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Local Seismic Network at the Olkiluoto Site Annual Report for 2007

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ABSTRACT

In February 2002, Posiva Oy established a local seismic network of six stations on the island of Olkiluoto. Later, in June 2004, the seismic network was expanded with two new seismic stations. At that time started the excavation of the underground characterisation facility (the ONKALO) and the basic operation procedure was changed more suitable for the demands of the new situation.

In the beginning of 2006, the target area of the seismic monitoring expanded to semi-regional scale. Four new seismic stations started in the beginning of February 2006 and the focus of interpretation was expanded to an area, called the *seismic semi-regional area*. At the end of 2006, two new borehole geophones were installed in order to improve the sensitivity and the depth resolution of the measurements inside the ONKALO block.

The purpose of the microearthquake measurements at Olkiluoto is to improve understanding of the structure, behaviour and long term stability of the bedrock. The studies include both tectonic and excavation-induced microearthquakes. An additional task of monitoring is related to safeguarding of the ONKALO.

This report gives the results of microseismic monitoring during the year 2007. Also the changes in the structure and the operation procedure of the network are described. The true orientation of the borehole sensor OL-OS13 was calculated. The correct orientation of triaxial seismometer is essential when the fault plane solution of an earthquake is calculated. The other borehole sensor OL-OS14 was permanently disconnected in October 2007.

The network has operated continuously in 2007. Altogether 2207 events have been located in the Olkiluoto area, in reported time period. Altogether 2207 events have been located in 2007. Most of them (1912) are explosions occurred inside the seismic semi-regional area and especially inside the ONKALO block (1891 events). The magnitudes of the observed events inside the semi-regional area range from ML = -2.1 to ML = 1.5 (ML = magnitude in local Richter's scale). All these events are explosions.

According to seismic monitoring the rockmass surrounding the ONKALO has been stable in 2007. One of the recorded events was a local microearthquake (M_L = 1.9) outside the target area of the network. That earthquake occurred 3.1.2007 in Laitila about 40 km from Olkiluoto. Joint interpretation of recordings of three seismic networks (Posiva, Finnish and Swedish national networks) was used when the preliminary fault plane solution of the Laitila earthquake was calculated: The reverse faulting occurred in a nearly vertical N-S oriented fault, which can be associated with mafic dykes in the area.The orientation of the compressional axis related to the microearthquake on (NW-SE) is consistent with the estimated maximum in-situ stress field in Olkiluoto and elsewhere in Finland.

Keywords: seismic network, microearthquake, monitoring, interpretation, safety, safeguards, stress field, fault plane

Olkiluodon seisminen asemaverkko. Vuosiraportti 2007.

TIIVISTELMÄ

Posiva Oy:n Olkiluodon paikallisella seismisellä asemaverkolla aloitettiin mittaukset vuoden 2002 helmikuussa. Aluksi asemaverkko koostui kuudesta seismisestä asemasta. Myöhemmin, kesäkuussa 2004, asemaverkkoa laajennettiin kahdella uudella asemalla. Niihin aikoihin aloitettiin maanalaisen tutkimustilan (ONKALO) rakennustyöt ja samalla asemaverkon toimintaperiaatetta muutettiin uuteen tilanteeseen paremmin soveltuvaksi.

Monitoroinnin kohdealuetta laajennettiin Olkiluodon lähiympäristöön kun neljä uutta seismistä asemaa aloitti toimintansa helmikuun alussa vuonna 2006. Samalla monitoroinnin kohdealuetta laajennettiin kattamaan ns. *seisminen semi-alueellinen alue*. Vuoden lopussa asennettiin vielä kaksi uutta porareikägeofonia. Niiden avulla pyritään parantamaan mittausten herkkyyttä ja seismisten tapausten laskettujen syvyyksien tarkkuutta ONKALOn alueella.

Mikromaanjäristysmittausten avulla pyritään lisäämään tietoa Olkiluodon kallioperän rakenteesta, liikkeistä ja stabiilisuudesta. Tutkimuksen kohteena ovat tektoniset ja louhinnan indusoimat mikromaanjäristykset. Mittaukset ovat myös osa ONKALOn ydinsulkuvalvontaa.

Tässä raportissa esitetään seismisen monitoroinnin tulokset vuodelta 2007. Raportissa kuvataan myös asemaverkon rakenteessa ja toimintaperiaatteissa tehdyt muutokset. Porareikäanturin OL-OS13 todellinen asento laskettiin vuoden 2007 aikana. Tieto on välttämätön, jos anturia halutaan käyttää siirrostasoratkaisun laskennassa. Toinen porareikäanturi OL-OS14 poistettiin asemaverkosta laitevian takia.

Asemaverkko monitoroi ilman toimintakatkoksia vuonna 2007. Olkiluodon alueelle paikallistettiin raportoidulla ajalla yhteensä 2207 tapausta. Suurin osa näistä (1912) oli seismisen semi-alueen alueella ja erityisesti ONKALO (1891 tapausta) alueella. Havaittujen tapausten magnitudit (ML) olivat välillä -2.1 – 1.5. Nämä kaikki olivat räjäytyksiä. Alueella ei ole havaittu ydinsulkuvalvonnan kannalta turvallisuuteen vaikuttavaa toimintaa.

Seismiset mittaukset osoittavat että ONKALOa ympäröivä kalliomassa on pysynyt stabiilina vuonna 2007. Asemaverkon kohdealueen ulkopuolelta rekisteröitiin yksi paikallinen mikromaanjäristys (M_L = 1.9). Se tapahtui 3.1.2007 Laitilassa, noin 40 km päässä Olkiluodosta. Maanjäristykselle tehtiin tulkinta, jossa käytettiin kolmen eri asemaverkon (Posiva sekä Suomen ja Ruotsin kansalliset asemaverkot) rekisteröintejä. Tulkinnan mukaan siirroksen mekanismi oli käänteissiirros joka tapahtui lähes pystysuorassa pohjois-etelä-suuntaisessa ruhjeessa. Järistys näyttäisi liittyvän alueen mafisiin juoniin. Laitilan mikromaanjäristykseen liittyvän puristusjännitysten suunta (NW-SE) on yhteensopiva Olkiluodossa ja muualla Suomessa tehtyjen jännitystilahavaintojen kanssa.

Avainsanat: Seisminen asemaverkko, mikromaanjäristys, monitorointi, tulkinta, turvallisuus, ydinsulkuvalvonta, jännityskenttä, siirrostaso

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1 INTRODUCTION

According to the Nuclear Energy Act, all nuclear waste generated in Finland must be handled, stored and permanently disposed in Finland. The two nuclear power companies, Teollisuuden Voima Oy (TVO) and Fortum Power and Heat Oy, are responsible for the safe management of the waste and for all associated expenses. These companies have established a joint company, Posiva Oy, to implement the disposal programme for spent fuel. Seismic monitoring is a part of this programme (Miller *et al*, 2002, Posiva 2003b and Posiva 2006). Possible applications of microearthquake monitoring at the repository are introduced in the Posiva's working report (Saari 1999).

In February 2002, Posiva Oy established a local seismic network of six stations on the island of Olkiluoto. The system is manufactured and installed by ISS International Limited (http://www.issi.co.za). This network was designed for monitoring the rock volume surrounding the preliminary location of the underground characterisation facility (the ONKALO). Later, in June 2004, the seismic network was expanded with two new seismic stations (OL-OS7 and OL-OS8). These stations made the network geometry more suitable for monitoring the final location of the ONKALO.

The technical features of the microearthquake monitoring system are described in details in the Posiva's working reports (Saari 2003 and Saari 2005). During the year 2005, the configuration of the seismic network has remained the same (Saari 2006).

In the beginning of 2006, the target area of the seismic monitoring expanded to regional scale. Installation works of the four new seismic stations (OL-OS9…OL-OS12) started on 30.1.2006 and the stations were in operation on 2.2.2006. The stations are equipped with three component 1 Hz geophones, which are suitable for investigations of regional tectonic seismicity. The new seismic stations locate from 3 to 7 km from the ONKALO.

At the end of 2006, two new triaxial geophones (OL-OS13 and OL-OS14) were installed into a borehole inside the ONKALO spiral. The new geophones aimed to improve the sensitivity and the depth resolution of the measurements inside the ONKALO block. They were fully integrated to the Posiva's network in 2007. Cable isolation of OL-OS14 was damaged during the installation and later were corrupted in 2007 the electric wires were corrupted. The sensor was permanently disconnected from the network in October 2007. The true orientation of the triaxial sensor OL-OS13 was determined in 2007.

The main target volume of the seismic monitoring is the underground rock characterisation facility and the rockmass surrounding it. According to the simulation done by ISS International Limited, the expected sensitivity near the ONKALO is of the order ML = -2.5. This simulation includes also the new borehole sensors. The regional sensitivity of the Olkiluoto area is approximately of the order of ML=-1.0 inside the Posiva's regional network.

In the beginning, the network monitored tectonic earthquakes in order to characterise the undisturbed baseline of seismicity of the Olkiluoto bedrock. When the excavation of the ONKALO started, in August 2004, the network monitors also excavation induced seismicity. Since February 2006 explosions and tectonic earthquakes are monitored in regional scale. This report describes the operation and results of the local seismic network in 2007.

The purpose of the microearthquake measurements at Olkiluoto is to improve understanding of the structure, behaviour and long term stability of the bedrock. The observations give an opportunity to approximate in what extent and where the bedrock is disturbed, the stability of the rock facility and the adjustment processes occurring in the surrounding rock mass. A further task is mapping of the disturbed weakness zones in the rockmass surrounding the excavated construction.

Identification of active fracture zones is an essential element in a comprehensive study of potential hazards related to the spent nuclear fuel. The zones of weakness adjust releasing stresses and strains of the rock mass as well as they are the main paths of hydraulic flow in the bedrock. The movements occurring on these zones accumulate during the lifespan of the repository and possibly can cause changes in the stability, stress field and groundwater conditions of the rock mass. When the fracture zone model is presented together with the observed seismic events, active or unstable zones can be identified. The interpretation can bring out changes in the rock mass that, for example, may result to re-evaluation of certain water conducting zone and even further cause changes to final disposal facility layout.

The main purpose of annual reports is to support modelling of the rockmass surrounding the ONKALO. If possible, interpretation of the observed seismicity related to certain areas or weakness zones of the rock mass is presented. The annual reports include also descriptions of technical events, like changes in the configuration of the seismic network, technical failures occurred, etc. The reports can be utilised as a source material in further going seismic, geophysical and/or rock mechanical interpretations.

Monitoring of regional tectonic seismicity aims at better understanding of ongoing seismotectonic processes in the Olkiluoto area. Although the focus of regional seismic monitoring is limited inside and close to the seismic network other regional earthquakes are also recorded and a stored in the Posiva's data archive. These recordings from the Olkiluoto site are valuable in seismic hazard studies, for example when attenuation of seismic signal is evaluated.

The seismic monitoring also is part of the safeguards project of Radiation and Nuclear Safety Authority of Finland. The nuclear non-proliferation control in ONKALO is based on the following sub-areas (Posiva 2006).

- Preliminary data: plans and drawings
- Implementation data: verification measurements, as built drawings, inspections and operating records,
- Monitoring data: Micro-seismic monitoring.

Therefore all the observed clusterings of explosions of the area are analysed and reported in the monthly reports. Explosions are watched also in longer time spans. If a slowly developing clustering of explosions is recognised, the origin of the clustering is explained as well. The results of the monthly reports are edited to the interim safeguard reports by Posiva.

2 OPERATION OF THE SEISMIC NETWORK

2.1 Upgrades of Instrumentation

There have not been any changes in the basic operation of the network in 2007. The performed upgrades are related to the quality of the seismic signal. Damaged sensors are replaced by new ones and the orientation of the new borehole sensor is calculated.

Four of the stations have suffered from disturbing 50 Hz noise, since the sensors partly damaged during the lightning in 2002. The damaged accelerometers were in stations OL-OS1 (E-W component), OL-OS2 (E-W and N-S), OL-OS5 (up-down) and OL-OS6 (E-W). That noise lowered the quality of recordings. In January 2006, the noise increased slightly in OL-OS6 and the E-W component was rejected from the monitoring procedure, on 18.1.2006. These four sensors were replaced by new ones on 26.4.2007. The quality of recording improved significantly. In OL-OS2, the 50 Hz noise remained still on N-S component but it is very weak. In all other sensors the noise disappeared and all components of OL-OS6 are now in use. The latter improvement is the most significant, because OL-OS6 is right in the ONKALO area. Now complete triaxial recordings of that station are again available.

Two new triaxial borehole geophones were installed inside the ONKALO spiral at the end of 2006. The bored hole (OL-PR10) was 250 m deep (from the earth surface) and the diameter of the hole was 115 mm. During the installation, the sensors and cables were taped on to the grouting tube and lowered down to the borehole. When the sensors were in the correct depths, the hole was filled with grout to fix the sensors firmly and to prevent any acoustic resonances. The upper sensor was named as OL-OS13 (depth about 139 m from sea level and the deeper one as OL-OS14 (depth about 237 m from the sea level). The new geophones aimed to improve the sensitivity and the depth resolution of the measurements inside the ONKALO block (Saari and Lakio 2007a).

The locations of the sensors were determined in January 2007, when the deviation of the borehole was measured. After that the new stations were integrated to the Posiva's network.

In the beginning of 2007, indications of malfunction appeared in components E-W and Up-Down of the sensor OL-OS14. In order to protect the only working component (N-S), the wires of the other sensor components were disconnected and the software settings of those components are "disabled" in January 2007. However, also the N-S component of OS-OL14 was corrupted in June 2007 (see Chapter 2.4).

Usually, the location of a seismic event is based on recordings of several seismic stations. However, it is also possible to locate seismic events by using one triaxial seismometer. The two parameters needed are the angle of incidence and distance. The latter is easily derived from the time difference between P- and S-arrival times. The angle of incidence is based on analysis of the particle motion of the recorded P-wave. Single site event location is included in the software package Jmts. This option was utilised when the true orientation of the sensor OL-OS13 was determined. Because the angle of incidence is affected by local structures (e.g. tunnel and fracture zones), the locations based on recordings of a single station are not as reliable as location based on more stations.

The correct orientations of triaxial seismometers are essential when the fault plane solution of an earthquake is calculated. Orientation of the vertical components of the borehole sensors can be approximated to be close to the orientation of the borehole at the depth of the sensor. Just after installation, the orientations of the horizontal components are generally unknown in deep boreholes. The true orientation of the sensor can be determined when a representative data set of accurately located blasts from various directions is available. Appendix 1 presents the calculations made when the orientation of OL-OS13 was determined. The true orientation of the sensor OL-OS14 cannot be determined, because the sensor was damaged soon after installation.

At the first step of the procedure, it was assumed that coordinates, dipping and dip direction were correctly estimated in the deviation analysis of the borehole. In this phase the only variable was the *roll* of triaxial sensor. Roll determines the difference between orientations of the true north and the sensors north component. The azimuth determines the horizontal angle of incidence of the seismic signal.

