DIGITAL ELEVATION MODEL FOR PHOTOGRAMMETRIC MEASUREMENTS OF SOIL EROSION

Dr. Julian C. Barbalata, professor
Dr. Roland Lebel, professor

Université de Moncton, ESF
165, Boulevard Hébert, Edmundston
New Brunswick, E3V 2S8, Canada.

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ABSTRACT

A mathematical model was developped for both stereophotogrammetric measurements and digital elevation model, to monitoring soil erosion. The model is based on projective methods and simultaneously adjusts ground distances and image plate coordinates by the least squares method. This formulation provides complete flexibility in the weighting of the photogrammetric observations and on the type of control necessary in the scaling and the orientation of the model. The end product of the photogrammetric process is a list of coordinates which define the spatial position of a finite number of discrete points. An interpolation procedure was used for modeling functions of two independent variables with irregular control distribution points. Practical experiments were carried out with UMK-1318 camera in clear cutting areas of an experimental forest. The photogrammetric measurements were performed on a Wild Aviolyt BC2 plotter and were processed by the author's programs DISTANCE and SURFACE.

KEY WORDS : Analytical Photogrammetry, Theory, DEM, Change Detection.

## INTRODUCTION

Soil erosion which leads to a decrease in soil productivity, is a major problem in forestry areas, especially after a clear cutting. (Sneddon &Jordan,1983).

Microtopography and movement of soil can be determined by measuring the elevation above a datum of a series of points defining a surface. If two measurements are made at different times, the change in elevation indicates whether erosion or deposition is occuring as well as the volume of of soil moved (Barbalata, 1972; Frasier & Hooper, 1983; Jackson & Ritchie, 1988; Lyon & All, 1986)

However, topographic methods of measurement (transit or level surveys and erosion pins) are cumbersome to implement and often of insufficient frequency or accuracy to detect small changes resulting from erosion process. Close- range photogrammetry, on the other hand, offers a means of obtaining accurate measurements of eroded surfaces and the differencies between these surfaces at different times, can give an indication of erosion or of deposition patterns and volumes (Welch & Jordan, 1983).

For these reasons, close-range photogrammetry was used to measure soil erosion resulting from forestry activities and a specific analytical photogrammetric model was developped to determine the ground coordinates of a grid points. Based on this three-dimensional coordinate file, a digital elevation model was developped and used to define the surface at a certain time.

## THE MATHEMATICAL MODEL OF COMBINED PHOTOGRAMMETRIC AND GEODETIC ONSERVATIONS

The idea of the bundle adjustment is to use the well known collinearity equations in order to obtain a unique solution for the system of observation equations by the least squares method (Armenakis & Faig, 1988; Barbalata, 1979, 1988-b, 1988-c, 1990; Brown,1976).
A mathematical model is presented in this paper, involving the bundle adjustment associated with geodetic distance measurements.

The observation equations which are appended to photogrammetric observation equations, are generated by a number "p" of slope distances "d", measured by precise surveying methods between the points which appear on the photographs. The equation had to be transferred into a Cartesian coordinate system and are given in linearized form (Barbalata, 1980) by the equation:

$$\bar{v} + \mathring{D}\Delta d = L \tag{1}$$

where:
$\bar{v}$ = residual vector in slope distance "d" equations,
$\mathring{D}$ = coefficient matrix of the Jacobians in slope distance equations,
$\bar{\Delta}_d$ = correction vector of coordinates of points which define the ends of each distance "d".
L = vector of discrepancy in slope distance equations.

The complete mathematical model is obtained by combining the photogrammetric linearized observation equations with equation (1):

$$\begin{bmatrix} v \\ \mathring{v} \\ \bar{v} \end{bmatrix} + \begin{bmatrix} B & \bar{B} & 0 \\ \mathring{B} & 0 & 0 \\ 0 & 0 & \mathring{D} \end{bmatrix} \begin{bmatrix} \Delta \\ \bar{\Delta} \\ \bar{\Delta}_d \end{bmatrix} = \begin{bmatrix} E \\ G \\ L \end{bmatrix} \tag{2}$$

where:
v = residual vector in collinearity equations,
$\mathring{v}$ = residual vector in constraint equations,
B = Jacobians in collinearity equations for orien tation parameters,
$\bar{B}$ = Jacobians in collinearity equations for ground object points,
$\mathring{B}$ = Jacobians in constraint equations.
$\Delta$ = correction vector of the orientation parameters,
$\bar{\Delta}$ = correction vector of the ground object coordinates.

