Using GPS in structural health monitoring

A.Knecht, L.Manetti
Computer Integrated Manufacturing Institute
University of applied sciences of southern Switzerland (SUPSI), CH-6928 Manno, Switzerland

ABSTRACT

Global Positioning System technology can provide position information with accuracy to a few millimetres in near real-time. Thanks to this level of precision, the movement of structures can be monitored. The falling tendency of GPS receiver pricing and their miniaturisation, along with their modest power requirements spurred a research and development project at SUPSI which resulted in a prototype system, deemed interesting for a number of applications.

It is shown that using carrier phase differential GPS, a network of receiver modules can be installed in order to perform monitoring and surveillance operations for small movements. Typical applications for this type of sensor network include monitoring of structures such as buildings, dams, bridges, as well as measuring the movement of landslides and rock formations.

The system consists of a number of small receivers installed on the object to be monitored. A radio-linked base station provides for data collection, post-processing, and monitoring for correct operation of the network. Ancillary sensors may be added to the single receiver units and their measurements synchronized to the positional measurements.
The base station may be programmed to initiate a warning or alarm action when absolute position differences or the velocity of movement exceed a pre-set limit.

Keywords: GPS, Navstar, satellite, structural monitoring, movement monitoring, landslide

1. INTRODUCTION

GPS technology is widely used in navigation, and has become an established technique in geodesy and surveying where it can provide position information with accuracies to a few millimetres. The measurement principle works worldwide, continuously and under all meteorological conditions, and therefore holds promise as a way to monitor the movement of 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.

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 is presented; in chapter 4, the system architecture is outlined. The main elements are described, and the aspects of communication infrastructure and 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

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. This method is widely used in navigation applications. It relies on the measurement of the 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 20-50m [1].

Another GPS measurement principle can bring the precision down to the order of millimetres, and is therefore suited to applications in surveying, geodesy 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 may be 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.

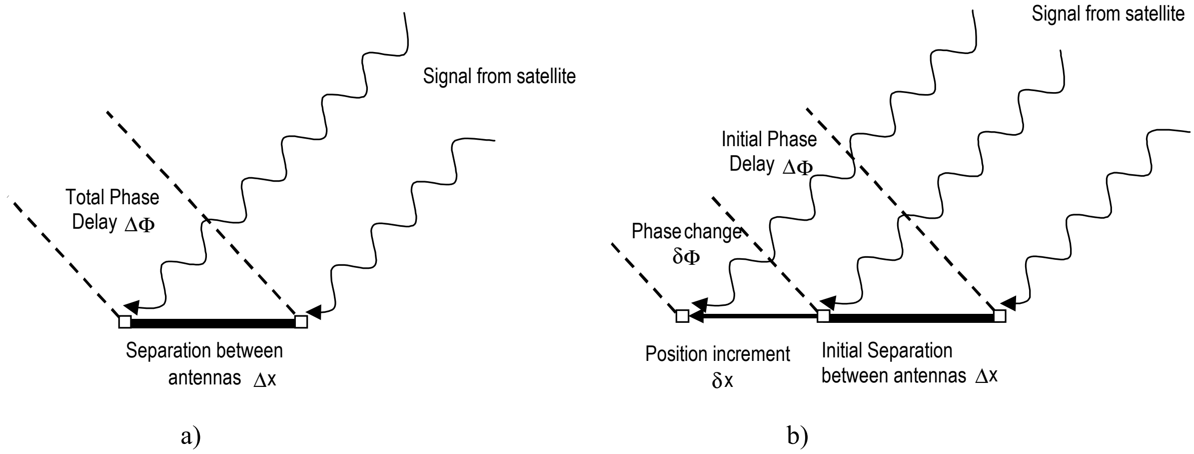


Figure 1: Separation between two GPS antennas is measured from the total phase delay between the received carrier signals.

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 postprocessing a large amount of data, a sufficient amount of computing resources, and is by definition non real-time.

3. MOTIVATION AND OBJECTIVES

The work described in this paper has been carried out at the University of Applied Sciences of Southern Switzerland as a multidisciplinary collaboration between the Institute for Computer Integrated Manufacturing, ICIMSI, and the Department of Civil Engineering and Architecture, DCT.

