20 years of maintaining the Swiss Terrestrial Reference Frame CHTRF

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Abstract. Between 1988 and 1995, the Federal Office of Topography (swisstopo) installed the Swiss Reference Network LV95 (Landesvermessung 95) as the national first network which is completely based on satellite observations to the global positioning system GPS. Together with the operation of the 30 permanent GPS stations of the Automatic GNSS Network Switzerland (AGNES), starting 1998, the LV95 stations represent the backbone of the geodetic reference frame and the national geodata infrastructure, the Swiss Terrestrial Reference Frame (CHTRF).

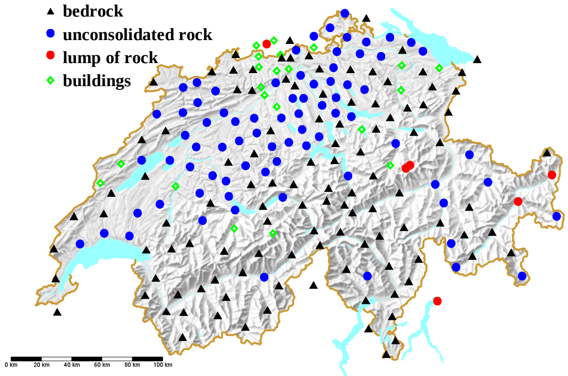
As a quality check and for studying the stability of the reference frame, swisstopo re-observed the whole network three times: 1998, 2004 and 2010. The comparison of the horizontal coordinates proved the stability of the reference frame on the cm level.

Furthermore, the detection of possible tectonic movements in the order of below 1 mm/year is achievable with the data set. Horizontal velocity vectors derived from the adjustment of the campaign data can also be compared with results of velocities derived from the permanent AGNES network. Reliable vertical velocities can be estimated only for the permanent stations and from the kinematic adjustment of all national leveling data since 1903. The analysis of the horizontal and vertical velocities is a further step towards the determination of a kinematic model for the recent crustal deformations in Switzerland.

Keywords. GPS, GNSS, campaigns, permanent networks, velocities, recent crustal deformations

1 Reference Network LV95 and Permanent Network AGNES

The reference network LV95 was installed by the Swiss Federal Office of Topography (swisstopo) between 1988 and 1995 and consists of about 200 points. The points were selected to ensure an optimal view to the Global Navigation Satellite Systems (GNSS). They were also selected from a geometrical point of view to allow an easy access to the national reference frame for the regional surveying authorities. Furthermore, the points were marked on the ground as stable as possible by tying the points directly to bedrock or to already existing buildings or by constructing concrete monuments in areas of unconsolidated rock (see Fig. 1). Therefore, not all points of the network are perfectly suited to study possible crustal deformations.



According to the maintenance concept for the geodetic surveying applications (Wiget et al. 2010), the points were re-observed every 6 years in order to guarantee a stable reference frame. During the campaigns, realized in the years 1998, 2004 and 2010, GPS data of a minimum of one night were collected. Even if the basic concept of the GPS campaigns persists, there were quite some changes in the history of the campaigns. Beside changes in the equipment (GPS receivers and antennas) and the communication means (radio modem versus mobile phone) the campaign type was changed considerably. Whereas in the early campaigns a dozen of persons and receivers were involved in the field, only 2 persons with 4 receivers are measuring simultaneously in the field, today. This is possible because of the permanent network AGNES providing continuously available backbone data contradictory to the early GPS campaigns with overlapping network designs.

The AGNES network was designed 1998 as a "follow-up" of the first re-observation campaign and was further developed to a complete network consisting of 30 stations allowing real-time positioning services in 2002. In 2007, the network was enhanced by the installation of combined GPS-GLONASS receivers and antennas. Today, totally 40 stations are operating simultaneously. 9 stations are operating with the original GPS-equipment in order to ensure long-term stability of the derived time series (Brockmann et al. 2008).

