Geotectonics in the Swiss Alps using GPS

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Abstract

Several projects at the Swiss Federal Office of Topography (swisstopo) deal with the estimation of tectonic movements using GPS and covering different scales:

- *Deformation Monitoring Andermatt (0-4 km): An L1 GPS receiver with solar panels for power supply was installed close to the permanent AGNES site Andermatt in order to demonstrate the potential of GPS for monitoring aspects. A detailed analysis shows the error sources of a GPS monitoring on short baselines.*
- *AGNES (< 300 km): A permanent monitoring of the AGNES sites based on hourly and daily solutions was established in order to detect possible site movements as quickly as possible.*
- *EUREF (< 3000 km): Phenomena in context with the earthquake in Bolzano (BZRG) in June 2001 were analyzed in detail (5-minute up to weekly solutions).*
- *Alpine Network (< 1500 km): A collaboration of the Alpine countries Austria, Germany, Italy, France and Switzerland was established in order to further densify the existing Alpine EUREF sites and to derive a detailed kinematic model of the crustal deformations in the Alpine area. An overview of the status of collaboration and the planned densification (more than 50 sites exist already) is given.*

1 Deformation monitoring Andermatt

For monitoring applications of engineering projects (e.g. permanent monitoring of the surface above a tunnel drivage), GPS is certainly a powerful tool. This holds true especially if the distances are too long for automated measurements with theodolites. Due to the fact that at the monitoring sites usually no communication infrastructure and power supply are available, an automated remote GPS station was developed in order to test a possible use even under extreme meteorological conditions in the Alpine area and to verify the accuracy level.

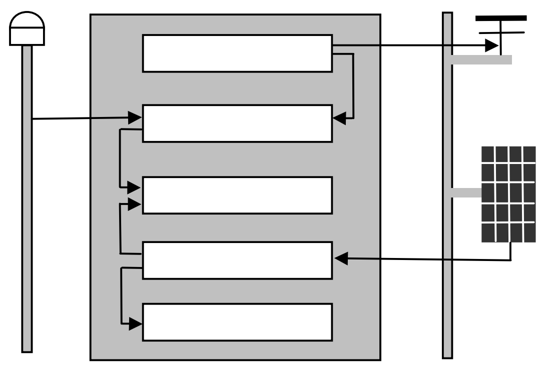

Fig. 1: Remote GPS station DMAN consisting of a GPS antenna, radio antenna, solar panel and an equipment box containing the GPS receiver and other electrical devices

Fig.1 and Fig. 2 show a diagram and a picture of the remote GPS station consisting of an L1 GPS receiver Geotracer 3140, the Satelline 2ASx radio modem, an antenna, a solar panel (Siemens SM20), and additional electronic devices such as power control and the battery.

Fig. 2: Remote GPS station DMAN as it is installed near ANDE

Using the solar panels in combination with the battery allows a daily observation window of 4 hours even if there are 7 days in a row without sunshine. A wake-up session was defined in which 4 hours of data are automatically measured and uploaded via radio modem to the next AGNES station (ANDE). From there the data are downloaded and processed with Bernese 4.2 [*Hugentobler et al., 2001*] at *swisstopo* in Berne.

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The system was in use from the end of 1999 till mid-2002. From Dec. 23, 1999 (see Fig.3, time label "1.") till Mar. 3, 2000, the remote site (later on called DMAN) was installed 60 m from the AGNES station. Afterwards (Oct. 24, 2000; see Fig.3, time label "2.") this site was moved by 3.7 km to the "Schneehüenerstock". One year later (Nov. 22, 2001, Fig.3, time label "3.") the antenna was replaced by a high-quality choke ring antenna TRM29659.00 in order to validate the impact of the antenna quality on the coordinate results.

A total of more than 2.5 years of 4-hour L1 solutions were analyzed (relative to ANDE). In only 2.5% of the cases during that time period were data of the remote site not available (not enough power, other unknown reasons).

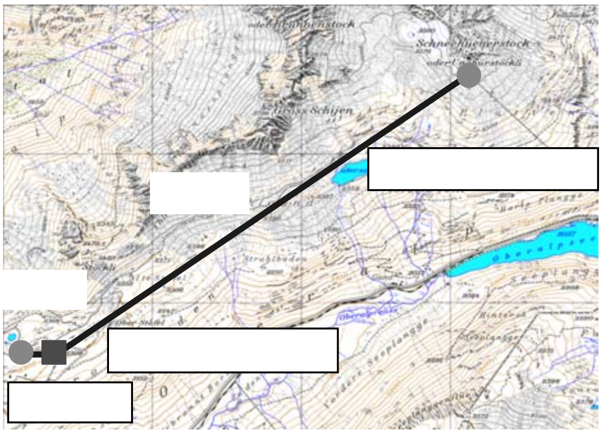

Fig. 3: Locations of the remote GPS sites (DMAN) compared to the AGNES site (ANDE)

