Displacement Measurements with GNSS and Radar Interferometry above the New Alp Traverse Tunnel Gotthard

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Abstract. Since the thirties of the last century, the national mapping agency of Switzerland swisstopo monitors on behalf of the canton of Uri and the Swiss Federal Railways SBB rock movements above the alp traverse Gotthard in the region of « Chli Windgällen » (Switzerland). Until 2003, an extensive traditional triangulation network was measured every 10 to 15 years from the opposite site of the valley. In 2012, the SBB launched a pilot project in the upper Reuss Valley between Sisikon and Wassen for an interferometric time series analysis on ERS and ENVISAT satellites datasets from 1992 to 2010. This work was done by Gamma Remote Sensing AG, Gümligen – Switzerland. In 2015 finally, swisstopo established in collaboration with the canton Uri a new monitoring concept – also as basis for further SAR interferometry projects – based on GNSS measurements (static and real-time kinematic RTK).

This paper presents the new geodetic network, the challenges modelling GNSS-RTK and static measurements in a mountain area with large height extensions, shows the results of the time series analysis with the displacements from 1933 to 2015 as well as a first comparison with the annual displacement rates from the SAR analysis.

Keywords. Deformation Monitoring, Rockslide, GNSS and Radar Interferometry

1 Introduction

In August 1936 occurred a serious rock fall at the western flank of the Chli Windgällen above the Gotthard alp traverse in Switzerland. As a consequence of this incident, swisstopo was mandated to determine the dimensions of the landslide using terrestrial photogrammetry. More than thirty years later in 1969, an extended triangulation network was measured which allowed a comparison with the national survey in the region dated from 1933. The first official monitoring concept from 1984 stipulated a three level surveillance: (1) annual crack measurements, (2) local measurements, the so-called « small triangulation », every 3 years and (3) the observation of an extended geodetic network (so-called « large triangulation » – see fig. 1) from the opposite side of the valley every 9 to 12 years. Since 1984 distance measurements have been performed additionally to the directions and elevation angles and since 1993 also GPS observations on selected survey points enlarged the net design. The traditional triangulation network was measurement for the last time in 2003. 9 surveying operators and 2 mountain guides needed about a week and many helicopter flights to perform all the measurements which were very laborious.

The improvement of the analysis method using SAR interferometry datasets and the possibility of a reprocessing backwards in time motivated the SBB 2012 to start a pilot project: 82 ERS and ENVISAT datasets from 1992 to 2010 should be reprocessed to determine terrain displacements. SBB assigned the mandate to Gamma Remote Sensing, who started the interferometric time series analysis without delay [U. Wegmülller et al., 2013].

