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ALERT: A Fully Automated Displacement Monitoring System

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ABSTRACT

Automated monitoring of earth filled dams and steep embankments allow early detection of instability and can be used to avoid or mitigate possible failures. A system that uses multiple and different types of sensors has been successfully developed, tested, and installed at the Diamond Valley Lake reservoir in California and the Highland Valley Copper mine in British Columbia to obtain three-dimensional displacements with a few millimeters accuracy. These systems use robotic total stations (RTSs) as the primary measurement sensors. The scheduling, control, processing, and QA/QC of the sensor measurements are fully automated. The system can be installed in remote areas with the data links being radios, wireless ethernet, or LAN. The observing sequences are repeated at predefined user selected intervals and results can easily be examined or the schedule changed without a site visit. Special algorithms have been developed to improve the system's accuracy and reliability by reducing the effects of systematic errors created by atmospheric refraction, unstable instrument/reference point positions, and configuration defects. The automated monitoring of RTS positions using GPS sensors creates additional operational flexibility and maintains system integrity when insufficient reference stations are available.

1 INTRODUCTION

A major concern involving any steep embankment is its stability. This is the case whether it is the side wall of an open pit mine, a steep slope next to a highway, or a structure like a dam or dike used to contain tailings or generate hydroelectric power. In general, for each case there is a slow movement of the formation before a failure actually occurs. With the advanced monitoring of a phenomenon's creep, particularly its acceleration, critical displacements can be detected before the object reaches its failure point.

The detection of possible failure areas allows remedial measures to be undertaken to mitigate the failure or at least allow the opportunity to evacuate equipment and personnel. The result is a much safer and more economical working environment, which in turn creates additional savings in liability premiums. However, an unreliable monitoring system can cause many false alarms, which in turn causes complacency and unwarranted and costly stoppages in production.

The Canadian Centre for Geodetic Engineering (CCGE) has created a software package that minimizes the effect of these types of systematic errors, hence, reducing the number of false alarms. The recent advances in automated geodetic instrumentation, such as robotic total stations (RTSs), have made it feasible to create a fully automatic monitoring system [Duffy et al., 2001]. Therefore, the primary measurement devices for the system are RTSs combined with meteorological sensors, all interfaced to a computer using wireless communication links. The wireless links allow for remote installations, which when combined with the automated scheduler, creates a fully automated system. Neither the data collection nor processing activities require human intervention, with changes to the scheduler, data collection, and processing parameters performed from the administrator's office. The stand-alone RTS system becomes even more reliable and flexible with the inclusion of Global Positioning System (GPS) sensors.

2 SYSTEMATIC ERRORS

The creation of a reliable system involves being able to resolve whether the computed displacements of object points are significant. The determination of a point's significance involves the propagation of both random and systematic errors. The random error contribution is very regular and predictable for geodetic observations and therefore does not pose any problem in determining its contribution to the significance testing of displacements. However, it is a completely different situation when considering the systematic errors. Again, the systematic errors themselves are well understood, but the magnitudes and directions of these errors are very difficult to determine in practice.

2.1 Refraction

Atmospheric refraction can change very dramatically throughout the day, creating a bias in displacement results computed at different times of the day. This can be seen very clearly on the left side in Figure 1, which illustrates the bias in the vertical displacement results for cycles that were observed in the afternoon and at night at the Diamond Valley Lake water reservoir in California. In this case, if only comparisons between single cycles were relied upon for alarms, many false alarms would be generated.