2 Re-observation Campaign CHTRF 2010

Between April and October 2010, 219 points of the reference network LV95 were re-observed in 15 field weeks with 2 operators each using 4 GPS receivers. Totally 16 operators drove 37'000 km by car accident-free. Most of the GPS receivers and antennas were already used in 2004 but in order to achieve better results and to allow a quality check of the campaign results, in average 43 hours of observations were collected. This is considerably more compared to 18 hours of data collected 2004 by spending only roughly 20% more personal effort.

In the summer months, the points in the alpine regions were measured. Due to obstructions of the mountains partly only 70% of the observations were collected. An average satellite visibility of 93% is satisfactory for an alpine country.

The data were analyzed using the Bernese Software 5.0 (Dach et al. 2007) with some additional features concerning GNSS ambiguity resolution (Schaer et al. 2007). The processing of the GPS data, including also the GNSS data of the permanent sites, followed a standardized semi-automated process. The selected processing options were harmonized with the options used in previous campaigns. Therefore, e.g. the antenna phase center variation (PCV) model is still based on a relative model, mostly derived from calibration campaigns using the test network in the area of the city of Thun (Brockmann 2000 and Brockmann et al. 2003). The LV95 points are usually linked to the next AGNES site which keeps the selected baselines short and always below 40 km. More than 95% of the ambiguities were successfully resolved using the two-step approach wide-lane / narrow-lane ambiguity resolution (statistics derived from 442 baselines). For 98 baselines below 10 km almost 100% of the ambiguities were resolved using directly L1/L2 observations and an ionosphere model provided by the Center for Orbit Determination in Europe (CODE). The baselines of the AGNES network were processed using GPS and GLONASS including ambiguity resolution.

As already mentioned before, the data set allows a simple validation of the results due to the longer observations covering two daily sessions.

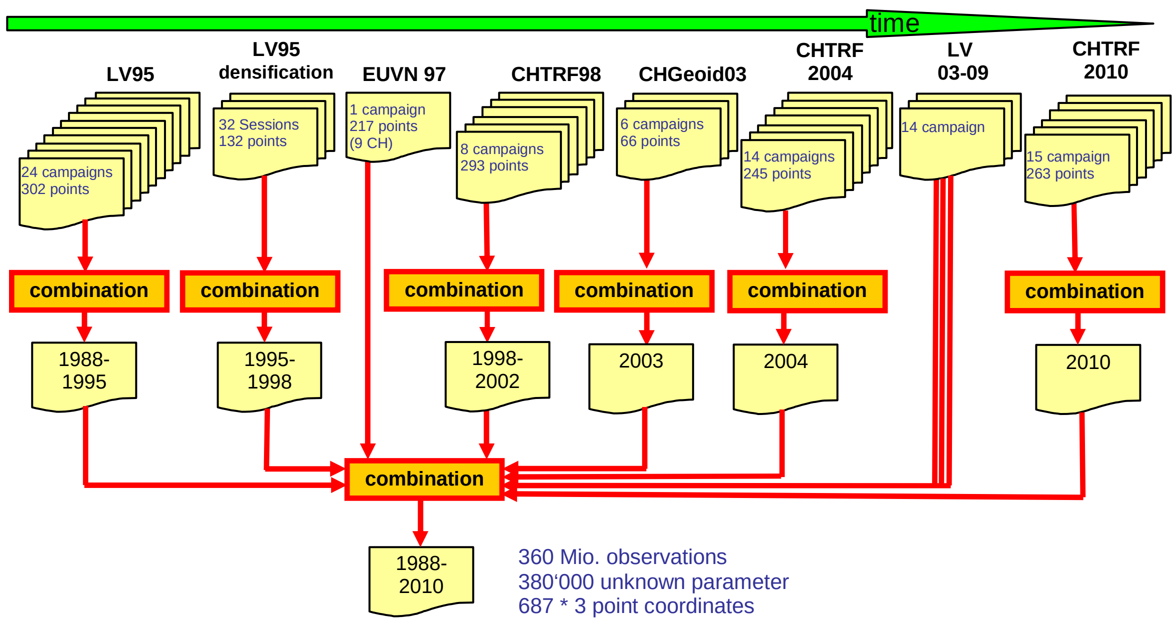


Fig. 2 Combination scheme for all campaigns between 1988 and 2010.