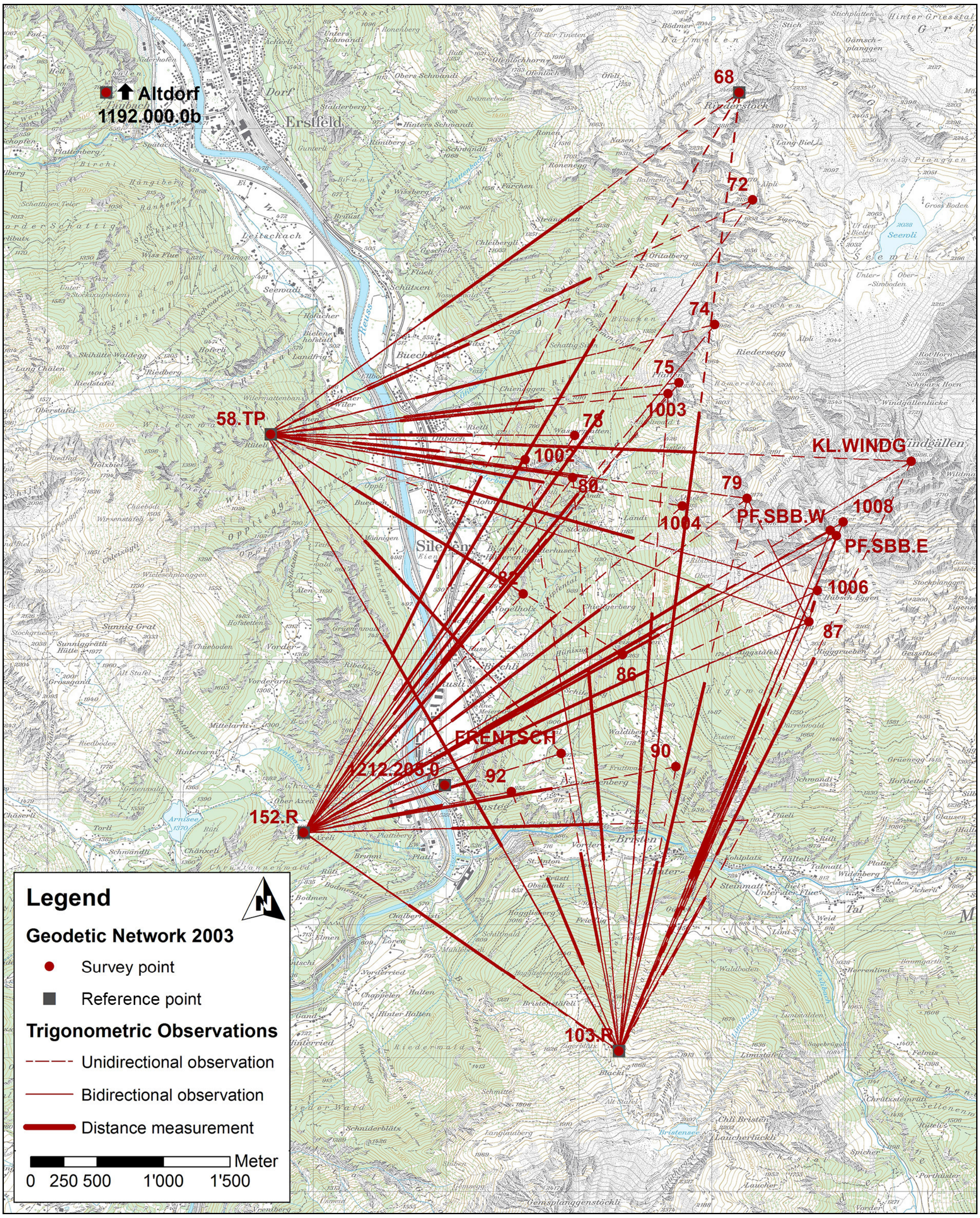

Fig. 1: The historical triangulation network observed from 1984 – 2003 with the observation types and the reference points. The course of the new Gotthard train base tunnel is visible on the map as double dotted line, e.g. under the survey points 78 and 80.

2 Concept of the new Geodetic Network based on GNSS

The concept of the new geodetic network stipulated a reliable determination and an accuracy of 2 cm in position and 5 cm in height according the client specification. So, each point has to be measured 2 times with 2 different GNSS receivers for a couple of minutes at a different time in the RTK modus using the Swiss Positing Service swipos. 6 selected points well distributed all over the monitoring area in position and height should be additionally measured in the static modus for at least 24 hours (see fig. 2). The plan was to improve the RTK measurements with the more accurate determined static points in the least squares adjustment. This could be necessary due to the fact that the height extension of the network is huge (457 m – 2986 m a.s.l.). Furthermore, the nearest 4 continuously operating CORS reference station of the automatic GNSS network Switzerland AGNES are 16, 39, 41 and 43 km away of the area below « Chli Windgälle » and on all different height levels. It is clear that on these far distant CORS stations could prevail completely different weather conditions so that the estimation of the troposphere parameters could be challenging.

The carefully elaborated measurement plan with transfers mainly by helicopter allowed the 2 teams with 2 persons each to complete the GNSS observations in 3 days (instead of 11 persons in 5 days). This under the condition of perfect and stable weather, so that the pilot could perform safely the necessary suspension landings.

The costs for the campaign could be reduced in comparison to the classical triangulation network altogether by about two-thirds. On the other hand the number of helicopter flights increased because every survey point had to be approached twice for reliability reasons.

3 Data Processing

The RTK measurements have been introduced in the least squares adjustment as they resulted from the Leica GNSS receivers. This in contrast to the static observations, which have been performed with Trimble equipment (GPS receiver 5700). The post-processing of these GNSS datasets have been done with the Bernese GNSS Software together with all the other observations from the AGNES CORS network of the same period. For the link from AGNES to the local geodetic network a ionosphere-free L3 solution was calculated while inside of the geodetic network L1 solutions have been prioritised. Alternative L3 solutions have been calculated for all the survey points. AGNES is mainly equipped with Trimble infrastructure and the Swiss positioning service swipos is running with the concept of virtual reference stations VRS.

While the actual accuracy in position for the RTK measurements was according to the expectations, the heights could only be determined with an accuracy of about 10 cm. Further analysis showed that the software used in the swipos positioning service operation centre to model the troposphere respects only the position of the rover but not the height differences. The so calculated path delays are not sufficient in case of faraway (in position and height) reference stations. But how to model a not adequate path delay in the least squares adjustment?

