2005 *(Lehmuskoski 2006)*.

The field works and the calculations were carried out with the same method that was used in the Third Levelling of Finland. Precise levelling in the GPS network was sometimes troublesome and slow because some levelling routes were outside of roads and the levelling of the GPS antenna platforms required an extendable tripod and two ladders.

2 LEVELLING ROUTES

The levellings were divided in five loops, eight small GPS pillar loops and one line. Their levelling routes and dates are shown in Table 1 and Figures 1-4.

Table 1. *Loops and lines, levelling routes and dates.*

Loop, GPS pillar or line	**Levelling route**	**Date**
OLKI A	03216-05217-GPS6-GPS7-GPS9-GPS8-03217-GPS4-GPS1-03218-GPS2-03216	13.9., 21.9.-2.10.2007
OLKI B	03218-GPS3-03218	28.9.2007
OLKI D	GPS7-GPS13-GPS7	25.-26.9. 2007
ONKALO	03216-05217-06217-06218-06219-06221-06220-03216	5.-8.10.2007, 20.9.2006
VLJ	GPS9-06213-06214-06215-06216-GPS9	9.10.2007, 21.9.2006
GPS	GPS2, GPS3, GPS4, GPS6, GPS7, GPS8, GPS9, GPS13	2.-4.10.2007
OLK A	51310-03212-03202-03203-03204-04001-03205-04002-03206-04003-AP4-03207-03211-04005-03208-04004-AP5-03216-03219	10.-21.9., 4.10.2007

