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Landslide Monitoring Using Low Cost GNSS Equipment – Experiences from Two Alpine Testing Sites

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Abstract: Simple GNSS navigation receivers, developed for the mass market, can be used for positioning with sub centimeter accuracy in a wireless sensor network if the read-out of the carrier phase data is possible and all data is permanently broadcast to a central computer for near real time processing of the respective base lines. Experiences gained in two research projects related to landslide monitoring are depicted in terms of quality and reliability of the results by the developed approach. As far as possible a modular system set up with commercial off-the-shelf components, e.g., standard WLAN for communication, solar batteries with solar panels for autarkic power supply and in cooperation of existing proofed program tools is chosen. The challenge of the still ongoing development is to have a flexible and robust GNSS based sensor network available – concerned not only for landslide monitoring in future.

Key words: Early warning systems, geo sensor networks, low cost precise differential GNSS, near real time processing**.**

1. Introduction

In context of global climate change, increasing tourism and the ongoing extension of settlements and infrastructure projects in many alpine regions a tightened conflict between land use and natural hazard prevention can be observed. However, awareness has risen considerably in the past and hazard mapping programs to identify all critical sites are performed. At the Bavarian Alps singly there are about 2.000 slides declared by the responsible authorities. Only few of them prone to failure at the moment but may be activated in future.

No doubt, exclusive, proven and pricey geodetic and geotechnical instrumentation for landslide monitoring tasks is available as well as for surface and subsurface deformations and also the triggering influences like precipitation and pore water pressure. Nevertheless, due to economic reasons potentially dangerous instable slopes often are only monitored sporadically – if at all – but not continuously. Thus, early warning in case of accelerated surface movements accompanied for instance by rising pore water pressure cannot be put in execution because this requisites a permanently operable measuring system on site. In order to overcome these shortfalls more efficient automated measurement techniques are requested – worldwide. All efforts in this direction are enormously stimulated by the impact of wireless sensor network (WSN) technology.

Key indicator for stability assessment at sliding slopes and also other moving objects are usually displacements at the surface which must be determined with accuracy in the sub centimeter range – or even better – at longer time scales, generally everlasting. Application of satellite based positioning is well known since years but normally conducted using high end geodetic receivers and antennas. It will be explained that also simple GNSS equipment can be used for such demanding challenges.

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2. Geo Sensor Networks for Monitoring Tasks

A wireless – respectively with regard to phenomena in a geographical space – geo sensor network (GSN) is an infrastructure comprising measuring, computing and communication elements that gives an administrator the ability to observe and react to events and particular phenomena in a specified environment [10]. Such a network always consists of the following basic components:

- an assembly of distributed sensor nodes on site (sensor field);
- an interconnecting network (usually, but not always, wireless-based in the field);
- a central point of information clustering (central data sink, master station);
- a set of computing resources at the central point (or beyond) to handle data analysis, event trending (alert), status querying, maintenance etc.

Organizationally a sensor network is subdivided into several so called sensor nodes which – in general – operate fully autarkic. Usually senor nodes are laid-out in a multifunctional manner for the recording of different quantities, e.g., environmental parameters but also internal parameters like remaining charging voltage. Although all networked sensor nodes must have the availability of localization (relative or absolute) to attribute the observed information, in a GSN designed for monitoring the positioning device is the sensing unit of utmost importance. As monitoring is a classical task in geodetic and geotechnical engineering already many commercial system solutions today are in practice basically geo sensor networks. The basic scheme of such a centralized network is depicted with Fig. 1. Beside the communication on site Internet is commonly used for remote control, maintenance and data transfer from relocated computers optionally subdivided by access rights, e.g., for stakeholders. Often a Web server is included for data storage and distribution.