On average, a "repeatability" (standard deviation; std) derived from the comparison of two session coordinates of 1.0 mm (north component) and 0.8 mm (east component) was achieved. Only 25 from 263 stations show horizontal repeatabilities between 2 and 6 mm std. The worst station (Sargans) showed a difference of 8 mm in the east component which might be correlated with larger artificial obstructions (e.g. trees) close to the point. This repeatability value is also confirmed by the AGNES sites, whose statistics is based on a more reliable basis of 76 daily sessions.

The repeatability values for the station heights can be specified with a standard deviation of 5.3 mm (39 from 263 sites between 10 and 30 mm std; worst site Bourg St. Pierre with session a difference of 40 mm). Especially stations with larger sky obstructions suffer from uncertain height estimations.

3 Combination of Results 1988 – 2010

The combination of all available campaign results was realized using the method of normal equation stacking (Brockmann 1997). The combination scheme is given in Fig. 2. Prior to the final combination, the normal equations of the campaigns were stacked in a "pre-combination" (e.g. all 15 weeks or 76 sessions of the CHTRF2010 campaign). Campaigns covering a time interval of several years, were directly introduced to the final combination (e.g. campaigns between the years 2003 and 2009).

The comparison of the number of processed GPS/GNSS observations during the last 20 years shows clearly the influence of the permanent stations and the increased number of satellites. All data analyzed in 2010 contribute with more than 50% to the total data (see Fig. 3).

The number of observed stations is roughly the same during the years. The early GPS campaigns without permanent networks and with very limited satellite constellations (max. 5-6 satellites during several hours of the day) contribute less than 1% to the total number of observations.

The campaigns between 1988 and 2004 were not re-processed. They are based on an analysis using older versions of the Bernese Software. Therefore, format conversions and conversions due to the various operating systems (Unix/Linux) had to be performed prior to the combination.

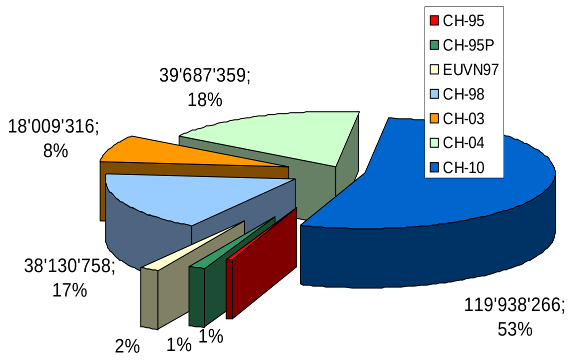


Fig. 3 Statistics of contributing number of observations.

