ADVANCES IN REAL-TIME GPS DEFORMATION MONITORING FOR LANDSLIDES, VOLCANOES, AND STRUCTURES

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Abstract

The timely identification of deformation associated with geologic hazards or ground settlement can save lives, avert large financial liabilities and avoid severe environmental damage. Until recently, deformation monitoring could only be accomplished by periodic optical surveys or by using electronic sensors (tiltmeters, TDR, electrodes, etc). Periodic surveys do not provide a real-time warning capability and automated sensors, though providing continuous data, do not yield conclusive information about displacement vectors. A recent development in GPS processing software described in this paper provides reliable, precise, real-time, automated 3D monitoring at the millimeter level. The unique software design, called control station processing (CSP), uses sophisticated processing of raw GPS data at a control station computer. The powerful CSP algorithms are virtually immune to potential false alarms or interruptions to continuous monitoring (such as cycle slips) that plague less robust GPS processing strategies, such as RTK. The CSP described here handles data from numerous receivers simultaneously and provides a comprehensive Internet-enabled automatic warning system. The result is a deformation monitoring system with unique new capabilities. Currently installed CSP systems show reliable 3D data at the millimeter-level that are not plagued by artificial position jumps. Data from monitoring an active landslide for fourteen months demonstrates that it is possible to monitor motion rates at the millimeter level with vector directions consistent with landslide failure models. GPS provides cost-effective and heretofore-unavailable 3D information that will revolutionize the geohazards-warning mission of engineering geologists.

Introduction

Recent advances in GPS processing technology have created a new generation of software products that provide reliable and precise 3D position information in real time for long-term deformation monitoring. These advances, combined with the dramatically lower price of single and dual-frequency GPS receivers, provide a new and exciting tool for geotechnical and structural engineers. The worldwide availability of Global Positioning System (GPS) signal coverage creates the potential for many exciting developments in automated monitoring of ground deformation at faults, landslides, volcanoes, well fields, and large manmade structures (dams, bridges, transmission towers, buildings, drilling platforms, etc.). Data from GPS receivers located at the target locations are transferred in real time via modem, wireless radio or network connection to a personal computer (PC) running the real-time processing software. Sophisticated algorithms within the PC-based software process these data using an innovative approach specifically tailored for real-time continuous monitoring. The algorithms employ Kalman filter triple-difference GPS carrier phase processing and can provide millimeter accuracy at many monitoring stations simultaneously. The 3D positions derived from the software for each station and updated as frequently as twenty times per second are reported in real time through a Windows graphical-user-interface. These software advances have enabled turnkey monitoring systems that provide continuous and unattended operation with true 3D monitoring capabilities. Because such systems are based upon differentially corrected GPS, data from each sensor can provide millimeter precision without the long-term drift associated with many other monitoring meters that rely on electronic sensors.

The system described in this paper is unlike other real-time GPS systems and represents a new level of robust monitoring technology. Data processing is performed on a powerful, centrally located PC. The GPS solutions are not computed at remotely located GPS receivers and then sent back to a central PC for display, as in other GPS monitoring systems. In this new control station processing approach, data flow has been reduced from two-way traffic to one-way traffic, which dramatically changes the field configuration of GPS field receivers. The elimination of two-way data flow greatly simplifies the design architecture and eliminates significant pieces of hardware. This combination of newly available robust 3D positioning software and a simplified system architecture improves performance and reduces costs, making GPS monitoring technology available for many new applications.

Continuous 3D monitoring of geologic features and large structures provides timely identification of deformation associated with earth movement and structure movement. This is valuable information and can be used to avoid loss of life, large financial expenditures and to minimize environmental damage. The advent of powerful new GPS processing software and a simplified system design, taken together with the rapidly falling prices of GPS hardware, provide engineers with a cost-effective solution for precise 3D monitoring of geohazards, dams and others structures. The data presented in this paper were collected on a large landslide in New York and clearly demonstrate the power of GPS for long-term deformation monitoring.

Description of Real-time Monitoring Software

The 3D monitoring software described in this paper is a 32-bit multitasking and multithreaded Windows PC-based package with a graphical-user-interface (GUI). The graphical interface provides detailed information and control for each station being monitored, which can be configured by the user for each project and can even be configured for each station within each project. The GPS algorithms for this software were designed and implemented by Dr. Benjamin Remondi (Remondi and Brown, 1999).

