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Precise Levelling Campaigns at Olkiluoto in 2012-2013

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ABSTRACT

In order to research vertical bedrock deformations in the Olkiluoto area, Posiva Oy and the Finnish Geodetic Institute began monitoring with precise levelling in 2003. At the moment, the measuring plan includes a loop between the GPS stations around the island, a levelling line from the island to the mainland, levelling loops over the ONKALO, the characterization facility for the final disposal of spent nuclear fuel, and VLJ, the low and intermediate level waste repository. The levelling to the mainland has been performed every fourth year and the levelling of the GPS stations every second year. The micro loops (ONKALO and VLJ) have been measured annually.

In this report, we present the Olkiluoto levelling observations, performed in 2012 and 2013. Local deformations have been analysed by comparing the height differences for different years.

In the Olkiluoto strait area, the height changes from 2011 to 2012 were within ± 0.1 mm

In the GPS station loop, in 2011-2013, the height of benchmark (BM) GPS3 changed + 0.69 mm. It is the only benchmark, which height has changed more than one millimetre from the year 2003. Second largest deformation happened at GPS1. Its height changed – 0.49 mm from 2011 to 2013.

In the ONKALO loop, largest height change, from 2011 to 2012 was – 0.37 mm. From 2012 to 2013, the largest height changes was – 0.4 mm.

In the VLJ loop, the most active deformation is related to the control benchmarks of GPS9. In 2012, these benchmarks were 0.6 mm lower level than 2011. From 2012 to 2013, both benchmarks rebounded so that deformation from 2011 to 2013 is – 0.38 mm. The other benchmarks have deformation within ± 0.11 mm, from 2011 to 2013.

In 2011, a new GPS station GPS16 was established. The GPS station has three control benchmarks on bedrock and one benchmark is part of a pillar. The height of the contol benchmark fastened to pillar changed one millimetre, from 2011 to 2013, relative to the control benchmarks on bedrock.

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

Tarkkavaaitusmittaukset Olkiluodossa 2012-2013

TIIVISTELMÄ

Geodeettinen laitos perusti Olkiluodon GPS-verkon 1994 ja suoritti ensimmäiset tarkkavaaitukset syksyllä 2003. Tällöin mitattiin GPS-verkko ja vaaituslinja Lapijoki-Olkiluoto. Mittaukset linjalla Lapijoki-Olkiluoto päätettiin suorittaa joka neljäs vuosi ja GPS-verkossa joka toinen vuosi. Syksyllä 2006 ONKALOn ja VLJ-luolan yläpuolelle perustettiin mikrosilmukat, joiden vaaitus suoritetaan vuosittain.

Tässä raportissa esitetään vuosien 2012-2013 havainnot ja analysoidaan Olkiluodon alueen kallioperän deformaatiota viime vuosien aikana. Kallioperän paikallista deformaatiota on tutkittu vertailemalla kiintopistevälin korkeuksien muuttumista eri vuosien mittausten välillä. Olkiluodon GPS-verkon ja ONKALOn deformaatio analysoidaan suhteessa koko alueen deformaatioon, eli kiinnitetyn pisteen korkeuslukemasta on korjattu vuosittainen maannousu. Olkiluodon salmen ja VLJ:n deformaatio on tutkittu kiinnitettyjen pisteiden suhteen, joiden korkeuslukemia ei ole korjattu vuosittaisella maannousulla.

Olkiluodon salmen alue oli stabiili 2011-2013. Muutokset 2011-2012 olivat korkeintaan ± 0.1 mm. GPS-verkon merkittävin deformaatio, 2011-2013, tapahtui pisteelle GPS3. Sen korkeus muuttui + 0,69 mm. Tällä hetkellä se on ainoa piste, jonka korkeus on muuttunut yli millimetrin vuodesta 2003. Toiseksi suurin muutos oli pisteellä GPS1 (– 0,49 mm).

ONKALOn suurin muutos 2011-2012 oli – 0,37 mm. Vuodesta 2012 vuoteen 2013 suurin muutos oli – 0,40 mm.

VLJ-silmukan tyypilliset liikkeet jatkuivat havaintojaksolla. Kiintopiste 06213 painui suhteessa kiinnitettyyn pisteeseen, ja suurimmat muutokset tapahtuivat GPS9:n kontrollipisteillä GPS9A ja GPS9B, jotka painuivat keskimäärin – 0,6 mm, 2011-2012. Seuraavana vuotena pisteet palautuivat siten, että muutos 2011-2013 oli – 0,38 mm. Muilla kiintopisteillä korkeudenmuutokset, 2011-2013, olivat korkeintaan ± 0,11 mm.

Vuonna 2011 perustetuille GPS-asemille suoritettiin uudellenmittaus vuonna 2013. Mittaukset osoittivat, että GPS16:n kontrollipisteen GPS16N:n korkeus oli muuttunut yli millimetrin suhteessa muihin kontrollipisteisiin. Kullakin uudella GPS-asemalla on neljä kontrollimerkkiä, joista kolme (”A”, ”B” ja ”C”) on kalliopisteitä ja yksi (”N”) on kiinnitetty pilariin.

Avainsanat: Kallioperän deformaatio, tarkkavaaitus, korkeuskontrolli, Olkiluoto, monitorointi.

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1 INTRODUCTION

Monitoring of bedrock deformation is a part of rock mechanics monitoring programme in the Olkiluoto area (Posiva, 2012). Important monitoring locations are a characterization facility for final disposal of spent nuclear fuel (ONKALO) and a low and intermediate level waste repository (VLJ). The levelling network has micro loops for the deformation monitoring of the ONKALO and the VLJ repository. Other parts of the network monitor large-scale vertical deformation in the island itself and its vertical deformation relative to the mainland.

The deformations of the ONKALO and the GPS networks are presented relative to the deformation of the whole research area. The VLJ and the Olkiluoto strait, which are small research networks, are presented relative to one fixed benchmark of the network.

Since 2003, vertical deformation of the Olkiluoto area has been studied using precise levelling. Results of the measurements have been published every second year in the Posiva working reports by Lehmuskoski (2004, 2006, 2008 and 2010) and Saaranen et al. (2012). The more detailed analysis of the deformation was presented in Saaranen et al. (2014).

2 DESCRIPTION OF THE LEVELLING NETWORK

All areas of interest in Olkiluoto have been connected by the levelling network (Figures 1 and 3). During the years, it has been further extended. In the beginning, in autumn 2003, it included the GPS network loops and the Olkiluoto–Lapijoki line, which connects Olkiluoto to the Finnish national precise levelling network in Lapijoki. The line gives information about the movement of the Olkiluoto area relative to the mainland. It was decided that this line should be surveyed every fourth year and the GPS network biennially (Table 1).

In 2006, the network was extended when new levelling loops were established and levelled at the ONKALO and the VLJ. Since 2007, the lines at Olkiluoto strait, the ONKALO and the VLJ have been levelled annually.

The locations of the benchmark intervals with the most significant height changes are presented in Figure 2. The height difference of benchmark interval 03208– 03211, over the Olkiluoto strait, changed 1.91 mm from 2003 to 2007 (Lehmuskoski, 2008). In the GPS network loop, height change of BM GPS6 and BM GPS9 was more than one millimetre relative to other benchmarks from 2003 to 2005 (Lehmuskoski, 2006). So, new loops were established onto the ONKALO and the VLJ. In 2007, it was noticed that in the loop ONKALO, BM 06220 was one millimetre higher than in 2006 (Lehmuskoski, 2008). In order to study deformation of BM 06220, BM 08201 and BM 08202 were added in 2008.

GPS monitoring for deformation research has been performed since 1995 (Nyberg et al., 2013). The control benchmarks of the GPS stations were included in the measuring plan when the GPS network was levelled for the first time in 2003. In 2005-2011, the heights of the GPS antenna platform levels have been measured. In 2013, only the antenna platform of GPS7 was measured. At the moment, most GPS stations operate continuously, and the levelling of antenna platform is no longer performed, because the levelling would disturb GPS observations. The new GPS stations GPS16, GPS17, GPS18 and GPS19 were established and levelled in 2011, and a new BM 13301, in 2013.

Table 1. *Measurement history of the Olkiluoto levelling network.*

	2003	2005	2006	2007	2008	2009	2010	2011	2012	2013
Olkiluoto-Lapijoki	*			*				*		
Olkiluoto strait	*			*	*	*	*	*	*	*
Olkiluoto GPS network loops (OLKIA, OLKIB)	*	*		*		*		*		*
ONKALO loop			*	*	*	*	*	*	*	*
VLJ loop			*	*	*	*	*	*	*	*

