

Long-Term Monitoring Using GNSS: Lessons Learned and Experiences from 20 years of Operation



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Abstract Global Navigation Satellite Systems (GNSS) like GPS, Galileo, GLONASS and Beidou are used for monitoring of civil structures and natural phenomena since the 1980s. However, most of the implementations were either short term or realized in a very controlled environment. In this article we report about the experiences of more than 20 years of GNSS based monitoring of a large-scale object. In 1999 the GNSS monitoring system was developed and installed at a deep-seated gravitational mass movement in Austria and it is still operating. The system gradually evolved during the years of operation to maintain a reliable operation and to take new developments of information and communication technology (ICT) into account. This included the change from radio communication to UTMS and continuous maintenance of the hardware (revision of GNSS stations, revision of solar collectors, exchange of batteries) as well as software maintenance (Firmware updates of GNSS receivers, software updates, change to new operating systems). Especially the constant changes in the used software system results in maintenance time, which is often underestimated. From these experiences we derive lessons learned which can be a guideline for other long-term GNSS based monitoring systems.

Keywords GNSS monitoring system · ICT · Landslides · Long-term monitoring · Mass movement · Early warning system

1 Introduction

Since the 1980s Global Navigation Satellite Systems (GNSS) are used for the monitoring of civil structures and natural phenomena. The advantages of GNSS to other geodetic techniques are independency of weather, the determination of deformations in 3D and its economic efficiency due to the automated operation.

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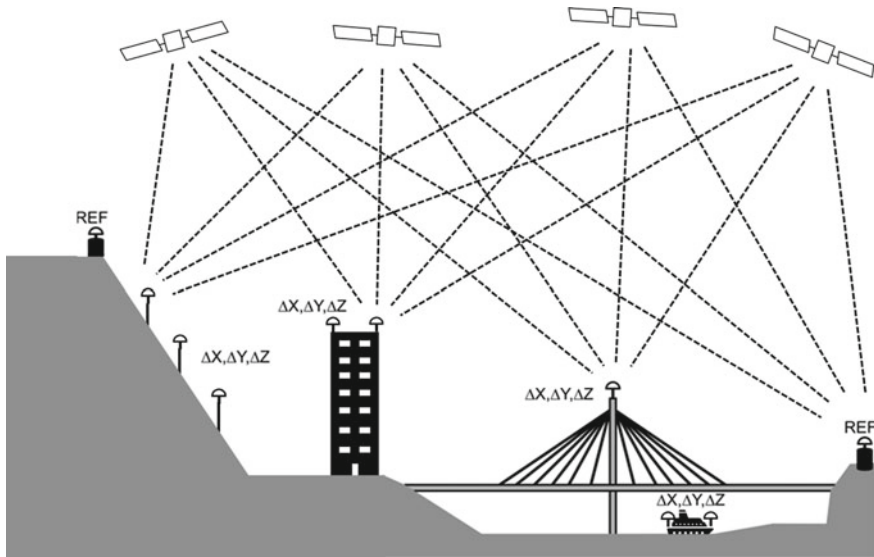


Fig. 1 GNSS Monitoring using one or more static reference stations (REF) and several rovers on moving objects (based on Lienhart and Ehrhart [5]). Note: exemplarily the required measurements to at least 4 satellites are shown for one reference station and 3 rovers

Therefore, GNSS was used in monitoring projects in different fields: suspension bridges [1], super-tall buildings [2], ships [3], landslides [4] and many more. Figure 1 shows the versatility of GNSS monitoring.

In 1999 a global GNSS measurement system was developed for the deformation monitoring of a deep-seated gravitational mass movement in Austria. Previously, traverse measurements, were carried out after a catastrophe in 1965/1966 [4]. The improvement with the GNSS monitoring system was seen in a continuous observation all year long, with minimum yearly maintenance work. This concludes to a better time resolution of the monitoring object with less working hours.

