# Deformations and global forces: Seismic and hydrostatic leveling records in the « Mont Terri » rock laboratory (Switzerland)

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**Key words**: Broadband seismometer, hydrostatic leveling system, high-precision ground deformation, long-term stability, vertical displacement, synchrotron, Earth tides

## SUMMARY

The Mont Terri rock laboratory is a research facility in the Jura Mountains of Switzerland. Investigations are being carried out in the 'Opalinus Clay' rock formation, which is a potential host rock for a future deep geological disposal of radioactive waste. The rock laboratory has been excavated from the safety gallery of the Mont Terri motorway tunnel.

In 1998, Gallery 98 was excavated parallel to the safety gallery. At the southern end of Gallery 98, a fault zone intersects the rock laboratory. This zone is called the Main Fault, and reveals a decametric displacement that took place during the folding and thrusting of the Jura Mountains about 10 Ma years ago. It is not known yet whether the Main Fault is still active. A feasibility study, using the best commercially available monitoring instruments, was performed to investigate possible movements. A 50 m long hydrostatic leveling system (Type PSI-SLS) was installed across the fault zone together with a broadband seismometer (STS-2.5). The combination of both instruments allows recording submicron-displacements within a large frequency range up to quasi steady state deformations. The global gravity forces due to Sun and Moon (expressed as Earth tides) and the micro-seismicity due to the waves in the Atlantic Ocean generate larger "noise" signals than the nearby motorway. This regular background noise is well known and can be used as a perfect calibration signal.

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## 1. INTRCODUTION

A feasibility study was performed using a broadband seismometer and a Hydrostatic Leveling System (HLS) across a geological fault zone, known as the Main Fault, in the Mont Terri rock laboratory in Switzerland. The goal of the feasibility study was to develop and to test various methods to monitor underground movements and deformations with the highest accuracy and resolution, ranging from long-term deformations (low frequency) up to the seismic range. The following questions had to be answered:

- Can we record any recent deformation on the Main Fault?
- Are the Earth tides recordable with the Hydrostatic Leveling System (HLS)?
- What is the level of seismic noise in the Mont Terri rock laboratory in the frequency range from quasi-static up to 200 Hz?
- What are the natural movements; what is the influence of traffic on the nearby highway; and what is the influence of the air turbulence originating in the nearby safety gallery?
- How large is the man-made noise due to the activities in the laboratory?
- Does the planned linear configuration of the HLS give different results compared to the circular configuration as it is implemented in the SLS accelerator at PSI?

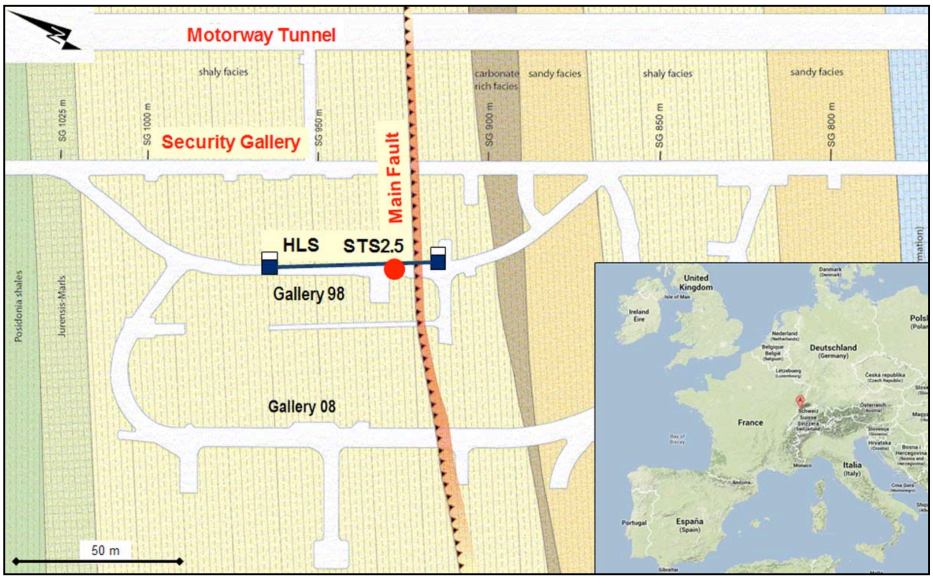


**Fig. 1):** Experiment location: blue: HLS; red dot: seismometer STS-2.5

To collect the data required to answer the questions posed a broad band seismometer was installed in Gallery 98 (Figures 1 & 2). It is the latest generation of one of the best broadband seismometers available from Streckeisen GmbH, the STS-2.5. It records the smallest ground motions very accurately. The seismometer is mounted on three feet and observes the small-scale local movements in 3 axes (3-components). However, it can only record measured movements for duration of up to a few hours.

