Permanent, autonomous monitoring of landslide movements with GPS

L. Manetti, M. Frapolli, A. Knecht
GEODEV Earth Technologies SA, CH-6928 Manno, Switzerland

ABSTRACT: The falling tendency of precision GPS receiver equipment pricing and their miniaturization, along with their decreasing power requirement, spurred a product development project addressing the remote monitoring of small movements as found in landslides, landslips or earth settlements as well as structures such as buildings, dams or bridges. The system consists of a number of small receivers installed on the object to be monitored. A control center provides for data collection, post-processing, and monitoring for correct operation of the network. Depending on the application, the communication between the single remote receivers and the control station can employ a radio link, cellular modem, or a cable. Ancillary sensors such as distance meters, pluviometers, or inclinometers may be added to the single receiver units. The equipment itself needs no maintenance, and fitting it with an accumulator and a solar panel enables autonomous operation over extended periods of time. The control center may be programmed to initiate special actions when relative position differences or the velocity of movement are found to be over a certain pre-set limit.

1 INTRODUCTION

1.1 *Background*

GPS technology is widely used in navigation and tracking, and has become an established technique in geodesy and surveying where it can provide position information with accuracies to a few millimeters. The measurement principle works worldwide, continuously and under all meteorological conditions, and therefore holds promise as a way to monitor the movement of land masses and structures. Successive generations of GPS receiver modules have seen a constant diminution of size, power consumption and cost. This allows to build sizeable networks of autonomous GPS measuring stations with a relatively modest investment.

1.2 *Paper organization*

This paper is organized as follows: In chapter 2 the functional principles of precision GPS measurements are briefly reviewed; in chapter 3, the background and motivation for the research and development is presented; in chapter 4, the system architecture is outlined. The main elements are described, and the aspects of communication infrastructure and measurement database management are examined. Also, the capabilities for remote configuration and alarm management are described. Chapter 5 presents the achievable precision of the resulting system and lists its inherent limitations. Finally, chapter 6 and 7 present conclusions and discuss future research and development activities.

2 FUNCTIONAL PRINCIPLES

2.1 *Code phase positioning*

GPS positioning is based on measuring the transit time of radio signals emitted by orbiting satellites. For a receiver to compute its stand-alone position, it must be in view of at least four satellites. Code Phase Positioning is widely used in navigation and low-precision tracking applications, and relies on the measurement of the modulated GPS signal code phase which exhibits a resolution of about 1m. The measurement is affected by several perturbations which bring the achievable precision to about 5-10m [1].

2.2 *Carrier phase positioning*

Another GPS measurement principle can bring the precision down to the order of millimeters, and is therefore suited to applications in surveying, geodesy as well as earth and structural monitoring. As illustrated in Figure 1 the separation between two receiver antennas at the ends of a baseline is measured (the first antenna is fixed, while the second is part of the object to be monitored) by measuring the total carrier phase delay between the two GPS signals arriving at the respective antenna locations. Using this method, the theoretical spatial resolution is a small fraction of the GPS signal carrier wavelength (~19cm). Unlike the stand-alone position solution, this method results in a differential position measurement. Since at the first instance of achieving carrier track, the total phase delay between the measurements seen at both receivers is unknown, the integer quantity representing the number of whole cycles needs to be found. This is called *initial integer ambiguity*, and solving it requires the observation of phase measurements over a period of time.

Precise static positioning using carrier phase differential GPS involves forming double differences to eliminate most errors common to both receivers, and integrating the measurement over time. The method thus requires collecting and post processing a relatively large amount of data, a sufficient amount of computing resources, and is by definition non real-time.