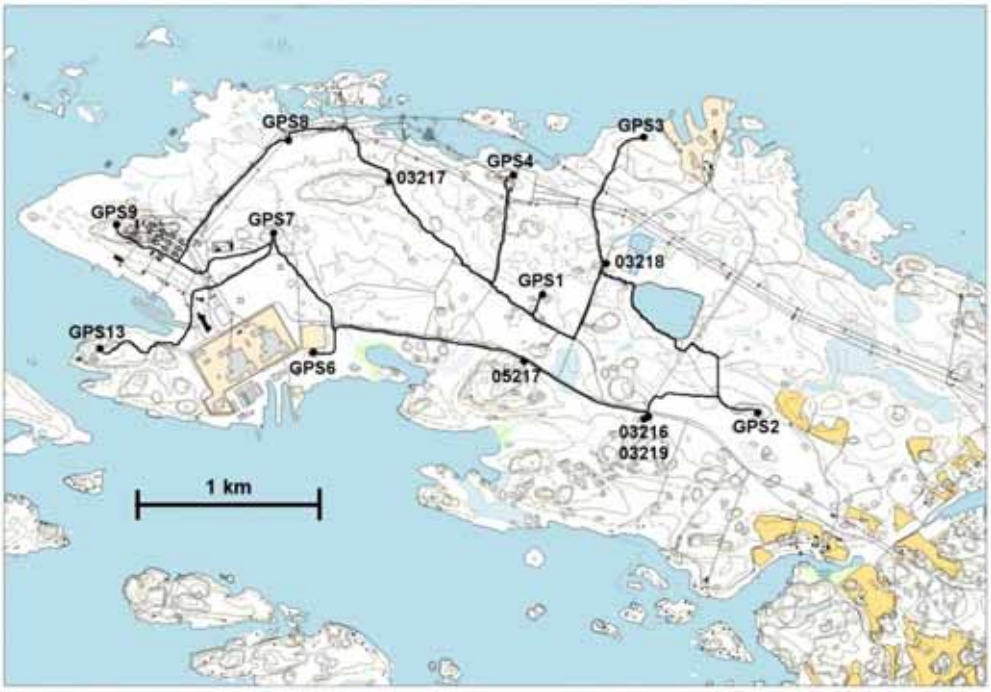

Figure 1. *Loops OLKI A, OLKI B and OLKI D.*

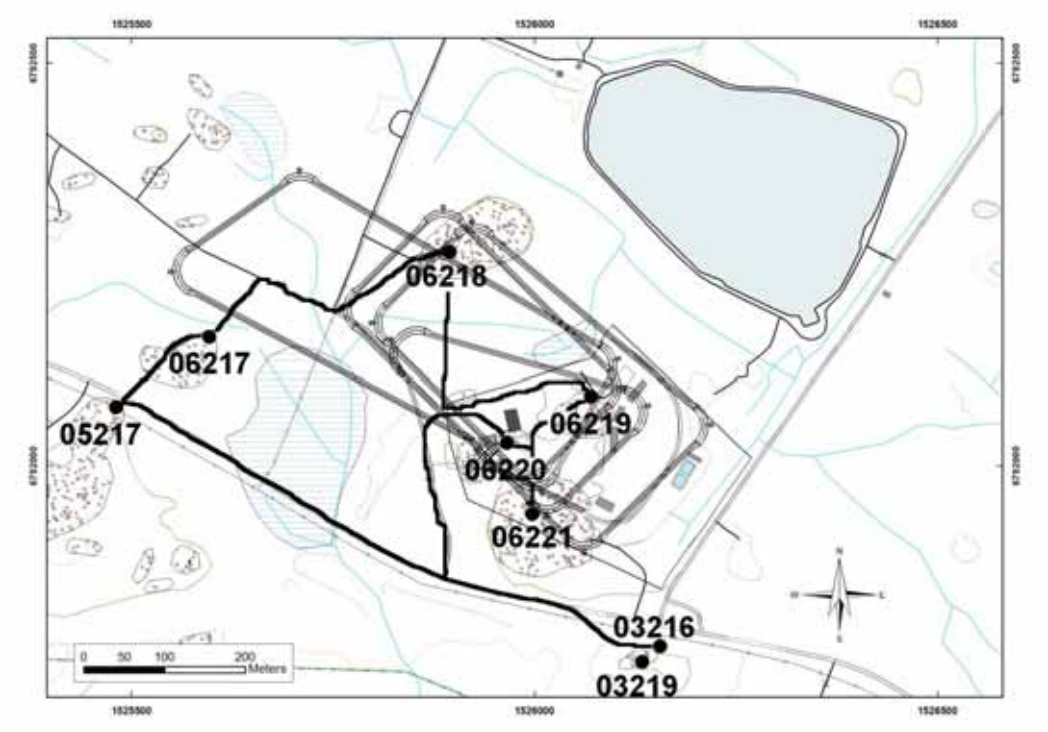

Figure 2. *Loop ONKALO.*

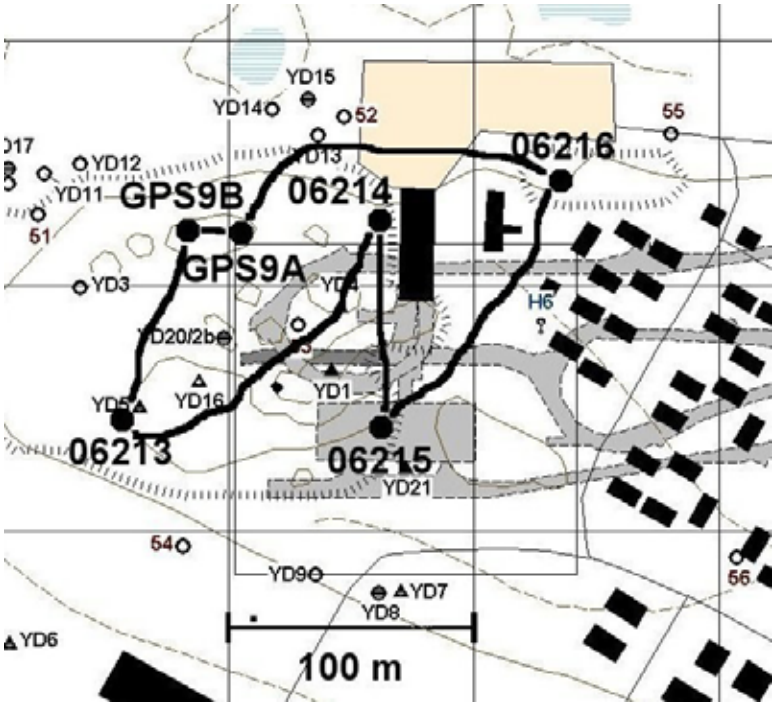

Figure 3. *Loop VLJ.*

Figure 4. *Line OLK A, Lapijoki-Olkiluoto.*

To distinguish other possible vertical crustal deformations from annual variation *(Lehmuskoski et al. 2006)*, the levelling campaigns in 2006 and in 2007 were carried out during the same season as the earlier campaigns in the turn of September and October.

The loop OLKI A was levelled earlier in 2003 and 2005 *(Lehmuskoski 2004 and Lehmuskoski 2006).* Compared to the levelling in 2005 the reserve mark GPS4A was not levelled in 2007 because it is nowadays beyond a wire-netting fence and it has also been damaged by some working machine. Because of extensive construction works on the Olkiluoto island the levelling route of the loop OLKI A was changed so that GPS9 was attached to it whereas earlier it constituted the loop OLKI C with GPS7 (compare Figure 1 and *Lehmuskoski 2006, Figure 1)*.

The levelling routes of the loops OLKI B has kept the same since 2003 (Figure 1), OLKI D since 2005 (Figure 1), ONKALO since 2006 (Figure 2) and VLJ since 2006 (Figure 3).

The antenna platform of the permanent station GPS1 which was levelled in error in 2005, was not levelled in 2007.

The line OLK A was levelled earlier in 2003, at that time twice (lines OLK A and OLK B) (*Lehmuskoski 2004)*. Between the levellings in 2003 and 2007 bench marks 03209 and 03210 were destroyed and bench marks 04001, 04002, 04003, AP4, 04005, 04004 and AP5 were established (Figure 4).

The approximate National Grid Coordinates (KKJ) in the zone 27º and the approximate geographical coordinates in EUREF-FIN system for all bench marks, GPS pillars and GPS reserve marks are given in Table 2. The coordinates have been used for computing tidal corrections and gravity values but they can also be used for searching the objects.

Table 2. *KKJ coordinates in zone 27° and geographical coordinates of bench marks, GPS pillars and GPS reserve marks.*

Bench mark	X-koordinate (km)	Y-koordinate (km)	Latitude (°)	Longitude (°)
51310	6796.265	3214.232	61.17053	21.68280
03212	6796.290	3214.189	61.17072	21.68197
03202	6796.404	3213.568	61.17129	21.67031
03203	6797.157	3212.085	61.17693	21.64173
03204	6798.578	3211.060	61.18887	21.62059
04001	6798.581	3211.035	61.18888	21.62012
03205	6799.810	3209.568	61.19878	21.59108
04002	6799.826	3209.568	61.19892	21.59106
03206	6800.808	3208.659	61.20702	21.57271
04003	6800.788	3208.647	61.20683	21.57252
AP4	6801.288	3207.835	61.21069	21.55671
03207	6802.055	3207.228	61.21709	21.54428
03211	6802.314	3206.363	61.21876	21.52785
04005	6802.334	3206.392	61.21895	21.52836
03208	6802.779	3205.831	61.22251	21.51728
04004	6802.736	3205.815	61.22211	21.51704
AP5	6803.292	3205.355	61.22673	21.50765
03216	6804.168	3204.117	61.23362	21.48334
03219	6804.154	3204.109	61.23349	21.48322
05217	6804.536	3203.479	61.23643	21.47094
GPS6	6804.680	3202.353	61.23686	21.44985
GPS6A	6804.687	3202.356	61.23692	21.44989
GPS6B	6804.683	3202.348	61.23688	21.44975
GPS7	6805.344	3202.190	61.24266	21.44577
GPS7A	6805.336	3202.192	61.24260	21.44582
GPS7B	6805.342	3202.181	61.24264	21.44561
GPS9	6805.467	3201.329	61.24311	21.42962
GPS9A	6805.475	3201.335	61.24318	21.42972
GPS9B	6805.472	3201.321	61.24315	21.42946
GPS8	6805.838	3202.321	61.24718	21.44742
GPS8A	6805.842	3202.324	61.24722	21.44747
GPS8B	6805.837	3202.326	61.24717	21.44752
03217	6805.553	3202.853	61.24504	21.45774
GPS4	6805.522	3203.497	61.24525	21.46971
GPS4B	6805.534	3203.495	61.24536	21.46967
GPS1A	6804.893	3203.610	61.23972	21.47281
GPS1B	6804.877	3203.609	61.23957	21.47281
03218	6805.010	3203.976	61.24104	21.47941
GPS2	6804.131	3204.730	61.23376	21.49476
GPS2A	6804.123	3204.733	61.23369	21.49483
GPS2B	6804.132	3204.723	61.23376	21.49463
GPS3	6805.666	3204.240	61.24710	21.48327
GPS3A	6805.668	3204.247	61.24712	21.48340
GPS3B	6805.674	3204.238	61.24717	21.48322
GPS13	6804.815	3201.194	61.23718	21.42815
GPS13A	6804.810	3201.187	61.23713	21.42803
GPS13B	6804.807	3201.199	61.23711	21.42825
06217	6804.590	3203.605	61.23701	21.47319
06218	6804.655	3203.890	61.23780	21.47836
06219	6804.478	3204.044	61.23634	21.48150
06221	6804.349	3203.994	61.23515	21.48078
06220	6804.432	3203.953	61.23586	21.47989
06213	6805.403	3201.332	61.24254	21.42978
06214	6805.445	3201.428	61.24299	21.43149
06215	6805.398	3201.444	61.24258	21.43186
06216	6805.469	3201.501	61.24326	21.43280

3 FIELD CREW, INSTRUMENTS AND OBSERVATIONS

Posiva Oy employed the assisting personnel for the levelling expedition from RTK-Palvelu Oy, which carries out the janitorial service of the nuclear power station of Olkiluoto. The crew and the instruments used are given in Table 3.

Table 3. *Field crew and instruments.*

Observer	Pekka Lehmuskoski
First rodman	Simo Muttilainen 2007, Mika Ryynänen 2006
Second rodman	Mika Kuttila 2007, Hannu Pihlajavaara 2006
Distance measurer	Sani Tenlen 2007, Suvi Tamminen 2007
Shadow man	Janne Nylund 2007, Pekka Ryynänen 2006
Levelling instrument	Zeiss DiNi12, number 320243
Rod pair (3 metres)	Zeiss Nedo LD13, numbers 13926 and 14092
Rod (1 metre)	Zeiss Nedo LD11, number 11640
Thermometer	Fluke 54 II
Rod bases	Turtles and spikes
Tripods	Zeiss normal, Wild built up and Zeiss extendable
Distance meter	Rollfix super
Umbrella	Alexo
Car	Toyota Hiace, UXY-346
Personal navigator	Garmin eTrex

The description of the levellings is given in *Lehmuskoski 2006, Chapter 3.* Appendices I:1-I:182 give information in the chronological order about every bench mark interval measured in 2007. Appendices I:183-I:214 give the corresponding information of the measurements in 2006. One page corresponds one bench mark interval in one levelling direction. The upper part of the page gives time, crew, instrumentation, road type and weather. The lower part gives observations and environmental data for every set up. At the end of the observation file there are the uncorrected elevation difference of the interval, its length and possible remarks. The work of the levelling team in 2007 is illustrated in the Figures 5-9.

