Austrian Journal of Earth Sciences | Volume 102/2 | 20 - 34 | Vienna | 2009

Monitoring the Aggenalm Landslide using Economic Deformation Measurement Techniques

John SINGER[1)*)], Stefan SCHUHBÄCK[2)], Peter WASMEIER[3)], Kurosch THURO[1)], Otto HEUNECKE[2)], Thomas WUNDERLICH[3)], Jessica GLABSCH[2)] & Judith FESTL[1)]

[1)] Technische Universität München, Lehrstuhl für Ingenieurgeologie. Arcisstr. 21, 80333 München, Germany;

[2)] Universität der Bundeswehr München, Institut für Geodäsie, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany;

[3)] Technische Universität München, Lehrstuhl für Geodäsie. Arcisstr. 21, 80333 München, Germany;

[*)] Corresponding author, singer@tum.de

KEYWORDS

reflectorless videotacheometric positioning system
time domain reflectometry
monitoring
landslide
GPS

Abstract

In context of global climate change and the continuous extension of settlement areas in the Alps especially due to tourism, an increasing conflict between land use and natural hazard prevention can be observed. This also includes deep seated landslides, which if activated can cause considerable damage to settlements and infrastructure and even can endanger lives.

To date the hazard potential of slow deep seated landslides often is underestimated. Due to economic reasons such potentially dangerous instable slopes if at all often are only monitored sporadically. The alpEWAS project ("development and testing of an integrative 3D early warning system for alpine instable slopes") is currently developing a low cost 3D monitoring and early warning system for landslides based on three innovative economic continuous measurement systems for underground and surface deformations: Time Domain Reflectometry (TDR), Reflectorless Video Tacheometry (VTPS) and Low Cost Global Navigation Satellite System (GNSS). These are merged with other sensors, which monitor typical trigger mechanisms (e.g. precipitation), into a geo sensor network, which provides remote online access to all data in near real time.

The alpEWAS system has been installed at the Aggenalm landslide, located in the Bavarian Alps near Bayrischzell, for a first field test. To date the system has reliably produced data for about 8 months, of which the first time series are presented. The amount of data is currently still not sufficient for a final evaluation of the new measuring systems during field use, but the preliminary results concerning the reliability and accuracy of the measurements are promising. The experiences made at this first field test will be of great importance for the medium-term goal: the development of a market-ready, flexible, economic early warning system for landslides.

In den Alpen ist im Kontext des globalen Klimawandels und der fortwährenden Ausweitung von Siedlungsflächen vor allem auf Grund des Tourismus ein wachsender Konflikt zwischen der Landnutzung und der Prävention vor Naturgefahren erkennbar. Dies gilt auch für tiefgreifende Hangbewegungen, die – wenn aktiviert – Siedlungen und Infrastruktur beträchtlichen Schaden zufügen, oder sogar Leben bedrohen können.

Bis heute wird das Gefährdungspotential von langsamen tiefgreifenden Hangbewegungen oft unterschätzt. Aus wirtschaftlichen Gründen werden gefährliche Hänge, wenn überhaupt, oft nur sporadisch messtechnisch überwacht. Das alpEWAS-Projekt („Entwicklung und Erprobung eines integrativen 3D Frühwarnsystems für alpine instabile Hänge") entwickelt deshalb momentan ein ökonomisches 3D Überwachungs- und Frühwarnsystem für Hangbewegungen, welches auf drei kostengünstigen, innovativen und kontinuierlich arbeitenden Messsystemen für die Überwachung von Deformationen an der Oberfläche und im Untergrund basiert: Time Domain Reflectometry (TDR), reflektorlose Video-Tachymetrie (VTPS) und preiswertes Global Navigation Satellite System (GNSS). Diese Messsysteme werden zusammen mit anderen, die typische Triggermechanismen wie z.B. Niederschlag überwachen, in ein Geo-Sensorennetzwerk integriert, das über eine WebGIS Umgebung einen Fernzugriff auf alle anfallenden Daten nahezu in Echtzeit ermöglicht.

Das alpEWAS System wurde in einer ersten Felderprobung im Bereich der Aggenalm-Hangbewegung (Bayerische Alpen nahe Bayrischzell) installiert und ist seit ca. 8 Monaten kontinuierlich in Betrieb. In diesem Zeitraum wurden, von kleinen Störungen abgesehen, die Messungen zuverlässig durchgeführt und die entsprechenden Daten erfasst. Erste Zeitreihen dieser Messergebnisse werden präsentiert. Für eine abschließende Beurteilung der neuen Messsysteme im Geländeeinsatz ist die Datengrundlage noch zu gering, jedoch scheinen sie hinsichtlich Genauigkeit und Zuverlässigkeit die in sie gesetzten Erwartungen zu erfüllen.

1. Introduction

In context of the global climate change an increase of extreme precipitation events is expected for Europe and the Alps (Alcamo et al., 2007). As heavy rainfall is an important trigger for landslides, the frequency of hazardous landslide events is also expected to rise. Luckily in most alpine regions the awareness of landslide hazards has risen in the last years, driven by national and regional hazard mapping programs (e.g. in Bavaria (LfU, 2009), Switzerland (Lateltin et al., 2005) and South Tyrol (Willerich et al., 2008).

Although many potentially hazardous landslides have been identified, due to economic reasons only few are continuously monitored, e.g. Hochmais (Tenschert, 1998) and Gradenbach landslide (Brunner et al., 2007). However, in order to evaluate the probability of a catastrophic event, continuous observations of the ongoing surface and subsurface deformations as well as of the triggering influences (e.g. precipitation and ground water levels) are essential, which - together with a geomechanical model of the instable slope - may make a quantitative assessment of the causal and temporal relation between the landslides movements and its triggers possible.

To date in many cases only sporadic measurements (geodetic surveys, inclinometers etc.) are performed, which is not sufficient when infrastructure or even human life is at risk. In order to overcome this, efficient and economic measurement systems for landslide monitoring are needed.

Therefore the alpEWAS*) research group is currently developing new economic measurement systems for the continuous acquisition of surface and subsurface deformations, which are combined with other sensors in a geo sensor network (GSN). The alpEWAS GSN is currently undergoing a first field test at the Aggenalm landslide in the Bavarian Alps.

2. The Aggenalm Landslide

The Aggenalm landslide is situated in the Bavarian Alps in the Sudelfeld region near Bayrischzell (Fig. 1a). In 1935, after being triggered by heavy rainfall, the Aggenalm landslide destroyed three bridges and the road which today leads to the Sudelfeld skiing area. Again after extreme precipitation in 1997 a debris flow originated from the landslide area and also blocked the road. Since 2001 the landslide has been surveyed periodically up to twice a year by the Bavarian Environment Agency (LfU, 2008), showing average movement rates of about two centimetres per year.

Geologically this area is part of the Lechtal Nappe of the Northern Calcareous Alps and is mainly built up of various Triassic and Jurassic limestones, dolomites and marls. In the project area the Kössener Schichten, an alternating sequence of dark colored limestones and marls, and the Oberrhätkalk, a massive partly dolomitic limestone, are exposed.

During the Alpine orogeny the rock mass was heavily faulted and folded into several large and small east-west oriented syn- and anticlines, of which the Zellerrain-Auerberg Anticline with its eastward dipping axis is responsible for the nearly slope parallel orientation of the rock mass in the Aggenalm landslide area (Fig. 1 and 2).

In the last ice age the area was covered by glaciers, which resulted in typical glacial morphology and the abundance of vari-