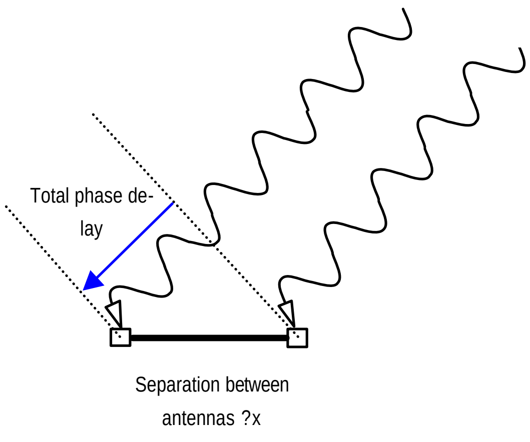

Figure 1. Differential carrier phase measurement principle

3 MOTIVATION AND OBJECTIVES

The work described in this paper is based on a research project at the University of Applied Sciences of Southern Switzerland’s ICIMSI institute.

The first specific objective of this project was to demonstrate the technical and commercial feasibility of using self-contained, low-cost single-frequency GPS receivers in differential carrier phase mode to solve a class of movement monitoring problems with reasonably high accuracy, for applications in buildings, dams, bridges, but also landslides and rock formations where movements are relatively slow. The second objective was to define a system architecture which could form the basis of a product line for structural and geotechnical monitoring.

The system was to fulfill the following general requirements:

- modular architecture
- connectivity via internet
- ease of installation, configuration and maintenance.

The equipment had to meet rather stringent cost objectives for the system as a whole, but most important for the single sensor units. In fact, it has been recognized that one of the factors of hindrance to the widespread use of movement monitoring with GPS is the cost of the remote sensor. An initial cost target was defined. Technically, the single remote sensor had to fulfill the requirements of

- compact size
- robustness and resistance to extreme environmental conditions
- autonomy from the power supply network, and finally
- freedom from maintenance and on-site intervention.

4 SYSTEM ARCHITECTURE

The system is called MMS for *Movement Measurement System*. It consists of a number of small mobile GPS receiver units (measurement stations) installed on the object to be monitored, plus one or more reference receivers installed at fixed, possibly surveyed locations around the object. The reference receiver units are identical to the mobile receiver units in every respect. Depending on the application, measurement stations are individually linked to a common control center by a cable, a radio link or a cellular modem. The control center provides for data collection as well as monitoring for correct operation of the network. It is remotely accessible through a dedicated communication channel, including an internet dial-up connection.

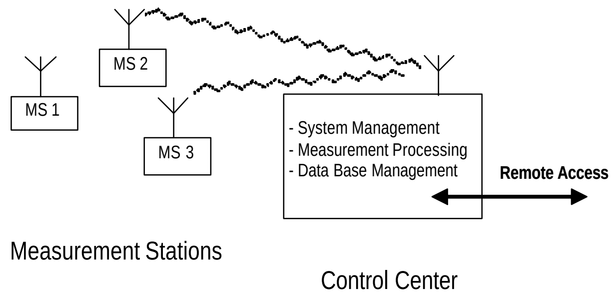

Figure 2. System block diagram

Every measurement station will collect GPS observation data for a sufficient amount of time, and the data will be transmitted to the control center for post-processing. The control center has the task of collecting the data from all receivers in the network while overseeing the single measurement stations for correct operation. The data from all measurement stations will be processed together, and the result will consist of the relative position of the various moving measurement stations with respect to the reference measurement stations.

4.1 *Remote sensors*

A measurement station consists of GPS receiver, a communication transceiver, an ancillary data acquisition unit, and a power supply management unit. A central processing unit oversees overall operation and schedules measurement and communication tasks. Figure 3 is a block diagram of the sensor unit. All electronic subsystems are mounted in an environmentally sealed enclosure.
The GPS receiver is a single-frequency receiver module characterized by low power consumption and good sensitivity. Since the stability of the local