Figure 5. *One set up of the bench mark interval 04001-03205 (Photo A. Hiironen) .*

Figure 6. *Preparing of the next set up (Photo A. Hiironen) .*

Figure 7. *Two set ups later (Photo A. Hiironen).*

Figure 8. *Bench mark interval 03205-04002 (Photo A. Hiironen).*

Figure 9. *Bench mark interval has been measured and the levelling instrument Zeiss DiNi 12 and the second rod man will have a brake (Photo A. Hiironen).*

4 REDUCTIONS

We used the Zeiss Nedo LD13 bar code 3 m invar rods with an aluminium frame for the ordinary precise levelling. Zeiss Nedo LD11 bar code 1 m invar rod with an aluminium frame was used when the elevations of the GPS antenna platforms were levelled. The rod calibrations were carried out both in 2006 and 2007 in August and October using the FGI vertical rod comparator *(Takalo 1999), (Takalo and Rouhiainen 2002).* The adjusted value for the levelling epoch was obtained by linear interpolation.

During the levelling the air temperature and the air temperature difference between 2.5 m and 0.5 m above the ground were registered with a Fluke 54 II thermometer at one minute intervals. Refraction correction was computed with the Kukkamäki formula *(Hytönen 1967).*

Tidal correction was computed with the formulas developed by *Heikkinen (1978).*

The Nordic land uplift model NKG2005LU was used when determining the land uplift correction *(Ågren and Svensson 2007).*

Appendices II:1 – II:8 include the calculation files of the line OLK A, the loops OLKI A, OLKI B, OLKI D, ONKALO and VLJ in 2007 and the loops ONKALO and VLJ in 2006. Respectively, Appendices III:1 – III:8 include the calculation files of the loops GPS2, GPS3, GPS4, GPS6, GPS7, GPS8, GPS9 and GPS13. Calculation files proceed in physical order from the first bench mark of the line or the loop to the last one.

5 RESULTS

5.1 Loop OLKI A

The bench marks of the loop OLKI A shown in Figure 1 and Table 1 were levelled clockwise using the shortest route and excluding GPS13 and GPS3. Because the area of this loop is small, the longest diagonal being less than 4 km, the elevation differences were computed in millimetres and the land uplift correction was not applied. In order to compare the N60 elevations of the bench marks of the loop to those derived from earlier campaigns the value for the nodal bench mark 03216 derived in 2003 (9522.538 mm) was kept fixed. The closing error of the loop (+1.47 mm) was adjusted linearly as the function of the levelled distance (Table 4). Figure 10 shows that GPS9 has an uplift of 1 mm during 2003-2005 and the points in the northern part of the network almost 1 mm during 2005-2007 compared to the nodal bench mark 03216. The reason of the rising of GPS6 during 2003-2005 was probably the blasting of the rock nearby during the construction work of the parking place.

Explanation of the columns of Tables 4-6:

1. Bench mark or reserve mark of GPS pillar
2. Distance of interval (km)
3. Sum of distances (km)
4. Elevation difference when rod, refraction and tidal corrections have been made (mm)
5. Adjustment correction (mm)
6. Final elevation difference (mm)
7. N60 elevation in 2007 (mm)
8. N60 elevation in 2005 (mm) *(Lehmuskoski 2006, Tables 4-7)*
9. N60 elevation in 2003 (mm) *(Lehmuskoski 2004, Tables 6-7)*
10. Change of N60 elevation (2007-2005) (mm)
11. Change of N60 elevation (2005-2003) (mm)
12. Change of N60 elevation (2007-2003) (mm)
13. Mean change of N60 elevation of reserve mark pair (2007-2005) (mm)
14. Mean change of N60 elevation of reserve mark pair (2005-2003) (mm)
15. Mean change of N60 elevation of reserve mark pair (2007-2003) (mm).

Table 4. *Results of the loop OLKI A.*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
03216	0.000	0.000		0.000		9522.538	9522.538	9522.538	0.000	0.000	0.000			
05217	0.759	0.759	170.92	-0.095	170.825	9693.363	9693.504	-	-0.141	-	-			
GPS6A	1.257	2.016	-6258.02	-0.253	-6258.178	3435.185	3435.200	3434.249	-0.015	0.951	0.936	-0.020	1.001	0.980
GPS6B	0.010	2.026	-198.59	-0.254	-198.591	3236.594	3236.620	3235.569	-0.026	1.051	1.025			
GPS7B	0.885	2.912	7574.44	-0.365	7574.329	10810.923	10811.038	10810.958	-0.115	0.080	-0.035			
GPS7A	0.012	2.924	-77.50	-0.367	-77.502	10733.421	10733.438	10733.238	-0.017	0.200	0.183	-0.066	0.140	0.074
GPS9B	1.142	4.066	-1491.28	-0.510	-1491.423	9241.998	9242.205	9241.273	-0.207	0.932	0.725			
GPS9A	0.016	4.082	524.54	-0.512	524.538	9766.536	9766.664	9765.683	-0.128	0.981	0.853	-0.168	0.957	0.789
GPS8A	1.382	5.464	-5748.76	-0.686	-5748.934	4017.602	4017.240	4016.886	0.362	0.354	0.716	0.362	0.344	0.706
GPS8B	0.006	5.470	423.15	-0.686	423.150	4440.752	4440.390	4440.056	0.362	0.334	0.696			
03217	0.817	6.287	6106.69	-0.789	6106.587	10547.339	10546.526	10546.412	0.813	0.114	0.927			
GPS4B	1.398	7.685	-3250.28	-0.964	-3250.455	7296.884	7296.216	7296.007	0.668	0.209	0.877			
GPS1B	0.969	8.654	1852.55	-1.086	1852.428	9149.312	9148.707	9148.712	0.605	-0.005	0.600			
GPS1A	0.016	8.670	-305.55	-1.088	-305.552	8843.760	8843.187	8843.052	0.573	0.135	0.708	0.589	0.065	0.654
03218	0.816	9.486	-206.66	-1.190	-206.762	8636.998	8636.434	8636.669	0.564	-0.235	0.329			
GPS2B	1.502	10.988	2558.46	-1.379	2558.271	11195.269	11195.275	11195.253	-0.006	0.022	0.016			
GPS2A	0.015	11.003	-42.19	-1.381	-42.192	11153.077	11153.115	11153.103	-0.038	0.012	-0.026	-0.022	0.017	-0.005
03216	0.793	11.795	-1630.45	-1.470	-1630.539	9522.538	9522.538	9522.538	0.000	0.000	0.000			
Sum	11.795		1.47		0.000									

