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GPS monitoring of bedrock stability at Olkiluoto nuclear waste disposal site in Finland from 1996 to 2012

Research Article

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Abstract:
The Finnish Geodetic Institute has studied crustal deformations at Olkiluoto nuclear waste disposal site since mid-90's. Biannual GPS measurement has been carried out in two local GPS networks. This paper analyses the GPS data processing effects on the coordinate solutions and presents the results of GPS monitoring from 1996 to 2012. The GPS data was processed using Bernese GPS Software 5.0. The GPS data processing and baseline analysis showed a 1.0 mm (max RMS) level agreement of observation and high bedrock stability in the area. Most of the horizontal trends were smaller than 0.1 mm/a. The troposphere estimation strategy had a clear effect on the horizontal trends at some sites. The strain rates were all very small, but we could detect motions near the Olkiluoto permanent station.

Keywords:
Crustal deformation • GPS • Local network.

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1. Introduction

Bedrock stability is one of the key requirements for the site of final disposal of spent nuclear fuel set by International Association of Atomic Energy (IAEA, 2006). Posiva Oy (an expert organisation responsible for the final disposal of spent nuclear fuel) is preparing a disposal facility, called ONKALO, deep in the bedrock of Olkiluoto Island located on the southwest coast of Finland in the Gulf of Bothnia. ONKALO has been under construction since 2004. The Finnish Geodetic Institute (FGI) has carried out research on crustal deformation (tectonic movements and isostatic uplift) at Olkiluoto, which is a part of a specific Olkiluoto monitoring programme (Posiva, 2012). These studies belong to the Rock mechanics section of monitoring programme.

The FGI started GPS monitoring in 1996, when local high-precision networks were established and biannual GPS measurement started at three candidate sites. The Olkiluoto area was selected for the final disposal site in 2001, and the research was concentrated to the area. Later the area of GPS monitoring network was expanded to mainland and electronic distance measurements between two GPS pillars were started to control the absolute accuracy and scale of GPS solutions.

The GPS time series over 15 years enable detailed research on local crustal deformations at Olkiluoto. Most of the GPS deformation studies are focused on estimating the deformation parameters (e.g. Cai et al. 2008, Stanionis 2005) and the GPS data processing is done routinely. At Olkiluoto, the expected displacements are very small (<1 mm/a) and therefore, the GPS processing parameters, e.g., choice of carrier phase frequency, ambiguity resolution method and atmospheric modelling, plays a significant role. Especially tropospheric modelling is an important element, which diminishes the accuracy of GNSS measurements and causes systematic biases (Rothacher, 2002). Site-specific limitations, like lack of low elevation data, make the modelling even more ambiguous. General principles for local networks are given in Dach et al. (2007), but their applicability for each case study needs to be verified. For

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example, Wielgosz et al. (2011) studied the tropospheric modelling for local GPS networks and recommended not estimating tropospheric delays at all unlike stated in Dach et al. (2007).
This paper concentrates on the analysis of the GPS time series and presents the results of the monitoring from 1996 to 2012. The effects of different processing parameters are analysed using tools in Bernese 5.0 in order to validate the solution. In addition, strains along the baselines are estimated.

2. Networks and observations

Biannual GPS measurement has been carried out in two local GPS networks (Fig. 1). The aim of the inner network is to monitor deformation on Olkiluoto island area, whereas the outer network monitors the changes between the mainland and the island. The inner network, established in 1994, consists of ten pillar points. Only one pillar has been destroyed up to now, and it was replaced in 2003. The outer network, established in 2003-2005, consist of four pillars. The baseline lengths range from 0.5 km to 2 km in inner network and from 5 km to 10 km in outer network.

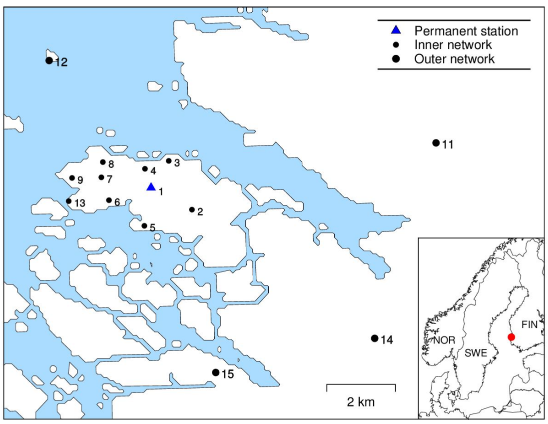

Figure 1. GPS observation sites at Olkiluoto.