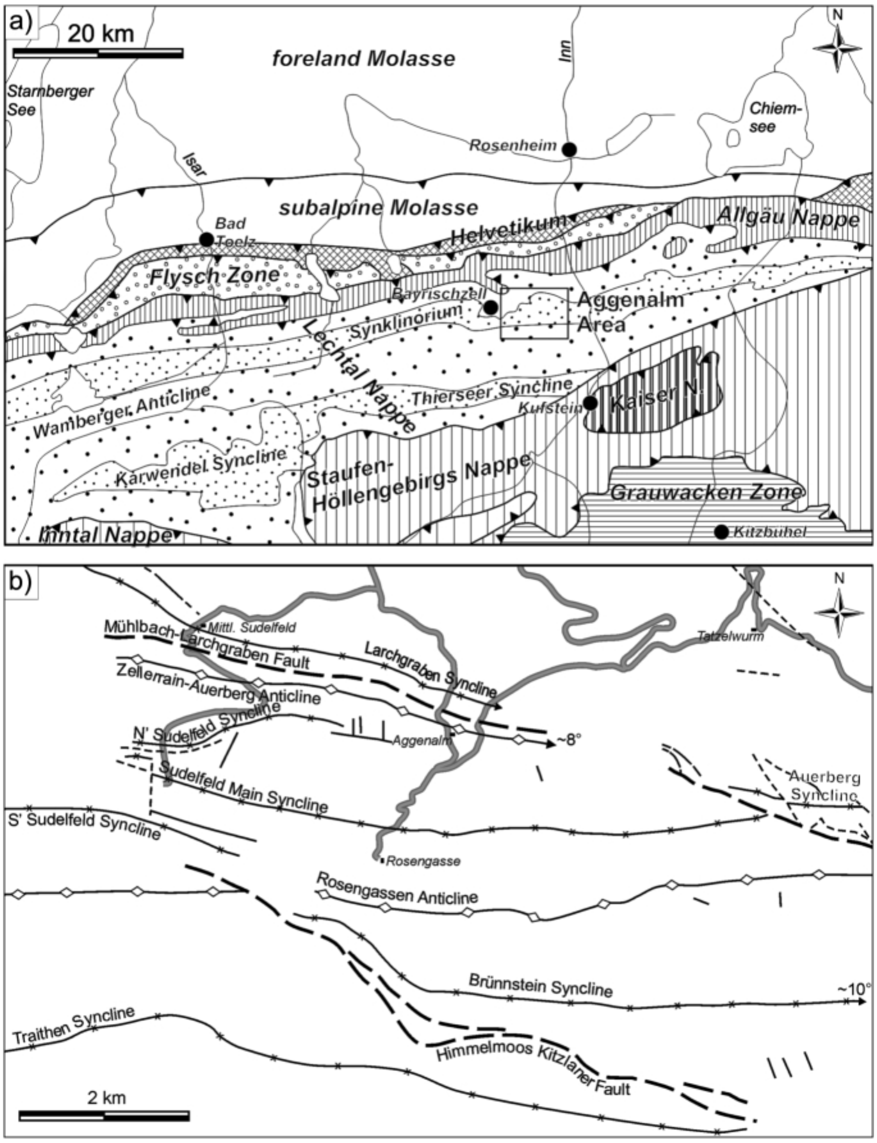

Figure 1: Figure 1a – Tectonic map of the Nothern Calcareous Alps between Lake Starnberg and Chiemsee. The Aggenalm landslide is situated in the Lechtal Nappe within the Synklinorium, a major Syncline – Anticline – Syncline fold belt, which can be traced through the whole region. Figure 1b – Detailed tectonic map showing the main tectonic features in the Aggenalm landslide area. Here the Synklinorium has a complex structure with several additional minor syn- and anticlines, of which the eastward dipping of the Zellerrain-Auerberg Anticline is responsible for the nearly slope parallel orientation of the rock mass within the Aggenalm landslide.

*) The research group “alpEWAS” (Development and testing of an integrative 3D early warning system for alpine instable slopes) is part of the geoscientific research and development program “Geotechnologien”, which is funded by the German Federal Ministry of Education and Research (BMBF).

ous glacier deposits.

The marls of the Kössener Schichten which underlie most of the slope are sensitive to weathering and with time are decomposed to a clay-rich residual rock. This process coincides with a distinctive reduction of the rock mass strength (Nickmann et al., 2006) and is thought to be mainly responsible for the instability of the slope (Jung, 2007).

In the upper part of the Aggenalm landslide, where the Oberrhätkalk slowly sinks into the plastically deforming decayed marls of the Kössener Schichten, the landslide mechanism can be classified as a rock spread according to Cruden and Varnes (1996). Further downhill, with increasing deformation, the rock mass continuously disintegrates and the mechanism changes into a very slow debris flow. Based on detailed map-

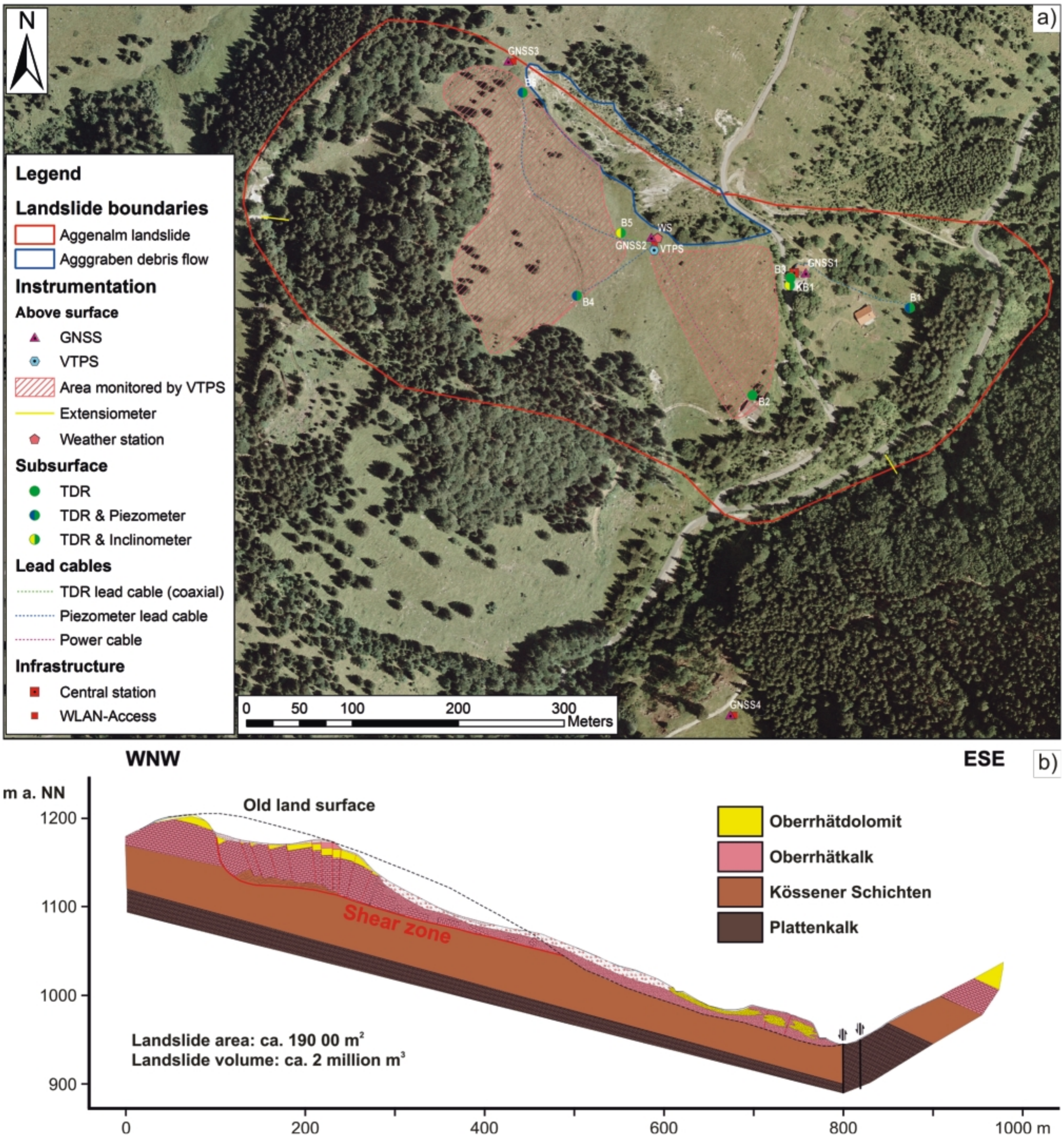

FIGURE 2: Figure 2a – Orthofoto of the deep seated complex Aggenalm landslide (red boundary) and the 1997 secondary debris flow (blue boundary). The position of the various measuring devices and infrastructure elements as well as the area monitored by the VTPS are superimposed on the image (edited according to Thuro et al., 2009). Figure 2b – Geological cross section (WNW-ESE) through the Aggenalm landslide. The dotted line represents an estimation of the land surface before the landslide. In the upper part of the landslide the Oberrhätkalk sinks into the underlying Kössener Schichten, whereby the rock mass is torn apart into several individual large rock slabs. With ongoing deformation the rock mass gradually disintegrates into debris, changing the landslide mechanism from a rock spread into a slow debris flow in the lower part of the slope. The landslide area, depth and volume are estimated based on detailed engineering geologic mapping and drilling log results (Jung, 2007).

ping results and the drilling logs this mass consists mainly of limestone and dolomite components of all sizes from very large rock slabs of several meters in diameter, partly with intact rock fabric, to gravel. This cavernous mass can reach a thickness of up to 25 m, below which again the Kössener Schichten are found. The debris, which slowly accumulated through time, was the origin of a large fast debris flow in 1997, which resulted in a deep ditch on the northern flank of the Aggenalm landslide. It is probable that further debris flows can originate from this area (Fig. 2a).

3. Aggenalm Landslide Monitoring concept

In order to be able to monitor the different landslide mechanisms within the complex Aggenalm landslide – each with presumably different deformation behaviour through time – extensive deformation monitoring is necessary. This is achieved at reasonable cost using the new economic measuring techniques Time Domain Reflectometry (TDR) for the detection of subsurface movements in boreholes, low cost global navigation satellite system (GNSS) and reflectorless videotacheometric positioning system (VTPS) for measurements of surface movements. By combining the data of these measuring systems, 3D deformation information can be gained not only with high spatial, but also with high temporal resolution, as all three systems can be operated continuously.

The VTPS station provides extensive measurements of the surface deformation (Fig. 2a). However, as an optical system, it is subject to weather interferences, making a reliable operation during bad weather conditions (e.g. heavy rain or fog) impossible. In order to be able to monitor critical areas also under disadvantageous conditions, GNSS sensors were installed at these locations (e.g. above the tear-off zone of the 1997 debris flow or next to sensitive infrastructure). The TDR measurements provide information about the location and activity of the subsurface deformation zones, thereby making a three dimensional assessment of the landslide dimensions (volume) possible.

The data provided by the different deformation measuring systems can also be cross checked for example at points, which are measured by both GNSS and VTPS. Also the TDR subsurface deformation measurements can be compared to the according surface deformation (VTPS and/or GNSS) at the top of the TDR borehole. This redundancy increases the reliability of the complete measuring system as it makes an automatic identification of erroneous measurements possible.