The normal equations for a least squares solution are then given by the following expression:

$$\begin{bmatrix} N + \mathring{N} & \hat{N} \\ \hat{N}^T & \bar{N} + \bar{N}_d \end{bmatrix} \begin{bmatrix} \Delta \\ \bar{\Delta} \end{bmatrix} = \begin{bmatrix} C + \mathring{C} \\ \bar{C} + \bar{C}_d \end{bmatrix} \tag{3}$$

The correction vector $\bar{\Delta}$ with dimensions 3nx1 is defined by two components:

$\bar{\Delta}_d$ with dimensions 6px1 and

$\bar{\Delta}_f$ with dimensions (3n-6p)x1

The coordinate corrections of the points included in $\Delta_d$ vector involve the contribution of observations of geodetic distances to photogrammetric observations of the end points of distance "p", whereas the $\Delta_f$ vector is concerned with (n-2p) points which were observed only photogrammetrically.

In the case of correlated observations, $\bar{N}_d$ is a full matrix which implies to invert a (6px6p) matrix and a number of n-2p matrices with (3x3) dimensions.

If the geodetic distance observations are considered as uncorrelated, then one can simplify the inversion of $\bar{N} + \bar{N}_d$ matrix. This operation is reduced to the inversion of a number of p matrices with dimensions (6x6).

By virtue of the structure of $\overset{\circ}{D}, \bar{\Delta}_d$ , $\bar{W}$ and L, the normal equations can be expressed in the expanded form:

$$\underset{(6x6)}{\bar{N}_d} = \text{Diag}\,(\underset{(6x6)}{\bar{N}_{d_1}}, \underset{(6x6)}{\bar{N}_{d_2}}, \ldots\ldots \underset{(6x6)}{\bar{N}_{d_p}})$$

$$\underset{(6x1)}{\bar{C}_d} = \left[\bar{C}_{d_1}\ \bar{C}_{d_2} \ldots\ldots\ldots\ldots\ldots \bar{C}_{d_p}\right]^T \tag{4}$$

$$\underset{(pxp)}{\bar{W}} = \text{Diag}\,(\underset{(1x1)}{\bar{W}_1}, \underset{(1x1)}{\bar{W}_2}, \ldots\ldots\ldots\ldots \underset{(1x1)}{\bar{W}_p})$$

in which:

$$\underset{(6x6)}{\bar{N}_{d\ell}} = \underset{(6x1)}{\overset{\circ}{D}{}^T_\ell}\ \underset{(1x1)}{\bar{W}_\ell}\ \underset{(1x6)}{\overset{\circ}{D}_\ell}$$

$$\underset{(6x1)}{\bar{C}_{d\ell}} = \underset{(6x1)}{\overset{\circ}{D}{}^T_\ell}\ \underset{(1x1)}{\bar{W}_\ell}\ \underset{(1x1)}{L_\ell}$$

$$\bar{W}_\ell = 1/\sigma^2_{d\ell}$$

The solution of the equation system is given by:

$$\underset{(6mx1)}{\Delta} = \left[\underset{(6mx6m)}{(N + \overset{\circ}{N})} - \underset{(3nx3n)}{(\hat{N} + \bar{N}_d)^{-1}}\ \underset{(3nx6m)}{\hat{N}^T}\right]^{-1} * \tag{5}$$

$$* \left[\underset{(6mx1)}{(C+\overset{\circ}{C})} - \underset{(6mx3n)}{\hat{N}\,(\bar{N}+\bar{N}_d)^{-1}}\ \underset{(3nx1)}{(\bar{C}+\bar{C}_d)}\right]$$

Once the vector of exterior orientation parameters $\Delta$ has thus been obtained, the vector of ground point coordinates can be computed from:

$$\underset{(3nx1)}{\bar{\Delta}} = \left[\underset{(3nx3n)}{\bar{N}+\bar{N}_d}\right]^{-1}\left[\underset{(3nx1)}{\bar{C}+\bar{C}_d}\right] - \left[\underset{(3nx3n)}{\bar{N}+\bar{N}_d}\right]^{-1} \underset{(3nx6m)}{\hat{N}^T}\ \underset{(6mx1)}{\Delta} \tag{6}$$

By virtue of the block diagonality of $N + \overset{\circ}{N}$ and $\bar{N} + \bar{N}_d$ matrices, each distance "$d_\ell$" and each point "j" can be treated independently after the evaluation of $\Delta$ vector:

$$\underset{(6mx1)}{\Delta} = \left[\underset{(6mx6m)}{S_T+\overset{\circ}{N}}\right]^{-1} \left[\underset{(6mx1)}{\hat{C}_T+\overset{\circ}{C}}\right] \tag{7}$$