The algorithm responsible for processing the GPS data in real time is a delayed-state Kalman filter which processes GPS carrier phase measurements as triple differences, and processes code measurements as double differences (Remondi and Brown, 1999). Treating the GPS carrier phase measurements, as triple differences within the Kalman filter is a processing strategy ideally suited for continuous, long-term monitoring of geohazards and structures. This processing strategy is extremely robust in terms of surviving momentary cycle slips. A cycle slip is a break in the GPS receiver's continuous phase lock on the signals transmitted from the GPS satellites. Cycle slips are virtually impossible to avoid on most monitoring projects and can be caused by momentary signal obstructions, loss of power, a low signal-to-noise ratio or any other event that causes a disruption in signal tracking.

The Kalman filter estimation technique described above is unaffected by momentary cycle slips, because they are statistically insignificant to the solution (Remondi and Brown, 1999). This is in marked contrast to the widely used double-difference GPS carrier phase processing strategy containing integer states which must be reset following a cycle slip. Most survey-grade real-time GPS systems in use today treat the GPS carrier phase measurements as double differences. Double-difference processing algorithms attempt to solve the integer number of carrier cycles between the GPS satellite and the GPS receiver on Earth. The double difference technique provides centimeter-level solutions minutes after starting the equipment; however, if the GPS receiver on Earth experiences a cycle slip (momentary loss of lock) the integer number is lost and the integer states must be reset for the beginning of a new search, causing an interruption in continuously accurate position solutions.

Periodic resets of the integer states within a double-difference carrier phase processing engine can be expected during long-term monitoring projects and are not desirable. Each reset carries the possibility of the integer being fixed incorrectly. An incorrect integer fix would result in an artificial position jump from the true position. The delayed-state triple-difference Kalman filter does not search for integers in order to achieve sub-centimeter accuracy and is therefore immune from position jumps caused by incorrect integer fixing.

Since cycle slips are inevitable during long-term monitoring projects, we believe that the delayed-state Kalman filter method which processes carrier phase measurements as triple differences is ideally suited for long-term continuous monitoring. The processing strategy is not as quick to converge on a sub-centimeter position as other techniques, but it is extremely tolerant of the cycle slips associated with long-term monitoring. After the triple-difference engine has converged, it provides instantaneous motion detection capabilities at the sub-centimeter level. We feel that since most monitoring projects are concerned with days rather than minutes, the relatively short initial convergence time required for the triple-difference Kalman filter is an appropriate tradeoff for robust performance, immunity from incorrect position fixes, and elimination of the associated false alarms.

System Architecture

The architecture of the Windows PC-based GPS processing software and the associated hardware described in this paper differs significantly from real-time GPS technology currently in use. Because of this, it makes sense to spend time explaining the substantive differences between the two. Currently available real-time GPS processing software is embedded in the GPS receiver, not resident on a Windows PC. Software embedded in the GPS receiver or any other piece of hardware is commonly termed firmware. The real-time firmware processing technique most often utilized by the large GPS manufacturers is commonly referred to as real-time kinematic (RTK) and is used extensively in the surveying and mapping community. The RTK method typically utilizes a double- difference carrier phase solution (instead of a triple-difference carrier phase solution) and relies upon integer fixing to provide instant or nearly instant integer resolution. Nearly instant integer resolution translates to nearly instantaneous centimeter level position solutions. It should be noted that the authors do not question the value and utility of the integer fixing double difference technique for most GIS, survey, and mapping work. The ability of the integer fixing double difference method to almost immediately provide a centimeter solution saves valuable time and greatly increases a worker's productivity. For applications where time is a constraint, the integer fixing method of carrier phase processing makes sense. The associated risk of incorrectly fixing the integers is an appropriate tradeoff for the enhanced productivity and can usually be mitigated by a skilled field operator.

Most real-time surveying, mapping and monitoring projects currently underway use the RTK method described above for computing a differential GPS solution. A fixed GPS base station transmits correctors in real time to one or more remotely located GPS receivers. Firmware within these remote GPS units receives the broadcast correctors from the base station and applies this information to compute a real-time solution. The integer fixing double-difference carrier phase processing method is the standard technique used to derive the real-time solutions. Precise positions output by the remote GPS receiver are most often utilized by, and were designed for, the operator of the remote receiver used for survey or mapping projects. An example of this would be a surveyor with a pen-based computer attached to the GPS unit. Real-time solutions computed by the GPS receiver stream into the pen-based computer on which a raster map has been loaded. As the surveyor moves from one location to the next, a dot moves across the map denoting his/her current position in real time. The surveyor now has a powerful real-time mapping software with a meaningful graphical interface while in the field. For long-term monitoring applications, the positions computed by the remotely-located GPS receiver could also be simultaneously sent back to a Windows PC that simply displays the already computed positions. Sending the precise, differentially-corrected positions from the field to the office requires two-way radio traffic and complicates the field implementation of a long-term monitoring network, especially with many remote stations.