It was assumed that the locations based on the recordings of the Posiva's network were true location. The true azimuth values of OL-OS13 were compared to azimuth values determined by single site recordings. The value of roll was fixed when the best correlation of least square fit to these azimuth values was found. After that the dipping of the vertical component was fine-tuned. The results of this procedure are presented in Table 2-1. Altogether 162 explosions were analysed for sensor orientation. The locations of the station OL-OS13 are quite satisfactory (see Appendix 1).

Table 2-1. *Characteristics in the borehole OL-PR10 at the depth of 139 m according to the deviation measurements of the borehole and according to the seismic analysis of the sensor OL-OS13 (see Appendix 1). Dipping 0 is horizontal and -90 is vertical down. Direction of dipping and roll: 0 and 360 degrees points to North. Elevation determined from the sea level. Coordinates are in the Finnish KKJ co-ordinate system (zone 1).*

	Dipping (deg.)	Dip direction (deg.)	Roll (deg)	North (m)	East (m)	Elevation (m)
Borehole	-77.6	344.45	?	6792190.76	1525941.99	-139.33
Sensor	-68.0	335	285	6792190.76	1525941.99	-139.33

2.2 Upgrades of data processing and interpretation

The interpretation of seismic data is performed within the frameworks of the lineament interpretation of the Olkiluoto area (Korhonen et. al 2005) and the geological model of the Olkiluoto site (Paulamäki et al. 2006). Those models applied in the visualisation and interpretation of the seismicity are the same as in 2006 and they are included in the visualisation software Jdi. The models are described in the previous annual report (Saari & Lakio 2007a).

Also the ONKALO model utilized in daily analysis in 2007 was the same as in 2006. The weakness of that model was that the other access tunnel and the ventilation shaft are not presented in this model generated in 2004. The new design model of the ONKALO was integrated in JDi in February 2008. The planned layout model is dated on 18.10.2007. The most pronounced improvement relative to the old one is that the access tunnels and the ventilation shafts are presented in the new ONKALO model. Unlike the old model, this model presents the whole profile of the tunnel. This model is applied in Chapter 4, where the results are presented.

All the three software packages were upgraded in 2007. While software was upgraded and tested the seismic stations were collecting data independently. The data was transferred later to the Olkiluoto server and further to Vantaa for analysis. Monitoring was not interrupted.

New versions of visualisation software package Jdi were installed in February (version 4.1), May (version 4.1.1) and December (Version 4.2). Main improvement in February was that now Jdi provides extensive help on all of its features. The version 4.1.1 was mainly the same as Jdi 4.1, which was installed on February 2007. The new feature is a dongle licensing support, that allows the user licence one copy of Jdi and run it on any PC or laptop where the software is installed and the dongle plugged into. This is done by moving the dongle between computers. A dongle is a hardware key that looks like a memory stick and plugs into the USB port of the PC. The new features of the third upgrade in 2007 are mainly related to data management of visualisation program. Also some bugs of the previous versions were fixed in each installation. The installations of the software did not interrupt or disturb the monitoring in Olkiluoto.

New version of the software package for data processing and analysis (Jmts version10.1.1) was installed on 15.5.2007. New procedures for selecting P- and S-wave window length are associated with seismic source calculations is one of the main improvements. Another important implementation is a new way to calculate the fault plane solution. In this method the amplitudes of P- and S-wave are utilised. The polarity data is ignored. The polarity of the first movement is often very difficult to estimate and even one incorrect polarity can cause completely wrong interpretation.

The Run Time System (RTS) system of the Olkiluoto server was upgraded and tested on 26.11.2007 by ISSI via ssh connection. Most of the changes to the old software (installed 7.12.2006) are internal bug fixes and some enhancements.

2.3 Interpretation practice

Inside the Olkiluoto site there will be several different study areas and models produced which will not necessary cover the same volume of rock (Posiva 2005). The selected volume of the rock depends on its application. However, for reasons of clarity, a standardized nomenclature is adopted. Altogether seven expressions are presented (Posiva 2005), and the following two of them are applied in seismological interpretation. According to that nomenclature: 1) Site area includes the well investigated area covered by deep boreholes and the associated shallow monitoring holes. 2) Any particular area larger than the Olkiluoto site is called semi-regional.

In 2005 the seismic network consisted of eight stations close to the ONKALO. The monitoring and interpretation was focused on volume called the ***seismic ONKALO block.*** The seismic ONKALO block is a 2 km *2 km *2 km cube surrounding the ONKALO (Saari 2006). It is assumed that all the excepted excavation induced events occur within this volume (site area).

Outside the network the location accuracy is not as good as inside or close to it. In 2006, when four new 1 Hz seismometers were available, the focus of interpretation was expanded to semi-regional scale. Inside this area, called the ***seismic semi-regional area*** the sensitivity and location accuracy of the seismic network is good or sufficient. It also covers the semi-region of the lineament interpretation of the Olkiluoto area (Korhonen et al. 2005).

The observations are presented separately for the seismic semi-regional area and the seismic ONKALO block by the visualisation by the program Jdi. The onset times of the events are recorded in Coordinated Universal Time (UTC), which is commonly used in seismic bulletins. Compatible time systems make the comparison and integrated use of seismic data fluent. For example, Posiva's recordings were used together with the recordings of Finnish and Swedish national networks when the fault plane solution of 3.1.2007 Laitila earthquake was calculated (Saari 2008). Local time in Finland is UTC + 2h during normal time and UTC + 3h during summer time.

It is likely that potential tectonic earthquakes occur in existing weakness zones of the bedrock. Lineaments coincide often with those zones. One of the main purposes of the semi-regional monitoring is to identify and characterize seismically active fracture zones. Activity somewhere in a fracture zone indicates potential activity also elsewhere in that structure. The ONKALO site is 6-8 km from the sides of the seismic semi-regional area, close to the middle of the area. The main orientation of lineaments is NW-SE. In that orientation, the seismic semi-regional area is 17-20 km long, close to the ONKALO (Saari & Lakio 2007a).

The lineament interpretation of the Olkiluoto area comprised geophysical and topographic data (Korhonen et. al 2005). The geophysical data included magnetic, electromagnetic, seismic and acoustic data from aerophysical, ground, and marine surveys. In the final integrated interpretation the lineaments are classified by their uncertainties. Those groups (low, medium, and high uncertainty) were added in the model applied in the seismic visualisation program when the new 1 Hz sensors (OL-0S9…OL-OS12) were installed (Saari & Lakio 2007a).

The geological model of the Olkiluoto site consists of four submodels: the lithological model, the ductile deformation model, the brittle deformation model and the alteration model (Paulamäki et al. 2006). The model is utilised in interpretation of seismic processes, for example, when active faults or faults or volumes prone to seismic movements are identified and analysed. Any unit of the model can be selected for closer visual analysis. That kind of approach is when the results of fault plane solution of microearthquakes are interpreted together with brittle deformation model (see e.g. Saari & Lakio 2007a).

Although, only the events occurred within the seismic semi-regional area are included in the event tables of the monthly reports, when earthquakes and potential earthquakes are concerned, the investigation area is not that limited. The observations of the Posiva's network are compared with the events reported in the bulletins of seismic events of Northern events. If there is an earthquake within a distance of 200 km from Olkiluoto in the bulletins, it is rather likely recorded also in Olkiluoto. Those recordings are reported and stored in the Posiva's data archive. The recordings from the Olkiluoto site are valuable in studies of regional seismicity, seismotectonics and seismic hazard.

Also other unusual events outside the seismic semi-regional area, such as events from the sea area, are under special attention.

The Institute of Seismology, Helsinki University, maintains the regional seismic station network in Finland. The nearest seismic stations are about 200 km from Olkiluoto: three SE, three East and one North from it. At the same distance, are also the nearest Swedish stations, at the western coast of the Bothnian Sea. The detection threshold of the Fennoscandian seismic stations is of the order of ML = 1.5 or less, in the Olkiluoto area. A new seismic station of the Institute of Seismology started to operate in the beginning of February 2007, in Laitila about 40 km from Olkiluoto. Before that, it has been on test run about one year.

The Posiva's 1 Hz seismic stations improve the understanding of the general seismotectonic behaviour of the Olkiluoto region. Although, the geophones are capable to observe explosions and earthquakes within a much wider area, the analysis is focused on the seismic semi-regional area. It is assumed that regional events occurring outside that area are located by the Finnish and Swedish regional seismic networks. The recordings of the Posiva's stations can be utilized, if necessary, to improve the interpretation based on recordings the national seismic stations.

Also teleseismic events, i.e. events occurring over 1000 km form Olkiluoto, are recorded. Those can be recognized by comparing the recordings to the bulletins of Institute of seismology, University of Helsinki (http://www.seismo.helsinki.fi/) and international data centres, such as EMSC/CSEM (http://www.emsc-csem.org/). Teleseismic events are rejected and not included in the data archive.

2.4 Data availability

Partial breaks in network operation, like failure of single station or component, are unavoidable in any continuous monitoring. However, those can lower the quality of operation, like the location accuracy of seismic events. Minimum number of stations needed for the event location is three. Now, when there are eight seismic stations in operation for monitoring the seismic ONKALO block and five for the seismic semi-regional area, temporal failure of one station has minor influence on the reliability of the operation or on the location accuracy.

The event detector of the each seismic station compares the short term average (STA) of the amplitudes to the long term average (LTA) of the amplitudes. The event detector starts recording data when the STA/LTA ratio exceeds the pre-set trigger value. The field stations monitor continuously, but only signals, which can be related to a seismic event, are sent to the central site computer. The recordings which are related to the same seismic event are associated automatically. An event is sent, when a predetermined number of seismic stations detect earth vibrations that exceed the trigger value within a certain time window. The number of sensors applied in event association was set to four. That number is low, because five of the stations inside the ONKALO block (OL-OS2, OL-OS3, OL-OS4, OL-OS7 and OL-OS8) are equipped with two different types of sensors. In addition to that, it was set another number of associations for the group of the 1 Hz seismic stations. If three of those five stations can be associated, the recordings are interpreted to be from the same source.

In practice, the design of the data management guarantees that simultaneous power or communication failure in all stations or nearly all stations is needed to cause an operation break of the seismic network. As in 2006, the network has operated continuously in 2007.

In Posiva's seismic measurements, a special attention has been paid to reliable data recording and transmission. All detected events are stored in the field stations until they are safely transmitted to the site computer. The central site PC in Olkiluoto associates the recordings of the same origin and emails the recorded events to the office computer in Vantaa, where the events are analysed.

Events are associated in the Olkiluoto site computer in real time. If connection to one of the stations is failed, the recording of that station is not associated. However, generally the analysis can be based on the recordings of the remained sites. The unsent event stays several months in the hard disk drive of the SAQS and it can be downloaded to the office PC, if necessary.

The possibility of data loss due to failure of the site computer is reduced by the redundant hardware configuration. Practically, when the data has arrived to the Olkiluoto server, it cannot be lost. Between Olkiluoto and Vantaa the data management is based on internet technology. Email server keeps the seismic data until the office computer has received the data.

The whole chain of data management is checked every day by a test signal. The signal controls the prevailing status of the seismic sensors and the data flow from a single station to the office computer in Vantaa. If the test signal from any sensor is missing or looks unusual, the troubleshooting is started. This kind of procedure aims to keep operational breaks as short as possible.

The two way data transmission between the new semi-regional seismic stations (OL-OS9…OL-OS12) and the server in Olkiluoto is done via radio links. The connection is polled every four seconds. If it appears that the connection is down, it is checked every two minutes to see if it can be re-established. The SAQS units are able to buffer the data, so no data is lost if there are short temporary interruptions (1-2 minutes) to the communication system. Data is also logged to the local disk on the SAQS as a backup should there be a need to recover data from an important event.

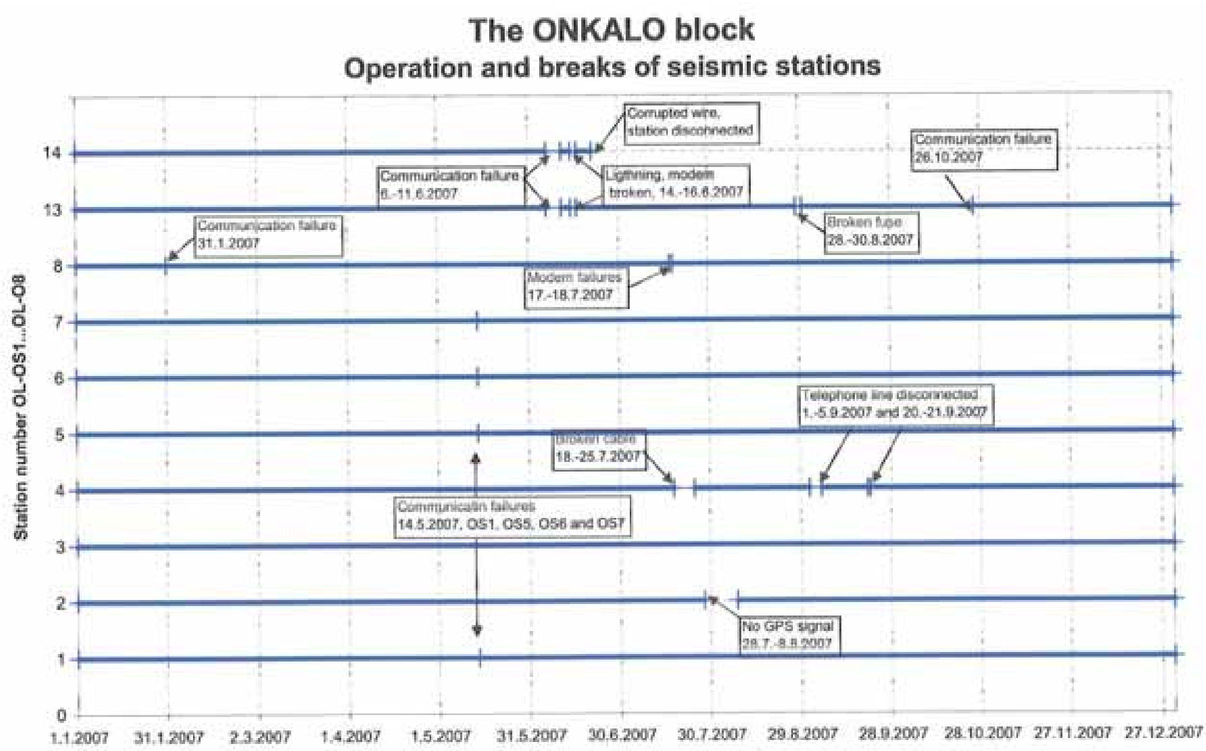
Four of the stations have suffered from disturbing 50 Hz noise, since the sensors partly damaged during the lightning in 2002. The damaged accelerometers were in stations OL-OS1 (E-W component), OL-OS2 (E-W and N-S), OL-OS5 (up-down) and OL-OS6 (E-W). That noise lowered the quality of recordings. In January 2006, the noise increased slightly in OL-OS6 and the E-W component was rejected from the monitoring procedure, on 18.1.2006. These four sensors were replaced by new ones on 26.4.2007. The quality of recording improved significantly. In OL-OS2, the 50 Hz noise remained still on N-S component but it is very weak. In all other sensors the noise disappeared and all components of OL-OS6 are now in use. The latter, improvement is the most significant, because OL-OS6 is right in the ONKALO area. Now complete triaxial recordings of that station are again available.