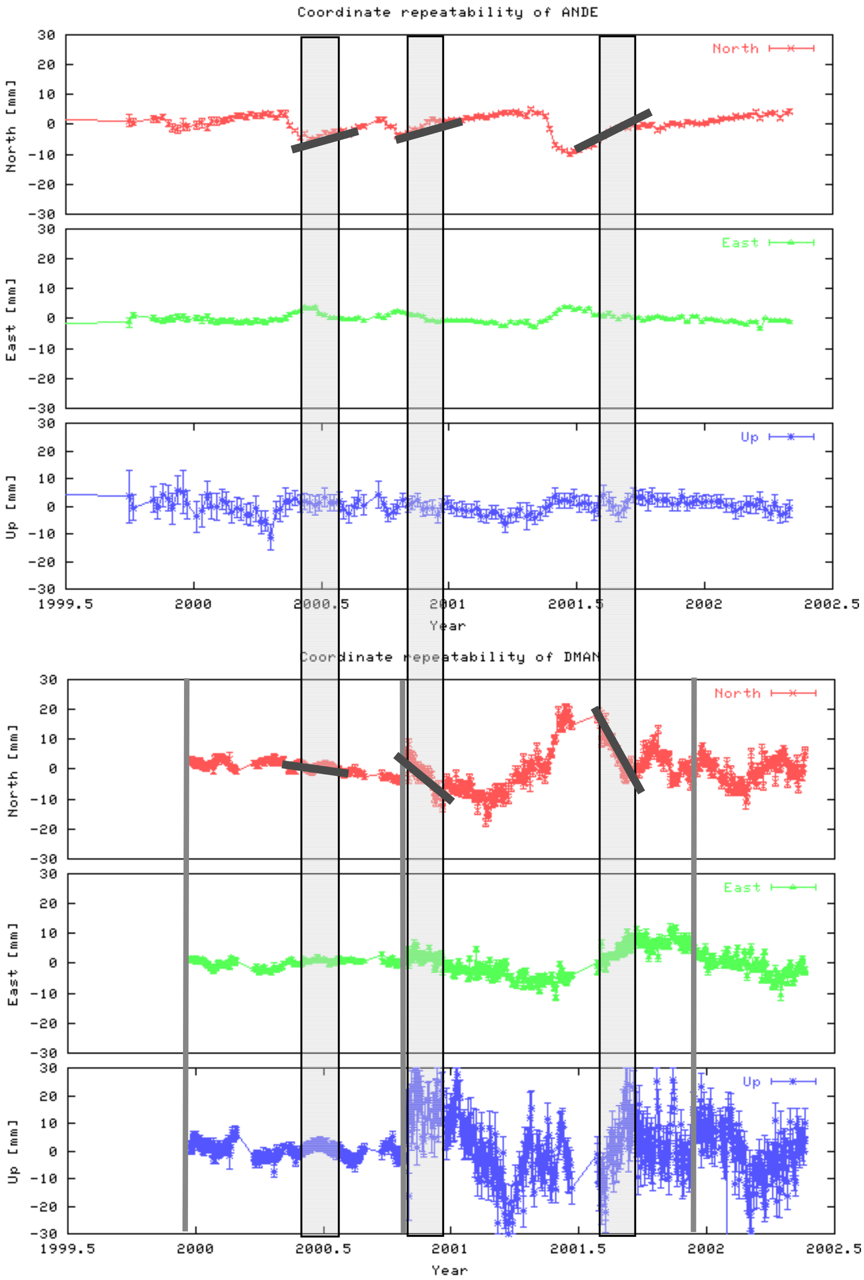

Fig. 4: Coordinate repeatabilities (north, east, up) for the AGNES site ANDE (weekly L3 solutions relative to Zimmerwald) in the upper diagram and for the remote site DMAN (4-hour L1 solutions relative to ANDE) in the lower diagram

Fig. 4 (lower part) shows the repeatability of the baseline analysis ANDE-DMAN for the components north, east and up (4-hour L1 solutions). The upper part of the diagram shows the repeatability of the AGNES sites ANDE relative to ZIMM (ZIMM-ANDE) extracted from the daily analyses of the AGNES network (see Chap. 2).

Three different periods (indicated by the labels “A”, “B”, and “C”) were analyzed with the focus on possible multipath effects in a more detailed way to investigate the origin of the clearly visible periodic biases in Fig. 4. The effects are extremely large in the north component. Whereas the trend in the time series ANDE-DMAN is small in section “A” (60 m baseline), there are much larger rates in the sections labeled “B” and “C” (10 mm and 15 mm/month respectively).

The “low-cost” antenna is certainly not causing the problem because the results based on the choke ring antenna also show this type of bias after time label “3.”.

