SUBSIDENCE MONITORING IN MOUNTAINOUS TERRAIN - AN EXAMPLE OF FOUR DIMENSIONAL PHOTOGRAMMETRY

Prof. Dr. Ing. W. Faig
University of New Brunswick
Canada

Commission V - XVth ISPRS Congress, Rio de Janeiro

ABSTRACT

Subsidence monitoring has become a real concern in mining areas because of safety considerations and increased ecological awareness. Among the physical and geometric monitoring methods, four dimensional photogrammetry can play a major role because of its area coverage and instantaneous recording capability.

Different photogrammetric approaches are discussed in this paper, with special consideration of problems and constraints due to alpine terrain conditions. Results of several years' monitoring above a hydraulic coal mine in the Rocky Mountains are given and compared to values obtained by other means.

RESUME

Le contrôle des affaissements est devenu un sujet d'inquiétude dans les régions minieres en raison des considérations de sécurité et de la conscience écologique. Parmi les méthodes de contrôle basées sur la physique et le géométrie, la photogrammétrie a quatre dimensions peut jouer un rôle prédominant a cause de son champ d'application et de ses capacitées d'enrégistrement instantanées.

Différentes approches photogramméteriques sont en discussion dans ce dossier, donnant des considérations speciaux aux problemes et aux constraintes causés par des conditions de terrain alpines. Des résultats de quelques années de contrôle au-dessus d une mine de charbon hydraulique dans les Montagnes Rocheuses sont donnés et sont comparés a des valeurs obtenues par d'autres moyens.

ZUSAMMENFASSUNG

Im Zusammenhang mit Umwelts - und Landschaftsschutz, sowie aus Sicherheitsgrunden hat die Uberwachung von Bergschaden betrachtlich an Bedeutung gewonnen. Mit der für sie charakteristischen Kurzzeitregistrierung und flachenhafter Uberdeckung, kann die vierdimensionale Photogrammetrie eine wichtige Rolle unter den physikalischen und geometrischen Uberwachungsverfahren spielen.

Dieser Beitrag behandelt verschiedene photogrammetrische Verfahren, insbesondere im Zusammenhang mit den von der Hochgebirgslage herruhrenden Problemen und Einschrankungen. Die Ergebnisse einer mehrjahrigen Uberwachung im Bereich eines hydraulischen Kohlebergwerks in den Rocky Mountains werden mit von anderen Verfahren erhaltenen Werten verglichen.

INTRODUCTION

Generally, subsidence is defined as a downward vertical displacement due to settling of overlaying rock formations into empty spaces created by mining operations. In highly mountainous terrain, this may often be accompanied by horizontal displacements, resulting in a sliding movement.

Subsidence monitoring has been an important task for many years in Europe where coal and minerals are being exploited beneath densely populated areas. Based on results obtained, prediction theories have been developed for various depth and strata conditions (e.g., Kratsch, 1974; Budryk & Knothe, 1953). These however, are applicable to flat and moderately undulating terrain only, which is not sufficient for the Canadian scene, where large coal mining operations take place in highly mountainous areas.

The growing awareness of our environment, improved safety regulations as well as the fact that our dwindling resources eventually have to be exploited beneath populated areas, has generated much concern and interest in the subject.

With no suitable prediction theories available, subsidence measurements at selected mountain sites have a two-fold purpose, namely to monitor specific movements and to gather data which together with information on overlaying rock masses can be utilized in the formulation of prediction theories.

Following the European approaches, which are also extensively applied elsewhere (e.g. Milliken, 1979), precision surveying approaches as well as rock mechanics studies, employing electronic and mechanical sensors such as tiltmeters, are now used in a number of mining areas in Canada (Chiang et al., 1979; Chrzanowski et al., 1980).

All these efforts are based solely on data obtained at specific points and thus do not do justice to the area coverage needed to represent such an area phenomenon, unless the point density is very high. The latter is no problem in Central Europe where - unlike in Canada - dense geodetic control is available. Therefore the application of photogrammetry has gained little use in this field (Bohonos, 1976).

