ACCURACY EVALUATION OF GEODETIC MONITORING OF DEFORMATIONS IN LARGE OPEN PIT MINES

Adam Chrzanowski
Canadian Centre for Geodetic Engineering
University of New Brunswick, Canada
E-mail: adamc@unb.ca

Rick Wilkins
A.Chrzanowski & Associates Ltd., Canada
E-mail: rwilkins@aca-ltd.com

Abstract: To optimize safety and production, open pit mines require the displacements of hundreds of targets to be continuously monitored using a fully automated monitoring system. Robotic total stations (RTS) with automatic target recognition provide the most efficient solution for this monitoring task. The ALERT system, developed in Canada, provides a fully automated software system for the collection, processing, and the visualization/analysis of the required monitoring data. However, the users of the system must understand that despite the increased precision and reliability of the new generation of RTSs, there are still problems in satisfying all of the monitoring demands. The most significant problems are: the accuracy limitation of RTS pointing to the object targets, the effects of atmospheric refraction, the instability of reference control point/RTS locations, and the configuration defects that arise through multiple-RTS networking solutions. Two examples of large open pit mines in both Western Canada and in the Andes in South America are presented and discussed in this paper. Solutions to some of the problems have already been incorporated into the ALERT software, but there are still some remaining problems, which require further studies.

1. INTRODUCTION

The stability of bench walls in open pit mines is a major safety issue. In general, there is usually a slow movement of the rock formation before a failure actually occurs. Therefore, with the continuous monitoring of creep and its acceleration in a deformation zone, warning can be given to evacuate equipment and personnel in advance of an impending failure. Due to the fracturing of the rock formation and the time dependent displacement phenomena, the monitoring systems in most large open pit mines require hundreds of targets to be continuously monitored with sub-centimetre accuracy at the 95% confidence level. Robotic total stations (RTS), with automatic target recognition (ATR), supported by software that controls fully automated data collection and data processing, provide the most efficient solution to the problem of displacement monitoring of such a dense array of targets.

Currently, Leica models TCA1800, TCA2003, and the more recent TCA1201 are among the most popular RTSs being used for monitoring displacements in open pit mines. The ALERT software suite ([1], [2]), developed at the Canadian Centre for Geodetic Engineering (CCGE) in cooperation with A. Chrzanowski & Associates (ACA) in Canada, provides powerful tools for fully automated RTS data collection, processing, analysis/visualization, and a user configurable alarm system that has many different levels of sensitivity. The system utilizes special algorithms for the automatic detection of unstable reference/RTS points and for the fully automated least squares adjustment of networks with configuration defects (i.e. multiple RTSs). The ALERT/RTS monitoring system has been operational at a number of large earth dams and large open pit mines in North and South America since 2000 (e.g., [3], [4])

Depending on the rock formations, some open pit mines require sub-centimetre displacement detection at the 95% confidence level [5]. These are very difficult requirements which cannot be obtained without addressing the following problems:

- The accuracy limits of the RTS/ATR pointing to the wall targets.
- The effects of atmospheric refraction, which is one of the oldest but still unresolved geodetic survey problem.
- The instability of reference/RTS point locations.
- The error propagation in connecting surveys between the RTS locations and stable reference points.
- The configuration defects inherent in multiple-RTS networks.
- The effect of multi-path and residual troposphere delay when using GPS for controlling the stability of RTSs.

Every mine site has different monitoring conditions and accuracy requirements. Therefore, each site requires some preliminary evaluation of the potential problems and achievable accuracy before a monitoring system can be successfully installed. This paper discusses and tries to quantify some of the above problems using data gathered with the ALERT/RTS system at two open pit copper mines, one in South America and the other in Western Canada.

2. EVALUATION OF ACCURACY LIMITS OF RTS OBSERVATIONS

2.1 Error Sources

An RTS observation triplet consists of both a horizontal and vertical direction combined with an electronically measured distance. In the context of deformation surveys, it is only the change in the measurements that is of interest and not the actual values themselves. Therefore, if the same instrument and the same procedures are used in the repeated surveys, the effects of the calibration and other constant systematic errors can be easily removed from the data set. Therefore, the determination of displacements of targeted points is generally expected to be more accurate than that obtained when determining the actual positions.