Small, about one second long pulses disturbed station OL-OS10, which has been triggering daily about 10.000 anomalous pulses in March. The pulses lowered occasionally the quality of the recordings in OL-OS10. They also increase the number of false events recorded in the Olkiluoto server. Generally the SAQS unit is in a separate hut close to the seismometer vault. In OL-OS10, also the SAQS unit is in the seismometer vault, about one meter from the sensor. It appeared that the pulses were generated by the hard disk drive of the SAQS unit. When the station recorded the triggered event to the disk, the disk was causing some vibration that was getting to the sensor and this causes a trigger and so on. Once it started like this it was going on several hours. The problem was solved after installing an isolation sheet below the SAQS unit on 5.4.2007. Apparently, SAQS unit or some cables were moved during a routine visit in OL-OS10 and the original conditions of the vault were changed in the end of February 2007.

Partial failures of the network, that just lower the quality of operation, are usually related to a single station. Typical duration of the break is from few hours to few days. Breaks related to rearrangement or troubleshooting of the monitoring are designed in advance to be as short as possible. Quite often they are caused by breaks in data or power cables related to different construction work conducted in the Olkiluoto area (Table 2-2). Three of the stations (OL-OS3, OL-OS10 and OL-OS12) have been running without any breaks in 2007 (Figure 2-1).

Table 2-2. *Partial failures of monitoring.*

Date	Duration	Comments	Station or PC
8.1.2007-	final	Wires of E-W and Up-down components corrupted, disconnected	OS14
31.1.2007	1 h 20 m	Communication failure	OS8
29.3.2007	3 h	Comm. failure between Olkiluoto and Vantaa	Office PC, Vantaa
14.5.2007	2 min 25 sec	Communication failure. Thunder	OS1, OS5 and OS7
14.5.2007	1 50 min	Communication failure. Thunder	OS6
6.-11.6.2007	5 days	Communication failure.	OS13 and OS14
14.-16.6.2007	1 day 13 h	Modems destroyed. Lightning	OS9, OS11, OS13 and OS14
15-28.6.2007	13 days	GPS broken. Lightning.	OS8
21.6.2007-	final	Wire of N-S comp. corrupted. Station closed	OS14
17.–18.7.2007	12 h 55 min	Short modem failures	OS8
18.-25.7.2007	7 days	Broken cable	OS4
28.7-8.8.2007	11 days	Cable of GPS antenna broken. Inaccurate timing.	OS2
13.-14.8.2007	1 day	Communication failure, Field PC moved	Field PC, Olkiluoto
28.-30.8.2007	1 day 11 h	Broken fuses	OS13
1.-5.9.2007	4 days	Communication failure. Installation work	OS4
20.-21.9.2007	20 h 40 min	Communication failure. Installation work	OS4
26.10.2007	1 h 22 min	Comm. failure. Loose cable connection.	OS13
30.10.2007	1 h	Communication failure, Installation work	OS9



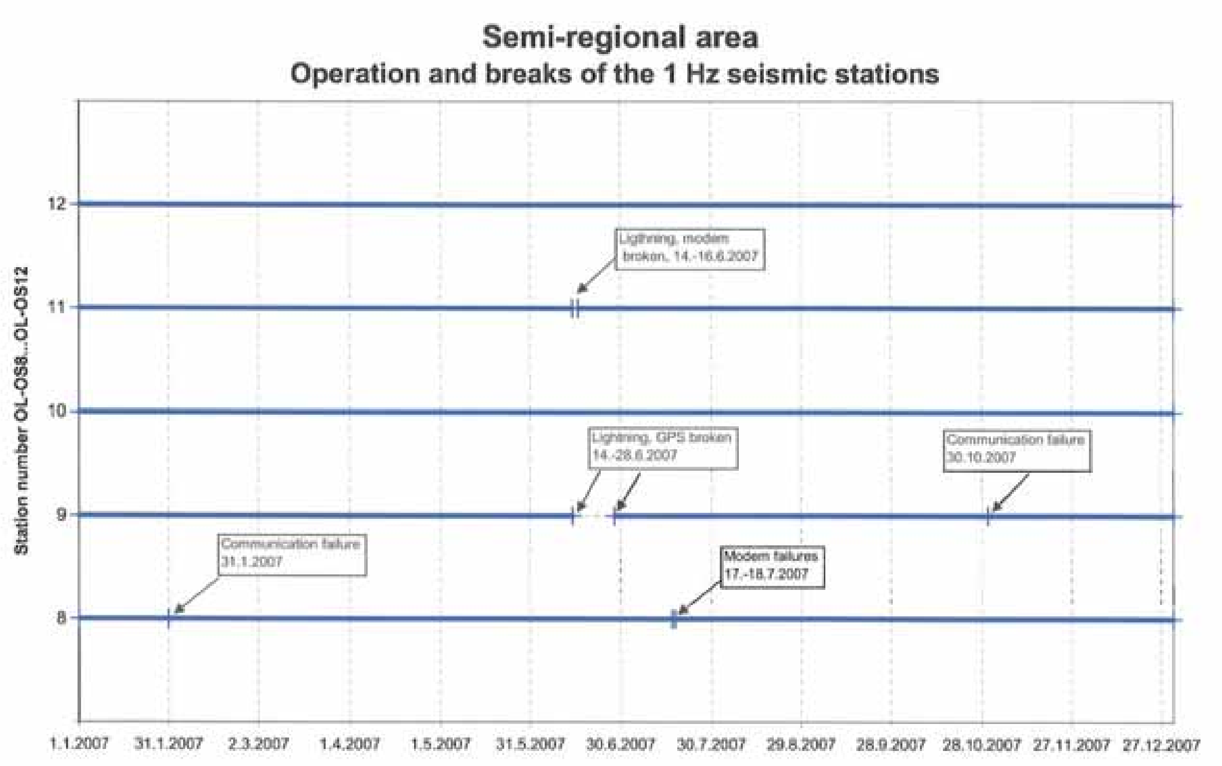


Figure 2-1. *Operation times and breaks of the seismic stations, in 2007. Upper diagram: Stations monitoring mainly the ONKALO block. Lower diagram: Station monitoring mainly the semi-regional area.*

Four stations have suffered just one short communication failure in 2007 (Table 2-2). The breaks were caused by a strong thunder on 14.5.2007. In stations OL-OS1, OL-OS5 and OL-OS7 the break was 2 minutes 25 seconds long. In station OL-OS6 the communication failure lasted one hour and 50 minutes.

The seismic station OL-OS8 had a communication failure, when a tree was cut down on the telephone line. The station was back in operation after 2 and half hours after the failure.

The borehole sensors (OL-OS13 and OL-OS14) are connected to the same SAQS unit. Those sensors had occasional communication failures after 6.6.2007. Data transmission as well cable connections were checked twice, but no reason for malfunction was found. Apparently one of the data cables was poorly connected or partly broken, because after 11.6.2007 the connection has worked properly. Similar failure occurred also on 26.10.2007.

Heavy thunder broke the modems of the stations OL-OS9, OL-OS11 and OL-OS13 in the radio mast close to the ONKALO. The failure started on 14.6.2007 at 18:14 o'clock and it was fixed on 16.6.2007 at 07:02 o'clock. Semi-regional monitoring was nearly interrupted one day and 13 hours. During the failure there were only three 1 Hz sensors in operation, which is the minimum number of stations required for monitoring the seismic semi-regional area (Figure 2-1).

After the thunder when the modem was fixed the station OL-OS9 seemed to be working, but the daily test signal did not arrive after 15.5.2007. The clock of that station was not running in correct time and the event association with other station failed. The GPS-antenna was broken during the lightning and the internal clock of that station shifted slowly from the correct timing. The station was back in operation when the new GPS antenna was installed on 28.6.2007.

The daily test signal was not received from the station OL-OS4 on 19.7.2007. The reason for this was a broken cable. The failure started on 18.7.2007 at 9:46 o'clock and the cable was fixed on 25.9.2007 at 9:20. The duration of the failure was nearly 7 days.

Station OL-OS8 had occasional short modem failures 17.-19.7.2007. The total duration of these failures was 12 hours 55 minute. The modem was replaced by a new one on 18.7.2007 at 8:46.

The daily test signal was not received from the station OL-OS2 on 3.8.2007. It appeared that the clock of the station was not in time. GPS antenna had not received a time update since 28.7.2007 at 02:59. After that the timing of the station was slowly shifted. On 3.8.2007 the time shift was so long that events and test pulses of the stations OS-OL2 were not accepted by the event association procedure of the Olkiluoto server. The reason for this was noticed and fixed on 8.8.2008 at 04:59 o'clock. The coaxial cable of the GPS antenna was cut in few pieces. Like a year ago, the cable was bit by an animal, apparently by a rabbit.

Station OL-OS13 had operation failure that started on 28.8.2007 at 11:40 o'clock. Two fuses in the equipment cabin were broken and they were replaced on 30.8.2007 at 06:26 clock. The total duration of the failure was 42 hours 46 minutes, i.e. 1 day 11 hours 46 minutes.

New power transmission line has been under construction in northern Olkiluoto in September 2007. Therefore the overhead telephone line to station OL-OS4 has been taken down from the poles and the data connection between OL-OS4 and the Olkiluoto sever has suffered few breaks. During first break (1.-5.9.2007) the connection was working from time to time, but practically the break was four days long. The other, shorter break started on 20.9.2007.

New data connection was installed on the surface above the station OL-OS9, which is in the repository of low and intermediate level nuclear waste. The rearrangement was done on 30.11.2007.

The most severe failure occurred in station OL-OS14. The borehole sensors OL-OS13 and OL-OS14 were installed the borehole OL-PR10 at the end of December 2006. It is impossible to fix or replace these sensors or their cables, because they are grouted in the borehole. In the beginning the year 2007 the daily test pulse of the deeper borehole sensor (OL-OS14) indicated that it was not working correctly. Slowly some indications of malfunction appeared in components E-W and Up-Down. It seems that the problem was caused by salty water entering some damaged part of the cable. It is not possible to say where and when that damage has happened. The only solution was to use the sensor as a uniaxial sensor (i.e. to use only N-S component). The wires of the other sensor components (E-W and Up-Down) were disconnected and the software settings of those components are "disabled" in January 2007.

The worst scenario was that it is probably only a matter of time before the leakage also starts to affect the last component of OL-OS14. That is what finally happened. The test signal from OL-OS14 arrived daily, but for some reasons the station was not recording seismic events anymore. The last event recorded on that station was on 21.6.2007 at 11:24:25, just before the long break in excavation of ONKALO. Different kinds of tests were done to find the reason for that. Finally ISSI, the manufacturer of the Posiva's seismic network announced: "The response of the test pulse indicates that there is a large 'capacitor' across the lines probably caused by water and some chemicals in it, which means that it does not get the voltage to the SAQS when the geophone moves". It was evident that also N-S component was affected by water. It was also likely that this damaged sensor was causing 50 Hz noise on the OL-OS13 situated in the same borehole. When OL-OS14 was permanently disconnected on 16.10.2007 the noise on OL-OS13 was clearly reduced. On the same day the settings of the Olkiluoto server were changed so that the station OL-OS14 is no more part of the seismic network.

There were also two breaks that just postponed the data transmission from seismic stations to the Olkiluoto server to Vantaa. During these breaks the field stations were in operation during the performed rearrangement and after it all the observed events were transmitted to the servers. Adjustment works of data cables cut the connection between Olkiluoto and Vantaa on 29.3.2007. The break lasted about 3 hours. Rearrangement of data managements in the tunnel technique building started on 13.8.2007. The Olkiluoto server was moved to a new place in the building and the IP address of the server was changed. Due to the change of the IP address the data communication procedures between the servers in Olkiluoto and Vantaa was reconfigured. The operation was completed on 14.8.2007 (Table 2-2).

3 EVENTS RECORDED BY THE SEISMIC NETWORK

3.1 Uncertainties relating to measurements

Identification of an individual earthquake among the cluster of excavation blasts includes elements of uncertainty. The majority of the excavation induced seismicity (Type A) tends to occur very close, in time and space, to the latest excavation blast. These events occur often in swarms and their seismic signals are not representing a typical earthquake signal. They are associated with the "fracture-dominated" rupture. Type B events are temporally and spatially distributed throughout the active excavation region. They represent "friction-dominated" slip in existing shear zone such as faults or dikes and have source properties similar to tectonic earthquakes (Richardson & Jordan, 2002). Type B events have many characteristic that make them easier to identify in comparison to type A events.

Although tectonic earthquakes are easier to identify than some of the induced earthquakes (type A), the orientation of seismic stations with respect to the hypocentre is essential. It is important to a seismic signal in many different directions. This is important not only for location but also for a successful identification of the seismic event and for calculations of the fault plane solution. This fundamental condition is fulfilled inside the seismic semi-regional area. Outside the area support of recordings of other seismic networks is valuable.

Accurate location of a seismic event is one of the key parameters of seismological interpretation. If location is incorrect, the subsequent seismological analysis is inaccurate. The velocity model (P-wave velocity, α = 5600 m/s and S-wave velocity, β=3250 m/s) based on the studies conducted in the study area (e.g. Front et al. 2001 and Cosma et al. 1996) seems to give rather good results within the seismic ONKALO block. Those are the preset default velocities for the station inside the seismic ONKALO block (OL-OS-1….OL-OS8). For the stations OL-OS9…OL-OS12, the corresponding default velocities are: α = 5800 m/s and β=3350 m/s. These velocities are used in automatic event association and location procedures. They are usually applicable also when the result of automatic location is improved manually. In that phase, the station specific velocities can be changed. That may be necessary, for instance, when a seismic signal arriving to a seismic station runs through a structure, which lowers the seismic velocity.

The seismological data processing software (Jmts) accepts just one P-wave and S-wave velocity. Simple velocity model serve automatic event location, which is necessary in mines where hundreds or thousands events occur in a day. This software limitation reduces the location accuracy of seismic events, if the velocity structure of the bedrock is complicated. However, the P- and S-onsets picked by the analyst are available. Those onsets times can be used as input for a more sophisticated program for event location.

The blasting work is generally detonated in sequences. Usually, that means that the S-phases are hidden in the signals of blasts following each other and the event location is based only on P-onsets. The lack of S-onset dilutes the location accuracy. Similar problem is related to above mentioned type A events. They occur very close, in time and space, to the latest excavation blast and their mechanism is similar to explosions. S-phases are difficult to distinguish. Therefore, a special attention is paid to the latest events of the blasting sequence.

