Chapter 15
Low Cost 3D Early Warning System for Alpine Instable Slopes: The Aggenalm Landslide Monitoring System

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Abstract In course of the alpEWAS (= alpine Early Warning System) research project a cost-effective landslide monitoring and early warning system has been developed between 2007 and 2010. The core of the project has been the development and testing of the three innovative, economically and continuously working measurement systems time domain reflectometry (TDR) for the detection of subsurface displacements in boreholes and reflectorless video tacheometry (VTPS) and low cost global navigation satellite system (GNSS) for the determination of 3D surface movements. These measurement systems are combined together with systems monitoring the trigger factors such as precipitation in a geo sensor network which can be accessed remotely through the internet, thus enabling to forward all data in near real time. The Aggenalm Landslide (Bavarian Alps in the vicinity of Bayrischzell) was chosen as a field laboratory for the alpEWAS project. For more than two years the system has been working continuously except for minor disruptions, acquiring and recording all data.

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15.1 alpEWAS Project Details

The joint research project alpEWAS—development and testing of an integrative 3D early warning system for alpine instable slopes—aims to combine innovative, efficient and cost-effective measurement techniques for landslide monitoring in a geo sensor network. The project has been funded by the geoscientific research and development program "Geotechnologien" of the German Federal Ministry of Education and Research (BMBF).

Recent events also within the runtime of the research project in the Alps as well as worldwide acknowledge the necessity to design efficient and cost-effective monitoring systems for instable slopes especially for areas that have yet not been monitored or only sporadically due to economic reasons. With the given option of a continuous remote access to the early warning system the stakeholder has the possibility to view and control all information of his scope centrally and to keep the general overview given a situation in which for example due to heavy rainfall several landslides have to be evaluated simultaneously.

The subject of the joint research project is the testing and advancement of three new measurement techniques (Fig. 15.1)

- Time domain reflectometry (TDR)
- Reflectorless video tacheometry (VTPS)
- Low cost GNSS (LCGNSS)

as well as their coaction as an early warning system and their integrative data analysis.

The project alpEWAS (for a closer description see (Singer et al. 2009c; Thuro et al. 2009) and http://www.alpEWAS.de) was outlined in five phases:

1. Selection and investigation of a project area.
2. Design and installation of the early warning system.
3. Learning phase of the early warning system.
4. Testing phase of the early warning system.
5. Automation and optimization of the early warning system.

In the Sudelfeld region—in close reconcilement with the Bavarian Environment Agency (Bayerisches Landesamt für Umwelt, BLfU)—the Aggenalm Landslide has been chosen as a test site since it features very good premises for the testing of new technologies in the field under alpine conditions. During the studies it became obvious that the present movement rates of 1 cm/a are smaller than expected at the initiation of the project and recently only a low hazard potential exists at the Aggenalm. Therefore the assessment of threshold values may be affected or limited (project phase 2 and 3).

Within the scope of the project software applications for the sensor control, data management, complex data processing and integrative data analysis have been developed. After expiry of funding the monitoring of the Aggenalm Landslide is continued by the involved institutes with reduced scope, however.

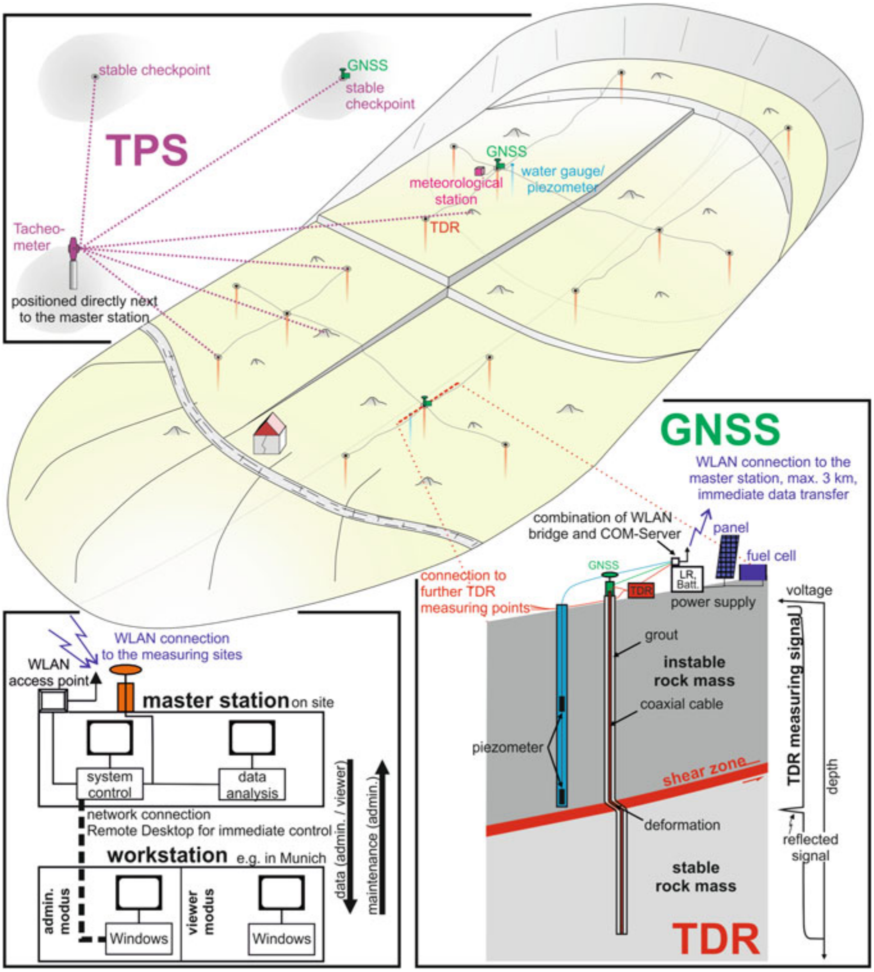

Fig. 15.1 Schematic depiction of the geo sensor network „alpEWAS“ at the aggenalm landslide

A geological review is given by Singer et al. (2009c); the geo sensor network with the technical features is described in Thuro et al. (2010) in detail. Figure 15.2 gives an overview of the different installed sensors of the geo sensor network and their positions at the Aggenalm Landslide.

Consecutively in addition to the aforementioned publications it will be reported on the three measurements techniques, some attained results as well as the combination and analysis of the data.

