# A FULLY AUTOMATED SYSTEM FOR MONITORING PIT WALL DISPLACEMENTS

***Paper presented at:***
***SME 2003, Cincinnati, OH***
***February 24-26, 2003***

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## ABSTRACT

Automated monitoring of steep or high embankments and excavations allows early detection of instability and can be used to avoid or mitigate possible slope failures. Systems that use multiple and different types of sensors have been developed and successfully tested at the Highland Valley Copper mine in British Columbia. These systems use robotic total stations (RTSs) as the primary measurement sensors, with surveys repeated at predefined intervals selected to optimize operational efficiency. A methodology has been developed to improve the system's accuracy and reliability by reducing the effects of systematic errors created by atmospheric refraction and unstable instrument and reference point positions. The inclusion of GPS sensors to monitor the RTS positions creates additional operational flexibility and maintains system integrity when insufficient reference stations are available.

## INTRODUCTION

The Highland Valley Copper mine (HVC) consists of the Lornex and Valley open pits. The Lornex Pit is excavated in a relatively poor quality deformable rock mass, with portions of its pit walls experiencing toppling instability and associated relatively high deformations [Newcomen et al., 2002]. By comparison, the Valley Pit walls are excavated in a fair to good quality, relatively brittle, rock mass. The pit walls are experiencing toppling, planar, and wedge instability with significantly smaller displacements. The differences in the potential modes of instability between the two pits, deformation characteristics of the rock mass, and the nature and magnitude of slope movements necessitates different levels of accuracy in pit wall monitoring.

Currently there are over 10 $km^2$ of pit walls exposed in the two pits with approximately 420 slope monitoring prisms (SMPs) installed to monitor wall movements. Monitoring information is used to track the development of unstable areas and assist in determining potential failure mechanisms. This allows the operation to continue to mine and monitor, thus optimizing extraction while maintaining the safety of personnel and equipment. Movement rate thresholds have been specified for various pit walls in the Lornex and Valley pits. These thresholds are used to guide operating procedures for pit personnel and equipment whenever slope movement rates are higher than normally observed background movements. As a result, determining pit wall movement rates as quickly and accurately as practicable is an essential tool in applying these guidelines.

A near real-time monitoring system currently operating in the Lornex Pit provides the mine engineering and operations teams with information that allows them to make informed and timely decisions regarding placement of equipment below marginally stable portions of pit walls. For this monitoring, HVC is currently using a single high precision Leica TCA1800 robotic total station (RTS) that has angular and distance accuracies of 1" and 1 mm, respectively. The monitoring system uses ALERT v2.2 software [A. Chrzanowski & Associates, 2002a] to fully automate the data collection and analysis activities. Each observed point is uniquely determined in all three coordinates by the RTS measurements of a horizontal direction, a slope distance, and a zenith angle. Observations from the single RTS are used to determine the displacements of each observed point (i.e., SMP), and average movement rates for the SMPs are calculated. For the Lornex Pit, an evaluation of the single RTS monitoring data has shown that errors in displacements can exceed 20 mm for lines of sight greater than 1 km [A. Chrzanowski & Associates, 2002b]. Depending on the elapsed time between surveys and the actual true magnitude of the movements, these errors can create higher than acceptable uncertainty in the calculated velocity of the pit wall. In the Lornex Pit, these displacement errors are tolerable due to the relatively high movement rates (up to 200 mm/day) and large accumulated displacements (>30 m) that have been experienced there. Therefore, the above system as it currently exists is capable of satisfying the needs of the monitoring program in this pit.

The Valley Pit, however, creates a different scenario for acceptable displacement detection, due to the relatively low background movement rates, the different potential mechanisms of instability and the associated smaller displacements that are tolerable before movements become of interest. As a result, based on experiences with previous wall instabilities, a detection capability of 5 mm of displacement per day has been designated as a threshold for this pit at which operating procedures may need to be modified.