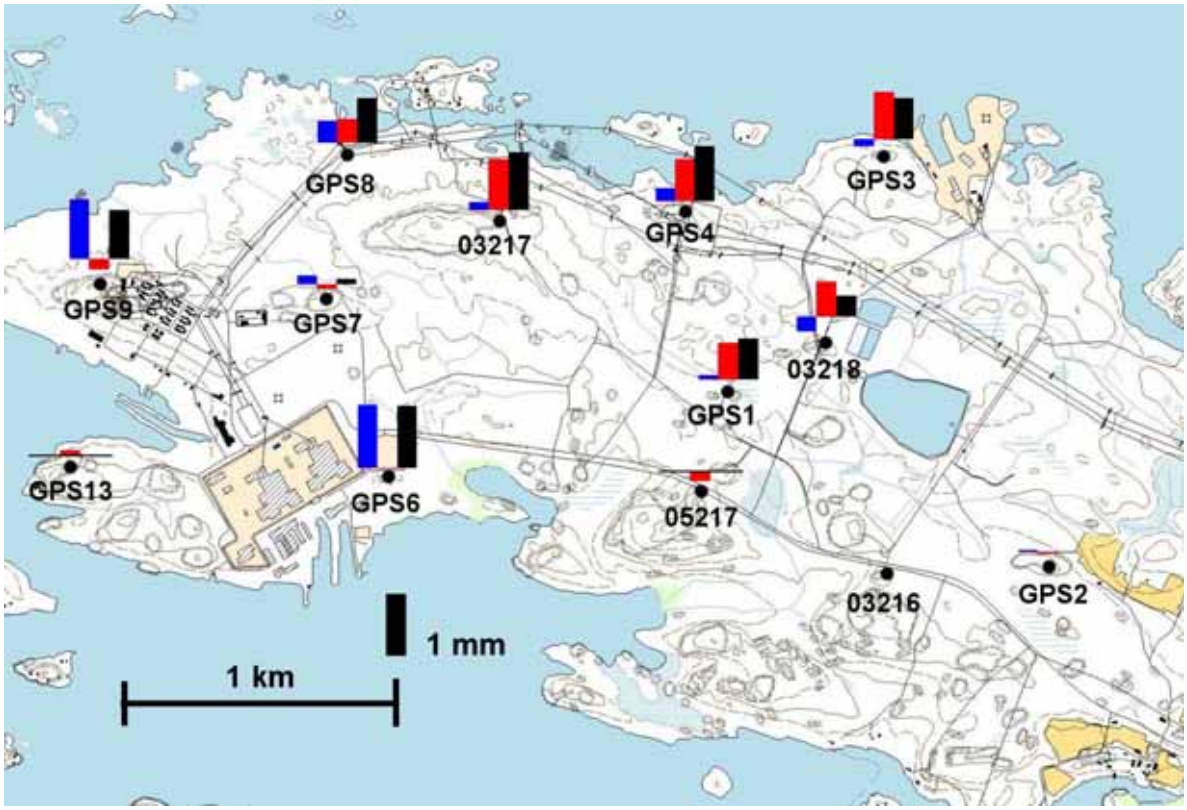

Figure 10. *Change of N60 elevation compared to bench mark 03216. Blue bar gives the change from 2003 to 2005, red bar from 2005 to 2007 and black bar from 2003 to 2007.*

5.2 Loops OLKI B, OLKI D, ONKALO and VLJ

Loops OLKI B, OLKI D, ONKALO and VLJ in 2007, ONKALO and VLJ in 2006, see Figures 1-3 and Table 1. Because the area of these loops is even smaller than in the case of loop OLKI A, the same computation method was used. When we computed new N60 elevations for the bench marks of these loops, we started from the bench mark 03216 and its N60 elevation 9522.538 mm derived from the levellings in 2003 *(Lehmuskoski 2004, Table 5)*. The N60 elevations for the nodal bench marks of these loops (03218, GPS7B, 03216 and GPS9A) were obtained by the adjustment of the loop OLKI A (Table 4, column 7). The closing errors of the loops (-0.18 mm, -0.13 mm, -0.51 mm, 0.04 mm, 0.27 mm and -0.21 mm) were adjusted linearly as the function of the levelled distance (Tables 5-10). The explanation of the columns for the loops OLKI B and OLKI D is the same as in Table 4.

Table 5. *Results of the loop OLKI B.*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
03218	0.000	0.000		0.000		8636.998	8636.434	8636.669	0.564	-0.235	0.329			
GPS3B	0.872	0.872	-2732.03	0.090	-2731.940	5905.058	5904.294	5904.389	0.764	-0.095	0.669			
GPS3A	0.012	0.884	-74.74	0.091	-74.739	5830.319	5829.554	5829.670	0.765	-0.116	0.649	0.764	-0.106	0.659
03218	0.860	1.744	2806.59	0.180	2806.679	8636.998	8636.434	8636.669	0.564	-0.235	0.329			
Sum	1.744		-0.18		0.000									

Table 6. *Results of the loop OLKI D.*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
GPS7B	0.000	0.000		0.000		10810.923	10811.038	10810.958	-0.115	0.080	-0.035			
GPS13B	1.493	1.493	-1884.04	0.065	-1883.975	8926.948	8926.876	-	0.072	-	-			
GPS13A	0.012	1.505	323.81	0.065	323.810	9250.758	9250.704	-	0.054	-	-	0.063	-	-
GPS7B	1.504	3.009	1560.10	0.130	1560.165	10810.923	10811.038	10810.958	-0.115	0.080	-0.035			
Sum	3.009		-0.13		0.000									

Explanation of the columns of Tables 7 and 8:

1. Bench mark or reserve mark of GPS pillar
2. Distance of interval (km)
3. Sum of distances (km)
4. Elevation difference when rod, refraction and tidal corrections have been made (mm)
5. Adjustment correction (mm)
6. Final elevation difference (mm)
7. N60 elevation in 2007 (mm)
8. N60 elevation in 2006 given by Table 11 (mm)
9. Change of N60 elevation from 2006 to 2007 (mm)

Table 7. *Results of the loop ONKALO in 2007.*

1	2	3	4	5	6	7	8	9
03216	0.000	0.000		0.000		9522.538	9522.538	0.000
05217	0.759	0.759	170.92	0.139	171.059	9693.597	9693.890	-0.293
06217	0.171	0.930	-2146.62	0.170	-2146.589	7547.008	7547.242	-0.234
06218	0.334	1.264	2444.79	0.231	2444.851	9991.859	9991.747	0.112
06219	0.478	1.742	-420.47	0.319	-420.382	9571.477	9571.370	0.107
06221	0.321	2.063	5169.27	0.378	5169.329	14740.806	14740.602	0.204
06220	0.124	2.187	-4765.68	0.400	-4765.658	9975.148	9974.459	0.689
03216	0.599	2.786	-452.72	0.510	-452.610	9522.538	9522.538	0.000
Sum	2.786		-0.51		0.000			

Table 8. *Results of the loop VLJ in 2007.*

1	2	3	4	5	6	7	8	9
GPS9A	0.000	0.000		0.000		9765.683	9765.683	0.000
GPS9B	0.016	0.016	-524.54	-0.001	-524.541	9241.142	9241.248	-0.106
06213	0.098	0.114	1368.38	-0.006	1368.375	10609.517	10609.260	0.257
06214	0.130	0.244	-619.53	-0.013	-619.537	9989.980	9989.577	0.403
06215	0.082	0.326	1083.34	-0.018	1083.335	11073.315	11073.021	0.294
06216	0.118	0.443	-3400.42	-0.024	-3400.426	7672.889	7672.437	0.452
GPS9A	0.291	0.735	2092.81	-0.040	2092.794	9765.683	9765.683	0.000
Sum	0.735		0.04		0.000			

Explanation of the columns of Tables 9 and 10:

1. Bench mark or reserve mark of GPS pillar
2. Distance of interval (km)
3. Sum of distances (km)
4. Elevation difference when rod, refraction and tidal corrections have been made (mm)
5. Adjustment correction (mm)
6. Final elevation difference (mm)
7. N60 elevation in (mm).