3. Low Cost GNSS System Design

Central idea of the self-developed system is the permanent broadcast of carrier phase (CP) raw data from the GNSS sensor nodes to a master station, where an automated near real time processing (NRTP) takes place [1-4]. Low cost means the utilization of simple navigation receivers with the required capabilities of tracking and read-out the CP raw data. These kinds of receivers do not need the availability of processing the augmented phased-based position by their own but must have an interface to embed the sensor in the GSN. Many of the available navigation receivers make use of the CP data for some internal smoothing operations and are commonly equipped with a serial or USB interface. For the utilization of such equipment in geodetic applications see also [6, 8].

With the here preferred "static" approach, the CP measurements have to be recorded over certain, in a principle freely selectable time span on board the node or directly at the master station. Usually, a time interval of 15 min can be considered. Beside the length of an epoch the recording frequency, e.g., 1 Hz, is to ascertain. GNSS enclosures who meet the mentioned requirements are for instance Novatel Smart Antenna and Novatel Smart-V1G Antenna, see Table 1. Their half-round shape and their environmental specifications (temperature, moisture, dust etc.) make them ideal for year-round surveillance in mountainous regions. Depending on the satellite visibility such kind of L1 receivers with a recording frequency of 1Hz generate about 0.3-0.6 MByte of binary data in a time period of 15 min.

Generally spoken, at every autarkic GNSS node about a third of the costs is the sensor, the power supply and the communication component. Beside the mentioned enclosures at Table 1 also u-blox receivers like the LEA-4T (www.u-blox.com) are already investigated [4]. With such kind of devices it seems to be possible to mount complete GNSS nodes less than €1000 in the near future.

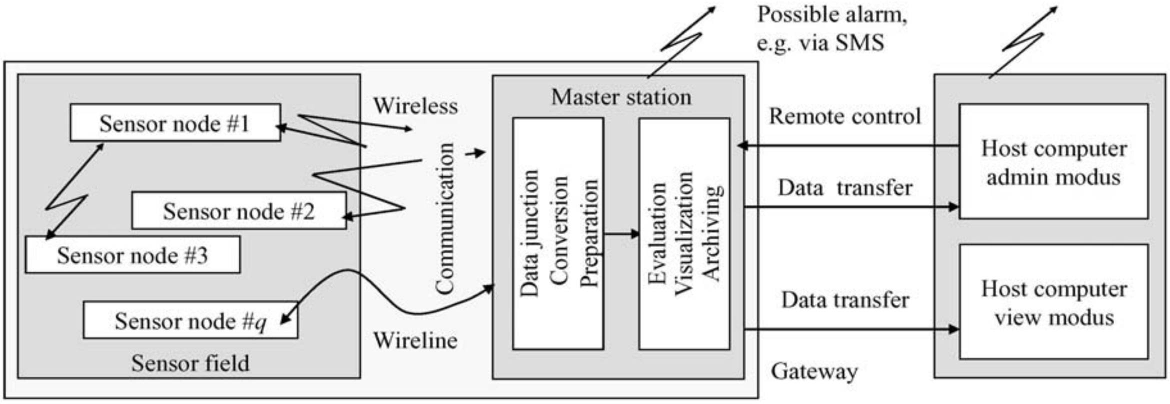

Fig. 1 Basic scheme of a centralized geo sensor network.

Table 1 Selected GNSS hardware components (specifications see data sheet information at www.novatel.com).

	**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
Weight: 575 g	Interfaces	RS-232, RS-422	RS-232, RS-422, USB
Size: 115 mm diameter	Environmental	MIL-STD-810E	MIL-STD-810F
90 mm height	Price	~ 800 €	~ 1200 €

A GNSS sensor node is presented by Fig. 2. A Novatel Smart Antenna is to be seen at right pole, the WLAN antenna and solar panel at the left pole. In front an isolated alu-box which contains the battery, charge controller and wireless device server. The height of the poles is about 2 meters due to the snow at winter.

Such sensor nodes can be combined to a monitoring network, see Fig. 3. Some nodes define the reference frame and others are at the structure in order to determine absolute displacements by the processed base lines $b_i^j(t)$. For every epoch k an independent base line solution is obtained depending on the actual satellite coverage during the day. Using 15 min intervals there are 96 solutions per day.