The GPS pillars were made of reinforced concrete on-site (Fig. 2). All the pillars were attached to the solid bedrock with iron bars. An antenna platform was installed on the top of the pillar at the same time the pillar was casted. The antenna is directly attached to the platform without any interface or forced centring device, thus its height and position is preserved between campaigns. We expect the pillars are stable and the possible movements we observe are due to deformation. Two auxiliary markers have also been established at pillars in 2001 to control the stability of the pillars using tacheometer observations every third year.
The Ashtech Z12 and μZ (until 2009.5) and Leica GX1230 series (2009.5 forwards) dual frequency receivers and Ashtech Dorne Margolin Choke Ring antennas have been used. A total of 32 and 19 campaigns have been carried out in inner and outer network, respectively. The point 12 has not been measured every time due to the weather conditions during campaigns. The same antenna

Figure 2. An example of a pillar point during a measurement campaign.

has been set up on the same pillar every time expect the first three years in order to eliminate the individual antenna phase centre errors. In addition, the antennas have been individually calibrated by Geo++ in 2010. The measurements have been carried out in 24 hour long observation sessions (except the first campaigns before 2000). The campaigns have also been timed approximately at the same time every year to minimize any seasonal effects. The inner network has been observed in two sessions and the outer network in a separate session due to limited number of antennas. Thus, the networks are connected only via Olkiluoto permanent station (pillar 1).

3. GPS data processing

The GPS data processing was carried out using Bernese GPS software Version 5.0 (`http://www.bernese.unibe.ch/`). The inner and outer networks were computed and analysed separately, because they are connected only via Olkiluoto permanent station and measured in different sessions.
The IGS re-processed satellite orbits and earth rotation parameters were used, which are all aligned to IGS05 reference frame and which are available until the end of the year 2007. Thus, there is no offset due to reference frame change except the most recent one (from IGS05 to IGS08). The reprocessed orbits provide also better quality for the years before 2000 (Steigenberger et al. 2008).
An independet set of baselines were selected using star method, where the Olkiluoto permanent station was as a star node. In this way the number of common observations were maximised. A double-difference phase residual screening was carried out before the parameter estimation. The threshold for a normalized zenith residual was set to 4 mm.

The ambiguity resolution of L1 and L2 ambiguities was studied using two algorithms: SIGMA, which is commonly used for short baselines and QIF, which is used for long observation times (24h) (Dach et al. 2007). Almost all ambiguities were resolved using SIGMA algorithm (98 % on average), whereas the resolution percentage remained at about 80 % in QIF. Thus, the ambiguities were resolved using SIGMA algorithm for both inner and outer networks. The inner network with very short baselines was computed using L1 observables together with local ionosphere models created by Bernese IONEST program. The Olkiluoto permanent station data was used for ionosphere modelling and 4-hour time interval applied. The mean of zero degree TEC parameters are shown in (Fig. 3). The solar cycle peak at 2002 is obvious as well as the current ascending trend. The outer network with longer baselines was computed using L3.

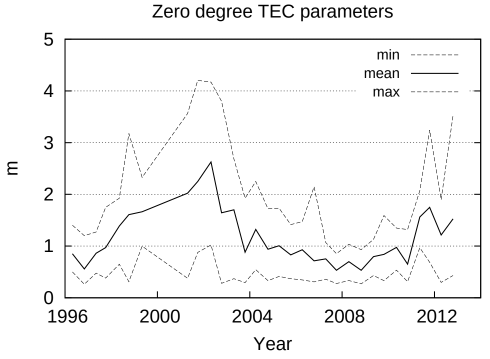

Figure 3. Zero degree TEC parameters of local ionosphere models.