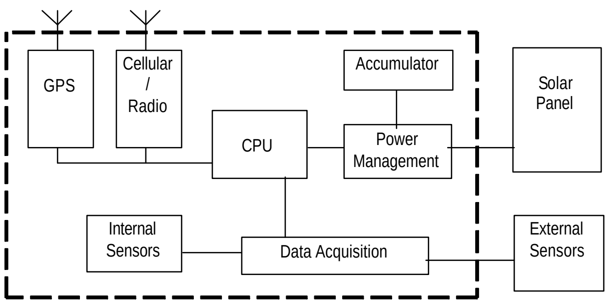

Figure 3. Measurement station block diagram

receiver reference clock is a factor influencing the precision of the carrier phase measurement, a high-quality clock source has been selected.
Ancillary sensors such as inclinometers, pluviometers, distance meters etc. may be added to the single stations where desired. To this purpose, the measurement station is equipped with three additional analog input ports and two digital input ports. As part of the initial station configuration, these additional measurement channels may be defined in terms of measurement interval, scale and resolution. When the equipment is in use, measurements from the ancillary sensors are synchronously logged and transmitted to the control center on demand. A spare RS-232 serial port is also provided for connection to an "intelligent" external sensor such as a laser distance meter.
A CPU runs a real-time operating system and a multi-task program written in standard "C". The program oversees the operation of the whole measurement station, manages the data acquisition and implements the communication protocols. Activation and deactivation of the single subsystems is sequenced according to the configuration. Care has been exerted in developing the program to reduce power consumption of the measurement station to a minimum. The CPU spends most of the time in a "doze" state with very low power consumption, and periodically wakes up to attend to measurement or communication tasks.
An important requirement is the ability for the measurement stations to operate for extended intervals in total autonomy and without requiring on-site human intervention. Fitting each station with an accumulator and a solar panel enables autonomous operation over extended periods of time, while the unit itself is essentially maintenance-free.

4.2 *Control center*

The control center consists of a rack-mountable industrial computer with standard equipment. The software is divided into three main components: measurement station manager, baseline processor, internet server. The measurement station manager communicates with the measurement stations and logs any sensor or link malfunction. Raw GPS measurement data is received from the remote measurement stations and stored in local memory. The baseline processor is responsible for post-processing the raw measurement data. The data is processed in batch, and the result consists of the positions of the various moving sensors relative to the reference sensors. The control center may optionally be equipped with an uninterruptible power supply (UPS) to bridge power brownouts or blackouts. A local, standard precision GPS receiver serves to download satellite visibility data (the almanac).

4.3 *Communication infrastructure*

When in operation, the system follows a repetitive sequence of phases of measurement, communication and processing. As illustrated in Figure 4, a measurement phase by the remote measurement stations coincides with the processing of data from the previous measurement phase by the control center.

The actual method of communication between measurement stations and control center may differ depending on the geographic location and the specific requirements of the monitoring project.

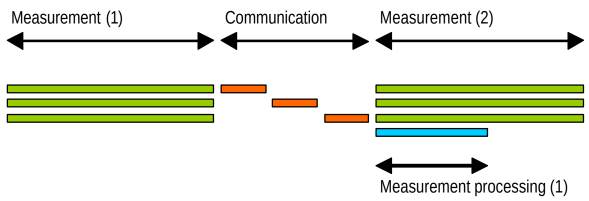

Figure 4. Operating sequence of Measurement stations and Control Center

Where a cellular telephone infrastructure is available and the application is uncritical in both timing and security level, a connection over a cellular modem is ideal. Examples are the long-term, weekly monitoring of a land subsidence, or the daily measurement of a breakwater protection structure. A radio link preferably using an ISM band is a good choice when the application is such that independence from existing telecommunication infrastructures is desirable or essential. This may be the case for landslide or mudslide monitoring, where the same or a possibly unrelated catastrophic event may cause overload or disruption of the cellular telephone infrastructure, thus rendering the monitoring and surveillance system unusable when its operation is needed most. With an ISM radio link, the cost of a single communication is negligible compared to the cellular solution, but the necessary equipment investment may be higher when distances over several km must be bridged between the measurement site and the base station, requiring the installation of radio relay stations. As a third possibility, a fixed cable connection between measurement sensors and base station may be feasible where the distances involved are relatively short and the measurement environment is well controlled. Examples are small hydroelectric dams or constructions. Irrespective of the actual nature of the physical data link, the communication protocol used between control center and sensors is always the same, and for this reason the different link types may be used interchangeably.