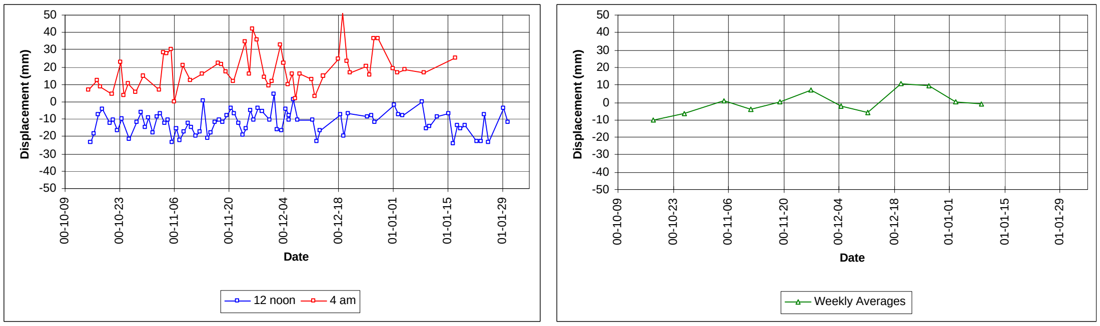


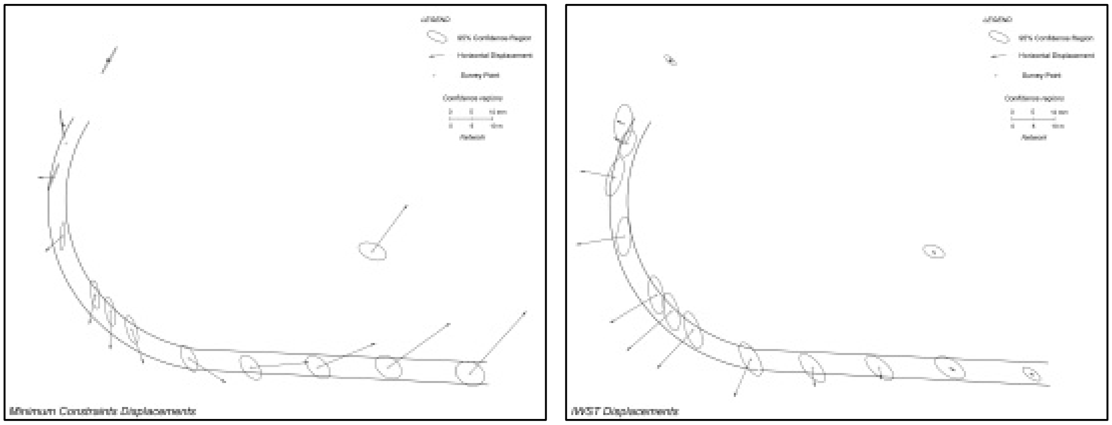
Figure 1 Comparison of time-of-day refraction effects and weekly averages

Therefore, cycle averaging is used to randomize the effects of the systematic atmospheric refraction errors. The averaging of cycles that have been observed at different times of the day, in different conditions, improves the accuracy and reliability of the displacement determinations. The plot on the right in Figure 1 illustrates the more reliable results obtained from the weekly averages. In slope stability monitoring, it is common to encounter lines of sight that graze the side of an embankment, where the temperature gradient increases as the line of sight approaches the surface. One can appreciate how a temperature gradient can change very rapidly with sun exposure, particularly between day and night. Areas that receive direct sunlight can produce temperature gradients of several degrees per metre that may fluctuate rapidly (i.e., scintillation). In contrast, the same area at night may have a very stable, slowly decreasing temperature gradient as it releases heat into the atmosphere.

2.2 Unstable Reference Points

In deformation surveys, the definition of the datum is adversely affected by the use of reference points that are erroneously assumed stable. This in turn gives a biased displacement pattern that can easily lead to a misinterpretation of what is really happening to the deformable object. The identification and removal of the effects of unstable reference points has been the focus of research at the University of New Brunswick (UNB).

A methodology utilizing an iterative weighted similarity transformation (IWST) was developed at UNB by Chen and Chrzanowski [Chen, 1983; Chen et al., 1990]. The techniques have been successfully applied in all types of engineering projects where reference point stability has been a concern (see Greening et al. [1993] and Chrzanowski et al. [1991]). An example of the UNB methodology used to determine the true displacement field at a concrete dam in the U.S.A. is illustrated here. Figure 2 shows the displacement field obtained when creating the datum using what were thought to be stable reference stations, versus the results utilizing the IWST to obtain the datum independent displacements. The displacement trend given on the right obtained from the IWST, with the datum biases removed, give the expected result of systematic concrete expansion between the May and December measurement cycles. This interpretation would be very difficult, if not impossible, to obtain from the figure on the left.


Minimum Constraints Displacements

IWST Displacements

Figure 2 Use of IWST to remove effect of unstable reference points

The methodology is based on using the stability of each of the reference points as a means of determining its contribution to removing the datum defects. It is an iterative process that computes the current iteration displacements based on the displacements from the previous iteration. This computational approach is utilized in the ALERT software to eliminate biases created by unstable reference points and RTSs.

2.3 Tropospheric Zenith Delay and Multipath

With the implementation of GPS sensors, the systematic effects of residual tropospheric zenith delay and multipath of phase signals become the primary limiting factors in achieving accuaracies of a few millimetres in short baselines [Bond et al., 2003].