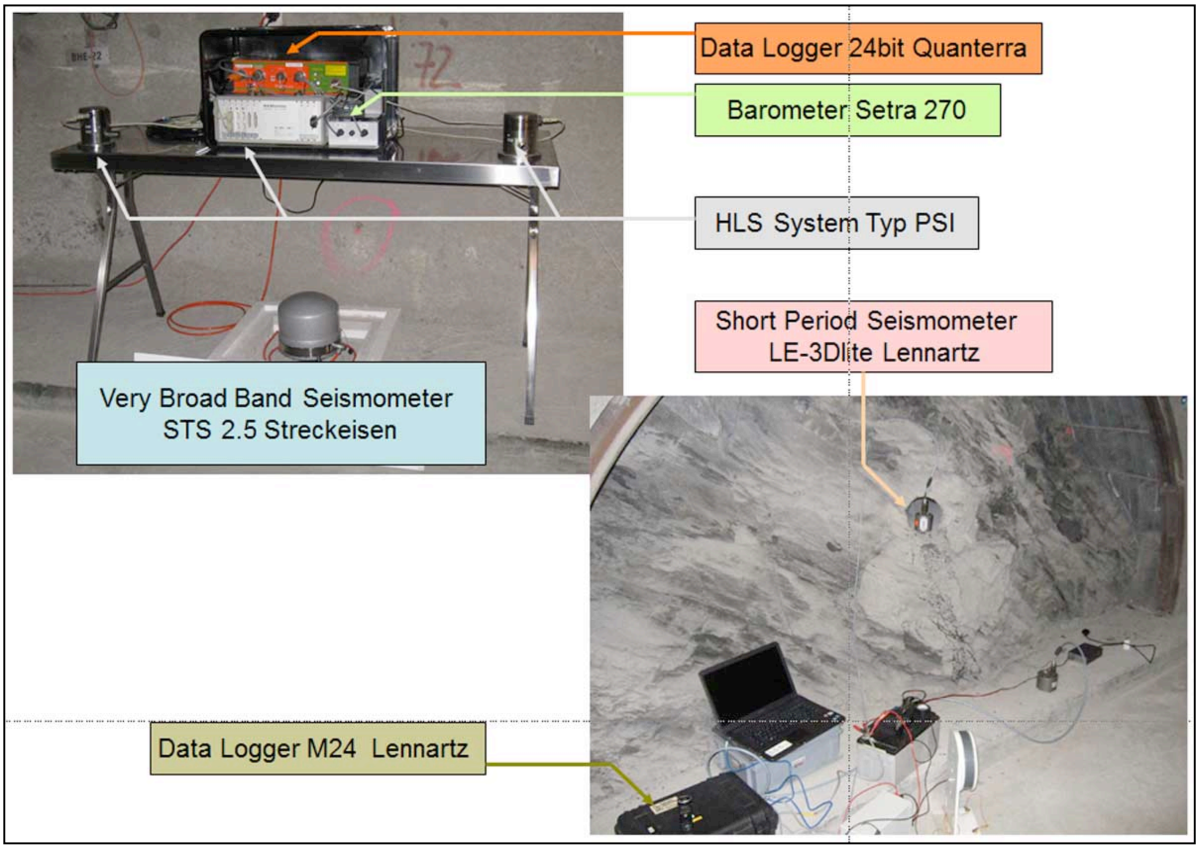


**Fig. 2):** Experiment equipment overview

In order to monitor the long-term, slow and quasi-permanent displacements, a transparent water tube of 50 m length was also installed. The tube is half-filled with liquid. Level sensors placed at each end of the tube measure the water level (Figure 3), essentially functioning like a large water level. We call it the Hydrostatic Leveling System (HLS). With the HLS, large-scale tilting or faulting of the rock mass in a range of less than 0.1 micrometer can be detected. These HLS level sensors were initially developed more than ten years (Ingensand, 2001) ago for the Paul Scherrer Institute (PSI), specifically for high precision ground monitoring of the Swiss Light Source Synchrotron (SLS) in Villigen (Switzerland) (Wei, 2004).

While data was being collected with the HLS, a group of Stuttgart University acquired seismic data with multiple low-cost high-frequency seismometers (LE-3Dlite Lennartz).

## 2. INSTRUMENTATION

### 2.1 Hydrostatic Leveling System HLS

Hydrostatic measuring systems are used for static or dynamic measurements in spacious areas. The advantages of hydrostatic measuring systems are their high accuracy and resolution compared to other modern geodetical instruments such as digital levelers or tachymeters.