4. Communication and Power Management

The widespread and cost-effective deployment of a sensor network particularly needs to make use of commercial off-the-shelf (COTS) wireless communication techniques and standardized protocols. Here the transfer of data from the sensor nodes to the master station is handled by an infrastructural WLAN. Customary hardware components (e.g., bridges, wireless

Fig. 2 GNSS sensor node at Aggenalm landslide.

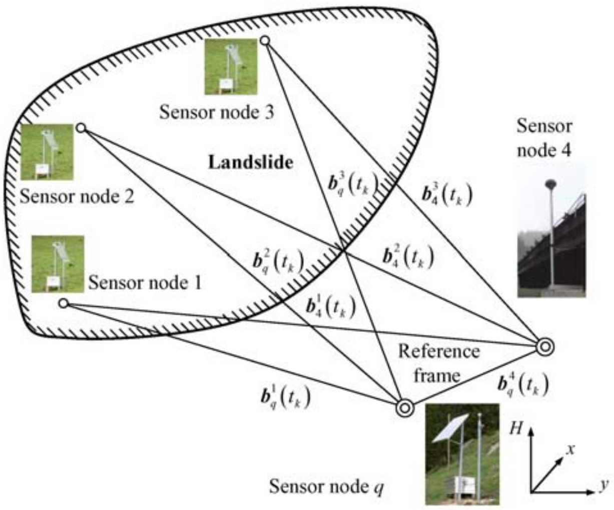

Fig. 3 Geometrical layout (monitoring network).

device servers) reach adequate data throughputs, have an easy way of addressability in the network and secure operation by codification. In terms of WSN this forms a simple star topology. Alternatively (more expensive) multi hop WLAN devices can be used if necessary. Compared to other common communication standards like conventional radio data transmission, ZigBee or Bluetooth, WLAN combines the preferences of a suitable high data rate over ranges of several 100 meters at moderate costs and energy consumption. In order to achieve comparable transfer rates over such distances special WLAN antennas have to be used. At the Hornbergl site, see sec. 6, more than 2 km have to be bridged for instance. However, a more or less free line-of-sight between the transmitters and receptors is essential.

Due to the fact that most of the COTS sensors are equipped with RS-232, RS-422 or USB a wireless device server converts the data to TCP/IP for WLAN. At the master station a bridge (access point) transforms the signals back to Ethernet. Of course wireless communication can be enhanced by Ethernet directly, e.g., if reference stations and master station are closed by. As long as there is no temporary data storage at the nodes all data have to be forwarded on-the-fly to the central data sink.

For a continuous operation of the whole system an uninterrupted power supply of the sensor nodes and the master station has to be ensured. All developed GNSS sensor nodes have a battery-operated autarkic power supply with recharge via solar panel. Additionally fuel cells are an alternative option. In an alpine environment high emphasis has to be put on the robust power supply during the whole year, considering all disadvantageous conditions as low temperatures, heavy snowfall or relatively long gaps without the opportunity of recharge. However, an autonomy factor of a few days is highly recommended when planning the battery capacities.

5. Data Evaluation

At the master station (with given 230 V power supply and Internet access) all binary data from the GNSS sensor nodes are collected and converted for an appointed base line processing. At the master station an uninterrupted power supply (USV) is as much important as secure data storage (mirroring on second hard disks or similar). The developed Central Control Application (CCA) written in LabView®, National Instruments, is the core element of the system, see Fig. 4. Subprograms, e.g., sensor activation are termed as virtual instruments (VIs) and a modular, prospective design offers to integrate a great diversity of GNSS sensors already. For base line processing the universal package GrafNav Waypoint (see www.novatel.com) is integrated so far. From any embedded software tool a command line based control is the essential requirement. At the end of every loop a new set of base lines are disposable for a subsequent analysis of the emerging 3D time series. The processing results including stochastic information are provided in ASCII format and stored in an open data base. Thus, any software for time series analysis and visualization can be adopted easily.