Based on the observations made during the events in 1935 and 1997 high precipitation and presumably the accompanied rise of pore water pressure was identified as the most probable triggering mechanism of the Aggenalm landslide. Therefore the monitoring system comprises next to deformation measuring systems also sensors for the acquisition of the amount of precipitation (weather station) and pore water pressures (piezometers installed into boreholes close to the assumed shear zone). Additionally during the winter the snow heights will be determined using the VTPS station in order to be able to estimate the water input to the slope during snow melt in spring.

Depending on the rate of deformation, after about 1 year of observation the combination of all above measurements should lead to the identification and quantification of causal and temporal relations between the triggering factors and the deformation. This, together with geomechanical computer models of the slope, will be the basis for the definition of critical threshold values for the deformation rate and triggering factors, at which a renewed activation of the Aggenalm landslide seems highly probable. From this point on the alpEWAS monitoring system can be operated as an early warning system (EWS), by releasing a warning when thresholds are surpassed.

3.1 Geo sensor network

In order to make a continuous operation and data retrieval of the alpEWAS monitoring system possible, all system components are integrated into a geo sensor network (GSN). Referring to wireless sensor networks (WSN) – defined as an infrastructure comprised of measuring, computing, and communication elements that gives an administrator the ability to instrument, observe, and react to events and phenomena in a specified environment (Sohraby et al., 2007) – in a GSN the location finding system is the fundamental sensing unit, that makes it a subject of geodetic concern, expressed by the according techniques and methods. Organizationally a GSN or WSN is subdivided into several so called sensor nodes which – in general – operate fully autarkic. A central computer centre manages all system operations, e.g. data collection and logging and also controlling of the sensor nodes.

The GSN at the Aggenalm landslide has the layout depicted in Figure 3. Altogether there are four sensor nodes which are located within and outside the landslide, two completely autarkic GNSS sensor nodes, the so called main sensor node, and the onsite computer station that also contains a separate sensor node. In addition there are a few VTPS reference prisms. Cable connections were established from the sensor nodes to all distributed boreholes containing the TDR, piezometer and/or inclinometer setup. This basically results from economic reasons, as the installation of a separate sensor node at each location with an own set of measuring devices, power supply and network access points although technically realizable would drastically increase hardware costs. Anyhow, the geological components except the manual operated inclinometer stations are fully integrated in the GSN.

The transfer of data from all sensor nodes to the computer centre is handled by an infrastructural Wireless Local Area Network (WLAN). Customary hardware components (e.g. bridges, wireless device servers) reach transfer rates of nominally 54 MBit/s (IEEE 802.11g). Compared to other common communication standards like conventional radio data transmission (transfer rates of about 9600 bps, range up to 30 km) or Bluetooth (transfer rate up to 700 kbps, range up to 100 m) WLAN combines the preferences of these systems – a high data rate over medium to high ranges. In order to achieve comparable transfer rates over distances of about 500 m and more, specific high quality WLAN-antennas have to be used. For remote maintenance and supervising a DSL internet connection via satellite is set up at the base station.

For a continuous operation of the measurement system an uninterrupted power supply of the different sensor nodes has to be ensured. Due to the use of a personal computer (with high power consumption), the central station should be connected to the local power network (220 V). At the Aggenalm landslide, although not mandatory, the main sensor node with a high diversity of different sensors (including VTPS, weather station and a webcam) also is cable-connected to the local power network. All other sensor nodes have a battery-operated autarkic power supply (solar panel, charge controller and battery). An additional fuel cell is installed at the GNSS reference sensor node, because during winter the solar radiation at this location is too low. Generally in an alpine environment high emphasis has to be put on the robust power supply during system design, considering all disadvantageous conditions as e.g. low temperatures, long snowfall or a relatively long gap without recharge (solar panel in shadow) in order to be able to reliably supply power to all sensors throughout the whole year.

3.2 Deformation Measuring Techniques

The backbone of the alpEWAS GSN are the economic deformation measuring techniques TDR, VTPS and low cost GNSS. Each of these systems was further developed to achieve the best possible cost-benefit ratio.

3.3 Time Domain Reflectometry (TDR)

The direct measurement of subsurface deformations is only possible in boreholes. To date, if continuous monitoring is required, usually inclinometer chains are used for this task. While these allow to determine subsurface deformations with high precision, the associated costs are quite high. So often continuous monitoring is rejected in favour of cheaper sporadic measurements.

With a Time Domain Reflectometry (TDR) measuring system continuous monitoring of subsurface deformation can be performed at 25 % and less of the costs compared to inclinometer chains (Table 1). The main reduction of cost is achieved by the decrease of the bore hole diameter (about 30 mm sufficient for TDR), the low hardware and installation costs per measuring site (about € 7000,- for the monitoring of typically 5 to 10 but up to 256 sites) and low maintenance costs (remote data retrieval and maintenance). However the landslide mechanism has to meet some premises in order to be able to use this measuring system, as it is limited to the detection of localized shear zones.

3.3.1 Measurement system layout

A TDR measuring system consists of three major elements:

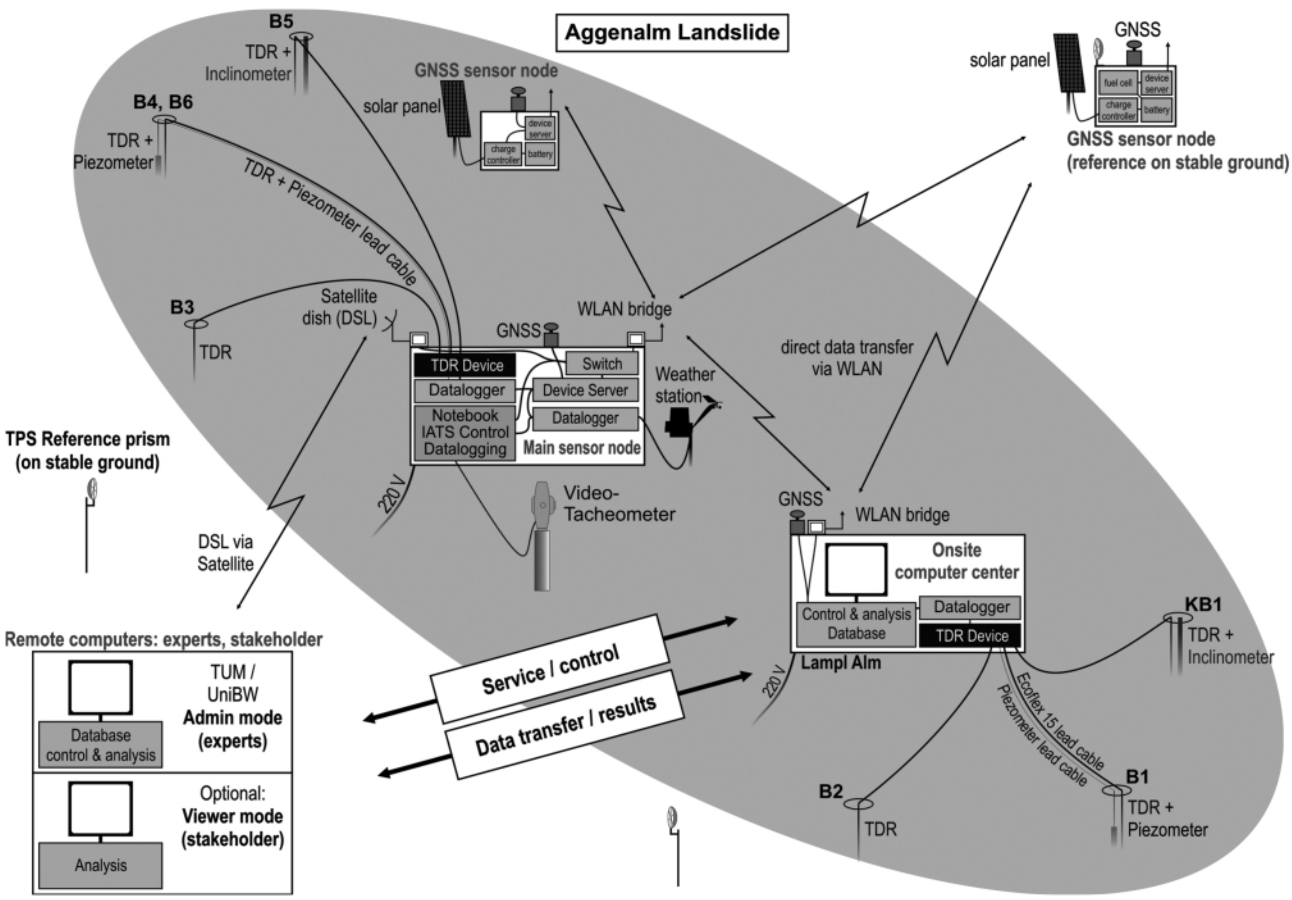

Figure 3: System layout of the alpEWAS GSN (Thuro et al., 2009).

1. the measuring device (TDR cable tester including data logger and multiplexer), 2. the measuring cable (usually semi rigid coaxial cable for easy installation) and 3. the lead cable (low loss coaxial cable) which connects the measuring cable to the measuring device.

For landslide monitoring the measuring cable is installed into a borehole and connected to the rock mass with grout. When the rock mass starts to move in a shear zone, the coaxial cable is deformed, altering the distance between inner and outer conductor of the cable. This change in the cables geometry can be identified, localized and analyzed using a TDR cable tester (Dowding et al., 1989; Lin et al., 2009; Singer et al., 2006).