Chapter 2 gives an overview of the monitoring object and the aim of the monitoring system. Its development, from manual measurements to the current system with a 24/7 operation with online presentation and early warning, is described in Chap. 3. Chapter 4 takes a closer look to the current system and to challenges that are faced in the long-term operation on the engineering side, where Chap. 5 focuses on additional challenges.

2 Mass Movement Gradenbach

The mass movement Gradenbach is located in the south of Austria. Over the last 20 years, the behavior of the movement was observed via GNSS monitoring. The

GNSS monitoring system consist of 2 reference sites on stable ground. One is located on the mountain ridge (R1) and the other one on an opposite hill (R2). With a large height distance of about 800 m, correct handling of atmospheric influence is crucial to achieve high accuracy of the position of the monitoring points. Gassner et al. [6] demonstrated a point precision of around 7 mm can be achieved with specially developed algorithms for the tropospheric modelling. An overview of the location is shown in Fig. 2.

As seen in Fig. 2 there are 5 monitoring sites in the deformation area. Since 2012, the sites MA and MC are monitored continuously. Those two sites were chosen, because they are easy to reach, show large deformations and are at different heights. The other monitoring sites are observed epoch wise.

The time series of the of the slope movement recorded by the monitoring stations is shown in Fig. 3. It can be seen, that there are years with steady low movement (~0.4 cm/month) and years with accelerated movements (up to 2 cm/day), where accelerating phases start in spring, during the snow melting season, and stop in the end of summer. However, additional acceleration phases can also occur [7]. Especially 2018 was a year with a lot of movement (more than 40 cm for MC), which shows the importance of the still ongoing monitoring in this area. With the distribution of GNSS sites, the behavior of the slope can be observed and an early warning system for the

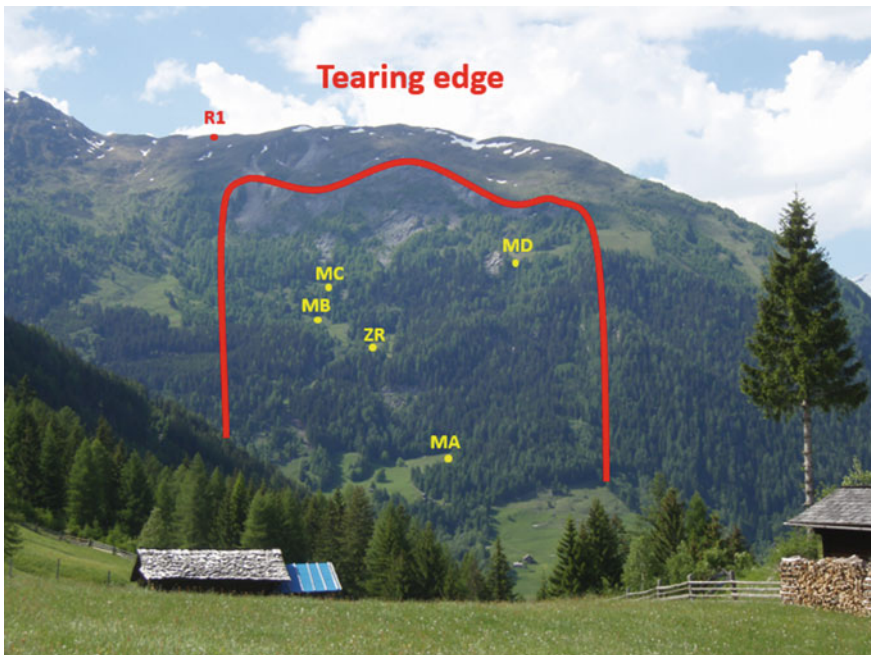


Fig. 2 Monitoring object: mass movement Gradenbach. Image taken from location of reference site R2

