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DEVELOPMENTS TOWARDS A LOW-COST GNSS BASED SENSOR NETWORK FOR THE MONITORING OF LANDSLIDES

Jessica GÜNTHER, Otto HEUNECKE, Sönke PINK and Stefan SCHUHBÄCK

Institute of Geodesy, University of the Bundeswehr Munich

Abstract: The use of GNSS for the monitoring of phenomena like landslides is well known to Engineering Geodesy since years. A challenge is to make low-cost hardware and disposable software equipment on a commercial off-the-shelf basis usable. This comprehensive task can be discussed with respect to the underlying theory of wireless sensor networks. The paper reports on the current developments at the Institute of Geodesy, UniBw Munich. First results with this comparatively new approach are depicted.

1. INTRODUCTION

No doubt, great advances in the recognition and mitigation of landslides have been made in the last few years. Exclusive integrated monitoring systems with early warning capabilities are available based on a wide variety of proven instruments, e. g. tacheometers or inclinometers, including respective standard software tools for hardware control and high sophisticated data evaluation. For economical reasons, however, all these techniques are not used on broad scale. At the same time the worldwide number of localities with an urgent need for monitoring is rising noticeably – not only for slide slopes. Thus, cost effective approaches are requested. The monitoring system under development at the UniBw Munich, which is concentrated at the moment mainly on the use of – at least in comparison – low-cost GNSS devices, aims to fill this gap. The challenge is to have a flexible, robust and commercial off-the-shelf GNSS equipment available which records continuously movements on the surface of a structure with an accuracy level of a few millimetres.

The developed GNSS monitoring system bases on the evaluation of carrier phase measurements over a certain, in principle freely selectable, time span. Usually, a time interval (epoch) of approx. 15 – 60 min is considered. These raw data are transferred wireless or wireline to a master computer and is analysed automatically in a staggered, self-styled processing. A so-called “dual system” separates between several processing stages with different available and proven software tools, known interfaces for data exchange prerequisite. Here one has to distinguish between raw data conversion, appointed base line processing etc. at every epoch k and the further evaluations especially by time series analysis. With the expected movement rates and necessary advance warning times at landslides, this common understanding of near real time available results – a delay of some minutes processing time has to be accepted, however – normally represents no restriction to the intended use in an early warning system.

The concept of (wireless) sensor networks is incorporated in all the ideas. Finally, the GNSS component can be seen only as a part of a more sophisticated combined system and should be used parallel together with other measuring devices. The system developed so far is already in use in two research projects in the alpine region.

2. GEO SENOR NETWORKS FOR MONITORING TASKS – THE BASIC CONCEPT

A (wireless) sensor network is defined as an infrastructure comprised of sensing (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). Often control and actuation is required in addition to just sensing, e. g. to engage a device for relocation. A sensor network, however, consists of the following four basic components:

1. an assembly of distributed or localized sensors;
2. an interconnecting network (usually, but not always, wireless-based);
3. a central point of information clustering (central data sink); and
4. a set of computing resources at the central point (or beyond) to handle data correlation, event trending, status querying, and data mining.