Yet, a photograph represents a complete and instantaneous record of an object - in this case, terrain affected by subsidence. A series of instantaneous records at different epochs thus provides an excellent measure of the terrain changes due to subsidence.

Although geodetic methods can provide higher absolute accuracies, the time required for a comprehensive survey may encompass several stages of settlement, which means that actual movements are left undetected as they just reduce the accuracy of the survey.

By shifting the actual measuring task from the field to the office, the completeness of photographic recording becomes very useful, as it is possible to go back to previous stages or to extend the measurements into areas previously assumed to be stable.

There are, of course, some drawbacks to photogrammetry as well, most notably the slow turn around time, and sometimes the accuracy limitation. It is thus desirable to combine and integrate photogrammetry with other geometric and physical monitoring systems for optimum results.

PHOTOGRAMMETRIC APPROACHES

A photograph is a two dimensional image of a three dimensional object. Two photographs of the same object, taken from different stations are needed to recover the third dimension (stereophotogrammetry), provided that they are either taken simultaneously, or else the object remains stationary and stable during the time between exposures. With other words, the fourth dimension (time) has to remain without influence, otherwise the result becomes incorrect. Just as two dimensional coverage from two different stations provides the 3rd dimension, three dimensional coverage at two different epochs provides the 4th dimension, namely the change of the object during the time interval between epochs.

With a changing object, simultaneous exposures are then required for proper stereocoverage. However, if the rate of change of the object is small, sequential exposures within a short time interval as given during aerial photography will not cause significant errors. This, of course is far superior to geodetic surveys, where the time for one complete series of observations is measured in days (hours at best), not in seconds.

Equivalent to the need of common points for relative orientation, there is a requirement for stable points between epochs. These could either be located in object space or else in image space. The latter case (e.g., projection centre plus principal point) would be ideal, as it is independent of the situation in object space, however is difficult, if not impossible to achieve.

A special approach can be utilized when the direction of movement is known. If it is possible to arrange the x-axis to be parallel to it, then multiple photographs with unchanged exterior and interior orientations provide "motion parallaxes", and thus a "stereo image" of the movement. This has been successfully applied to glacier movements using terrestrial as well as aerial photogrammetry (Faig, 1966) where reductions due to changes in exposure station and attitude are required. For subsidence monitoring, where the major component of movement is vertical, this special case is not applicable.

In addition to purely interpretive methods (using any type of remote sensing), where changes are noted and recorded without actually measuring them (Earth Satellite Corp., 1975; Russel et al., 1979), the following photogrammetric evaluation methods can be applied:

-- comparison of contour lines for the two epochs;
-- movement determination using mathematically defined object points (i.e., grids, profiles);
-- movement determination using physically defined points (i.e., targetted or natural points).

The first two are based on elevation measurements and thus on the assumption that subsidence is primarily a vertical movement, which does not necessarily hold under difficult terrain conditions as apparent from the tests described later in this paper.

The third approach is generally valid and thus will be treated in more detail in the following section.

Contour comparison takes advantage of the analogue information in photographs. Using photographs from different epochs, two or more sets of contours are produced and superimposed. Any differences exceeding the plotting accuracy signify subsidence. This method has been successfully applied in glacier studies, and is most effective in flat terrain with smaller contour intervals. However, even then it provides more a general impression that a quantitative evaluation.

Similar to geodetic approaches, mathematically defined points located along profiles or in grids are utilized where photogrammetry replaces conventional elevation measurements. This method can be further generalized without the requirement of even recovering the same mathematical locations by forming a digital elevation model for each epoch. This type of measurement has been successfully applied in open pit mining and volume determination, as well as in subsidence areas in flat terrain. It provides elevation changes accurately, and for further processing, digital mapping techniques can be readily adapted. It is most suited for automation.

GENERAL APPLICATION OF 4D-PHOTOGRAMMETRY

As mentioned before, the purpose of 4D-photogrammetry is to determine movements in object space which occured during the time span between stereo coverages. Since it is quite possible that ground control is also subjected to movements, it is desirable to compute the movement vector in an arbitrary system, e.g. the model coordinate system of one of the epochs, and subsequently perform an absolute orientation. This means that the ground control needs to be coordinated for one epoch only.