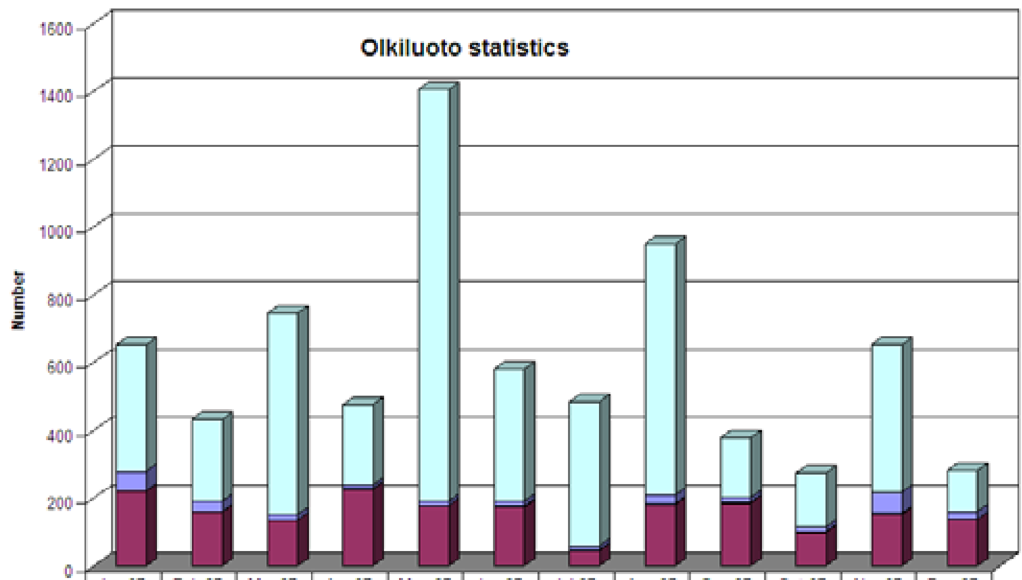
When the event is detected, it is immediately emailed to the office PC in Vantaa, where it is automatically analysed. The location and magnitude of an event is determined when the email has arrived, basically in few minutes. The result of automatic analysis is uncertain and always verified manually. The decision of the seismic source (explosion or earthquake) is done by experienced analyst.

3.2 General statistics

Altogether 7314 (Figure 3-1) events and 365 daily test signals have been recorded, in 2007. The number of rejected events was 5107. Those recordings were caused by lightning (e.g. about 800 recorded thunders in May and over 400 in August), coincident artificial noise (vehicles, visitors, construction work, forest work, additional network test signals etc.) and natural noise (e.g. wind shaking trees or strong waves hitting the shoreline) or by a combination of those. Testing of the network operation caused about 300 rejected events in November 2007.

The number of accepted events was 2207. The majority of those (1861 events) occurred inside the seismic ONKALO block (86 %). Altogether 316 of the accepted events have been located outside the seismic ONKALO block. Only 21 of them are located inside the seismic semi-regional area. The other 295 accepted events have been located mainly close to the semi-regional area.

The majority of accepted events were explosions. One of the recorded events was a microearthquake (M_L = 1.9) that occurred 3.1.2007 in Laitila about 40 km from Olkiluoto. That event is more in details later in this report. Excavation induced microearthquakes or semi-regional tectonic earthquakes were not recorded in 2007.



	Jan 07	Feb 07	Mar 07	Apr 07	May 07	Jun 07	Jul 07	Aug 07	Sep 07	Oct 07	Nov 07	Dec 07
rejected	372	241	596	237	1214	390	425	742	176	160	434	120
other accepted	59	31	16	12	13	13	12	25	14	13	62	25
semi-regional other	1	1	0	2	1	3	3	1	2	3	4	0
ONKALO block	220	159	135	225	178	174	45	182	186	99	152	136

Figure 3-1. *Monthly statistic of the monitoring in the Olkiluoto area in 2007.*

The activity of the seismic semi-regional area is dominated by the activity of the seismic ONKALO. After that the overall activity inside the seismic semi-regional area has been rather constant (Figure 3-2). The annual average number of events has bee of the order of 184 per month. The increase of the cumulative number of events slows down few times (in May, June, July and October). These are related to periods of lower excavation activity in the ONKALO. The highest activity rates are of the order of 20-25 events per day.

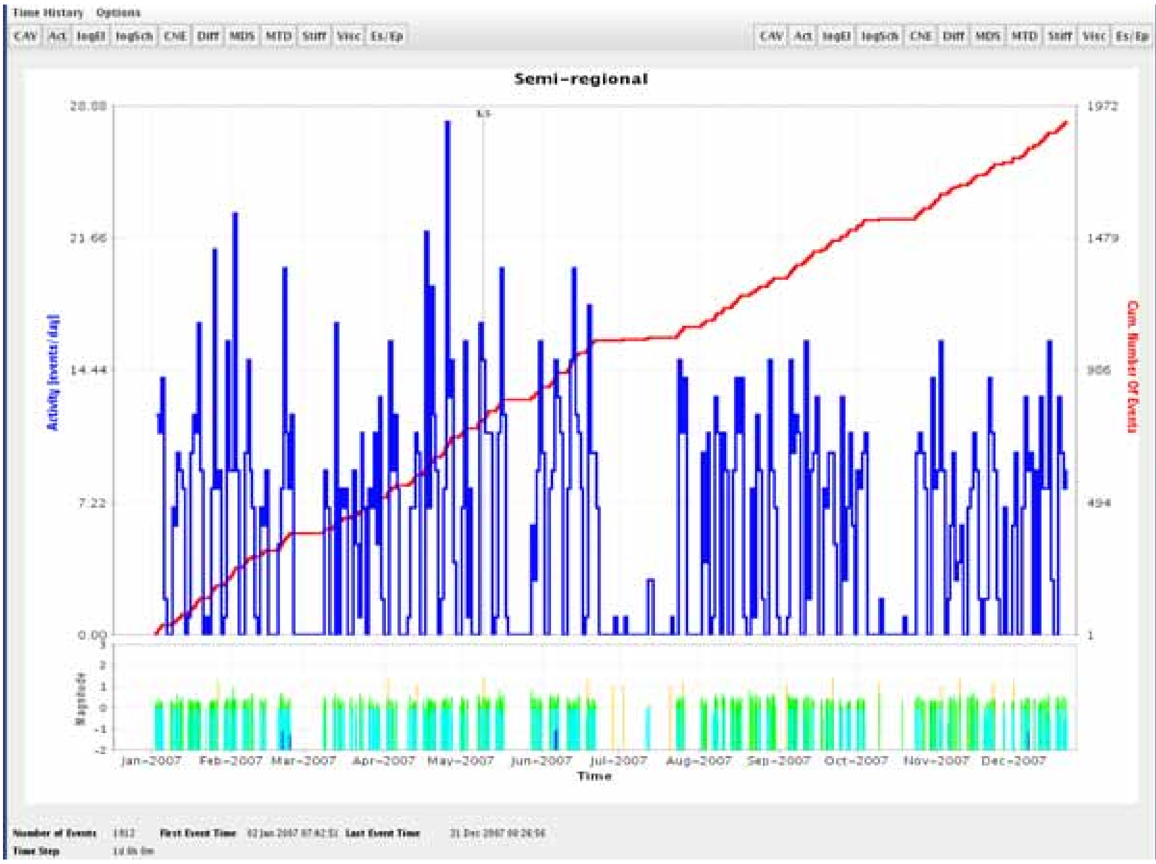


Figure 3-2. *Events per day (blue) and cumulative number of events (red) inside the seismic semi-regional area, in 2007.*

4 EXPLOSIONS

4.1 Seismic semi-regional area

Because the seismic monitoring is part of the safeguards project of Radiation and Nuclear Safety Authority of Finland (Posiva 2006), the observed are explosions inside the seismic semi-regional area are located. If a clustering of explosions is recognised, the origin of the clustering is verified. The interpretation practice applied is presented in Chapter 2.3)

The events located in the seismic semi-regional area have been presented in Figure 4-1. The magnitudes range from ML = -2.1 to ML = 1.5. The events outside the ONKALO have occurred at the surface. The number of those events is much smaller than in 2006.

The main clustering of epicenters outside the ONKALO block represents explosions from the rock quarry owned by Interrock Oy. Otherwise, there is only one event outside the Olkiluoto island. That explosion is related to construction works close to the southern border of the semi-regional area, in the northern part of the city of Rauma. The rest of the construction blasts of that site are located south of the border.

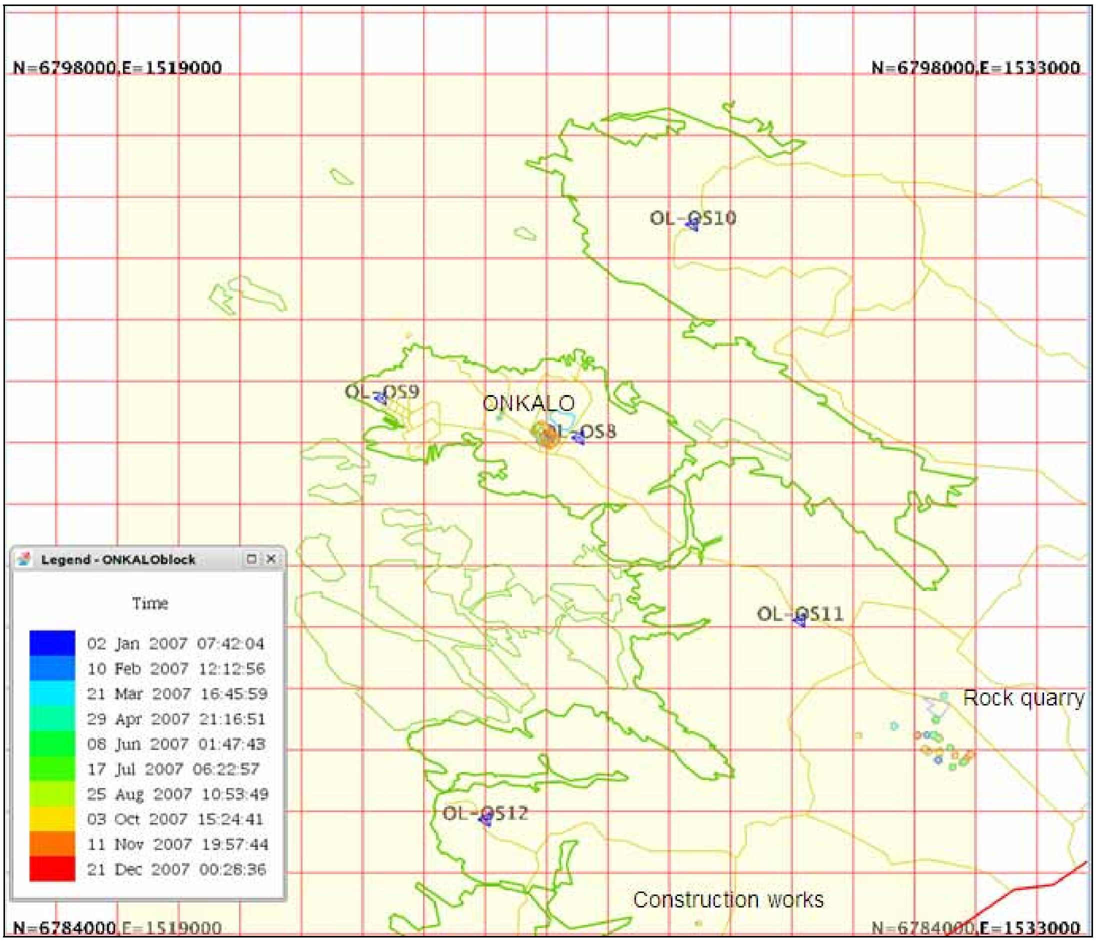


Figure 4-1. *Observed 1912 events in the seismic semi-regional area (light brown), in 2007. Seismic stations equipped with 1 Hz geophones are shown as blue triangles. Events are coloured by time. The size of sphere is relative to the events magnitude. Grid size is 1 km*^{2}.

Also at Olkiluoto the number of sites related to construction works is smaller than in 2006 (Figure 4-2). Most of the activity at the Olkiluoto is related directly to the construction works of the ONKALO. There are two sites where the epicenters are not related to the ONKALO construction works. One event is located just outside the northwestern shore line of the island. The event was located only by five stations including two rather distant stations (OL-OS11 and OL-OS12) outside the Olkiluoto Island. This makes the location of the event inaccurate. The event is related to the construction works of the now power transmission line. The true location should be more south on the island. A chain of five explosions in the western part of the ONKALO block are related to construction works of the new cable channel. Indications of illegal or inappropriate works by outside actor, which would have influence on the safety of the ONKALO, cannot be found.

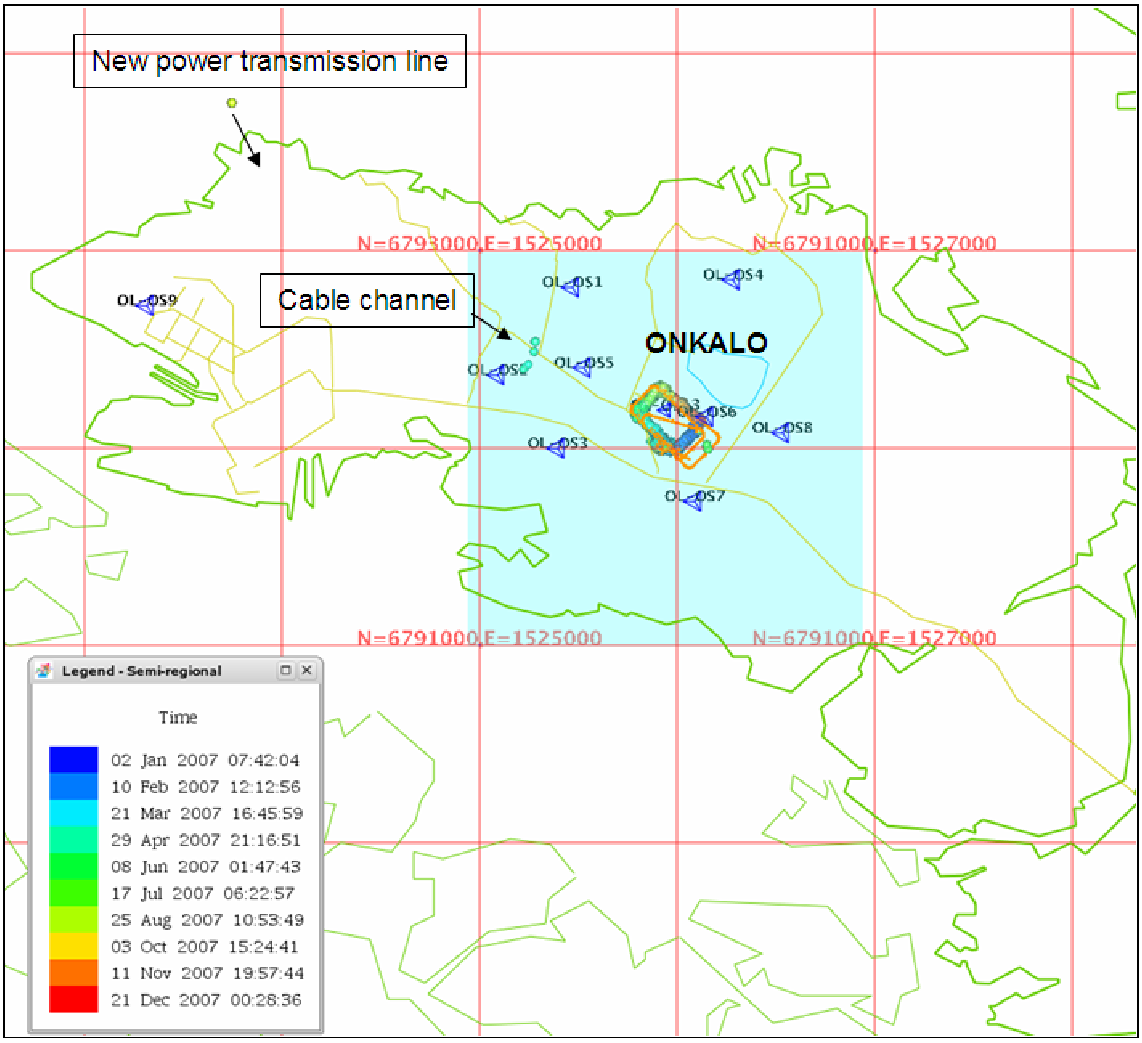


Figure 4-2. *Explosions at the island of Olkiluoto in 2007. Events are coloured by date. Seismic stations are shown as blue triangles. The ONKALO block is presented by blue shading. Events are coloured by time. The size of sphere is relative to magnitude. Grid size is 1 km*^{2}.