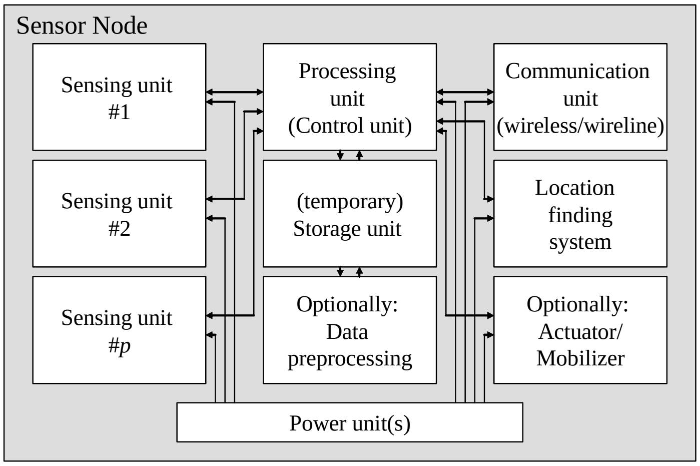

Figure 1- Typical sensor node design

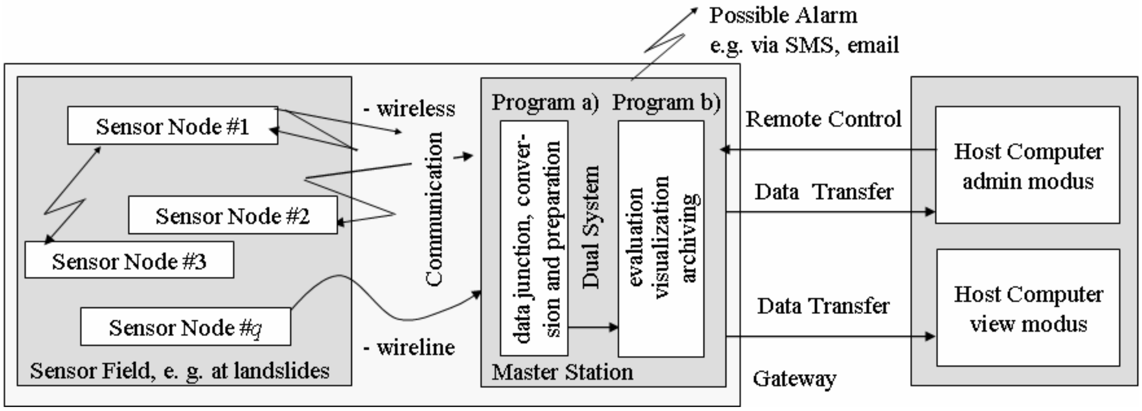

Figure 2 - Basic scheme of a monitoring geo sensor network

Although all networked sensors must have the availability of localization (relative or absolute) to attribute the observed information, at least implicitly when a sensor node got its known predetermined position, within geo sensor networks the positioning and changes of the positions of the sensors are of special meaning. Fig. 1 depicts a typical senor node, Fig. 2 the basic scheme of a geo sensor network (GeoSN) with respect to monitoring. Within geo sensor networks one of the sensing units normally is designed for positioning and no extra location finding system is required. In addition, of course, often several other information, e. g. temperature and humidity, are observed in a GeoSN, too. One among other applications of a GeoSN is monitoring as a classical task of Engineering Geodesy.

3. GNSS-BASED MONITORING SYSTEM'S DESIGN

In particular the following characteristics were stated for the GNSS monitoring system's design, which will be called GeoSN-UniBwM in the following:

- application of low-cost GNSS sensor technology (with a possible point position quality of at least a few millimetres, normally just simple L1 receiver respectively boards);
- WLAN-Communication between the sensor nodes (wireless data transmission on site), enhanced and continued by wireline techniques if necessary and suitable;
- autonomous power supply of the sensor nodes in the field;
- proofed for (nearly) all weather conditions and rough environmental situations;
- flexibility of the analysis through (any time adaptable) options of near real time processing (NRTP);
- possibilities for remote maintenance and request of the system (remote desktop operation);
- separation between data recording, pre processing and essential evaluation (especially time series analysis) using predefined interfaces;
- possibility of inco-operation of existing (proofed, powerful) program tools;
- open system to integrate other sensors respectively to be adapted to other sensors.

Some of the main aspects shall be depicted briefly. For further details see Pink (2007), Schuhbäck (2007) and Kotthoff (2008). Landslides as a first application for the developed system respectively the system still under development is selected because of its relatively slow and more or less steady movements. Other applications with lower displacement rates or highly dynamic environment might need other instrumentation than simple GNSS L1 boards.

3.1. Real Time Kinematic vs. Near Real Time Processing

Using GNSS for monitoring several principles must be kept separated, see Fig. 3. Real time kinematic (RTK, Fig. 3a), the common procedure for site surveying and setting out, demands a reference station where the correction signals for the rover(s) are generated. Usually these signals are spread by radio using for instance the RTCM protocol. At the rover the baseline is processed in real time. The established ground and satellite based augmentation services, which also represent own categories of GeoSNs, are working on this scheme (see e. g. Retscher, Moser, 2001). For online monitoring the baseline information from the different rovers must be brought together instantly at a master or base station. Thus a second radio channel is required for the transmission of those completely processed baseline(s), see Fig. 3b. Such an operable system is described e. g. by Jäger, Bertges (2004). At the master station the baselines are collected, analyzed and depicted graphically.