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: a) modular architecture b) connectivity via internet c) 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 a) compact size b) robustness and resistance to extreme environmental conditions, c) autonomy from the power supply network, and finally d) freedom from maintenance and on-site intervention.

4. SYSTEM ARCHITECTURE

The system consists of a number of small mobile GPS receiver units (sensors) 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, remote units are individually linked to a base station by a cable, a radio link or a cellular modem. The base station provides for data collection, monitoring for correct operation of the network. It is remotely accessible through a dedicated communication channel, including an internet dial-up connection.

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

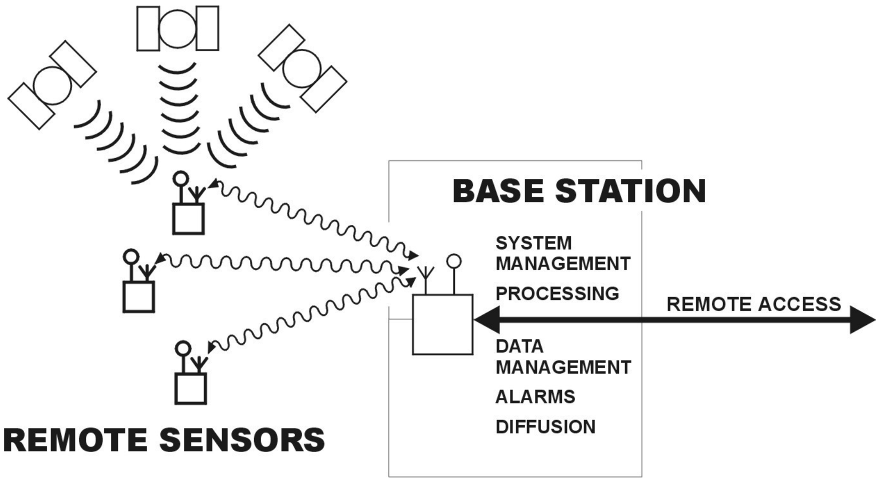


Figure 2: Monitoring system overview

REMOTE SENSORS

A remote sensor 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. Fig. 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 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 accelerometers, inclinometers, pluviometers etc. may be added to the single stations where desired. To this purpose, the unit 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 base station on demand. A spare RS-232 serial port is also provided for connection to an "intelligent" external sensor such as a laser distance meter.

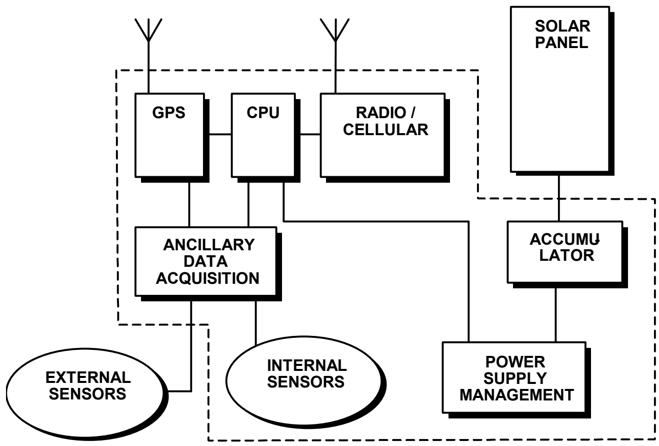


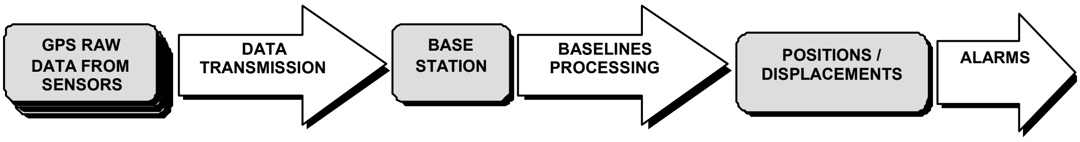
Figure 3: Sensor unit block diagram.

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 sensor, 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 sensor unit 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 measuring units 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.

BASE STATION

The Base Station consists of a rack-mountable industrial PC with usual equipment. The software is divided into three main components: remote sensor manager, baseline processor, internet server. The remote sensor manager communicates with the remote sensor units and logs any sensor or link malfunction. Raw GPS measurement data is received from the remote



sensors 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 base station 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 almanach).