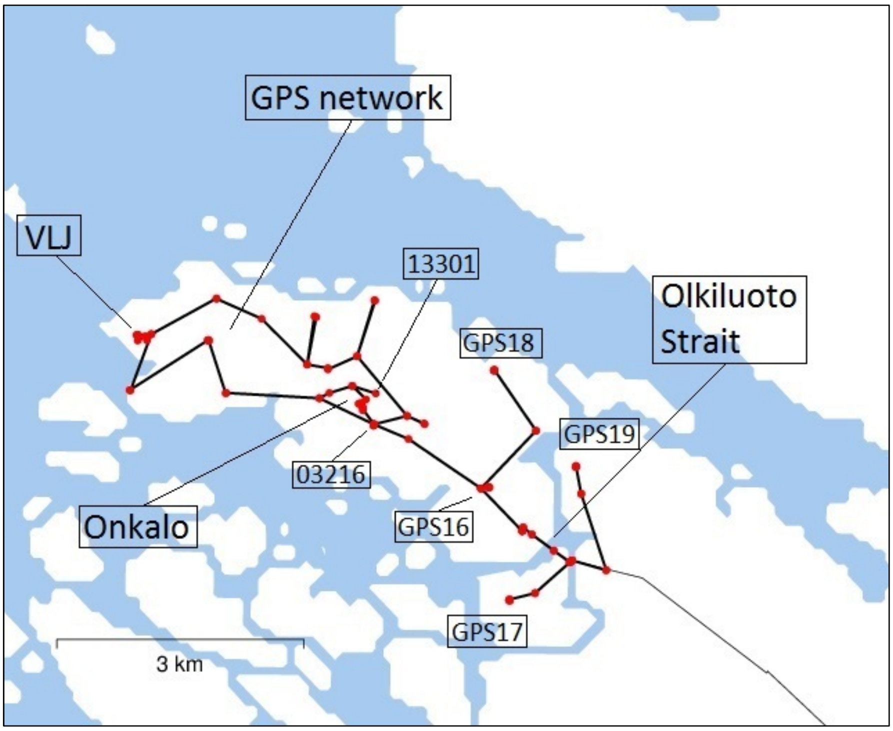

Figure 1. *The levelling network in 2013. Thick lines and red dots denotes observations and benchmarks in the 2013 adjustment. BM 03216 is a fixed BM in the adjustment. BM 13301 is a new BM, which was established in 2013. The GPS stations (GPS16, GPS17, GPS18 and GPS19) were established in 2011, and levelled second time in 2013. The locations of the benchmarks, which were in the analysis, are presented in Chapter 6, in Figures 5, 6, 8, 10 and 12.*

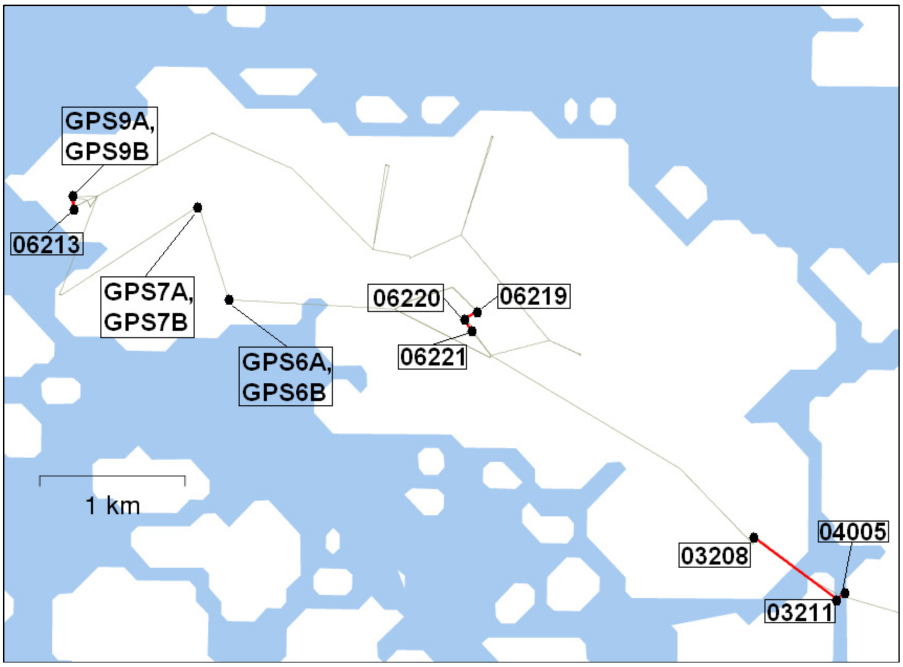

Figure 2. *The locations of the benchmark intervals with the most significant height changes (levelling fault lines).*

3 DESCRIPTION OF THE LEVELLING WORKS IN 2012 AND 2013

Observations were performed according to the plan as shown in Table 1. ONKALO, VLJ and Olkiluoto Strait were observed in both years. In 2013, larger observation work included the GPS network loop on the island, and levelling for the GPS stations GPS16, GPS17, GPS18 and GPS19 (Figure 1).

The measurement crew and instruments in the 2012 and 2013 levellings are presented in Table 2. Posiva Oy employed the assisting personnel for the levelling campaigns.
The adjustment result, benchmarks and their EUREF-FIN coordinates are presented in Appendix I. Coordinates have been observed by Garmin eTrex GPS receiver. Accuracy of the coordinates can be some metres.

The calibrations of the levelling rods were carried out before and after the field campaign, using the FGI vertical rod comparator; Takalo (1999), Takalo and Rouhiainen (2002). The scale corrections and thermal expansion coefficients are presented in Tables 3 and 4. Detailed description of the calibrations is presented in the Appendix VIII.

Table 2. *Field crew and instruments in the 2012 and 2013 levelling measurements.*

Surveyor 2012 and 2013	Paavo Rouhiainen
Levelling expedition 2012	Riina Aerila, Jesse Koskinen, Teppo Peltola and Simo Muttilainen
Levelling expedition 2013	Jaanus Hansen, Juuso Laiho, Katri Majuri, Simo Muttilainen, Sami Saarinen, Jaakko Simula and Paula Sookari
Observation days	24.9.-28.9.2012 2.9.-3.10.2013
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	Wild GST 20 normal, Zeiss extendable
Distance meter	Rollfix
Umbrella	Alexo
Car	Toyota Hiace, UXY-346
Personal Navigator	Garmin eTrex

Table 3. *Rod calibrations of the rods 13926 and 14092.*

Year	**Month**	**Day**	**Rod 13926** Thermal expansion (µm/m/°C)	**Rod 13926** Scale correction (µm/m) at 20°C	**Rod 14092** Thermal expansion (µm/m/°C)	**Rod 14092** Scale correction (µm/m) at 20°C
2012	8	20	0.88	– 0.74	0.77	+ 0.97
2012	10	8	0.70	– 1.80	0.64	– 0.44
2013	8	20	0.82	– 2.00	0.72	+ 0.20
2013	10	18	0.69	– 4.60	0.64	– 3.20

Table 4. *The calibration results of the rod 11640.*

Year	**Month**	**Day**	**Rod 11640** Thermal expansion (µm/m/°C)	**Rod 11640** Scale correction (µm/m) at 20°C
2013	8	20	0.75	– 14.0
2013	10	18	0.82	– 15.4

4 THE DETERMINATION OF THE HEIGHTS FOR 2012 AND 2013

In this chapter, deformations of the GPS network and ONKALO relative to the whole levelling field, are described. In a computation method we correct deformation rate of a fixed BM 03216. In 2012, BM 06214 has been used in the loop VLJ, and BM 03208, was used in the Olkiluoto strait computations.

In the local deformation analysis, in Chapter 6, we compare only the heights which were measured in the continuous network i.e. heights were adjusted using a single fixed benchmark and both benchmarks were included in the same network. For every year we use different fixed value, so that we correct the deformation of fixed benchmark. We start this chapter with a short description of the deformation model, which is based on the repeated levellings 2003-2011, Saaranen et al. (2014).

4.1 Deformation model of the Olkiluoto area

Because the levelling produces only height and land uplift differences, in the land uplift analysis fixed height and land uplift values for BM. 03216 were used. The height 9.870 m is in the new Finnish height system N2000; Lehmuskoski et al. (2008) and Saaranen et al. (2006). The starting value for the land uplift values, 5.439 mm/y, is taken from the Nordic land uplift model NKG2005LU (Ågren and Svensson, 2007). In the deformation analysis, the average uplift rate, 5.523 mm/y, has been removed from the uplift rates (Figure 3).

According to deformation analysis, local subsidence area includes the ONKALO loop. The VLJ loop is in the rising area. Its mean deformation rate is + 0.05 mm/y. The ONKALO has an average deformation rate of – 0.10 mm/y, and the Olkiluoto strait has a small subsidence value of – 0.03 mm/y. In the Olkiluoto strait area, the benchmarks on the island are rising and on the other side of the strait they have opposite deformation. The Lapijoki area has a deformation rate similar to that of the ONKALO, i.e. – 0.11 mm/y. This rate was based on the average value of the three easternmost benchmarks of the Olkiluoto–Lapijoki line. In the model, the standard deviation of the land uplift rate at Lapijoki is about ± 0.3 mm/y and on the island ± 0.1 mm/y. The standard deviation is relative to the fixed BM 03216.