A completely other way is the use of simple GNSS OEM boards and antennas. Both encapsulated is sometimes referred as enclosures. Here the sensing devices just need the availability of code and phase tracking and temporary raw data storage, but no additional processing unit inside. Therefore, such a board or enclosure is much cheaper than a receiver with RTK availability ("rover"); the relation is about 1:10. A serial interface (e. g. RS-232, RS-422, RS-485 or USB) is needed to transmit the raw data of the preconfigured receiver for instance via WLAN, see Sec. 3.2., to a master station, see Fig. 3c, where all processing is done. This task, configured in a batch mode, starts with the conversion of the raw data to a format of the appended software tool and performs the computing of the baselines. It is up to the administrator to determine which receiver respectively node serves as a reference point (stable point) and which as an object point, the terms reference station and rover with respect to RTK terminology make no sense. Furthermore, the configuration of the receivers, e. g. length of an epoch, recording frequency, elevation mask etc., is up to the system's administrator. This configuration also has to be operated by the serial interfaces because boards do not have an own control unit and display.

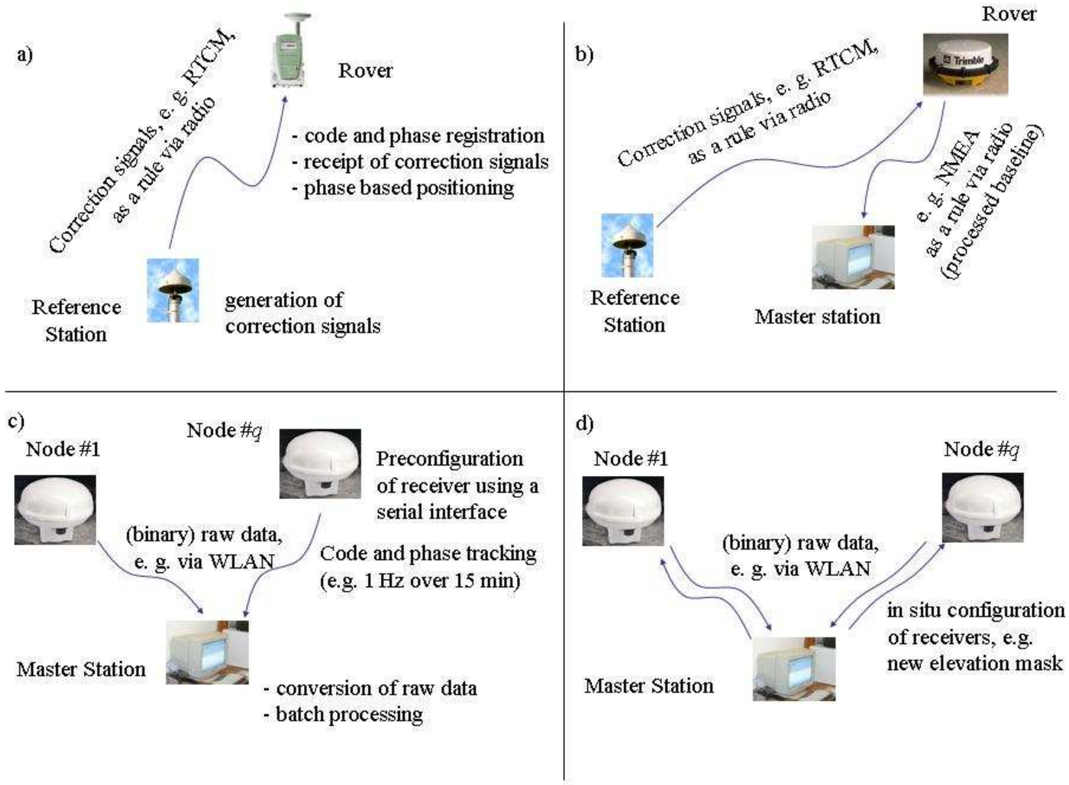

Figure 3 - RTK (a), online (b), NRTP - 1 channel (c), NRTP - 2 channels (d)

Depending on the software package for the baseline processing some options can be selected by the administrator (see e. g. Hartinger, 2001). The baselines including their variance and covariance information can be adjusted for a geodetic net solution (distance measurements in all combinations), too. Within GeoSN-UniBwM the universal package GrafNav (Waypoint, 2007) is used so far. In comparison with the RTK modus a lot of possibilities are given applying this approach. Especially a detailed quality check can be performed. The resulting accuracy of this near real time processing (NRTP) procedure is assumedly very much higher than RTK, comparable receiver specifications presumed. The availability of the GNSS raw data enables the administrator to supply a verification of the results, e. g. by repetition of the whole processing at any time. If there is a second channel – or one bidirectional channel using well predefined time slots – available, also an in-situ, event-based configuration of the senor nodes is optionally possible, see Fig. 3d. With regard to such an event-based possibly more intensive sensor operation also the link and power budgets, see Sec. 3.2 and 3.3 should be planned comprehensively.