For each distance "l" the $\bar{\Delta}_{d\ell}$ vector solution is:

$$\underset{(6x1)}{\bar{\Delta}_{d\ell}} = \left[\underset{(6x6)}{\bar{N}+\bar{N}_d}\right]^{-1}_\ell \left[\underset{(6x1)}{\bar{C}+\bar{C}_d}\right]_\ell - \left[\underset{(6x6)}{\bar{N}+\bar{N}_d}\right]^{-1}_\ell \underset{(6x6m)}{\hat{N}^T_\ell}\ \underset{(6mx1)}{\Delta} \tag{8}$$

For each point "j", the $\bar{\Delta}_j$ vector solution is:

$$\bar{\Delta}_j = \bar{N}_j^{-1}\, \bar{C}_j - Q_j\, \Delta \tag{9}$$

for j = (2p+1, 2p+2, ......n)

where:

$$\underset{(6mx6m)}{S_T} = \sum_{l=1}^{p} \underset{(6mx6m)}{S_{2\ell-1,2\ell}} + \sum_{j=2p+1}^{n} \underset{(6mx6m)}{S_j}$$

$$\underset{(6mx1)}{\hat{C}_T} = \sum_{l=1}^{p} \underset{(6mx1)}{\hat{C}_{2\ell-1,2\ell}} + \sum_{j=2p+1}^{n} \underset{(6mx1)}{\hat{C}_j}$$

Because each distance "$d_\ell$" is defined by two end points: 2l-1 and 2l, it results the following normal coefficient equation matrix:

$$\underset{(6mx6m)}{S_{2\ell-1,2\ell}} = \underset{(6mx6m)}{(N_{2\ell-1}+N_{2\ell})} - \underset{(6mx6)}{\hat{N}_{2\ell-1,2\ell}}\left[\underset{(6x6)}{\bar{N}_{2\ell-1,2\ell}} + \bar{N}_{d\ell}\right]^{-1} \underset{(6x6m)}{\hat{N}^T_{2\ell-1,2\ell}} \tag{10}$$

$$\underset{(6mx1)}{\hat{C}_{2\ell-1,2\ell}} = \underset{(6mx1)}{(\hat{C}_{2\ell-1}+\hat{C}_{2\ell})} -$$

$$- \underset{(6mx6)}{\hat{N}_{2\ell-1,2\ell}} \left[\underset{(6x6)}{\bar{N}_{2\ell-1,2\ell}} + \underset{(6x6)}{\bar{N}_{d\ell}}\right]^{-1}\left[\underset{(6x1)}{\bar{C}_{2\ell-1,2\ell}} + \underset{(6x1)}{\bar{C}_{d\ell}}\right]$$

and for each stereotriangulated point (j=2p+1, 2p+2, .....n), the corresponding matrices:

$$S_j = N_j - R_j \quad ; \quad R_j = \hat{N}_j - Q_j$$

$$Q_j = \bar{N}_j^{-1}\, \hat{N}_j^T \quad ; \quad \hat{C}_j = \hat{C}_j - Q_j^T\, \bar{C}_j \tag{11}$$

Finally, to evaluate the $\bar{\Delta}_{d\ell}$ correction vector which corresponds to end points of each geodetic measured distance $d_\ell$, it is necessary to consider the following matrices and vectors:

$$\left[\underset{(6x6)}{\bar{N} + \bar{N}_{d\ell}}\right] = \left[\underset{(6x6)}{\bar{N}_{2\ell-1,2\ell}} + \underset{(6x6)}{\bar{N}_{d\ell}}\right]$$

with:

$$\left[\underset{(6x6)}{\bar{N}_{2\ell-1,2\ell}}\right] = \text{Diag}\,(\underset{(3x3)}{\bar{N}_{2\ell-1}}; \underset{(3x3)}{\bar{N}_{2\ell}})$$

and :

$$\left[\underset{(6x1)}{\bar{C} + \bar{C}_{d\ell}}\right] = \left[\underset{(6x1)}{\bar{C}_{2\ell-1,2\ell}} + \underset{(6x1)}{C_{d\ell}}\right] \tag{12}$$

with :

$$\underset{(6x1)}{\bar{C}_{2\ell-1,2\ell}} = \left[\underset{(3x1)}{\bar{C}_{2\ell-1}}\ \underset{(3x1)}{\bar{C}_{2\ell}}\right]^T$$

A computer program called DISTANCE was developped and its formulation is based on the principle of olservation equations, as described in the above paragraph.