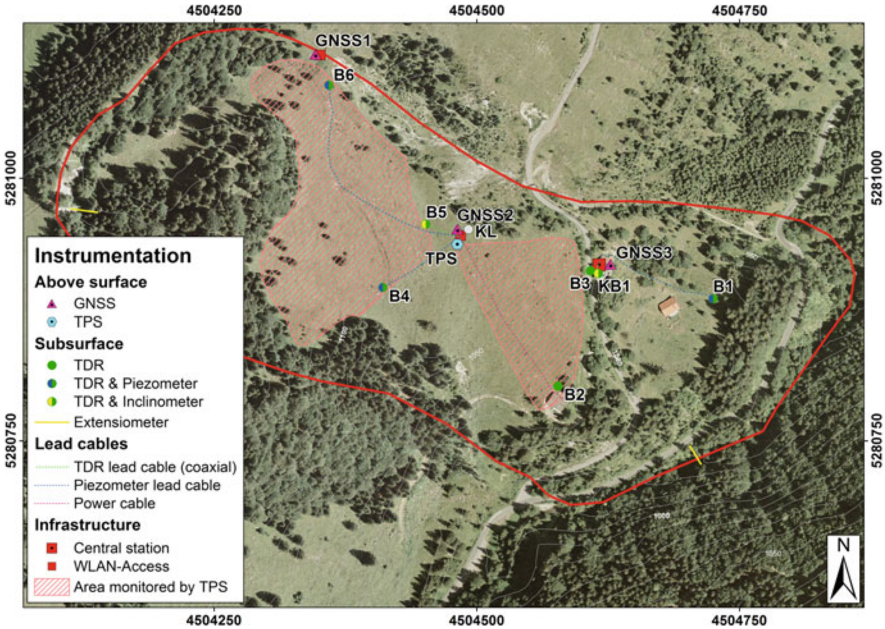

Fig. 15.2 Installation setup of the different sensors installed at the Aggenalm landslide (*red boundary*) depicted in an orthophoto (Singer et al. 2009c)

15.2 Researched Measurement Techniques

15.2.1 Time Domain Reflectometry

Using time domain reflectometry (TDR) to monitor subsurface deformations, a special type of coaxial cable is installed in a borehole. By sending electromagnetic pulses into the cable, changes in the cable's geometry can be detected, thus the amount of deformation is quantified. Several different parameters—the type of cable used (lead and measurement cable) and the grout composition (cement, bentonite, cement additives)—play an important role in the quantification of TDR deformation measurements. These parameters have been determined by means of calibration tests in a comprehensive laboratory program (Singer 2010; Singer et al. 2009b, 2010).

The results of all the laboratory tests combined with experiences from field surveys of the TDR system were incorporated into an installation handbook, which gives standardized installation recommendations consisting of a combination of cable type and grout composition for different geological settings and typical mass movement mechanisms and velocities. Next to the preparation and completion of the installation handbook the TDR deformation analysis software was worked on and refined.

The TDR system, that has been installed at the Aggenalm Landslide, is continuously operating since November 2008 (begin of installation and operation September

2007) and acquires measurements hourly. The TDR system has proven to be a reliable measurement system at large. Over the total period since the beginning of operation, the data loss sums up to about 18 % of the planned measurements mostly because of power shortages and late data retrieval (full data storage before the start of the automatic data acquisition). For the time since the start of the fully automatic data retrieval the data loss adds up to 10 %. Here, a major annoyance in January 2010 accounts for the loss of data. It can be assumed that in future an even higher performance can be achieved due to the automatic data retrieval and data storage as well as the developed Status Monitor Software as the time since February 2010 has already shown.

The field test at the Aggenalm has shown that most of the cables (lead and measuring cables, connectors; mostly installed subsurface) proved to be robust concerning the weather, also during winter. Up to date no significant deformations have been measured with the TDR system at the Aggenalm Landslide, therefore the signal and deformation analysis could only be used and tested for the evaluation of laboratory tests.

Figure 15.3 shows the results of the TDR measurements at the Lampl-Alm (B3) node. Depicted are the reflection coefficient—depth curves as a time series in relation to the reference measurement in October 2008 as well as the results of the inclinometric measurements. The TDR time series shows no measureable deformations, the reflection coefficient doesn't change at all during the depicted time period, only the characteristic noise can be seen. The results of the inclinometric measurements (Fig. 15.3) show slight movements (max. 1–2 mm for KB1). The difference between

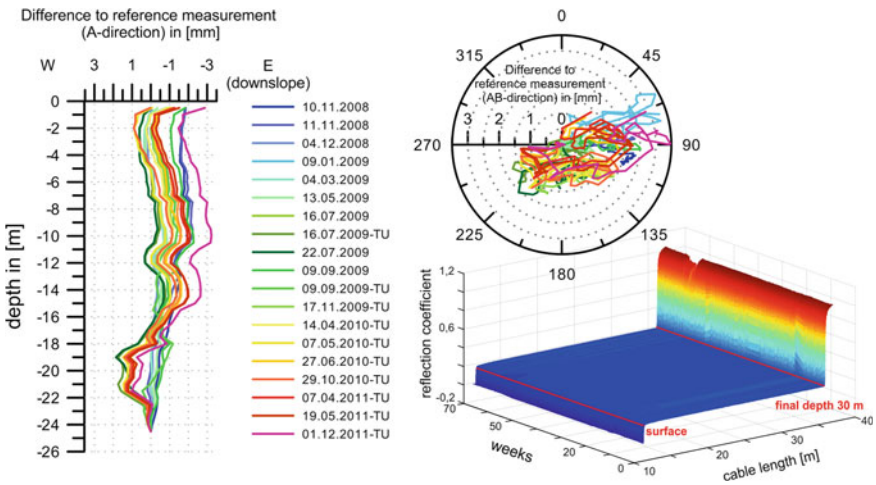

Fig. 15.3 Time series of the inclinometric measurements (*left*) and the TDR measurements (*bottom right*) at the sensor node KB1 and B3 (lower Lampl-Alm). The inclinometric measurements show compared to the reference measurements some small insignificant variations of about 1–2 mm. Over a time span of 70 weeks no deformations (variation of reflection coefficient) can be detected in the TDR measurements

the inclinometric results and the movements measured by the GNSS component (GNSS 3 is located right next to KB1—the inclinometric measurement site) is due to the fact that technical problems arose while establishing KB1; with a depth of about 24.5 m the probable shear zone wasn't reached. The TDR system, which has been installed at a greater depth parallel to KB1 in B3, still does not show any significant deformations, which can be explained by the small amount of deformation which has not yet been able to fracture the grout surrounding the coaxial cable—a prerequisite for a deformation analysis with TDR.