Table 9 . *Results of the loop ONKALO in 2006.*

1	2	3	4	5	6	7
03216	0.000	0.000		0.000		9522.538
05217	0.763	0.763	171.43	-0.078	171.352	9693.890
06217	0.166	0.929	-2146.63	-0.096	-2146.648	7547.242
06218	0.341	1.270	2444.54	-0.131	2444.505	9991.747
06219	0.364	1.634	-420.34	-0.168	-420.377	9571.370
06221	0.270	1.904	5169.26	-0.196	5169.232	14740.602
06220	0.126	2.030	-4766.13	-0.209	-4766.143	9974.459
03216	0.596	2.626	-451.86	-0.270	-451.921	9522.538
Sum	2.626		0.27		0.000	

Table 10. *Results of the loop VLJ in 2006.*

1	2	3	4	5	6	7
GPS9A	0.000	0.000		0.000		9765.683
GPS9B	0.016	0.016	-524.44	0.005	-524.435	9241.248
06213	0.075	0.091	1367.99	0.027	1368.012	10609.260
06214	0.129	0.220	-619.72	0.064	-619.683	9989.577
06215	0.079	0.299	1083.42	0.088	1083.444	11073.021
06216	0.124	0.423	-3400.62	0.124	-3400.584	7672.437
GPS9A	0.294	0.717	2093.16	0.210	2093.246	9765.683
Sum	0.717		-0.21		0.000	

The Figures 11 and 12 show that the bedrock above ONKALO and VLJ Repository is not very stable. Vertical movements up to one millimetre within small loops during one year are not usual. The levelling campaigns in future will show if the rising of the bedrock over the caves continues as expected.

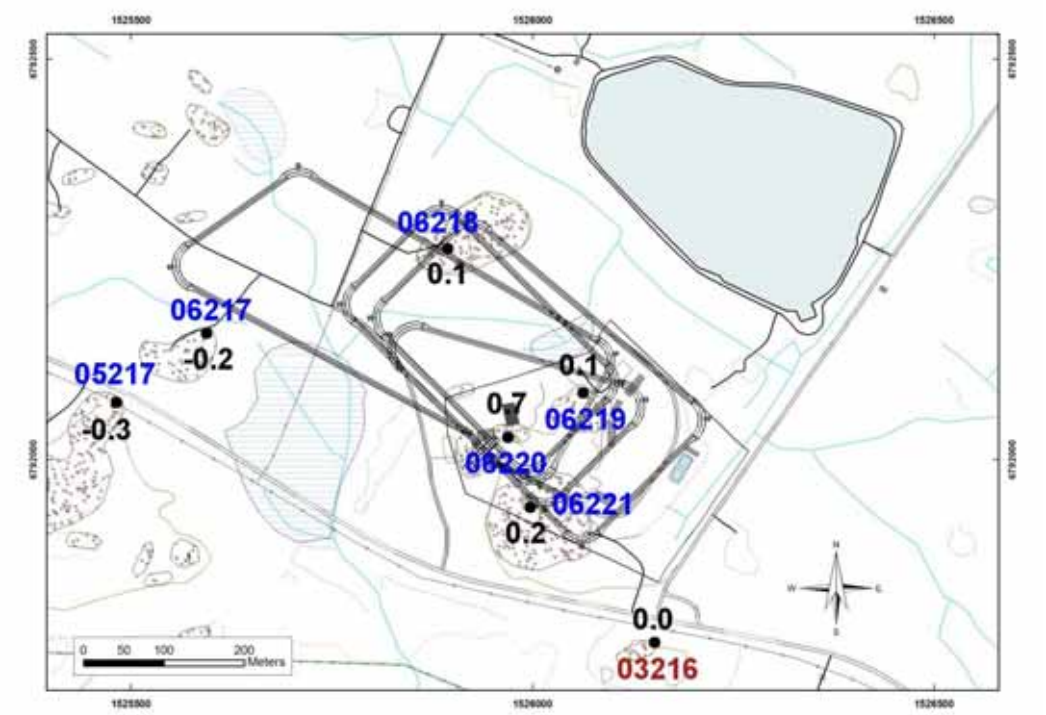

Figure 11. *Change of N60 elevations on top of ONKALO from 2006 to 2007 compared to bench mark 03216 (mm).*

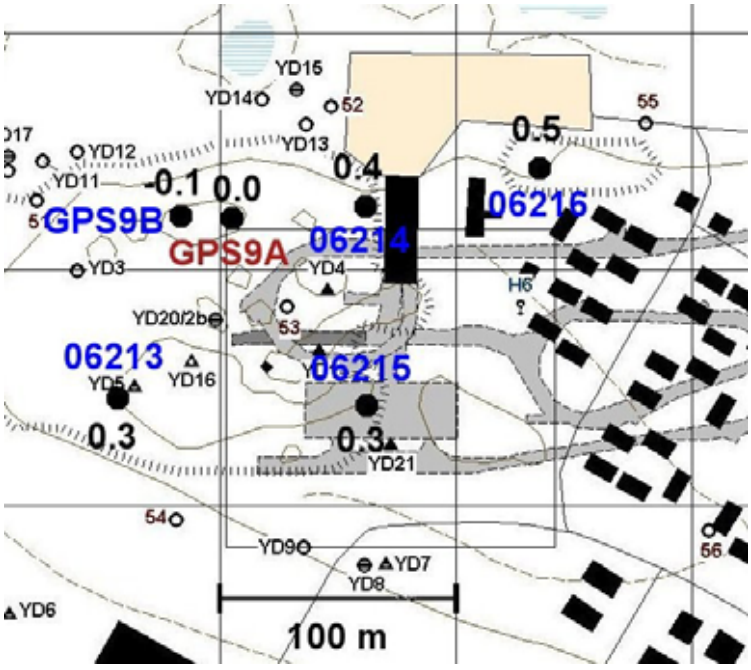

Figure 12. *Change of N60 elevation on top of VLJ Repository from 2006 to 2007 compared to reserve mark GPS9A (mm).*

5.3 GPS antenna platform loops

Because the loops are very short, 22 m - 82 m, their closing errors –0.05 mm, 0.02 mm, -0.08 mm,0.04 mm, -0.01 mm, 0.05 mm, 0.03 mm and 0.07 mm (Appendices III:1 – III:8) were not used for computing the accuracy of the levelling campaign. Also, the measurements possibly were not as accurate as the ordinary precise levelling because of the extendable tripod, which was not very steady especially in windy weather. That is why the N60 elevations of the reserve marks given by the adjustment of the loops OLKI A, OLKI B and OLKI D were kept fixed and the closing error of each GPS antenna platform loop (reserve mark A – GPS antenna platform – reserve mark B – reserve mark A) was adjusted as the function of the levelled distance.

Because the rod on the antenna platform was always the one metre rod number 11640 and the rod on each reserve mark was the three metre rod number 14092, their datum level difference (the difference of the zero point of the scale from the bottom plate) was measured (0.039 mm) and reduced from the levelling results (Table 13, column 8).
The levelling was focused on the bolt on the antenna platform *(Lehmuskoski 2006, Figures 5-6)*. To obtain the N60 elevation of the antenna platform, the height of the bolt (19.855 mm) was reduced from the levelling results (Table 13, column 9).