## THE MATHEMATICAL MODEL OF DEM

The development of mathematical models that predict soil erosion and deposition on three-dimensional catchments also requires techniques that can measure distributed soil movement in order to test and to verify the model. In the case of water erosion risk, the most popular predictive model is the universal soil loss equation (USLE):

$$A = RKLSCP \tag{13}$$

where:

A is the average annual soil loss per unit area (in tonnes/ha),

R is a measure of the erosivity of the rain fall or the surface runoff in a given region,

K is the inherent erodibility of a particular soil,
L is a dimensionless slope-length factor,
S is a dimensionless slope-steepness factor,
C accounts for the effects of land management,
P reflects specialized soil conservation practices.

For a particular soil landform class, a characteristic slope length is computed from a digital elevation model (DEM). The use of DEM data to generate the L, S factor values, is an essential component to evaluate equation (13).

The developments in analytical photogrammetric methods have resulted in the increasing availability of digital elevation data and use of DTM in various engineering planing and design (Balce, 1987; Barbalata, 1988; Barbalata and Lebel, 1991; Wong and Siyam, 1983). The aim of this chapter is to elaborate a mathematical model for the determination of surface relief and elevation.

The major steps of this investigation are:

(a) Generate a grid pattern with different spacing (generally d/3) where "d" is the average distance between neighbouring points stereotriangulated by the method described in the precedent part, respectively:

$$d = \frac{1}{s}\sum_{i=1}^{s} d_i$$

where s is the total number of considered distances.

(b) Devide the surface in zones of approximately even slopes and a number of n=4..8 control points which were stereotriangulated.

(c) Determine from spatial coordinates of control points the characteristic coefficients of the eqution of the plane:

$$Z = a + bX + cY \tag{14}$$

where $\bar{X}_j$, $\bar{Y}_j$ control point coordinates are the reduced coordinates to the center of the zone "c" with the coordinates $X_c$, $Y_c$, respectively:

$$\bar{X}_j = X_j - X_c\ ; \quad \bar{Y}_j = Y_j - Y_c$$

$$r_j^2 = \bar{X}_j^2 + \bar{Y}_j^2; \quad (j = 1,2 \ldots n; \quad n = 4\ldots 8)$$

The general system of error equations can be expressed in matrix form as:

$$AU - Z = V,$$

where:

$$\underset{(nx3)}{A} = \begin{bmatrix} 1 & \bar{X}_1 & \bar{Y}_1 \\ 1 & \bar{X}_2 & \bar{Y}_2 \\ \vdots & \vdots & \vdots \\ 1 & \bar{X}_3 & \bar{Y}_3 \end{bmatrix}; \qquad \underset{(3x1)}{U} = \begin{bmatrix} a & b & c \end{bmatrix}^T;$$

$$\underset{(nx1)}{Z} = \begin{bmatrix} Z_1 \\ Z \\ \vdots \\ Z_n \end{bmatrix}; \qquad \underset{(nx1)}{V} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} \tag{15}$$

The system of normal equations formed from weighted independent observations is solved by least squares:

$$\underset{(3x1)}{U} = \underset{(3x3)}{N^{-1}}\ \underset{(3x1)}{C} \qquad \text{where:} \tag{16}$$

$$\underset{(3x3)}{N} = A^T WA; \quad \underset{(3x1)}{C} = A^T WZ; \quad \underset{(nxn)}{W} = \text{Diag}(W_1, W_2, \ldots W_n)$$

$$W = 1/\bar{r}_j^2$$

Because the normal equations operating on a common parametric vector are additive, one can write:

$$\underset{(3x3)}{N} = \underset{(3x3)}{\sum_{j=1}^{n} N_j}\ ; \quad \underset{(3x1)}{C} = \sum_{j=1}^{n} C_j\ ; \quad \underset{(3x3)}{N_j} = A_j^T W_j A_j$$

$$\underset{(3x1)}{C_j} = A_j^T W_j Z_j \tag{17}$$

(d) Determine the predicted reference variance from:

$$\sigma^2 = \frac{V^T W V}{f}; \quad f = n-3 \quad \text{wherein} \tag{18}$$

$$V^T W V = \sum v_j^2 w_j\ ; \quad v_j = A_j U = Z_j$$

(e) Generate the digital elevation data on the grid pattern using the equation:

$$Z_{i,k} = a + b\bar{X}_{i,k} + c\bar{Y}_{i,k} \tag{19}$$

where both "b" and "c" coefficients represent the slope on OX and OY directions, respectively.