15.2.2 Reflectorless Video Tacheometry

One of the goals of the alpEWAS project was to gain first practical experience in field using an innovative instrument type which is not commonly used for displacement monitoring yet: a video tacheometer (VTPS—video tacheometric positioning system). At this stage the Topcon Imaging Station is the only instrument available on the market which in principle has a video functionality with the necessary precision (Topcon Positioning Systems, Inc. 2008). Other instruments—the Trimble Spatial Station VX and the Leica Viva TS15—could be used only with major cutbacks due to their image resolution and field of view (Leica Geosystems AG 2010; Trimble Navigation Limited 2010). All the instruments mentioned cannot be used scientifically, as the cameras cannot be read out by external devices. External camera control is only possible so far using a Leica Geosystems prototype, which has been coopered in a small batch of only five instruments. It consists of a TPS1200 tacheometer (Leica Geosystems AG 2007) with access to all instrument subsystems, which has been modified with an internal camera (now called IATS2—Image Assisted Total Station 2nd edition). Various limitations by design, especially regarding practical handling, need still to be accepted and have to be abolished by the manufacturer for later marketability. Among others, this includes the tentative cable guiding and the tarring of the modified telescope layout. The prototype is explained in Wasmeier (2009b) and, together with its extensive calibration, in Wasmeier (2009a). Also the obtainable accuracies were examined which in the field are approx. $\sigma < 1$ mgon on average, but under bad conditions up to $\sigma > 2$ mgon. Under laboratory conditions, a repeatable accuracy capability of < 0.15 mgon has been proved.

At the Aggenalm project site the method was used to capture object points distributed on the slope from a central setup point by means of polar measurements and check for displacements. Beforehand, this is quite similar to the conventional setup of a permanent or temporarily tacheometric monitoring system without net measurement. But in contrary to that, in the alpEWAS approach only natural targets and no retroreflecting prisms were used. This goal, on the other hand, also implicates, that permanent measurements will not be possible due to slope exposition and the long-lasting snow coverage in the Sudelfeld area. Especially in wintertime long gaps have to be accepted, as the built-in camera is not specified for temperatures below 0 °C

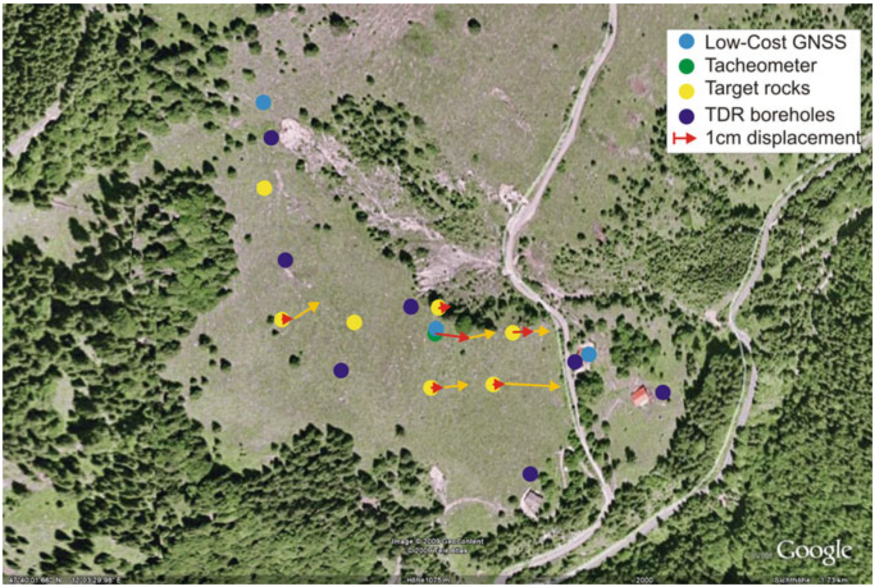

Fig. 15.4 Measurement points at the Aggenalm landslide. The arrows mark the displacement vectors of VTPS between fall 2008 and summer 2010. Target points without vector have not been measured in all epochs due to some failures

In Fig. 15.4 the measurement points in the Aggenalm Landslide are shown. The arrows mark the planar displacement vectors between fall 2008 and fall 2009 (red) and between fall 2009 and summer 2010 (orange). Tacheometric target points without vectors haven't been measured in all epochs due to single measurement failures in target detection or range measurement. The displacements are between 3 and 12 mm, which are not significant due to the necessary setup of the measurement pillar position using stable reference points in big distances, but regarding orientation and absolute value they are highly feasible, also compared to GNSS results.

The advantage of video tacheometry compared to conventional and approved methods lies in the variability of possible target structures which can be both artificial (target marks or reflectors) and natural. Here, depending on the target type, a more or less complex detection algorithm is necessary, which, as a rule, has to be individually designed for the single case. Basically, a big pool of operators and procedures from digital and industrial image analysis is available. The standard chain of work of a target detection using VTPS is shown in Fig. 15.5. At the Aggenalm, surface rocks have been used for natural targeting; but for monitoring purposes in the field also e.g. debris tear-off edges, (parts of) buildings and other natural targets are possible. The measurement principle is an edge-based matching relying on a teaching-phase during the installation of the system. If real deformation detection is the goal, other methods can be used, which e.g. have been evaluated at the TU Wien using the same prototype instrument (Reiterer et al. 2010). Further application possibilities can be found in (Thuro et al. 2010).