4.2 Seismic ONKALO block

The explosions (1891 events, ML = -2.1…0.8) located inside the seismic ONKALO block are presented in Figure 4-3. In addition to the explosions down in the ONKALO, there are few epicentres located at the surface of the block. The origins of the events further away from the ONKALO site are explained already in the previous Figure. Some surface facilities are built also at surface above the ONKALO itself. Those can be seen more clearly in Figure 4-4.

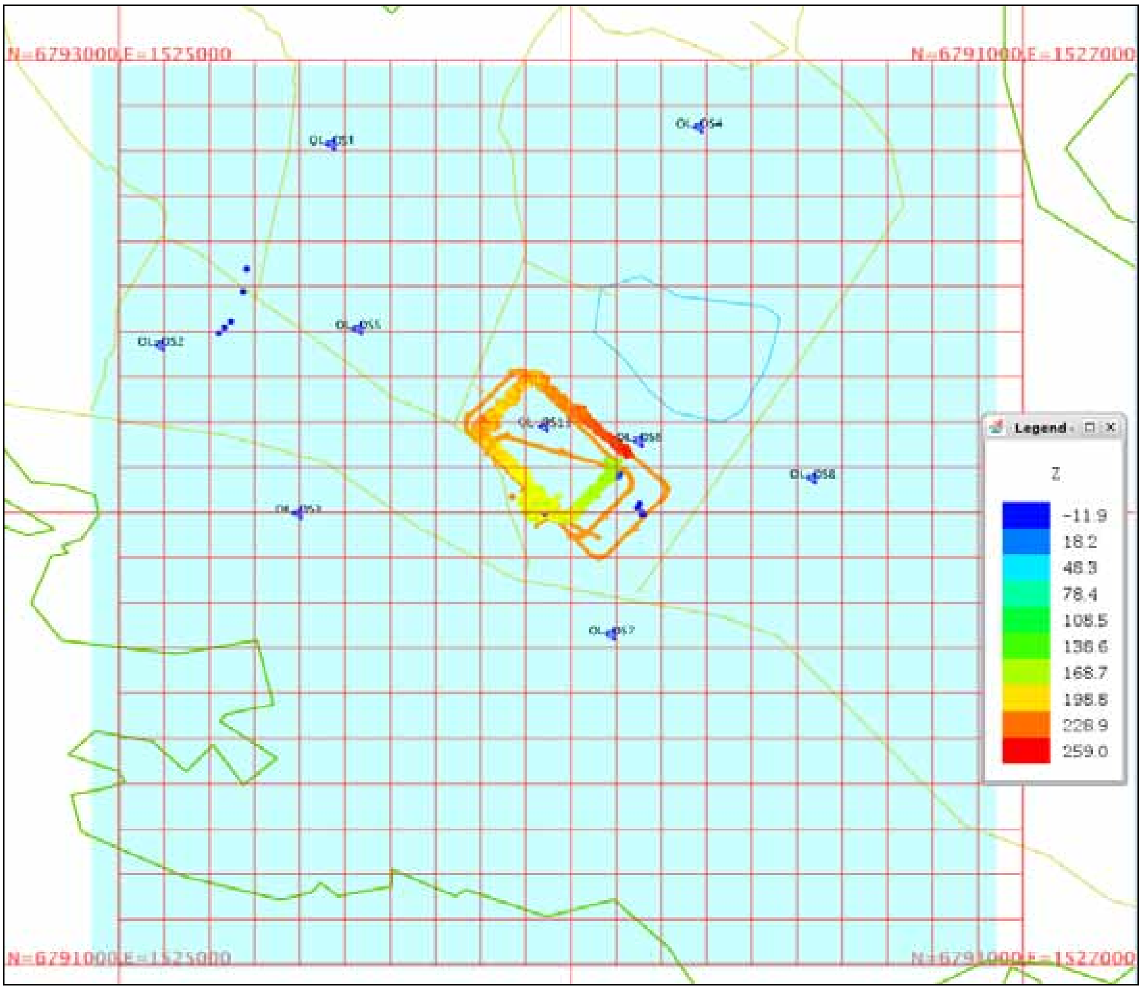


Figure 4-3. *Explosions (1891 events) inside the seismic ONKALO block, in 2007. Depth in colours (negative value above the sea level). Distance between gridlines is 100 m.*

The excavation of the ONKALO proceeded from the depth of about 160 meters to about 245 meters in 2007 (Figures 4-4 and 4-5). The origin of the blasts was verified from the daily reports of SK-Kaivin Oy, which is responsible about the excavation of the ONKALO.

The excavation blasts coincide nicely with the Posiva's planned layout of the ONKALO dated on 18.10.2007. The individual epicenters further away from the tunnel are mainly located by less than five seismic stations or the recordings of the seismic signal are contaminated by some disturbance. The locations of those events are not as accurate as general.

However, some variation of the location accuracy can be seen. For example, along the long straights the accuracy is generally rather good, but in the shorter SW-NE oriented straight the epicentres are slightly shifted NW from the model. The same shift is shown also in locations of explosions blasted in the accesses of the ventilation shafts and maybe also in the area where vertical inaccuracy is detected (Figure 4-5).

That systematic shift of locations can be related to the network geometry combined with variation on seismic wave velocities in different locations of the excavation or in different directions. One explanation to this anomaly of location may relate to anomalous velocity due to the orientation of the pervasive foliation/anisotropy of the bedrock that dips in the ONKALO area towards SE with a medium dip of the order of 40 – 60 degrees (see e.g. Mattila et al. 2008).

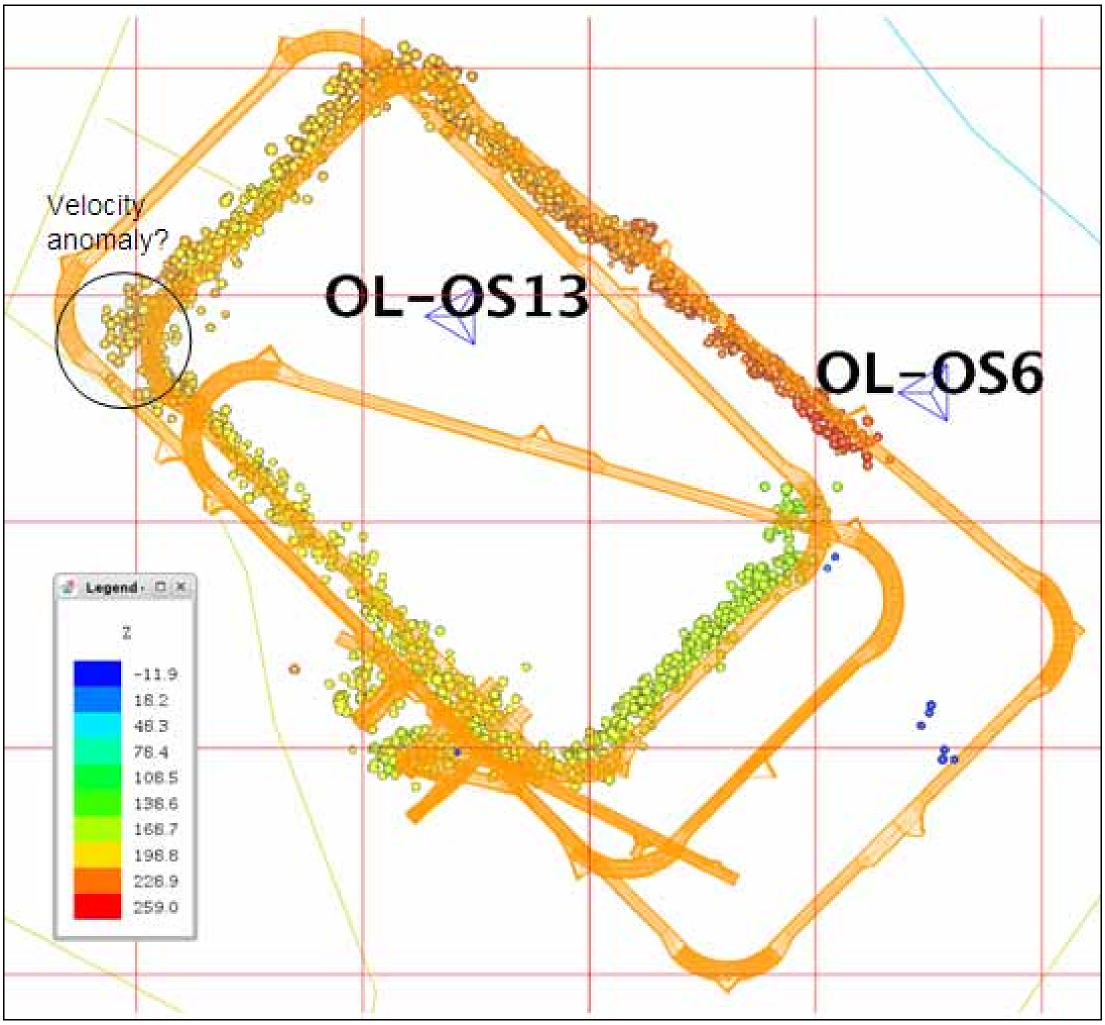


Figure 4-4. *The located explosions (1886 events) of the ONKALO area in 2007. The size of sphere is relative to magnitude. Distance between gridlines is 100 m. The potential velocity shown by a circle refers the vertical inaccuracy seen in Figure 4-5.*

In vertical direction the location accuracy improved relative to the preceding years, because the first underground station (OL-OS13) was available in 2007. Generally the locations seem to be close to the bottom of the access tunnel. The inaccuracy in vertical direction may be related to the same factors as in horizontal direction. However, local, site dependent variations can be seen in vertical location accuracy. In few areas the events locations tend to be below the real location. The most pronounced site of anomalous locations is shown at the depth of about 200 m (Figure 4-5). That anomaly may be associated with complex velocity model caused by brittle fault zones. For example nearly vertical fault zone BFZ-123 and nearly horizontal fault zone BFZ-098 are running close that site of anomalous velocity (see e.g. Mattila et al. 2008).

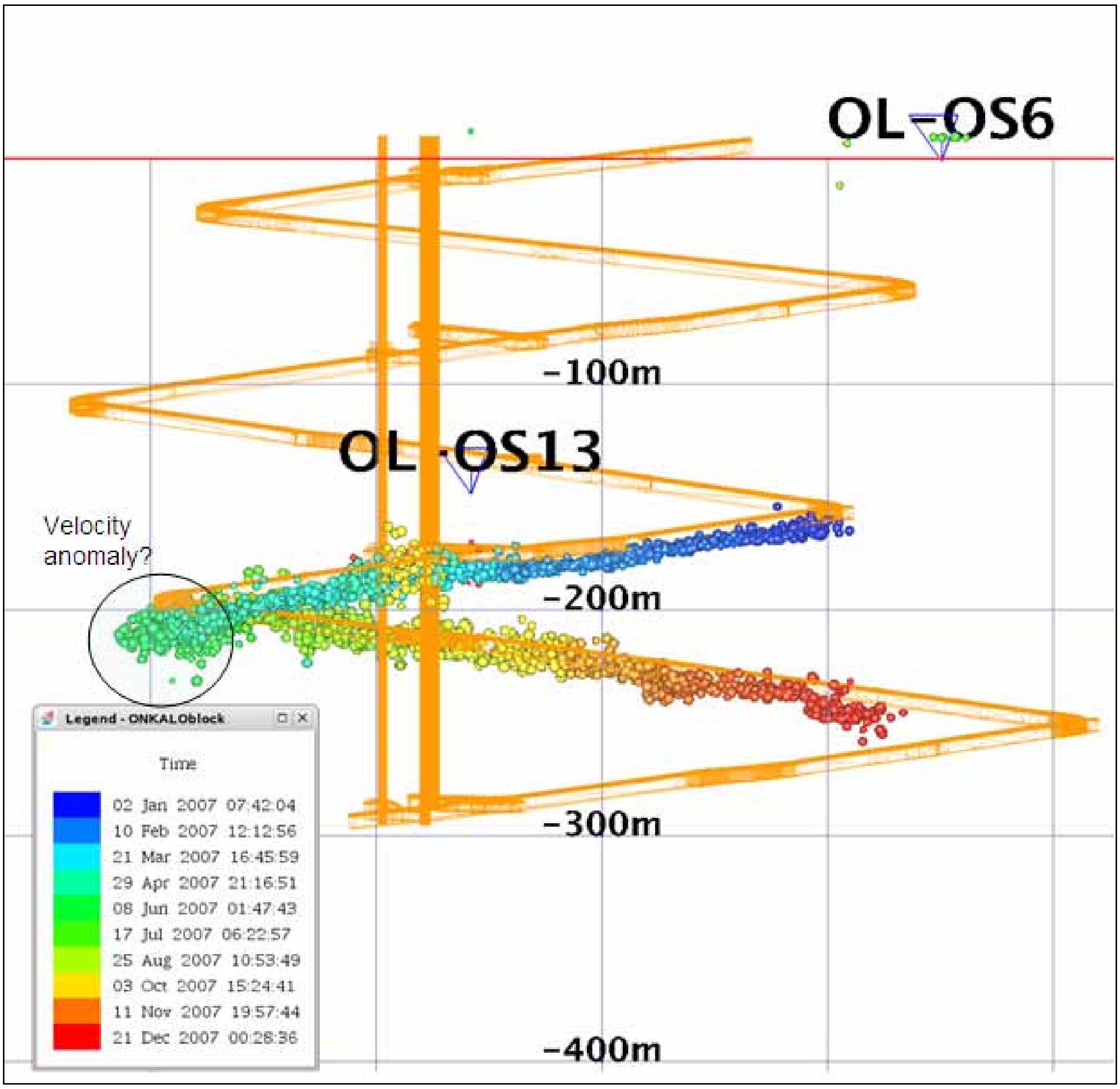


Figure 4-5. *Cross section of the explosions inside the seismic ONKALO block from south. Potential velocity anomaly is shown by a circle.*

The purpose of Posiva's nuclear non-proliferation control is to ensure that activities in the final disposal facility comply with all relevant laws and degrees as well as the obligations prescribed in international agreements. The aim of the nuclear material control in the disposal facility is also to ensure that the facility, especially in its underground part, has no rooms, materials or operations outside the system of nuclear material accounting and the that the waste canister remain in their declared positions during the operation and after the closure of the facility (Posiva 2006). It has been demonstrated (Saari & Lakio 2007a) that micro seismic monitoring is a capable tool to find “hidden rooms”.