In comparison with the ordinary RTK modus using high end receivers a lot of possibilities are given applying the NRTP approach. It is for instance up to

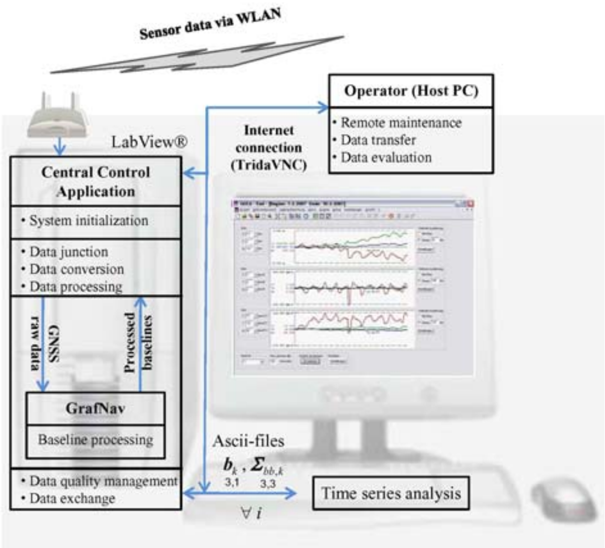

Fig. 4 CCA data flow.

the administrator to determine which sensor node serves as a reference station and which as an object point on the structure, see Fig. 3. Main advantage is given by the recorded meta information on used satellites and signal to noise ratio (S/N). Finally, all the well-known options of high sophisticated post processing in a geodetic monitoring network adjustment are possible and, nevertheless, the approach is not restricted to low cost receivers solely. Also high end equipment, if available, can be combined.

6. Experiences from Two Alpine Testing Sites

6.1 Project Aggenalm Landslide

At the Aggenalm landslide, the test site of the alpEWAS project ("Development and testing of an integrative 3D early warning system for alpine instable slopes"; see www.alpewas.de) in the Bavarian Alps, the low cost GNSS devices are integrated in a multifunctional sensor network together with other automated monitoring techniques (e.g., time domain reflectometry in boreholes). Beside the development of new measuring techniques the goals of the project were to design a comprehensive data base and to make a quantitative assessment of the causal and temporal relation between landslides movements and its triggers.

In the following only results of the developed low cost GNSS system will be discussed in terms of quality and reliability but no interpretation with respect to the state of slope stability is made. For a description of the geological situation at the Aggenalm refer to [9, 11, 12].

Fig. 5 shows the Aggenalm area (about 1050 meter above sea level) with node #4 as reference station and three nodes on the slope. The master station is installed in a hut near #3. Monitoring started beginning of 2009 and since then the system works fairly well. The base line lengths are about 500 meters, but the quality of base line solutions is constraint by the surrounding mountain ridges (mainly in the south) and resulting diffraction effects [5], especially during arise and go down of satellites. At node #1 (upper abridgement) additionally some trees are obstacles.

Limitation to only $q = 4$ GNSS sensor nodes debts due to the research budget but does not handicap the methodic investigations. The functionality of the system suffers mainly from the harsh environmental conditions in the Alps with more or less 6 month of snow, sometimes up to 1.5 meter. Problems with the autarkic power supply lead to break downs of sensor nodes temporarily. The worst case scenario–which already occurred–is completely snow covered GNSS and WLAN antennas for days.