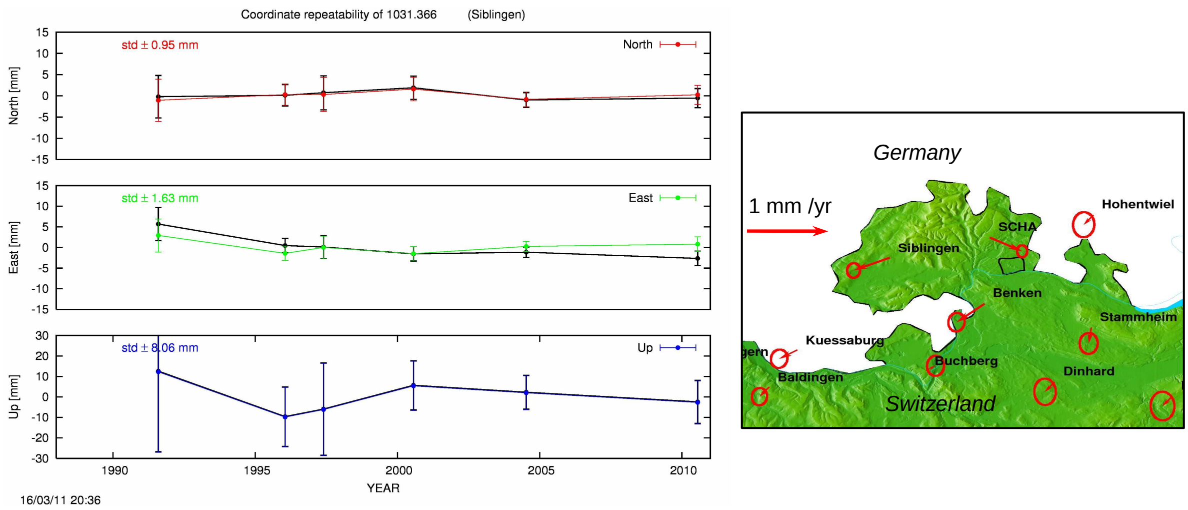


Fig. 4 Repetability of site Siblingen in North Switzerland (left diagram) with horizontal velocity estimation (in black without velocity estimation). The velocity vector of Siblingen and for surrounding sites is displayed in the right diagram.

The combination of the results of all campaigns was performed in an iterative way by setting up several solution types. The parameter set (estimation of horizontal velocities), the options concerning the datum definition and also the handling of individual station specialities in the campaigns were optimized. The main optimization criterion is the agreement between the contributed solutions and the combined solution.

The estimation of horizontal velocities makes only sense for sites covering at least a time interval of 4 years and for sites observed at least 3 times. This is fulfilled for about 233 sites out of totally 687 site occupations measured in the various campaigns.

As an example, the time series of an LV95 reference point and the illustration of the velocity vector is given in Fig. 4. To judge the significance of the velocity estimation, the statistics using all stations contributing to the combination is given in Fig. 5. The agreement of the contributing solutions with the combined solution is improved especially for the first and the last campaign. This effect reaches up to 58% and is an expected feature when stations are not stable, resulting in larger residuals at the beginning and at the end of the time interval. Totally, an improvement of 30% is achieved which underlines the assumption that site movements can be significantly estimated in the analysis of campaign data covering 20 years.

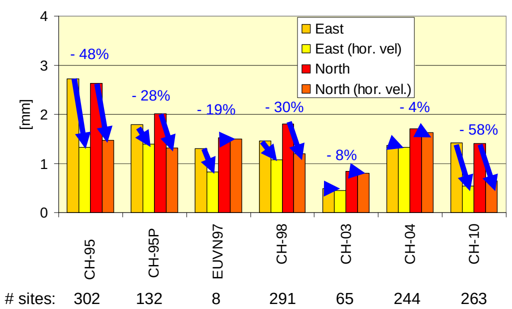


Fig. 5 Improvement of the standard deviation for the horizontal coordinate components when estimating velocity parameters.

4 Stability of Coordinate Reference Frame LV95

As reference solution for the comparison with the officially published coordinates a static combination type was selected. This type agrees with the static definition of the reference system used in federal surveying. The combined coordinate set is centered to epoch 2000.0. For the datum definition, the combined solution was aligned to the reference frame LV95 by using minimum constraints (no-translation conditions) with respect to the officially published coordinates of the permanent AGNES sites. The alignment to all AGNES sites was realized with a helmert standard deviation of 2.0 mm horizontally and 6.2 mm vertically.

Fig. 6 shows the Helmert residuals of 205 published LV95 points with the combined (and to AGNES aligned) static combination solution. The standard deviation of this comparison is about 4-5 mm for all components. This is excellent in view of the fact that the published horizontal coordinates are rounded to 1 cm. According to the maintenance concept for the geodetic surveying applications (Wiget et al. 2010), published coordinates need to be updated if they exceed a limit of 2 cm horizontally and 3 cm vertically. This limit was not reached by any of the reference points. Therefore, none of the published reference coordinates was modified.