For RTSs mounted permanently in protective shelters, the main sources of error for the repeated horizontal/vertical direction measurements are the following:

- random errors of pointing to the target and
- systematic effects of atmospheric refraction (if the effects change with time).

The repeated distance measurements are mainly affected by the varying density of air (changes in meteorological conditions) and the resolution of the phase difference measurements. Most other sources of error found in distance measurements (i.e. calibration error, modulation frequency error, etc.) are strongly correlated in repeated distance measurements. This implies that if the same instrument is used to measure the distance in repeated cycles, these errors get differenced out in the displacement calculations. Therefore, for distances up to about 2000 m one may estimate that the accuracy of the distance differences (radial component of the displacement) can be obtained within a few millimetres at the 95% confidence level (even if meteorological measurements are only taken at the RTS site). This indicates that the displacement radial component can be determined cycle-to-cycle with a much higher accuracy than the remaining two perpendicular to the line of sight components. Therefore, the discussion below will primarily concentrate on the accuracy of horizontal/vertical direction measurements.

2. 2. Test Sites

The achievable accuracy of displacement monitoring using the ALERT system was determined from two data sets of continuous observations to a series of targets located at two different open pit mines, one located in the Andes in South America (named here as SA Mine) and the other in Western Canada named here as BC Mine). The two sites offer quite different environmental conditions.

The SA copper mining operation consists of several open pit mines at an elevation of approximately 3000 m above sea level. The largest of these pits has approximate dimensions of 2.5 km x 3.5 km (at the rim) with a depth of 1000 m. The area is very arid, with very predictable weather conditions of more than 300 sun days per year with an annual temperature ranges of about 3^0C to 28^0C with maximum day/night differences of about $15C^0$. The monitoring system at this pit consists of several RTS instruments (Leica TCA 1800, TCA 2003, and TCA 1201) located at strategic locations on the rim and at various elevations within the pit. All of these instruments are connected, controlled, and supported by the ALERT software system.

Fig 1 Typical view from an RTS shelter

In contrast, the BC copper mine in Western Canada is at an elevation of 1500 m at the rim with a depth exceeding 600 m. The weather is quite variable with temperatures ranging from -30°C in the winter to over +30°C during the summer.

At both mine sites, the RTSs are located at various elevations in protective shelters equipped with glass panel windows. Fig. 1 shows the front of a typical observation shelter with the view it has of the open pit mine in the background.

2.3 Evaluation of the pointing error

The pointing error of the direction measurements is primarily a result of two sources:

- The limit of the angular (instrumental) resolution of the automatic target recognition system.

- The random deflections of the line of sight produced by heat waves in the form of air bubbles (eddies) of varying density flowing across the line of sight([6], [7]. The size of the eddies may differ from a few millimetres to a few metres. On a sunny day the air eddies are very short and travel fast creating the effect of “shimmering” of the target image. However, during clear calm night conditions, the air eddies are longer and travel slower producing sudden deflections of the line of sight at time intervals that can range from a few seconds to a few minutes.

In field observations, the pointing error caused by the instrumental resolution of the automatic target recognition cannot be separated from the random deflections of the line of sight caused by heat waves. Therefore, only the combined effect can be analyzed.

The pointing error for the SA mine was determined from 46 hours of continuous observations to 10 selected targets at distances ranging from 380 m to 2500 m. The conditions during the measurements were clear skies with temperatures ranging from about 8°C to 22°C. The test data was gathered from two different locations using both the TCA1800 and TCA2003 instruments located at the pit rim.

At the BC mine, the pointing error was estimated from two sets of continuous observations with each having a duration of 45 days (July/August and October/November). Observations were analysed from 5 targets that were observed in varying atmospheric conditions of hot mid summer and cool late fall.

At both sites, the lines of observations were selected to represent observations across the open pit, along the bench walls, and over land. All the observation lines analysed show a diurnal cyclic pattern of changes in both the horizontal and vertical directions. This pattern indicates the effect of diurnal changes of atmospheric refraction. Fig. 2 illustrates this diurnal tendency for one series of direction observations obtained for one line of sight over the two day period.