The Valley Pit is roughly circular with a diameter of approximately 2.5 km from pit crest to pit crest. This creates long lines of sight to the reference and object points, which translates directly into reduced accuracy when using a single RTS located on the pit rim. The sight lengths to the SMPs can be shortened by moving the RTS down into the pit, but this has the consequence of limiting the flexibility in choosing reasonably stable reference/control targets with sufficiently short sight lengths. The advantage gained by reducing object point sight lengths is lost by an inability to accurately locate the RTS within the work area due to the increased reference target sight lengths. A viable solution to this problem; however, is to reduce the dependence on stable reference targets by monitoring and updating the position of the RTS using GPS. With this method, a new RTS location is determined and provided for each observation cycle.

The concept of the GPS feasibility study was to establish a stable GPS station, away from the deformation

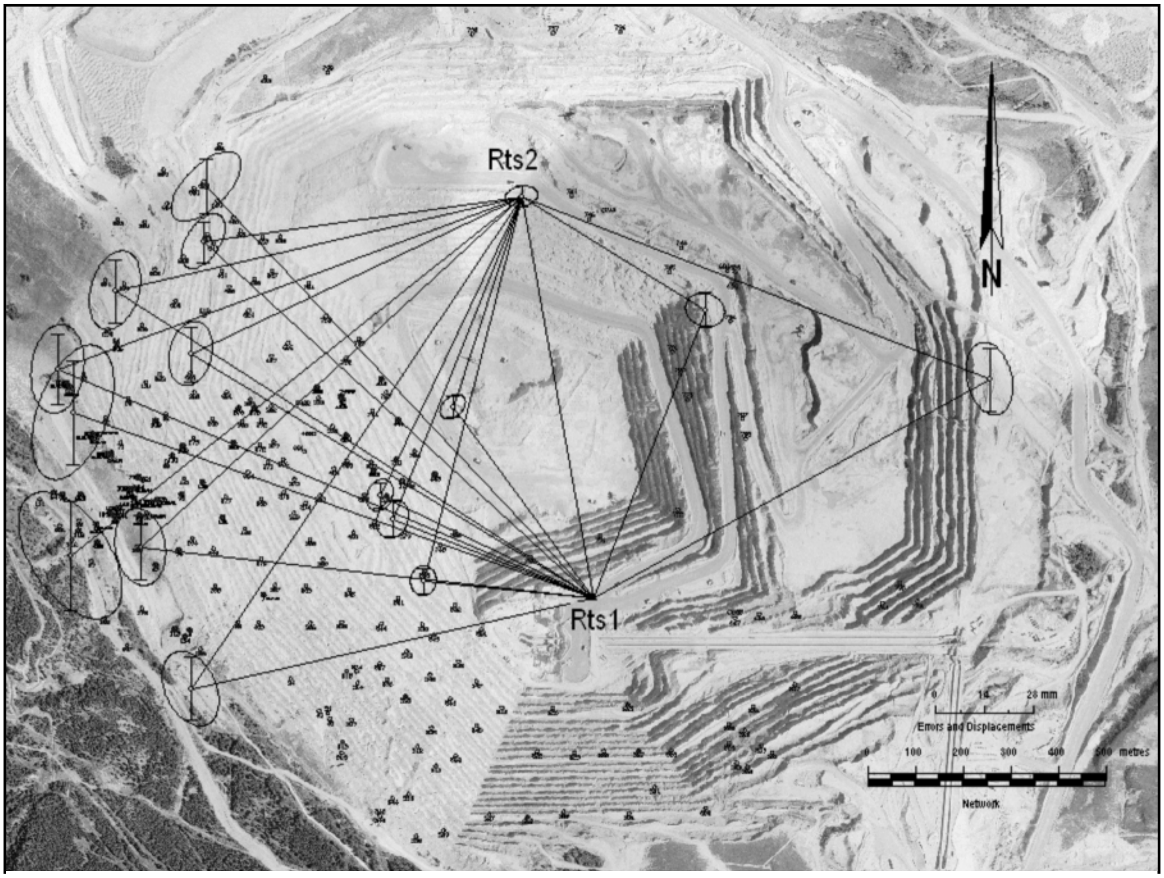


**Figure 1. The pre-analysis for the Valley Pit monitoring design.**

areas, to be utilized as a master station with no expected movement. Additional GPS stations were established at each of the RTS locations. Changes in the computed baselines between the master and the RTS locations represent the displacement of the RTS itself. The goal was to determine whether the GPS positions of the RTSs can be determined to <5 mm in both horizontal and vertical components. If successful, this approach can be used to update the RTS positions, cycle-to-cycle, eliminating the need for sighting most of the reference targets (although one is still needed to initialize the RTS orientation).

Therefore, to improve the displacement detection accuracy, either (1) the sight distances to the object points must be reduced while maintaining RTS position accuracy or (2) more observations must be taken to increase the redundancy. As a result, a monitoring scheme has been designed for the Valley Pit that would take advantage of additional observations by surveying the SMPs with multiple RTSs (Figure 1), while collecting GPS data for a feasibility study.

The multiple RTS scheme was designed and tested in late summer, 2002. The investigations included:

1) A detailed site analysis, including possible RTS, reference target, and object target locations with a pre-analysis to obtain the expected displacement results based on the selected network geometry.
2) Field verification of the configuration and collection of test data to finalize the optimal configuration for multiple RTSs.