Looking at the comparison in more detail we discover a significant Helmert parameter in East direction of 5.7 mm. The most dominant part of this bias can be contributed to the fact that in the analysis of the early campaigns no antenna models or only very basic models were used. Antenna calibrations taking into account different offsets of the L1 and L2 phase centers were introduced the first time in 1990. Furthermore, the datum definition was realized by constraining the coordinates of only one station (geo-station Zimmerwald) to a specific ITRF93 value and using global transformation formulas to convert to the ETRF93 reference frame (Boucher and Altamimi 2011). The systematic tilt in north-south direction in the height residuals of the order of +7 mm (north) to -7 mm (south) furthermore shows that at present there is a small inconsistency between the reference frames realized by the AGNES stations and the reference fame realized by the published coordinates of the LV95 reference stations.

5 Horizontal Velocity Field

The horizontal velocity field determined from data between 1988 and 2010 is given in Fig. 7. Additionally, the results derived from the permanent AGNES network and the results derived from campaign data in 2004 (Brockmann et al 2005) are plotted to demonstrate the uncertainties coming from the various estimations. With the exception of some locally instable points the velocities are well below 1 mm/year.

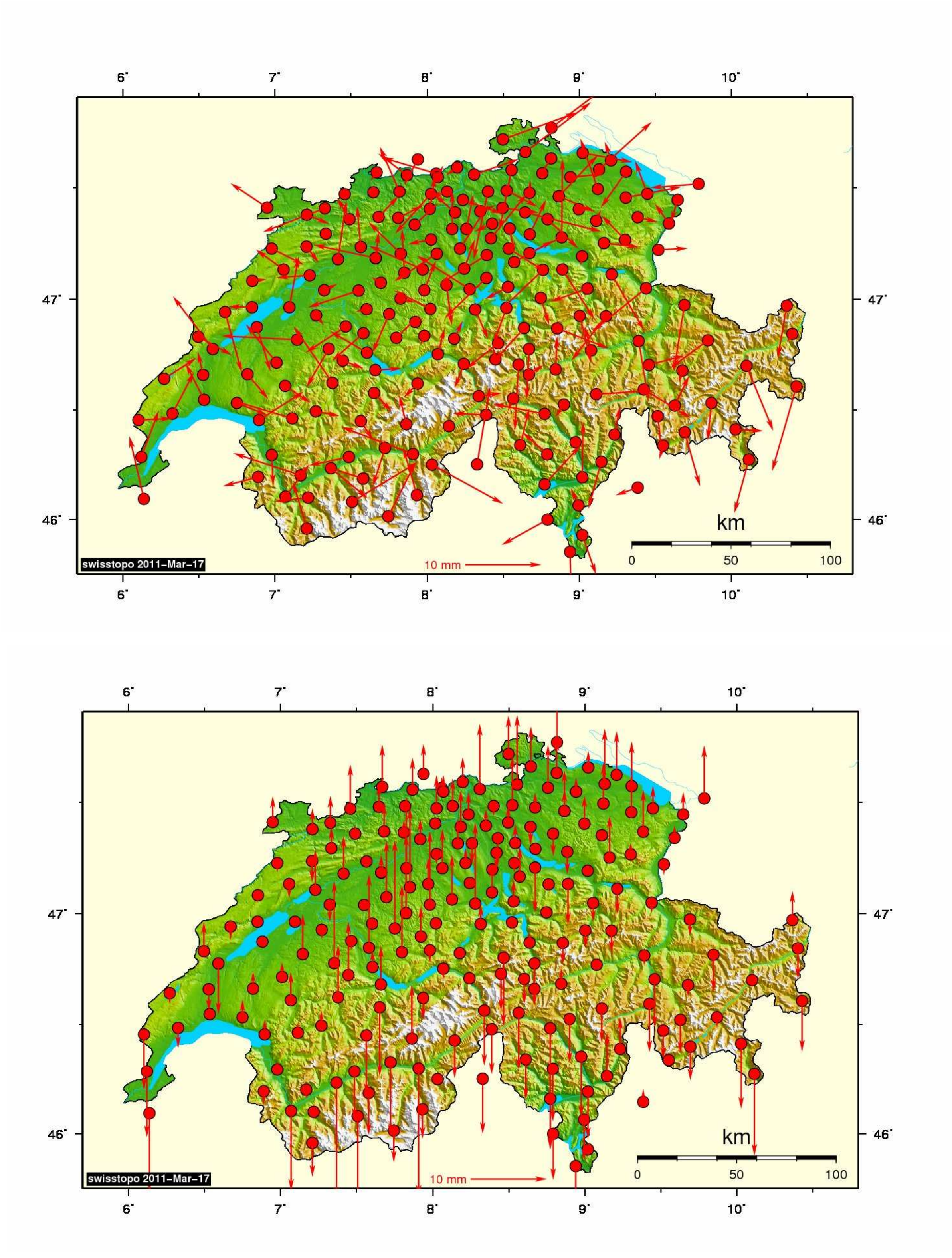


Fig. 6 Horizontal Helmert residuals (upper diagram) and vertical residuals (lower diagram) of the comparison of the combined solution with the published coordinates of 205 LV95 reference points. Helmert translation parameters: N: 1.1 mm, E: 5.7 mm, U: -3.5 mm. Standard deviation: N: ±4.2 mm, E: ± 4.0 mm, U: ± 5.3 mm.
Residuals ZIMM: N: -2.3 mm, E: 0.4 mm, U: -4.2 mm.

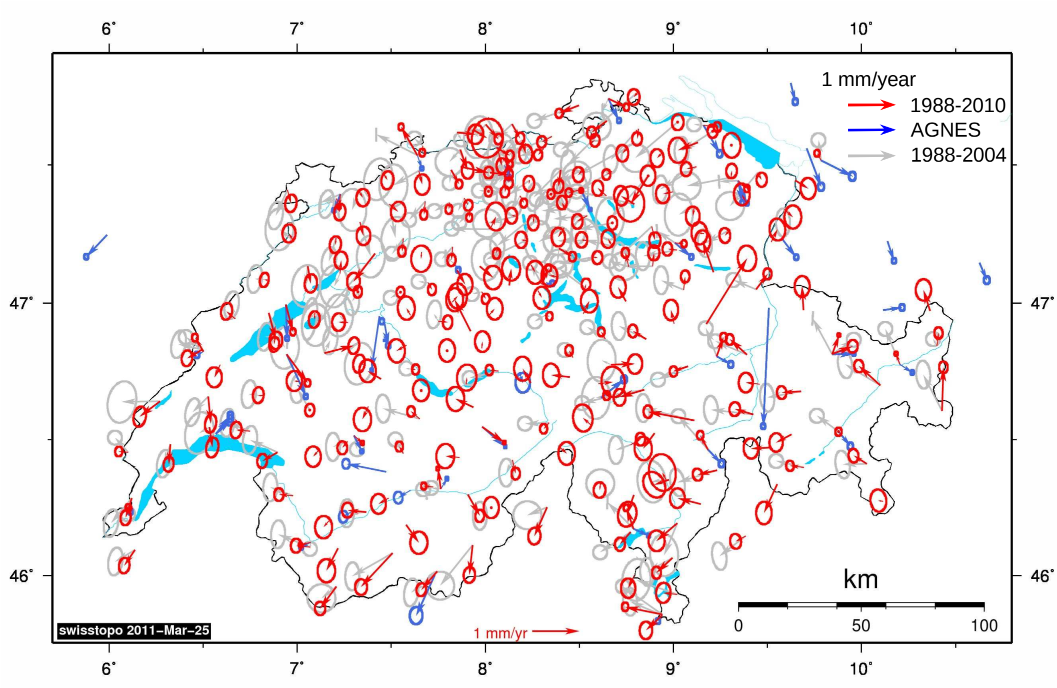


Fig. 7 Horizontal velocity field estimated by various methods with respect to geo-station Zimmerwald. The error ellipses are derived from the formal errors of the adjustment multiplied with an empirical factor of 15.