In order to separate the errors of pointing from the systematic effects of refraction, the sample standard deviations of single pointing were calculated from differences (true errors) of consecutive pairs of observations (seperately for each position of the telescope). The results were grouped into 4 hour time intervals to analyse the calculated sample standard deviations at various time of the day. Due to the space limit of this presentation, only averaged standard deviations of pointing for daytime and nighttime conditions are listed in Table 1.

SITE	Horizontal Directions			Verical Directions		
	Daytime	Nighttime	24 hrs	Daytime	Nighttime	24 hrs
SA Mine	2.6“	3.7“	3.1“	4.0“	4.7“	4.3
BC Mine (July)	2.4“	2.3	2.3“	3.8“	3.8“	3.8“
BCMine (Nov.)	2.8“	3.4“	3.1“	4.1“	3.7“	3.9“

Table 1: Average standard deviations of single pointing (in seconds of arc)

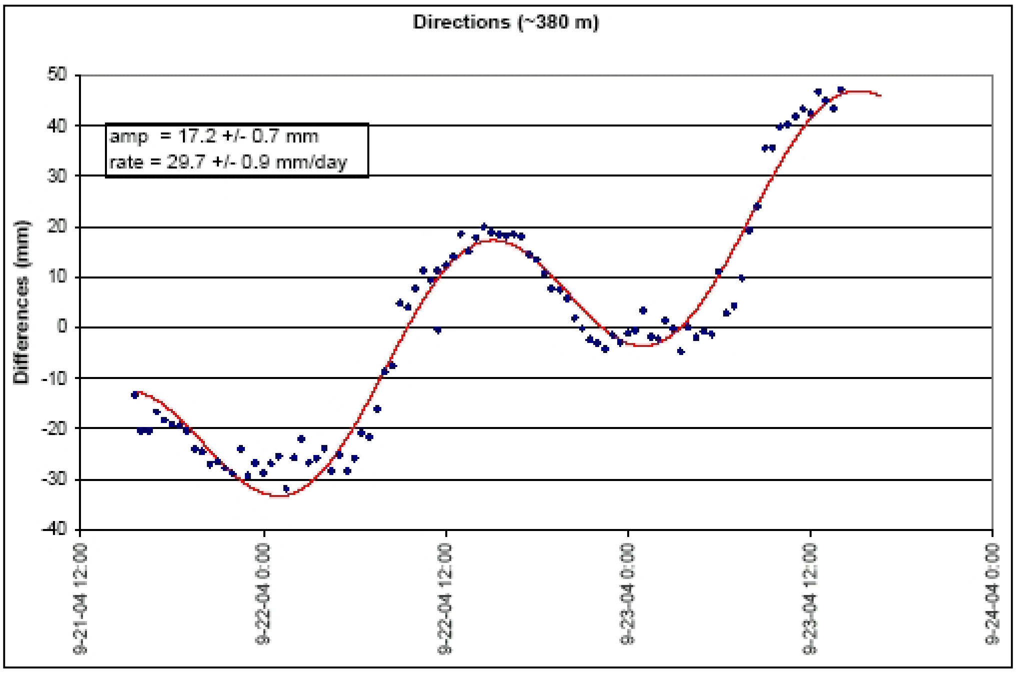

Fig. 2 Typical diurnal pattern of pointing changes

As expected, the horizontal directions show a better accuracy than the vertical directions. It is interesting to note that the achieved pointing accuracy at BC site is practically the same or only slightly better than at SA mine.The November result at BC mine, despite the much lower temperature than in July, do not give better results. Summarizing, one may say that the overall standard deviations of single pointings in the environment of open pit mines are about 3“ for horizontal directions and 4“ for vertical.

Since the random error of a direction measurement in one position of the telescope is equal to the error of an angle observed in one set (two positions of the telescope) between the reference and the object targets, the pointing error of 4" will produce an error of 40 mm at the 95% confidence level in the displacement determination of a point at a distance of 1000 m if observed in one set. Thus, if one would like to obtain, for example, the accuracy of 10 mm, the point would have to be observed in 16 sets of angle measurements (assuming that there are no other sources of errors).

2.4 Effects of Atmospheric Refraction

The refraction effects at both SA and BC mines were estimated from the described above series of continuous observations. The diurnal cyclicity of the plots (Fig.2), which was exhibited in the observations to all targets, can be explained by changes of the temperature gradients across the line of sight between the daytime and nightime observations. Table 2 lists the maximum observed diurnal changes Δe in the target positioning.