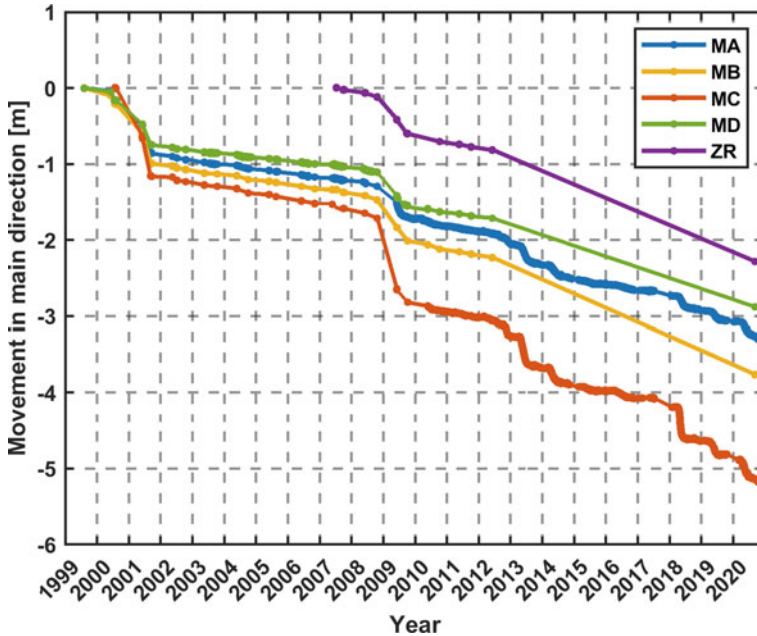


Fig. 3 Time series of the monitoring stations in the main direction of slope movement

local community, based on empirical data, is provided. Furthermore, the impact of counter measures like an additional drainage system can be assessed.

3 System Development

The system development can be divided into three main stages, starting from manual measurements to a continuous monitoring system over the summer to the current system of a continuous operation with online presentation. Table 1, shows an overview of the used hardware and software over the years. Remarkably, the GNSS Antennas are still working after more than 20 years and the receiver hardware has only been upgraded once. However, a significant amount of labor went into the constant upgrade to the latest operating systems which was necessary due to IT-security reasons and drivers for peripheral devices like modems.

Table 1 Timeline of the system development

		Hardware			Software		
		Antenna	Receiver	Data transfer	Analysis Software	Windows Systems*	Online Presentation
Manual Measurements	1999	Choke-Ring Antenna		Local Internal Storage	GRAZIA	NT	
	2000					2000	
	2001				XP		
	2002						
Continuous Measurements	2003		Ashtec	Radio Link	KFrün	Vista	
	2004						
	2005						
	2006			7			
	2007						
	2008						
Yearlong Measurements	2009	Novatel	UMTS	Bernese with IGMS Routines	8	gbonline	
	2010						
	2011						
	2012						
	2013						
	2014		10				
	2015						
	2016						
	2017						
	2018						
2019	Canary						
2020							
2021							

* Not all Versions were used

3.1 Manual Measurements

From 1999 to 2002 measurements were carried out for 72 h, two times a year, one in spring and one in autumn. The whole equipment had to be carried by foot to the measurement locations and the data was stored on the laptop and on the internal memory of the receivers, Fig. 4. Calculations were carried out manually after the measurement with GRAZA, a software from GPSofT developed at the University of Calgary. This first era was also used to develop and implement algorithms for an improved multi-path elimination and height dependent tropospheric corrections [6].