For tropospheric zenith delay, the elevation component is very difficult to differentiate from the zenith delay, therefore, any residual bias is mapped directly into the baseline height component. To differentiate between the two requires the observation of low elevation satellites, which unfortunately due to the natural mask angle typically created by pit walls, are in very short supply. In addition, in slope stability applications (e.g., open pit mining) it is very common to have large height variations between stations, which may magnify this effect.

In simple terms, multipath is created by receiving both the primary and reflected or disbursed waves at the antenna. The reflected waves have the effect of biasing the range measurements by some amount that depends on the satellite position, trajectory, and location of the reflecting surfaces. The bulk of the multipath is predominantly of short wavelength lasting just a few minutes [Bond et al., 2003]. In the open pit mine applications there are many surfaces that signals can reflect/disburse from to create multipath, creating a very harsh GPS environments.

3 MULTI SENSOR CAPABILITY

The use of multiple sensors improves the accuracy, and particularly the reliability, of the displacement results. Each RTS observes a distance, horizontal direction, and zenith angle and therefore is only able to uniquely determine the three-dimensional position of each target point that is observed. This does not allow for any statistical analysis or verification of the results for each cycle. In these cases, it is not possible to separate bad pointings or refraction effects that are contained in one cycle from the actual movement of the object point.

When simply treating the observations from multiple RTSs independently the situation improves dramatically. For every object point that has multiple observations, it can be verified whether any computed displacement is similar for both sets of observations and whether they agree with the previous cycle results. Therefore, it creates a mechanism for identifying possible mispointings or refraction effects before a false alarm is activated.

However, the best situation occurs when observations from multiple RTSs are combined. This allows for a complete statistical analysis for the measurements from each cycle. Any blunders in the pointings, as well as an estimate for whether the precision of the observation set was as expected, will be identified. Small mispointing or refraction errors are reduced, as they are smoothed by the least squares process. The largest improvement is in the determination of the horizontal displacements. When multiple RTSs are combined the horizontal coordinates become a function of the observed distances (which are less affected by temperature gradients), while the horizontal directions serve simply as a blunder detection tool. The result is horizontal coordinates that remain consistent to a few millimetres, cycle-to-cycle, and only change if the point actually moves beyond these amounts. Of course, this is based on the assumption that meteorological sensors are being used, allowing the distances to be corrected for atmospheric variations.

Unfortunately, unless the lines of sight are very steep, the distances contribute very little to the elevation of the point. The elevations are therefore still primarily determined by the zenith angle measurement, which can be adversely influenced by refraction. The refraction effects on the zenith angles cannot be eliminated, but can be reduced by using multiple RTSs and reducing the sight lengths. However, the closer the RTSs are to the monitoring area, the greater the chance of having an unstable instrument location. In addition, the distances to most reference targets would increase. This in turn would force the bulk of the inaccuracies to the reference target observations, which would reduce the confidence in being able to detect an unstable instrument, particularly in height.

A solution to this problem is to add additional sensor types to the analysis that are less dependent on sight lengths and atmospheric conditions. A GPS antenna, mounted with each RTS, would allow the position of the observing station to be determined independently for each cycle. Each instrument position can be updated for each cycle, eliminating the need to observe multiple reference targets. The update would be with respect to a master station outside the zone of influence. For complete reliability, multiple master stations could be utilized. This would make it possible to verify the stability of the master stations by using the IWST methodology. Feasibility studies of GPS performance have been conducted at HVC (see section 5.2 below).

Another feasible approach for verifying stability, that uses fewer GPS receivers, would be to install some geotechnical or rock mechanics instrumentation to monitor the change in antenna position. The additional instrumentation could be used anywhere within the area of concern to help improve the reliability of the monitoring system.

4 SOFTWARE DESIGN PHILOSOPHY

CCGE has developed a comprehensive automated monitoring system [Lutes et al., 2001]. The ALERT software implements the methodology for deformation monitoring and analysis that is described in this paper. The system has continued to evolve, with features being added to improve accuracy, increase reliability, and address user needs as they are identified.

The software allows for a remote control and pre-programming of observations with RTSs and other sensors. It allows fully automatic reduction and processing of positioning surveys, automatic identification of unstable reference stations using the IWST, and automatic determination and graphical presentation of displacements of monitored points with their variance-covariance information.