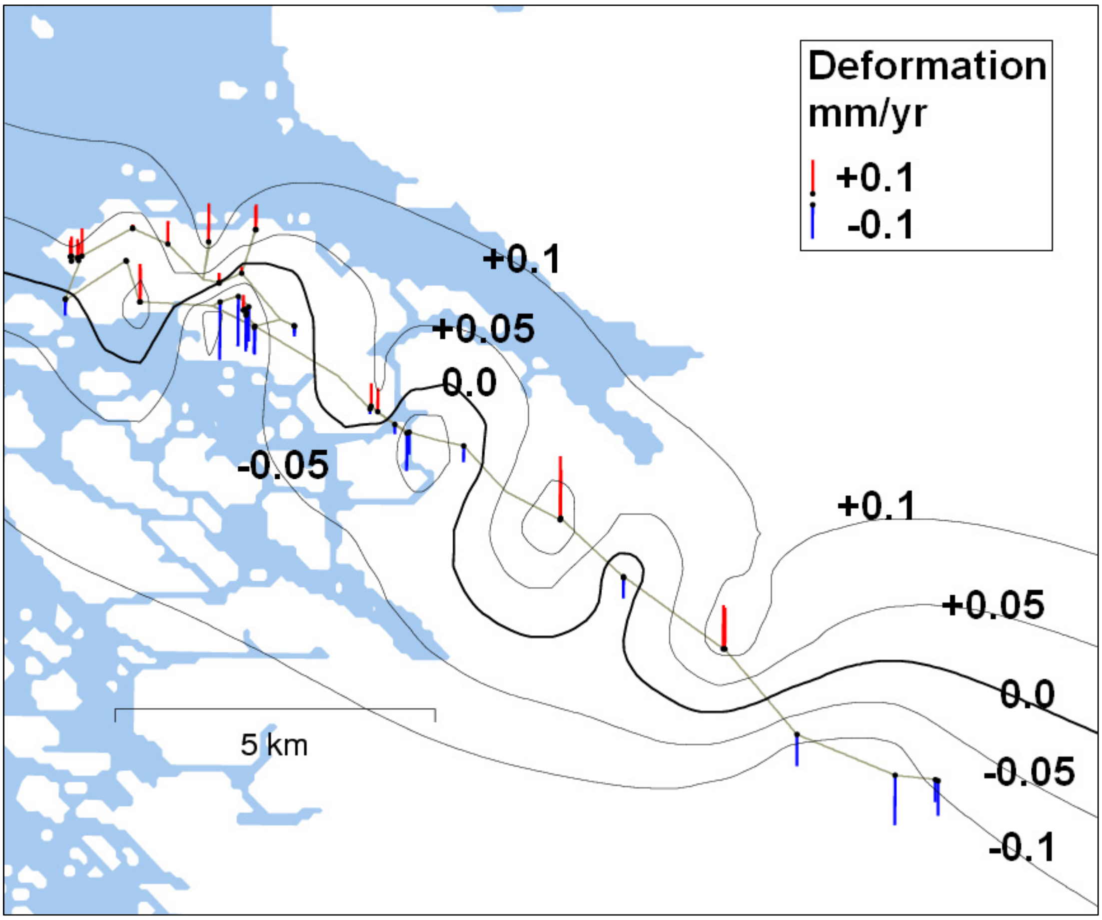

Figure 3. *The Olkiluoto levelling deformation model(mm/y), which is based on observations from 2003 to 2011 (Saaranen et al., 2014). In the model, the average land uplift has been removed. In the Olkiluoto-Lapijoki line deformation is based on three levellings, and thus the deformation rates are less reliable than on the island, where exist more levellings in small levelling loops. The algorithm for the contours is presented in Smith and Wessel (1990).*

4.2 Adjustment of 2012 and 2013 observations

Starting value at BM 03216 is 9.870 m in 2003. The benchmark is located in Olkiluoto island near the ONKALO. This location is on the subsidence area of the research network. In Table 5, there are deformation values of the fixed benchmarks, and in Table 6, there are deformation corrected height values.

Table 5. *Fixed benchmarks in the adjustments and their deformation rate relative to the levelling network.*

BM	**03216**	**06214 /VLJ**	**03208 /Strait**
Deformation rate	– 0.084 mm/y	+ 0.056 mm/y	+ 0.067 mm/y

Table 6. *Fixed benchmarks and the starting values, in metres, in the yearly adjustments. BM 06214 is fixed in the VLJ adjustment and BM 03208 in the Olkiluoto strait adjustment. In 2004, some new benchmarks were established without network measurements.*

Year	**03216**	**06214 /VLJ**	**03208 /Strait**
2003.7	9.87000	-	-
(2004)	-	-	-
2005.7	9.86983	-	-
2006.7	9.86975	10.33764	-
2007.7	9.86966	-	-
2008.7	9.86958	10.33775	10.06007
2009.7	9.86950	-	10.06013
2010.7	9.86941	10.33786	10.06020
2011.7	9.86933	-	-
2012.7	9.86924	10.33797	10.06033
2013.7	9.86916	-	-

An adjustment program is Local X- Positioning system. An adjustment method is a constrained net. The weight of each observation is inversely proportional to the distance of the benchmark interval. A priori accuracy in the adjustment has been 1.0 mm/√km and in a statistical testing reference variance 1.0 (unitless) was used. In the adjustment, there are 22 benchmarks in 2012, and 58 in 2013.

The adjustment results are presented in the Appendices I-III. The heights of the benchmarks are presented in Appendix I. Observations in the adjustments, Appendix II and III, are from computation documents, which are presented in Appendix IV.

In the computation documents, which are usually called line papers, the height difference is mean of forward and back measurements, which are listed in the Appendix V. Benchmark intervals have been measured in both directions in order to minimise systematic errors, which are typical for levelling measurements (Takalo et al. 2002). The height differences are corrected for rod meter, tidal deformation and refraction before the adjustment (Saaranen et al., 2014). In a line paper the computed corrections and height differences can be seen. Every levelling observation is therefore based on at least two measurements. In the adjustments mean values have been used.

The observation documents are presented in the Appendix VI and VII. Measurements are in chronological order. One page represents one benchmark interval and one levelling direction. The upper part of the page shows time, crew, instrumentation, road type and weather. The lower part includes rod readings, sighting distances and environmental data for every step. At the end of the observation file there are an uncorrected height difference, distance between benchmarks and possible remarks.

5 THE ANALYSIS OF THE LEVELLING FAULT LINES

Levelling fault lines do not express exact locations of fault lines. It simply emphasizes, that the bedrock locations of benchmarks have different vertical movements between the observation epochs. It is possible, that the height difference is due to levelling error. In the significancy computation, we use the distance and height change between the successive benchmarks, and the standard deviations of the levelling years (Lehmuskoski, 2006).

The uncertainty of measurement in levelling is relative to the measured distance. The smaller the levelled distance and its uncertainty are, the smaller are the movements that can be reliably detected. The standard deviations for the yearly levellings are presented in Table 7. The standard deviations of the levelling since 2010 are from the levelling network adjustments. For the previous levelling values were estimated by the Formula 1 (Kääriäinen, 1966).

$$\tau^2 = \frac{1}{n+1}\left(\sum_{i=1}^{n} \frac{\varphi_i^{\,2}}{F_i} + \frac{\varphi^2_{\,e}}{F_e}\right), \tag{1}$$

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.

***Table** 7. Standard deviations for the levelling campaigns* ($\mathrm{mm}/\sqrt{\mathrm{km}}$).

2003	2005	2006	2007	2008	2009	2010	2011	2012	2013
± 0.10	± 0.14	± 0.17	± 0.23	± 0.12	± 0.14	± 0.27	± 0.23	± 0.20	± 0.26

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

$$\tau_\Delta = \sqrt{\tau_1^2 + \tau_2^2}, \tag{2}$$

Where τ_1 and τ_2 are the standard deviations of the campaigns.

The critical value can be considered significant, when the change of the height is more than threefold of the standard deviation of the discrepancy:

$$S_\tau = |[y(i,j,k_1) - y(i,j,k_2)]/[\tau_\Delta \sqrt{l(i,j)}]| \tag{3}$$

In the formula (3), $y(i,j,k_1)$ is the observed height difference in the year k_1, τ_Δ is the standard deviation, and $l(i,j)$ is the length, in kilometres, of the levelling line between the benchmarks i and j. The deformation can be considered significant if the significance level $S\tau > 3$. In other words, the change in the height difference is more than three times the standard deviation of the difference. For instance, if the height difference of one kilometre long interval has changed from 2003 to 2011 more than 0.75 mm, the change can be considered to be significant.

Complete results of the levelling fault line analysis, from 2003 to 2011, is presented in Saaranen et al. (2014, Appendix V). In this report we present list of 30 most significant deformations, in 2003-2013 (Table 8). In the table, the most significant deformations are presented, so some benchmark intervals are shown several times. For example the deformations from BM 06220 to BM 06219 and BM 06221 are significant in many comparisons. The locations of the levelling fault lines are presented in Figure 2. In the local deformation section, we present for every measurement area the most significant deformations, which have observations from 2012 or 2013.

Table 8. *The most significant deformations inside the benchmark intervals in the Olkiluoto research network. The largest deformation is 11.1 times larger than the standard deviation of the difference between the observations, which were performed from BM 06220 to BM 06221, in 2006 and 2013.*

	BM (from)	**BM (to)**	**Significancy S_τ**	**Deformation [mm]**	**Distance [km]**	**Year**	**Year**	**Area**
1	06220	06221	11.1	– 1.15	0.111	2006	2013	ONKALO
2	06220	06221	9.7	– 0.85	0.111	2006	2012	ONKALO
3	04005	03211	9.1	– 0.51	0.038	2008	2013	STRAIT
4	04005	03211	9.0	– 0.41	0.038	2008	2012	STRAIT
5	04005	03211	8.0	– 0.46	0.038	2009	2013	STRAIT
6	06219	06220	7.7	0.73	0.131	2006	2012	ONKALO
7	04005	03211	7.6	– 0.56	0.038	2010	2013	STRAIT
8	04005	03211	7.5	– 0.36	0.038	2009	2012	STRAIT
9	04005	03211	7.4	– 0.50	0.038	2007	2013	STRAIT
10	06219	06220	7.2	0.81	0.131	2006	2013	ONKALO
11	03211	03208	7.2	1.42	0.770	2003	2012	STRAIT
12	GPS9A	06213	7.2	0.64	0.085	2011	2012	VLJ
13	04005	03211	7.0	– 0.46	0.038	2010	2012	STRAIT
14	04005	03211	6.7	– 0.40	0.038	2007	2012	STRAIT
15	06220	06221	6.5	– 0.62	0.111	2008	2013	ONKALO
16	03211	03208	6.4	1.57	0.770	2003	2013	STRAIT
17	GPS9B	06213	6.0	0.56	0.093	2011	2012	VLJ
18	06216	GPS9B	5.9	– 0.82	0.282	2006	2012	VLJ
19	06220	06221	5.7	– 0.66	0.111	2007	2013	ONKALO
20	GPS6B	GPS7A	5.3	– 1.38	0.860	2003	2013	OLKIA
21	GPS13B	GPS13A	5.3	– 0.17	0.012	2005	2013	OLKIA
22	03218	GPS3B	5.2	1.33	0.851	2003	2013	OLKB
23	GPS3A	03218	5.1	– 1.31	0.862	2003	2013	OLKB
24	GPS9A	06213	4.8	0.34	0.085	2009	2012	VLJ
25	06216	GPS9A	4.7	– 0.81	0.437	2006	2012	VLJ
26	GPS9A	06213	4.6	– 0.38	0.085	2008	2013	VLJ
27	03216	GPS6A	4.4	1.77	2.080	2003	2013	OLKIA
28	03218	GPS3B	4.4	1.19	0.851	2005	2013	OLKB
29	GPS3A	03218	4.3	– 1.19	0.862	2005	2013	OLKB
30	06220	06221	4.1	– 0.32	0.111	2008	2012	ONKALO