In principle, all elements of a monitoring network may be accessed either locally or remotely from any part of the world. This eases remote diagnostics, as well as applications where more than one network needs to be monitored from a centralized location.

4.4 *Measurement database*

Given a project that involves many objects to be permanently or regularly monitored, the tasks of assuring the long term management of the large volume of measured data and the short term and dynamic sensor configuration can quickly become problematic. For this reason, as part of the development of the movement measuring system, a standard database structure has been defined and implemented. The purpose is to dispose of a standard and flexible structure to be used with general measurement and monitoring projects using different systems and sensors. The data model defines, for the scope of a given project, all relevant entities and their relationships. It is therefore organized upon three layers: a measurement-specific layer, a configuration layer and a system-specific layer.

The model and database structure are designed to fulfill the requirements of a range of remote monitoring tasks, and the structured access to the database guarantees independence from a particular hardware or software manufacturer.

4.5 *Remote access and configuration*

All important visualization and configuration functions may be effected at the control center, or remotely with a browser. This is particularly convenient in cases where more than one object must be monitored from a single location. This scheme also allows for remote diagnostics and troubleshooting of the system, with benefits of timeliness and cost.

The system software residing in the control center takes full advantage of the Java programming language, and the intrinsic ability of a Java program to be run either locally, or downloaded from an arbitrary location and activated as an applet.

The main view of the monitoring process is the movement screen, shown in Figure 5.

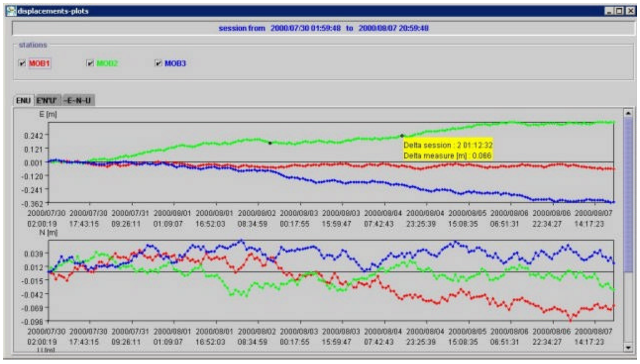

Figure 5. Movements in three dimensions are plotted on the movement screen

The measurements of three-dimensional movements may be tabulated or plotted in relative or cumulative terms. Data from single sensors may be included or excluded from the visualization, and movements may be visualized over particular time intervals.

The system configuration screens allow to define sensor parameters, measurement timing and intervals, alarm setup, and ancillary sensor activation. Of particular interest is the satellite visibility simulation screen.

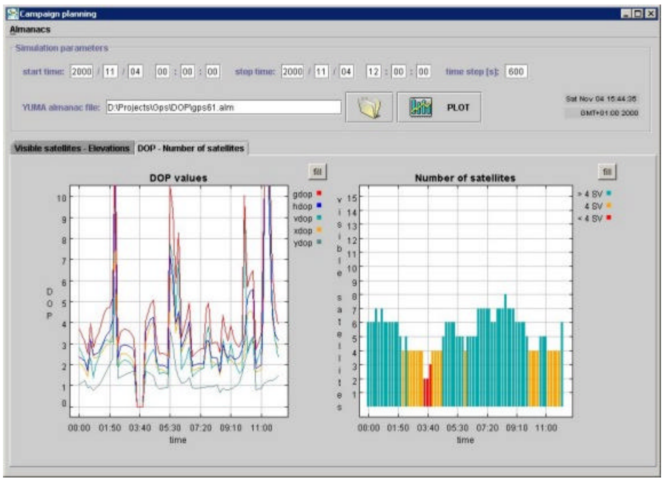

Figure 6. Satellite visibility prediction screen

This screen, shown in Figure 6, can be used as an aid in achieving the best possible measurement precision, when planning the measurement timing and intervals. Based on the effective horizon at the measurement site and on the GPS satellite orbit predictions which are downloaded by the GPS receiver local to the control center, the satellite visibility screen displays a measure of the expected quality of position measurements at a given time in the future.