GNSS sensors who meet the requirements for NRTP according to Fig. 3c/d are for instance Novatel Smart Antenna and Novatel Smart-V1G Antenna (the latter available since October 2007). Some of their technical specifications are collected at Tab. 1; remarkable is the increase of the carrier phase determination with the new V1G. Their half-round shape and their environmental specifications (temperature, moisture, dust etc.) make them ideal for year-round monitoring in mountainous regions. Due to non-comparability of the two mentioned different receiver types, all instruction sets had to be arranged separately, but of course a combined use in a sensor field is possible.

	Novatel Smart Antenna	Novatel Smart-V1G Antenna
GNSS	GPS	GPS + Glonass
Receiver type	Superstar II	OEMV-1G
No. channels	12 L1 GPS	14 L1 GPS 12 L1 Glonass
Accuracy carrier phase	1 cm rms	0,15 cm rms
Data rate	max. 10 Hz.	max. 20 Hz
Power	9-24 V; 1,4 W	9-24 V; 1,2 W
Interfaces	RS-232 / RS-422	RS-232 / RS-422 / USB
Environmental	MIL-STD-810E	MIL-STD-810F

Weight: 575 g

Size: 115 mm diameter x 90 mm height

Table 1 - Specifications of selected GNSS boards (data sheet information, see www.novatel.com)

3.2. Data Communication and Network Design Issues

The widespread and cost-effective deployment of a sensor network particularly needs to make use of commercial off-the-shelf (wireless) communication techniques and standardized protocols, in detail please see e. g. Shoraby et al. (2007). Without any detailed further discussion in this paper mainly according to the link budget WLAN (IEEE 802.11b/g) is chosen as the most suitable technology for the purposes of GeoSN-UniBwM. Wireline connections are restricted due to the necessary high installation efforts in the field, but internet connection of the master and the host computers is presumed. The emerging data amount for a Novatel 12 channel L1 receiver is about 305 Byte/sec. Taking 15 min. as an epoch length a data packet of 274,5 Kbyte has to be dispatched. Using ordinary radio data transmission (9.6 Kbps) this will last about nearly 4 min. The same packet dispatched with 11 Mbps (standard WLAN) takes 0.2 sec. Therefore, new boards with much more than 12 channels and a network consisting of many GNSS sensor nodes may be together with many other devices, will not cause problems according to the WLAN link budget. Also compared by acquisition costs, power consumption and addressability in a network (TCP/IP) WLAN is superior to radio data transmission. It has to be mentioned that most of the standard devices are only equipped with serial interfaces, see Sec. 3.1. Therefore, a COM-server unit has to be included at the sensor nodes for the conversion to the network protocol. Even in a low-cost system approximately one third of the GNSS sensor node costs are required for the communication component. The main advantages of an infrastructural WLAN lumped together are:

- sufficient range of coverage (several km) by using appropriate antennas, but free line of sights are necessary;
- optionally enhancement of range by relais stations;
- high data rates (up to 54 Mbps), thus, many nodes can be incorporated in the net;
- distinct addressability of COM-server/bridge units;
- free available and secure operation by codification;
- combined use together with wireline nodes and ethernet using access points.

3.3. On Site Power Management

Secure energy supply is of paramount importance for all sensor nodes; see Fig. 1, especially with regard to long-term monitoring and permanent year-round operability. Often only at the master station, see Fig. 2, a regular power supplement (110/230V) is available, but all other nodes are stand-alone and need an autarkic power management based on rechargeable batteries. At a sensor node the sensing and eventually actuation units, the embedded processor and the communication unit are the sources of power consumption. However, a detailed power consumption budget has to be set up individually for every sensor node.

The recharge of the batteries of an unattended sensor node can be done by solar cells, wind propellers or fuel cells for instance. Within GeoSN-UniBwM normally back-up batteries in combination with solar cells (80 W) and charge controllers are used at the field stations. Taking into account a power consumption of about 2.9 W for all units at a node, a supply voltage of 12 V and a battery capacity of 130 Ah the autonomy factor of every GNSS sensor node without recharge is more than 22 days (Kotthoff, 2008). Power management never caused problems in the studies performed so far, but approximately one third of the over all GNSS sensor node costs are required for the energy supply.