6 LOCAL DEFORMATIONS

Local deformations in the different parts of the network is presented in this chapter. In the comparisons we use the heights for 2012 and 2013, which are presented in the Appendix I. Heights for the previous years and the complete analysis of the deformation can be found in Saaranen et al. (2014).

6.1 Olkiluoto Strait

Olkiluoto strait is an eight hundred metres long benchmark interval, which connects the island to the mainland. From 2003 to 2007, BM 03208 on the Olkiluoto island had lifted 1.91 mm up compared to BM 03211 on the mainland. To study this interval more precisely some new benchmarks were established in 2008, and it has been measured annually since 2007. The height change of the interval 03208-03211 has stabilised since 2008, and in 2012 and 2013 height difference was close to that of 2008. In 2013, the Olkiluoto strait BM 03208 was connected to BM 03216. From 2011 to 2013, the movement of BM 03208 was – 0.42 mm relative to BM 03216.

The deformation over the Olkiluoto strait is presented in Figures 4 and 5, and Tables 9 and 10. The height differences relative to BM 03208 were computed for every benchmark and for every year. The deformation between the years was then determined by removing the benchmark height in 2008. If we compare BM 03208 to the other benchmarks on the island, we observe no remarkable deformation. The height changes of BM 04004 and BM 08203 are about ± 0.1 mm, during the observation period, relative to BM 03208. The largest difference was at BM 04004, – 0.16 mm, in 2013 relative to the year 2008.

The latest deformation happened, in 2010-2011, in a short interval between the BM 03211 and BM 04005. In 2011, the height difference was about a half millimetre more than in the previous measurements. In 2012 and 2013, the benchmark interval was stable. If we compare height relative to 03208 and year 2011, we see that height of BM 03211 was stable within ± 0.08 mm, and 04005 within ± 0.03 mm.

For all the benchmarks, the height change from 2011 to 2012 was within ± 0.1 mm, and the average deformation was 0.00 mm. From 2012 to 2013, the average deformation was – 0.11 mm. Every benchmark had a negative deformation between the years. The largest difference was at BM 04004 (– 0.19 mm). It is possible that the fixed BM 03208 had a local positive maximum value in 2013.

Table 9. *Deformations since 2008 over the Olkiluoto strait.*

	2009	2010	2011	2012	2013
04004	– 0.08	0.04	0.10	0.03	– 0.16
08203	0.01	0.05	0.07	0.11	0.03
08204	0.33	– 0.10	0.15	0.09	0.02
03211	0.39	– 0.10	0.00	0.06	– 0.08
04005	0.44	– 0.15	0.45	0.47	0.42

Table 10. *The most significant deformations over the Olkiluoto strait, which have a measurement from 2012 or 2013.*

	BM (from)	**BM (to)**	**Significancy S_τ**	**Deformation [mm]**	**Distance [km]**	**Year**	**Year**
1	04005	03211	9.1	– 0.51	0.038	2008	2013
2	04005	03211	9.0	– 0.41	0.038	2008	2012
3	04005	03211	8.0	– 0.46	0.038	2009	2013
4	04005	03211	7.6	– 0.56	0.038	2010	2013
5	04005	03211	7.5	– 0.36	0.038	2009	2012
6	04005	03211	7.4	– 0.50	0.038	2007	2013
7	03211	03208	7.2	1.42	0.770	2003	2012
8	04005	03211	7.0	– 0.46	0.038	2010	2012
9	04005	03211	6.7	– 0.40	0.038	2007	2012
10	03211	03208	6.4	1.57	0.770	2003	2013
11	03216	03219	3.6	0.11	0.019	2003	2012
12	04005	08204	3.4	– 0.38	0.226	2008	2012
13	03216	03219	3.4	0.13	0.019	2003	2013
14	04005	03208	3.4	– 0.89	0.729	2007	2012
15	03208	04004	3.2	– 0.25	0.051	2011	2013
16	03208	03216	3.1	– 1.06	2.380	2003	2012
17	04005	08204	2.9	– 0.40	0.226	2008	2013
18	04005	03208	2.8	– 0.84	0.729	2007	2013
19	04005	08204	2.7	– 0.43	0.226	2010	2012
20	03216	03219	2.7	0.13	0.019	2007	2013

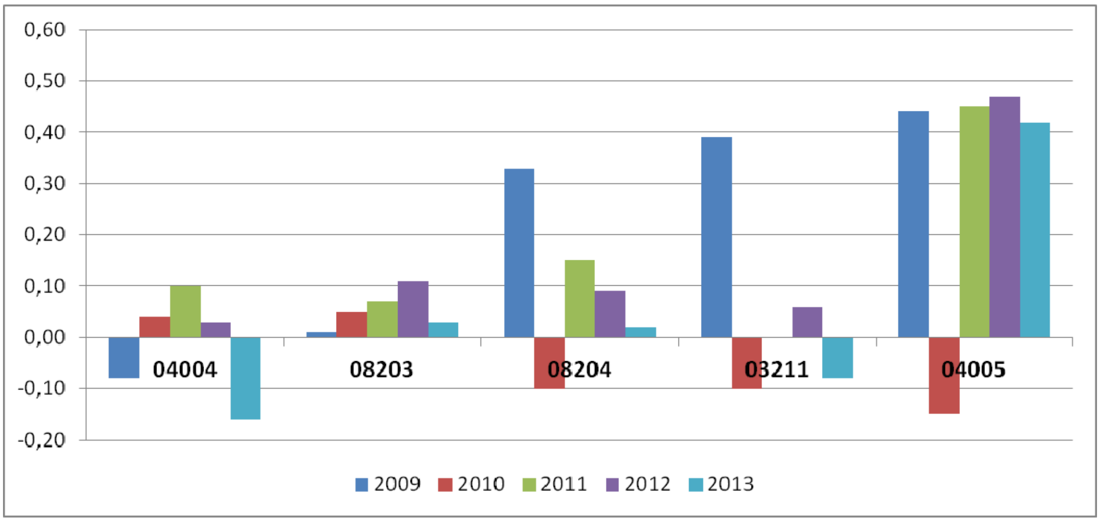

Figure 4. *The visualisation of the deformation over the Olkiluoto strait (in millimetres). In the comparison, BM 03208 on the island has been fixed. The deformation is relative to the year 2008.*

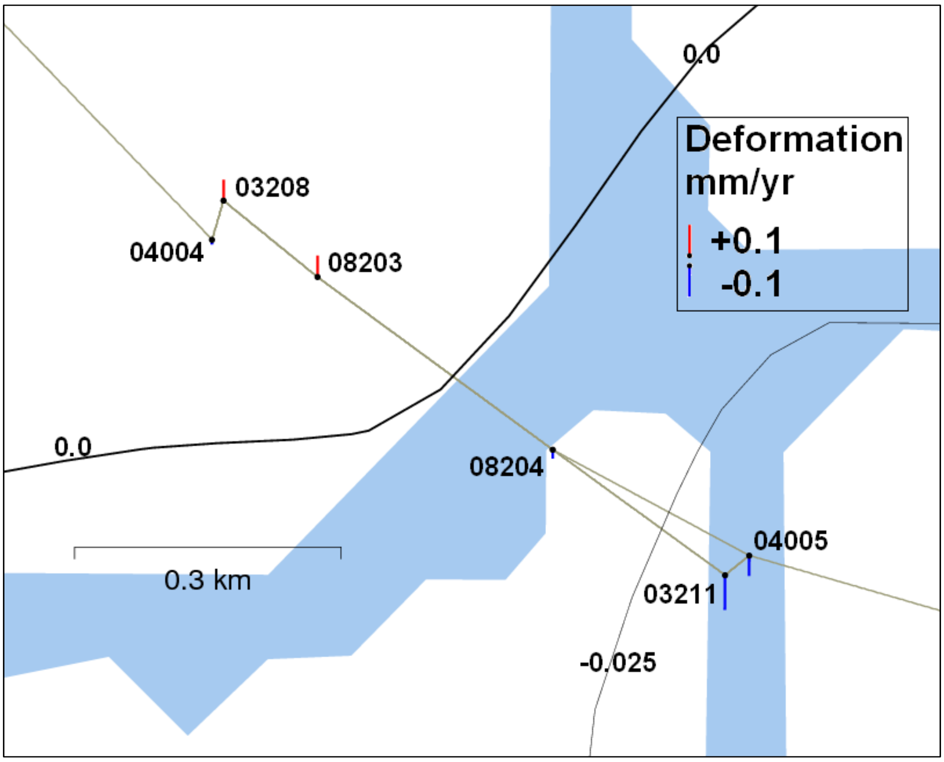

Figure 5. *Line Olkiluoto strait has six benchmarks. The latest deformation happened between BM 04005 and BM 03211, in 2010-2011 (Saaranen et al., 2014).*

6.2 Deformation of the island

GPS network loop is a loop around the island. There are two micro loops on the island, ONKALO and VLJ, which will be discussed in the sections 6.3 and 6.4. The local stability of the GPS stations will be discussed in section 6.5. The most significant new deformations are presented in Table 11, and the deformation relative to the whole network is shown in Table 12.