The system described here differs substantially from an RTK system and does not utilize broadcast correctors from base stations at the receivers. Furthermore, it does not rely upon remotely-located GPS receivers to compute precise positions. In the initial design phase of the system, this method was pursued but it was found to be limiting and problematic for long-term monitoring. There is no questioning the viability of using double-difference carrier phase processing for most survey and mapping applications. Long-term monitoring projects; however, are better served with a centrally-located PC running the less risky and more robust Kalman filter triple-difference carrier phase software. The control-station-processing design consists of real-time streaming of raw (uncorrected) GPS data from the reference base station(s) and the remotely-located GPS receivers back to a control station PC located at the office or wherever the operator chooses to situate it. The processing software running on the control station PC, receives these real-time streams and simultaneously computes precise positions for all GPS stations based on corrections generated from the known base station position(s), as shown in Figure 1. Since the data is streamed one way only, it greatly reduces the required bandwidth. Less bandwidth means less radio hardware, which translates to lower cost per station installed.

As mentioned earlier, there are many other advantages to the control-station-processing design for long-term monitoring. Long-term monitoring projects do not require a position to be reported at the remote sites in isolated areas that are difficult and often dangerous to reach. It makes sense to gather and store primary raw data from all of the stations being monitored at a centrally-located PC which is easily accessible to multiple employees within an organization. This design has the added benefit of offering the opportunity to connect the PC to a local area network (LAN) within the agency or corporation responsible for the monitoring. Once the PC running the processing software is connected to the network, many users within the organization can safely access information.

Processing the GPS data on a Windows PC offers additional benefits for long-term real-time monitoring projects. Computing power on a desktop PC is many times that of GPS receiver. The central processing unit (CPU) embedded within the GPS receiver is, for profit margin requirements, many times less powerful than the CPU located within the average consumer’s desktop PC. Because of this, the processing algorithms within the GPS hardware do not have the power and flexibility of the processing algorithms running on a much more powerful desktop PC. The real-time processing software running on the Windows PC can be individually tuned for each monitoring application. Sophisticated configuration screens within the software even allow the operator to continually fine-tune each site based upon unique multipath characteristics, unique baseline lengths, unique elevation differences and other characteristics unique to that site. This utility provides the system operator with a substantial precision advantage over conventional real-time GPS systems such as RTK survey systems. The off-the-shelf double difference RTK system is by necessity designed in a generic fashion to serve the majority of GPS users – the surveying and mapping community - but limits configuration by the end user. By contrast, the 3D monitoring software described here, once configured, runs unattended and provides solutions that are more precise than RTK systems. We believe that the double-difference RTK technology is appropriate for its intended use within the surveying and mapping community but is problematic when deployed for long-term monitoring projects.

Landslide Monitoring

On December 15th, 1999, Condor installed a real-time GPS monitoring system on a large landslide in upstate New York (see Photo 1). This system consists of four dual-frequency GPS sensors located on the slide, and one GPS reference station located approximately 1.5 km from the slide. The GPS base reference station and the four GPS sensors located on the slide stream data in real-time via digital wireless radios to a Windows 2000 workstation running at an adjacent control facility. This system provides a continuous monitoring capability by computing solutions for each point on the slide every five seconds. The software displays the deformation information in a series of charts and graphs that clearly indicate the magnitude of deformation at each site and the rate of change for each site. All data is automatically written to files on the local PC and then automatically sent via FTP to a central server. An alarm module has also been installed which allows the facility operator to program deformation alarms in each motion component, and to program alarms for rate of change thresholds in each component. If an alarm is exceeded at any of the four sites on the slide, then an email or page is sent to an authorized set of users.

Each site on the landslide is powered by an independent solar array with battery storage adequate for fifteen days of autonomous operation with no input from the solar panels (see Photo 2). A large battery array co-located with each system allows each site on the slide to continue to operate through the cloudy winter months. The entire system was specifically designed to withstand power outages at each remote site as well as at the base station. If this occurs, the system automatically comes back on line, without producing any false alarms. Since its installation on December 15th 1999, this system has not produced a single false alarm. The authors attribute this to the robust design of the GPS processing architecture.

