A11. GPS observations at Mt. Hochstaufen

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Weblinks: http://www.erdbeben-in-bayern.de/
http://www.alps-gps.units.it/

Objectives

In this project the aim was to monitor long-term deformations due to swarm earthquakes on a moun-
taintop within millimetre accuracy for positional coordinates by means of relative, static and non-
permanent GPS measurements. Due to the short project duration without the occurrence of meaningful
earthquakes no significant deformations were expected, therefore the accomplished studies may indi-
cate the benchmark for this monitoring method in Alpine Space. The measurements were realized by
the Chair of Geodesy at the Technische Universität München and include two measurement cam-
paigns in 2006 and 2007. A third campaign after an earthquake reaching 3.5 on the Richter scale in
September is foreseen for May 2008.

Geology and Microseismics

Mt. Hochstaufen (1775 m) belongs to the
Staufen Massif which is an east-west striking mountain chain in southeastern
Germany, northwest of Bad Reichenhall in the Berchtesgadener Land.
The summit region consists of limestone (Wettersteinkalk), which shows distinct
signs of Karst formation. Haselgebirge43, a leached and weathered breccia of
evaporitic permo-triassic sediments, can be found in some outcrops on the northern
flank of the Staufen Massif and in the Reichenhall Basin. Presumably, Hasel-
gebirge also exists in the innermost fold cores of the Staufen Massif (Kraft et al.,
2006). A detailed description of tectonic setting and the geology of the Staufen Massif can be found in
e.g., Erhardt (1931), Henrich and Zankl (1981) and Weede (2002). Geologic evidence for mass
movements at the southern flank of Mt. Hochstaufen was recently summarized by Weede (2002).
Large east-west striking open fractures can be found near the summit of Mt. Hochstaufen. They reach
a length of several hundred meters and openings of up to 3 m. Those fractures could be followed to a
depth of nearly 100 m below the surface (Glaser, 2004). Gravitational collapse and/or subsidence due
to leaching of the Haselgebirge are debated as causative processes.

43 Typically the salt content of Haselgebirge is 50%
Mt. Hochstaufen is always vulnerable to earthquakes, so-called swarm earthquakes seem to be closely related to heavy rainfall. In July 2005, extreme rainfall led to flood damage in the region and swarm earthquakes up to a magnitude of 2.8 on the Richter scale were triggered. In September 2007 an earthquake reached 3.5 on the Richter scale. Fortunately earthquakes of this strength do not cause major damage but the area Mt. Hochstaufen is monitored by a scientific network consisting of seismometers and additional measuring devices (groundwater levels and meteorological observables).

Geophysicists at the Ludwig-Maximilians-University in Munich carried out a study of the spatio-temporal behaviour of earthquakes, fluid-related parameters and precipitation in the swarm earthquake area. The observations and first interpretations indicate that seismicity in the Staufen Massif is influenced and partially even triggered by meteorological events. Almost every rain event matches a corresponding event in the time-shifted (~ 10 days) seismicity record (Kraft et al., 2006).

Network Design

Geodetic monitoring solutions are described as a spatial network of observables (in the case of GPS these are vectorial baselines). The conceptual design of the monitoring network consists of a network with 4 control points (reference network) and 13 observation points on the summit of Mt. Hochstaufen. Additionally a fifth control point could be used thanks to the Interreg IIIB “Alps GPSQuakenet” project that runs the Geodetic Alpine Integrated Network (GAIN) with one station settled in suitable distance to Mt. Hochstaufen.

The observation network is a local network which covers an area of only 4.7 hectares with a maximum baseline length of < 400 m and a maximum altitude difference of 106 m (1664 to 1770 m). The locations were installed in close consultation to geologists to describe possible movements of 5 separated blocks. The five control points were installed in the regional surrounding of the mountain within 4 and 11 km and a maximum baseline length of 17 km. The points were chosen to be located evenly distributed in all directions on about the same altitude level (1280 to 1702 m) in order to low tropospheric delay. For the present all these points were assumed to be stable. Since the massif is followed by a plane in the north-eastern part, the last control point is down in the valley at 470 m. Unfortunately this point had to be excluded from further investigations due to damaged point marking.