Previously most interesting deformations are related to GPS stations GPS6, GPS9 and GPS13 (Figure 6). For example, between 2003 and 2005, the heights of the GPS stations GPS6 and GPS9 raised more than one millimetre relative to levelling research network (Figure 7). GPS13 had an interesting height minimum in 2009. Height was 0.7 mm lower than two years before, but in 2011 it was almost at the same level as in 2007, and the difference between the 2011 and 2013 heights is only 0.02 mm.

During the years, the GPS station GPS3, has been stable. So it is quite suprising, that in 2011-2013 its height changed + 0.69 mm. It is only benchmark, which height has changed more than one millimetre from the year 2003. Second largest deformation happened at GPS1. Its height changed – 0.49 mm from 2011 to 2013. Height of GPS7 changed – 0.32 mm. Other deformations were within ± 0.3 mm.

Table 11. *The most significant benchmark interval deformations in the GPS network loop, which have a measurement from 2012 or 2013.*

	BM (from)	**BM (to)**	**Significancy S_τ**	**Deformation [mm]**	**Distance [km]**	**Year**	**Year**
1	GPS6B	GPS7A	5.3	– 1.38	0.860	2003	2013
2	GPS13B	GPS13A	5.3	– 0.17	0.012	2005	2013
3	03218	GPS3B	5.2	1.33	0.851	2003	2013
4	GPS3A	03218	5.1	– 1.31	0.862	2003	2013
5	03218	GPS3B	4.4	1.19	0.851	2005	2013
6	03216	GPS6A	4.4	1.77	2.080	2003	2013
7	GPS3A	03218	4.3	– 1.19	0.862	2005	2013
8	GPS6A	GPS6B	3.9	0.11	0.010	2003	2013
9	GPS7A	GPS7B	3.9	0.15	0.012	2007	2013
10	GPS13B	GPS13A	3.9	– 0.15	0.012	2007	2013
11	GPS9A	GPS9B	3.8	– 0.12	0.013	2003	2013
12	GPS9A	GPS9B	3.7	– 0.12	0.013	2008	2013
13	GPS2A	03216	3.5	– 0.87	0.790	2003	2013
14	GPS7B	GPS13B	3.5	1.23	1.411	2009	2013
15	GPS4B	GPS1A	3.4	– 0.94	0.980	2003	2013
16	03218	GPS3B	3.3	0.89	0.851	2009	2013
17	GPS9A	GPS9B	3.3	– 0.14	0.013	2010	2013
18	GPS2A	03216	3.3	– 0.86	0.790	2005	2013
19	03218	GPS3B	3.1	0.99	0.851	2007	2013
20	GPS3A	03218	3.1	– 0.99	0.862	2007	2013

When the heights of GPS points were compared, we used the mean of their control mark pair with the exceptions of GPS2 and GPS4, whose other pair had been damaged. The control mark GPS2B was measured in 2011. It was found to be damaged by a working machine in 2009, so, it was not used in the comparison with the previous measurements. A new control BM GPS4C for GPS4, was established in 2011.

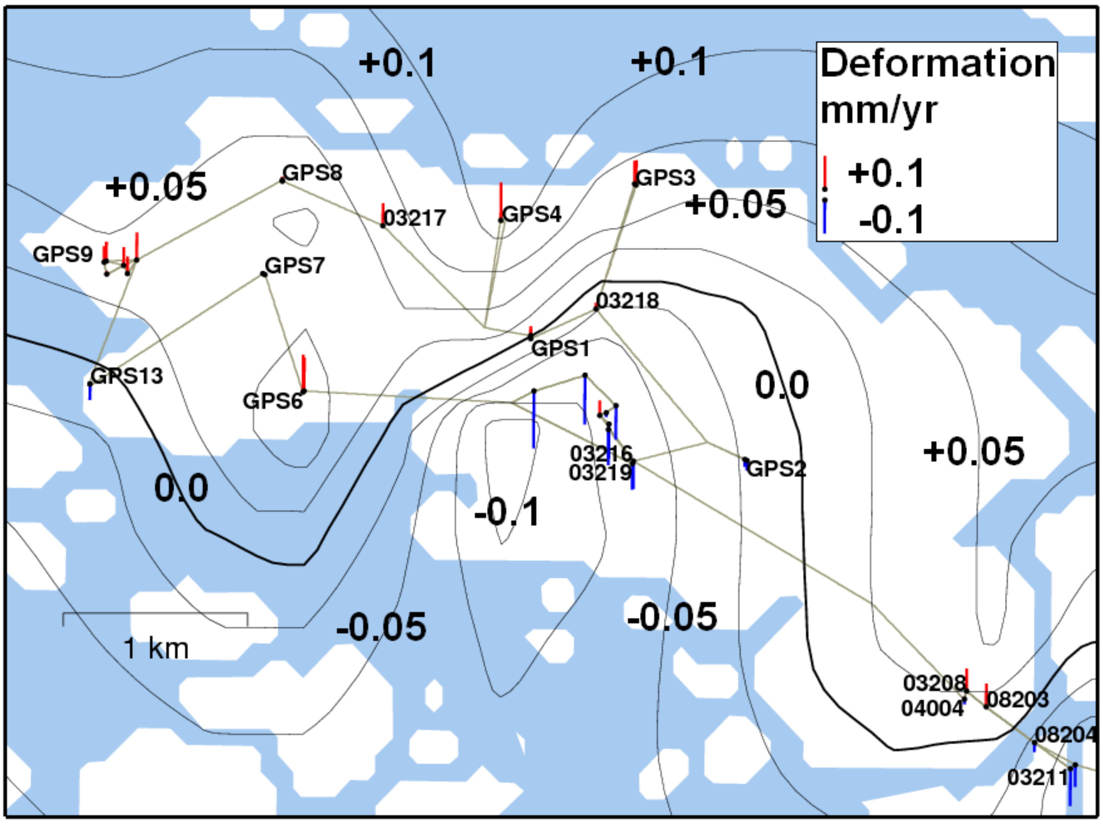

Figure 6. *The benchmarks on the island and their deformation relative to the mean deformation of the levelling network (Saaranen et al., 2014).*

Table 12. *Deformation of the Olkiluoto island relative to the year 2003 and the average deformation of the Olkiluoto research area (in millimetres).*

	2005	**2007**	**2009**	**2011**	**2013**
03216	– 0.17	– 0.34	– 0.50	– 0.67	– 0.84
GPS2A	– 0.16	– 0.37	– 0.41	– 0.18	0.03
03218	– 0.41	– 0.02	– 0.21	0.01	– 0.25
GPS3	– 0.28	0.31	0.24	0.39	1.07
GPS1	– 0.11	0.31	– 0.06	0.16	– 0.33
GPS4B	0.04	0.53	0.40	0.87	0.63
03217	– 0.06	0.58	0.02	0.50	0.25
GPS8	0.17	0.36	– 0.13	0.10	0.21
GPS9	0.80	0.45	0.28	0.62	0.44
GPS13		– 0.11	– 0.85	– 0.21	– 0.23
GPS7	– 0.03	– 0.26	0.19	– 0.06	– 0.37
GPS6	0.83	0.65	1.17	0.93	0.99

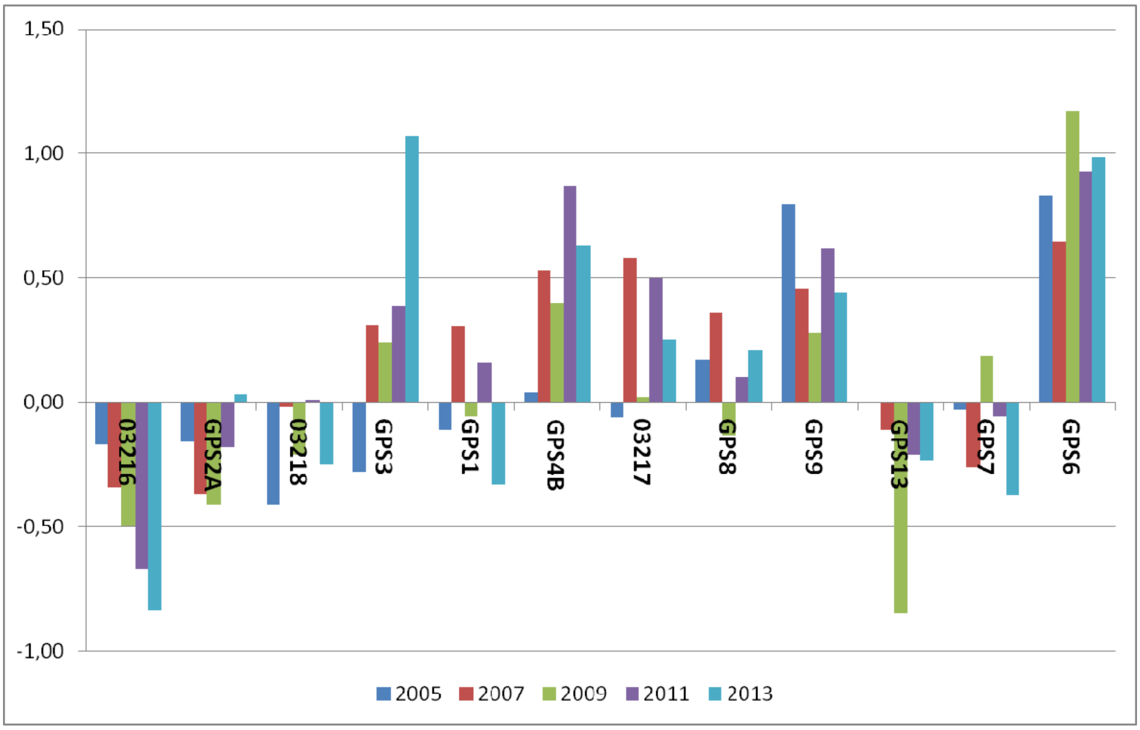

Figure 7. *The visualisation of the deformation relative to the year 2003 and the average deformation of the Olkiluoto research area (in millimetres). BM. 03216 has been fixed in the yearly adjustments with a linear subsidence rate. The deformation of GPS13 is relative to the year 2005.*