For the RTK observation, the functional model has been adapted so that for each session a height translation as well as a z-scale factor could be estimated. Additionally, a much higher weight has been attributed to the static observations in an independent session by reducing the theoretical standard deviation.

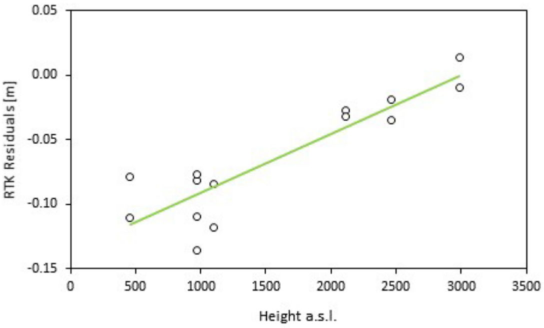

Fig. 2: Linear regression estimation for the residuals (RTK observations) in function of the point height. For the static observations, the L3 solutions were introduced in the least squares adjustment.

The result of the linear regression is shown in Fig. 2. The several points at the same height are multiple RTK-measurements. All points are measured at least twice to achieve a better reliability. With this approach, the result could be significantly improved: The estimated translation of 13.7 cm and the scale factor of 45.6 ppm are highly significant, so that “better” heights could be retrieved.

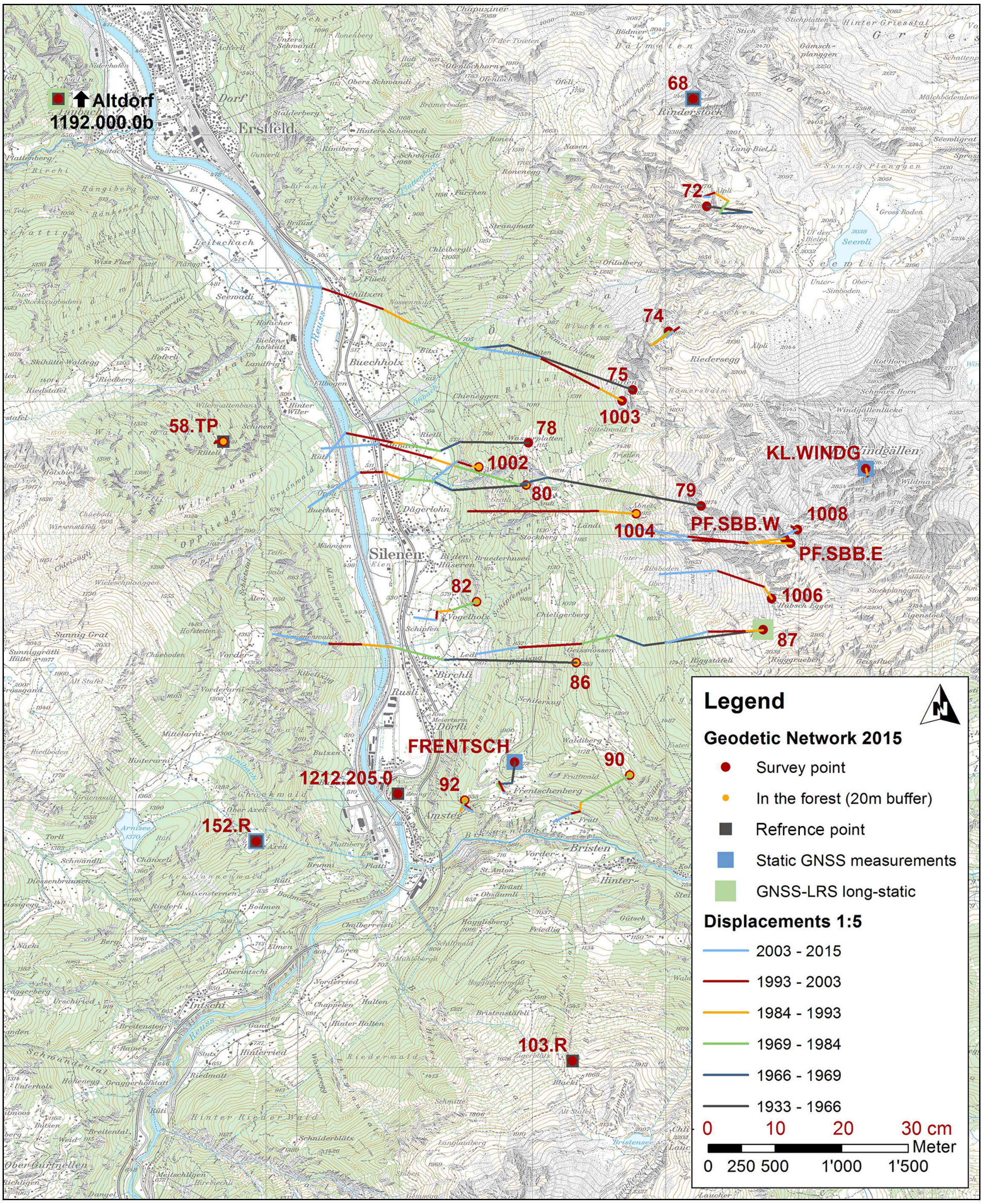

Fig. 3: The new GNSS network bases on RTK measurements with the Swiss Positioning Service swipos supported by static and long-static local reference stations LRS. Furthermore, the reference points as well as the displacements vectors for 6 epochs from 1933 – 2015 are shown.

4 Results

In Fig. 3 the position displacement vectors for the different epochs since 1933 are shown. Vectors longer than 2 to 3 cm are generally significant on a confidence interval level of 95% for the epoch 2003 – 2015. Given that the time intervals are not equal, a normalized annual movement rate for the last two epochs 1993 – 2003 and 2003 – 2015 has been calculated. Fig. 4 shows that the mean displacement rate stays stable in position for the majority of the survey points over the two last epochs. An influence from the 2009 completed base tunnel caused by the drainage of the mountains could so far not be detected. Possibly, the pending analysis of the height displacements will show more. The drain of the mountains results mainly in a subsidence of the surface as we know for instance from the Gotthard highway tunnel.

5 Comparison of the Displacements estimated by the GNSS Measurements and the SAR Interferometry

A comparison with the displacements rates published by [U. Wegmülller et al., 2013] shows first of all that the SAR interferometry gives us high density information about the deformation in the western flank of Chli Windgällen. But on the other hand hardly any information could be retrieved for the lower part of the slide area because of the forests and the topography: No stable surfaces like rock can be found here for the Persistent Scatterer Interferometry PSI. The installation of special reflectors in this area could maybe help in the future.