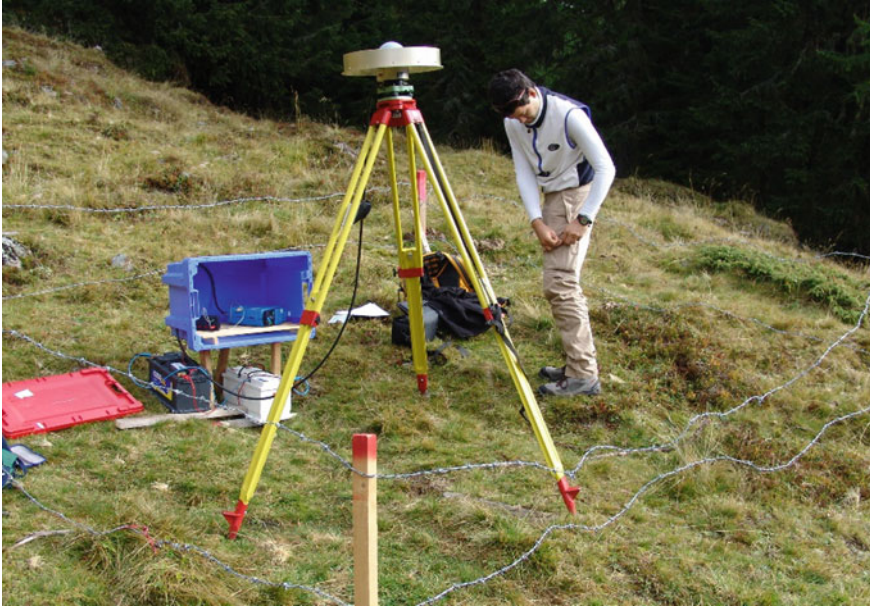


Fig. 4 First manual measurements

3.2 *Continuous Measurements*

In the second phase, data was collected during the whole summer and the data collection changed to a real time transfer over radio link to a calculation center in the valley, where coordinates were calculated with KRun, a program developed at the Institute of Engineering Geodesy and Measurement Systems (IGMS) of TU Graz., see Fig. 5. Those improvements could be established with the use of solar panels which continuously charge back-up batteries for an uninterrupted power supply to the instruments. Furthermore, this era laid the foundation for the current system. First, tests with different receivers and antennas lead to usage of the current hardware. Second, license agreements with the land owners for operating the sites a whole year were contracted [8].

3.3 *Yearlong Measurements*

In the current state of the system the stations are not dismantled anymore, Fig. 6. Once a year in spring, maintenance work is done at all sites. Especially the snow in the winter damages the stations, or moves their center point away from the marker point. This maintenance work is therefore essential. The data transfer was changed to a Universal Mobile Telecommunications System (UTMS) connection, so the data



Fig. 5 Continuous measurements with data transfer over radio link, left: radio antenna at a site, right: radio antenna at the calculation center



Fig. 6 Current system with data transfer over UTMS

is sent directly to Graz, where it is processed automatically and then added to an online presentation tool [9]. This system is explained in more detail in Chap. 4.

4 Current System

As mentioned in Chap. 2, the monitoring system consists of the data collection at the monitoring sites and the data processing, which is carried out at IGMS, in Graz.

Figure 7 shows the systems at both places. The left side shows a photo of the reference site R1, with its equipment, on the top of the hill in around 2100 m. The right side is a drawing of the data processing computer in Graz. The data transfer is done via Universal Mobile Telecommunications System UMTS.

4.1 Monitoring Site

For a better understanding of the setup at a site Fig. 8 shows a photo of a site and 3 colors are used to distinguish between the Parts: Data Acquisition (blue), Communication (green) and Infrastructure (red).

Infrastructure. The infrastructure part, consisting of a tripod, solar panel, batterie, fence and a box for lightning protection, is very important for operating functional.

The fence is needed to keep cows and sheep away from the station without harming them. It is made out of wood and barbed wire, which both suffer under the weather conditions during winter. This is why it is very important to repair it every spring before the animals come back to the slope, since a broken or not properly tensioned fence may harm animals. Besides animal suffering, an incident may also have an impact on the relation to the land owner resulting in a termination of the land-use license agreement. Fortunately, vandalism has not been a problem so far.