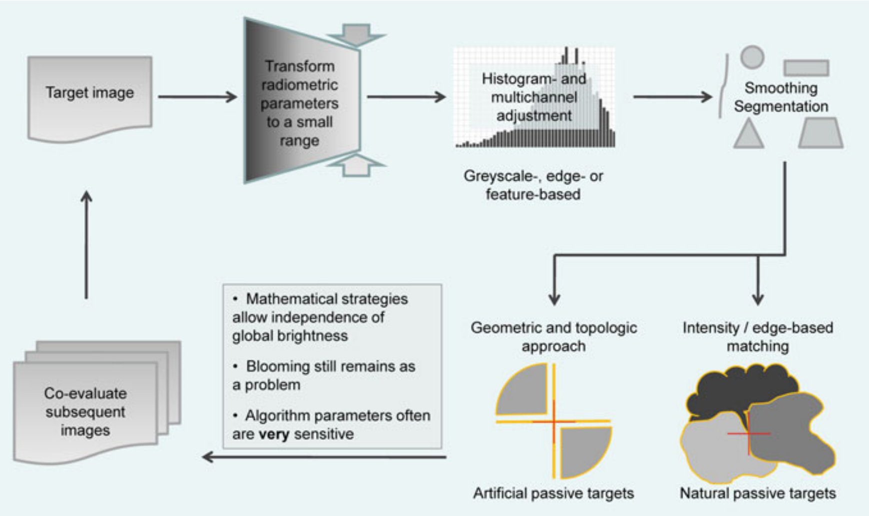

Fig. 15.5 Flow chart of a target point detection

For every image-based analysis the complexity of the algorithms and therefore the reliability of the result have to be questioned critically. Especially in industrial image-driven applications, illumination and other environmental parameters get optimized by default. This is not possible with video tacheometry, especially when working outdoors. Reliability rates of more than 90 % are achievable in exceptional cases only. This was the same in the alpEWAS project; so the goal of an autonomous video tacheometric measurement system had to be abandoned in favor of a semi-automatic, user-controlled measurement process.

Figure 15.5 shows the flowchart of target point detection. Measurement images first become homogenized to be able to use uniform operators and parameters for the deduction of attributes and objects. Final target point detection itself is mainly done using descriptive rules (geometric, topologic and/or radiometric) or matching algorithms. Evaluation of consecutive images imitates integration by time of some normally distributed measurement deviations in the images and therefore raises the accuracy statistically.

Video tacheometry, which was used for displacement monitoring of non-signaled objects in geodesy for the first time, has proven functionality especially under controllable conditions (e.g. indoors). When using in the field, distinct limitations became apparent in the course of the project—mostly because of refraction effects and chaotic short-term atmospheric turbulences. These influences of course also affect traditional tacheometric targeting, but are particularly critical with video tacheometric image processing due to its time-consuming detection algorithms and sensible parameterization. Further developments in this field therefore need to be threefold, while results in one branch will also be input information to the others:

- Advances in hardware to overcome the prototype status. This is primarily the task of the instrument manufacturers, but therefore dependent on economic factors. This makes it a challenge for scientific research to point out appropriate fields of use as well as to evaluate advantages and drawbacks.
- Further enhancements of convenient algorithms. Reliability and scope of application of the usable algorithms have to be improved and accordingly adopted to the special tasks of video tacheometry. To this, also additional fields of usage need to be found and handled in pilot schemes. An example for that could be video tacheometric vibration determination.
- Modeling of atmospheric influences. The main problem of derogation of video tacheometric measurements—refraction and air flickering—has to be analyzed with a special view to the new instrument type and, if it proves possible, to be minimized by empirical or modeled corrections. An according research project is currently in progress (DE-MONTES, http://www.de-montes.eu, 2011–2012) at the Chair of Geodesy (TUM).

15.2.3 Low Cost Global Navigation Satellite System (LC GNSS)

The satellite supported monitoring component of the geo sensor network at the Aggenalm Landslide consists of an all-weather proofed low cost GNSS measurement system based on simple, cheap and robust navigation receivers produced for the mass market. The applied receivers allow a phase tracking of the American GPS as well as the Russian Glonass satellites. Using such receivers permanently, monitoring of discrete points at the surface of the slide is possible with sub centimeter accuracy. In context of a geo sensor network the GNSS stations are just called sensor nodes in the following.

In order to achieve the aspired accuracy with the mentioned equipment, only L1 code and carrier phase receivers are used in combination with a high sophisticated near real time processing. This means that over a predefined period of time—usually 15 min—carrier phase raw data is recorded continuously. By wireless communication techniques (WLAN) all raw data is transmitted "on the fly" to a central computing station. As soon as the data from the different sensor nodes—at least one station should be on stable ground (reference station) and the others are spread on the slope (there are three such stations at the Aggenalm)—is available the baseline processing can start immediately. If there are more reference stations disposable the possibility of a geodetic network adjustment is given. In contrast to ordinary real time kinematic applications the whole evaluation with the developed approach can be designed and controlled individually. In the alpEWAS project it could be shown that accuracies can be achieved which normally can only be obtained by geodetic high-end receivers.

Beside design and construction of the GNSS sensor nodes (Fig. 15.6, right side) focus was laid on the software component called Central Control Application (CCA), which is developed by using LabView®, National Instruments. All steps in the workflow (Fig. 15.6, left side) from the configuration and initialization (1) to the

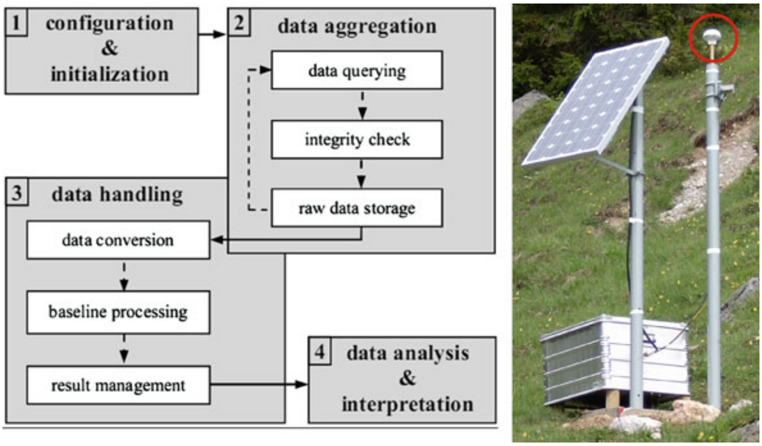

Fig. 15.6 Work flow of the central control application and design of a complete GNSS node with marked antenna in *red* (Glabsch et al. 2010a)

continuous data recording (2) and the parallel operating near real time processing (3) to the transmission of results (4) is controlled and executed. A modular, prospective design offers the option to integrate a diversity of GNSS sensors. Only the corresponding program implementation has to be realized because all receivers deliver binary data only. Individual design of the evaluation is given by the steps 3 and 4 starting with the carrier phase raw data conversion. The processed information obtained from the GNSS nodes (coordinates of the points, quality parameters, and GNSS status information) is stored in a MySQL database and updated every 15 min. All data collected by the geo sensor network is promptly available in a central data sink for an enclosed integrated evaluation, see Sect. 15.3. For further technical details of the developed measuring system please see Glabsch et al. (2009; 2010a; 2010b).