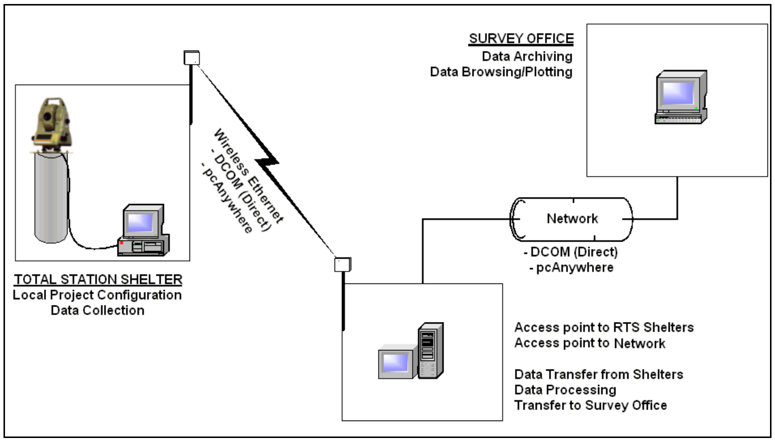


Figure 3 A typical computer network configuration for remote access.

The system takes advantage of the core functionality of the Microsoft Windows NT systems (e.g., NT 4.0, Windows 2000, and Windows XP). There is full support for remote operation via LAN and Internet connections and provider-independent database access (Figure 3 illustrates a typical configuration). In addition, the software's observation and processing tasks are automated according to any desired schedule and the system is able to recover from power outages with no user intervention.

Rigorous geodetic observing and quality control protocols are adhered to. The raw directions, zenith angles, and distances collected by the RTS are corrected for atmospheric conditions and instrument and target offsets. The sets are combined using a rigorous least squares station adjustment, followed by data reduction algorithms employing least squares adjustments to screen blunders from the data set.

Several network configuration options are supported. A single RTS may observe any number of reference and object points, with observations to subsets of points and multiple schedules possible. Several single-RTS networks may be controlled by a single computer, or by multiple computers with all data being automatically transmitted to a central facility for processing. To improve accuracy and enhance reliability, ALERT supports multiple-RTS configurations where targets are observed simultaneously by more than one instrument. The processing of this data requires a special least squares algorithm that adjusts observation differences with respect to a chosen reference epoch.

The displacements, derived with respect to a user-defined base cycle, are analyzed using the IWST. The effect of rigid-body translations or rotations are removed from the displacements, and the resultant datum-free displacements for the reference points are assessed in terms of their significance. If any reference points are found to have moved significantly, they are not used in the final calculation of coordinates.

The result of data processing is a series of time-tagged coordinate values that are stored in the project database. Plotting utilities allow rapid visualization of displacement trends and advanced trend analysis, such as grouping observation cycles into mean values to smooth the effects of daily refraction. Because the database is in a readily accessible format, the end user can easily extract coordinate values using standard Structured Query Language (SQL) queries and build plotting and analysis tools to meet specialized needs.

It can be helpful to examine the time series for a given point, to see the day-to-day repeatability of coordinate solutions and to determine if there is a systematic trend in the position differences. The storage of coordinate solutions in a relational database makes it very easy to selectively examine subsets of the data (e.g., Figures 1, 4, and 7). SQL allows the user to specify virtually any criterion to choose the particular solution set desired.

5 APPLICATIONS

5.1 The Diamond Valley Lake Project

The Metropolitan Water District of Southern California is using the ALERT system for continuous monitoring of three large earth filled dams at the Diamond Valley Lake water reservoir (see Duffy et al. [2001] and Wilkins et al. [2003]). Since October 2000, eight Leica TCA1800 RTSs, permanently installed in specially designed shelters, perform automatic measurements to 232 target prisms at pre-programmed time intervals. The system has been routinely giving displacements, with better than 5 mm accuracy, on a weekly reporting schedule. Figure 4 depicts the results of cycle-to-cycle, single day average, and the weekly averaged displacements for a single target point.