According to (Moffit et al., 1980), the model coordinates of an epoch A can be calculated after the five parameters of relative orientation have been defined analytically with the aid of the coplanarity condition. They are

$$\begin{bmatrix} X_M \\ Y_M \\ Z_M \end{bmatrix}_A = \begin{bmatrix} X_{01} \\ Y_{01} \\ Z_{01} \end{bmatrix} + \lambda \begin{bmatrix} u_1 \\ v_1 \\ w_1 \end{bmatrix} + (0.5)d \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} \qquad (1)$$

where

$[Z_M\ Y_M\ Z_M]^T$ = model coordinates of epoch A

$[X_{01}\ Y_{01}\ Z_{01}]^T$ = arbitrary coordinates of the left perspective centre

$[u_1\ v_1\ w_1]^T$ = refined photo-coordinates of the left photo

$[e_x\ e_y\ e_z]^T$ = vector components of the minimum distance between two conjugate rays

λ, d = scalar multipliers (functions of relative orientation parameters)

An absolute orientation of that model if possible and desired, is achieved by a spatial similarity transformation.

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix}_G - SR_{(\omega,\phi,\kappa)} \begin{bmatrix} X_{MA} \\ Y_{MA} \\ Z_{MA} \end{bmatrix}_i - \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = 0 \qquad (2)$$

where

$[F_1\ F_2\ F_3]^T$ = functions of similarity transformation

$[X_P\ Y_P\ Z_P]_G$ = object coordinates of point P_i

$[X_{MA}\ Y_{MA}\ Z_{MA}]_i^M$ = model coordinates of point P_i in epoch A

$[X_T \; Y_T \; Z_T]^T$ = translation vector

$R_{(\omega,\phi,\kappa)}$ = rotation matrix

S = scale factor

Depending on the type of the available ground control points, either all the equations of (2), or the first two, or the last, can be used to determine the 7 unknown parameters. Equation (2) is of the form $F(\bar{X},L) = 0$ and has the following linearized form (Wells et al., 1971),

$$A\,X + B\,V + W = 0 \tag{3}$$

in which

$${}_mA_7 = \frac{\partial F_{j=1,3}}{\partial X_{i=1,7}}, \quad {}_7X_1 = [\delta S,\ \Delta\omega,\ \delta\phi,\ \delta\kappa,\ \delta XT,\ \delta ZT]^T$$

$${}_mB_n = \frac{\partial F_{j=1,3}}{\partial L_{i=1,n}}, \quad {}_nV_1 = [v_{XM1} \; v_{YM1} \; v_{ZM1}, \; \ldots \;, \; v_{ZMn}]^T$$

$${}_mW_1 = [F_1^o \; F_2^o \; F_3^o \; \ldots \; F_m^o]^T$$

m = $2H + V$, $n = 3(H + V)$
H = number of horizontal control points
V = number of vertical control points

The superscript (^{o}) indicates that W is the value of the function computed from initial approximate values of the 7 unknown parameters.

After the 7 parameters have been computed, the scale and the rotations are stored for further processing. Computation of the object coordinates from model coordinates of epoch A is optional.

Similarly, the model coordinates of epoch B are computed (equation (1)) again after the appropriate relative orientation parameters have been defined analytically.

Then, a spatial similarity transformation is applied to transfer model epoch B to the model coordinate system of model epoch A. Reference points, i.e., points which appear in both models but are not affected by movements, are used to determine the transformation parameters using equation (2). The seven unknown parameters are computed similarly to equation (3). The only difference lies in the formation of the design matrix B. Here B consists of two submatrices since the model points of epoch A are treated as observations and thus have their own covariance matrix. Therefore,

$${}_{[2H+V]}B_{[6(H+V)]} = [B_1 \quad B_2]$$

and

$B_1 = \dfrac{\partial F}{\partial L_A}$, L_A = observations corresponding to model epoch A