TDR can simplified be described as "cable-based radar" (O'Conner and Dowding, 1999): The TDR cable tester emits electric pulses which are sent through a coaxial cable. When these pulses approach a deformed portion of the coaxial cable a signal is reflected to the cable tester. As with radar, due to the known propagation velocity of the electromagnetic wave within the coaxial cable, by measuring the time span between emission and reception of the electric pulse, the distance to the deformation can be determined with high accuracy. Furthermore the analysis of the reflected signal (amplitude, width, etc.) can reveal information about the type and amount of deformation (Singer et al., 2009).

If the measuring cable is bent with a large radius (for landslides: gradual deformation over several decimetres or meters of soil) the distance between the inner and outer conductor of the coaxial cable is not changed sufficiently to produce a TDR signal. Therefore TDR measurements generally are limited to discrete deformation zones with a width of centimetres to decimetres. In this context the mechanical properties of the grout used to connect the measuring cable to the surrounding rock mass is of utmost importance. But not only the grout composition (strength, mode of deformation) influences TDR measurements, also the measuring cable type (conductor material, diameter) and lead cable type and length (signal attenuation) have to be considered. Prior to installation all these parameters have to be chosen according to the expected deformation mechanism and velocity of the landslide.

3.3.2 Quantification of installation parameter influences

In order to characterize and then optimize the installation parameters of the TDR measuring system, a large number of laboratory shear tests were conducted in an especially developed test stand (Singer et al. 2006), which allows to shear grout columns with varying diameters at different shear rates and with varying shear zone thicknesses. Main focus was thereby put on the grout: different cement-bentonite-water mixtures were analyzed (Festl, 2008), starting from mixtures which usually are used when installing inclinometers. Considering also the viscosity and stability (shrinkage) of the grout, only a relatively small variety of mixtures seem suitable for TDR installation (Fig. 4).

Depending on the type and speed of the observed landslide different grout mixtures should be used. E.g. for a slow rock slide (> 1.6 m / year according to Cruden and Varnes, 1996), mixtures with high water and bentonite content should be used, resulting in a higher measurement lifespan of up to about 30 cm before cable failure. In an extremely slow earth slide (< 1.6 cm / year) a mixture with less water and medium bentonite content should be used, which leads to a high sensitivity but not too high strength of the grout. This ensures that the moving rock mass is able to fracture the grout and will not plastically flow around the grout column.

When selecting the grout mixture also the borehole diameter has to be considered as another factor controlling the total strength of the grout column. For good measuring results (especially in soft rocks) the coaxial cable should be covered by at least 1 cm of grout. For a typical 12 mm semi rigid coaxial cable (see below) the minimum drilling diameter thus would be 32 mm. The centred installation of the coaxial cable can be assured using spacers, as they are used for armoured concrete.

Functionality	**TDR**	**Inclinometer**	**Inclinometer chain**
Localization of deformation (Accuracy)	✓ mm - cm	✓ dm - m	✓ dm - m
Quantification of deformation (Accuracy)	✓ mm - cm	✓ mm	✓ mm
Orientation of movement	×	✓	✓
Max. deformation amount (localized shear deformation)	cm - dm	cm	cm
Continuous measurements	✓	×	✓
Remote data access, maintenance	✓	×	✓
Multiplexing	✓	(✓)	×
Restrictions	limited to localized shearing	none	none
Costs (1 site, 20 m depth)*	**TDR**	**Inclinometer**	**Inclinometer chain**
Drilling (exclusive drilling site setup, travel expenses etc.)	€ 1200	€ 1600	€ 1600
Installation costs (material only)	Coaxial cable, connectors, accessories € 150	Inclinometer casing, lids, accessories € 250	Inclinometer casing, lids, cables, accessories € 300
Hardware (measurement equipment only)	TDR device, data logger, Multiplexer € 6000	Inclinometer probe, cables € 12000	Inclinometer chain, data logger > € 20000
Maintenance (electricity, data transmission)	< € 100 / month	Several 100 € per measurement	< € 100 / month

* As actual costs greatly depend on the onsite situation (geology, accessibility, local labor costs etc.), the numbers given can only be rough estimates.

Table 1: Comparison of functionalities and costs of TDR and inclinometer systems.

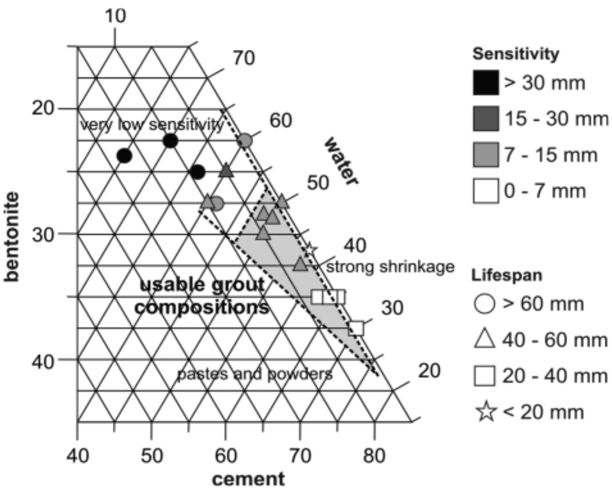

Figure 4: Results of several TDR shear tests with different cement-bentonite-water mixtures (mass-%) (according to Festl, 2008, edited). The shear tests were conducted with a shear width of 15 mm and a shear rate of 2 mm / min. In each test the sensitivity and the cable lifespan was determined. Additionally the shrinkage of the grout during hardening was measured. As the grout has to be pumpable during installation, also the viscosity limits the useable grout mixtures for TDR deformation measurements (grey area).

Besides an exclusive borehole installation, TDR cables can often also be installed into sheared inclinometer casings, thereby considerably extending the usability of an existing borehole.

Generally any coaxial cable can be used as measuring cable. O'Connor and Dowding (1999) suggest using semi rigid coaxial cables, as these on the one hand make an easy installation possible, and on the other hand seem to enable to achieve a relatively high reproducibility (and thus accuracy) in the TDR measurements. A well tried rigid coaxial cable for deformation measurements is the Commscope P3-500 JCA with 12 mm diameter, aluminium outer conductor, copper cladded steel inner conductor and a PVC jacket, which is available at a comparable low price of about 3 €/m. The jacket protects the aluminium cable from corrosion, which is an issue especially when installed into ground water.

One great advantage of the TDR measuring system is that multiple measuring cables can be read out with one measuring device, thereby drastically reducing the costs per measuring site. In order to achieve this, the different measuring sites have to be connected to the TDR measuring device using high quality low loss coaxial cables. However, with increasing length an exponential attenuation of the signal was observed, limiting the lead cable length depending on the type of cable used to under 150 m (Woytowitz, 2008). In order to prevent cable failure of long cable stretches during critical phases of high landslide movements, the cable is looped at several positions throughout the cable enabling the cable to withstand several decimetres to meters of extension.

3.3.3 Calibration

All the installation parameters discussed in the previous chapter have to be considered, when analysing TDR signals. Based on the ongoing laboratory shear tests installation parameter combinations are currently being defined for typical landslide settings. For these combinations extensive calibration shear tests are performed in order to quantify the reproducibility and accuracy of the TDR measurements and to determine calibration curves as basis for an automated signal analysis, which will allow to not only determine the position of the deformation zone with high accuracy, but also the amount of deformation. In the laboratory environment accuracies below 5 mm have been achieved for the quantification of the deformation amount.

With help of the newly developed TDR signal analysis software "tumTDR" the raw data received from the measuring device can be visualized in various different ways, allowing an experienced user to perform a first evaluation and interpretation of the collected data. After that an automated deformation analysis of the data is possible, whereby deformation zones are automatically identified and the deformation is quantified

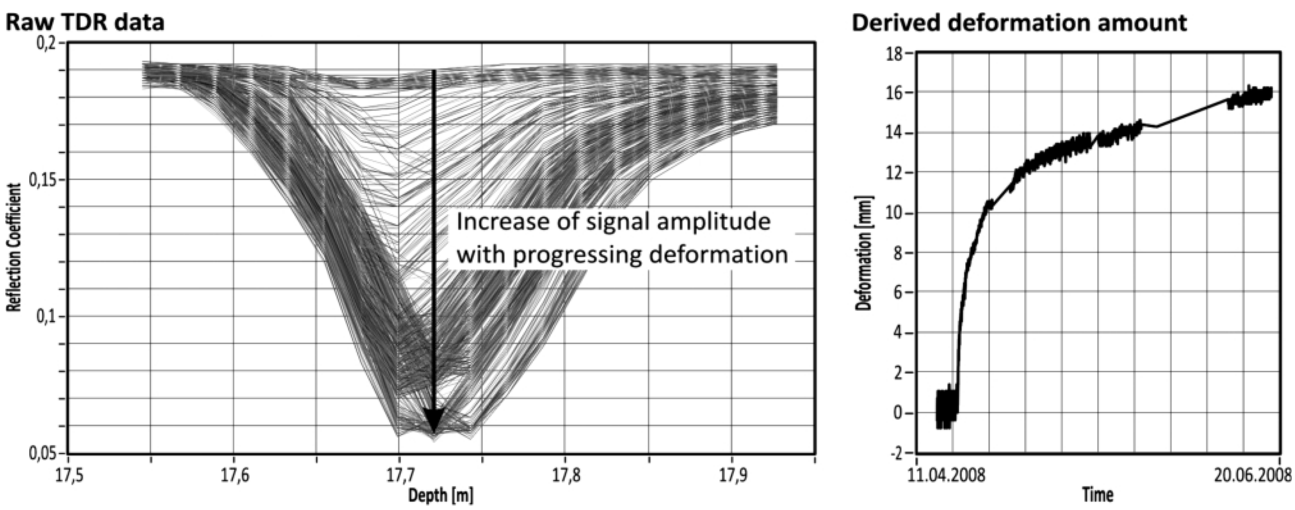

Figure 5: Results of a TDR field test in a slow earth flow (Gschliefgraben landslide, Gmunden, Austria). The depth of the shear zone can be determined with high accuracy. In lack of a calibrated installation the accuracy of the deformation amount cannot be stated, although the results were in compliance with inclinometer measurements conducted parallel to the TDR measurements.

using the calibration curves determined in the laboratory shear tests (Singer et al., 2009). The software currently is in a beta status with all major functions operable.