With the current state of the software and the designed sensor nodes a continuous and robust operation of the low cost GNSS monitoring component is realized. Currently, only rare malfunctions occur which are mainly caused by energy shortages. In particular at the central station and the multi-function node in the middle of the slope longer power outages in the 230 V electricity supply system lead to some failures. Only short power black outs can be bridged by an uninterrupted power supply (UPS). Beside these energy shortages a secure GNSS system operation of the autonomous stations is a challenge especially at alpine winters (partial complete snow cover of the antennas and solar panels for days or weeks). An appropriate choice of reliable equipment and the dimensioning of the devices lead to a reliable year-round operation.

Some results of the GNSS monitoring component at the Aggenalm are presented in Figs. 15.7 and 15.8. A more complete look at the picture is given in Sect. 15.3.2.1. In the following the position components (easting Y, northing X, where Y is approximately downhill) are depicted for the period March 2009—December 2010 by a

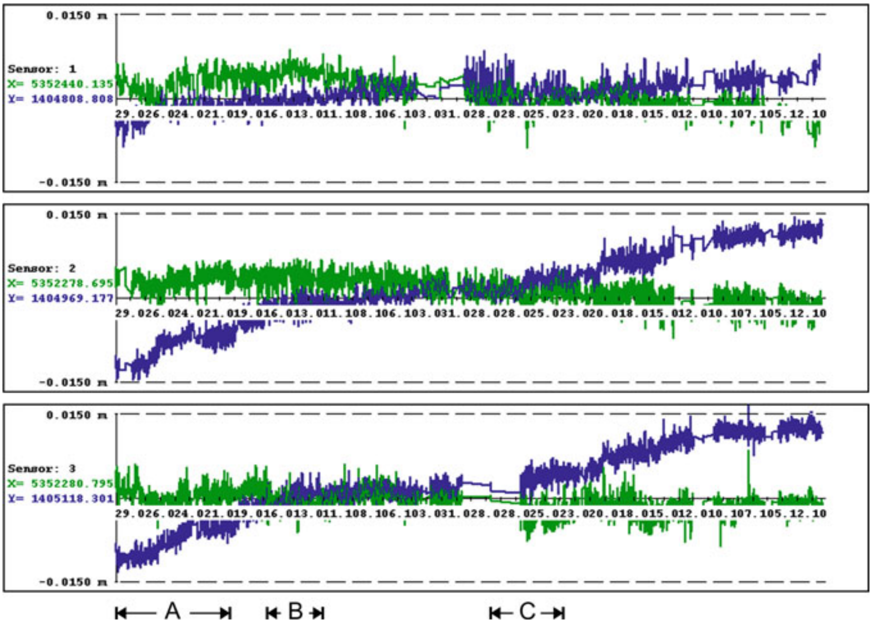

Fig. 15.7 Variations of the sensor nodes 1–3, time period March 2009 to December 2010, moving average (node 1: 12, node 2 and 3: 6 h)

moving average filtering based on a robust estimator. The filter extends over 24 epochs (nodes 2 and 3) and 48 epochs (node 1). Using a time interval of 15 min to acquire the carrier phase measurements the filter length corresponds to 6–12 h. The choice of this filter type and length is the consequence of partially bad obstructions (due to surrounding mountain ridges, trees) at the sensor nodes that lead to temporarily incorrect processing results—even in some cases a successful solution can't be computed at all. Despite some technical problems and the resulting data gaps (Fig. 15.7) long-term trends of the movement can be captured satisfactorily. The time series at node 2 and 3 show slide acceleration phases during springtime (snow melt) in slope direction Y (blue charts).

Presumably due to the low snow coverage in spring 2010 (C) a comparable behavior as in spring 2009 (A) cannot be seen. The effect of a heavy rainfall event in June 2009 (B) is also detectable. An enlarged view for the period 15.03.−15.08.2009 shows the impact of snow melt (end of March to end of April) and the intense rainfall in June 2009 (last two weeks) exemplary at sensor node 2 at Fig. 15.8 especially in slope direction.

The used GNSS monitoring component is based on standard components for sensors, power supply (batteries with solar panels) and WLAN communication. In the actual configuration a complete autarkic GNSS sensor node (Fig. 15.6, right side) requires an investment of about € 3,000. The developed Central Control Application allows a reliable system operation. Although the achieved accuracies with filter

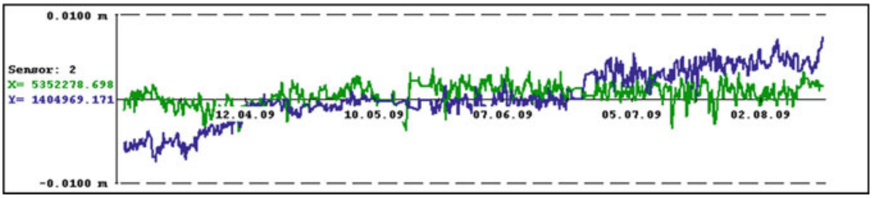

Fig. 15.8 Sensor node 2, variations during 15.03. – 15.08.10, moving average (12 h)

lengths of about 6 h already permit to evaluate long-term behavior of a slope even with only small changes during the year, the full potential of simple navigation receivers for surveillance tasks has not been tapped yet. For an improved early warning a (significant) shortening of the filter length is an essential challenge. Overall, it was possible to examine the use of low cost GNSS sensor technology intensively. The gained results demonstrate that the low cost monitoring approach can successfully be used alternatively to precise tacheometric geodetic surveys or expensive high-end GNSS receivers.

15.3 Data Management and Integrative Data Analysis

15.3.1 Data Management

The alpEWAS Control software package (Fig. 15.9) was developed as a modular software package to control the entire data management within the project. The flexible layout offers an ideal adjustment of the software's sub-programs to the underlying measurement system.

A central component is the open source MySQL database. The link between the geo sensor network, respectively the sensors installed at the field site, and the database is established by sensor plugins. Besides the sensor control, status monitoring and readout of pre-processed data as well as the communication of information via a standardized communication protocol a first analysis is conducted. This provides next to pre-processed data also prompt usable information (1st level results) for further integrative analysis. Various monitoring tools permanently check the current status of the system in order to detect the exceedance of critical system parameters (such as thresholds) as well as failures of individual sensors or subprograms. If one of these malfunctions is detected the system administrator is informed immediately, thus long-time data loss can be avoided. The alpEWAS Live Viewer (Fig. 15.10) is another helpful tool for system maintenance. The interface informs the user about the current system status. Furthermore data can be displayed as time series using different filter options and combinations.