Figure 1 displays approximately 24 hours of data from one of the sites on the landslide (REM1). This data was collected immediately after the system was installed on December 15th, 1999. The jagged lines are the motion components and the smoother lines are the Kalman filter error estimates. The blue line is the UP/DOWN motion, the red line is the NORTH/SOUTH motion, and the green line is the EAST/WEST motion. The horizontal dashed line at zero represents the starting coordinates of the station. The starting coordinates for each site on the slide were established by collecting 100 hours of GPS data at each site on the slide, and then processing these data relative to the reference station located nearby. The reference station coordinates were derived by processing 72 hours of data relative to nearby National Geodetic Survey (NGS) CORS stations. The base line distance between the reference station and station REM1 on the slide is approximately 1.2 km.

These data in Figure 1 clearly illustrate an important performance characteristic of the processing architecture described in this paper. Figure 1 is a plot of the five-second solutions for site REM1 over a 24-hour period. Since this figure represents data collected almost immediately after the installation of the system, the “motion” of each component in this figure is noise (the landslide has not moved enough to be detected). The software can be configured to be very precise, producing the small noise component (+/- 3 to 4 mm) seen in this figure. An important Kalman filter parameter, Q, is set at a value of 1.00e-10 for processing the data from the landslide in real-time. The performance shown in Figure 1 is typical for each site across the fourteen months the system has been operational. Changing atmospheric conditions such as electrical storms, rainfall and snow will inflate the noise for short periods of time, but these situations represent a small percentage of the data collected. The processing task for each site maintains a 24 hour moving average in addition to the real-time processing. The 24 hour moving average dampens the noise at each site and produce very good daily solutions for each site (+/- 1-3mm).

Figure 2 through 5 represent cumulative horizontal displacements for Station REM1 for six different time periods. These six figures are plan views with 0,0 (center of figure) representing the starting coordinates for each site. Any motion away from the starting coordinate is displayed as a vector that clearly indicates the magnitude and direction of the deformation. Each graph is produced by the processing software in real-time (horizontal and vertical) and can be re-created later by running the data through a playback module supplied with the software. Figure 2 displays the horizontal displacement vector for station REM1 immediately after the installation of the system (December 17, 1999). The displacement vector displayed in Figure 2 can be considered noise because the landslide did not move a detectable amount during the 48-hour period immediately after the system installation. The “motion” we see in Figure 2 is the inherent noise of the system in real-time. Figure 3 represents the cumulative displacement from December 15th, 1999 through April 25th 2000. A clear displacement vector radiating northwesterly from the origin (0,0) can be seen in Figure 3. From Figure 3 we can clearly see that station REM1 is moving towards the NW with the preponderance of the deformation occurring in the West component. The direction and the magnitude of REM1 motion displayed in Figure 3 are in excellent agreement with the historic survey data from the landslide and in excellent agreement with coincident tilt meter data from a site near REM1.

Figures 4 and 5 also represent the cumulative displacement of station REM1 for September 8th, 2000 and January 17th, 2001. Both of these figures clearly display the landslide slowly moving WNW (downhill) over time. During this time there have been no artificial position jumps caused by software processing. The information from the other three GPS stations show the same WNW trend with slightly greater or lesser deformation vectors depending on what quadrant of the slide the station is located. Information from the GPS monitoring system located on the landslide in upstate New York is proving to be extremely valuable. These data have allowed the geotechnical engineers studying the slide to precisely determine the deformation rates at each of the four sites and to determine the plunge angle at each site. Figures 6 and 7 displays a summary of the deformation vectors and associated rates of the landslide through January 17, 2001. Real-time GPS monitoring systems allow engineers to quickly and easily compile graphs such as this.

The information in Figures 2 through 7 provides the geotechnical engineers studying the slide with true 3-dimensional information. Unlike other instrumentation on the slide (e.g. tilt meters, inclinometers etc), the output data from the GPS processing software is 3-dimensional and is not plagued with drift problems. This data helps the engineers and scientists studying the slide to gain a deeper understanding of the mechanics of the landslide deformation and failure.