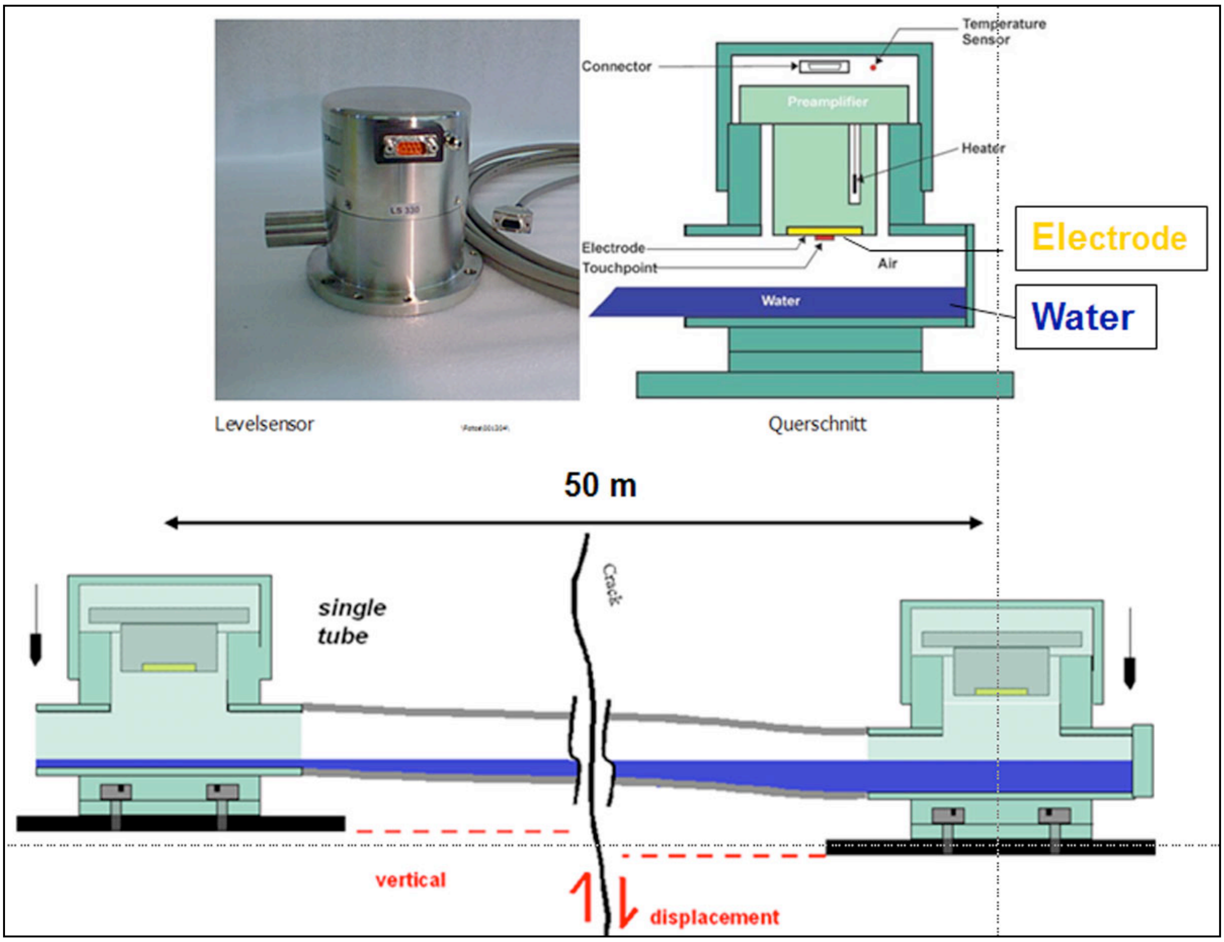


**Fig. 3):** HLS measuring principle

The fundamental principle of every hydrostatic leveling system is based on the fact that the water surface always aligns with an equipotential surface (Figure 3). In connected measuring cups the law of communicating vessels applies, meaning that in each of the measuring cups the water level is at the same height (Meier, 2012). The used HLS Type “PSI” was developed for the Swiss Light Source Synchrotron (SLS) at the Paul Scherrer Institute (PSI), where 192 HLS sensors have been monitoring the height changes of the magnets along the 300 m long circumference of the synchrotron continuously over a period of more than 10 years. The interconnection between the sensors is done with a half filled tube, which gives the most accurate results.

## 2.2 Seismometer STS 2.5

The Streckeisen STS-2.5 is a high-performance, portable, broadband, triaxial seismometer (Figure 4). The sensor performance is equal to the world-standard STS-2 broadband sensor. It has a dynamic range of 145 dB, low power consumption (average 0.45 W) and covers a wide temperature (-20 C to 70 C guaranteed) and humidity (0-100% RH) range without the need for readjustment. The sensitivity is constant at 1500 Volts/(meter/sec) from ~ 0.01 Hz (120 s) - 50 Hz, with parasitic resonances above 140 Hz for the vertical and above 80 Hz for the horizontal component. The STS-2.5 can resolve ground noise between 10 mHz and 10 Hz at the quietest locations in the world. At MontTerri the STS-2.5 allows to resolve ground noise over an even broader frequency band.

## 2.3 Seismic data acquisition Quanterra Q330S+

The Q330S+ is the newest member of the world-standard Q330 family, and is an advanced 6-channel broadband, high-resolution seismic data recorder. It uses the proven IP networking technology in a very low-power field package (12VDC nominal, ~1.0 W avg. cycled, ~2.4 W avg. continuous). The telemetry protocols use industry-standard UDP (User Datagram Protocol) or TCP (Transmission Control Protocol) transport layers. The dynamic range of the Q330S+ is typically ~138 dB wideband RMS, while the low frequency may exceed 145 dB. Sampling can be done at a rate up to 1000 samples per second. The sensitivity of the digitizer is $2^{24}$ counts / 40 V or 2.4 microvolts/count. The time base is precision TCXO, locked to GPS, so no adjustment is necessary. Instead of two 3-component seismometers two HLS channels and one barometer channel were connected to the Q330+. The data was stored internally on a PC-formatted removable 64 GB USB stick. During operations the data can be inspected in real-time over Ethernet.

## 2.4 Barometer

The precision barometric signal is derived from a Setra System model 270. It is able to resolve very small changes in air pressure (0.1 Pa rms @ 1Hz) over a large pressure range. The analog version of the Quanterra barometer contains an analog output for use with external A/D. The barometer housing includes a small circuit board containing an isolated DC/DC converter. This version has a low-voltage cutoff, and requires a minimum of ~ 11 V to operate. Power required is ~ 550mW @ 12 V. The calibration factor for the barometer output is 7000 counts / hPa.

## 3. INSTALLATION

### 3.1 Seismometer

On 4 September 2012, the seismometer STS-2.5 and the data acquisition unit Quanterra Q330S+ were set up for testing and checks in a cavern outside Gallery 98 (Figure 5). On 5 September 2012, the seismometer was moved to its final position in Gallery 98 (Figure 1), diagonally across the HE (Heater Experiment) niche on the concrete pedestal, located 10 m away from the door. The seismometer was not oriented to the geographic North direction, but instead the x-component was aligned parallel to the gallery, the y-component transverse to it and the z component vertically up. To shield the seismometer against temperature variations and air draft a 10 cm thick Styrofoam box, covered with a rescue blanket was used.

**Fig. 4):** Seismometer STS2.5

**Fig. 5):** Installation of the seismometer STS2.5

### 3.2 HLS

The installation of the HLS system across the Main Fault in Gallery 98 started on 4 September 2013 (Figure 6). The two HLS sensors were mounted on stainless steel consoles (Figure 7). Since the shotcrete was much thicker than expected, up to 50 cm in thickness, the consoles were mounted with 2 M20 threaded rods of 100 cm length. The rods were fixed with two components adhesive 50 cm deep in the Opalinus Clay. Neither the rods nor the consoles are in contact with the shotcrete. To prevent the Opalinus Clay from absorbing humidity, the space between rods and shotcrete was sealed with silicone.

The two HLS sensors were connected by transparent acrylic glass (PMMA) tubes of 2 m length, joined by silicon tube segments, adding to a total length of 50 m. For horizontal installation of the tubes a Leica laser was used. A suspension device, at fairly regular intervals of about 1 m, was used to carry out the mounting of the tube. It consists of vertically installed threaded rods, fixed to the shotcrete on the upper end, and a clamp on the lower end for tube attachment and vertical adjustment. Because of the frequently readjustments necessary in the beginning, the suspension device should be optimized for the next installation.