An important interface is the link between the onsite computer center and the end user being interested in information about the current status. The data management

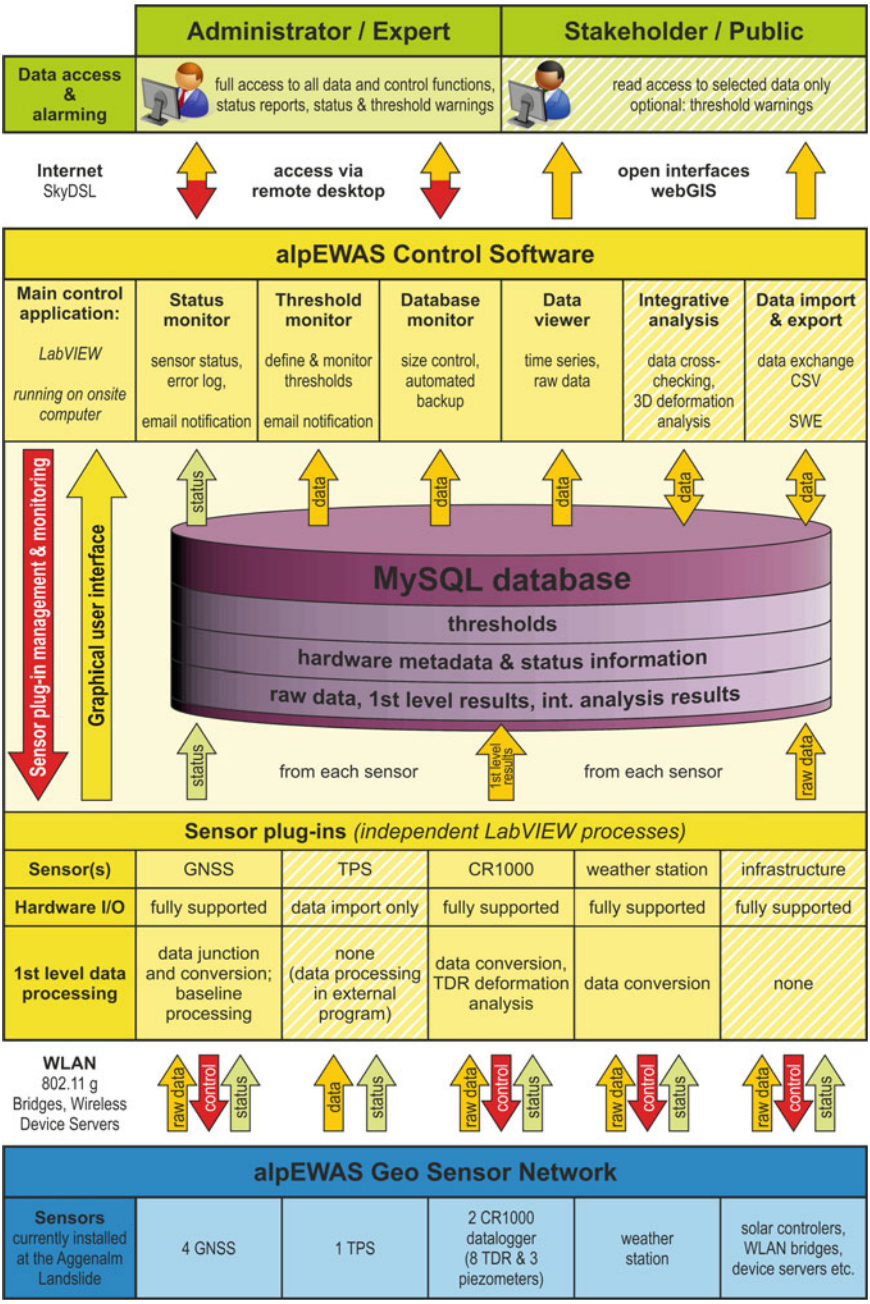

Fig. 15.9 Schema of alpEWAS control, management and data analysis software

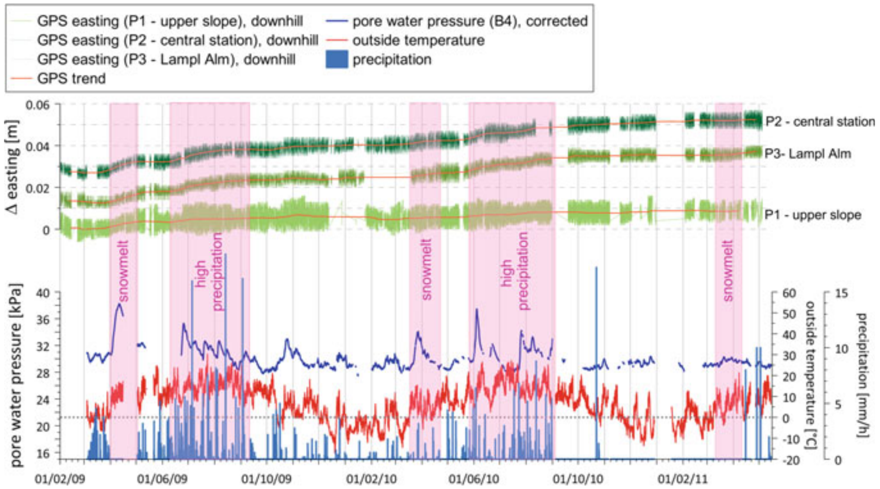

Fig. 15.10 Precipitation and temperature at the central station node and pore water pressure at node B4 as well as GNSS (GPS) deformation measurements of all 3 GNSS nodes for a time span starting February 2009 to May 2011. The gray dotted line marks 0 °C to better show the beginning of the snow melting periods every year

concept is as follows: By reflecting the database constantly from the master computer to a second data server (slave) possessing a broadband connection at the project office high data integrity and almost unlimited parallel data access from several users can be achieved. Complex and computationally intensive analysis can be split to several machines this way if necessary.

For data exchange between heterogeneous systems (interoperability) it is possible to query all results by means of access authorizations via standardized interfaces. Standards such as the worldwide standard of handling space-orientated data for an interoperable benefit being developed by the Sensor Web Enablement (SWE) initiative of the Open Geospatial Consortium (OGC®) are currently being integrated.