Because the rod readings were not on an average the same for both rods, as is the case when performing ordinary precise levelling, but 248 cm for the three metres rod and 23 cm for the one metre rod, the rod correction used in this case was not the mean of their individual corrections, but their weighted mean according to the average reading.

Explanation of the columns of Table 11:

1. Reserve mark or antenna platform
2. Distance of the interval (m)
3. Sum of the distances (m)
4. Elevation difference, when rod, refraction and tidal corrections have been made (mm)
5. Elevation difference compared to initial bench mark of the loop (mm)
6. N60 elevation measured in 2005 *(Lehmuskoski 2006, Tables 4-7)*
7. Adjustment correction (mm)
8. Datum level difference correction (mm)
9. Reduction to the antenna platform (mm)
10. N60 elevation of the antenna platform in 2007 (mm)
11. N60 elevation of the antenna platform in 2005 (mm), *(Lehmuskoski 2006, Table 8)*
12. Change of the N60 elevation (mm), column 10 - column 11.

Table 11. *Results of the levellings of the GPS antenna platforms.*

1	2	3	4	5	6	7	8	9	10	11	12
GPS2A	0	0	0	0	11153.115	11153.115					
GPS2	23	23	2413.08	2413.08		11153.067	-0.039	-19.855	13546.253	13546.209	0.044
GPS2B	15	38	-2370.84	42.24	11195.275	11153.035					
GPS3A	0	0	0	0	5829.554	5829.554					
GPS3	9	9	2550.46	2550.46		5829.540	-0.039	-19.855	8360.106	8360.039	0.067
GPS3B	10	19	-2475.69	74.77	5904.294	5829.524					
GPS4B	0	0	0	0	7296.216	7296.216					
GPS4	40	40	2520.77	2520.77		7296.260	-0.039	-19.855	9797.136	9797.039	0.097
GPS4B	42	82	-2520.86	-0.09	7296.216	7296.306					
GPS6A	0	0	0	0	3435.200	3435.200					
GPS6	12	12	2304.31	2304.31		3435.181	-0.039	-19.855	5719.597	5719.579	0.018
GPS6B	13	25	-2502.85	-198.54	3236.620	3435.160					
GPS7A	0	0	0	0	10733.438	10733.438					
GPS7	11	11	2349.82	2349.82		10733.485	-0.039	-19.855	13063.411	13063.412	-0.001
GPS7B	10	21	-2272.31	77.51	10811.038	10733.528					
GPS8A	0	0	0	0	4017.240	4017.240					
GPS8	10	10	2468.88	2468.88		4017.271	-0.039	-19.855	6466.257	6466.214	0.043
GPS8B	6	16	-2045.78	423.10	4440.390	4017.290					
GPS9A	0	0	0	0	9766.664	9766.664					
GPS9	24	24	2589.06	2589.06		9766.692	-0.039	-19.855	12335.858	12335.791	0.067
GPS9B	20	44	-3113.57	-524.51	9242.205	9766.715					
GPS13A	0	0	0	0	9250.704	9250.704					
GPS13	9	9	1290.45	1290.45		9250.702	-0.039	-19.855	10521.258	10521.280	-0.022
GPS13B	20	29	-1614.19	-323.74	8926.876	9250.616					

We see that the elevation difference changes between the pillars and their reserve marks are small, maximally 0.1 mm, so we can say that the pillars have been stable from 2005 to 2007.

5.4 Line OLK A, Lapijoki-Olkiluoto

The line OLK, Lapijoki-Olkiluoto, was measured twice in 2003 (OLK A and OLK B) and once in 2007 (OLK A). The mean of OLK A and OLK B in 2003 was used when the results of the different periods, 2003.72 and 2007.72, were compared. The results of this line in 2007, where all measured bench mark intervals are involved, are given in the Appendix II:1, see also Figure 4. The results of all common intervals for the levellings in 2003 *(Lehmuskoski 2004, Table 5)* and in 2007 are given in Table 12. We see that during four years the end of the line on the Olkiluoto island (03216) has risen 3.3 mm compared to the beginning of the line on the continent (51310) (column 7) although according to the Nordic land uplift model NKG2005LU it should be risen only about 0.7 mm (column 10). The anomalous land uplift values are given in column 12 and in Figure 13, which show also how the greatest part of this uplift occurs on a short bench mark interval including the inlet separating the Olkiluoto island and the continent. Figure 13 shows also how the island has tilted during four years, see also Chapter 5.1.

Explanation of the columns of Table 12:

1. Bench mark
2. Distance of interval (km)
3. Sum of distances (km)
4. Elevation difference in 2007 (mm)
5. Elevation difference in 2003 (mm)
6. Change of the elevation difference (mm)
7. Sum of the change of the elevation difference or land uplift compared to 51310 (mm)
8. Land uplift given by the model NKG2005LU (mm/y)
9. Land uplift correction for the interval during 4.00 years (mm)
10. Land uplift correction compared to 51310 during 4.00 years (mm)
11. Anomalous land uplift for the interval according to NKG2005LU during 4.00 years (mm)
12. Anomalous land uplift during 4.00 years according to NKG2005LU compared to 51310 (mm).

Table 12. *Results of line OLK A, Lapijoki-Olkiluoto, in 2003 and in 2007.*

1	2	3	4	5	6	7	8	9	10	11	12
51310							5.26946				
03212	0.08	0.08	1481.610	1481.210	0.400	0.400	5.27010	-0.003	-0.003	0.397	0.397
03202	0.83	0.91	-3267.980	-3267.750	-0.230	0.170	5.27598	-0.023	-0.026	-0.253	0.144
03203	2.05	2.96	-6056.340	-6056.360	0.020	0.190	5.29643	-0.082	-0.108	-0.062	0.082
03204	1.85	4.81	-368.860	-370.545	1.685	1.875	5.32235	-0.104	-0.212	1.581	1.663
03205	2.07	6.88	14860.470	14861.295	-0.825	1.050	5.34866	-0.105	-0.317	-0.930	0.733
03206	1.52	8.40	-14505.080	-14506.140	1.060	2.110	5.36765	-0.076	-0.393	0.984	1.797
03207	2.03	10.43	-7298.970	-7298.905	-0.065	2.045	5.39296	-0.101	-0.494	-0.166	1.551
03211	0.91	11.34	-1635.730	-1635.135	-0.595	1.450	5.40183	-0.035	-0.529	-0.630	0.921
03208	0.77	12.11	8172.590	8170.675	1.915	3.365	5.41107	-0.037	-0.566	1.878	2.799
03216	2.38	14.49	-190.090	-190.025	-0.065	3.300	5.43911	-0.112	-0.679	-0.177	2.622
03219	0.02	14.51	1020.140	1020.140	0.000	3.300	5.43899	0.000	-0.679	0.000	2.622