$B_2 = \frac{\partial F}{\partial L_B}$, L_B = observations corresponding to model epoch B

In addition, every reference point provides three observation equations because its x,y,z model coordinates are known.
At this stage every point in the area of interest subjected to movement will have two sets of coordinates, since epoch A and B respectively are referred to the same coordinate system. Obviously, the differences between each pair of coordinates represent the model displacement vectors.

$$\begin{bmatrix} dX_M \\ dY_M \\ dZ_M \end{bmatrix}_i = \begin{bmatrix} X^1_{MB} \\ Y^1_{MB} \\ Z^1_{MB} \end{bmatrix}_i - \begin{bmatrix} X_{MA} \\ Y_{MA} \\ Z_{MA} \end{bmatrix}_i \tag{4}$$

where

$[dX_M \; dY_M \; dZ_M]^T_i$ = model displacement vectors of point P_i

$[X^1_{MB} \; Y^1_{MB} \; Z^1_{MB}]^T_i$ = coordinates of point P_i of model epoch B in the model epoch A coordinate system

$[X_{MA} \; Y_{MA} \; Z_{MA}]^T_i$ = coordinates of point P_i in model epoch A coordinate system

Now the actual components of the displacements along the three ground coordinate directions are obtained by applying the already stored 4 parameters (scale and rotations) to the model displacement vectors. Explicitly, the ground displacement vectors are given by:

$$\begin{bmatrix} DX \\ DY \\ DZ \end{bmatrix}_i = SR_{(\omega,\phi,\kappa)} \begin{bmatrix} dX_M \\ dY_M \\ dZ_M \end{bmatrix}_i \tag{5}$$

STUDY AREA

This project is part of an extensive study on strata mechanics in connection with a hydraulic coal mining operation in rugged Rocky Mountain terrain in British Columbia. The coal seam is very thick 12 to 14 m with a steep dip angle of 30° to 50°. As shown in Figure 1, the surface terrain rises steeply from the outcrop of the seam, resulting in a rapid change of cover depth.

The strata above the mined seam is adversely affected by roof caving, which is evident in faults, folds and washouts. Since 1975, limited monitoring of the surface subsidence above the extraction panels has been carried out, first by intersection surveys to fixed targets, later by electronic tacheometry. In the last few years, a series of tiltmeters were placed on the slope and tied into a telemetric system (Chrzanowski et al., 1980). The whole area was also covered by three sets of aerial photography (at 1:7000 photo scale) flown at yearly intervals. The surveying and tilt information thus provides data for independent check of the photogrammetric work.

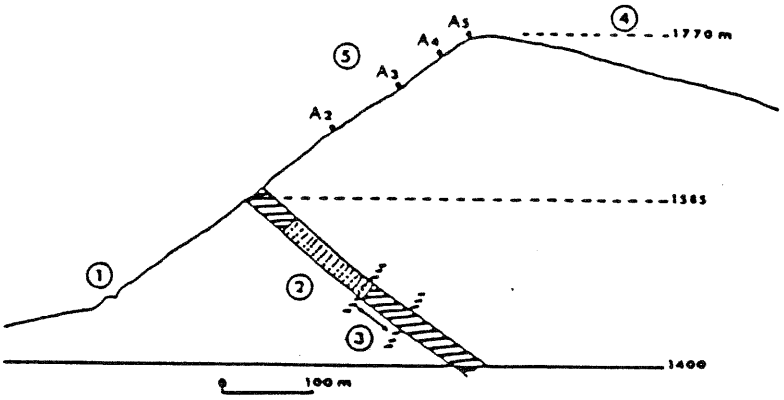

Fig. 1: Terrain and Coal Seam Cross Section.
1) haul road; 2) exploited area; 3) planned exploitation;
4) elevation; 5) physical subsidence stations

EVALUATION OF THE PHOTOGRAPHY

Preliminary studies showed that under these extreme topographic conditions the horizontal subsidence component is often nearly as large as the vertical one, thus a combination of sliding and settling occurs. With mathematically defined points (profiles, DTM), only partial information on the subsidence is obtained as illustrated in Figure 2. Thus this method was not further pursued, and only physically defined object points were measured.