The possibility to excavate an illegal access to the ONKALO, have been concerned when the safeguards are discussed. In that context, a concept of hidden illegal explosions, detonated at the same time as the real excavation blasts, has been presented. According to the experience gained in Olkiluoto, it can be concluded that, as long the seismic network is in operation and the results are analysed by a skilled person, it is practically impossible to do so. As in earlier years there are several examples of legal explosions performed close in time and space. For instance, explosions in the accesses to the ventilation shafts as well as in the main tunnel of the ONKALO were detonated simultaneously in December 2007. Explosions from these sites were clearly distinguishable. Seismic monitoring of excavation done by tunnel boring machine has been investigated in a separate report (Saari and Lakio 2007b).

As regards to safeguards the conclusion of the explosions inside the seismic ONKALO block are similar to those in the seismic semi-regional area. Indications of illegal or inappropriate works, which would have influence on the safety of the ONKALO, cannot be found.

5 EARTHQUAKES

In 2005 there were three and in 2006 two observation of excavation induced seismicity inside the ONKALO block. The interpretation practice and the personnel responsible for the analysis has been the same as during the previous years. The new borehole geophone OL-OS13 has improved the sensitivity and the depth resolution of the measurements inside the ONKALO block. The network of five 1 Hz geophones designed for monitoring of semi-regional tectonic seismicity and explosions has been in operation the whole year of 2007. Also the network of eight seismic stations designed for monitoring the seismic ONKALO block has been in continuous operation. In spite of those facts, there are no observations of semi-regional tectonic seismicity or excavation induced seismicity inside the ONKALO block.

There are two earthquakes in the bulletins of Institute of seismology, University of Helsinki (FENCAT, http://www.seismo.helsinki.fi/) that have occurred within 100 km from Olkiluoto in 2007 (Table 5-1). In that sense the year was exceptional, because there are altogether nine known within that distance in FENCAT. The former earthquake occurred 22 years earlier in 1986.

Table 5-1. *Earthquakes within a distance of less than 100 km from Olkiluoto in 2007 according to FENCAT. Date (year.month.day) onset tie (UTC), coordinates, and Local magnitude (M_L).*

Date	Time	^oN	^oE	M_L	Place-name
2007.01.03	05:16:18.1	60.90	21.92	1.9	Laitila
2007.02.10	23:38.58.3	60.86	22.28	0.6	Yläne

The above mentioned two earthquakes and their relation to the seismicity and seismotectonics of the Olkiluoto area are described in details by Saari (2008). The event in Yläne was very small and it was hardly seen in few recorded seismograms. The interpretation of this event is uncertain (Personal communication with Marja Uski, October 2007). However, it is included in FENCAT. It can be seen that it was not an explosion, but rather likely it was a generated by frost. It was not recorded in Posiva's seismic stations.

The Laitila earthquake (M_L = 1.9) occurred 3.1.2007 about 40 km from Olkiluoto. The event was recorded also by the six triaxial geophones (OL-OS7…OL-OS12) of the Posiva's seismic network (see Figure 5-1). According to the recordings of the Posiva's network the displacement related to this event was 1 mm. In source calculations, the fault area is approximated by a circle. The source radius of the Laitila earthquake was about 43 m (Saari 2008). The recordings give also very good data when the attenuation of seismic signal in the Olkiluoto area is concerned.

The recordings of the Posiva's network were submitted to the Institute of Seismology, in order to improve the final analysis of the event. The Laitila event was recorded also in the seismic stations of the Institute of Seismology as well as in stations of Swedish National Seismic network (SNSN). Recordings of those three seismic networks were utilised when the location of the earthquake was re-estimated (Table 5-1) and also when the fault plane solution of the event was calculated.

The preliminary fault plane solution of the Laitila event was calculated in the Institute of Seismology, University of Helsinki. The analysis was based on recordings of seven stations of the institute of Seismology and two of Posiva and two stations of SNSN. According to the preliminary interpretation, the event occurred in nearly vertical N-S oriented fault. That interpretation fit nicely the mafic dykes in the site of the epicenter of the earthquake. The fault type was reverse faulting, where the eastern side has moved downwards relative to the western side. The orientation of compression related to the event was NW-SE ((Marja Uski, Personal communications, See details in Saari 2008). The orientation of the compressional axis is consistent with the estimated maximum in-situ stress field in Olkiluoto and elsewhere in Finland (e.g. Posiva 2003a and Reinecker 2005).

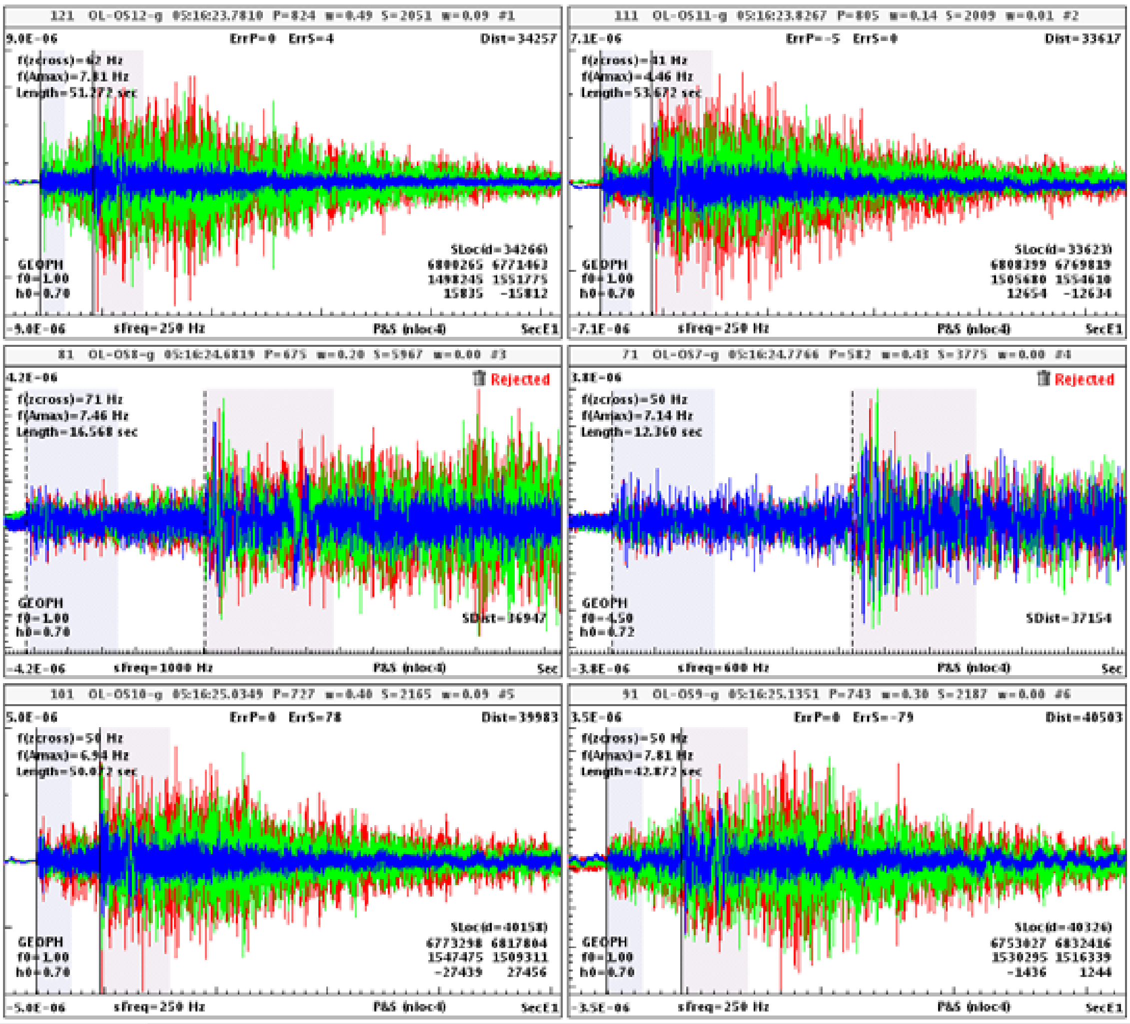


Figure 5-1. *Posiva's recording of the Laitila earthquake 3.1.2007. Different component of recordings are shown by different colours (Blue = vertical, Green = E-W and Red = N-S). Stations OL-OS9, OL-OS10, OL-OS11 and OL-OS12 were used when the event was located in Posiva's own analysis. Stations OL-OS8 and OL-OS7 were rejected in that procedure. Picks of P- and S-onset are shown by vertical lines.*

6 SUMMARY

This report summarizes the status of operation and results of the local seismic network in 2007. In February 2002, Posiva Oy established a local seismic network of six stations on the island of Olkiluoto. In the beginning, the network monitored tectonic earthquakes in order to characterise the undisturbed baseline of seismicity of the Olkiluoto bedrock. When the excavation of the ONKALO started, in August 2004, the network monitors also excavation induced seismicity. In that context two new seismic stations were installed.

In the beginning of the year 2006 the main target volume of the seismic monitoring was the underground rock characterisation facility and the rockmass surrounding it. The seismic network consisted of eight seismic stations designed for monitoring tectonic and excavation induced seismicity inside the network. The network included also two additional sensors for monitoring more distant seismic events. All the sensors were at the earth’s surface.

During the year 2006 the network has expanded with six new sensors. Installation of four new seismic stations equipped with triaxial 1 Hz geophones started the monitoring of semi-regional tectonic seismicity and explosions in February 2006. The new seismic stations locate from 3 to 7 km from the ONKALO. The fifth 1 Hz geophone was already in station OL-OS8, close to the ONKALO. Two borehole geophones were installed inside the ONKALO spiral at the end of 2006. The depths of the sensors are 139 m and 237 m. The borehole geophones aim to improve the sensitivity and the depth resolution of the measurements inside the ONKALO block.

There have not been any major upgrades of instrumentation in 2007. The performed upgrades are related to the quality of the seismic signal. Four partly damaged sensors were replaced by new ones. These stations suffered from disturbing 50 Hz noise, since the sensors partly damaged during the lightning in 2002. The cable of the deeper borehole sensor OL-OS14 was damaged during the installation. Within the year of 2007 the electric wires of sensor OL-OS14 corrupted slowly. In addition, the damages in electric wires caused disturbances to the upper sensor OL-OS13. Station OL-OS14 was permanently closed in October 2007.

The true orientation of the upper borehole sensor OL-OS13 was calculated. The correct orientation of triaxial seismometer is essential when the fault plane solution of an earthquake is calculated.

Main upgrades of data processing and interpretation were limited to software. All the three software packages were upgraded in 2007. New version of the software package for data processing and analysis (Jmts version10.1.1) was installed in May 2007. New versions of visualisation software package Jdi were installed in February (version 4.1), May (version 4.1.1) and December (Version 4.2). Jdi and Jmts are in the Vantaa office computer. The Run Time System (RTS) system of the Olkiluoto server was upgraded in November 2007. This software is responsible for the automatic acquisition of the data from the seismic stations.

The network has operated continuously in 2007. Partial failures of the network, which just lowered the quality of operation, were usually related to a single station.

Altogether 2207 events have been located in 2007. Most of them (1912) are explosions occurred inside the seismic semi-regional area and especially inside the ONKALO block (1891 events). The magnitudes of the observed events inside the semi-regional area range from ML = -2.1 to ML = 1.5 (ML = magnitude in local Richter's scale). All these events are explosions.

As regards to safeguards the conclusion of the explosions inside the seismic ONKALO block are similar to those in the seismic semi-regional area. Indications of illegal or inappropriate works, which would have influence on the safety of the ONKALO, have not been found.

The interpretation practice and the personnel responsible for the analysis has been the same as during the previous years. The sensitivity and the location accuracy of the measurements of the seismic network are better than during the previous years. Improvements of Finnish and Swedish national seismic networks have gained improvement of sensitivity also regional scale in Olkiluoto. In spite of those facts, there are no observations of semi-regional tectonic seismicity or excavation induced seismicity inside the ONKALO block in 2007. It can be concluded that according to seismic monitoring the rock mechanical conditions in the rockmass surrounding the ONKALO have been stable in 2007.

One of the recorded events was a local microearthquake (M_L = 1.9) outside the target area of the network. That earthquake occurred 3.1.2007 in Laitila about 40 km from Olkiluoto. The event was recorded also by the six triaxial geophones of the Posiva’s seismic network. These recordings from the Olkiluoto site are valuable in studies of regional seismicity, seismotectonics and seismic hazard. According to Posiva’s recordings the fault displacement related to the Laitila event was 1 mm and the source radius about 43 m.

Joint interpretation of recordings of three seismic networks (Posiva, Finnish and Swedish national networks) was used when the preliminary fault plane solution of the Laitila earthquake was calculated: The reverse faulting occurred in a nearly vertical N-S oriented fault which can be associated with mafic dykes in the area. The orientation of compression related to the event was NW-SE.

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APPENDIX 1: ORIENTATION OF SENSOR OL-OS13

SENSOR OL-OS13

OL-OS13 station coordinates are x = 6792191, y = 1525942 and z = -139.326. Sensor is installed in borehole, which is dipping β = -77.61° in direction of strike α = 344.45°. Dip angle in these calculations is angle from horizontal plane and strike is angle from north rotated clockwise. These angles were measured directly from borehole. Besides these angles orientation of the sensor needed roll angle γ, which is angle of the sensor rotating clockwise around sensors z-axis in a borehole. In progress of orientation we used locations from Jmts-programs. This program produces two kinds of locations: first normal network location which uses all available stations and second uses only one triaxial station to produce location. The sensor orientation was defined comparing these locations.

Euler angles

Two of three axis of coordinate system were rotated three times to obtain orientation of the borehole sensor (Figure A-1). First rotation was z-axis which was rotated with angle of strike = α, second rotation was x-axis which was rotated with angle of dip = β and third rotation was again rotation of z-axis with angle of roll = γ.