Conclusions

Recognizing that long-term GPS monitoring is a separate and different problem than surveying and mapping work is the first step in designing a robust automated monitoring system. Treating the GPS carrier phase measurements as triple differences within the Kalman filter as opposed to double differences is appropriate for long-term deformation monitoring. The double-difference GPS carrier phase method provides the nearly instantaneous solutions necessary for the short occupation times demanded by the survey community, but does not provide the robust performance and immunity from cycle slips demanded by those engaged in long-term automated monitoring. It is our belief that most monitoring projects are concerned with days rather than minutes, and that a longer initial convergence time is an appropriate tradeoff for robust performance and immunity from incorrect position fixes with the associated false alarms. A centrally-located PC for processing raw GPS data is likewise not typically used by the survey and mapping community, but again makes sense for those involved in long-term real-time monitoring. Positions are normally not needed at the remote sites and a much more powerful processing strategy can be deployed on the PC. This, in turn, greatly simplifies the system architecture, dramatically lowers the cost of the systems, and thus makes the technology more accessible. A centrally located computer can also be a shared resource serving multiple purposes in addition to processing GPS data in real time. Data management modules can create post-mission files for a cadastral or GIS department and even provide broadcast correctors for real-time survey and mapping purposes. A centrally located computer linked to a network or to the Internet allows immediate notification if motion thresholds are exceeded, and also provides immediate access to valuable real-time deformation information for all interested parties within an organization.

Deformation information from an active landslide in upstate New York demonstrates that this new GPS technology works extremely well in the field and is providing valuable new information on landslide deformation. The natural output from a GPS monitoring system is 3-dimensional, thereby eliminating the messy and inferential calculations associated with 2-dimensional instrumentation. Furthermore, GPS is not plagued with the drift problems commonly associated with other geotechnical instrumentation. This winning combination of 3D information, low price, continuous operation and robust performance indicates that GPS will occupy a more prominent position in geotechnical and structural instrumentation in the years to come.

References

Remondi, Benjamin W., and Brown, Grover R. Triple Differencing with Kalman Filtering: Making it Work. GPS Solutions, Volume 3, Issue 3, (1999).

Bios

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David Rutledge is the Program Manager for Condor's Real-time Positioning group. He holds a B.S. in Structural Geology from San Francisco State University. David managed the GPS Reference Station Program at Magellan Corporation prior to joining Condor. While at Magellan, David led a design team that successfully introduced several real-time GPS software programs. David worked for the United States Geological Survey (USGS) as a Geologist in the Seismology Division before joining Ashtech (Magellan) in 1996. John H. Kramer, Ph.D.

Jack Gnipp

Jack Gnipp is the Survey Division Manager for Condor Earth Technologies, Inc. of Sonora, California and a GPS specialist. He is a licensed land surveyor in the states of California, Idaho and Utah and has been at his profession for 26 years.

John Kramer

Dr. Kramer, Senior Hydrogeologist for Condor Earth Technologies, Inc., directs project work on mine closure activities, subsurface investigations, environmental monitoring and remediation. He also acts as a systems integrator for digital data collection and real-time monitoring using the Global Positioning System (GPS). Through Condor, he integrates hardware and software to accomplish data collection for Geographic Information Systems (GIS). He has published numerous articles in journals and books on a wide variety of topics related to hydrogeology and has presented short-courses and training lectures on digital field mapping at the state and national levels.

Photo 1. Northeast view of the slide in upstate New York. Note the hummocky terrain associated with landslide topography. Station REM1 is just beneath the tower.

Photo 2. Installation of battery array and GPS sensor at Station REM1.