The troposphere modelling was based on Saastamoinen apriori model mapped with Dry Niell mapping function. Zenith path delay parameters were estimated using Wet Niell mapping function at 1-hour intervals for individual sites relative to Olkiluoto permanent station. At low elevation angles the azimuthal asymmetry of the local troposphere at observation sites becomes an important error source and is commonly accounted for by estimating horizontal tropospheric gradients (Meindl et al. 2004). However, in the case of a small-area network, the effect of estimation horizontal gradients needs to be studied more closely to avoid unrealistic trends or systematic biases.

The data set was processed in two ways. In the first approach (referred as grad), the gradients were estimated using the Tilting model of Bernese software at 24-hour interval (Dach et al. 2007). The model takes into account the tilting of the tropospheric mapping function. In the second approach (referred as nograd), the gradients were not estimated.

The differences between linear trends of station NEU-coordinates time series were checked, as the trends of time series are the main output for further analysis. The largest difference in north and east trends were 0.19 mm/a and 0.12 mm/a, respectively, for the site 2 (Fig. 4). The mean differences were 0.10 mm/a and 0.06 mm/a in north and east, and the minimum differences 0.01 mm/a and 0.03 mm/a, respectively. The results showed that the estimation of horizontal gradients has an effect of maximum 0.2 mm/a on horizontal trends that gives a more realistic insight into the uncertainty level of the estimated trends. However, we cannot conclude about the best approach based only on these differences.

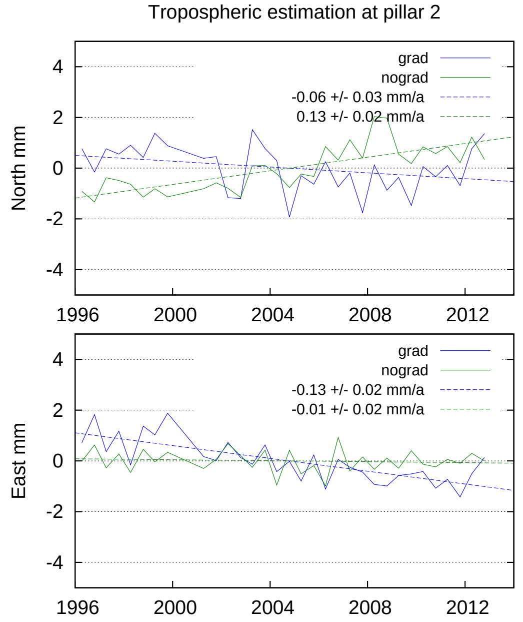

Figure 4. An effect of tropospheric gradient estimation at pillar 2. Blue lines correspond to the coordinate solution with gradient estimated and green lines without gradient estimation.

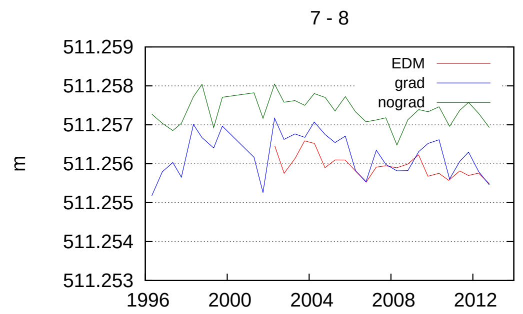

Figure 5. Comparison of EDM and GPS estimates of baseline length between sites 7 and 8

The GPS solutions were also compared to the time series of high-precision EDM measurement performed simultaneously with GPS observations from 2002 to 2012. EDM measurements took place between sites 7 and 8 using calibrated Kern Mekometer ME5000. The EDM measurements are metrologically traceable to the definition of the metre. The total uncertainty of EDM baseline in