Rotation matrix for R_1 (z-axis), R_2 (x-axis) and R_3 (z-axis):

$$R_1(\Phi) = \begin{pmatrix} \cos\Phi & \sin\Phi & 0 \\ -\sin\Phi & \cos\Phi & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

$$R_2(\Theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\Theta & \sin\Theta \\ 0 & -\sin\Theta & \cos\Theta \end{pmatrix} \tag{2}$$

$$R_3(\Psi) = \begin{pmatrix} \cos\Psi & \sin\Psi & 0 \\ -\sin\Psi & \cos\Psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

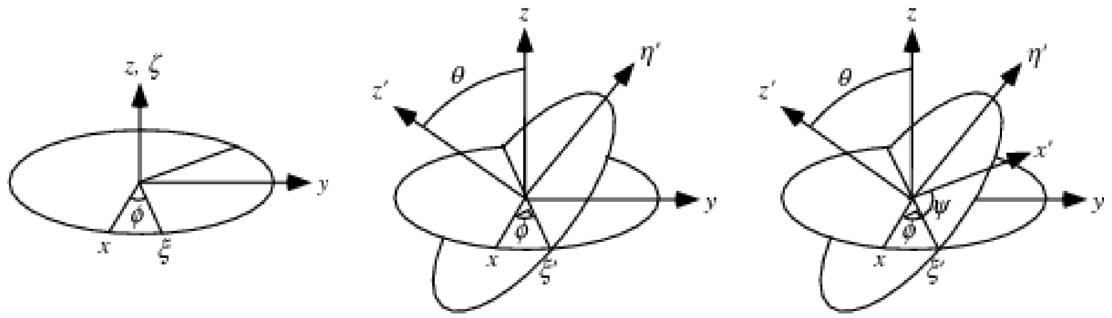

Figure A-1. *Three Euler angles for z-axis (Φ), x-axis (Θ) and z-axis (Ψ). Reference: http://mathworld.wolfram.com/EulerAngles.html*

Matrix calculation for strike (α), dip (β) and roll (γ):

$$R = R_3(\alpha)R_1(\beta)R_3(\gamma) = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & \sin\beta \\ 0 & -\sin\beta & \cos\beta \end{pmatrix}\begin{pmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (4)$$

New coordinates equations calculated from equation 3:

$$N' = E*(-\sin\alpha*\cos\gamma - \cos\alpha*\cos\beta*\sin\gamma) + N*(\sin\alpha*\sin\gamma + \cos\alpha*\cos\beta*\cos\gamma) - Z*\sin\beta*\cos\gamma \quad (5)$$

$$E' = E*(\cos\alpha*\cos\gamma - \sin\alpha*\cos\beta*\sin\gamma) + N*(\cos\alpha*\sin\gamma - \sin\alpha*\cos\beta*\cos\gamma) - Z*\sin\alpha*\sin\beta \quad (6)$$

$$Z' = E*-\sin\beta*\sin\gamma - N*\sin\beta*\cos\gamma + Z*\cos\beta \quad (7)$$

Sensor orientation

Two different kinds of locations were used to orientate the OL-OS13 sensor. For one event there are three locations: one is with station network location, which is most accurate and the two less accurate are single triaxial station locations (Figure A-2). Blue squares (Network) are network locations of the blast located with Jmts. Yellow triangles (Triaxial2) and red squares (Triaxial2) are stations OL-OS13's symmetrical single triaxial station locations for the same events. Only the one set of those symmetrical locations are true. The other set is opposite side of the sensor. Red triangle is OL-OS13.

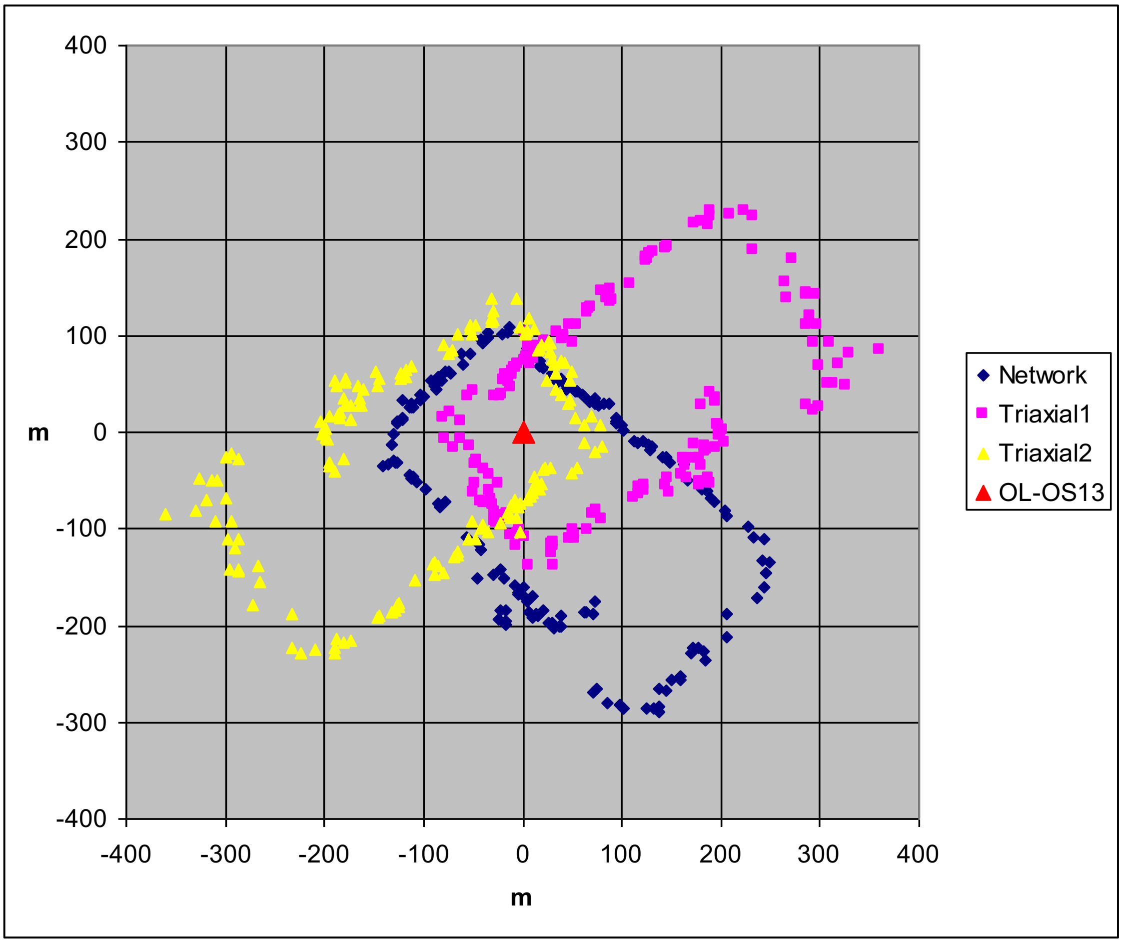

Figure A-2*. Original situation. Locations viewed from up. Network location (blue squares), yellow triangles (Triaxial2) and red squares (Triaxial1) are stations OL-OS13's (red triangle) single locations.*

The events used in this orientation are from 2 February 2007 to 16 April 2008. There are 162 different events. Their distances are from 100 to 350 meters from OL-OS13. Event depths range from -170 to -280 meters, which means 30 to 140 meters below OL-OS13.

When already known strike and dip are placed in the equation 5, 6 and 7, single triaxial stations locations can be rotated (Figure A-3).

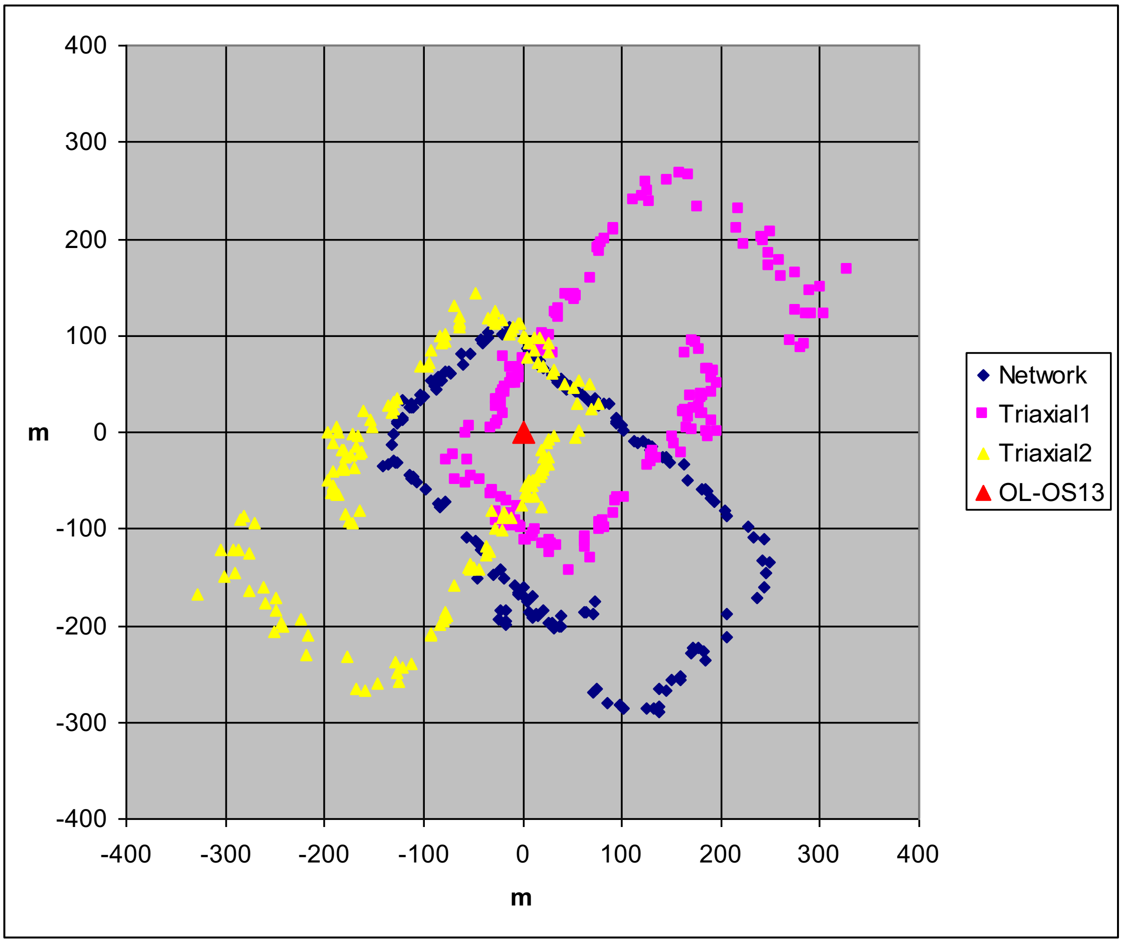

Figure A-3. *Original situation with borehole corrections. Locations viewed from up. In this Figure sensor locations are rotated with α = 344.45˚ and β = -77.61˚ relative to station OL-OS13 (red triangle). Roll is not included. Yellow triangles (Triaxial2) and red squares (Triaxial1) are station OL-OS13's single locations. Blue squares are real Jmts- locations (Network).*

The value for the roll is estimated by eye from Figure A-3. The purpose is to get yellow triangles or pink squares to match with blue squares like in Figure A-4 and A-5. The roll is positive angle rotated clockwise around sensors z-axis.

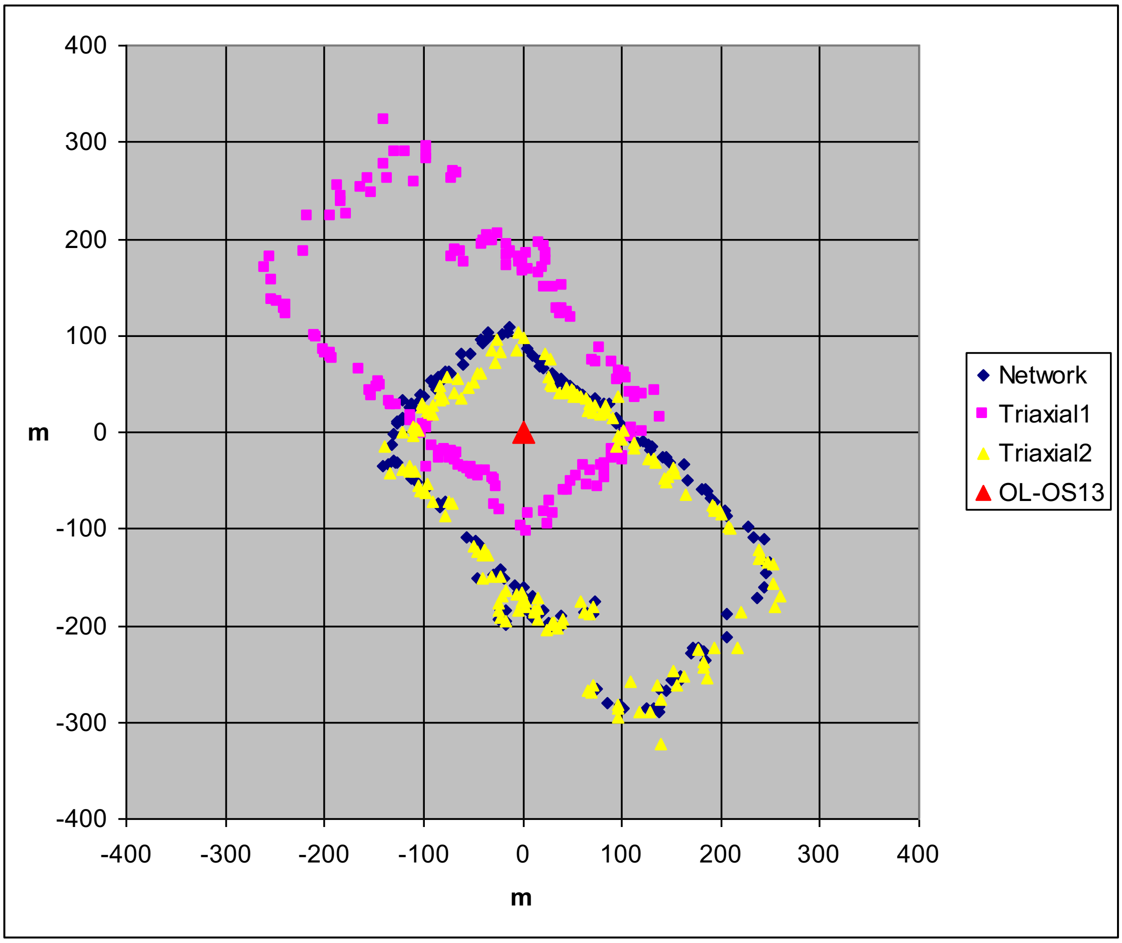

Figure A-4. *Fully rotated locations viewed from up. In this Figure sensor locations are rotated with α = 344.45˚, β = -77.61˚ and γ = 276 relative to station OL-OS13 (red triangle). Yellow triangles (Triaxial2) and red squares (Triaxial1) are station OL-OS13's single locations. Blue squares are networks Jmts- locations.*

View from side shows how good source information was. Because borehole is larger than sensor, they are not necessarily in same position. Figure A-5 we show that sensor dip could be a little better. The sensor angles are improved with a help of Figures A-4 and A-5.