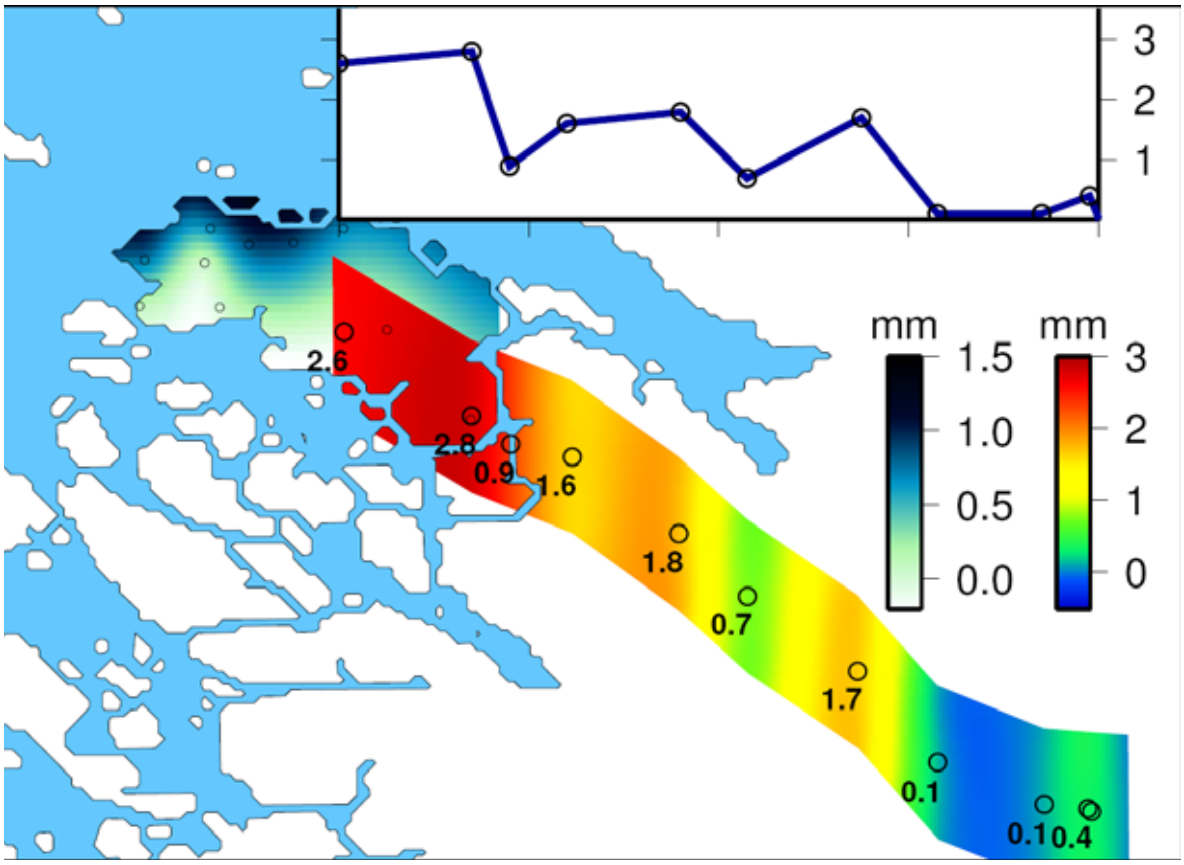

Figure 13. *From 2003 to 2007, anomalous land uplift accorging to NKG2005LU compared to 51310 (in the right lower corner) and elevation changes on the Olkiluoto island compared to 03216 (value 2.6 in the middle of the island).*

6 ACCURACY

The accuracies of the levellings in 2006 and 2007 were estimated by the formula 6.1 *(Kääriäinen 1966, page 52)*

$$\tau = \frac{1}{n+1}\left(\sum_{i=1}^{n} \frac{\varphi}{F_i} + \frac{\varphi}{F_e}\right), \qquad (6.1)$$

where n = number of the loops, φ_i = closing error of the loop, F_i = circumference of the loop, φ_e = closing error of the circumference of the network and F_e = length of the circumference of the network.

The lengths and the closing errors of the levelled loops are listed in Table 13. Formula 6.1 gives now for $\tau = \pm$ 0.23 mm/√km in 2007 and $\tau = \pm$ 0.17 mm/√km in 2006. The corresponding accuracy estimate for the levelling campaign in 2003 was ± 0.10 mm/√km *(Lehmuskoski 2004, page 11)* and in 2005 ± 0.14 mm/√km, respectively *(Lehmuskoski 2006, page 19)*.

Table 13. *Lengths and closures of the loops.*

Loop	**Length *L* (km)**	**Closure φ (mm)**
2007		
OLKI A	11.795	1.47
OLKI B	1.744	-0.18
OLKI D	3.009	-0.13
ONKALO	2.786	-0.51
VLJ	0.735	0.04
Circumference	20.069	0.69
2006		
ONKALO	2.626	0.27
VLJ	0.717	-0.21
Circumference	3.343	0.06

When we compare the results of two campaigns, the standard deviation for their difference is estimated by the formula 6.2

$$\tau_\Delta^2 = \tau_1^2 + \tau_2^2, \qquad (6.2)$$

where τ_1 and τ_2 are the accuracies of the comparable campaigns. So we get the standard deviation for the comparisons:

2007-2006 ± 0.29 mm/√km,

2007-2005 ± 0.27 mm/√km and

2007-2003 ± 0.25 mm/√km.

For the comparison 2005-2003 the standard deviation was 0.17 mm/√km (Lehmuskoski 2006, p. 11). The critical value, when the elevation difference change can be considered significant, is the threefold of the standard deviation of the discrepancy. For instance, if the elevation difference of one kilometre long interval has changed from 2006 to 2007 more than 0.87 mm, the change can be considered significant.

7 SIGNIFICANCE OF THE DISCREPANCIES

When we compared the results of the fifteen kilometres long line OLK, Lapijoki-Olkiluoto, the land uplift corrections were computed using the model NKG2005LU and after this the elevation differences of successive bench mark intervals were compared. On the other hand, when we computed the results for the small loops on the Olkiluoto island, where the theoretical land uplift changes are small, land uplift corrections were not used. The N60 elevation derived for 03216 from the campaign in 2003 was fixed for later campaigns. Then the closing errors of the loops were adjusted and the N60 elevations and elevation differences for different campaigns were computed. When the N60 elevations of GPS points were compared, we used the mean of their reserve mark pair with the exception of GPS4B, whose pair GPS4A had been damaged between 2005 and 2007.

7.1 Loops OLKI A, OLKI B and OLKI D

Table 14. *Significance of the elevation difference changes of the intervals.*

Interval	Distance (km)			Change of elevation difference (mm)			Significance of standard deviation		
	2003-2005	2005-2007	2003-2007	2003→2005	2005→2007	2003→2007	2003→2005	2005→2007	2003→2007
03216→GPS6	2.09	2.03	2.09	1.001	-0.020	0.981	**4.1**	0.1	2.7
03216→05217		0.76			-0.141			0.6	
05217→GPS6		1.27			0.121			0.5	
GPS6→GPS7		0.89			-0.046			0.2	
GPS7→GPS9	1.23	1.15	1.25	0.816	-0.101	0.715	**4.3**	0.4	2.6
GPS7→GPS13		1.49			0.129			0.4	
GPS7→GPS8	0.55			0.204			1.6		
GPS8→03217	0.81	0.81	0.81	-0.230	0.451	0.221	1.5	1.9	1.0
03217→GPS4B	1.45	1.42	1.43	0.209	-0.145	0.064	1.0	0.5	0.2
GPS4B→GPS1	1.02	0.98	1.01	-0.144	-0.079	-0.223	0.8	0.3	0.9
GPS1→03218	0.86	0.84	0.84	-0.300	-0.025	-0.325	1.9	0.1	1.4
03218→GPS3	0.94	0.88	0.93	0.131	0.200	0.331	0.8	0.8	1.4
03218→GPS2	1.55	1.51	1.55	0.252	-0.586	-0.334	1.2	1.8	1.1
GPS2→03216	1.12	0.95	0.96	-0.017	0.022	0.005	0.1	0.1	0.0

We see that only the N60 elevations of GPS6 and GPS9 in 2003-2005 have changed significantly. However, Figure 10 shows that after the western part of the Olkiluoto island had risen in 2003-2005 the northern part started to rise. The gradient is not very big but the direction is definite.