COMMUNICATION ARCHITECTURE

When in operation, the system follows a repetitive sequence of measurement, communication and processing (Fig. 4). The actual method of communication between remote sensors and base station may differ depending on the geographic location and the specific requirements of the monitoring project. Where a cellular 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 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 possiblity, a fixed cable connection between measurement sensors and base station may be feasible where the distances involved are relatively short and the object 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 base station and sensors is always the same, and for this reason the different link types may be used interchangeably.

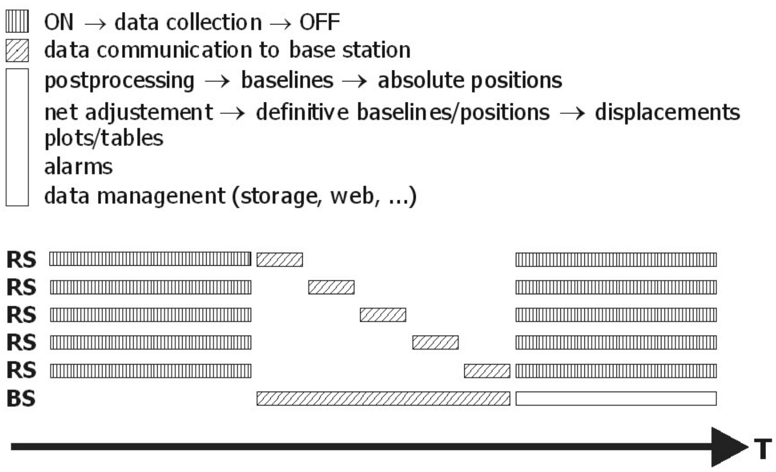


Figure 4: System timing diagram showing measurement, communication and processing phases.

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.

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 goal of the data model is to define, for the scope of a given project, all relevant entities and their relationships. The data model is therefore organized upon three layers: a measurement-specific layer, a configuration layer and a system-specific layer.

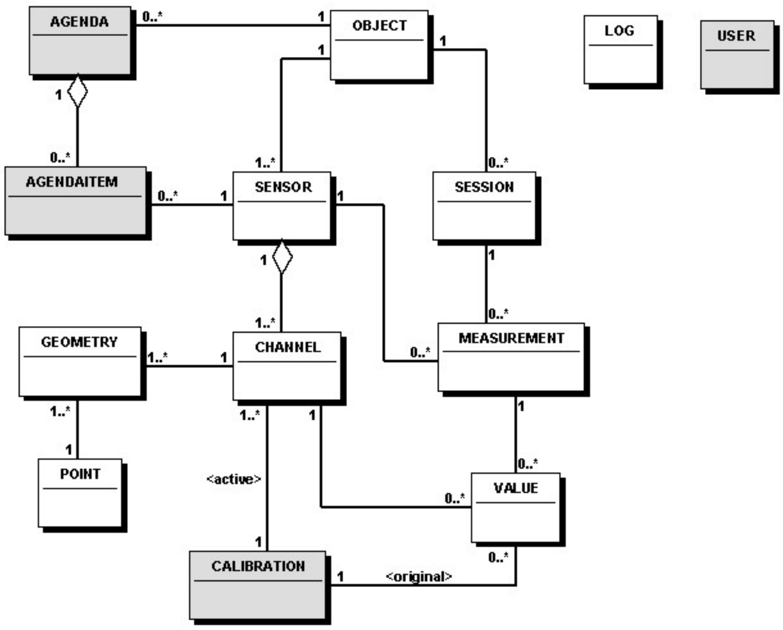


Figure 5: Entity Relationship Model using the UML notation

Referring to Fig. 5, the model foresees the following entities in a monitoring project:

- an *object* to be monitored in the scope of the project
- *sensors* used by a monitoring system to collect data about defined properties of the monitored objects
- *channels* of a sensor represent a specific collection unit for a sensor
- the *position* of single channels in form of a geometry network and a topology network
- a *measurement* represents a single collection event
- *sessions* represent a set of measurements relating to a given state in time of the monitored object
- *values* represent the value of the property that has been collected by a channel through a measurement
- a *log* represents a passive observer of all events that take place in the monitoring system, such as calibrations, warnings, failures, user notes, etc.

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

REMOTE ACCESS AND CONFIGURATION

All important visualization and configuration functions may be effected at the base station, 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 base station 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.