3) Evaluation of the multiple RTS test data set to determine achievable displacement accuracies from cycle-to-cycle and from averaged data to reduce refraction effects.
4) Setting up and gathering of GPS data to determine the feasibility of using GPS to monitor the RTS positions.

Currently the GPS feasibility study is a work in progress and therefore those results are not included in this paper.

## DETAILED SITE PRE-ANALYSIS

Possible locations for RTSs in the Valley Pit were determined prior to conducting the field work. Locations were selected and prioritized in order of suitability to fulfill the geometric network requirements. Constraints were also placed on locating the RTSs due to the mining sequence and areas that were planned for blasting operations. An assortment of possible object point locations at various bench elevations were initially laid out on paper, from which optimum locations were selected to give a good spatial distribution and a variety of sight lengths for the test. An error analysis was performed using a least squares simulation of random error propagation using the expected observation errors. The expected error ($\sigma_\alpha$) used in the analysis for an angular observation performed with the Leica TCA1800 RTS has been determined using the following equation [Blachut et al., 1979].

$$\sigma_\alpha = \left[ \frac{\sigma_r^2 + \sigma_p^2 + \sigma_l^2}{2 \cdot n} \right]^{1/2} \quad (1)$$

where,

$\sigma_r$ error in a single reading (0.5”)

$\sigma_p$ error in a single ATR pointing (2.0”)

$\sigma_r$ mislevelment error in a single direction (0.5”)

$n$ minimum number of expected sets (3)

Similarly the expected error ($\sigma_d$) used for a distance ($d$) measured with the Leica TCA1800 is given by the following equation [Blachut et al., 1979].

$$\sigma_d = \left[ \sigma_a^2 + \left( \sigma_b d \ 10^{-6} \right)^2 \right]^{1/2} \quad (2)$$

where,

$\sigma_a$ constant error (1 mm)

$\sigma_b$ distance dependent error (2 ppm)

Once the test network was established a new analysis based on the actual geometry was performed. The results of this analysis are illustrated by the error regions in Figure 1. These error regions represent the expected accuracy at the 95% confidence level of cycle-to-cycle displacements determined from the given geometry. From this figure two conclusions are readily apparent:

1) Targets located <1000 m from the RTSs are expected to meet the specifications at the 95% confidence level.
2) Targets located >1000 m from the RTSs are not expected to meet the specifications, cycle-to-cycle, at the 95% confidence level without some additional averaging.