3.3.4 First experiences

To date TDR has been installed in several landslides (e.g. Gschliefgraben landslide, Gmunden, Upper Austria, Austria, and Doren landslide, Doren, Vorarlberg, Austria) by the Technische Universität München, where the TDR measuring system has been proven functional (Fig. 5), but in lack of a calibrated setup the amount of deformation could not be determined accurately.

The TDR installation at the Aggenalm landslide is the first field test for an calibrated TDR installation as has been described above. The parallel installation of TDR and inclinometers will make an evaluation of the measurement accuracy in field possible.

After about 8 months of continuous operation the TDR measuring system has proven to be very reliable in all weather conditions. The only system failures occurred due to power loss and were not related to the measuring equipment itself. The installation of an uninterruptable power supply to bridge short power losses within the local power network has prevented further data loss in the last months.

Figure 6: The IATS prototype in its housing at the Aggenalm landslide test site.

3.4 Video tacheometry (VTPS)

At many sites with active landslides, geodetic surveying methods for the detection of deformation rates are actually in use (for an overview, e.g. see ClimChAlp, 2008). If there is only low risk exposure, time-discrete epoch measurements in intervals of several months or even years are sufficient, which then result in spatial displacement vectors of points selected in the origin epoch. This is done by means of a classical deformation analysis and provides input information for geological appreciation. Preconditions for that are long-lasting, permanent monuments resp. target signalisations in the moving area.

At high movement rates, impending slope failure and accordingly high risk for man and goods, permanent monitoring systems are used. In most cases these consist of a tacheometer at a fixed observation point in the stable area, plus permanent, retro-reflecting target prisms on the moving site. Permanent systems are expensive in installation (equipment, power-supply, data connection and application software) and need regular maintenance; but give a continuous image of the observed surface displacements and therefore are suited to serve as early warning systems. Of course, such systems cannot predict a sudden slump, but rather reveal increasing movement rates in those areas which have previously been identified as of interest.

Precise monitoring tasks require high-level instruments in accuracy, which makes the tacheometry component the most cost-intensive sensor in the joint project alpEWAS. It is therefore the goal to minimize the target-installation costs and at the same time increase the targeting flexibility. This is achieved by the use of video tacheometry techniques which are yet prototypal in deformation measurement today. The long-term objective is to use natural objects (such as surface rocks) as target structures and check them repeatable for displacements. The loss of target points by destroyed reflectors are avoided and the observation range can easily be expanded to additional areas without any installation effort e.g. when critical areas are identified not before the course of the monitoring task.

The basic principle of video tacheometry can be seen as a more sophisticated extension of the usual automatic prism recognition approach: identification and sighting of targets is no longer solely done by a human operator, but partly or even

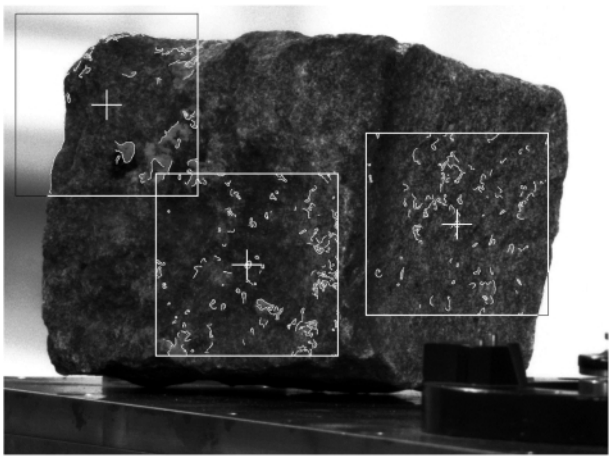

Figure 7: Example of a cobblestone as natural target. Target points and corresponding matching structure areas are shown.

completely automated. To do so, the field of view has to be imaged on a high-resolution sensor, so the eyepiece has to be fully replaced by a camera device, or a camera needs to be integrated in the telescope housing additionally. Commercial solutions with the latter layout have risen on the market recently; leading manufacturers are Topcon (Topcon, 2008) and Trimble (Trimble, 2007). Available systems, however, are intended only for the passive overlay of projected and real data in the live image, documentation purposes and supported and simplified recognition of potential target points e.g. by routines of automated corner extraction. The straight-forward assignment of image information for proprietary applications is limited or not possible at all. Because of that, in the alpEWAS project an off-the-shelf prototype (Image Assisted Total Station IATS) was acquired in cooperation with Leica Geosystems. It offers a 5 megapixel CMOS coloured camera instead of the usual eyepiece and complete remote access to all controls and data with full common tacheometer functionality. Figure 6 shows the instrument on its pillar in the Aggenalm landslide test site.

Based on the well-known photogrammetric collinearity equations calibration parameter sets for arbitrary focus positions can be determined. With that, the associated spatial direction (azimuth, elevation) can directly be derived for every single pixel in the image. This allows not only the measurement of single target points, but also of linear and laminar structures, which not necessarily have to appear simultaneously in the same image. A combination of object parts due to image mosaiking is even possible without overlapping regions. Detection of targets is done using edge or gray value operators, e.g. with sub-pixel precise matching algorithms which even work flexibly when local or global intensity changes and/or occlusions or clutter occur (Steger, 2002). To get spatial coordinates, as last step a distance measurement to the target is performed. While working without signalisation, this has to be done reflectorless. Depending on the target structure, today distances up to 500 meters can be detected reliably.

In extensive laboratory tests the principle of video tacheometry showed a very high accuracy potential for measurements under controlled environment. The camera resolution allows an angular resolution of approx. 1 ppm in the image (0.1 mm over 100 m, roughly twice as good as the absolute resolution of the basic tacheometer) with tangential movements. Movements in observation direction are solely captured by the distance measurement, which have an absolute accuracy of < 2 mm + 2 ppm. An example for matching a natural target nearly without inner texture is shown in Figure 7.

Three (arbitrarily chosen) points on a cobblestone together with extracted edges in their surroundings form the target information. When sliding the stone, the system is capable of unambiguously identifying its new position, aiming it and performing measurements. The results of some example tests show differences of each point to the real absolute movement values of < 1 mm when sliding for several cm. It is notably, that nearly no outline edges are used in this case, but just random elements. As these do not change between the epochs, they are fully sufficient; but reliability and robustness of the method are of course dependent on strong and lasting edge structures especially for bigger observation distances and outdoor-usage. In this case image acquisition is often subject to high environmental influences, which affect both image quality and the resulting object detection. Mainly, these are meteorological effects (scintillation, air flickering) which may cause blurring and apparent deformation and dislocation of targets or target-defining edge structures in the image. In practical use, this problem may be restricted by averaging several short-term measurements (Wasmeier, 2009a). Outdoors the angular accuracy to expect is reduced to approx. 1 mgon, which leads to an absolute equal positioning accuracy both in tangential as radial direction of about 2 – 3 mm over a distance of 150 m. As this is a limiting factor which can be more easily overcome with the use of reflectors, video tacheometry will not become a far-range application system for 500 m or more. Of course, the targeting to prisms functionality is not lost with the use of cameras and can be combined with natural object targeting very easy. Furthermore, being an optical system using visible light without active targeting radiation, sufficient visibility is essential. Scheduled measurements during darkness or heavy weather (snow, rain, fog) are possible not at all or only restricted. Research using low-cost infrared diodes (LED) has proved successful, but are as well as prisms contrast to the project goal to dispense with using artificial target signalisation. The system therefore is qualified for long-term monitoring tasks without impending of sudden catastrophic slope failures as there are certain periods which cannot be used for observation.

Target points can be chosen arbitrarily dense due to the free selection of natural target objects (i.e. possibly manmade, but in either case unsignalised objects) as long as there are enough in the visible area. In particular, targeting density and distribution can be adapted to actual preconditions and upcoming cognitions at any time during the monitoring process. The system is flexible to target changes (appearance, perspective, alteration) and may be constructed artificially self-learning, so target losses are mini-

Model	Novatel Smart Antenna	Novatel Smart-V1G Antenna
GNSS	GPS	GPS + Glonass
Receiver type	Superstar II	OEMV-1G
No. of channels	12 L1 GPS	14 L1 GPS 12 L1 Glonass
Accuracy carrier phase	1 cm rms	0.15 cm rms
Power	9-24 V; 1.4 W	9-24 V; 1.2 W
Interfaces	RS-232, RS-422	RS-232, RS-422, USB
Price incl. VAT	~ 800 €	~ 1200 €

NovAtel

Figure 8: GNSS hardware components.

mized. Accessing the instable and probably dangerous area is not necessary any more.