Statistically, the velocity field estimated from campaign data "1988-2010" is equal to a zero velocity field with a standard deviation of below 0.3 mm/yr per component (233 sites including instable sites are used). This is less than for the results achieved 2004 (0.4 mm/yr per component for 172 sites). Especially for sites in the north-eastern part of Switzerland the newly derived velocities are much smaller and they are not any longer pointing south-west (towards Zimmerwald). The agreement of the velocity field of 22 AGNES sites with a zero field is given with a std of 0.2 mm/yr. These statistical numbers indicate that the assumption of a stable horizontal reference frame is applicable for most surveying applications in Switzerland. Nevertheless, there are some interesting areas (e.g. the Valais in the southwest part of Switzerland) with similar and significant movements of several points which need further investigations.

6 Vertical Velocity Field

Due to the limited number of campaign measurements using different antenna equipment und due to the general problem to estimate reliable heights using GPS (correlation between antenna model uncertainties and tropospheric parameters, geometry effects) it is not yet useful to derive vertical velocities from the campaign data set. Vertical velocities using the GNSS technique can only be estimated from the permanent AGNES network. Brockmann et al. (2009) showed an alpine uplift of about 1.2 mm/year of the Swiss territory with respect to the stable part of the Eurasian tectonic plate using also GNSS data from the European Permanent Network (EPN). Comparisons with the results derived from more than 100 years of Swiss levelling data (Schlatter 2007) showed quite good agreements between the two techniques. According to the vertical uplift model RCM04 derived from the levelling data the alpine areas are rising 1.5 mm/year with respect to an arbitrary selected reference point "Aarburg" located at the south foot of the Jura Mountains, 50 km north-east from Zimmerwald. We therefore expect vertical rates with respect to the Eurasian plate of some alpine sites of about 3 mm/year. The combination of vertical velocity information coming from different sources and the combination with the horizontal velocity model need to be developed in the future (see Villiger et al. 2011).

7 Conclusions

The measurements and the analysis of the CHTRF2010 campaign were very successful and suited to maintain the stability of the Swiss reference frame. The average observation time per point of 43 hours enabled a simple validation by comparing 2 session results. 1 mm standard deviation was reached for the horizontal components, whereas for the vertical a std of 5.3 mm was achieved.

A combination of all campaigns since 1988 was performed in order to derive a horizontal velocity field. The horizontal repeatabilities reached a std of 1.7 mm (1.2 mm with estimating velocities) and 6.8 mm vertically. The associated velocity field shows only very small movements with respect to the reference point Zimmerwald. The significance level for a horizontal velocity component is in the order of 0.3 mm (standard deviation). Vertical velocities cannot yet be estimated using GNSS campaign data. Only for the permanent stations vertical velocities, showing the rising of the Alps, can be estimated from the long-term GNSS analysis.

The comparison with the officially published coordinates shows differences below a level where coordinates need to be updated (2 cm horizontally; 3 cm vertically). Nevertheless, we find a small bias between the realization of the reference frame using AGNES stations (East shift of 5.7 mm and systematic north-south tilt of the order of 7 mm).

More details about the campaign and its analysis are documented in (Brockmann 2010).

With these results we can state:

- The LV95 network consists of stable points.
- The maintenance method (campaign measurements and analysis) is suited to maintain the reference frame on a very high precision level.
- in view of the quality demands for most surveying applications the assumption of a stable reference frame is still valid.
- For scientific applications a 3D velocity model will be developed and compared with geological and geophysical models.

The next re-observation of the complete LV95 reference network is planned for 2016 – might be already using GPS-GLONASS-GALILEO combined receivers and antennas.

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