Fig. 7 Current system, left: Photo of a site, right: Data processing in Graz, Data Transfer via UMTS

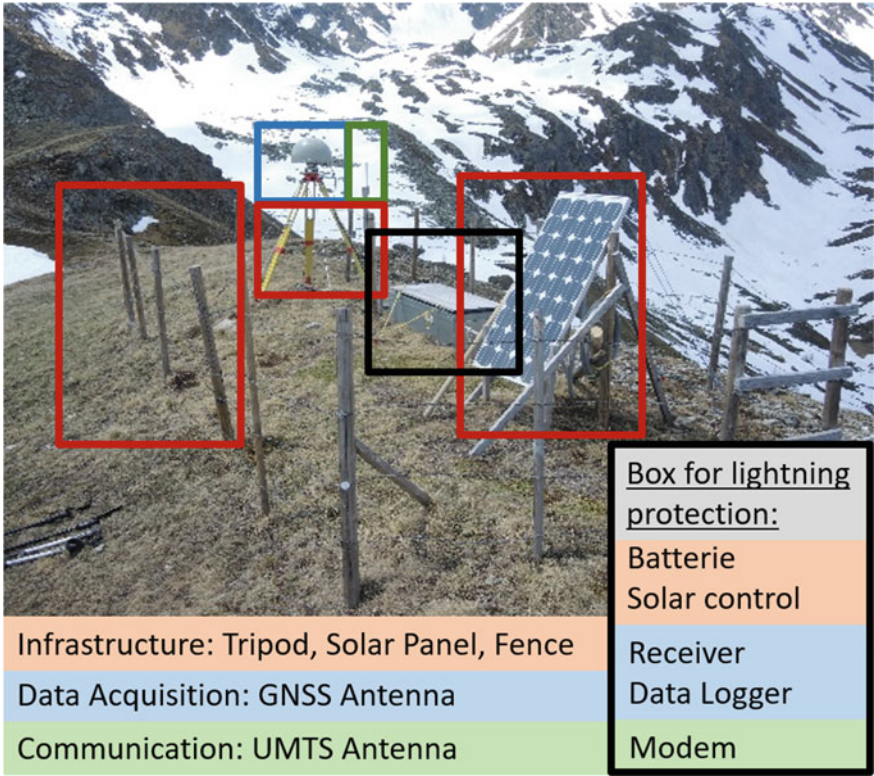


Fig. 8 Equipment at a site

Also, the tripod, made out of wood, needs to be checked for functionality during maintenance work and, in case of malfunction, replaced.

The electricity circle containing the solar panel, the solar control and the battery are checked every year. Batteries should be changed every 5–10 years for environmental reasons.

Data Acquisition For GNSS data acquisition every site is equipped with a GNSS antenna, a receiver, a data logger and the needed cable connections. Currently the GNSS antennas used at the sites are choke ring antennas with radons and used since the beginning of the GNSS measurements. They work totally fine, and no problems have been detected so far. There was one change of GNSS receivers in 2009 to upgrade to receivers with lower power consumption and more satellite channels. Since then, the receiver needed one firmware update, because of an early Global Positioning System (GPS) week roll over in 2017. Because the system is supposed to run without permanent intervention, the missing firmware update was not recognized immediately leading to a loss of data for a few months. Because of End of Life (EOL) notifications for our receivers, no more updates will be available, and in case of a severe error, new receivers need to be purchased [10].