(f) In accord with (Jancaitis and Junkins, 1973) the surface of each square is well defined by a polynomial function of the form:

$$F_Z = Z = \sum_{p=0}^{3}\sum_{q=0}^{p} a_{pq} X^{p-q} Y^q + a_{4,1} X^3 Y + a_{4,3} XY^3 \tag{20}$$

The polynomial function (20) with twelve terms, satisfies at two essential conditions:

(1) Continuity of elevation data between neighbouring squares and continuity of the slope along of an adjacent side of two neighbouring squares.

(2) Continuity of the slope of perpendicular directions considered at the ends of adjacent sides of each neighbouring square.

For each grid square one can generate a set of twelve observation equations, three equations for each corner respectively, of the form:

$$\sum_{p=0}^{3}\sum_{q=0}^{p} a_{pq} X^{p-q} Y^q + a_{4,1} X^3 Y + a_{4,3} XY^3 = Z_{i,k} \tag{21}$$

$$\frac{\partial F_Z}{\partial X} = b\ ; \qquad \frac{\partial F_Z}{\partial Y} = c$$

or in matrix form:

$$\underset{(3x12)}{B_{ik}}\ \underset{(12x1)}{\Delta} = \underset{(3x1)}{C_{ik}}$$

wherein

$$\underset{(3x12)}{B_{ik}} = \begin{bmatrix} 1 & X & Y & X^2 & Y^2 & XY & X^3 & Y^3 & X^2Y & XY^2 & XY^3 & X^3Y \\ 0 & 1 & 0 & 2X & 0 & Y & 3X^2 & 0 & 2XY & Y^2 & Y^3 & 3X^2Y \\ 0 & 0 & 1 & 0 & 2Y & X & 0 & 3Y^2 & X^2 & 2XY & 3XY^2 & X^3 \end{bmatrix}$$

$$C_{ik} = \begin{bmatrix} Z & b & c \end{bmatrix}^T_{ik}$$

For a grid square, the system corresponding to four corners will be:

$$\underset{(12x12)}{B}\ \underset{(12x1)}{\Delta} = \underset{(12x1)}{C} \qquad (22)$$

in which:

$$B = \begin{bmatrix} B_{i,k} & B_{i,k+1} & B_{i+1,k} & B_{i+1,k+1} \end{bmatrix}^T$$
$$T = \begin{bmatrix} T_{i,k} & T_{i,k+1} & T_{i+1,k} & T_{i+1,k+1} \end{bmatrix}^T$$

with the least squares solution:

$$\Delta = B^{-1} C \qquad (23)$$

The B matrices being identical for all grid squares, it is necesary to invert only once and then to apply the prediction function (20) to obtain a digital elevation data for a certain point inside the considered square.

(g) Compute the predicted variance $\sigma_p^2$ from:

$$\sigma_p^2 = \frac{1}{m} \sum_{i=1}^{m} v_i^2 \text{ , with } v_i = \bar{Z}_i - Z_i \qquad (24)$$

By choosing adequately the side of grid squares one can establish a concordance between $\sigma_p$ and $\sigma_z$ of stereotriangulated points.

A computer program SURFACE was elaborated according with the above predicted DEM. The output of this program provides:

(1) The residuals $v_j$ and RMS in equation (18).

(2) The digital elevation data for all points which defined the grid squares in eq. (19).

(3) The predicted polynomial function $F_z = Z$ from eq. (20) for all points which generate a new densified grid.

(4) The residuals $v_i$ and RMS (24) for control and stereotriangulated points.

## EXPERIMENTAL PROCEDURE

To obtain information on characteristic surface roughnesses in a forest area after a clear cut and to monitor the dynamical erosion process, a close-range photogrammetric technique was used.

The metric camera used in this project was a Zeiss UMK-1318. Monochrome film Kodak was used with natural light. The lighting was chosen so as to accentuate the surface without to cause loss of details in the shadowed areas.

For the photogrammetric measurements, control was provided by twelve points evenly distributed in the research zone.Their positions were determined by geodetic method, using microtriangulation and microtrilateration methods.