3.4. Data Flow and Data Processing

The core system component is the central control application running at the master station; see Fig. 4, program a) with an optionally thorough remote maintenance and request of the system. A batch routine, within GeoSN-UniBw programmed under LabView, is requested to initialize the system (sensor and path definitions etc.), to monitor the WLAN communication, to collect and temporary store the raw data of all involved GNSS sensor nodes, and finally to accomplish the further data handling. GeoSN-UniBwM is designed as a dual system; see Fig. 2, which separates between a program for data junction, conversion and preparation and a second program for the evaluation, visualization and archiving of the epoch by epoch growing time series (Pink, 2007). Prior to the baseline processing the different Novatel raw data are converted to the format of the utilized processing package. At the moment GeoSN-UniBwM works with GrafNav (Waypoint, 2007). GrafNav is a very powerful package with different options for the baseline computing. The finally processed baselines $\boldsymbol{b}_k^i$, where i denotes the individual node combination and k indicates the respective epoch including their variance and co-variance information $\boldsymbol{\Sigma}_{bb,k}^i$ are than transformed into the format of the subsequent analysis software (program b). If a network adjustment is taken into consideration, the baselines may also be rewritten as $\hat{\boldsymbol{b}}_k^i$.

For the final analysis step the software package GOCA (see www.goca.info) with its open ASCII interface (so-called GKA-Files) was chosen. GOCA is a powerful tool with nearly all analysis tools, for instance moving average filtering, Kalman-Filtering and trend estimation, for 3D time series including ambitious possibilities for the visualization and possible alarms depending on appointed thresholds (e. g. Jäger, Bertges, 2004).

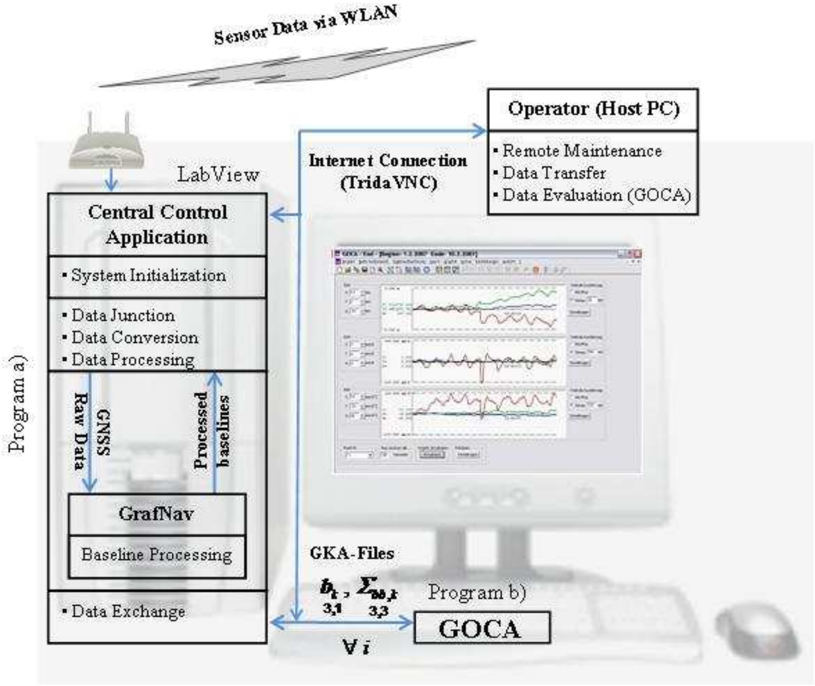

Fig. 4 - Data flow within GeoSN-UniBwM (compare Schuhbäck, 2007, and Fig. 2)

4. PERFORMANCE TESTS

Several performance tests are already carried out at the campus in Munich, especially by Pink (2007). Fig. 5 depicts the variations in X, Y, H of an unalterable baseline with a length of b^1 = 795 m between January and April 2007. The epoch length is 15 min recorded with 1 Hz using the Novatel Smart Antenna (see Tab. 1). Parallel a second baseline of b^2 = 265 m using the same reference point was observed, see Fig. 6. The interruptions in both series are caused by a gale (deviation of the WLAN beam antennas) and due to some experiments with the power supply, the WLAN network etc. during the test run. The system's failure performance during the complete tests was very satisfactory. However, some outliers and gaps are to be seen.