It is also possible that the bias indicates real movements. Compared to the stable site ZIMM it seems that even the ANDE site moves but with smaller variations. The opposite signs of the movement rates are reasonable if it is assumed that the ANDE site is mainly responsible for the movements.

Fig. 5 indicates in which way the data of sections “A”, “B” and “C”, each 60 "sessions" long, were analyzed. From the available 4 hours of data different solutions were processed. One solution used all 4 hours of data, a second solution used only the 2 hours in the center, and in a third solution 2-hour intervals were shifted every day by 4 minutes in order to ensure that for at least 29 days the results are based on exactly the same satellite constellation.

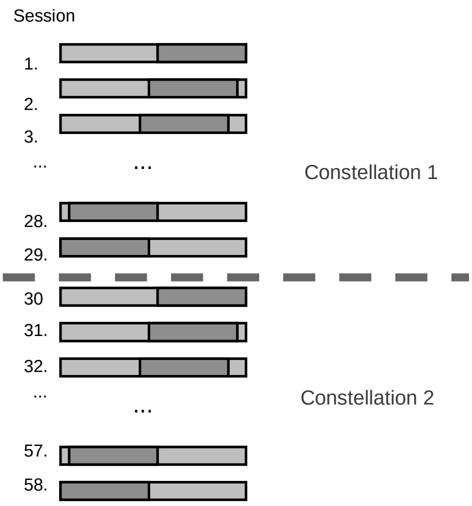

Fig. 5: Processing scheme (shifted 2-hour solutions by 4 minutes) used to analyze the influence of multipath effects on the baseline results ANDE-DMAN

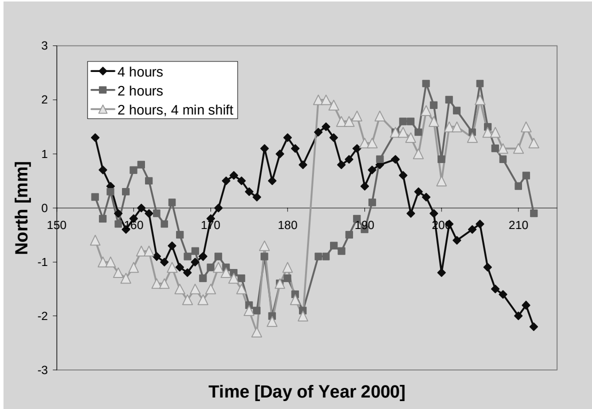

Fig. 6: Repeatability (north component) of the 60 m baseline ANDE-DMAN (section “A”) for L1 solutions based on a different selection of observation intervals (4 hours, central 2 hours, 2 hours shifted by 4 minutes every day)

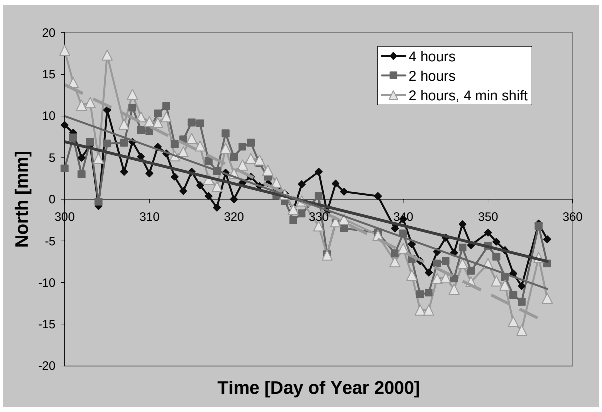

Fig. 7: Repeatability (north component) of the 3.7 km baseline ANDE-DMAN (section “B”) for L1 solutions based on a different selection of observation intervals (4 hours, central 2 hours, 2 hours shifted by 4 minutes every day)

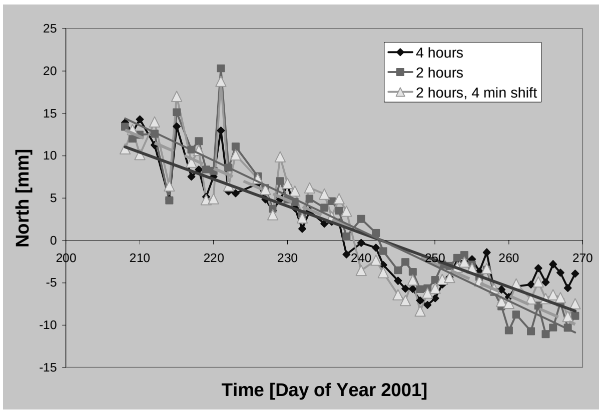

Fig. 8: Repeatability (north component) of the 3.7 km baseline ANDE-DMAN (section “C”) for L1 solutions based on a different selection of observation intervals (4 hours, central 2 hours, 2 hours shifted by 4 minutes every day)

After the 29 days the processing was started again with a new sliding time window or a new satellite constellation.