**Fig. 6):** HLS acrylic glass tube installation using a laser beam in the rock laboratory, Gallery 98

**Fig. 7):** HLS sensor North on stainless steel console mounted with 2 one meter long M20 threaded rods

## 4. MEASUREMENTS

### 4.1 Costa Rica Earthquake - Relation of signal and noise

Around 4 hours after the installation of the seismometer on the final position in Gallery 98, on 5 September 2012, a strong earthquake occurred in Costa Rica (Figure 8).

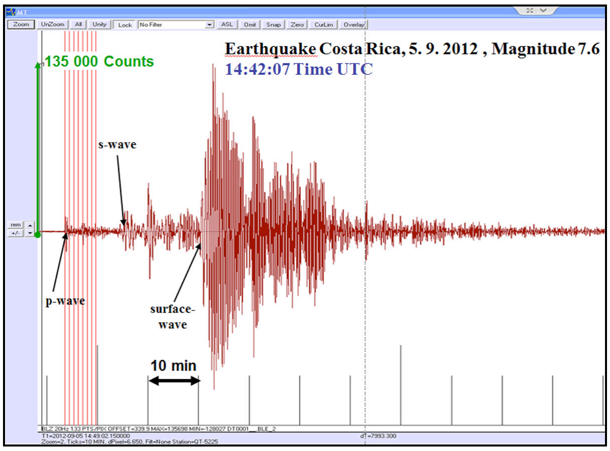


**Fig. 8):** Costa Rica Earthquake, 5 September 2012, magnitude 7.6, recorded at Mont Terri rock laboratory. Plot scale 135 000 counts

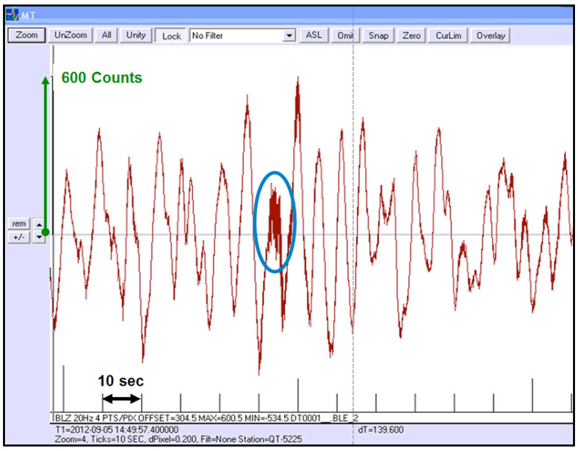


**Fig. 9):** Microseismic noise, shortly before the Costa Rica Earthquake from 5 September 2012. Plot scale 600 counts

The plot of the recorded signal shows 10 min intervals in the time domain (x-axis) and an automatically scaled y-axis of 135’000 counts. One count is the lowest digitizing unit.

Due to the automatic scaling, there is no signal visible at the beginning of the plot. However, 17 minutes after the earthquake P-waves (primary waves) were detected at Mont Terri, followed by S-waves (secondary waves) after approximately 30 minutes, and finally surface waves 45 minutes later.

An enlarged detail of the ambient 'noise' at the beginning of the diagram is shown in Figure 9. The length is about two minutes and the peak amplitude is about 600 counts. The signal represents the typical marine microseisms "noise", which has a period of about 7 seconds. The origin of this noise will be explained in section 5.1.

The superposition with higher frequencies in the middle of the plot (blue circle) could be the result of works in the rock laboratory or cars passing on the nearby highway.

### 4.2 Masset, Canada Earthquake and Earth tide recorded with HLS

After finishing the installation of the HLS system on 12.10.2012, the first strong earthquake recorded with both systems was in Masset, along the Pacific coast of Canada, on 28.10.2012 (Figure 10). The green dot in the north shows the location of the earthquake. This earthquake took place 53 days after the Costa Rica earthquake (Figure 8).