Figure 7. Sensor configuration window

The sensor configuration screen, also shown in Figure 7, allows to configure operating parameters of a single measurement station. Parameters include the approximate initial position of a sensor and the communication link to be used. Here the sensor can be defined to be either moving, or to be used as a reference.

5 PERFORMANCE AND LIMITATIONS

5.1 *Performance*

Based on a number of tests involving separations between measurement stations ranging from 0 to about 10Km, and observation times from 12 to over 30 min, the basic precision achievable with the present system can be budgeted as 7 mm ± 1.5*(baseline length in km) in the horizontal plane. Due to the satellite geometry, precision in the vertical plane is slightly degraded. The influence of the baseline length on measurement precision is due to the differing influence of troposphere and ionosphere on the refraction of the GPS signals traveling to the two receivers. Since the GPS receivers used are of the single frequency type, there is no practical means to appropriately model or measure this influence and to compensate for it.

5.2 *Limitations*

The visibility and geometry of the satellite constellation during observation periods has a direct influence on the measurement quality. This may be of concern in applications where the sky view of the concern in applications where the sky view of the single sensors is significantly obstructed by e.g. trees, high constructions or mountainous terrain.

An important limitation on possible uses of the described system is due to the non real time nature of the measurements. This factor effectively excludes the monitoring of objects for oscillatory movements. On the other hand, this may be an advantage in some applications since for the same reason the system is tolerant of oscillations or vibrations at the centimeter level, integrating possible oscillations over the observation period.

A second limitation stems from the time delay of approximately 20 minutes between the actual observation and the availability of the measurement, thus lengthening the time to a possible warning or alarm report.

6 FUTURE DEVELOPMENTS

While the monitoring system described in the paper may be effectively used in many practical applications, a number of refinements and further developments are possible and indeed foreseen. An important further development will allow the system to be used for real-time monitoring, based on the property of the measurement principle that once a static measurement has been taken, relative movement is seen as an additional change in the signal phase. An interesting area of further activity would focus on the development of algorithms for warning and alarm generation. Lastly, the sensor module can be re-engineered with the objectives of reducing both size and power consumption. This in turn would bring any desirable combination of the following benefits: smaller accumulator, smaller solar panel, and increased autonomy to bridge periods with no or little sunshine.

7 CONCLUSIONS

Using Global Positioning System technology to provide differential position information with sub-centimeter level accuracy in structural and land monitoring applications was investigated. A project has been described where a network of low-cost GPS sensors, a base station with a standard database definition and a flexible communication structure concur do define a system suitable for many integrated movement monitoring tasks. The single software elements of the system were described with an emphasis on the remote configuration and visualization programs. The results presented in this paper indicate that a base precision of less than one centimeter is achievable in many practical monitoring situations.

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9 REFERENCES

1. Hofmann-Wellenhof, B., Lichtenegger, H., & Collins, J. GPS Theory and Practice. Springer Verlag, Wien New York, fourth, revised edition 1997.
2. Seeber, G., Satellite Geodesy: Foundations, Methods, and Applications. Walter Gruyter, Berlin New York 1993.
3. Leick, A., GPS Satellite Surveying. John Wiley and Sons, Inc., New York, 2nd edition 1997.
4. Lowry, A. & McLeod, R., PMos: A real time precise DGPS continuous deformation monitoring system, SAGEM Australasia Pty Ltd, 1997
5. Behr, J., SCIGN-USGS, Hudnut, K., King., N., USGS, Monitoring Structural Deformation at Pacoima Dam, California Using Continuous GPS, 1997
6. Hyzak, M., Tucker, C., Duff, K., GPS Networks for Structural Monitoring: From Highway Bridges to Mach 10 Rails, Applied Research Laboratories, University of Texas at Austin 205 1997
7. Manetti, L., Knecht, A. Permanente und autonome Erdrutschüberwachung mit GPS, Mensuration, Photogrammetrie, Génie Rural, N° 7, 2000, Switzerland