It should be pointed out that by their very nature, error estimates from pre-analyses are considered too optimistic as they do not consider any systematic effects such as refraction and localized target instabilities. Therefore, even targets within the 1000 m range may require some additional averaging to meet the specifications.

## THE ALERT SOFTWARE SYSTEM

All of the data for the dual instrument tests was gathered and processed through the ALERT automated monitoring and analysis software system created by the Canadian Centre for Geodetic Engineering [Lutes et al., 2001; Wilkins et al., 2002]. 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 (i.e., GPS, meteorological, and geotechnical). It allows fully automatic reduction and processing of positioning surveys, automatic identification of unstable reference stations using the iterative weighted similarity transformation (IWST) [Chen et al., 1990] and automatic determination and graphical presentation of displacements of monitored points with their variance-covariance information.

The system takes advantage of the core functionality of the Microsoft Windows NT operating 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 2 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.

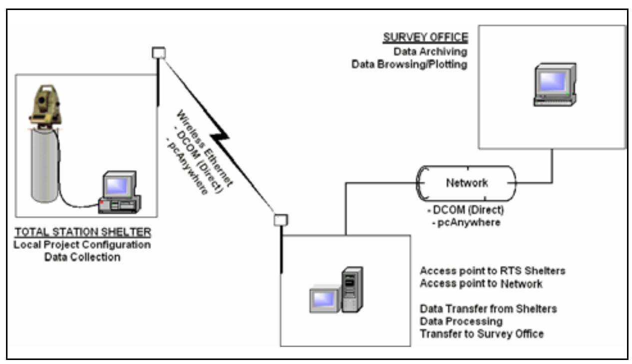


**Figure 2. A typical configuration for remote access.**

Rigorous geodetic observing and quality control protocols are adhered to. All target points are observed in multiple sets of face left and face right RTS pointings. 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 displacements, derived with respect to a user-defined base cycle, are analyzed using the IWST. The effect of rigid-body translations and 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 calculation of final 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. The storage of coordinate solutions in a relational database makes it very easy to selectively examine subsets of the data. SQL allows the user to specify virtually any criterion in order to choose the particular solution set desired.

## GATHERING AND EVALUATION OF RTS TEST DATA

### Data Collection Process

A field trial was conducted to verify that the target positions were acceptable and to initiate the data collection process. As much dual RTS data as was practical was gathered so that trends in targeted points could be identified and a reasonable number of daily averages could be determined. For this test survey, cycles were run at 4 hour intervals.

A total of 12 target points and 2 RTS locations were used in the test survey. The geometry between the target points and RTSs is illustrated in Figure 1. Sight lengths ranged from 400-1300 m with differences in elevation ranging between 60-400 m. Target points that were observed from both RTS locations required dual SMPs to be installed, which is illustrated in Figure 3. The dual SMPs are required due to the manufacturer's specified ± 20 degree design limit on reflector pointing.

The test set up for the dual RTS system made it possible to analyze the trends and evaluate the feasibility of the system. However, the meteorological data at RTS-2 was not recorded for a portion of the test, making it impossible to correct the distance observations for the meteorological variations for those cycles. This created a scale error that can clearly be seen on the cycle-to-cycle plot displayed in Figure 4.