6.3 Micro loop ONKALO

The ONKALO is in the subsidence area, but BM 06220 has an unique deformation rate, which seems to be a very local phenomenon (Figures 8 and 9). Its neighboring benchmarks are stable, but the observations from BM 06220 are in the levelling fault line list (Table 13). It can be seen in Figure 9, that mostly deformation happened between 2006 and 2007. Since then it has been stable relative to the levelling network. Deformation of BM 06220 has been only + 0.05 mm in 2011-2012, and – 0.08 mm in 2012-2013.

Largest height changes from 2011 to 2012 are at BM 06217 (– 0.37 mm) and BM 06219 (+ 0.22 mm). From 2012 to 2013, the largest height changes happened at BM 08201 (– 0.40 mm), BM 06221 (– 0.38 mm), BM 08202 (– 0.27 mm), and BM 06218 (+ 0.23 mm). Other deformations in a year were less than 0.2 mm. It is interesting to see that for every benchmark the height change had different sign between the years 2011-2012 and 2012-2013. Only benchmark with larger than 0.3 mm deformation from 2011 to 2013, was BM 06221 (– 0.33 mm).

The height changes are relative to BM 03216. If we study observation history, we can see that the fixed BM 03216 seems to have a peak height in 2010 (Table 14 and Figure 9). In Figure 9, it can be seen, that the other benchmarks in the ONKALO loop have local minimum height in 2010.

Table 13. *The most significant benchmark interval deformations in the loop ONKALO.*

	BM (from)	**BM (to)**	**Significancy S_τ**	**Deformation [mm]**	**Distance [km]**	**Year**	**Year**
1	06220	06221	11.1	– 1.15	0.111	2006	2013
2	06220	06221	9.7	– 0.85	0.111	2006	2012
3	06219	06220	7.7	0.73	0.131	2006	2012
4	06219	06220	7.2	0.81	0.131	2006	2013
5	06220	06221	6.5	– 0.62	0.111	2008	2013
6	06220	06221	5.7	– 0.66	0.111	2007	2013
7	06220	06221	4.1	– 0.32	0.111	2008	2012
8	06221	08201	3.6	0.16	0.036	2008	2012
9	06220	06221	3.5	– 0.34	0.111	2009	2013
10	06220	06221	3.5	– 0.36	0.111	2007	2012
11	06220	06221	3.3	– 0.41	0.111	2010	2013
12	06218	06219	3.3	0.51	0.337	2006	2012
13	08202	06220	3.1	– 0.17	0.050	2009	2012
14	06217	06218	3.0	0.54	0.331	2006	2013
15	08202	06220	3.0	0.19	0.050	2008	2013
16	06217	06218	3.0	0.46	0.331	2006	2012
17	06218	06219	2.9	0.51	0.337	2007	2012
18	06220	06221	2.7	– 0.30	0.111	2012	2013
19	06220	06221	2.6	– 0.30	0.111	2011	2013
20	08202	06220	2.6	0.19	0.050	2012	2013

Table 14. *The deformation in the ONKALO loop relative to the average deformation of the Olkiluoto research area (in millimetres).*

	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
03216	– 0.09	– 0.17	– 0.25	– 0.34	– 0.42	– 0.51	– 0.59
06217	– 0.32	– 0.52	– 0.59	– 1.07	– 0.74	– 1.11	– 0.96
06218	0.02	– 0.23	– 0.29	– 0.76	– 0.53	– 0.65	– 0.42
06219	0.02	0.08	– 0.12	– 0.46	– 0.36	– 0.14	– 0.30
06220	0.60	0.76	0.77	0.23	0.54	0.59	0.51
06221	0.11	0.23	– 0.04	– 0.51	– 0.31	– 0.26	– 0.64
08201			– 0.16	– 0.69	– 0.49	– 0.33	– 0.73
08202			– 0.16	– 0.51	– 0.34	– 0.17	– 0.44

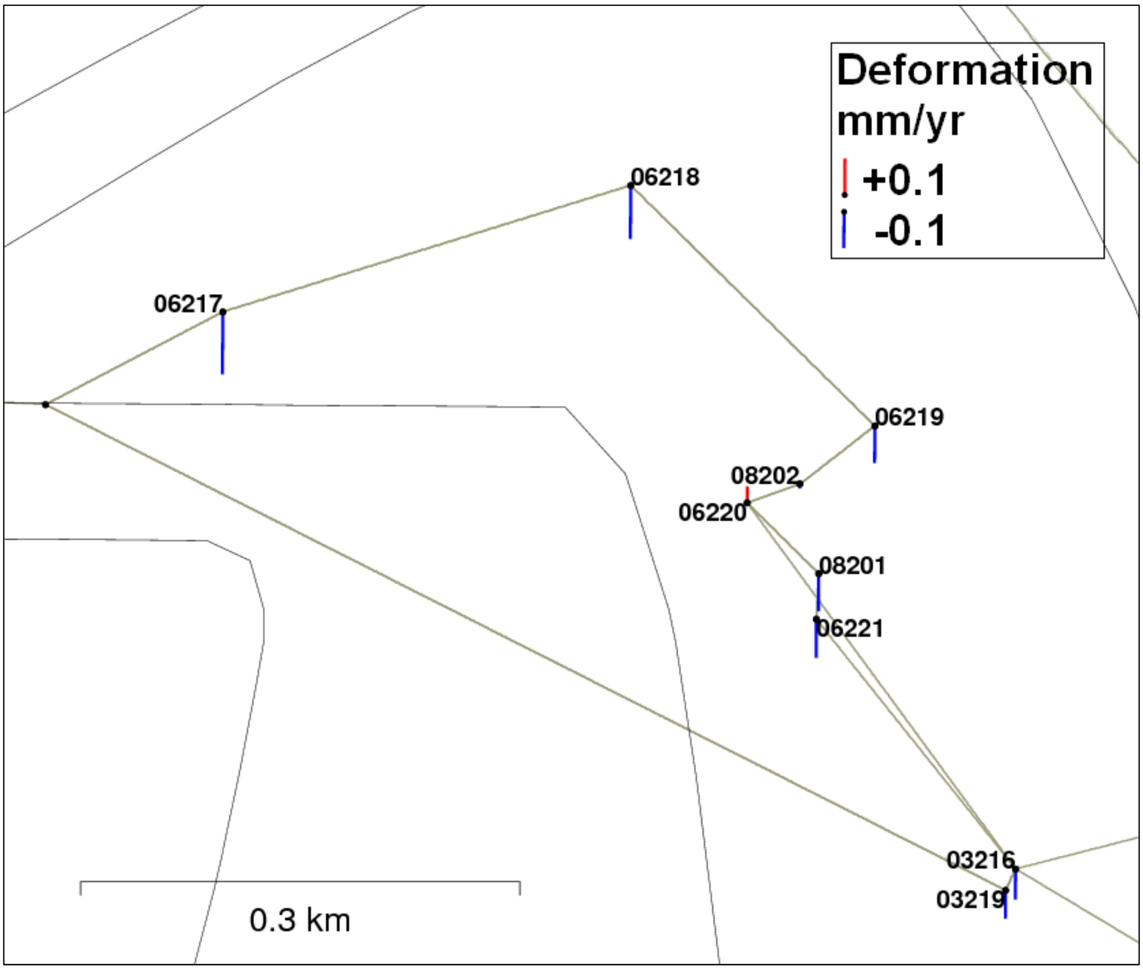

Figure 8. *Benchmarks in the loop ONKALO and their deformation relative to the mean deformation of the levelling network (Saaranen et al., 2014).*