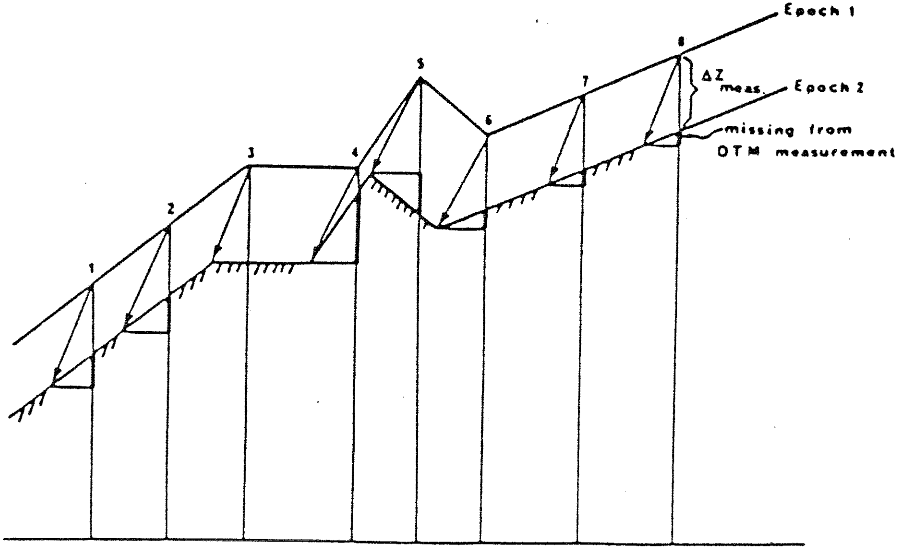

Fig. 2: Movement vectors and height variation.

Pretargetted points appear ideal, and have been utilized in some projects (Brown, 1973 & 1982), however they require a rather controlled and maintained environment, which is seldom available. Easily identified natural points are quite suitable, however, their number and distribution is often such that the coverage is spotty at best. This problem was overcome by using stereo cross-identification between epochs. Having the photographs of the same approximate scale, the left dispositive of epoch A was set onto the left picture-carrier of a Wild PUG4 Point Transfer Device. On the right picture-carrier the right diapositive of epoch B was set. This arrangement has three benefits: First the points are marked permanently on the diapositive for further processing. Secondly, it verifies the points appearing on the photographs in both epochs, and thirdly, it facilitates the measuring procedure.

Since the points are marked on one photograph of each epoch, their stereo identification is easily achieved with the overlapping photograph of the corresponding epoch. Utilizing the model displacement vector method, photography for three epochs was evaluated.

The absolute accuracy of the photogrammetric results is evident from comparison with movements between epochs 1 and 2 obtained by ground surveying techniques of targetted points as shown below.

In addition, Figure 3 shows a comparison between the horizontal movement vectors obtained from photogrammetric results and from the ground surveying techniques.

The movements between epochs 2 and 3 were significantly smaller, however, there was again excellent agreement between photogrammetric and surveying results.

Comparison of Coordinate Differences E2-E1.

	ΔX[m]		ΔY[m]		ΔZ[m]	
Point No.	Photo	Survey	Photo	Survey	Photo	Survey
50	-0.84	-0.83	-0.28	-0.32	-0.81	-0.73
51	-0.69	-0.73	-0.28	-0.24	-0.59	-0.51
52	-1.31	-1.28	-0.66	-0.57	-1.09	-1.15
53	-1.15	-1.15	-0.48	-0.58	-0.91	-0.95
54	-0.61	-0.69	-0.35	-0.38	-0.65	-0.62
T1	-0.41	---	-0.16	---	-0.54	---
T2	-0.07	0.00	0.00	0.04	-0.02	-0.08
T3	0.00	-0.02	0.04	0.01	-0.04	-0.06

NOTE: Point T1 was surveyed only once thus no movement can be computed.