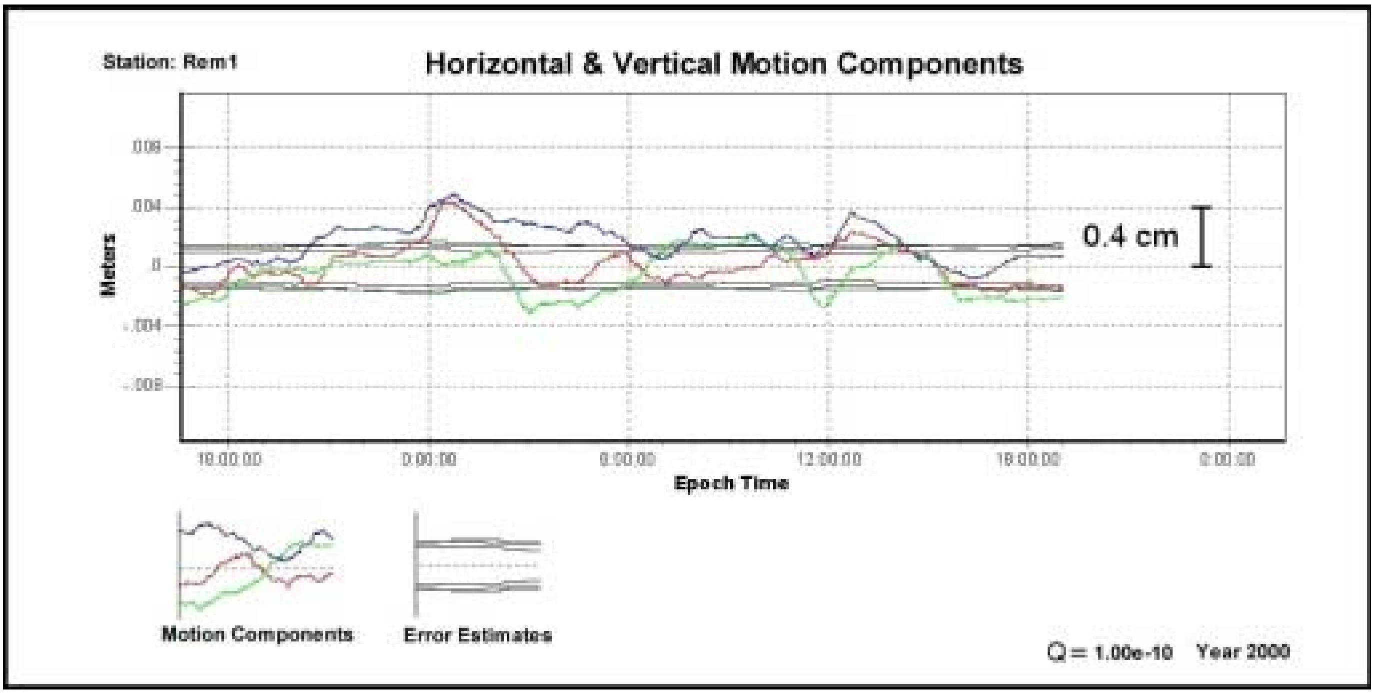


Figure 1. Figure 1 displays the horizontal and vertical motion components for station REM1. The data presented in this graph were collected immediately after installation of the real-time GPS monitoring system. Each motion component is oscillating around 0, which represents the starting coordinates established on December 15th, 1999.

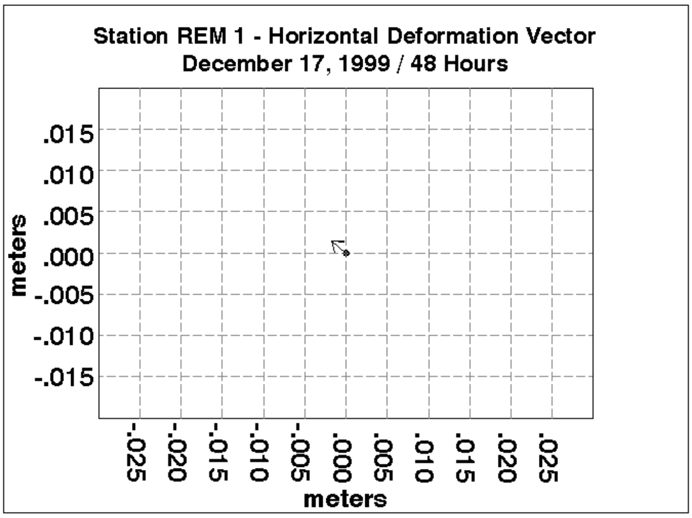


Figure 2. Plan view of the deformation at station REM1 48 hours after installation of the system. The center of the graph represents the starting coordinates of the station established on December 15, 1999.

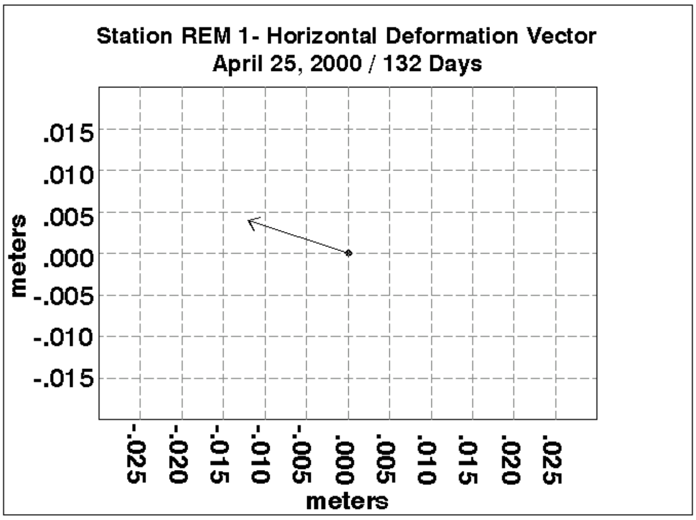


Figure 3. Plan view of the deformation at station REM1 132 days after installation of the system. The center of the graph represents the starting coordinates of the station established on December 15, 1999.