From Fig. 6 it can be concluded that for the short 60 m baseline (section “A”) multipathing is the dominating factor. The jump in the center of the time series due to the constellation change is clearly visible. The 4-hour and 2-hour solutions are therefore a result of an “average” impact of the slowly changing constellations. Nevertheless, it must be underlined that the order of magnitude is small (3 mm jump due to the constellation).

Fig. 7 and 8 summarize the results for the longer baseline (sections “B” and “C”). Almost independent from the observations (or the satellite constellation respectively) the rate remains unchanged. Multipath effects, therefore, do not explain the rates in the time series.

Especially for monitoring tasks the reliable detection of slowly changing deformation is essential. Originally it was planned to operate the GPS remote system at a stable place in order to verify the accuracy level. From our results it might be concluded that already quite large relative movements of up to 15 mm/month (lasting for a period of 2 months) between ANDE and DMAN (at “Schneehüenerstock”) as well as for the AGNES site ANDE itself were detected.

2 Monitoring of the AGNES stations

Swisstopo has been building up and operating an automated GPS network for Switzerland (AGNES) since 1998. The final expansion of 29 permanently operating GPS tracking stations was reached at the end of 2001. AGNES is a multipurpose network serving scientific applications (geodynamics and atmospheric research) as well as surveying applications (reference frame maintenance, densification of the reference frame). In addition, a positioning service is offered on a commercial basis under the product name *swipos*-GIS/GEO® (Swiss Positioning Service for GIS and Geodetic Applications).

The data of the AGNES sites are being monitored since the end of 1998 on a daily basis and since Dec. 2001 on an hourly basis. In addition to the 29 AGNES sites, 40 additional sites (EUREF and other networks) are processed using the Bernese GPS Software Version 4.2 [*Hugentobler et al., 2001*] (Fig. 9). This monitoring allows the detection of possible site movements and other site or receiver-related problems. An updated multi-year solution solving for the site coordinates and velocities is automatically generated if an additional week of data is processed. The results (estimated velocity, repeatability plots, etc.) are available under http://www.swisstopo.ch/ (survey section). Examples of repeatability plots are given in [*Schneider et al., 2002*].

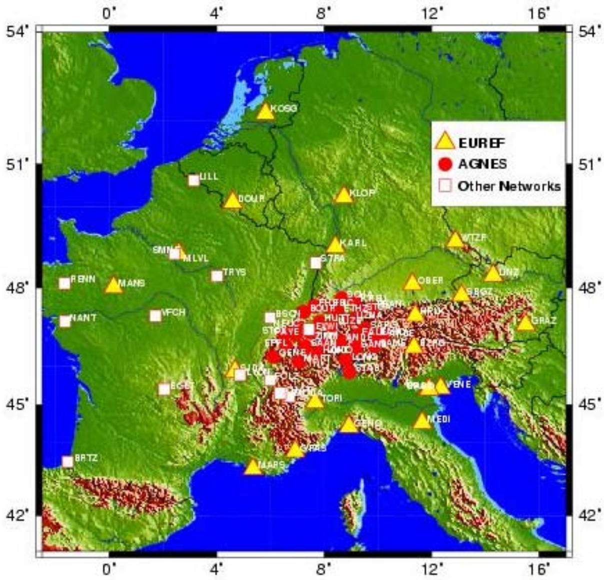

Fig. 9: Location of the AGNES sites, EUREF sites, and sites of other GPS permanent networks monitored by *swisstopo*

Site velocities (see Fig. 10) are estimated for sites with a time series longer than 0.5 years using the full variance-covariance information of the weekly solutions. All estimated site movements are smaller than 2 mm/yr. It seems that the sites of the Swiss Plateau (stations in a strip from Geneva in the southwest to Pfänder in northeastern part such as Huttwil (HUTT) and Luzern (LUZE)) are moving slightly northwest. Movements of the Alps in the southeastern part cannot be detected reliably (time series too short). Nevertheless, the sites Davos (DAVO) and Locarno (LOMO), sites with almost 4 years of observations, do not show significant movements.

The uncertainties of possible vertical movements are worse by approximately a factor of 3 compared to the horizontal velocities. From levelling observations covering a time span of more than 100 years, the Alpine uplift could be estimated very precisely for a dense network of stably monumented markers (southwestern part of the Alps is rising with approximately up to 1.5 mm/yr ± 0.3 mm/yr) [*Gubler et al, 1981*]. It is therefore important to combine the horizontal movements detected by GPS with the vertical movements from levelling.

Velocities were also derived from coordinate differences stemming from the various GPS campaigns between 1988 and 2002. Despite the long time span of maximally 14 years and the high density of more than 100 sites, no significant movements of particular regions are detectable.