**Figure 3. A dual SMP installation at a control point.**

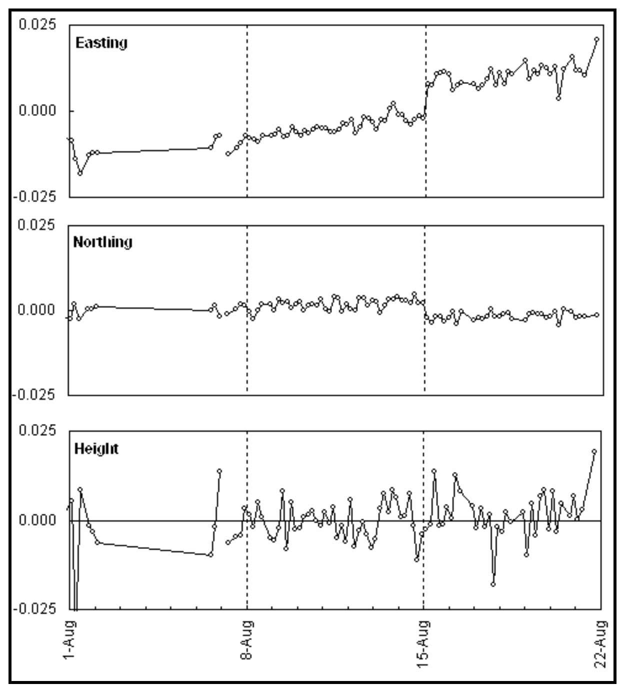


**Figure 4. Typical cycle-to-cycle displacements.**

### Evaluation of Dual RTS Data

The processing of the data for coordinates is made more complex by the fact that each RTS did not physically shoot the same SMP (see Figure 3). Due to the configuration defects created by the multiple reflectors, the dual RTS data was processed using the observation difference approach. Observation differences are computed between the current cycle and the base cycle, and a special least squares algorithm computes displacements directly. A base cycle was selected for the processing that contained observations for all of the data points. Target points that were observed from only a single RTS were eliminated from the analysis.

An initial processing using just the selected reference points and the RTSs to define a datum was not successful due to instabilities detected in prisms located along the crest of the open pit. This suggests that it may be very difficult to identify suitable target points to use as references. Therefore, the data was re-processed, treating all of the stations involved as datum points. As a result, the calculated locations may be slightly biased by datum changes caused by groups of target points displacing in similar directions. The amount of the bias is very difficult to determine as it is dependent on the combined effect of the actual individual point displacements and overall pit movement of each observed point and the RTS locations.

The evaluation of the test survey included:

1) Cycle-to-cycle accuracy of detected displacements.
2) Half-day (12 hr) averaged cycles.
3) Full day (24 hr) averaged cycles.
4) Determination of pit bottom stability.

Cycle-to-Cycle Evaluation: Figure 4 illustrates a typical cycle-to-cycle change in horizontal and vertical coordinates relative to the base cycle for one of the observed points. In general, the results indicate that the cycle-to-cycle horizontal displacement can be detected within a tolerance of 5 mm for all targets that were observed by both RTSs in these cycles. Vertical displacements within 5 mm can also be determined for targets that are an average distance of 900 m or less from the RTSs. For average distances 900-1200 m, the vertical displacement detection becomes 10 mm. However, it should be noted that the cycle-to-cycle vertical displacement changes exhibit an occasional larger variation that still requires some investigation. For the targets in this test, no average sight distances are greater than 1200 m, therefore, the achievable accuracy beyond this length is unknown.

It is worth noting that the RTS-1 and RTS-2 plots indicate a slight general trend upward of approximately 1 mm/day for the RTS locations. This is an indication that all of the targets observed are actually moving down as a group due to ongoing slope deformations. This is consistent with previous slope monitoring results in the Valley Pit.

Half-Day and Full Day Averages: The primary systematic error contribution in surveying the Valley Pit walls is atmospheric refraction. Two half-day averages were determined by combining 3 cycles of observations (i.e. 12 hours). The cycles observed between 12 noon and 12 midnight were used for the first half-day average, while the remaining cycles formed the second average. The refraction effects are expected to be random within these 12-hour blocks. Appropriately scheduled intervals give the geotechnical engineers the ability to check movements when they first arrive in the morning and again in the early afternoon hours. A representative plot of the half-day averages, for the same SMP as plotted in Figure 4, is shown in Figure 5. Half-day average data points that are incomplete due to missing RTS cycles are clearly identified on the plots.