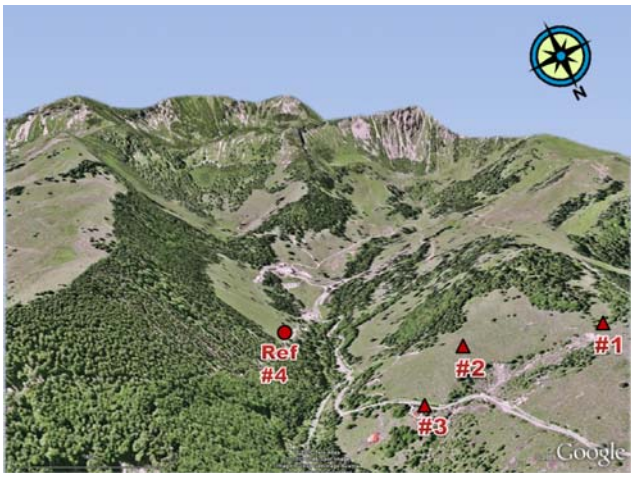

Fig. 5 Perspective view on the location of the sensor nodes at Aggenlam with shadowing situation due to mountain ridges.

Table 2 separates between disposable and exploitable base line solutions at Aggenalm in June 2010. Malfunctions with power supply and the communication in the field are reasons for deficits in disposability. Restricted satellite coverage then lead to further shortfalls in the base line processing with no satisfactorily results. Especially at node #1 quite a few solutions are neglected by the automated quality management of the system. Finally during this month standard deviations for plane coordinates of 3.2 mm and 6.7 mm for the height component are achieved (mean values). Applying moving average (MA) filtering to reject outliers and to bypass gaps the accuracy can be improved. By a MA filter of 6 hours for instance, according to law of error propagation the standard deviations should be 20% of the indicated amounts of Table 2.

The progression of surface displacements at sensor node #2 is depicted by Fig. 6, which also gives an impression on the quality of the obtained results (some gaps due to malfunction are to be seen). In two years there are nearly 3 cm of movements in slope direction. A detailed view allows the identification of increased movements during snowmelt (especially in 2009, whereas winter 2010 was rather dry) and periods of intensive rain in summer (see Fig. 7). For early warning purposes of course shorter latency than a 6 hour filter is to recommend which demands for a better data quality in future, however.

Table 2 Reliability and data quality June 2010 at Aggenalm.

Base line	Solutions		Empirical standard deviation of epoch	
	Disposable %	Exploitable %	plane (mm)	height (mm)
b_{ref}^{1}	88.4	58.9	4.8	8.6
b_{ref}^{2}	82.3	72.3	2.8	6.6
b_{ref}^{3}	91.8	84.3	2.0	5.0

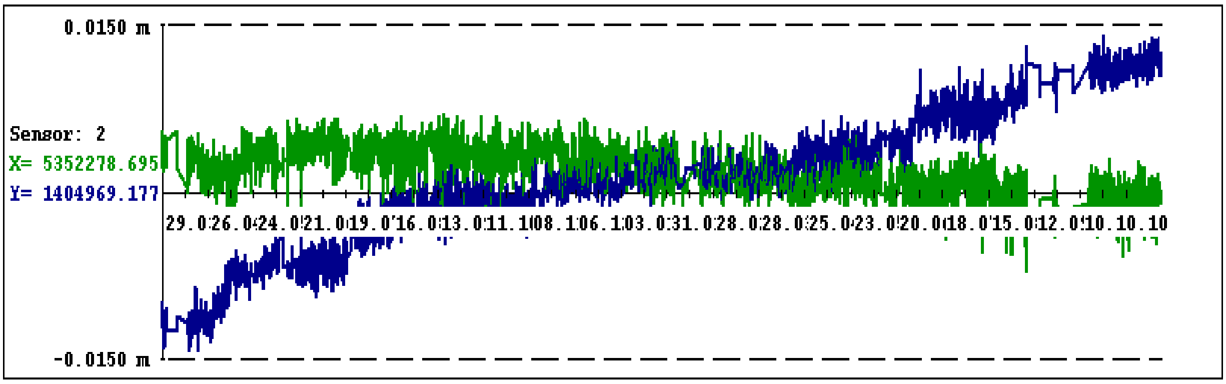

Fig. 6 Plane coordinates (Y – easting – is approximately slope direction) at Aggenalm, sensor node #2 from March 2009 to October 2010. MA filter of 6 hours.