The primary advantage of video tacheometry is the possibility to perform simultaneous and continuous surveys of linear and laminar natural features as e.g. tear-off edges or debris flows, which cannot be equipped with reflectors. Another application for reflectorless tacheometry within the alpEWAS project is surface scanning. Like a terrestrial laser scanner, a tacheometer is capable of rasterizing the observed area and generating a 3D surface model. With measurement speed being significantly lower (<1 point per second), those models must be narrowed to selected small regions or only use a rather coarse raster in the whole. Small-area scans together with image-extracted information have the ability to improve displacement detection, while spacious scans can be e.g. used for random determination of snow heights during wintertime as an additional source of information on the expected water infiltration due to snow melt in spring, this being a common trigger for mass movements.

Video tacheometry for surveying and monitoring tasks and for autonomous target detection and recognition is at ist beginnings in Geodesy. Research with different prototypes available is performed at various places at the moment (Wasmeier, 2009b). Its usage in the scope of the alpEWAS project is an academic feasibility study, which wants to find out about the potential, but also the limitations in continuous service. Further commercial development for such tasks is not planned within the alpEWAS project, but defined as a project consecutive goal in cooperation with the manufacturer.

3.5 Low Cost Global Navigation Satellite System (GNSS)

3.5.1 System design and characteristics

Within the alpEWAS GSN the task of the all weather proofed low cost satellite based system is to continuously determine 3D surface movements at specific points of the instable slope with sub centimetre accuracy. The system possesses the following characteristics:

- Application of low cost GNSS sensor technology;
- Elements of a geo sensor network (wireless data transfer, autarkic power supply);
- No restrictions with respect to the number of used sensors;
- Possibility to incorporate existing (proofed, powerful) program systems;
- Near real time data processing;
- Flexibility of the analysis through (at any time adaptable) post processing options;
- Separation between data recording and essential evaluation, defined interfaces ("dual system");

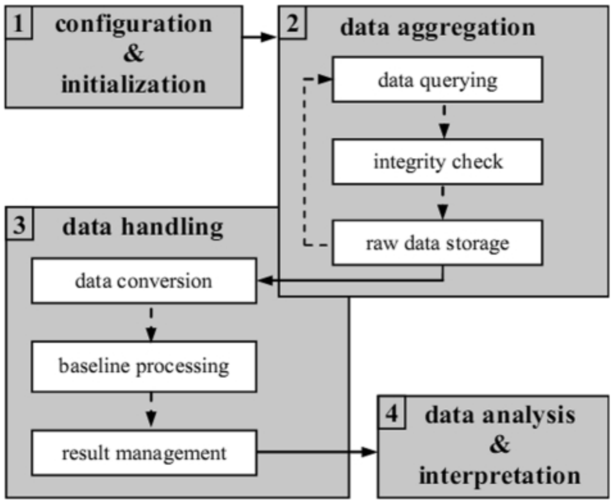

Figure 9: Flow chart of GeoSN-UniBw (Glabsch et al., 2009).

In order to reach the aspired accuracy of a few millimetres with the used low cost GNSS hardware, primarily L1 code and carrier phase sensors (further details see Figure 8) and a post processing data analysis has to take place in near real time at the base station. In a defined time interval, usually 15 minutes, sensor raw data (carrier phase) is logged and subsequently forwarded to the base station. The baselines between the reference station (placed in a stable area) and diverse object points (placed at the instable slope) are calculated in order to get the 3D position of each rover at a certain time. Compared with other standardized methods like real time kinematic GNSS measurements (position solution in real time, reachable accuracies of about 1 to 3 cm using high-class geodetic dual frequency receivers) and proper post processing of long time intervals, this method is called "near real time processing (NRTP)". The attainable accuracy is about a few millimetres depending on baseline length, satellite visibility, filter length and other processing options. Satellite based monitoring of landslide phenomena are for instance described by Hartinger and Brunner (2000) and Bäumker and Fitzen (1998). The GNSS hardware used in the alpEWAS project features the

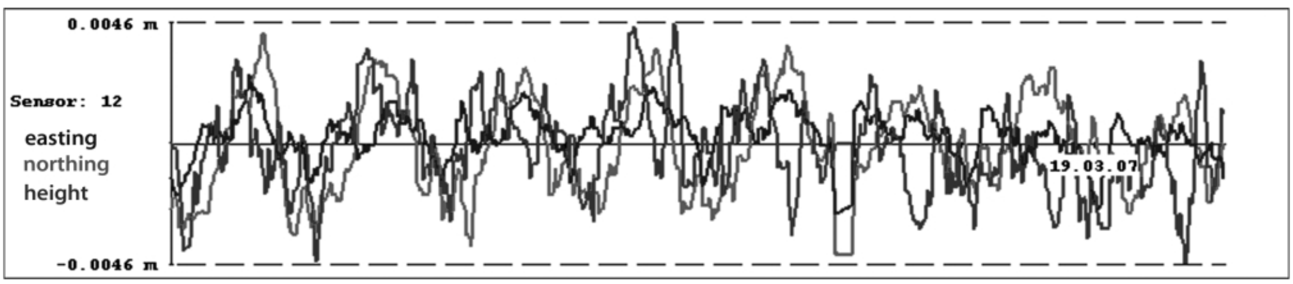

Figure 10: Result of a 265 m baseline (2.5 h solutions, moving average filtering) between March 12th and 19th 2007, (Glabsch et al., 2009).

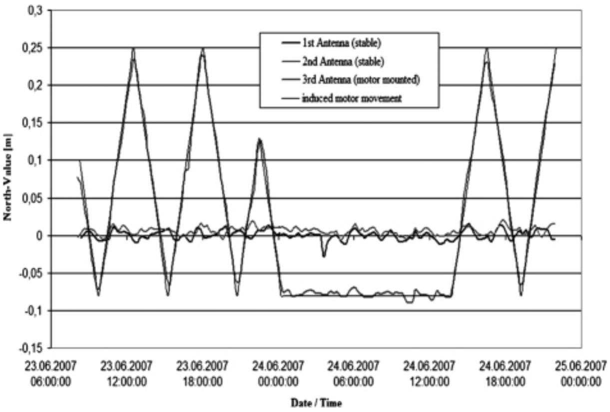

Figure 11: Comparison “true” vs. “measured” displacements and adjacent unchanged baselines, (Günther et al., 2008).

technical specifications depicted in Figure 8.

3.5.2 Software and data flow

The core of the software component is the central control application. Developed using the graphical programming language LabView®, National Instruments, all necessary steps from system initialization, data collection to the handover of processed and checked baselines for a subsequent time series analysis are actuated and supervised. Several subprograms, e.g. sensor activation are termed as so called virtual instruments (VIs). A modular, prospective design offers the option to integrate a great diversity of geodetic and non-geodetic sensors. Only the corresponding program implementation has to be realized. Interfaces permit an embedding of existing and proved software packages, especially for baseline processing (e.g. GrafNav) or for time series analysis and visualization. The work flow of the individual program segments is depicted in Figure 9.

Step 1 in the work flow embraces configuration and initialization. Information from an in advance created configuration file – addressing of the sensors, storage paths and intervals (= length of epochs), addressing of integrated external software – is loaded. After a successful initialization step 2 – data aggregation – is started. In the majority of cases binary carrier phase data is read out from the sensors and gradually written in a log file after an integrity check. Reaching the preset time interval, the log file is closed, a new created and parallel to the ongoing data recording step 3 – data handling – begins. Corresponding to the requirements of the GNSS baseline processing software tool the binary log files are converted into a readable input format and together with a parameter file the baseline processing can be executed. All results are collected and transformed to an ASCII-based input file for step 4 - data analysis and interpretation.

Due to the fact, that all recorded raw data can be recalled at any time, a high flexible data analysis can be accomplished at the discretion of the system’s operator. A reprocessing of all raw data (baselines processing) with different adapted and optimized parameter settings (e.g. new length of intervals, satellite excluding) is possible if necessary at any time.

Figure 12: Winter impressions at Aggenalm test site. Main sensor node with GNSS sensor (Novatel Smart V1G-Antenna) and weather station.

3.5.3 First experiences

To what extent low cost GNSS sensors can be used for landslide monitoring in practice is discussed in the following section: In order to be able to detect movements with high sensitivity it is important to get 3D point positions with high accuracy. At the same time the noise of the measurements should be as low as possible. However, the criterion for exclusion is that the expected movement is (at least 3 times) larger than the measurement accuracy (standard deviation).

First tests of the GNSS monitoring system at the campus in Munich, especially by Pink (2007) proved that with low cost GNSS sensors this goal generally can be achieved. Figure 10 depicts the 2.5 h solution results (filtered by moving average) of an unalterable baseline with a length of 265 m (horizontal coordinates and height component). The epoch length is 15 min, recorded with 1 Hz using the Novatel Smart Antenna. The remaining variations including some systematic effects are less than ± 5 mm, which gives a very optimistic view on the system’s achievement accuracy potential. Still some daily effects are to be seen which should be eliminated in future with more sophisticated processing options. The standard deviation is about 2 mm.

Another significance test was made with a special motion device constructed by Pink (2007). Figure 11 shows the experiment with the induced “true” versus the “measured” displacements (15 min solutions). The device was aligned in southnorth direction and stepwise horizontal motions were performed (idle time of 15 minutes) with an increment of 3 cm. Additionally two stable Smart Antennas were incorporated in the experiment. Their variations of all test items are again at the order of a few millimetres.

Beside the proof of the general functionality during campus tests, since 2007 the system concept is in practical use in two research projects. One in the Tyrolean Mountains (Glabsch et al., 2009) and another at Aggenalm landslide (see below).