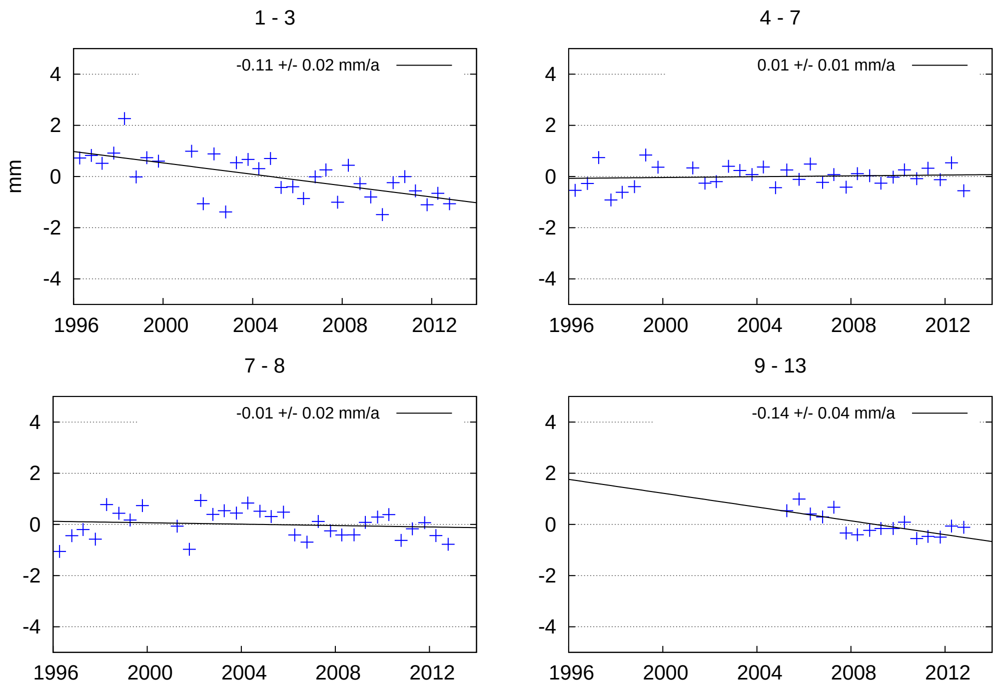

Figure 6. Deviation of baseline length time series for the inner network.

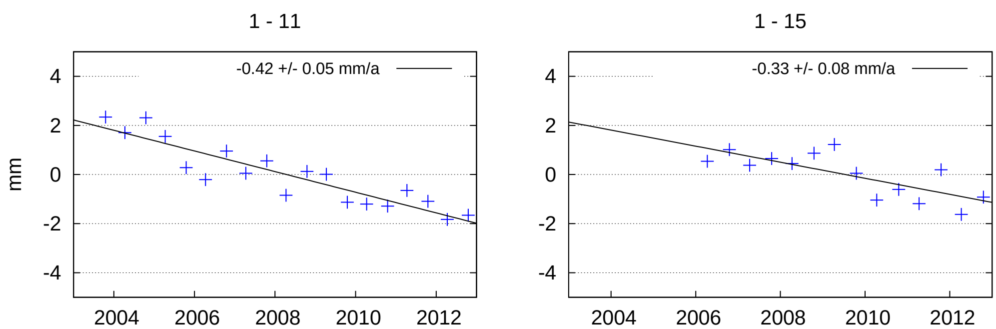

Figure 7. Deviation of baseline length time series for the outer network.

the traceability chain using internationally recommended methods, such as GUM (BIPM JCGM, 2008) was roughly 0.2 mm. In GPS measurements there is no comparable traceability or single recommended processing method for observations. Therefore we regard the results from EDM as true values. The comparison between grad and nograd GPS results showed a 1.1 mm systematic difference between themselves (Fig. 5). The solutions shifted on average 0.37 mm (grad) and 1.42 mm (nograd) from EDM estimate. Therefore, the solution with gradient estimation was selected as the final solution.

The ITRF2008 coordinates were estimated to the Olkiluoto permanent station and the datum was defined by tightly constraining Olkiluoto permanent station (pillar 1) to its ITRF2008 coordinates in the epoch of the measurement campaign. The observations were computed on a daily basis, and daily normal equations were stacked into a session solution.The final network solution rms was 1.9 mm for inner network and 1.1 mm for outer network.

4. Analysis of baseline strains

The deformation analysis was carried out by estimating changes along the baselines. The baseline lengths of all pillar pairs were computed and linear trends fitted. In addition, the strain rates along the baselines were computed by dividing the change rate by the baseline length. The baseline length time series showed a good agreement of the observations carried out over 15 years (Fig. 6 and 7). The RMS of residuals of the baselines length time series varied from 0.2 to 0.9 mm.