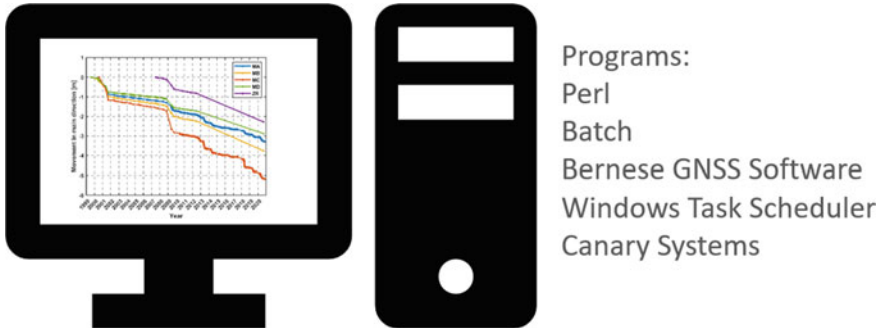


Fig. 9 Data processing in Graz with its main tasks and programs

Communication For the communication part, a modem with a SIM card and a UMTS antenna is needed. So far, the modems work properly, but there are no digital drivers available to access them. For accessing the modem, a Windows XP notebook is used. Furthermore, there is also an EOL notification, which will lead to a replacement, in case of severe errors. The UMTS antenna is exposed to all weather conditions, which are very harsh in this area. Therefore, it has to be changed every now and then.

4.2 Data Processing in Graz

Figure 9 covers the data processing in Graz. It uses the programs: Perl, Batch, Bernese GNSS Software [11], with built in tropospheric modelling algorithms by IGMS, Windows Task Scheduler and Canary Systems (ML Web v.2019.1.0.46, [12]) to cover the whole data processing part from importing data to an online presentation of the coordinates.

Hardware and Operating System The computer is a Windows Computer with a high-end server mainboard from 2011. Until the end of 2019 Windows 7 was used as an operating system, but with the end of the support for Windows 7 in the early 2020, the system needed to be upgraded. Some programs could not run with Windows 10 anymore. Another disadvantage with Windows 10 is the constantly installed updates and reboots of the computer. Those updates could result in compatibility problems with the monitoring system. All in all, it is not a high-end computer anymore, and because of the constant data writing and access to the hard disk, it suffers in speed and capacity.

Software Focusing on the software of the computer, the data process contains different software packages accessed by various programming languages and coordination tools to get all necessary additional data (orbit correction data, ionospheric data) and to calculate coordinates. This system is therefore dependent on the IT-infrastructure of institutions that provide the data and updates in their IT-environment

- **Change of the FTP address:**
 The URL of our FTP server has changed from `ftp://ftp.unibe.ch/aiub` to `ftp://ftp.aiub.unibe.ch`. The old URL is no longer active. **Please adapt your scripts if needed.** If you do not use FTP to download our products you can still use `http://www.aiub.unibe.ch/download`

Fig. 10 Notification for FTP server address change on the website: <http://www.bernese.unibe.ch/>

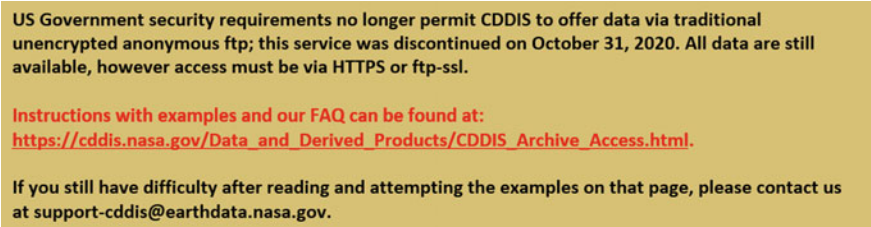


Fig. 11 Notification for FTP access change on the website: <https://cddis.nasa.gov/>

result in updating the data processing scripts. Adaptation can be e.g. the change of domain names from servers (Fig. 10) or change of the way of accessing servers, e.g. FTP to FTP-SSL (Fig. 11) and are mainly caused by enhanced security standards. Additionally, some files for Bernese GNSS Software expired in 2020 and had to be created again (planetary ephemeris).

Online Presentation The system need only little supervision and changes like those mentioned before can be left unseen for some time, which results in manually reprocessing old data. With the current Online Presentation Platform, those changes are detected earlier and it is possible to react timely.