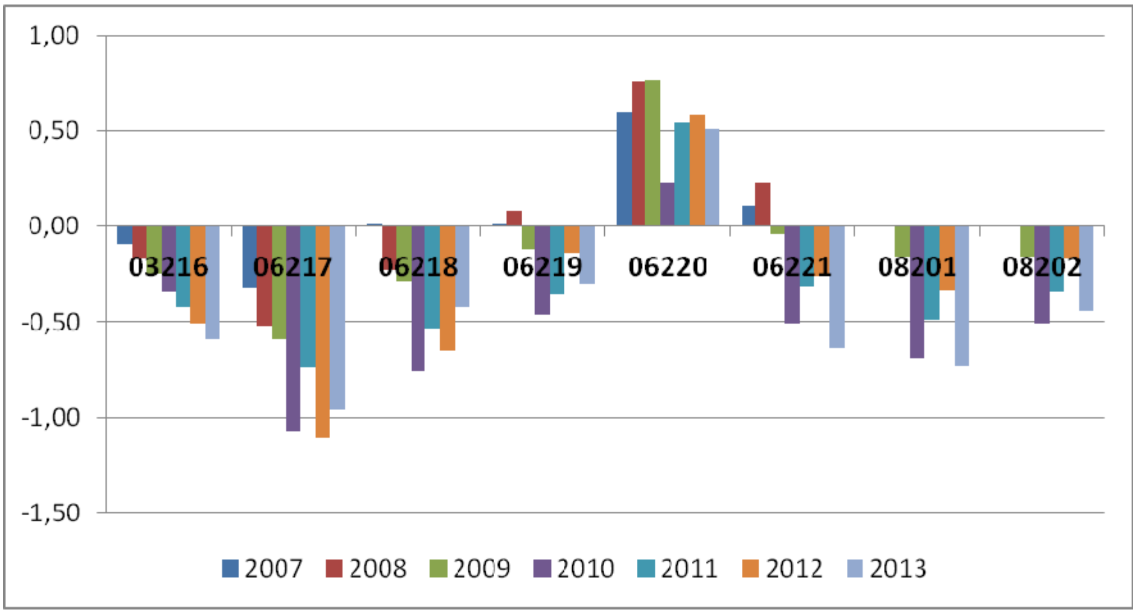

Figure 9. *The visualization of the deformation in the ONKALO loop relative to the average deformation of the Olkiluoto research area (in millimetres).*

6.4 Micro Loop VLJ

In the VLJ loop (Figure 10), the most active deformation is related to the control benchmarks of GPS9 (Tables 15 and 16, and Figure 11). This movement does not have any systematic behaviour. The deformation is like the other benchmarks, except for BM 06213. It is interesting, that BM 06213 has a linear subsidence deformation relative to the other benchmarks in the VLJ loop. This linear subsidence continues in the observations of 2012 and especially of 2013.

From 2011 to 2012, BM GPS9A (– 0.64 mm) and BM GPS9B (– 0.56 mm) had significant height change. The deformation of the benchmark intervals 06213– GPS9(A,B) are at the top of the significant deformation list (Table 15). The other benchmarks of the VLJ loop had deformation within ± 0.06 mm.

From 2012 to 2013, both GPS9A (+ 0.26 mm) and GPS9B (+ 0.18 mm) rebounded, so that deformation from 2011 to 2013 is – 0.38 mm for the both benchmarks. This is typical behaviour for those benchmarks. Their relative motion is small. The other benchmarks have deformation within ± 0.11 mm, from 2011 to 2013.

Table 15. *The most significant benchmark interval deformations in the loop VLJ.*

	BM (from)	BM (to)	Significancy S_τ	Deformation [mm]	Distance [km]	Year	Year
1	GPS9A	06213	7.2	0.64	0.085	2011	2012
2	GPS9B	06213	6.0	0.56	0.093	2011	2012
3	06216	GPS9B	5.9	– 0.82	0.282	2006	2012
4	GPS9A	06213	4.8	0.34	0.085	2009	2012
5	06216	GPS9A	4.7	– 0.81	0.437	2006	2012
6	GPS9A	06213	4.6	– 0.38	0.085	2008	2013
7	GPS9B	06213	3.9	0.31	0.093	2006	2012
8	GPS9A	06213	3.9	0.30	0.085	2006	2012
9	GPS9A	06213	3.8	– 0.36	0.085	2012	2013
10	GPS9B	06213	3.8	0.28	0.093	2009	2012
11	06216	GPS9B	3.8	– 0.62	0.282	2011	2012
12	GPS9A	06213	3.6	– 0.39	0.085	2010	2013
13	06216	GPS9A	3.5	– 0.70	0.437	2011	2012
14	06213	06214	3.4	0.40	0.146	2006	2013
15	GPS9A	06213	3.3	– 0.33	0.085	2007	2013
16	GPS9B	06213	3.2	– 0.34	0.093	2007	2013
17	06216	GPS9B	3.2	– 0.53	0.282	2006	2013
18	06216	GPS9B	3.1	– 0.39	0.282	2008	2012
19	GPS9B	06213	3.0	– 0.26	0.093	2008	2013
20	06213	06214	3.0	0.30	0.146	2006	2012

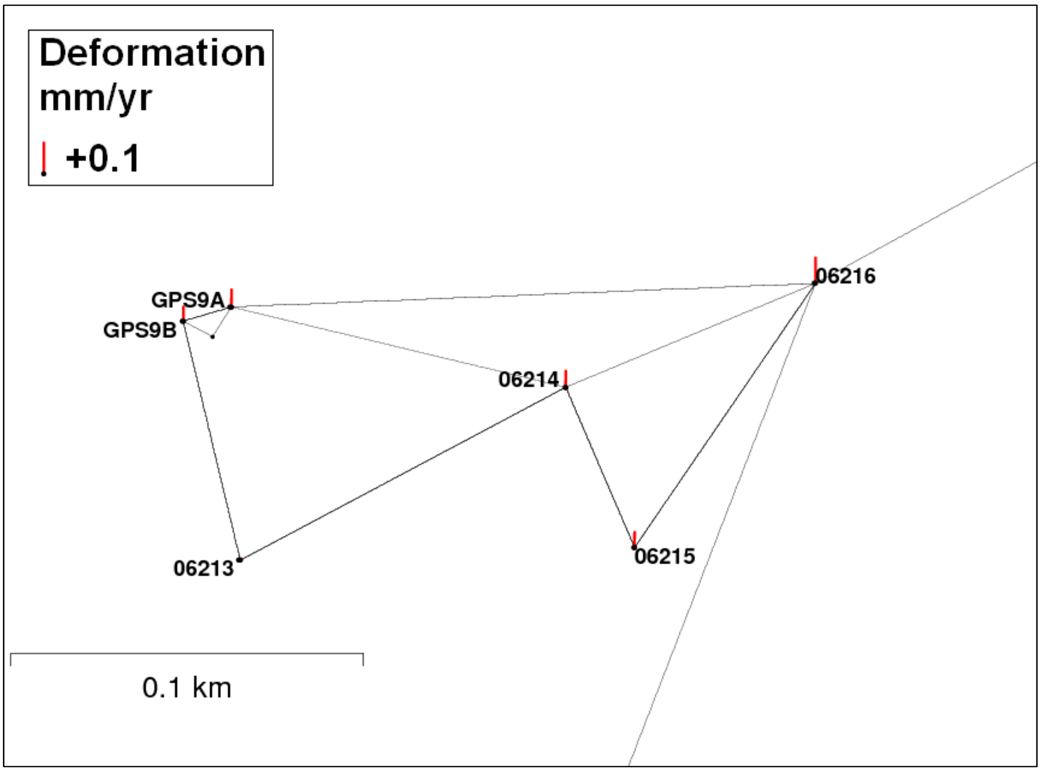

Figure 10. *The benchmarks in the Loop VLJ and their deformation rate (Saaranen et al., 2014).*

Table 16. *Deformation in the VLJ loop relative to the year 2006, and the fixed BM 06214 (in millimetres).*

	2007	2008	2009	2010	2011	2012	2013
06213	– 0.14	– 0.15	– 0.23	– 0.17	– 0.30	– 0.30	– 0.40
06215	– 0.10	– 0.19	– 0.04	– 0.13	– 0.02	– 0.05	0.09
06216	0.05	– 0.01	0.18	0.13	0.15	0.21	0.10
GPS9A	– 0.41	– 0.47	– 0.19	– 0.50	0.04	– 0.60	– 0.34
GPS9B	– 0.51	– 0.44	– 0.26	– 0.45	– 0.05	– 0.61	– 0.43

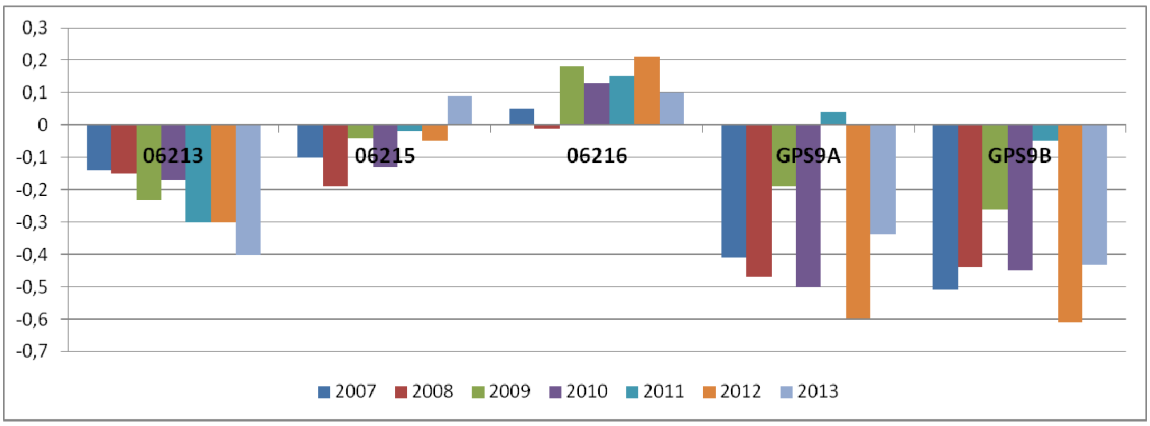

Figure 11. *The visualisation of the deformation in the VLJ loop relative to the year 2006, and the fixed BM 06214 (in millimetres).*

6.5 Other benchmarks

In this section, the deformation of BM GPS7 and the new benchmarks is presented. In 2010, a new BM 10301 was established. The deformation of the benchmark is presented in Table 17. When we analyse the deformation of BM 10301 relative to the whole network, we correct yearly deformation rate of BM 03216. From the ONKALO analysis, we can notice that BM 03216 had a peak value in 2010, which seems to be about 0.2 mm. So, we study deformation relative to the year 2011. The largest difference was in 2010.