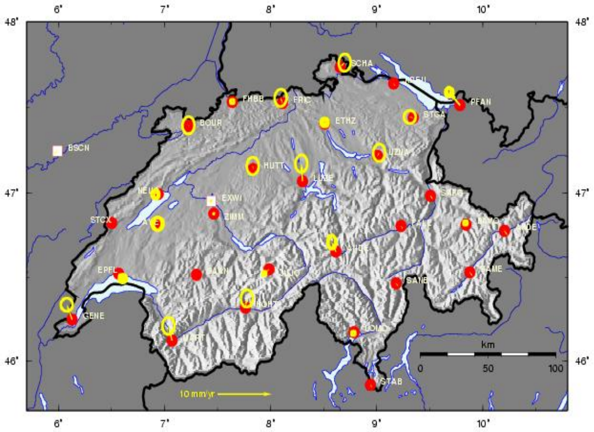

Fig. 10: Site velocities in ITRF00 (relative to Zimmerwald) for sites with a “history” of more than 0.5 years

It is assumed that the early “relatively weak” GPS solutions from the first epochs of observation are responsible for that due to the sparse GPS constellations in the years 1988-1990. It is planned to re-observe the complete network in the year 2004.

3 GPS monitoring of station Bolzano (EPN) during the Lana earthquake

On July 17, 2001, the Lana earthquake occurred at 15:06 UTC with a magnitude of 4.8 near the EUREF GPS permanent site Bolzano (BZRG). Bolzano is located 120 km west of the nearest AGNES site Davos (DAVO). According to Fig. 9 BZRG is monitored by *swisstopo* on a daily basis. Fig. 11 shows the time series of weekly solutions which clearly indicate a jump of about 2.5 cm north and 1.0 cm east nearly at the time of the earthquake.

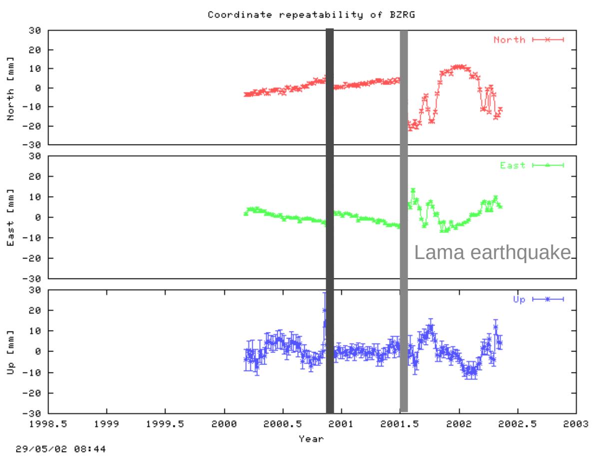

Fig. 11: Time series of weekly solutions (north, east, up) of Bolzano (BZRG)

The detected movements and some preliminary geophysical interpretations [*Caporali et al., 2001*] nevertheless did not match with the movements detected at the site Merano (MERA), where also a permanent GPS receiver was installed and which is located almost directly at the epicenter. Unfortunately, data are missing from the day of the earthquake, but data are available before and after the event.

Two phenomena are difficult to explain:

- The “noise” in the repeatabilities of the horizontal coordinates immediately after the earthquake is drastically increased.
- After 3 months the coordinates returned almost to the original position (lasting for another 3 months) and have again been moving since Feb. 2002.

The GPS processing parameters (rms of unit weights, percentage of ambiguity resolution, etc.) are comparable before and after the earthquake. We therefore had a closer look at the coordinate repeatabilities and processed a baseline from BZRG to the nearest AGNES site Davos (DAVO). Fig. 12 shows the coordinate repeatabilities for daily solutions and indicates the time interval for which we processed even 3-hour solutions, 1-hour solutions, and 5-minute solutions (Fig.13 - Fig.15) relative to the AGNES site Davos (DAVO).

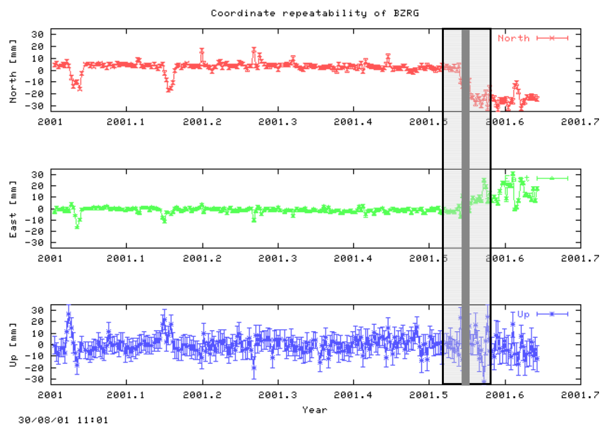

Fig. 12: Time series of daily solutions (north, east, up) of Bolzano (BZRG)