The main functions of the Live Viewer are the permanent status information of the systems' state and the possibility to graphically display first results. It can be freely chosen which data base (master or slave) the Live Viewer accesses.

15.3.2 Data Analysis

Since the beginning of February 2009, a continuous monitoring of all sensors with the possibility of remote access and control has been realized, thus permitting to perform time series analysis on the collected data. From prior landslide events in the years 1935 and 1997 and first results of the geomechanical model it has been fancied that one of the major influencing factors on the movements of the Aggenalm

Landslide is the precipitation partly in combination with the snow melt. Aim of the data analysis is to validate the slope's movement characteristics using the data at hand and to identify and quantify the correlations between precipitation, pore water pressure (piezometer) and deformation measurements using time series analysis.

15.3.2.1 Time Series Filtering

Figure 15.10 shows plots of the potential triggering factors, precipitation and pore water pressure (plus temperature) for a time span of almost 2.5 years. The GNSS measurements are more or less continuously recorded since February 2009 and are depicted for all 3 sensor nodes at the Aggenalm Landslide as well. A limiting factor for the analysis are the relatively small deformation rates of about 1 cm/a at the maximum (Fig. 15.10, GNSS P1 about 1 cm and GNSS P2 and P3 about 2.0–2.5 cm in the last 2.5 years). With the VTPS technique comparable results were attained whereas the TDR system couldn't detect subsurface displacements yet, since the clamping process seems still to be in progress (see Sect. 15.2.1).

A small increase of the displacement rate can be observed several times in the time series from February 2009 to May 2011 (Fig. 15.10) after periods of high precipitation and/or snow melt. In spring 2009 and 2010 after the onset of the snow melting period the pore water pressure exceeded 33 kPa (pink shaded areas in Fig. 15.10), whereas in spring 2011 hardly any influence on the pore water pressure by the snow melting can be observed. In spring 2009 the rise in pore water pressure caused by the snow melting from about 30 to 38 kPa equals a water table rise of about 0.8 m. But also after extreme precipitation events, e.g. in July and August 2009 and June 2010, the pore water pressure exceeded 33 kPa. Exemplarily this can be shown on a section of 60 days from June 22nd to August 22nd 2009, where only rare losses of data occurred. Herewith first optical interpretations and comparisons are possible.

For the preparation of the precipitation data a 6 and a 12 h cumulative has been calculated, respectively. This smoothing provides a better comparability with the piezometer and GNSS data. The pore water pressure data set shows a smooth gradient and had to be corrected by the influences of the barometric pressure. To improve the GNSS data furthermore an additional low-pass filter can be applied (Fig. 15.10). Due to different sampling intervals in the data acquisition—the pore water pressure and precipitation are acquired in a five minute interval whereas the GNSS positions are processed for every 15 min—all data has been resampled with the same time interval. Finally, because of minor data losses a 6 h resampling was chosen for Fig. 15.11, where the filtered and resampled time series of precipitation and pore water pressure for the above mentioned 60 day interval are depicted.

One can see that a few days after a major rainfall event (>20 mm in 2 days) the pore water pressure begins to rise (from 30 to 35 kPa, equal 0.5 m). Because of the relatively short time span of identical time series and only few days of heavy precipitation the system (rainfall, increase in pore water pressure, change in GNSS coordinates) can yet not be described by more sophisticated models.

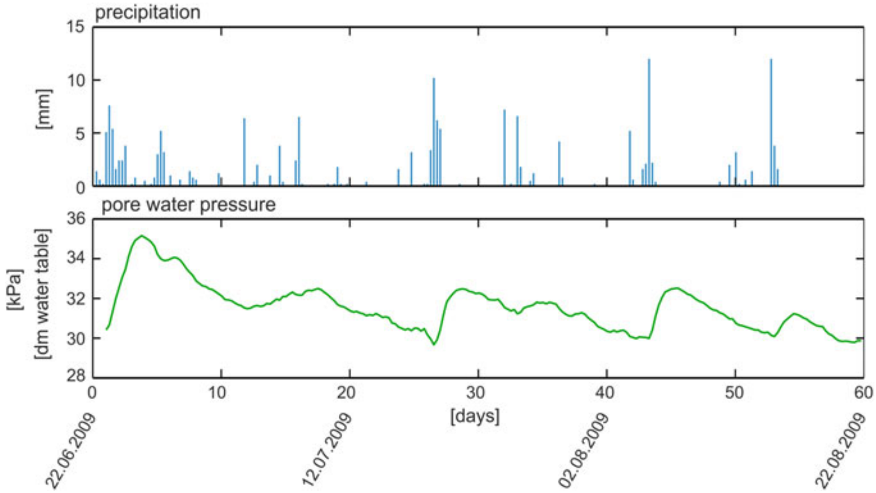

Fig. 15.11 Precipitation and pore water pressure for the period June 22nd to August 22nd 2009 (filtered, 6 h intervals) (Thuro et al. 2010)

15.3.2.2 Time Series: Cross Correlation Analysis

In this first attempt the quantification of the time gap between rainfall and an according rise in pore water pressure was the major objective. To show the temporal dependency cross correlations from the filtered and resampled data were calculated. The analysis of the time span of 60 days shows a correlation between precipitation and the pore water pressure with a delay of 2–3 days, but cross correlation of the piezometric time series with GNSS results did not confirm a significant temporal dependency even though similar characteristics can visually be identified. The numerical analysis (Tadayonfar 2011) of the Aggenalm Landslide may explain why: A rise in pore water pressure of about 6 m (more than 5 times of the hitherto maximum of 1.2 m) would be necessary to get a stronger increase in movement rate. Therefore with the present events the GNSS results in particular are still within its noise making it difficult to get a significant correlation.

Figure 15.12 shows two time series for a shorter span of only 10 days, starting June 23rd 2009. The first two days a strong continuous rainfall (∼25 mm in 2 days) can be observed. The cross correlation of the time series shows a time delay of about 2.5 days. Similar results have been calculated for comparable events—the time delay between precipitation and rise in pore water pressure varies depending on the amount of rainfall as well as system's prerequisites and is about 2–5 days. The time offset after the onset of the snow melt seems to be greater. Here the analysis showed results of about 4–5 days.