The positioning error e due to refraction is a function of the gradient of temperature dT/dx occuring across the line of sight. It can be derived from the basic theory of refraction that the approximate relationship between e and temperature gradient can be expressed by the equation:

$$e = \left(\frac{3.9Ps^2 10^{-5}}{T^2}\right)\frac{dT}{dx} \tag{1}$$

where: s distance to the target in [m]
P barometric pressure in [mb]
T absolute temperature [^{o}K]
$\frac{dT}{dx}$ temperature gradient [^{o}C/m] perpendicular to the line of sight

Since the effect of refraction increases proportionally to the square of the distance, it follows that the RTS locations should be as close as possible to the targets being monitored.

From the observed daily changes Δe, back analysis can be used to estimate the average changes of the horizontal (dT/dx) and vertical (dT/dz) temperature gradients required to cause the observed changes in the target position.

Distance [m]	Δe horiz. [mm]	Δe vert. [mm]	ΔdT/dx [C^o/m]	ΔdT/dz [C^o/m]	Comments
Effect of refraction at SA mines (September)					
380	35	90	0.7	1.8	About 1.2 m above terrain, partially over opening
391	56	130	1.0	2.4	About 1.2 m above terrain, partially over opening
975	120	60	0.36	0.18	Above opening, along the pit wall
1540	200	110	0.24	0.13	Across the open pit
Effect of refraction at BC mine (July)					
1457	180	60	0.19	0.06	Across opening
1371	175	60	0.21	0.07	Across opening
1154	140	75	0.24	0.13	Across opening, close to wall
872	100	50	0.30	0.15	Along but above the wall
89	9	7	2.56	1.99	Over land, close to the ground

Table 2 Maximum changes in position and back calculated average temperature gradients

The theory of free heat convection states that the gradient of temperature increases proportionally to the square of the sensible heat flux (difference between net incident radiation and heat flux into the ground) and is inversely proportional to the square of the density of air ([8], [9]). At an elevation of 3000 m the sun heat flux is expected to be larger while the density of air to be smaller than that seen at sea level. Therefore, it was expected that the temperature gradients at the SA mine would be larger than at the BC mine at lower elevation and in less arid conditions. The results shown in Table 2 do not quite confirm the assumption, particularly horizontal gradients, which are similar at both sites.

The temperature gradients shown in Table 2 were calculated under the assumption that a constant gradient takes place across the entire length of the line of sight, producing a circular refraction path. Of course in reality the gradient changes vary along the line according to changes of the topography of the heat radiating surface. The sight lines of 380m, 391m and 89m m in Table 2 show, as expected, the largest temperature gradients. The three lines are similar in that they are only about one metre above the ground with a portion running very close to the edge of the pit, thus for these lines the horizontal temperature gradients are also significant.

It must be noted that the effects of refraction are much more severe when large temperature gradients occur near the RTS rather than if they occur closer to the target [10]. This is important criteria to consider when designing the location of RTS stations.

The effect of refraction can be minimized either by daily averaging of the monitoring results or by developing a technique that would model and predict the effects of refraction as a function of the time of day. The day-to-day pattern of the refraction effects is expected to be quite regular in the predictable weather conditions at the SA mine. Therefore, the daily averaging would practically remove the systematic effect of refraction if daily results (one averaged monitoring result every 24 hours) are sufficient. If more frequent results are needed, the modelling and prediction technique must be developed. Otherwise, cycle-to-cycle (epoch-to-epoch) results will show large erroneous displacements. For example, if observation cycles would be repeated every three hours, than the cycle- to-cycle horizontal refraction errors to the target at the distance of 1457 m at the BC mine or to the target at the distance of 1500 m at the SA mine could reach the value of 180/4 = 45 mm and 200/4 = 50 mm repsectively.

3. 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.

A methodology utilizing an iterative weighted similarity transformation (IWST) of displacements for the identification of unstable reference points was developed at the University of New Brunswick [11] in the early 1980s. The methodology is based on using the similarity transformation of displacement components d_i with the condition $\Sigma|d_i|$ = min. The weights of individual displacement components are inversely proportional to the absolute value of the component itself. The transformation is an iterative process that is repeated until subsequent iterations reach a preselected convergence criterion. The IWST method has been successfully applied in all types of engineering projects where reference point stability has been a concern.