Alpine conditions, even in wintertime with long periods of snow coverage (Fig. 12) did not have great negative effects on the system's performance and data could be collected nearly continuously.

3.5.4 Perspective

As mentioned the chosen approach using low cost GNSS sensors in landslide monitoring tasks could be approached. The potential of these techniques is still not fully utilized; further efforts have to be made in order to improve the measurements especially in terms of reliability and accuracy.

The recent development of GeoSN-UniBw is concentrated on the achievement of a comprehensive, pervasive quality check of all computing steps especially for GNSS. Thus, reliability will be improved significantly in future. Other activities are concentrated on the mitigation of multipath influences and the investigation of sensor components in a price segment of less than € 250.

4. Measurement Results from the Aggenalm Landslide

To date the GNSS and TDR systems as well as the weather station and piezometers have collected about 8 months of data (October 2008 to May 2009). The VTPS system has mainly been tested and calibrated in the laboratory and has not been in operation on site for a longer period of time. It is planned to start an extensive field test of the VTPS device in the late summer of 2009.

During snow melt in March to May 2009, when a snow cover of about 2 m (Figure 12) was removed, the pore water pressures measured in the piezometers B4 and B6 increased up to nearly 10 kPa, which corresponds to a ground water level rise of about 1 m (Fig. 13). The reaction time of the pore water pressure to above freezing temperatures (onset of snow melt) is about 2 to 3 days. This is about the double time span the ground water levels need to react to strong precipitation events (thunder storms), as it was observed in various heavy rainfall events.

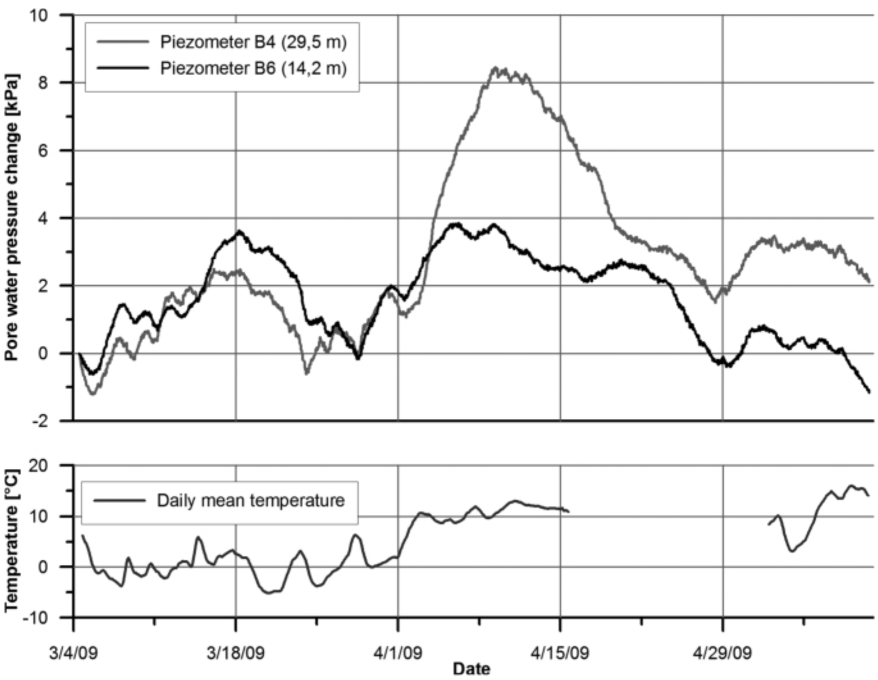

Figure 13: Daily mean temperature (bottom graph) and change in pore water pressure (top graph; reference: March 4th 2009) at two sites (B4 with piezometer installed at 29.5 m depth and B6 at 14.2 m depth) within the Aggenalm Landslide during the snow melt period 2009 (March to May 2009). In the shown time span of about 2 months a 2 m thick snow cover was melt down. The pore water pressure reacts within about 2 to 3 days to temperatures above zero degrees Celsius. The maximum pore water pressure change of about 9.6 kPa (B4) corresponds to a ground water level rise of almost 1 m. The gap in the temperature measurements was caused by an short power outage, which caused the weather station data logger to hang.

The according results of a time series analysis from the GNSS measuring system at the station #3 (onsite computer centre) are depicted in Figure 14. The raw baseline calculation results were filtered by a moving average filter with 24 epochs (6 h solutions, mean value). The position components (X, Y) show about the factor of two less variation than the results of the height component.

Altogether the variations stay clearly below 1 cm. The aspired goal of reaching accuracies in sub-centimetre level was therefore achieved. Despite of the rise of pore water pressure due to the snow melt, no significant movements (trend in data) were detected by the GNSS so far.

The results of a TDR subsurface deformation measurement is shown in Figure 15 exemplarily from site B5 (near main sensor node) for the time from October 1st 2008 to June 1st 2009. As in the GNSS measurements no significant deformation was detected so far, which is also confirmed by the according inclinometer measurements at site B5, which to date do not show any significant deformation (only chaotic aberrations of less than 2 mm compared to reference measurement over the complete length of the inclinometer casing).

5. Conclusion

Each of the low-cost deformation measuring systems TDR, GNSS and VTPS have individually proven to reliably detect

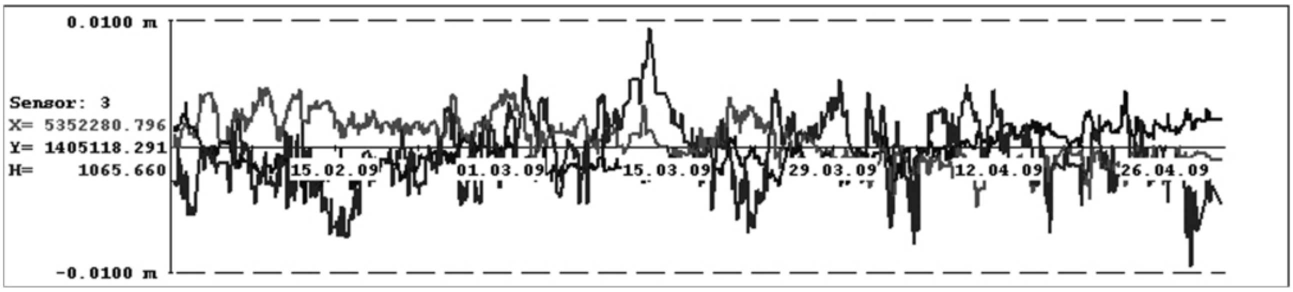

Figure 14: First exemplary results of the Aggenalm landslide GNSS measurement system (February – April 2009, moving average filter).

movements with sub-centimetre accuracy in laboratory tests and partly in other field installations. When combined to a geo sensor network with shared infrastructure, the costs per measuring site are further reduced and coordinated data retrieval and processing in near real time (within minutes) is made possible. This enables to reliably (sensor redundancy) detect critical deformations of the observed landslide and to release alarms if certain deformation thresholds are surpassed. By integrating sensors which provide information about the triggering influences (eg. rainfall and ground water levels), causal and temporal correlations with the deformation can be revealed, possibly making an early warning based on thresholds for the triggering factors possible.

The alpEWAS GSN installed at the Aggenalm landslide has now (May 2009) been operational for 8 months. To date only few minor system failures (mainly due to power outages) occurred, which resulted in a loss of data. Due to the remote maintenance functionality the system failures were usually noticed and repaired within a few hours or days thereby drastically minimizing the loss of data. With ongoing operation the reliability of the GSN has continuously been increased. The system therefore has proven its functionality in alpine environment even through wintertime with snow heights of up to 2 metres.

The deformation of the Aggenalm Landslide in the past 8 months has been too low to be detected clearly by the alpEWAS measuring systems. An increase of movement triggered by snowmelt or heavy precipitation events could not be identified, although e.g. the snow melt resulted in a major increase of ground water levels of up to about 1 m. As historical records state heavy rainfall as trigger for the past hazardous events at the Aggenalm Landslide, obviously the rainfall events in the observed time span were not sufficient to influence the landslide. This is confirmed by the geodetic survey of the Aggenalm Landslide which is performed by the Bavarian Environment Agency every year, which also shows a distinct reduction in the long term landslides movements in 2008 to average values around 1 cm / year (LfU, 2008). However it is expected, that the long term deformation trend will become visible in the alpEWAS GSN measurements by the end of 2009 latest.

The experiences gathered at the Aggenalm Landslide so far are the first step in the development of a market-ready and widely applicable low cost 3D monitoring and early warning system for alpine instable slopes, which hopefully will find widespread acceptance and application.