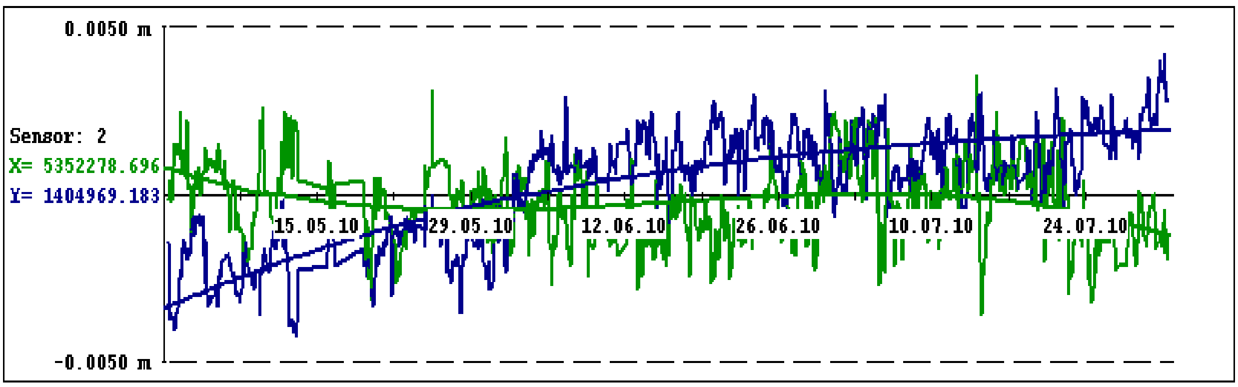

Fig. 7 Plane coordinates at Aggenalm during a heavy rain period, sensor node #2 from May 2010 to July 2010. MA filter of 6 hours.

6.2 Project Hornbergl

The second test side is Hornbergl Mountain in the Tyrolian Alps. Since more than 20 years the deformation process is observed by periodic geodetic measurements in addition to manifold geological examinations [7]. For a brief treatment of the Hornbergl geology [2]. The verification of the direct effect of external influences like heavy rainfall and snowmelt in springtime on the deformation process and its potentially accelerated movements was not possible satisfactorily with the manually performed methods so far. Therefore an online low cost GNSS monitoring system was installed in summer 2007.

Two autarkic sensor nodes #1 and #2 are situated at about 1700 m above sea level (see Fig. 8) at critical regions of the slope and have direct line of sight to the base station which is located at the old cable car station in the valley (900 m above sea level, stable area).

The base line lengths are about 2 km. Like in the previous described project the quality of base line solutions is negatively influenced by broad obstructions in places which are conditional to the location of the sensor nodes made with regard to geological needs preferentially and not alone to satellite visibility aspects. Worse conditions in combination with longer base lines lead to slightly declined results in Hornbergl project compared to Aggenalm landslide. Table 3 shows the quality of the base line solutions in the project. As to be seen the total amount of disposable solutions reaches almost the optimum. Because no malfunctions in this period were detected the missing solutions exactly correspond to the number of not computable solutions due to very bad visibility conditions, e.g., not enough satellites in an epoch at all. Standard deviation for plane coordinates of 5.5 mm and 12.7 mm for the height component were achieved (mean values). The higher value for the height component mainly bases

Fig. 8 Hornbergl landslide with marked sensor nodes.

Table 3 Reliability and data quality June 2010 at Hornbergl.

Base line	Solutions		Empirical standard deviation of epoch	
	disposable %	exploitable %	plane (mm)	height (mm)
b_{ref}^{1}	97.3	63.4	5.3	12.9
b_{ref}^{2}	98.4	66.0	5.6	12.4

on the altitude difference between the object points on the mountain and the reference station in the valley. There are approx. 800 m difference at Hornbergl and approx. 120 m at Aggenalm.