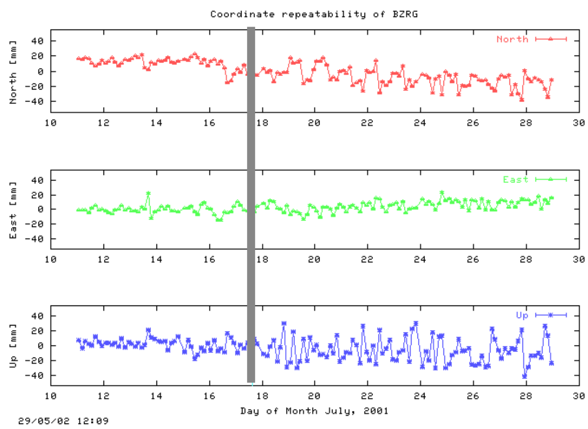

Fig. 13: Time series of 3-hour solutions (north, east, up) of Bolzano (BZRG) relative to Davos (DAVO) for July 11 - July 29

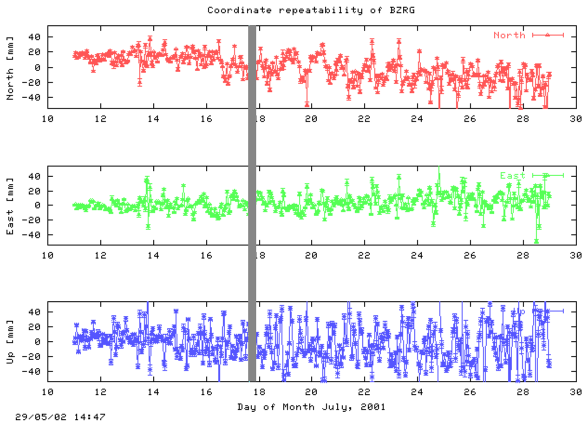

Fig. 14: Time series of 1-hour solutions (north, east, up) of Bolzano (BZRG) relative to Davos (DAVO) for July 11 - July 29

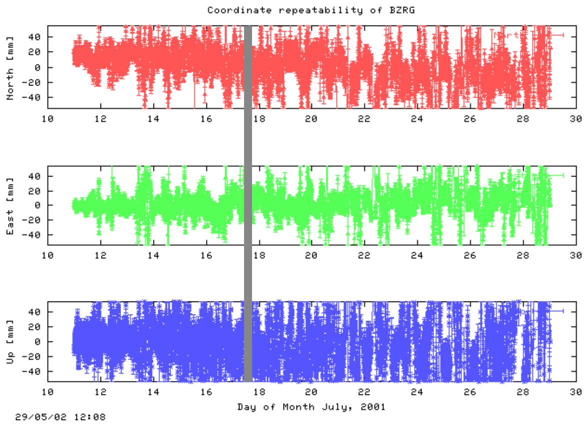

Fig. 15: Time series of 5-minute solutions (north, east, up) of Bolzano (BZRG) relative to Davos (DAVO) for July 11 - July 29

It is seems that the "noise" in the repeatabilities increased already on July 13 (4 days before the earthquake).

Fig. 16 - 18 show the tracked GPS data for the days July 15 - 17 (day of year 196 – 198). These figures were generated at the EUREF central bureau [*Takacs et al., 2001*]. Whereas a perfect tracking is given on July 15 (and also for all days earlier), it seems that on the following days observations with an azimuth between 0 and 110 degrees and an elevation between 0 and 35 degrees were missing.

We therefore reprocessed the hourly solutions and systematically excluded all observations in the mentioned azimuth and elevation cut-off interval. Fig. 19 shows the coordinate repeatabilities for the north component with and without using this part of the data. The differences are below 1 mm before July 16 and later on almost zero because there are no data available in that data segment.

From these tests and from the fact that again in 2002 observations are also missing in the same azimuth and elevation interval, it can be concluded that the missing observations are an indication of a receiver/antenna problem, and that the missing data themselves (only 10 % of the available data) are not causing the detected offsets and increased noise in the repeatabilities.

A correlation between increased noise (July 13), a jump in the coordinate series (linearly increasing from July 13 - July 28 by 2.5 cm and later on dropping back), missing observations (between July 16 and mid-2002 the amount of missing observations is sometimes more and sometimes less), and the earthquake itself (July 17) could not be proved.

Corrective action is to replace the BZRG receiver / antenna equipment. After the change of the antenna with an antenna of the same type on July 8, 2002 no biases are visible in the time series.