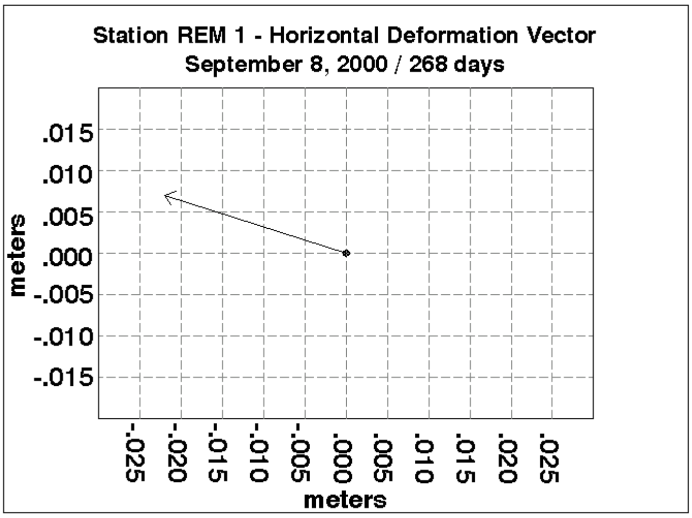


Figure 4. Plan view of the deformation at station REM1 268 days after installation of the system. The center of the graph represents the starting coordinates of the station established on December 15, 1999.

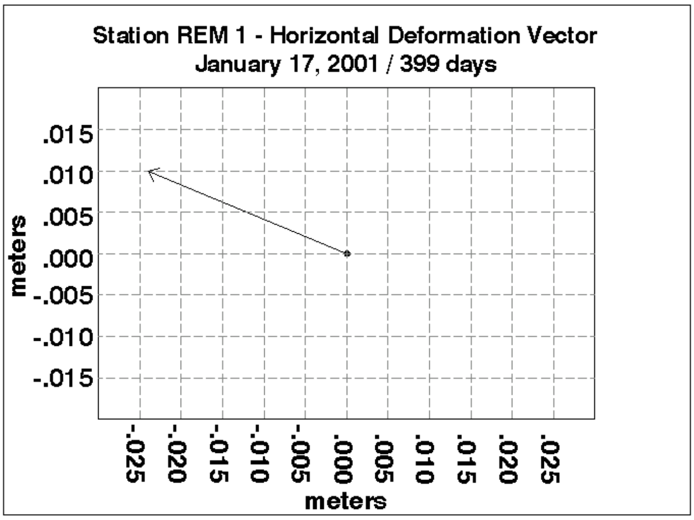


Figure 5. Plan view of the deformation at station REM1 399 days after installation of the system. The center of the graph represents the starting coordinates of the station established on December 15, 1999.