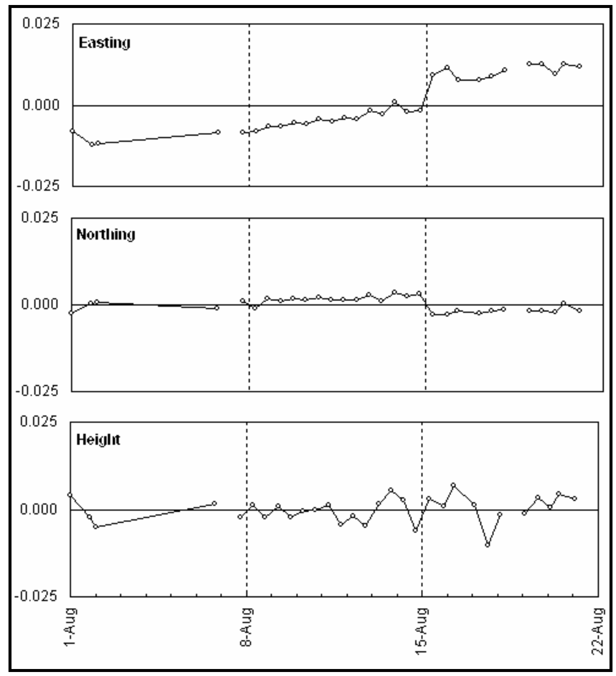


**Figure 5. Typical half-day averaged displacements.**

The half-day results for targets located with average distances less than 900 m are much smoother than the cycle-to-cycle results and are within 5 mm accuracy for both horizontal and vertical displacements. For average distances greater than 900 m, the horizontal displacement detection remains within the 5 mm tolerance, but the vertical displacement detection increases to 5-8 mm.

If only a daily summary report is required for the Valley Pit, taking daily averages would further improve the results. For this data set, a single daily result would represent the average of the six cycles that were observed that day. The full day average plots show that all of the significant systematic variations have been smoothed by the averaging. This can be clearly seen in Figure 6 which represents a typical plot, for the same SMP as plotted in Figures 4 and 5, with full day averaging. All that remains is the residual refraction and target instability effects. The basic trends that could be seen in the cycle-to-cycle and half-day averages are much smoother. Detection of horizontal and vertical movements within an accuracy of 5 mm/day can be realized with daily averaging for all the targets involved in the test.