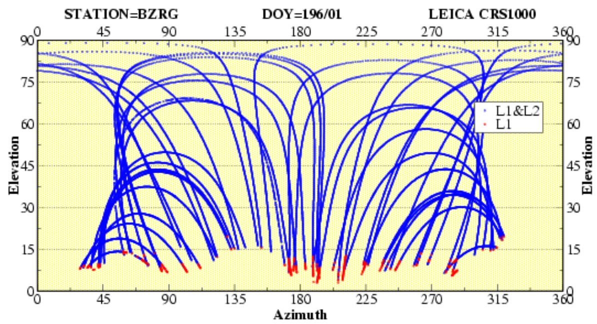

Fig. 16: Observed GPS data in BZRG on Jul 15, 2001 (day of year 196)

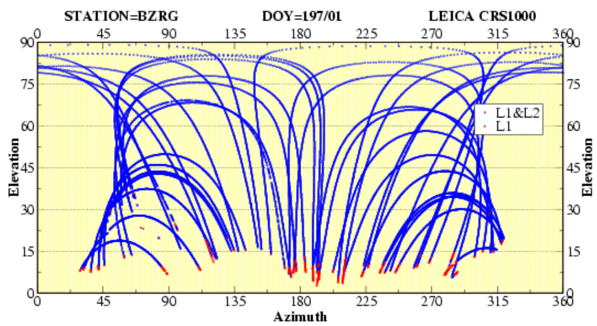

Fig. 17: Observed GPS data in BZRG on Jul 16, 2001 (day of year 197)

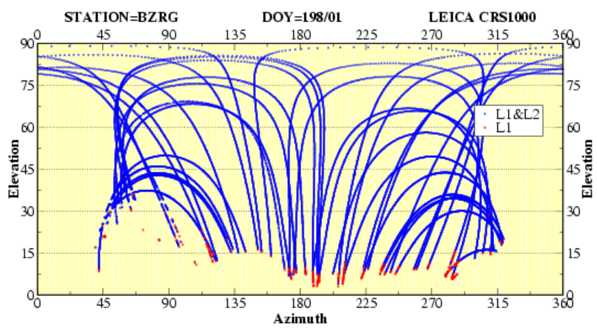

Fig. 18: Observed GPS data in BZRG on Jul 17, 2001 (day of year 198)

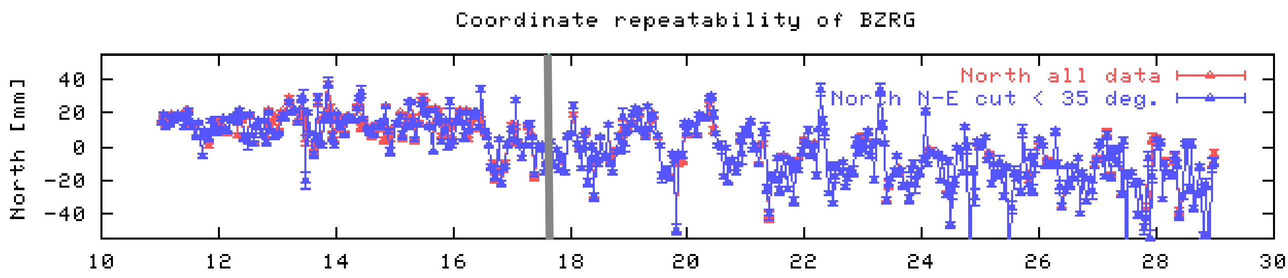

Fig. 19: Time series of 1-hour solutions (north) of Bolzano (BZRG) relative to Davos (DAVO). One time series is based on all available GPS data, for the second time series all data with an azimuth between 0 and 110 degrees and an elevation between 0 and 35 degrees were excluded

4 Alpine network

In order to further densify the European Permanent Network EPN and to derive a densified kinematic model of the movements of the entire Alpine area, the Alpine countries share the results of there national GPS networks [*Brockmann et al., 2001b* and *Brockmann et al., 2002*].

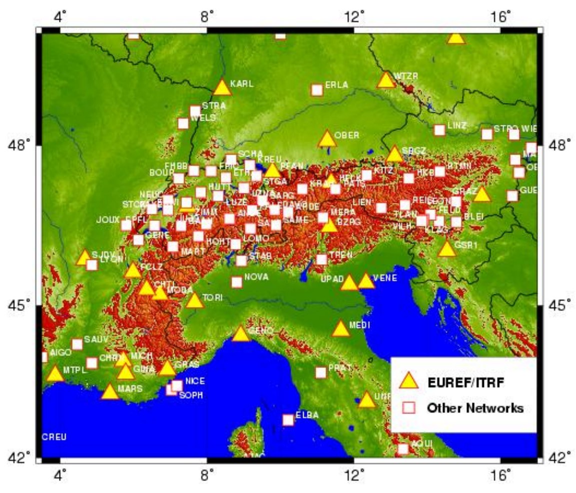

Fig. 20: Permanent GPS stations in the Alpine region (EUREF and additional sites)

Fig. 20 shows that in addition to the EUREF sites, there are almost twice as many sites which are not integrated in EUREF. There would be even more data available, but most of these data are owned by commercial companies and neither the RINEX data nor any processed weekly SINEX files are available. Even if many of the sites are not perfectly monumented as required for geotectonic studies, it is useful to analyze the presently available results of the different processing centers. Tab. 1 summarizes the status of the available additional stations, the available time span of station coordinates, the availability of weekly SINEX files, the availability of coordinate combinations covering several years of data, and the willingness of the contributing centers to analyze the data.