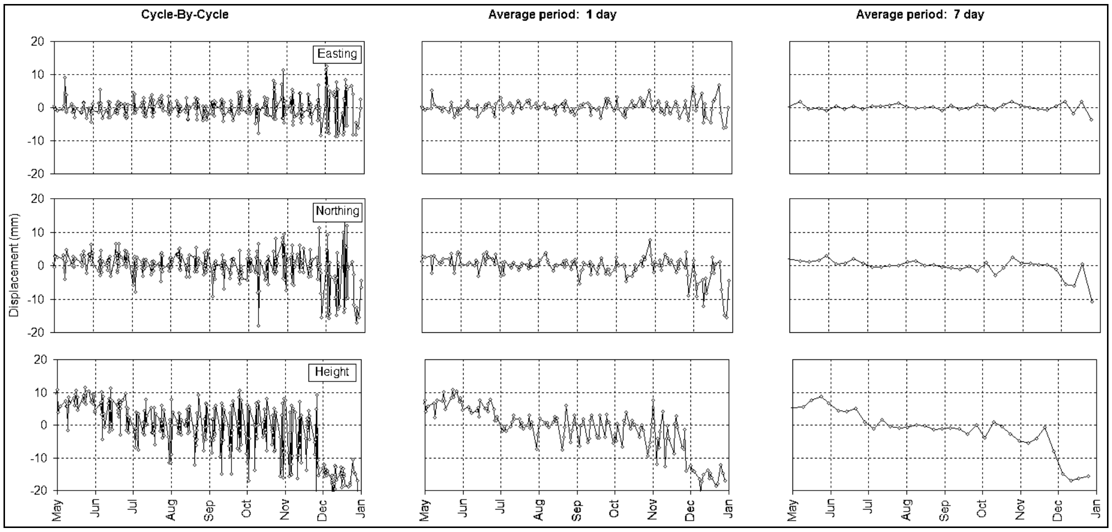


Figure 4 Cycle-to-cycle, single day, and weekly averaged displacements

5.2 Highland Valley Copper Mine

The monitoring system application at the Highland Valley Copper (HVC) mine in British Columbia, Canada is more difficult than at Diamond Valley Lake due to the increased sight lengths, more demanding accuracy requirements, and increased reporting frequency. HVC uses more than 420 target prisms and the ALERT system to monitor pit walls in two very large open pit mines, the Lornex and Valley pits, that have very different accuracy requirements [Wilkins et al., 2003]. In total, four RTSs are used for monitoring with two located in each of the pits. The Valley pit, having the more stringent requirements due to its hard rock composition, has long lines of sight that exceed 1200 m and requires displacement detection accuracy to be better than 5 mm [Newcomen et al., 2003]. Figures 5 illustrates a typical RTS installation shelter for the Valley pit with a view of the extremely steep pit wall in the background.

In this environment, the long sight lengths create a very hostile environment with large variations between cycles due to refraction. The long sight lengths, combined with the systematic effects of refraction, make it impossible to detect displacements at the 5 mm level with a single RTS. Therefore, the monitoring system makes use of sighting targets with multiple RTSs to increase the redundancy, hence, the accuracy of the displacement determinations (see section 3 above). The use of multiple RTSs has a further benefit in that the horizontal positions of the targeted points can now be uniquely determined by the intersection of the distances. Figure 7 illustrates the cycle-to-cycle displacements and the half-day and full-day averages determined for an object point using dual instruments at an average sight length of 1100 m.

Figure 5 A shelter with RTS and GPS in the Valley Pit

Figure 6 A stand alone RTS with GPS on the pit floor

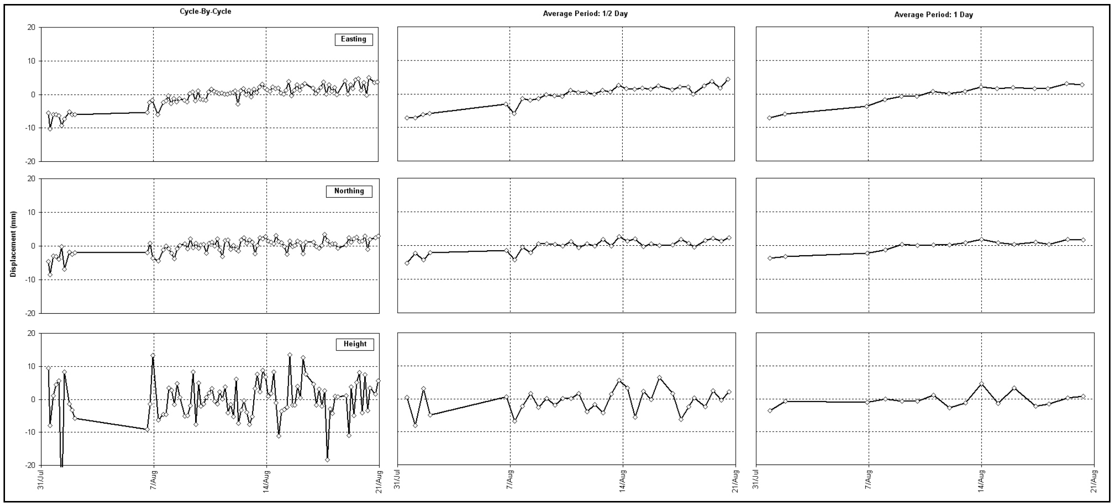


Figure 7 Cycle-to-cycle, half-day, and full-day averages for a point observed by dual RTSs