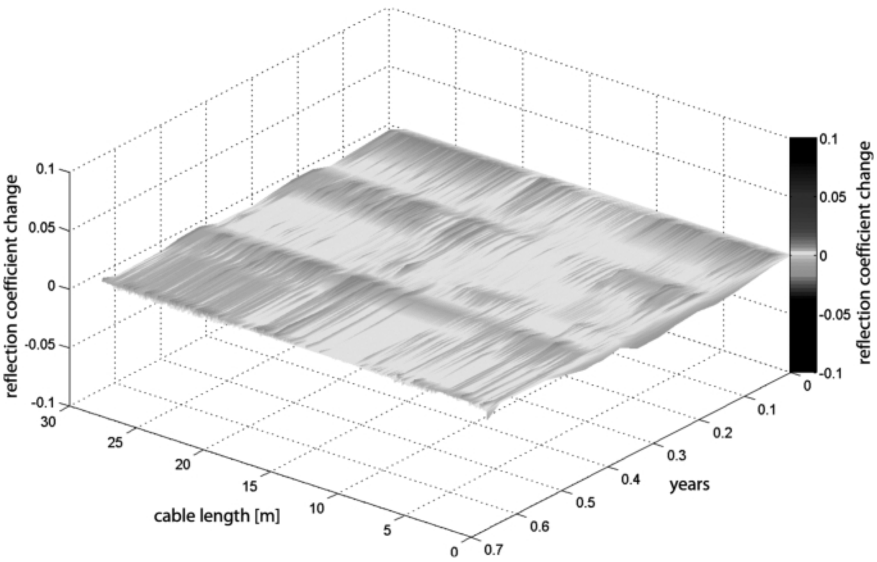

Figure 15: Colour coded presentation of the change of the TDR reflection coefficient along the 29 m long measurement cable of borehole B5 from October 1st 2008 (reference measurement) to June 1st 2009. In case of a deformation of the coaxial cable, the reflection coefficient would be reduced (compare Figure 5), causing notable negative values in this graph. The slight changes in the reflection coefficient shown here are noise caused by outside influences as e.g. temperature changes and variations in the power supply voltage.

Acknowledgements

The alpEWAS project is funded by the German Federal Ministry of Education and Research (BMBF) in the geoscientific research and development program “Geotechnologien”. The alpEWAS team would like to thank all persons who supported the project during design, installation and operation, especially the municipality of Oberaudorf and the landowners as well as the tenants of the Aggenalm.

References

Alcamo, J., Moreno, J.M., Nováky, B., Bindi, M., Corobov, R., Devoy, R.J.N., Giannakopoulos, C., Martin, E., Olesen, J.E. and Shvidenko, A., 2007. Europe. Climate Change 2007: Impacts, Adaptation and Vulnerability. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (eds.). Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 541-580.

Bäumker, M. and Fitzen, H.-P., 1998. High Precision Slow Motion Monitoring with Low Cost GPS Receivers in Real Time. In: Proceedings IAG-Symposium on Geodesy for Geotechnical and Structural Engineering, Eisenstadt, April 20–22, 1998.

Brunner, F. K., Woschitz, H. and Macheiner K., 2007. Monitoring of deep-seated mass movements. In: Aftab, M. (ed.). The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-3). November 13-16, 2007, Vancouver, Canada.

CLIMCHALP, 2008. CLIMCHALP Interreg IIIB Alpine Space WP6: Slope Monitoring Methods – A State of the Art Report. Munich, February 28th.

Cruden, D.M. and Varnes, D.J., 1996. Landslide types and processes. In: A.K. Turner and R.L. Schuster (ed.). Landslides: Investigation and Mitigation. Transportation Research Board – National Research Council. Special Report 247, 36-75. Washington, National Academy Press.

Dowding, C. H., Su, M. B. and O'Connor, K. M., 1989. Measurement of Rock Mass Deformation with Grouted Coaxial Antenna Cables. Rock Mechanics and Rock Engineering, 22, 1, 1–23.

Festl, J., 2008. Eignungsprüfung von Zement-Bentonit-Suspensionen als Injektionsgut bei TDR Deformationsmessungen. Unpublished Master thesis, Lehrstuhl für Ingenieurgeologie, TU München, 54 pp.

Glabsch, J., Heunecke, O. and Schuhbäck, S., 2009. Monitoring the Hornbergl landslide using a recently developed low cost GNSS sensor network. Journal of Applied Geodesy, 3, 179-192.

Günther, J., Heunecke, O., Pink, S. and Schuhbäck, S., 2008. Developments Towards a Low-Cost GNSS Based Sensor Network for the Monitoring of Landslides. 13th FIG International Symposium on Deformation Measurements and Analysis, Lisbon, May 12 – 15 2008.

Hartinger, H. and Brunner, F.K., 2000. Development of a monitoring system of landslide motions using GPS. In: Proceedings of 9th FIG Symposium on Deformation Measurements, Olsztyn 2000, 29–38.

Jung, S.C., 2007. Untersuchungen der Hangbewegung an der Aggenalm östlich des Sudelfelds zwischen Bayrischzell und Oberaudorf (Investigation of the Aggenalm Landslide situated east of the Sudelfeld region between Bayrischzell and Oberaudorf). Unpublished Diploma thesis, Lehrstuhl für Ingenieurgeologie, Technische Universität München, 82 pp.

Lateltin, O., Haemmig, C., Raetzo, H. and Bonnard, C., 2005. Landslide risk management in Switzerland. Landslides, 2005 (2), 313-320.

Lin, C.P., Tang, S.H., Lin, W.C. and Chung, C.C., 2009. Quantification of Cable Deformation with Time Domain Reflectometry - Implications to Landslide Monitoring. Journal of Geotechnical and Geoenvironmental Engineering, 135 (1), 143-152.

LFU – Bayerisches Landesamt für Umwelt, 2008. Geodätische Überwachung der Rutschung Aggenalm im Sudelfeld. 8. Folgemessung am 15.10.2008. Unpublished report, Archive No. 3476. Bayerisches Landesamt für Umwelt, München, 12 p.

LFU – Bayerisches Landesamt für Umwelt, 2009. Projekt Georisiken im Klimawandel. Vorhaben Gefahrenhinweiskarte Bayrische Alpen. Alpenteil Landkreis Miesbach. Final project report. Bayerisches Landesamt für Umwelt, München, 80 p.

Nickmann, M., Spaun, G. and Thuro, K., 2006. Engineering geological classification of weak rocks. In: Culshaw, M., Reeves, H., Spink, T. and Jefferson, I. (ed.). IAEG Engineering geology for tomorrow's cities. Proceedings of the 10th IAEG International Congress, paper number 492. Nottingham, United Kingdom.

O'Connor, K.M. and Dowding, C.H., 1999. GeoMeasurements by Pulsing TDR Cables and Probes. CRC Press, Boca Raton, USA.

Pink, S., 2007. Entwicklung und Erprobung eines multifunktionalen Geosensornetzwerkes für ingenieurgeodätische Überwachungsmessungen. Dissertation. Scientific series of the Studiengang Geodäsie and Geoinformation. University of the Bundeswehr Munich. Issue 83, 180 pp.

Singer, J., Festl, J. and Thuro, K., 2009. Computergestützte Auswertung von Time Domain Reflectometry Messdaten zur Überwachung von Hangbewegungen. In: Marschallinger, R. and Wanker, W. (eds.). Geomonitoring, FE-Modellierung, Sturzprozesse und Massenbewegungen, Beiträge zur COG-Fachtagung Salzburg 2008, Heidelberg, Wichmann, 19-34.

Singer, J., Thuro, K. and Sambeth, U., 2006. Development of a continuous 3d-monitoring system for unstable slopes using time domain reflectometry. Felsbau 24 (3), 16-23.

Sohraby, K., Minoli, D. and Znati, T., 2007. Wireless Sensor Networks – Technology, Protocols, and Applications. New York: John Wiley and Sons, 328 pp.

Steger, C., 2002. Occlusion, Clutter, and Illumination Invariant Object Recognition. Proceedings of the ISPRS working group III/5 "Photogrammetric Computer Vision", Vol. XXXIV, Part 3A/B, Graz.

Tentschert, E., 1998. Das Langzeitverhalten der Sackungshänge im Speicher Gepatsch (Tirol, Österreich). Felsbau, 16 (3), 194-200.

Thuro, K., Wunderlich, Th., Heunecke, O., Singer, J., Schuhbäck, S., Wasmeier, P., Glabsch, J. and Festl, J., 2009. Low cost 3D early warning system for alpine instable slopes – the Aggenalm Landslide monitoring system. Geomechanik & Tunnelbau, 2 (3), 221-237.

Topcon, 2008. Topcon ImagingStation - Long Range Scanning, Imaging and Robotic Total Station, Brochure, March 2008.

Trimble, 2007. Trimble Spatial Station VX Data Sheet.

Wasmeier, P., 2009a. Videotachymetrie – Sensorfusion mit Potential. AVN 07/2009, 261-267.

Wasmeier, P., 2009b. Grundlagen der Deformationsbestimmung mit Messdaten bildgebender Tachymeter. DGK Reihe C 638, München 2009.

Waypoint, 2007. Waypoint Product Group. GrafNav / GrafNet User Guide. Publication Number OM-200000105.

Willerich, S., Mair, V. and Thuro, K., 2008. Hazard map, risk assessment, planning of mitigation measures and their realization in alpine regions – case study of Cortaccia, South Tyrol. Geomechanik & Tunnelbau, 1 (2), 139-148.

Woytowitz, F., 2008. Untersuchung des Einflusses der Koaxialkabel-Zuleitungslänge auf TDR-Deformationsmessungen. Unpublished bachelor thesis, Lehrstuhl für Ingenieurgeologie, TU München, 24 pp.

Received: 27. June 2009
Accepted: 2. November 2009

John SINGER[1)*)], Stefan SCHUHBÄCK[2)], Peter WASMEIER[3)], Kurosch THURO[1)], Otto HEUNECKE[2)], Thomas WUNDERLICH[3)], Jessica GLABSCH[2)] & Judith FESTL[1)]

[1)] Technische Universität München, Lehrstuhl für Ingenieurgeologie. Arcisstr. 21, 80333 München, Germany;

[2)] Universität der Bundeswehr München, Institut für Geodäsie, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany;

[3)] Technische Universität München, Lehrstuhl für Geodäsie. Arcisstr. 21, 80333 München, Germany;

[*)] Corresponding author, singer@tum.de