In 2013, the stability of the GPS pillar GPS7 was controlled. Height difference change, from 2011 to 2013, between the GPS7 antenna platform and the control benchmarks GPS7A and GPS7B, is – 0.17 mm (Table 18). During the observation, a small one-metre-long rod is placed on a bolt fastened on the GPS antenna platform. One assistant has a three-metre rod on a control benchmark, as in an ordinary levelling, and another assistant is standing on a ladder.

In 2011, new GPS stations GPS16, GPS17, GPS18 and GPS19 were established (Figures 1 and 12). Deformation from 2011 to 2013, is presented in Tables 19 and 20. The deformations of the stations are not significant.

These GPS pillars have four control benchmarks: “A”, “B”, “C” are on bedrock and “N” is a part of a pillar. The height of the contol benchmark GPS16N has changed one millimetre relative to other control benchmarks of GPS16. It is possible, that GPS16N has been damaged somehow.

Table 17*. Deformation of BM 10301 relative to the year 2011 (in millimetres).*

Year	Height difference	Deformation relative to BM 03216	Deformation relative to the whole network
2010	1309.83	– 0.37	– 0.28
2011	1310.20	+ 0.00	+ 0.00
2012	1310.10	– 0.10	– 0.19
2013	1310.41	+ 0.21	+ 0.04

Table 18*. Average height diffrence from the control benchmarks GPS7A and GPS7B to the GPS7 antenna platform level, in 2011 and 2013, measured to the bolt “A” on the antenna platform level. The height difference includes the height of the bolt “A” 19.91 mm.*

From	To	Year	Height difference (mm)
GPS7A and GPS7B	GPS7 antenna platform	2011	+ 2311.11
GPS7A and GPS7B	GPS7 antenna platform	2013	+ 2310.94
Deformation from 2011 to 2013 (mm)			– 0.17

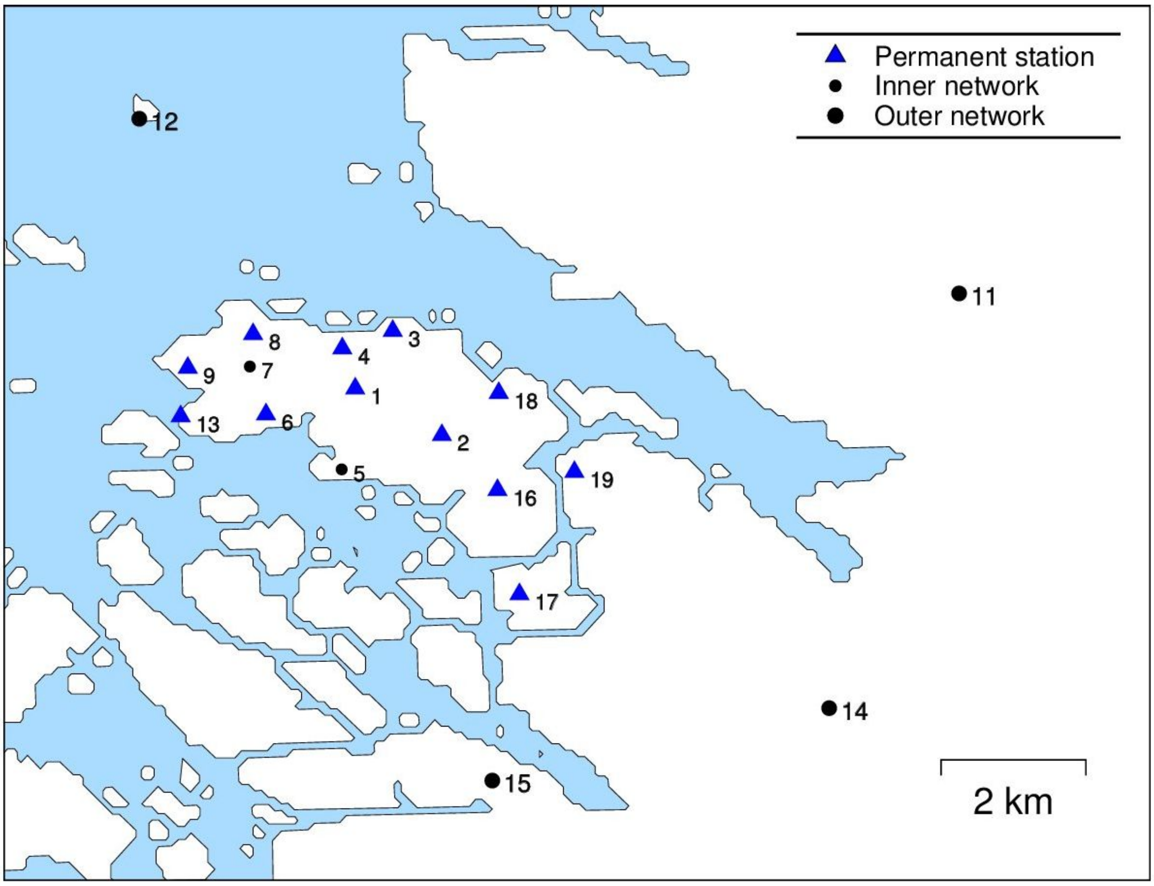

Figure 12. *The locations of the GPS stations. The deformation results, which were based on the GPS observations, were presented in Nyberg et al. (2013). Picture: S. Nyberg.*

Table 19. *The deformation of control benchmarks of the GPS stations GPS16, GPS17 and GPS19, relative to BM 03208, from 2011 to 2013.*

BM	Observation from BM 03208, in 2011	Observation from BM 03208, in 2013	Deformation 2011– 2013 (mm)
GPS16A	– 3958.04	– 3957.48	0.56
GPS16B	– 3493.68	– 3493.01	0.67
GPS16C	– 3802.25	– 3801.61	0.64
GPS16N	– 3224.21	– 3224.63	– 0.42
GPS17A	6431.91	6432.09	0.18
GPS17B	5921.31	5921.59	0.28
GPS17C	5656.83	5657.05	0.22
GPS17N	6969.36	6969.49	0.13
GPS19A	279.06	279.43	0.37
GPS19B	702.21	702.50	0.29
GPS19C	269.66	269.93	0.27
GPS19N	1249.24	1249.63	0.39

Table 20. *The deformation of control benchmarks of the GPS station GPS18, relative to BM 03216, from 2011 to 2013.*

BM	**Observation from BM 03216, in 2011**	**Observation from BM 03216, in 2013**	**Deformation 2011– 2013 (mm)**
GPS18A	317.31	317.10	– 0.21
GPS18B	54.43	54.42	– 0.01
GPS18C	375.97	375.87	– 0.10
GPS18N	1286.37	1286.30	– 0.07

The errors due to a special extra bolt on an antenna platform, and a zero error of a rod were corrected before the analysis. The levelling was focused on a bolt on an antenna platform. To obtain the height of the antenna platform, the height of the bolt has to be reduced from the levelling results. In 2013, the bolt "A" was used, and its height was 19.91 mm. A levelling rod can have so called zero point error. It has been eliminated using the same rod on a benchmark at the starting and ending benchmarks. In the GPS platform measurements we use different rods, so the zero point error has to be corrected.

SUMMARY

The precise levellings in Olkiluoto were started in autumn 2003. Deformation results have been reported every second year. In this report observations and new deformation results are presented from 2012-2013.

Observation data includes the measurements of GPS network and the micro loops ONKALO and VLJ. The deformation in the Olkiluoto area was analysed using a kinematic deformation solution and heights which had been computed relative to the mean deformation of the area. Using the height difference changes of the benchmark intervals, the probable levelling fault lines were sought.

The analysis shows that the bedrock over the Olkiluoto strait is stable. The height changes from 2011 to 2012 were within ± 0.1 mm, and from 2012 to 2013, the largest difference was only – 0.19 mm.

In the GPS station loop, in 2011-2013, the height of GPS3 changed + 0.69 mm. After this deformation, it is only benchmark, which height has changed more than one millimetre from the year 2003.

In the ONKALO loop, BM 06220 has an unique deformation, but during the last years it has been stable. Since 2011, deformation of BM 06220 has been within ± 0.1 mm. The largest height change from 2011 to 2012, was at BM 06217 (– 0.37 mm), and from 2012 to 2013 at BM 08201 (– 0.40 mm).

In the VLJ loop, the most active deformation is related to the control benchmarks GPS9A and GPS9B. Their mean deformation was – 0.60 mm, from 2011 to 2012. After that they rebounded, so that deformation from 2011 to 2013 is – 0.38 mm. The other benchmarks have deformation within ± 0.11, from 2011 to 2013.

During the levelling campaigns, in 2003-2013, some deformations were found, but their nature seems to be local, and not continuing many years. In the beginning, the strait was the most active area. According to the latest observations, bedrock in the Olkiluoto strait area, and the VLJ loop area outside GPS9, are stable. ONKALO area has larger differences, but changes are less than 0.5 mm. New remarkable deformations were not found, in 2012-2013, except the height change of the contol benchmark GPS16N, which was one millimetre lower, relative to the other control benchmarks of GPS16, than it was in the previous measurement in 2011. It is most likely, that the change is due to a damage rather than a large local deformation.

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LIST OF APPENDICES