The progression of surface displacements at sensor nodes #1 and #2 is depicted by Figs. 9-10 (time series filtered by a MA filter of 12 hours), which also gives an impression on the quality of the obtained results (some gaps due to malfunction are to be seen again). The seemingly higher noise of the time series of #1 results in a different scaling of both graphics in order to display the whole movement. In the years 2009 and 2010 sensor node #1 has a totally displacement of 5 cm and #2 even has a displacement of 32 cm in horizontal direction. A detailed view to the figures shows phases of rising and phases of decreasing movement rates.

At the moment the self-developed CCA is enhanced in a way to remove automatically faulty phase measurements caused by diffraction effects before base line computing on the basis of the tracked signal to noise ratio of the satellites' signals.

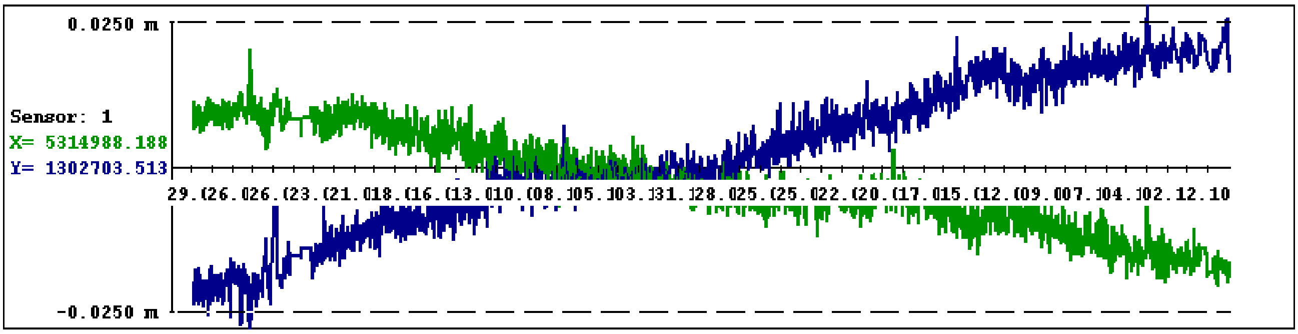

Fig. 9 Plane coordinates at Hornbergl, sensor node #1 from January 2009 to December 2010. MA filter of 12 hours.

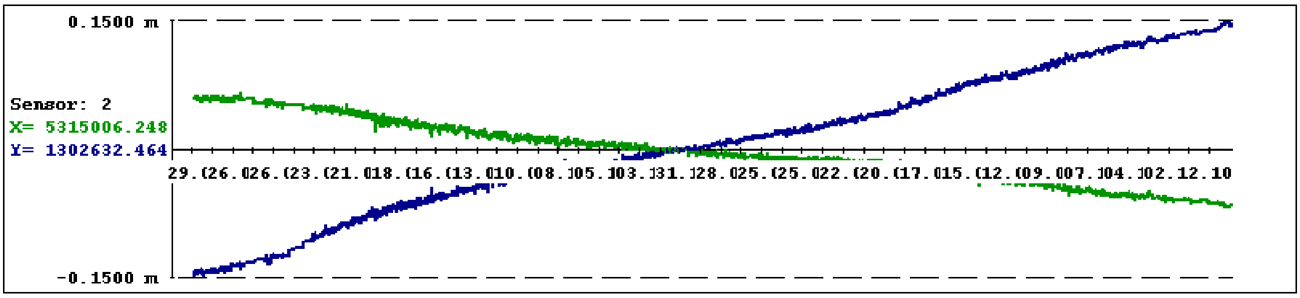

Fig. 10 Plane coordinates at Hornbergl, sensor node #2 from January 2009 to December 2010. MA filter of 12 hours.

7. Conclusions

The practicable application of low cost GNSS equipment for landslide monitoring is proofed in two research projects already. Although accuracies in the millimeter range are obtained which can be compared nearly with ordinary tacheometric measurements, the full potential is not exploited yet. Recently the focus is made on a more sophisticated modeling and data handling. To archive a better and reliable early warning capability of such systems further developments still are requested but promising. At the moment a first system set up at a ship hoist during reconstruction is executed for structural monitoring reasons.

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