Although results from dual instrument sightings meet the specifications it isn't feasible to use this approach to monitor all areas requiring continuous monitoring. In addition, the very long sight lengths at the Valley pit and the large displacements at the crest of the Lornex pit make it very difficult to find suitable locations for reference points. Therefore, a feasibility study has been undertaken to evaluate the possibility of using GPS to monitor and update the RTS locations between cycles. The primary goals of the study are to determine what accuracies are achievable, the best observing sessions, length of sessions, minimum required satellite geometry per session, and available report frequency. Figure 6 depicts a stand alone RTS/GPS hybrid test unit that was installed on the pit floor for an initial three day test period.

As mentioned in section 2.3, an open pit mine is a very hostile environment to try to achieve a few millimeters accuracy in baseline components (particularly elevation). Due to the high pit walls, complete satellite outages occurred twice a day for approximately half hour durations. In addition, there were long periods (up to 1.5 hours) where only 4 satellites were available. Nonetheless, the preliminary results of the three day test data obtained on the floor of the pit are encouraging. Figure 8 shows the baseline component results when arbitrarily cutting the data into twenty four consecutive three-hour sessions. The height component clearly shows a downward trend with spikes occurring at the sessions where satellite coverage is the weakest. With better session optimization and planning it is expected that the tolerances of less than 5 mm can be achieved.

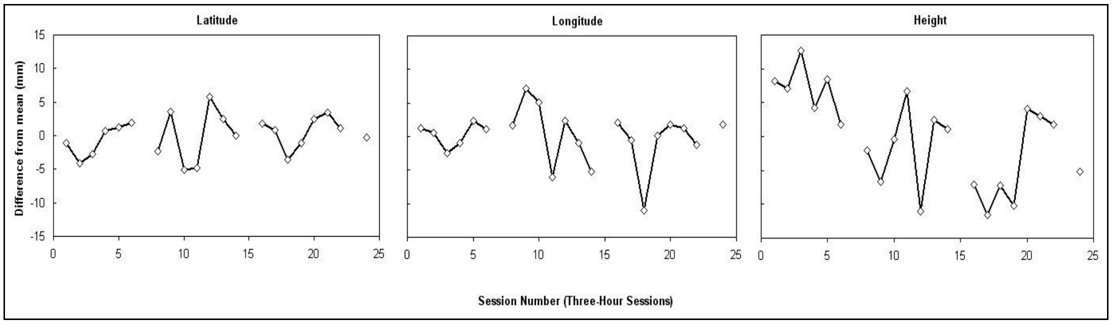


Figure 8 Plot of baseline component variations for 3 consecutive days of 3-hour sessions for a station on the Valley Pit floor

6 CONCLUSIONS

The real time monitoring system developed by CCGE offers the possibility of fully automated reliable monitoring in remote areas. Once the system has been implemented, no human intervention is required to obtain displacement results. The observation gathering and processing can be scheduled to take place at preset intervals. Even if power failures occur, the system will automatically resume exactly where it left off without the loss of any data cycles.

The use of multiple sensors increases the accuracy, and more importantly the reliability of the system. Horizontal displacements are better determined, and redundant vertical observations, although not fool proof, increase the reliability of height determinations. The inclusion of GPS sensors allows the instruments to be located closer to the monitored area (shorter lines of sight), which creates a significant increase in the system’s vertical reliability. The preliminary GPS baseline component results indicate that better than a 5 mm accuracy will be possible for at least some periods of the day.

The inclusion of a variety of sensor types creates an extremely flexible monitoring system. GPS augmented with geotechnical sensors could create a very reliable method of maintaining instrument stabilities. If deemed beneficial, the geotechnical sensors could also be implemented as stand alone instruments. This would provide another means of increasing the monitoring scheme’s reliability. Research and development activities are continuing in this area.

With these increases in reliability the number of false alarms will be dramatically reduced. Of course, one needs to err on the side of caution, but many unwarranted alarms can be eliminated.

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