Five convergent photographs of a targetted test range with 120 maximum angle of convergence were observed on a monocomparator and the observations were processed through a bundle adjustment combined with geodetic distance observations by DISTANCE program. With the coordinates of triangulated points, digital elevation data were initially generated on a grid pattern with a grid spacing of: 1mx1m; 0.5mx0.5m; 0.25mx0.25m and 0.1mx0.1m. These data sets constituted the basic data sets of this study. Based on these data, a perspective view of the predicted surface was generated (Fig. 1 and Fig. 2).

Digital elevation data represent the situation in the autumn 1991. To evaluate the change in elevation and the volume of soil moved, a cycle of two measurements per year are planned.

## CONCLUSIONS

The objective of this investigation was to determine the feasibility of using analytical photogrammetric methods and a DEM to monitoring dynamical erosion process.

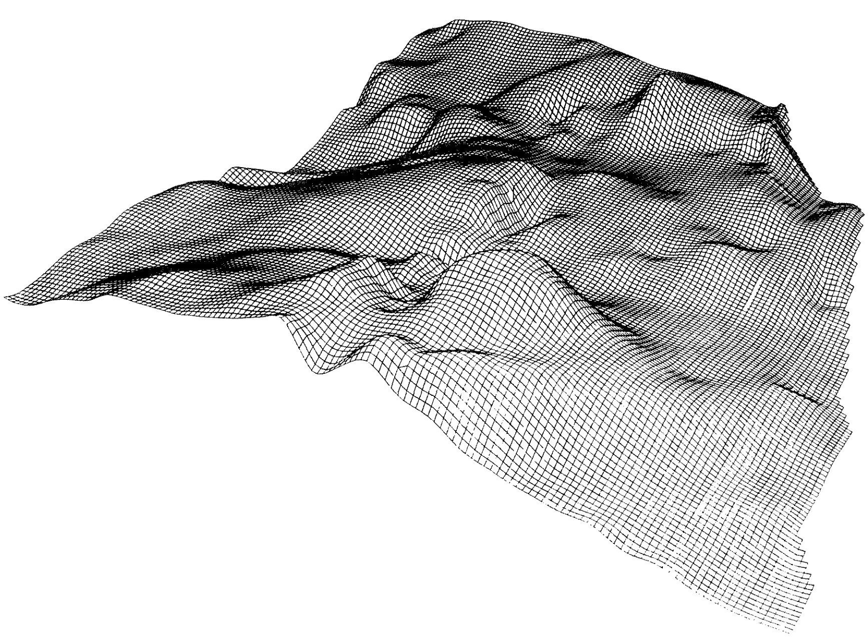

Fig.1 Three-dimensional representation of forestry area - right view

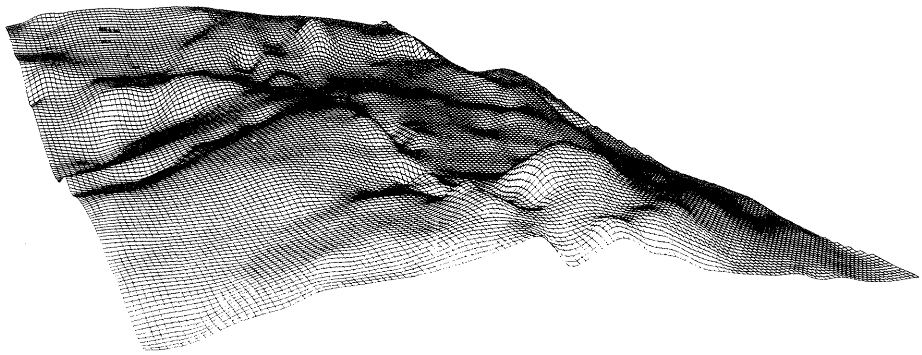

Fig.2 Three-dimensional representation of forestry area - left view

The analytical photogrammetric surface modeling offers an economical alternative to the classical field survey. Among the advantages, the following may be underlined:

- All points on the surface are determined with essentially the same accuracy.
- The coordinates of other points, especially of control points, external to the surface considered, can readily be determined to the same accuracy.
- Based on the combined bundle adjustment with geodetic distance measurements, an exact solution for the orientation is derived, which leads to a simultaneous least squares adjustment of projective parameters and of ground point coordinates.
- Concerning the Digital Elevation Model, the results obtained with different sets of data through the program SURFACE, atest that the polynomial function familly with twelve parameters, predicts a realistic and accurate topographic surface.

The results of the triangulation adjustment and of DEM for the first epoch of photogrammetric measurement (autumn 1991) corroborated the findings of the feasibility study. These results, along with an account of the modeling analysis procedure adopted, are summarized in Barbalata & Lebel (1991).

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