The accuracy of the displacement vectors as determined by photogrammetry was thoroughly investigated. In addition to the standard deviation for unit weight, the variance-covariance matrices for each point in both epochs were determined. Using this information, error ellipsoids at the 95% confidence level were computed. The displacements were tested against these using the χ^2 test for significance. With one exception, all movements passed the test and thus have to be considered significant. Furthermore, the variances were propagated to the displacement vectors to obtain a standard deviation for each displacement. These standard deviations averaged 2 cm with several being as low as 2 or 3 mm, while one reached 4.9 cm. Even this largest standard deviation represents only 7 μm in the photograph for the 1:7000 photo scale.

Since ground control was available for each epoch, the photogrammetric results were verified by independent evaluation using two bundle adjustment programmes GEBAT (El Hakim, 1979) and UNBASC2 (Moniwa, 1977).

The model displacement method however proved to be indispensible when the area of coverage had to be extended well beyond the control for the original flight. A second set of photographs plus newly coordinated control within the active area was sufficient to obtain the necessary results, which not only confirmed predicted values, but also located a fault line, which was later verified on site.

CONCLUSIONS

This investigation showed that 4D-photogrammetry is well suited for subsidence monitoring as it provides the required accuracy and desired area coverage. It also proved that methods which have been successfully applied to flat terrain cannot necessarily be transferred to areas with extreme topographical conditions. There are of course a few problems with ground coverage and vegetation as well as with different shadow combinations for the different photographic missions, thus somewhat influencing the coverage and point density. These however are not critical.

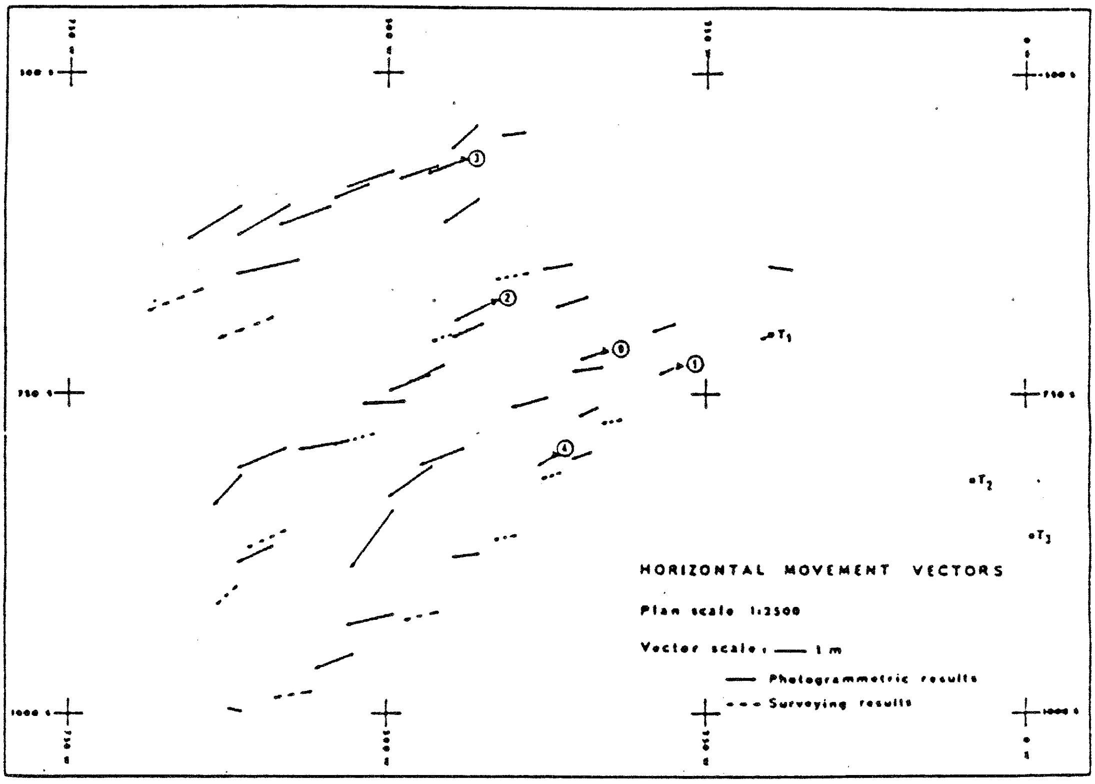

Fig. 3: Horizontal movement vectors.