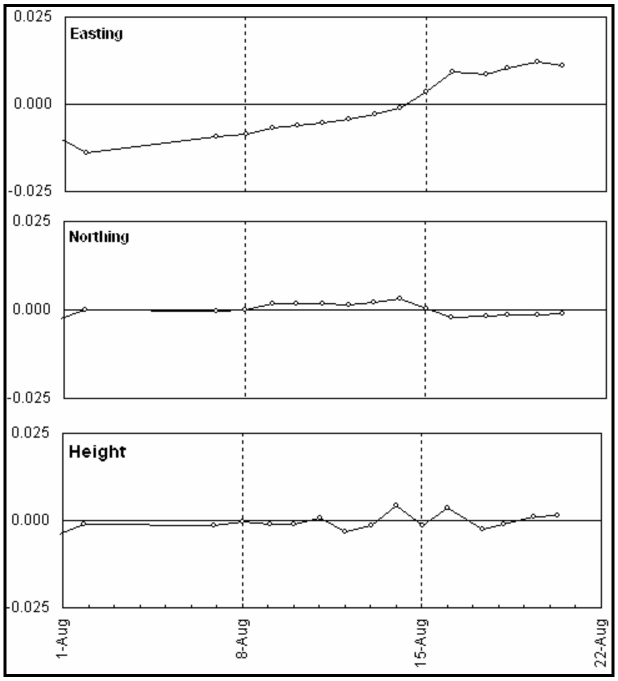


**Figure 6. Typical full day averaged displacements.**

Pit Bottom Stability: For a brief period during the dual RTS test, observations were measured from the two RTSs to a temporary station located at the pit bottom. The purpose of these observations was to determine how stable the pit bottom might be for establishing control points or non-permanent RTS locations. Unfortunately, due to blasting schedules, the data collection had to be cut short and therefore the test observations do not provide enough data to derive concrete conclusions. However, in analyzing the limited data set it does appear that the pit bottom is quite stable, suggesting that it is a desirable place to install additional control points or an RTS. Of course, any point established in the pit bottom could only be of temporary use due to the ongoing excavation and blasting. However, the gain in datum stability obtained by establishing these points may more than offset the drawbacks of being only temporary. Therefore, if logistics permit their establishment, temporary control points at the pit bottom could certainly increase the accuracy of the surveying and strengthen the displacement solutions.

An RTS position established in the pit bottom close to the pit wall being monitored would have the desired effect of reducing the sight lengths to the object points; hence, increasing the accuracy of the displacement determinations. The established RTS station could be used as both an RTS and a target point. The limited test results suggest that the change of position of the RTS can be determined to <5 mm accuracy when sighted from two RTSs. Therefore, its position could be updated by other RTSs while it is sighting a series of close range SMPs. This would create a user mode that would allow improved accuracy in monitoring of localized areas of instability where cycle-to-cycle results are required, such as in areas where equipment and personnel are working directly below areas of higher-than-background movement rates. Obviously, this would not be the typical scheme due to the number of expensive instruments deployed, but it does offer a monitoring solution for sensitive areas.

## CONCLUSIONS AND RECOMMENDATIONS

A single RTS monitoring system is being used to monitor slope movements in near real-time in Highland Valley Copper's Lornex Pit. A multiple RTS system has also been successfully developed and tested in the Valley Pit. From the initial testing and data analysis of the multiple RTS system the following conclusions can be made.

1) A dual RTS system will satisfy the Valley Pit monitoring requirements for horizontal movements for all targets with average sight lengths of less than 1200 m. Half-day and full day averages improve the reliability of the horizontal detection capability.
2) The vertical displacement detection capabilities based on average sight lengths for cycle-to-cycle, half-day, and full day averages are as shown below:

**Table 1. Vertical displacement detection capabilities.**

| | **<900 m** | **<1200 m** |
|---|---|---|
| Cycle-to-cycle | < 5 mm | < 10 mm |
| Half-day averages | < 5 mm | 5-8 mm |
| Full day averages | < 5 mm | < 5 mm |

3) An RTS location in the bottom of the pit positioned using observations from other RTSs would allow more accurate cycle-to-cycle monitoring by reducing the distances to the object targets.
4) It does not appear that any of the selected control points along the crest of the Valley Pit are suitable. However, there is evidence that targets located on lower benches might provide the stability required to be used as a reference point. This would require the use of a larger number (a minimum of 5) of well dispersed reference points so that slope movements in one area would not adversely affect the datum.
5) If logistically possible, reference points established at the pit bottom are expected to be more stable than along the pit crest. In addition, reference points located at the pit bottom would strengthen the geometry in determining vertical solutions. However, blasting would make these points somewhat temporary and at times very prone to movement.

It is believed that GPS is a viable solution for updating the RTS positions in the Valley Pit. This becomes even more evident when looking at conclusion (4) above. With the use of GPS, control points located around the pit rim can be virtually eliminated. This still requires additional investigations to verify that the accuracy of GPS elevation changes meet the requirements.

RTSs routinely surveying the Valley Pit walls with multiple cycles per day will be used to determine movement trends in near-real time. At HVC this monitoring system is tied into the mine's dispatch system to communicate early warnings of slope movements to mine operations and engineering personnel [Newcomen et al., 2000]. In turn, this information is used to update slope movement maps daily, weekly, or monthly, depending on movement rates and location of equipment and personnel at the pit bottom.

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