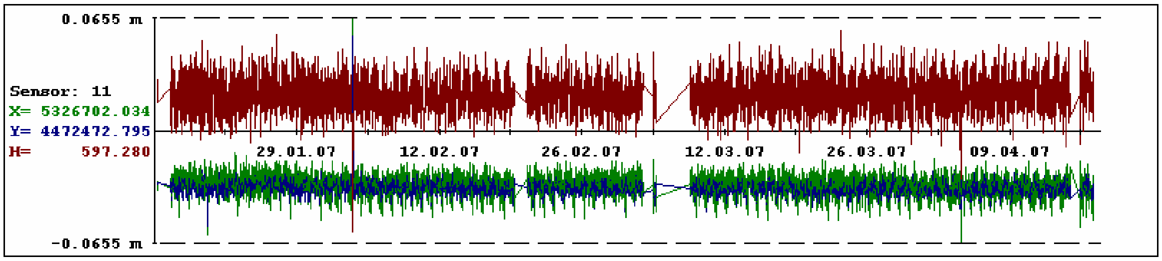

Fig. 5 - Variations of a 795 m baseline (15 min. solutions) between January 15th and April 17th

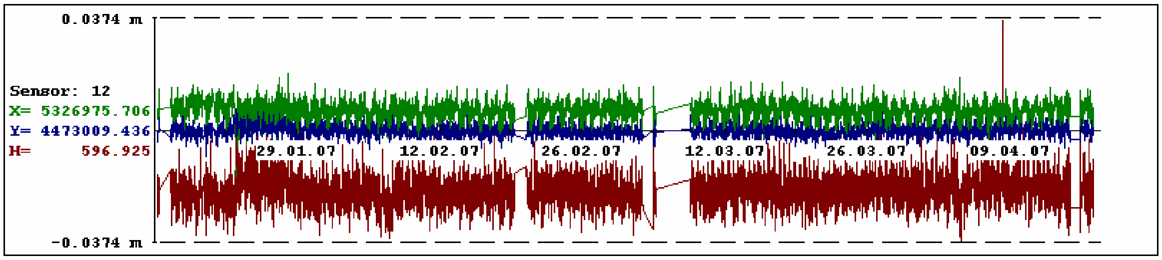

Fig. 6 - Variations of a 265 m baseline (15 min. solutions) between January 15th and April 17th

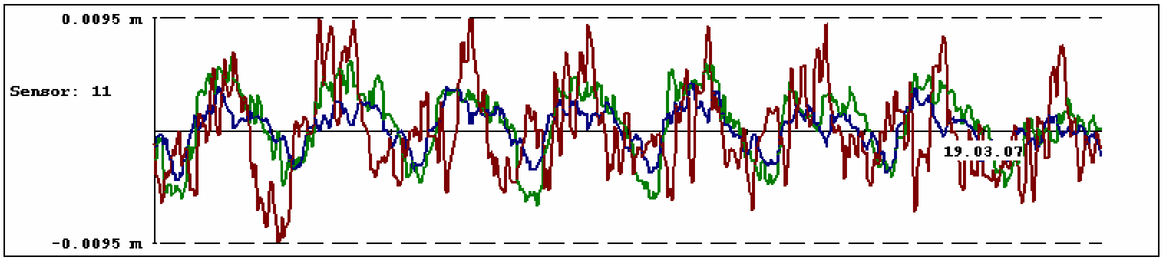

Fig. 7 - Variation of the 795 m baseline (2.5 h solutions) between March, 12th and 19th 2007

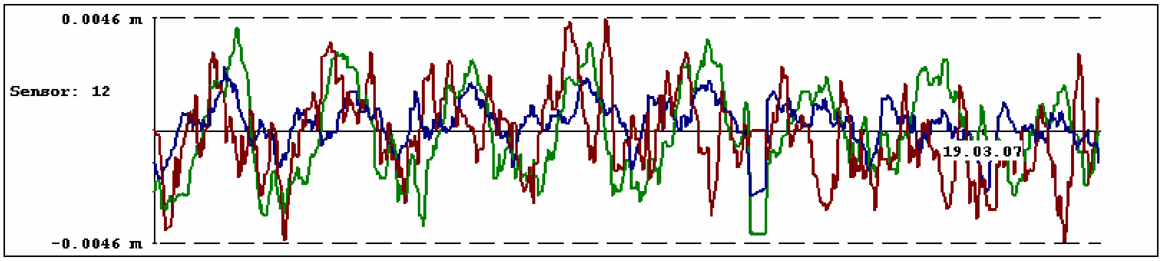

Fig. 8 - Variation of the 265 m baseline (2.5 h solutions) between March, 12th and 19th 2007