ACKNOWLEDGEMENTS

The author wishes to acknowledge with thanks the contributions made by his assistant, Mr. C. Armenakis, and by Dr. A. Chrzanowski (UNB) and Dr. Y.M. Fisekci (CANMET) towards the successful completion of the photogrammetric investigation.

REFERENCES

Armenakis, C. (1983) "Subsidence Determination by Aerial Photogrammetry" M.Sc.E. Thesis, Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B.; also UNB Technical Report No. 93.

Bohonos, B. (1976) "Determination of Large and Fast Changing Displacements and Deformations of Mining Surfaces on the Basis of Earlier Photographs and the Results of their Use" (in Polish) Proceedings of the Institute of Geodesy and Cartography, Warszawa, Poland.

Brown, D.C. (1973) "Accuracies of Analytical Triangulation in Applications to Cadastral Surveying" Surveying and Mapping, Vol. XXXIII, No. 3.

Brown, D.C. (1982) "STARS - A Turnkey System for Close Range Photogrammetry" Proceedings of the Symposium on Precision and Speed in Close Range Photogrammetry, York, England, Int. Archives of Photogrammetry 24(5).

Budryk, W. and Knothe, S. (1953) "Einfluss des Untertageabbaus auf die Erdoberflache vom Gesichtspunkt der Sicherung der Objekte" Bergakademie ; 5:59-62; 1953.

Chiang, C.S.W., Fisekci, M.Y., Bannerman, W. (1979) "Strata Control Instrumentation at Hydraulic Operation Mining of a Thick and Steep Coal Seam in Western Canada". Proceedings of the 3rd Canadian Symposium on Mining Surveying and Rock Deformation Measurements, Sudbury, Ontario.

Chrzanowski, A., Faig, W., Kurz, B., Makosinski, A. (1980). "Development, Installation and Operation of a Subsidence Monitoring and Telemetry System", Report submitted to CANMET, Calgary.

Earth Satellite Corporation (1975) "Use of Photo Interpretation and Geological Data in the Identification of Surface Damage and Subsidence". Report ARC-73-111-2554, prepared for Appalachian Regional Commission. Department of Environmental Resources, Commonwealth of Pennsylvania.

El Hakim, S.F. (1979) "Potentials and Limitation of Photogrammetry for Precision Surveying" Ph.D. Dissertation, Department of Surveying Engineering, Unviersity of New Brunswick, Fredericton, N.B.; also UNB, Technical Report No. 63.

Faig, W. (1966) "Photogrammetry Applied to Arctic Glacier Surveys" Defence Research Board #D Phys R(G) Hazen 27, Ottawa.

Faig, W. Armenakis, C. (1982) "Subsidence Monitoring by Photogrammetry" Proceedings of the Fourth Canadian Symposium on Mining Surveying and Deformation Measurements, Banff, Alberta.

Kratzsch, H. (1974) "Bergschadenkunde", Springer-Verlag Berlin, New York.

Milliken, B.E. (1979) "Coal Subsidence Surveys - Illawarra Escarpment, N.S.W., Australia". Proceedings of the 3rd Canadian Symposium on Mining Surveying and Rock Deformation Measurements, Sudbury, Ontario.

Moffit, F.H. and Mikhail, E.M. (1980) "Photogrammetry" Harper & Row Inc., New York, 3rd edition.

Moniwa, H. (1977) "Analytical Photogrammetric System with Self-Calibration and its Applications". Ph.D. Dissertation, Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B.

Russell, O., Ameto, R., Leshendok, T. (1979) "Remote Sensing and Mine Subsidence in Pennsylvania" ASCE - Transportation Engineering Journal, Vol. 105, No. TE2.

Wells, D.E. and Krakiwsky, E.J. (1971) "The Method of Least Squares". Lecture Notes No. 18, Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B.