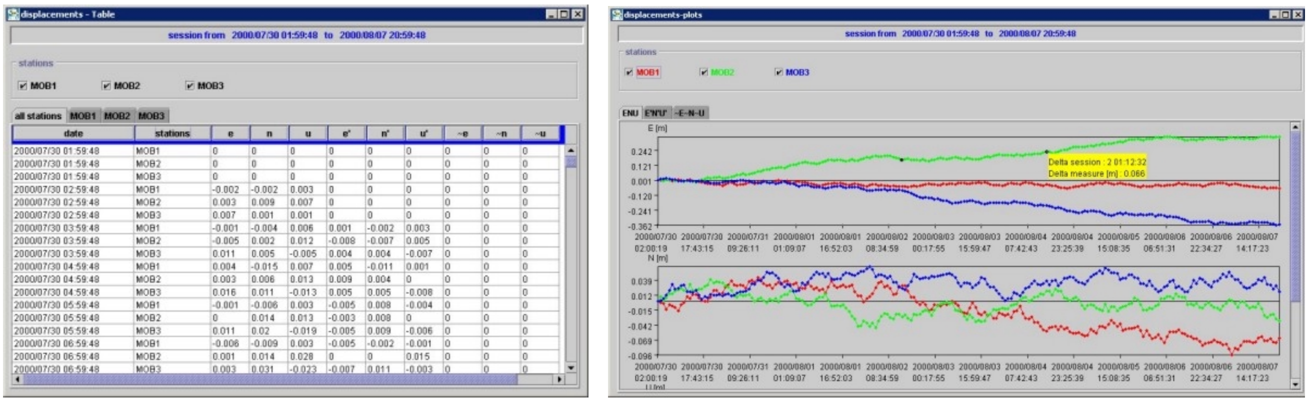


Figure 6: Tables and plots of measured displacements

The main view of the monitoring process is the movement screen, shown in Fig.6. 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 visibilty simulation screen. This screen, shown in Fig. 5, 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 base station, the satellite visibility screen displays a measure of the expected quality of position measurements at a given time in the future.

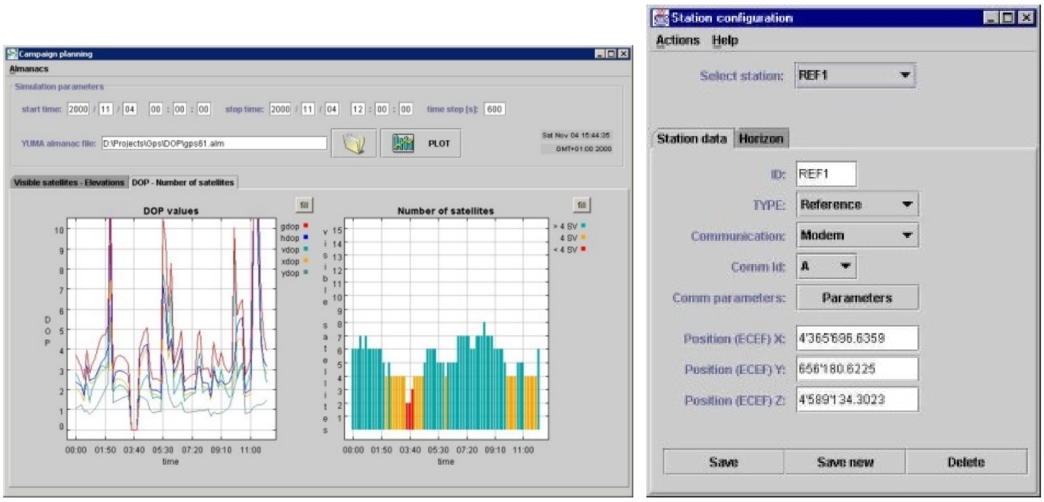


Figure 7: Satellite visibility simulation aids in measurement scheduling (left), station parameters (right)

The sensor configuration screen, also shown in Fig. 7, allows to configure operating parameters of a single measurement sensor. 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.

ALARM MANAGEMENT

The base station may be programmed to initiate a warning or alarm event when absolute position differences, or the velocity of movement of a single sensor or a group of sensors on a monitored object are found to be over a certain pre-set limit. The associated action to a warning or alarm event may be defined as sending an email message to a predefined address, sending a short textual (e.g. SMS) message to a user over the cellular telephone network or a pager network.