For the online presentation we use the program Canary System, where limits can be set and automatic e-mail notification is sent. (Screenshot in Fig. 12), in case of exceeding limits or if no data is available to import. It also includes a security

Alarm Notification

The following alarms have been triggered:

Alarm Name	Alarm Source	Alarm Status	Alarm Type	Date Triggered	Previous Alarm	Alarm Threshold	Current Value	Notes
GBGPS	MC#3D VERSCHIEBUNG 1MONAT	ON	Three Level - High Low	5/2/2020 10:00:00 PM	N/A	0.05	0.05	
GBGPS	MC#3D VERSCHIEBUNG 1MONAT	ON	Three Level - High Low	5/3/2020 2:00:00 PM	5/2/2020 10:00:00 PM	0.05	0.06	
GBGPS	MC#3D VERSCHIEBUNG 1MONAT	ON	Three Level - High Low	5/4/2020 6:00:00 AM	5/3/2020 2:00:00 PM	0.05	0.05	
GBGPS	MC#3D VERSCHIEBUNG 1MONAT	ON	Three Level - High Low	5/4/2020 6:00:00 PM	5/4/2020 6:00:00 AM	0.05	0.05	

Fig. 12 Screenshot of an automatic E-Mail Notification after reaching a set limit

protection. Our previous self-programmed Version in PHP & HTML was online from 2012 to 2016, but then hacked and spam mails were sent from this server. This should not happen with our current online presentation tool.

Communication Furthermore, our mobile operator changed the IP addresses of the modems to private IP addresses, which resulted in the impossibility to access them. This problem has already been solved from our mobile provider by resetting to a public IP address.

5 Additional Challenges

The engineering part of a monitoring system is challenging, but especially in a long-term project other challenges occur.

One of those problems is that the people who accepted license agreements of monitoring systems leave and their successors are not interested anymore. This constant change over time also occurred at our institute, which highlights the importance of an excellent documentation.

In Chap. 3, harsh winters are mentioned. Those tones of snow results in trees bursting, danger of avalanches and closed roads during the winter. After the winter, the road must be cleared from the fallen trees and the road is often not accessible until early summer. This phenomenon of massive snowfall happened both in November 2019 and in December 2020 (Fig. 13).



Fig. 13 Massive snow, closed roads and fallen trees during winter

6 Summary

For over 20 years now a GNSS monitoring system was developed, improved and maintained on a mass movement in the Austrian alps. The system evolved from manual epoch measurements to a full-automatic monitoring system with a data transport over UMTS and an online presentation.

In those 20 years the IT-infrastructure of the system changed and needed to be modified to keep operational. Security reasons were the major part of those adaptations. Nevertheless, those changes need to be detected and a very important tool to spot them is the online presentation of the data. If no data is updated, there is something wrong with the system.

Modifications in the engineering hardware are rarer, but there won't be a support of aging hardware anymore. Especially in the rural area with a lot of snow, maintenance work has to be done every spring, to keep the system operative.

Never forget a good documentation, especially on long-term projects.

7 Conclusion and Outlook

A long-term monitoring system will run through a lot of changes, that need to be faced. Those can occur in various fields. Obviously, a steady development takes place in hardware and software and in the way of communication, but also changes in responsibilities or extreme weather will occur. These variations need to be addressed so supervision and maintenance time is always required.

On the other hand, with a data series of more than 20 years conclusions on the long-term behavior of the mass movement can be made, which are very important for an early warning system and the impact of counter measures like additional drainage systems can be assessed.

This article focuses on the long-term monitoring using GNSS. However, satellite measurements are only one part of the deformation measurements at the Gradenbach mass movement. Additionally, terrestrial total station measurements are available since 1968, fiber optic strain measurements are performed since 2007 and wire extensometer data is available since 1999. Furthermore, the measurement program is constantly upgraded, taking new technology developments into account. Recently, corner cube reflectors for satellite based interferometric synthetic aperture radar (InSAR) were installed to complement the GNSS measurements.

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