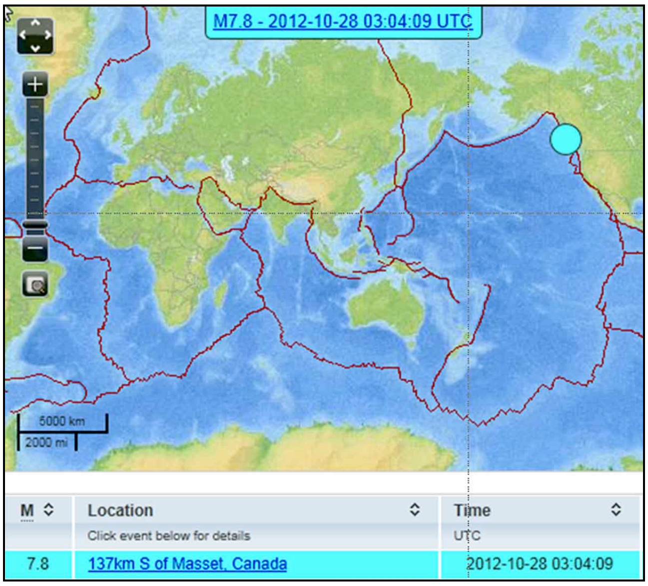


**Fig. 10):** Masset Canada earthquake, 28.10.2012 03:04h, magnitude 7.8

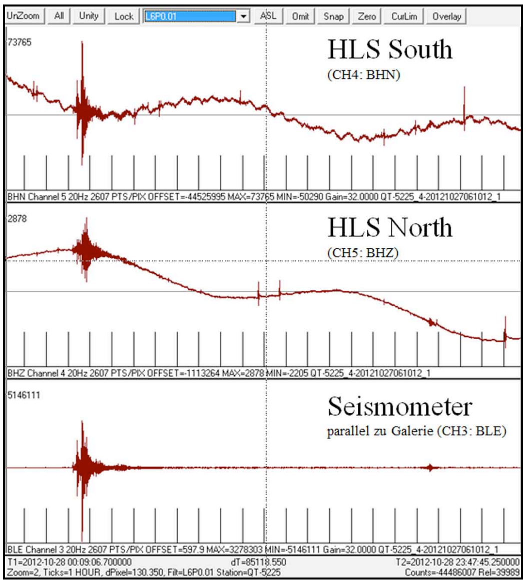


**Fig. 11):** Masset Canada Earthquake, HLS and seismometer one day record

The plots in Figure 11 show a time period of 1 day. They indicate good correlation of the recorded signals of the event between the HLS and the seismometer channels. For the seismometer, the channel parallel to the gallery showed the strongest signal (channel shown in Figure 11). The HLS plots reveal low frequency, semidiurnal waves with an opposite sign and a signal drift in the time domain. The waves represent the Earth tides, whose dominant components have a period of ~12 and ~24 hours. The signals show the different characteristics of the two systems. The seismometer displays a velocity proportional signal, whereas the HLS records the tilt angle between two HLS sensors. The tilt is calculated from the distances of the electrodes in the sensor (see Figure 3) to the free water surface at each end of the tube. The signal drift is due to evaporation of the HLS liquid and cancels when the tilt is determined from the difference. The HLS Signal South shows a local oscillation of about 45 min, which is not visible on the HLS Signal North. The source of this oscillation is presently unknown.

### 4.3 HLS three weeks record with record of a remote earthquake

During the recorded 3-week time interval over the 2012/13 New Year, an earthquake with a magnitude of 7.5 took place in Alaska on 5 January 2013. The following plots show remotely taken screenshots of the online signals recorded for this earthquake for different time periods after the event (Figures 12, 13). In the upper left corner of the screenshots, the GPS signal for absolute time synchronization is visible. The width of the time window is 120 seconds.
Figure 12 shows the signals of the Alaska earthquake at the Mont Terri rock laboratory 90 minutes after the event. In case of the HLS (channel 4 and channel 5) it can be recognized that the signals of level sensor north and south have opposite characteristics, i.e. wave peak and wave trough are opposed. In contrast, the signals of the HLS north sensor and the seismometer channel 3 (orientation horizontal, parallel to the tunnel) are almost synchronous.

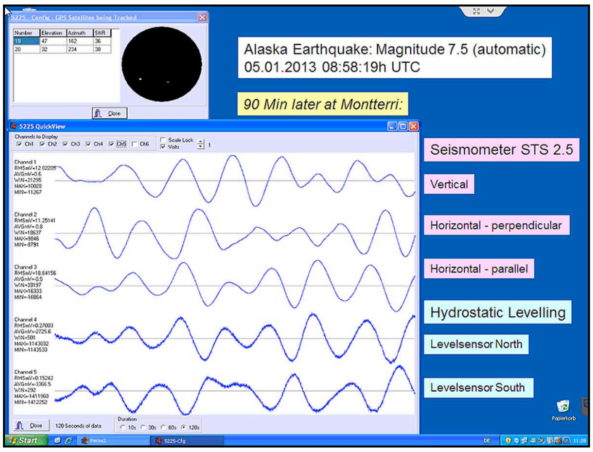


**Fig. 12):** Alaska Earthquake, 05.01.2013 08:58:19 h, recorded 90 min later at Mont Terri. The time window is 120 sec. The dominant period of the waves is about 30 sec

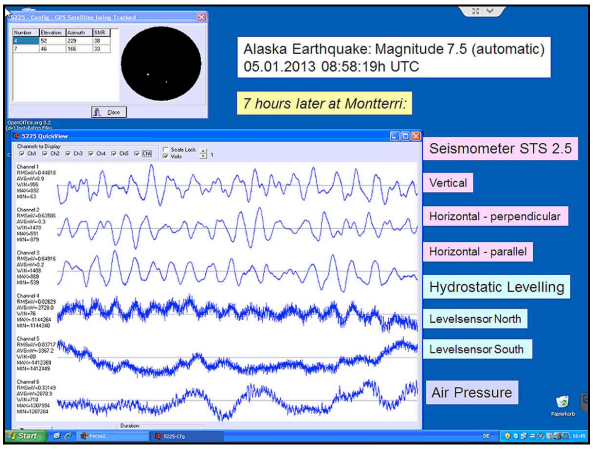


**Fig. 13):** Alaska Earthquake, 05.01.2013 08:58:19 h, recorded 7 hours later; additional air pressure channel. The time window is 120 sec. The dominant period is now 7 sec, the marine microseisms, which is visible also at HLS.

After 7 hours, due to the automatic scaling the signals are much noisier, especially the HLS signals (Figure 13). In this figure the air pressure is also displayed (channel 6). The signals of the seismometer and the HLS sensor north show the marine microseisms. No correlation of the signals with the air pressure can be seen. However the signal of the HLS sensor South no longer shows the opposite sign compared to the HLS sensor north as is visible in the previous plot. Please note that the far HLS sensor (North) shows a perfect correlation with the horizontal component of the seismometer (channel 3), but not the close HLS sensor (South).

## DISCUSSION OF THE RESULTS

### 5.1 Low background noise record with seismometer

At the Mont Terri rock laboratory we expected quite noisy results because of the traffic in the nearby highway tunnel, the normal work done in the laboratory, and the ventilation of the tunnel. However, the noise recorded with the broadband seismometer STS-2.5 was very low. Figure 9 shows the noise recorded one hour after the installation. The noise is dominated by the marine microseisms with a period of about 7 seconds. The origin of this noise is the load of the waves coming from the Atlantic Ocean (Friedrich et al., 1998). We call the microseisms ”noise”, but in fact it can also be used as a calibration signal. In winter this signal can be up to ten times larger than in summer. Large storms over the Atlantic Ocean lead to a temporarily increased signal. At quiet places the marine microseisms can be resolved very well everywhere in Europe. Near cities this 7 second periods can often not be seen, because the noise generated by the traffic is larger than the marine microseisms, although it can be resolved by applying a low-pass filter.