Deriving 2.5 h solutions by moving average filtering with GOCA the results are emphasized for both baselines for a representative week in March 2007, see Fig. 7 and 8. Quite clear are remaining apparently systematic effects with a daily period, assumedly induced by multipath. The remaining variations including these systematic effects are less than +/- 10 mm for the longer and less than +/- 5 mm for the shorter baseline, which give a very optimistically view on the system's achievement accuracy potential. A further low pass filtering would increase the accuracy as well as the impairment of the multipath influence, however.

To verify the system's accuracy a special motion device was constructed by Pink (2007). This motion device can perform automated displacement patterns up to 35 cm with an uncertainty less than 0.1 mm and the Smart Antenna mounted on top of the moving sledge. Fig. 9 shows an experiment with the induced “true” (black) versus the “measured” (red) displacements (15 min. solutions). The device was aligned in south-north direction. The discrepancies remain below 10 mm in general as to be seen. Two other stable Smart Antennas (blue, green) in the neighbourhood are depicted additionally.

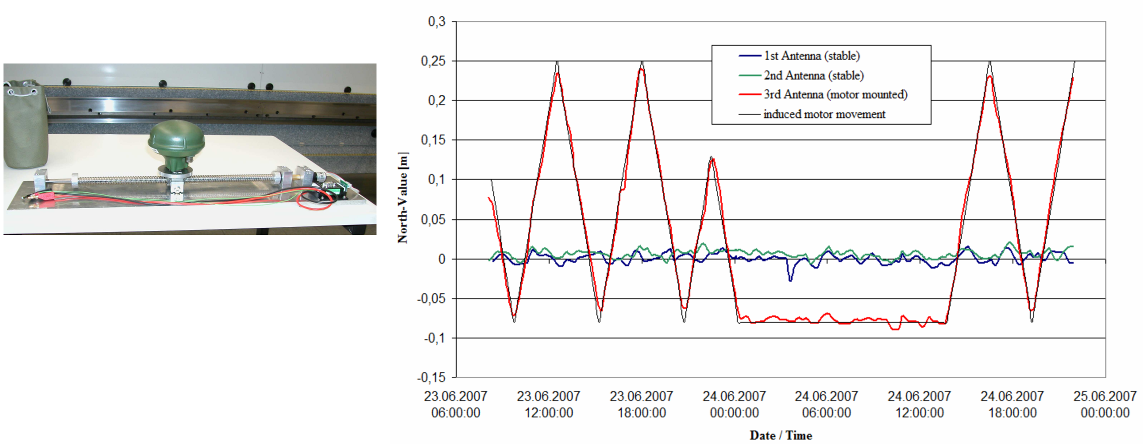

Fig. 9 - Motion device (left) and comparison “true” vs. “measured” displacements (right)

5. TEST SITES IN THE TYROLEAN AND BAVARIAN ALPS - OUTLOOK

To get more experiences two test sites are established at the Tyrolean Alps (operable since summer 2007) and at the Bavarian Alps (operable since spring 2008). The baseline lengths in Austria are about 2.1 km with height differences of nearly 800 m between the reference point in the valley and the two object points at the slide (Fig. 10). Presumably due to systematic troposphere effects and signal obstacles the accuracy decreases in comparison with the test scenarios in Munich, but cm-level still is possible. Operation during winter with approx. 1.5 m of snow was no problem.