7.2 Loop ONKALO

Explanation of the columns of Tables 15 - 16:

1. Bench mark interval
2. Mean length (km)
3. Change of the elevation difference (mm)
4. Significance of the standard deviation 0.29 mm/√km

Table 15. *Significance of the elevation difference changes of the intervals from 2006 to 2007.*

1	2	3	4
03216→05217	0.76	-0.293	1.2
05217→06217	0.17	0.059	0.5
06217→06218	0.33	0.346	2.1
06218→06219	0.48	-0.005	0.0
06219→06221	0.32	0.097	0.6
06221→06220	0.12	0.485	**4.8**
06220→03216	0.60	-0.689	**3.1**

We see that the bench mark 06220 has risen significantly during one year. Next campaigns will show, if the neighbouring bench marks 06218, 06219 and 06221 follow it when the quarrying of ONKALO exceeds (see also Figure 11).

7.3 Loop VLJ

Table 16. *Significance of the elevation difference changes of the intervals from 2006 to 2007.*

1	2	3	4
GPS9A→GPS9B	0.02	-0.106	2.6
GPS9B→06213	0.10	0.363	**4.0**
06213→06214	0.13	0.146	1.4
06214→06215	0.08	-0.109	1.3
06215→06216	0.12	0.158	1.6
06216→GPS9A	0.29	-0.452	2.9

We see that the area is divided into two parts, the north-western part, where GPS9A and GPS9B are, seems to stay in place while the other bench marks are rising compared to them (see also Figure 12).

7.4 Line OLK, Lapijoki-Olkiluoto

Explanation of the columns:

1. Interval
2. Mean length (km)
3. Change of the elevation difference (mm)
4. Significance of the standard deviation 0.25 mm/√km.

Table 17. *Significance of the elevation difference changes of the intervals from 2003 to 2007.*

1	2	3	4
51310→03212	0.08	0.397	**5.6**
03212→03202	0.82	-0.253	1.1
03202→03203	2.01	-0.062	0.2
03203→03204	1.82	1.581	**4.7**
03204→03205	2.03	-0.930	2.6
03205→03206	1.49	0.984	**3.2**
03206→03207	2.00	-0.166	0.5
03207→03211	0.91	-0.630	2.6
03211→03208	0.74	1.878	**8.7**
03208→03216	2.34	-0.177	0.5
03216→03219	0.02	0.000	0.0

Figure 14. *Change of elevation difference after land uplift correction from 2003 to 2007 compared to 51310, ((mm), black numbers) Manifold of the standard deviation, if it exceeds the critical value 3.0 (red numbers).*

Within three intervals, 03203-03204, 03205-03206 and especially 03211-03208, where the inlet separates the Olkiluoto island from the continent (Figure 14) the rising exceeds the critical value or is significant (see Chapter 6). The value of the interval 51310-03212 exceeded also the critical value, but it was possibly caused by the change of the micro climate around 03212. Earlier the bench mark was in a lightless spruce forest, nowadays the forest has been cut down.

8 FUTURE PLANS

The levellings in the networks and lines will be continued according to the original plan:

Autumn 2008: micro loops ONKALO and VLJ,

Autumn 2009: loops OLKI A, OLKI B, OLKI D and micro loops ONKALO and VLJ,

Autumn2010: micro loops ONKALO and VLJ,

Autumn 2011: line OLK A (Lapijoki-Olkiluoto), loops OLKI A, OLKI B, OLKI D and micro loops ONKALO and VLJ.

In addition, based on the results in 2006 and 2007 we suggest:

Autumn 2008: line OLK A, if we find bedrock within the 0.8 km long critical interval 03211-03208, we will establish some new bench marks and level them,

Autumns 2009-2011: Re-levelling of the interval 03211-03208 including the new bench marks established in 2008.

9 SUMMARY

The precise levelling of the GPS network of Olkiluoto was established on the Olkiluoto island in autumn 2003 to monitor the vertical crustal deformations. At the same time the island was connected to the precise levelling network of Finland at Lapijoki. In autumn 2005 the first remeasurement of the GPS network was carried out. In autumn 2006 the micro networks upon ONKALO and VLJ Repository were established and levelled. In autumn 2007 the following remeasurements were carried out: the first remeasurement of the line Lapijoki-Olkiluoto and the micro networks of ONKALO and VLJ Repository and the second remeasurement of the GPS network. All the bench marks established have been fastened in bedrock. The levellings and the computations have been carried out in the same way as in the Third Levelling of Finland. The most interesting results of the campaign in 2007 were the significant elevation difference change of the interval 03211-03208 on the line Lapijoki-Olkiluoto and the anomalous rising of the bench mark 06220 upon ONKALO.

10 ACKNOWLEDGEMENTS

I thank Prof. Markku Poutanen, FGI, for Figure 13, Mr. Paavo Rouhiainen, FGI, for rod calibrations, Mr. Veikko Saaranen, FGI, for helping in computer problems and Dr. Heikki Virtanen, FGI, for computing the gravity values.

REFERENCES

Ahola, J., H. Koivula, M. Poutanen and J. Jokela (2007): GPS operatioins at Olkiluoto, Kivetty and Romuvaara in 2006. Working Report 2007-56, Posiva Oy. Olkiluoto.

Heikkinen, M. (1978): On the tide generating forces. Publications of the Finnish Geodetic Institute No 85. Helsinki.

Hytönen, E. (1967): Measuring of the refraction in the Second Levelling of Finland. Publications of the Finnish Geodetic Institute No. 63. Helsinki.

Kääriäinen, E. (1966): The Second Levelling of Finland. Publications of the Finnish Geodetic Institute No. 61. Helsinki.

Lehmuskoski, P. (2004): Precise Levelling of the Olkiluoto GPS Network in 2003. Working Report 2004-7. Posiva Oy. Olkiluoto.

Lehmuskoski, P. (2006): Precise Levelling of the Olkiluoto GPS Network in 2005. Working Report 2006-27. Posiva Oy. Olkiluoto.

Lehmuskoski, P., P. Rouhiainen, V. Saaranen, M. Takalo and H. Virtanen (2006): Seasonal Change of the Bedrock Elevation at the Metsähovi Levelling Test Field. Nordic Journal of Surveying and Real Estate Research Vol. 3, No. 1. Helsinki.

Takalo, M. (1999): Verification of Automated Calibration of Precise Levelling Rods in Finland. Reports of the Finnish Geodetic Institute No. 99:7. Kirkkonummi.

Takalo M. and P. Rouhiainen (2002): On System calibration of Digital Levels. Proceedings of the 14th General Meeting of the Nordic Geodetic Commission, October 1-5, 2002, Espoo, Finland pp. 278-283. Ed. M. Poutanen and H. Suurmäki, FGI, Kirkkonummi.

Ågren, J. and R. Svensson (2007): Postglacial Land Uplift Model and System Definition for the New Swedish Height System RH2000. LMV-Rapport 2007:4. Gävle.