The grey shaded part in Figure 14 shows the noise spectrum of the seismometer record (vertical component) during a 4 hour period on 25 December 2012, 0 h - 4 h UT. The horizontal axis spans from $10^{-3}$ Hz (=17 min) to 250 Hz (=0.04 s). The vertical axis displays the acceleration power spectral density in dB relative to an acceleration of 1 $m/s^2$. Such diagrams are well known in broadband seismometry. A quiet site would show up as a line in the lower part of that diagram and a noisy site in the upper part. The record from the broadband seismometer, Streckeisen STS-2.5, is shown in blue and from the short period seismometer, Lennartz LE-3Dlite, in red. The grey line shows the New Low Noise Model (NLNM), which is the lower envelope of vertical acceleration power spectral densities from many globally distributed seismic observatories (Peterson, 1976). No station with lower seismic noise than the NLNM is known. It is obvious that the blue line has a similar shape to the NLNM line. However, vertical noise in the rock laboratory is 10 to 20 dB higher than the global minimum. The highest peak is around 7 seconds, which corresponds to the marine microseismic peak. Between 8 and 2 seconds the records of the seismometers Streckeisen STS-2 and Lennartz LE 3Dlite are exactly on the same line. From 0.5 Hz to higher frequencies the red curve recorded by the LE-3Dlite turns to a straight line, continuing up to 200 Hz. This line does not represent the environmental noise, but the instrumental noise of the LE-3Dlite. Only signals that are clearly above that line can be detected. Such a signal can be seen at around 8 Hz. At that frequency the short period seismometer LE-3Dlite, as well as the broadband seismometer STS-2.5 show the same peak. According to the specification of the STS-2.5 the instrumental noise is below the Peterson Low Noise Model in the plotted frequency range. All the peaks in the blue spectrum above 1 Hz come from anthropogenic noise sources like pumps, compressors and other equipment. The increasing noise floor for frequencies above 2 Hz is most likely due to the traffic on the motorway. In the lower frequency range, around $10^{-2}$ Hz (ca. 2 min) the site is very quiet.

## 5.2 Expanded background noise with HLS

The left part of Figure 14 shows the plot of the power spectral density expanded with the HLS signal spectrum (green line). This green line is calculated from a 3-week record. The HLS measures the height difference of a water surface relative to the rock to which the HLS is attached. The water surface adjusts itself normal to the vector of gravity, whose direction relative to the rock changes in response to tidal forces. The resulting signal is equivalent to a small periodical horizontal acceleration. On the other hand, the signal from the seismometer is proportional to the vertical ground velocity, which has been converted to acceleration for this analysis. The frequency content of both signals can therefore be compared, but not the noise level. The noise level of the HLS starts about 50 dB higher than the seismometer. In contrast to the seismometer, the HLS is not placed at one position only and it is also not isolated against thermal influence. The prominent peaks at periods of 1 day and 0.5 days are the signals of the Earth tides.

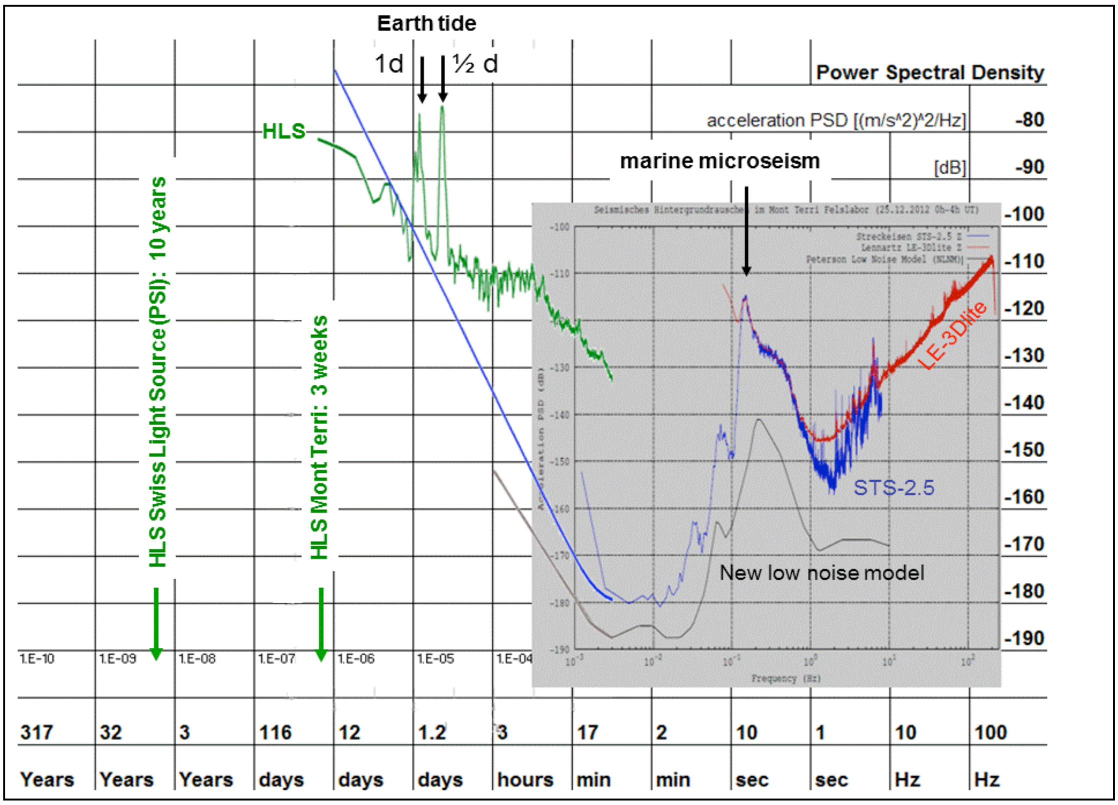


**Fig. 14):** Seismic background noise expanded with HLS Signal

The straight line seen on the left hand side of Figure 14 shows the theoretical self generated noise that is typical of broadband seismometers. Left of this line the ground motion cannot be observed with seismometers because the noise generated by the instrument is higher than the signals detected from the ground. With a broadband seismometer, seismic signals with periods up to one day can reasonably be recorded, but the signals are normally not processed up to such long periods. At lower frequencies, systems that are sensitive to static horizontal acceleration such as the HLS offer better performance. The label “HLS..3 weeks” indicates the observation period at “Mont Terri”. At the “SwissLightSource” Synchrotron a continuous HLS dataset spanning more than 10 years is available. This allows us to document yearly and secular events.