Furthermore, the following GNSS survey points can be identified as being in the area with SAR displacements rates (from south to north): FRENTSCH, 90, 87, 1006, PF.SBB.E|W, 79, 1003, 75, 74 and 72. A comparison of the displacement rates shows that the published values are essentially identical for the border of the slide area (points FRENTSCH, 90, 74 and 72). On the other hand for the upper part of the slide area (points 1006, PF.SBB.E|W, 79, 1003 and 75), the GNSS measurements show slightly higher rates with 7 to 8 mm/year in comparison to the SAR rates with 5 mm/year. The empiric accuracy of the GNSS displacement rates (confidence interval 95%) is between ± 1.6 and ± 2.5 mm/year for the epoch 2003 – 2015.

6 Conclusions and Outlook

The triangulation network can be replaced by GNSS-RTK observations. Due of the large height extension of the network, additional static measurements on selected survey points on different altitude levels are essential. In the least squares adjustment a z-translation and a height scale factor have to be estimated. Thus, the achievable accuracy remains about the same in comparison to the triangulation network.

It has to be kept in mind that the use of a positioning service in mountain areas instead of a local reference station could reduce the height accuracy in case of faraway reference stations on different altitude levels.

Although the new alp traverse tunnel Gotthard has been completed 6 years ago, no significant change in the deformation rates could be detected up to now.

SAR interferometry is an interesting complement to the geodetic observation methods. If the slope orientation fits to the satellite orbit and observing direction, a high density of continuously, but one-dimensional deformation rates could be gained from the SAR without the need of being present in the land slide area. GNSS observations, on the other hand, give us very accurate 3-dimensional displacement vectors with a statistically clearly defined precision but for discrete points only.

Further clarification needs the fact that there are differences in the detected displacements rates by SAR interferometry and the geodetic observations. However, the two time intervals for the calculation of the annual rates are not completely congruent.