Network Installation

Since non-permanent GPS campaigns always are a logistical challenge as well, two main actions were implemented to reduce effort and to increase accuracy:

- **Monumentation:** the installation of the observation points was realized by threaded bolts with holes made by a drilling machine. This kind of marking is cost-effective and means only a small intervention into the environment. Besides, this allows a reliable forced centering of the GPS antennas.
- **Antenna mounting:** since no infrastructure leads to the mountain top, the equipment (GPS receivers, antennas, batteries for power supply) had to be carried up. To minimize weight, un-
handy wooden tripods were replaced by self-constructed antenna mountings (Fig. 86, Fig. 87). This construction has proved its worth at several points: Low antenna heights enabled a set-up close to the marked points; additionally no antenna heights had to be measured in place but in laboratory which eliminated one typical error source (the antenna can be levelled with three tribrach screws; a metal ball forces a constant antenna heights in every epoch)

![Construction of antenna mounting](image1)

![Field setup](image2)

**Fig. 86: Construction of antenna mounting**  **Fig. 87: Field setup**

**GPS Measurements**

- **Time Table:** Epoch 0 in Aug. 2006 & Epoch 1 in May 2007 (Epoch 2 foreseen in May 2008)
- **Observations:** static, relative GPS (RGPS). This technique to achieve highly accurate GPS results is based on the use of so-called double differences of GPS phase data between two stations and two satellites. The receiver systems were run in static mode for ~60 hours consisting of 5 sessions with a data frequency of 15 seconds. This involves measuring points at least twice and creates safety checks against problems that would otherwise go undetected.
- **Equipment:** 9 dual-frequency GPS receivers (3 × Leica 1200, 6 × Leica 530). Specifications in observation mode as mentioned above: Accuracy of baseline 5 mm + 0.5 ppm (horizontal) and 10 mm + 0.5 ppm (vertical).

**Data Processing and Deformation Analysis**

The baselines were post-processed using standard software Leica Geo Office (LGO) V4.0 which is included in delivery of the system. Such commercial software packages use standard algorithms and are the state of the art in medium-sized surveying offices. In comparison with scientific GPS software LGO is expected to deliver good results for local and regional GPS networks. Due to long observation
times and excellent satellite availability the baselines were estimated with a very high precision (internal accuracy).

Network adjustments and deformation analysis of both epochs was calculated in GeoTec Panda/Defana V1.3 (PANDA). The high redundancy of the network lead to very precise coordinates of about 1 mm (1σ) for the horizontal component which has to be seen sceptically. These values indicate the internal accuracy of the networks. This assumption was confirmed by a first comparison of the adjusted networks, which resulted in apparent horizontal point movements of 3 to 10 mm for the observation network and more than 15 mm for some points of the reference network. Based on high internal accuracies but low repeatability of the networks, deformation analysis is not possible because every point movement would be assumed to be highly significant.

To avoid this problem, an approach considering a global movement was used. The global movement allows you to accommodate the point accuracies to the measurement circumstances. Such a definition is useful if the precision of the comparative networks is very high due to a forced centering but the external accuracy still contains systematic errors which are not considered in the stochastic model. This can be prevented by magnifying the standard deviations of each point. In this example two factors were considered: the variations of the antenna’s phase-centres as well as the limited precision for the set up of the antennas over the observation points.

The deformation analysis then was tested with a confidence interval of 95% (2σ) showing no significant movements on the mountaintop (Fig. 89). However, two stations in the reference network show significant movements in 3D. Neglecting the less accurate height component (a well known effect of GPS), these movements are close below significance as well (Fig. 88). But it is the subject of further investigations whether these points can be assumed to be stable or whether long baselines cause inaccurate results.

**Conclusion**

Static RGPS with long observation times is suitable to detect horizontal displacements of ~5 mm per epoch. Higher accuracies can only be achieved by using a permanent GPS network marked with stable pillars or by using a scientific GPS software and accurate modelling of phase-centre variations of GPS antennas.

Nevertheless, high precision (internal accuracy) can be achieved since the method allows putting redundancy into a network if many receivers are used at the same time. This is mainly because no direct line-of-sight between the receivers is necessary. At Mt. Hochstaufen 9 receivers were used leading to a redundancy of more than 400. Thus, the customer has to distinguish exactly between the terms of “precision” and “accuracy”.

Our example combining two campaigns within a time span of seven months showed no significant displacements. To find realistic results, the stochastic model had to be influenced manually by allowing global movement resp. increasing standard deviations of systematic errors like phase-centre variations and limited precision for the stable set up of the antennas.
Fig. 88: Horizontal displacements in the regional GPS network around Mt. Hochstaufen

Fig. 89: Horizontal displacements in the local GPS network on the top of Mt. Hochstaufen
References