### 5.3 Correlation of HLS signal with horizontal component of the seismometer

With the HLS system detection of remote earthquakes is also possible, as shown in Figure 11. This is surprising finding because the water is not able to flow sufficiently quickly along the 50 m tube. An explanation of this behavior is given in Figure 12. It shows an online screenshot of the waves of the Alaska earthquake recorded at the Mont Terri rock laboratory 90 minutes after the event. This plot displays very good correlation between channels 3 and 4. Channel 3 is the horizontal component of the seismometer, which is oriented along the tunnel axis. Channel 4 is the HLS sensor to the North. Seven hours later, the earthquake is not visible anymore (Figure 13). At this point, as usual, the marine microseism is again the largest signal. Note, however, that the HLS sensor North (channel 4) still correlates with the horizontal component of the seismometer (channel 3). A similar correlation was observed between the horizontal component of a seismic signal and a differential pressure system when monitoring a bridge (Meier, 2010). In figure 13 the local air pressure is plotted too. Obviously, in this period range there is no correlation between the air pressure and the signals, neither the seismic nor the HLS signals. Now it is possible to understand why the HLS can react so fast. It would seem that it has a short-term and a long-term response. The high-frequency response is controlled by the horizontal acceleration of the tube while the water tends to remain in its place due to inertia. At one end of the tube system, where the HLS sensors measure the position of the liquid surface, the liquid level rises because of the inertia of the liquid while at the opposite end the level is reduced. The low-frequency response on the other hand is given by the water transport in the tube due to the changes in gravity (tilting).
The HLS signal of the south sensor shows a small oscillation with a period of about 45 minutes. Presently we don’t have an explanation, but we don’t think that there is a ground displacement with that period at the position where the HLS sensor is mounted. This is because we do not see a corresponding signal in the seismometer data. We hypothesize that could originate from an internal oscillation of the water level due to the fact that the acrylic glass tube is not straight in the first 10 m adjacent to the South sensor.

### 5.4 Exceptional correlation between the observed signal of the HLS and synthetic tides

Due to fewer disturbances to the HLS system occurring during holidays, a 3-week interval over the 2012/2013 New Year period was analyzed. For the HLS we calculated a synthetic signal over this period, based on the installation parameters of the HLS system and assuming a spherically symmetric, elastic Earth model (Wenzel, 1997). This synthetic tide signal includes (1) the perturbation of the gravitational potential due to the Sun and the Moon and (2) the elastic deformation of the Earth in response to the gravitational forces from these two celesitial bodies. (1) is important because the liquid surface in the HLS follows an equipotential surface and (2) is important because the HLS is sensitive to deformations in the form of tilt. The calculated signal (black) and the recorded HLS difference signal (red) were superimposed (figure 15; 10 s samples). The two datasets agree well except for some superimposed very-low-frequency noise that must be of local origin. Taking the difference between the two HLS sensor readings enables us to eliminate signal drift. The scale on the vertical axis is in nanoradians [nrad]. The amplitude of 100 nrad over a length of 50 m gives a level difference of 5 micrometers. For the residual displacement (difference between black and red line) a moving average of 100 s was applied (blue line).