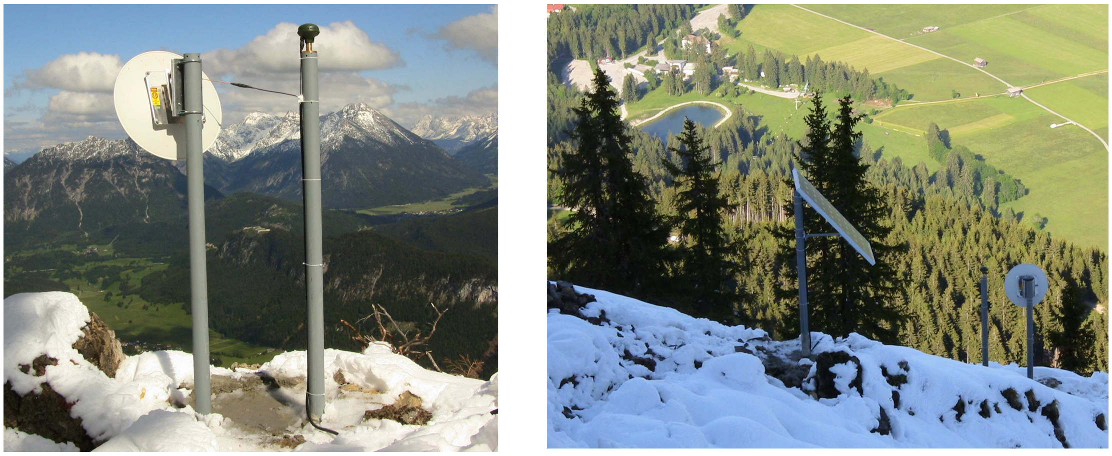

Fig. 10 - Impressions from the Tyrolean Alps near Reutte at an altitude of approx. 1700 m: GNSS sensor nodes equipped with Novatel Smart Antenna, WLAN beam antenna and solar panel.

At the second test side Sudelfeld in Bavaria the comprehension of the GNSS monitoring component into a widespread geo sensor network is one of the tasks of the project alpEWAS (alpine Early WArning System). The other instruments to be included are temperature and humidity devices, pore water pressure units, inclinometers based on time domain reflectometry (TDR, see Singer, Thuro, 2007) and a tacheometer (TPS).

At the moment the research within GeoSN-UniBw is focussed on the application of the new V1G enclosure with Glonass option, on finding the optimal GrafNav tuning parameters for baseline processing and to archive a pervasive quality check of all computing steps at the central control application. Thus, reliability and accuracy of GeoSN-UniBw will be further enhanced.

Acknowledgment

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References

Hartinger, H. (2001): *Development of a Continuous Deformation Monitoring System using GPS.* Engineering Geodesy – TU Graz. Aachen: Shaker, ISBN 3-8265-9484-3

Jäger, R., Bertges, M. (2004): *Integrierte Modellbildung zum permanenten Monitoring von Bauwerken und geotechnischen Anlagen.* Interdisziplinäre Messaufgaben im Bauwesen – Weimar 2004. DVW Schriftenreihe Band 46, pp. 101-139

Kotthoff, C. (2008): *Planung, Installation und Erprobung einer GNSS-gestützten Überwachungskomponente im BMBF-Projekt alpEWAS.* Diploma Thesis, University of the Bundeswehr Munich (not published)

Pink, S. (2007): *Entwicklung und Erprobung eines multifunktionalen Geosensornetzwerkes für ingenieurgeodätische Überwachungsmessungen*. Schriftenreihe Studiengang Geodäsie und Geoinformation Universität der Bundeswehr München, Heft 83

Retscher, G., Moser, R. (2001): *Untersuchung und Vergleich von Local-Area- und Wide-Area-DGPS-Diensten.* Allgemeine Vermessungsnachrichten, Vol. 10, pp. 341-351

Schuhbäck, S. (2007): *Geodätische Überwachung der Massenbewegung am Hornbergl bei Reutte/Tirol*. Diploma Thesis, Technical University Munich (not published)

Singer, J., Thuro, K. (2007): *Monitoring mit Time Domain Refectometry (TDR).* In: Brunner (ed.): Ingenieurvermessung 07, Graz April 17th – 20th 2007, Wichmann Heidelberg, pp. 259 - 270

Sohraby, K., Minoli, D., Znati, T. (2007). *Wireless Sensor Networks – Technology, Protocols, and Applications.* New York: John Wiley and Sons, ISBN 978-0-471-74300-2

Waypoint (2007): *Waypoint Product Group. GrafNav / GrafNet User Guide.* Publication Number OM-200000105

Corresponding author's contact

Otto HEUNECKE
Otto.Heunecke@unibw.de
Institute of Geodesy, University of the Bundeswehr Munich,
Werner-Heisenberg-Weg 39, D 85577 Neubiberg
Germany