The correlation of the presented time series gives a first view on a possible analysis method. Longer time series as well as a greater number of significant precipitation events should allow a further and more detailed interpretation of the cause-and-effect

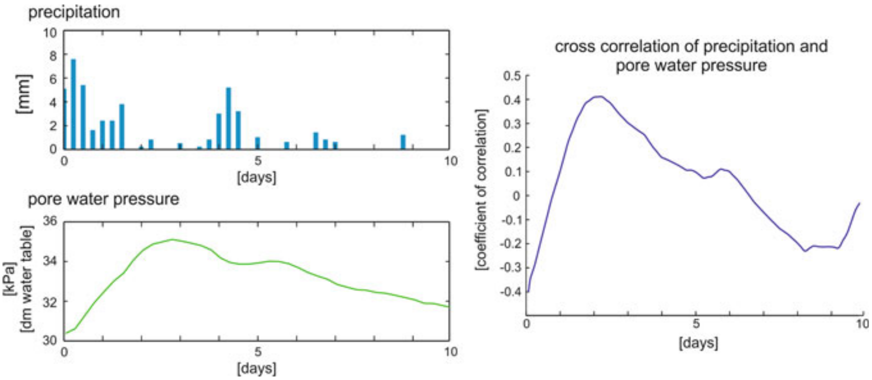

Fig. 15.12 Precipitation and pore water pressure for the 10 day period June 23rd to July 3rd 2009 including a cross correlation (Festl et al. 2011; Thuro et al. 2010)

chain. In particular greater point movements in the GNSS data should make it possible to integrate these in the analysis and also detect dependencies between trigger events and deformation, however.

15.4 Conclusion and Perspective

The developed measurement techniques TDR and low cost GNSS are more or less based on already existing hardware components, while the video tacheometer hasn't been introduced to the market yet, and is still available as a prototype from Leica Geosystems only. New developments in the video tacheometry were mostly accomplished in the fields of the adaption of the system layout for the measuring task "slope monitoring" and in signal analysis and sensor control. The efficiency of TDR and low cost GNSS for continuous monitoring could be proved. Decisive are the developed software components for the data management and complex data analysis. These measurement techniques are now on the cusp of marketability, whereas the range of application isn't limited to mass movements but can be extended to other monitoring tasks such as the monitoring of structural elements (Singer et al. 2009a).

References

Festl J, Singer J, Thuro K (2011) The Aggenalm landslide—first findings of the acquired monitoring data. In: Proceedings of the international symposium on rock slope stability in open pit mining and civil engineering. Vancouver, Canada, 18–21 Sept: 7 p

Glabsch J, Heunecke O, Schuhbäck S (2009) Monitoring the Hornbergl landslide using a recently developed low cost GNSS sensor network. JAG 3: 179–192

Glabsch J, Heunecke O, Schuhbäck S (2010a) Development and testing of a low cost sensor PDGNSS landslide monitoring system using the example of the aggenalm landslide in the bavarian alps. In: Altan O, Backhaus R, Boccardo P, Zlatanova S (eds) Geoinformation for disaster and risk management. JB GIS, Copenhagen, 63–70

Glabsch J, Heunecke O, Schuhbäck S (2010b) Überwachung von Rutschhängenmittels low-cost GNSS Empfängern im near real time processing. In: Wunderlich T (ed) Ingenieurvermessung 10. Wichmann, Berlin, 275–288

Leica Geosystems AG (2007) Leica TPS1200+ Series. XI.07 738600de, Herbrugg, 16 p

Leica Geosystems AG (2010) Leica Viva TS15. Data sheet, Herbrugg, 1 p

Reiterer A, Huber N, Bauer A (2010) Bildbasiertes Erfassen und Matching homologer Punkte mittels Feature-Vektoren—Funktionsweise und Evaluierung beim Einsatz in einem Deformationsmesssystem. In: Wunderlich T (ed) Ingenieurvermessung 10. Wichmann, Berlin, 241–254

Singer J (2010) Development of a continuous monitoring system for instable slopes using time domain reflectometry (TDR). Dissertation, Chair of Engineering Geology, Technische Universität München

Singer J, Grafinger H, Thuro K (2009a) Monitoring the deformation of a temporary top heading invert using time domain reflectometry. Geomech Tunn 2: 238–249

Singer J, Festl J, Thuro K (2009b) Computergestütze Auswertung von time domain reflectometry Messdaten zur Überwachung von Hangbewegungen. In: Marschallinger R, Wanker W (eds) Geomonitoring, FE-Modellierung. Sturzprozesse und Massenbewegungen, Heidelberg, Wichmann, 19–34

Singer J, Schuhbäck S, Wasmeier P, Thuro K, Heunecke O, Wunderlich T, Glabsch J, Festl J (2009c) Monitoring the Aggenalm landslide using economic deformation measurement techniques. Austrian J Earth Sci 102: 20–34

Singer J, Thuro K, Festl J (2010) Development and testing of a time domain reflectometry (TDR) monitoring system for subsurface deformations. In: Zhao J, Labiouse V, Dudt JP, Mathier JF (eds) Rock mechanics in civil and environmental engineering. Taylor and Francis Group, London, 613–616

Tadayonfar G (2011) Numerische Modellierung der Großhangbewegung Aggenalm mit FLAC. Dissertation, Chair of Engineering Geology, Technische Universität München

Thuro K, Wunderlich T, Heunecke O, Singer J, Schuhbäck S, Wasmeier P, Glabsch J, Festl J (2009) Low cost 3D early warning system for alpine instable slopes—the Aggenalm landslide monitoring system. Geomech Tunn 2: 221–237

Thuro K, Singer J, Festl J, Wunderlich T, Wasmeier P, Reith C, Heunecke O, Glabsch J, Schuhbäck S (2010) New landslide monitoring techniques—developments and experiences of the alpEWAS project. JAG 4: 69–90

Topcon Positioning Systems Inc (2008) Topcon imaging station—long-range scanning, imaging and robotic total station. Revision A 7010–0876, Livermore, 4 p

Trimble Navigation Limited (2010) Trimble VX spatial station—Datasheet. 022543-261F, Singapore, 4 p

Wasmeier P (2009a) Grundlagen der Deformationsbestimmung mit Messdaten bildgebender Tachymeter. Dissertation, Chair of Geodesy, Technische Universität München

Wasmeier P (2009b) Videotachymetrie—Sensorfusion mit Potential. AVN, vol 7. Wichmann Verlag, Heidelberg, 261–267