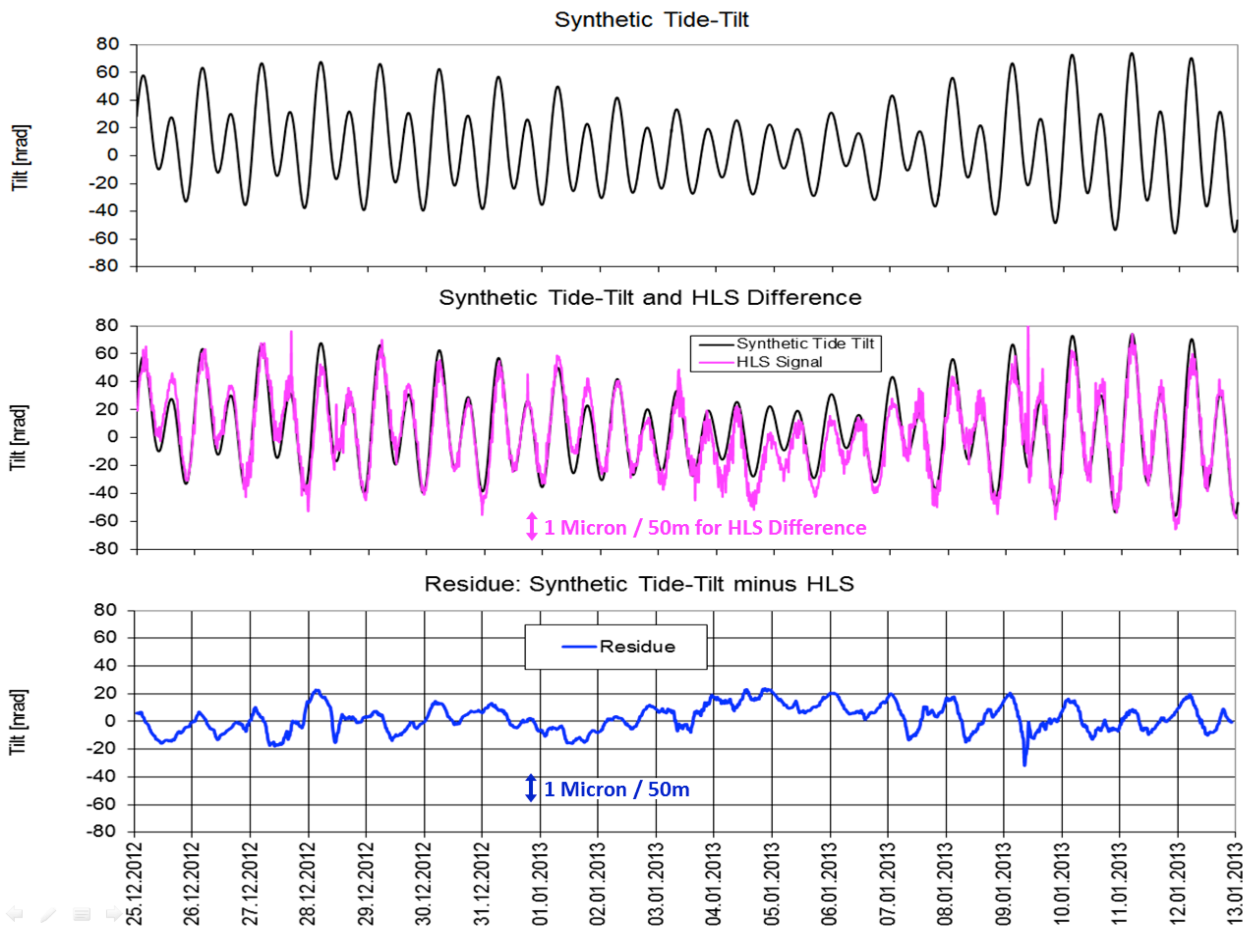


**Fig. 15):** Superposition of synthetic tide-tilt and HLS results (shifted) and difference plot

The residual curve mainly shows daily periods. The differences between the synthetic tides and the observed tidal signal can have several causes including instrumental drift, deformations due to atmospheric loading, and cavity effects. Longer undisturbed datasets and a more detailed analysis would be needed to identify the causes of the differences.

The HLS System as installed is not able to distinguish between rigid rotation and local deformation, because measurements are made at two positions only. Even if in figure 15 there is no visible displacement within the Earth tide level, it does not imply that the rock-formation along the 50 m line is rigid. It is possible that local movements of rock compartments are equilibrating each other.

## 5. LESSONS LEARNED

The Mont Terri rock laboratory is, seismically, a very quiet place even though the highway passes close by. Ground velocity measurements with a high performance, very broadband seismometer deliver highly accurate results even though the tunnel system is open to the safety gallery of the near motorway, and the environmental shielding of the seismometer consists of no more than a Styrofoam box.

The HLS system (Type PSI) provides accurate results too. Thermal isolation is not needed. In the present configuration the HLS has a short-term and a long-term behavior. It does not only measure static vertical displacements between the end pots, but also short-term (seismic) accelerations in the horizontal direction along the tube. Because the water cannot escape at the end of the tube, the signal of short-term displacements is amplified in correlation with the inner dimension of the HLS sensor. At the PSI Synchrotron the HLS is configured in a circular tube path. In this configuration we are not able to observe this kind of signal amplification, mainly because the water surface in the tube is larger and the water can displace freely. Thus the selected linear configuration used at Mont Terri is beneficial for observing precise timing events, such as earthquakes, with the HLS.

With the seismometers we cover a bandwidth of 5 decades and together with the HLS at least 9 decades. Tidal tilt of the solid Earth delivers a daily calibration signal of 5 microns along the 50 m tunnel. The broadband seismometer fills the gap between high frequency events and quasi steady-state conditions with the highest accuracy.

## 6. OUTLOOK

For trustable long-term measurements with the HLS, we have to be sure that the HLS Sensors are stably mounted. Furthermore, geodetic referencing of the local mounting is necessary so that in case of accidental inputs to the HLS console the measurements are not lost, but a correction of the dataset according to the recorded man-made accidental step can be done based on the pre-established geodetic reference points.

Proposed further steps:

- Modeling the water level changes due to horizontal acceleration in bent tubes would help to predict the short-term behavior of the HLS. This would help to understand the observed time constants.
- To prove whether the oscillations of the HLS sensor south are true displacements it would be worthwhile to install the tube in a completely straight line configuration rather than the current bent setup. Also, the broadband seismometer should be placed on the same side as the HLS sensor south in relation to the Main Fault.
- Use of more HLS Sensors along the tube. This allows us to distinguish between rigid rotation and deformations as described in section 5.4.

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## BIOGRAPHICAL NOTES

**Edi Meier** is managing director of the engineering company Edi Meier + Partner AG, Winterthur, Switzerland. He studied Geophysics at ETH Zurich. Subsequently he worked as a manufacturer of seismic instruments (Streckeisen Switzerland) for six years and founded his own engineering company in 1987. Since 1995 the company is collaborating in research and development of new instruments with the Institute of Geodesy and Photogrammetry of ETH Zurich.

**Christophe Nussbaum** is the project manager of the Mont Terri underground rock laboratory, which is located in the NW Switzerland in a claystone formation. In 2000 he obtained the grade of Ph.D from the University of Neuchâtel (Switzerland) for his study in structural geology about the large scale structure of the Eastern Southern Alps and its relationship with the neotectonic seismicity. From 2005 to now he is leading the research program of the international Mont Terri project. His main research is dedicated to the tectonic deformation of claystone from nanoscale to regional scale, with focus on fault mechanisms, fault reactivation, porosity, permeability and characterization of paleofluids in fault zone.

**Rudolf Widmer-Schnidrig** is staff researcher at the Black Forest Observatory (BFO), which is located in south-western Germany and is jointly operated by the Karlsruhe Institute of Technology (KIT) and the Stuttgart University. He studied Geophysics at ETH Zurich and received his Ph.D. in 1991 from the Institute of Geophysics and Planetary Physics at the Scripps Institution of Oceanography in La Jolla, California. His main research interests are the free oscillations of the Earth, low-frequency seismology and the structure of the Earth's mantle and core. At BFO he is also involved in the operation of seismometers, gravimeters, strain meters and a long baseline fluid tilt meter.

## CONTACTS

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