The collaboration of the Alpine countries can be summarized as follows:

- Rinex data will not be made available to interested groups; Rinex data of "commercial" sites will not be processed. Data processing is the responsibility of the individual countries. If there are "interesting" sites available, the owners should be encouraged to ensure permanent processing of the stations by themselves or by someone in the project team.
- Results of combinations of SINEX files covering several years are freely available.
- Results of weekly SINEX files will be freely available in part (memorandum of understanding, joint publication or other restrictions).
- 2-3 centers will analyze the individual SINEX data.
- Combinations will focus mainly on the integration in EUREF.

The last item is essential. The "Alpine Network" project is a perfect example for a densification of the European reference frame. There exist two possibilities to integrate the national networks into the EPN:

1. Combination based on already combined ITRF / ETRF solutions and the national combined solutions. The advantage of this approach is that station problems, etc., are already handled. On the other hand, it is not possible to model the velocities of the sites in a more sophisticated way, which is essential if sites are monumented on roofs, etc. In such cases possible periodical variations also need to be considered.
2. Combination based on the original weekly solutions of the national networks and the EPN network [*Habrich, 2001*]. Coordinates and velocities can then be derived with a better modeling of the behavior of each individual station.

First results and comparisons between different kinds of combinations will be realized in the second half of 2002.

CENTER	SINEX	TYPE	# stations x(y)	START	Distr.	Combin.
BKG	BKG.SNX	2	60(0)	1995.0	0	0
	WEEKLY.SNX	1	7(0)	1995.0	a	0
		1	13(0)	1996.0	a	0
		1	13(0)	1997.0	a	0
		1	35(0)	1998.0	a	0
		1	43(0)	1999.0	a	0
		1	45(0)	2000.0	a	0
		1	60(0)	2001.0	a	0
		1	60(0)	2002.0	a	0
IGN	RGP.SNX	2	23(5)	2001.5	a	1
	WEEKLY.SNX	1	14(1)	1998.5	a	1
		1	17(3)	1999.0	a	1
		1	19(4)	1999.5	a	1
		1	25(5)	2000.0	a	1
		1	27(5)	2000.5	a	1
		1	31(5)	2001.0	a	1
		1	39(9)	2001.5	a	1
LPT	LPT.SNX	2	52(29)	1998.5	a	1
	WEEKLY.SNX	1	20(9)	1999.0	g	1
		1	20(9)	1999.5	g	1
		1	20(9)	2000.0	g	1
		1	30(12)	2000.5	g	1
		1	43(20)	2001.0	g	1
		1	52(29)	2002.0	g	1
OLG	OLG.SNX	2	35(2),15(8)	1998.5	0	0
	WEEKLY.SNX	1	30(1),10(2)	1998.5	a	1
		1	30(2),10(4)	1999.0	a	1
		1	35(2),15(5)	1999.5	a	1
		1	35(2),15(5)	2000.0	a	1
		1	35(2),15(8)	2001.0	a	1
PURDUE	REGAL.SNX	2	48(10)	1996.0	a	1
(CNRS)	WEEKLY.SNX	1	48(10)	1996.0	g	1
UPAD	UPAD.SNX	2	?(4 I, 5 A)	2000.0	0	0
	WEEKLY.SNX	1	?(4 I)	2000.0	g	1
		1	?(4 I, 5 A)	2001.5	g	1

Explanation:

CENTER : Name of the institution
TYPE: : 1: weekly, 2: combined SINEX
 # stations x(y) : x:total, y:additional to ITRF/EUREF Alpine sites
START : Time of first observation (of first weekly solution)
Distribution : a : solution is available to all groups
g : solution will be made available to other groups only in exchange or only in form of a "Memorandum of understanding" or a special contract or ...
u : not available to other groups
0 : not available because not generated
Combination : 1 : interested to perform combinations with Sinex files of type 1 / 2
0 : no intention to do a combination

Tab. 1: Questionnaire filled out by the partners of the Alpine network

5 Conclusions

GPS is used at *swisstopo* for different applications in the area of geotectonics. Promising results were obtained for distances ranging from some kilometers up to several 100 km. The permanent GPS network AGNES and its continuous monitoring plays an important role for geotectonics. Based on this network, monitoring applications as shown with the example of the permanent monitoring of a remote site, are possible. Sites with GPS antenna problems, as shown with the test study of the Bolzano site, are also clearly detectable. This is important for separating station movements from artificial effects stemming from malfunctioning GPS receiver/antenna equipment.

The AGNES network as well as other national permanent networks may be perfectly integrated in the European reference frame. The "Alpine Network" project realizes a densification for the countries of the Alpine area.

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