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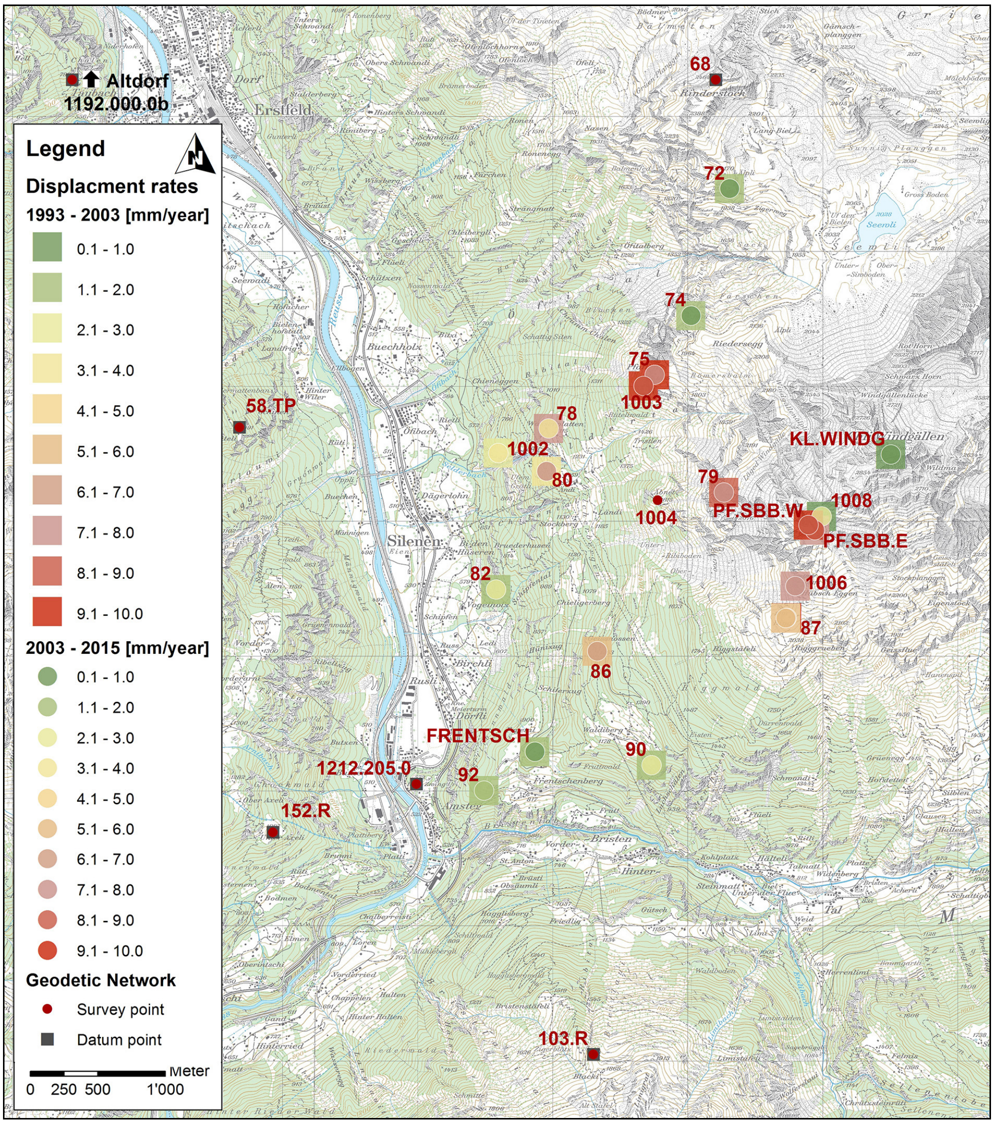

Fig 4: Annual displacement rates from the trigonometric and GNSS observations for the survey points for the epochs 1993 – 2003 (squares) and 2003 – 2015 (circles). Essentially there are no substantial differences between the epoch-rates.

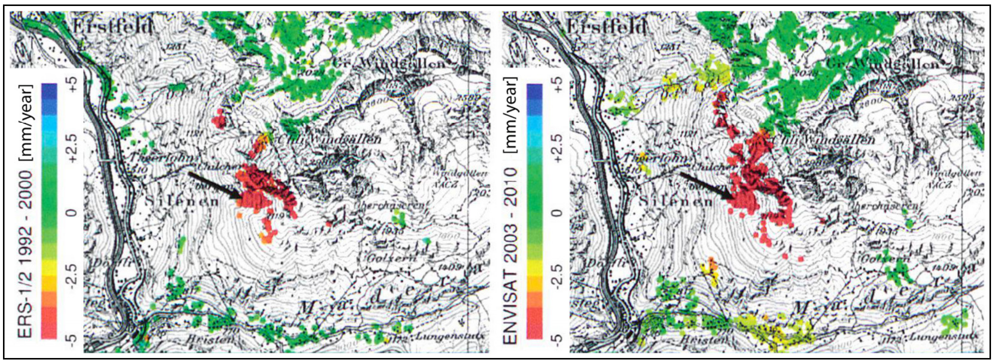

Fig 5: Annual displacement rates from the SAR interferometry from [U. Wegmülller et al., 2013] for the same area.