Most of the baselines showed very small motions: 80 % of trends were smaller than 0.10 mm/a. Roughly one fourth of the change rates could be considered as statistically significant at 1% significance level. The estimated strains along baselines are illustrated in Fig. 8 and 9 for inner and outer networks. The inner network pattern (Fig. 8) is dominated by the largest strain between pillars 9 and 13 (−0.24 ppm/a). The time series of 13 is half the length of other sites and the uncertainty of the baseline velocity estimate and related strain is therefore larger. On the other hand, the tropospheric gradient estimation had a relatively large effect (0.16 mm/a) on the northwards trend of the pillar 9. As the baseline is almost north-south directional, propagates the uncertainty of the baseline velocity to the baseline length strains fairly straight.

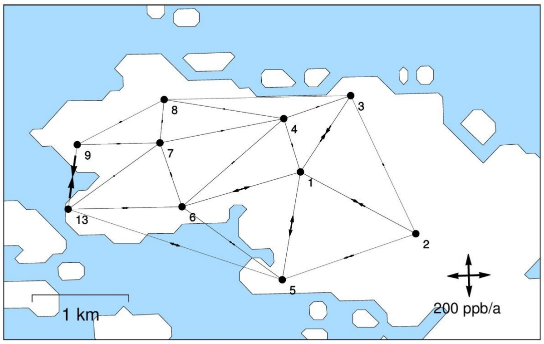

Figure 8. Strains along baselines in the inner network.

Both the inner and outer network strains show a small south-eastwards motion of the pillar 1. The estimated strains for inner network baselines 1–2 and 1–3 were −0.08 ppm/a and −0.11 ppm/a, respectively. In the case of the outer network, slightly smaller strains were estimated for baselines east of site 1 (−0.04/−0.07 ppm/a). As the strain was observed both in inner and outer network stations, we may conclude that the pillar 1 is slowly moving south-eastwards.

5. Conclusions

The 15 years GPS monitoring in the Olkiluoto area has shown high bedrock stability in the area. Since the first measurements the field work has been carried out in a consistent manner, which enabled the use of the full time series for the deformation analysis: a total of 32 measurement campaigns in inner network and 19 in outer network.

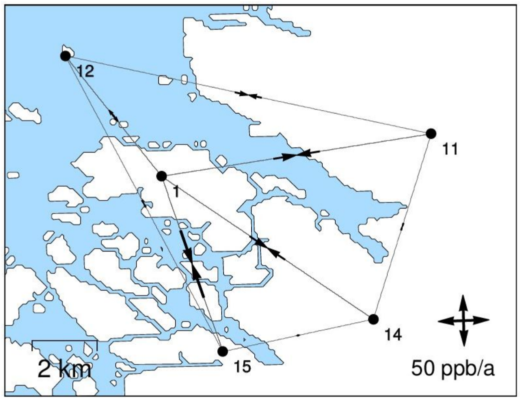

Figure 9. Strains along baselines in the outer network.

As the motions and strains are very small, the GPS processing strategy and parameters have a crucial role when analysing the deformations. The GPS processing tests showed that millimetre level differences may easily come up depending on the minor modifications of the processing parameters. Especially the use of the troposphere horizontal gradients in the case of small-area high-precision networks has to be studied further. The results showed that the estimation of troposphere horizontal gradients affects up to 0.2 mm/a horizontally to station trends.

GPS baseline analysis showed a 1.0 mm (max RMS) level consistency of baseline lengths. The strain rates were all very small, but we could detect small motion related to the OLKI permanent station (pillar 1). The motion can be either real (due to actual motion) or spurious (due to mismodelled GPS observation data). The largest strain observed between pillars 9 and 13 is probably affected by short time series of pillar 13 and the tropospheric modelling effects. The permanent observations at all sites will be essential to verify the change rates and strains.

The Olkiluoto research is mainly motivated by the long-term safety of nuclear waste disposal, but the high quality data (GPS, EDM and levelling) also enables scientific research on how to treat a small-area high-precision deformation network. The research will continue with the comparisons of different data sets (levelling, EDM) and later with the permanent time series.

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