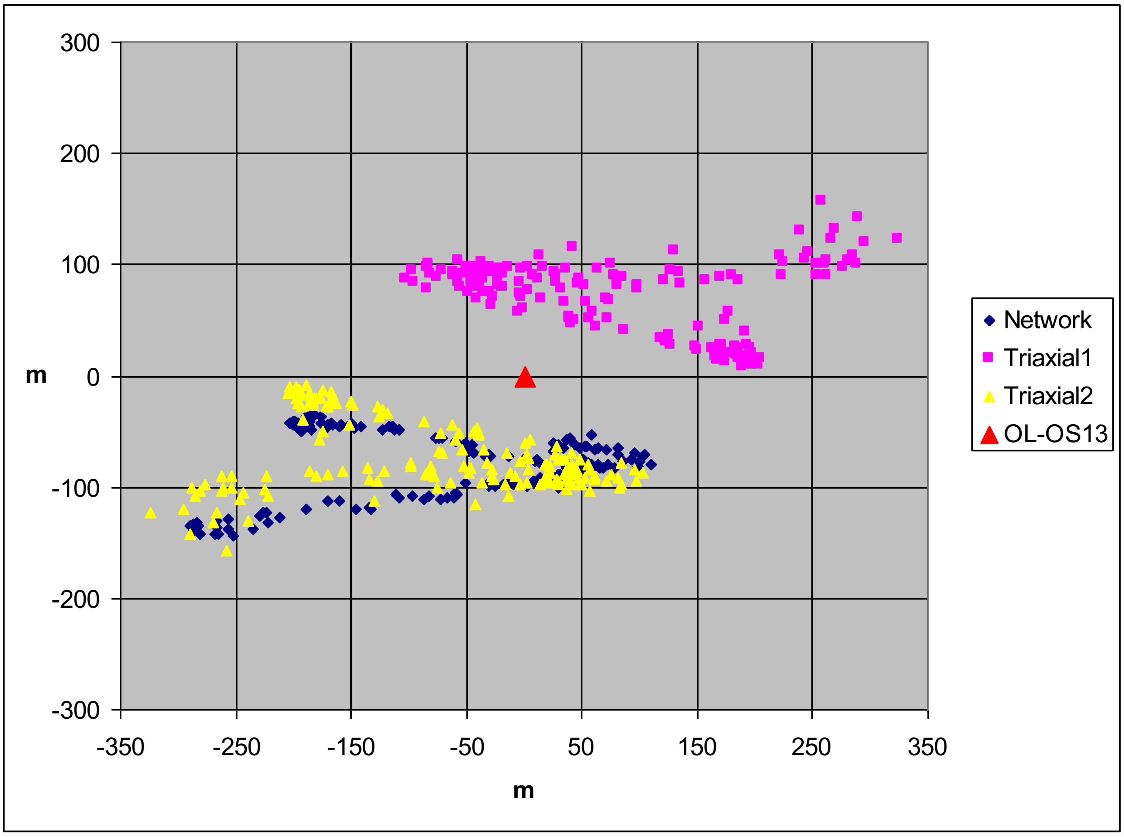

Figure A-5. *Fully rotated locations viewed from south. In this Figure sensor locations are rotated with α = 344.45˚, β = -77.61˚ and γ = 276 relative to station OL-OS13 (red triangle). Yellow triangles (Triaxial2) and red squares (Triaxial1) are station OL-OS13's single locations. Blue squares are networks Jmts- locations.*

If we give dip a new value of -68˚, we get better values for different angles: strike α = 344.45˚, dip β = -68˚ and roll γ = 276˚. This is the final dip value. After fixing azimuth difference (Figure A-6 and A-7) and dip difference (Figure A-8 and A-9) to be as small as possible we get better α and γ values to the station orientation. This fixing is made by eye and least square fit.

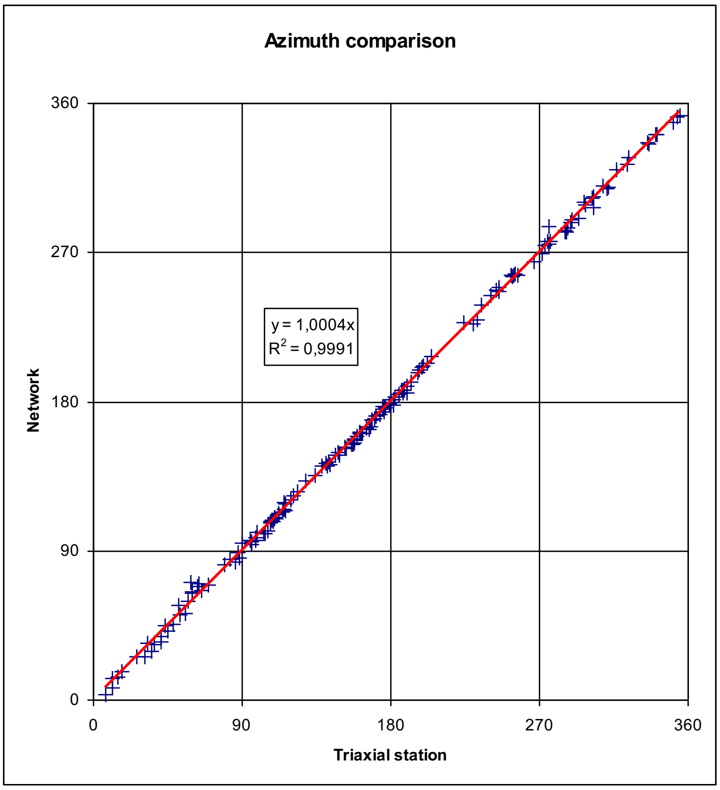

Figure A-6. *Final solution. The azimuth comparison between network (y-axis) and triaxial station (x-axis). The azimuth values are blue cross signs and red line is trend line. Slope for trend line is y=1.0004x and power of correlation coefficient is R^2=0.9991.The azimuth determines the horizontal angle of incidence of the seismic signal.*

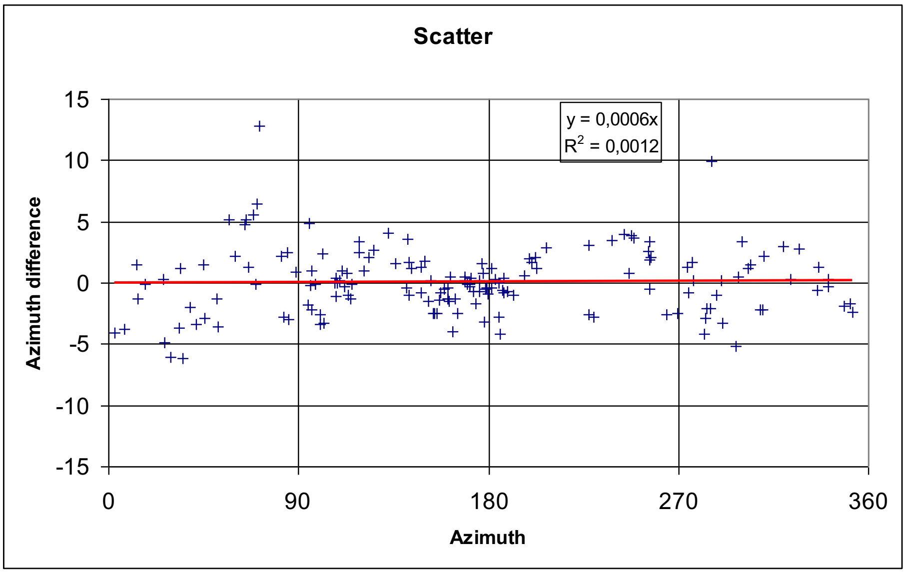

Figure A-7. *Final solution. Scatter of azimuth difference between networks and triaxial stations azimuths. Blue cross signs are difference versus azimuth at certain azimuth angle. The red line is a trend line with slope y=0.0006x and power of correlation coefficient R^2=0.0012. The azimuth difference is mainly less than 5°.*

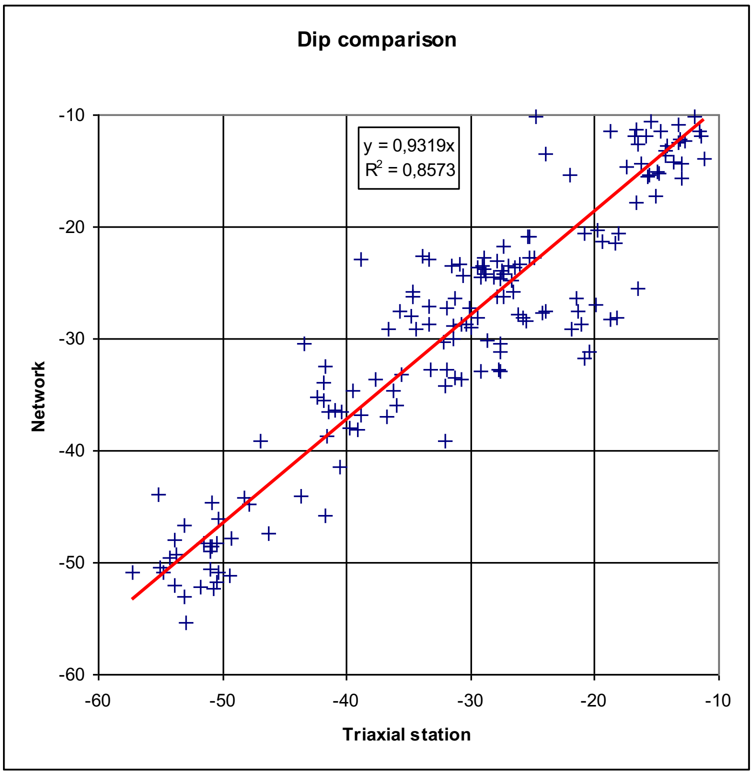

Figure A-8. *Final solution. Dip comparison between network (y-axis) and triaxial station (x-axis). The dip values are blue cross signs. The red trend lines slope y=0.9319x and power of correlation coefficient* R^2*=0.8573.*

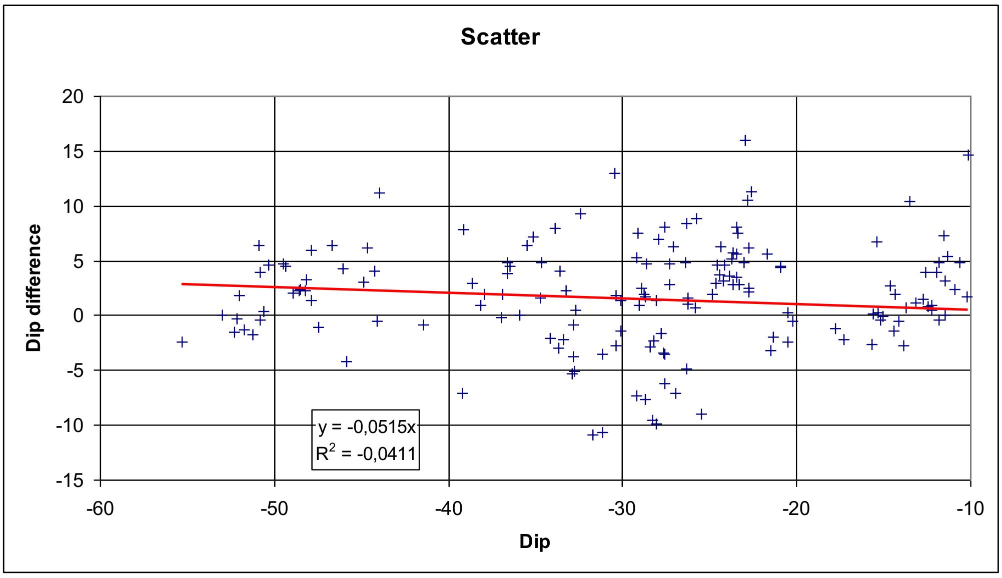

Figure A-9. *Final solution. Scatter of dip difference between networks and triaxial stations dips. Blue cross signs are dip difference versus real dip. The red trend lines slope is y=-0.0515x and power of correlation coefficient* R^2*=-0.0411. The dip difference is mainly less than 10˚.*

After all of these fixings and fine tunings the final values for sensor orientations are: strike α = 335˚, dip β = -68˚ and roll γ = 285˚. Final Figures A-10 and A-11 shows the uniformity between network and triaxial locations.

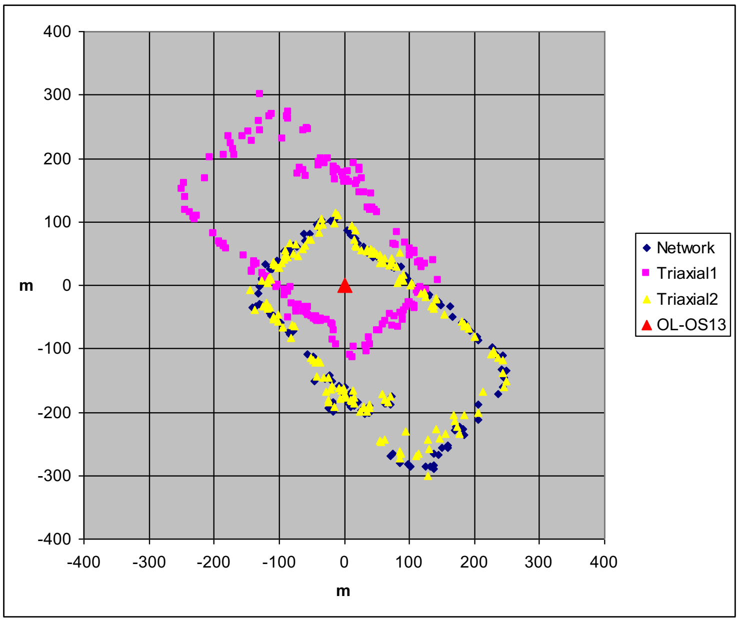

Figure A-10. *Final locations viewed from up. In this Figure sensor locations are rotated with α = 335˚, β = -68˚ and γ = 285˚ relative to station OL-OS13 (red triangle). Yellow triangles (Triaxial2) and red squares (Triaxial1) are station OL-OS13's single locations. Blue squares are real Jmts- locations (Network).*

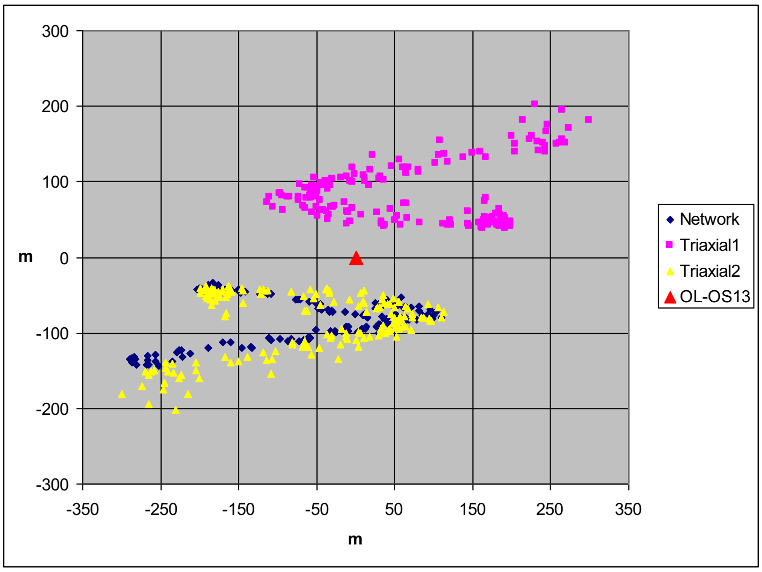

Figure A-11. *Final locations viewed from south. In this Figure sensor locations are rotated with α = 335˚, β = -68˚ and γ = 285˚ relative to station OL-OS13 (red triangle). Yellow triangles (Triaxial2) and red squares (Triaxial1) are station OL-OS13's single locations. Blue squares are networks Jmts- locations.*