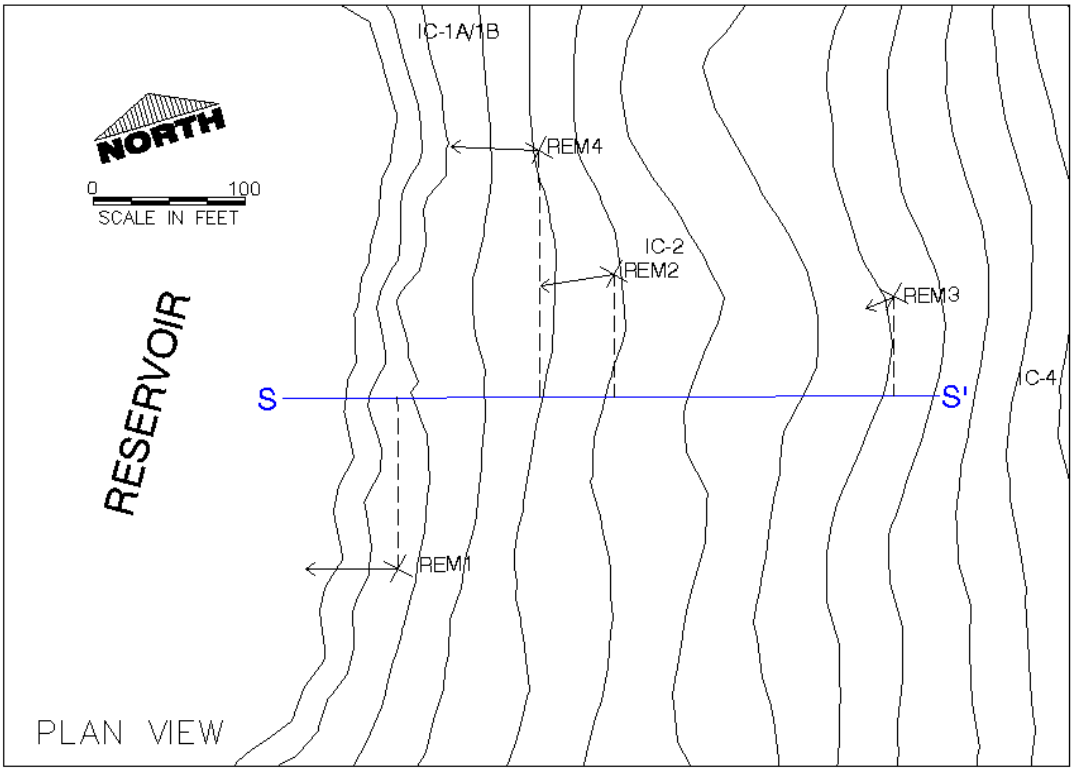
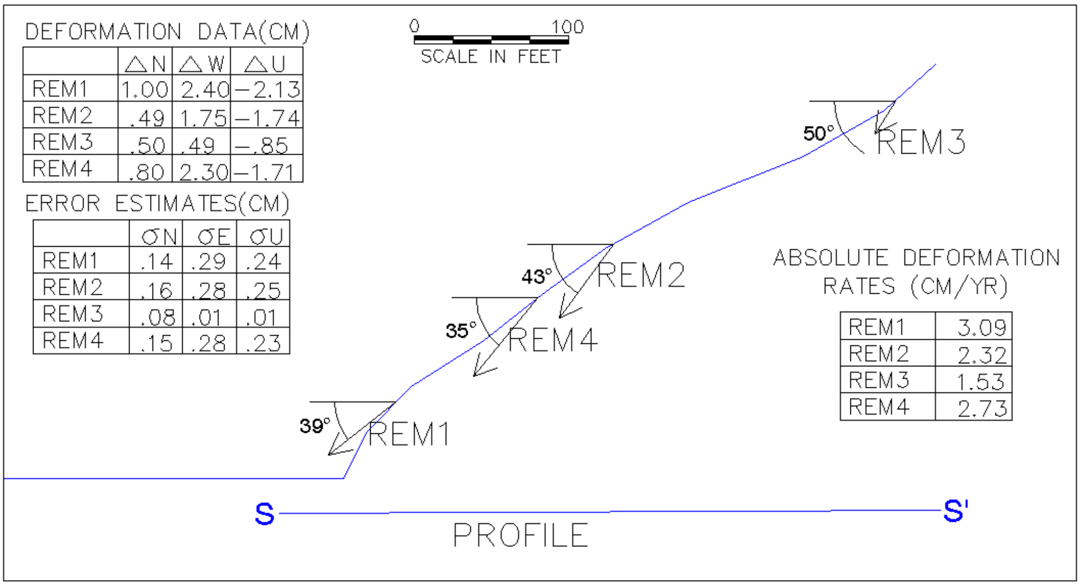


Figure 6. Plan view of four GPS monitoring points on landslide. Data in this figure represent cumulative displacement from December 15, 1999 through January 17, 2001. The deformation vectors at each site are exaggerated so they can be seen on the smaller scale map. The GPS measurements are in agreement with all landslide failure models and existing survey data.


DEFORMATION DATA(CM)

	△N	△W	△U
REM1	1.00	2.40	−2.13
REM2	.49	1.75	−1.74
REM3	.50	.49	−.85
REM4	.80	2.30	−1.71

ERROR ESTIMATES(CM)

	σN	σE	σU
REM1	.14	.29	.24
REM2	.16	.28	.25
REM3	.08	.01	.01
REM4	.15	.28	.23

ABSOLUTE DEFORMATION RATES (CM/YR)

REM1	3.09
REM2	2.32
REM3	1.53
REM4	2.73

Figure 7. Cross section view generated from Figure 6. GPS monitoring allows engineers to quickly and easily establish deformation vectors through time and to establish absolute deformation rates. Plunge angles for each site can also be easily determined. Data in this figure represent cumulative displacement from December 15, 1999 through January 17, 2001 (data from REM3 through September 8th).