ALERT software includes the fully automated identification of unstable reference points using the IWST and removes the unstable points from the datum definition for displacement calculations. In order to get the optimal results it is recommended to have a minimum of 5 reference points with good geometry included into the monitoring scheme.

4. CONNECTING SURVEYS TO STABLE REFERENCE POINTS

Monitoring schemes in open pit mines not only have wall targets to be monitored, but must include several stable reference points located beyond the effects of mining. Usually, the reference points are located outside of the pit close to the rim. Very often, in order to minimize the distances from the RTS to the observed wall, the instruments must be located on the wall benches below the rim or even at the bottom of the pit in potentially unstable environments. In addition to being potentially unstable, this creates a problem in obtaining direct visibility from those RTSs to the reference points.

Two possible solutions are recommended:

- In the case when multiple RTSs are being used, the observations between the RTSs combined with observations to common reference points are included into the monitoring scheme. This allows the reference information to be brought into the pit using a network approach.
- If it isn't possible to position the RTSs in the pit t o have direct visibility to reference points than GPS observations are included at each RTS. This allows the RTS positions to be automatically updated by this hybrid RTS/GPS approach.

The use of RTS/GPS hybrid system has been discussed in an earlier publication [12].

The network connection between the RTS shelters and the stable reference points is accomplished by obsereving selected distances and directions between the RTSs themselves and between RTSs and the reference points. Since the RTS observations are made through glass panels of their shelters to eccentrically mounted prisms at other RTSs, configuration defects are created in the network. In deformation surveys, the configuration defects are overcome by performing the network adjustment using observation differences. The ALERT software provides a fully automatic network adjustment using this observation difference approach. The adjusted changes in the observations between any two cyclces of observations result in obtaining corrected coordinates of the RTSs, which are automatically included in the process of calculations of displacements of the wall targets.

The main problem of the networking surveys in large open pit mines is the changeable visibility between network points. Moving machinery, dust, and changeable weather conditions do not allow for all the targets to be observed in each cycle of the network observations. This causes changes of the network configuration between the repeated surveys, which in turn may produce biases to the orientation of the network and to the corrected coordinates of the shelters. Therefore, the connecting network requires a very careful design and preanalysis of its accuracy and reliability with a good margin left for the possible configuration changes. As large number of redundant observations should be included into the observation scheme.

On the example of connecting surveys at SA mine (8 RTSs and 12 reference control points with some distances exceeding 2500 m), one can detect displacements (day to day) of RTSs with a sub-centimtere accuracy at 95% confidence level if the network is observed in several cycles, which are evenly spread over 24 hours and averaged. The same network, if observed only in one cycle gives the accuracy (cycle to cycle) of RTS displacements of about 10-30 mm with possible much larger individual "spikes" depending on the configuration change due to missing observations.

4. CONCLUSIONS

Random effects of heat waves flowing across the line of sight and systematic effects of refraction still remain as the main problems in determining displacements through geodetic measurements. Both effects can be succesfully controlled if a number of sets of angular meaurements are evenly spread and averaged over 24 hour periods. To increase the accuracy and frequency of results, more work is required on developing techniques for modelling and filtering the effects of pointing errors and refraction.

At present, sub-centimetre accuracy of displacement detection at 95% confidence level is achievable on a daily basis (one averaged result every 24 hours). This result is obtainable from single RTS observations to target points that have lines of sight of 600 m or less. At distances up to 1200 m, displacements of 20 mm (at 95% confidence level) can be detected with observations from a single RTS. Since the accuracy of distance measurements with RTS is considerable higher than of the direction measurements, the accuracy and frequency of results of horizontal displacements can be dramatically increasd when distances to the targets are measured from two or more RTSs simulatneously. Here, one has to weigh the accuracy vs. economy. The above accuracies do not include (if applicable) errors of network connection to the reference points.

Problems of instability of reference points and RTS locations have been solved by including the iterative weighted similarity transformation (IWST) of diplacements into the automatic data processing.

Despite the problems discussed above, displacement monitoring with robotic total stations remains the most efficient method for high frequency monitoring results. All the discussed problems must be carefully considered when designing a monitoring scheme.

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