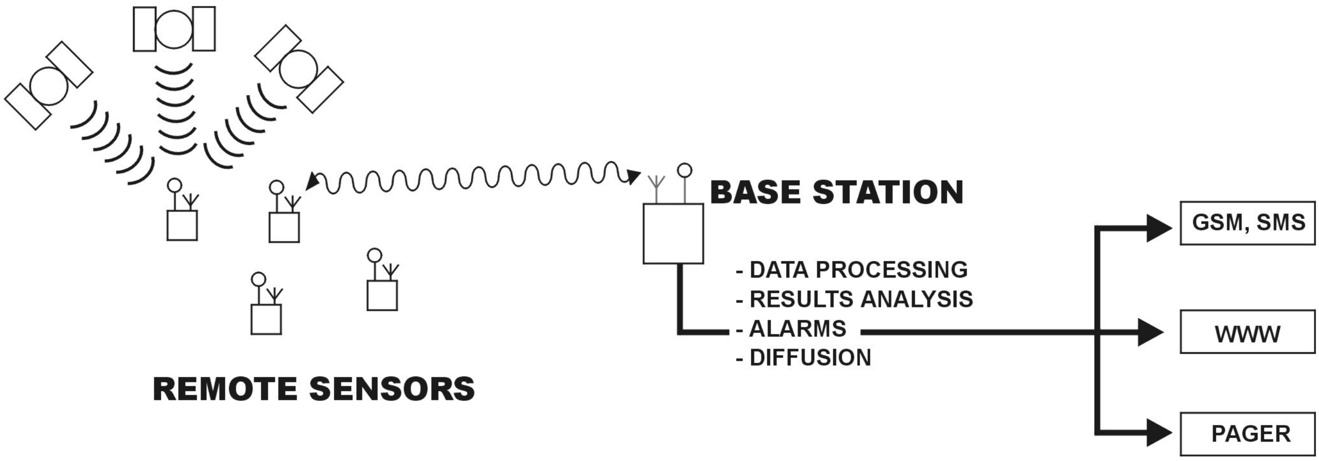


Figure 8: Alarm handling

5. PERFORMANCE AND LIMITATIONS

Based on a number of tests involving separations between remote sensors 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 7mm ± 1.5*(baseline lenght 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 travelling 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.

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 single sensors is significantly obstructed by e.g. trees, high constructions or mountainous terrain.

The most important limitations on possible uses of the described system are attributable to the non real time nature of the measurements. This factor effectively excludes the monitoring of objects for oscillatory movements. The measurement principle is however tolerant of oscillations or vibrations at the centimetre level, and integrates the oscillations over the observation period. A second limitation stems from the time delay of approximately 20 min. between the actual observation and the availability of the measurement, thus lenghtening 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. 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-centimetre level accuracy in structural and land monitoring applications was investigated. A project was 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.

8. ACKNOWLEDGMENTS

The authors would like to thank Bernardo Ferroni, Emilio Di Francesco, Gianpaolo Nodiroli and Giuseppe Pitta of ICIMSI, as well as Katia dalle Fusine, Edy Lehmann and Rodolfo Visconti of DCT for their valuable contributions to this project. The development project has been financed in part by the Swiss Commission for Technology and Innovation, CTI.

9. REFERENCES

1. Hofmann-Wellenhof, B., Lichtenegger, H., & Collins, J. (1997). GPS Theory and Practice. Springer Verlag, Wien New York, fourth, revised edition.
2. Seeber, Günter (1993). Satellite Geodesy: Foundations, Methods, and Applications. Walter Gruyter, Berlin New York.
3. Leick, Alfred (1995). GPS Satellite Surveying. John Wiley and Sons, Inc., New York, 2nd edition.
4. Adam Lowry, Roderick McLeod, PMos: A real time precise DGPS continuous deformation monitoring system, SAGEM Australasia Pty Ltd, 1997
5. J. Behr, SCIGN-USGS, K. Hudnut, N. King, USGS, Monitoring Structural Deformation at Pacoima Dam, California Using Continuous GPS, (1997)
6. Mike Hyzak, Camille Tucker, Keith Duff, 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