AERIAL TRIANGULATION

AND

DIGITAL MAPPING

Lecture Notes for

Workshops given in 1984-85

by

WOLFGANG FAIG

Monograph 10
School of Surveying
The University of New South Wales
Kensington, N.S.W., Australia

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SECTION 1: AERIAL TRIANGULATION

SESSION I: INTRODUCTION

Aerial triangulation (or aerotriangulation) is a general term for photogrammetric methods of coordinating points on the ground using a series of overlapping aerial photographs.

In the past, aerial triangulation was applied to provide photo control for mapping purposes only. Although this has remained as its major application, aerotriangulation procedures are nowadays used in a variety of fields, such as control densification, legal and cadastral surveys, extra-terrestrial mapping and engineering photogrammetry.

Development of Aerial Triangulation

The field developed along three distinct concepts, namely: radial, strip, and block triangulation. These developments were not consecutive in time; however, the advent and rapid development of digital computing technology has definitely shifted the emphasis towards block triangulation.

Radial Triangulation is based on the fact that angles measured in a photograph at the iso-centre are true horizontal angles and are thus directly suitable for planimetric triangulation, equivalent to ground surveys. Since the iso-centre is located halfway between the principal point and the photo-nadir, and since these two coincide for perfect vertical photography, the fiducial centre provides a suitable approximation for this graphical approach. Once the principal points of the neighbouring overlapping photographs were transferred, the horizontal rays could be drawn for each photo (usually on transparent paper). These planimetric bundles can then be assembled along a strip or in a block with at least two ground control points providing the scale. Multiple intersections define the other points.

Attempts to obtain numerical solutions have led to the design of special angle-measuring instruments, such as the Wild Radial Triangulator RT1, however due to the low accuracy of ±1cgon (≈ 30"), which was further reduced because of tilts, this was never accepted in practice.

Radial triangulation was most popular in the 1950's where slotted and stereo-templates layouts were commonly used to provide photo-control for mapping purposes. This simple mechanical approach provided adequate accuracy and its extent was limited only by the physical space available for the layout. Thus airplane hangars and similarly large buildings were used for this purpose. These large layouts visibly demonstrated the internal mechanical strength of blocks as compared to strips which are laterally quite weak.

Further refinement of the radial triangulation approach led to the development of the Jerie Analogue Computer, which however was soon surpassed by digital computers and appropriate software developments.

Strip Triangulation started in the 1920's when the aerial photographic mission was recreated on a Multiplex. The two significant facets of this are dependent pair relative orientation (using elements of one camera/projector only, as the other's position is to remain fixed), and scale transfer to assure uniform scale along the strip. The sequential dependent pair relative orientation plus scale transfer, starting from a controlled model is usually referred to as "cantilever extension" and is equivalent to an open traverse in surveying. If there is ground control at the end and possibly in between, the procedure is referred to as "bridging", equivalent to a controlled traverse in surveying, which also is weakest in the middle.

The size of the Multiplex restricted the length of the strips which led to the development of "1st order" plotters in the 1930's (e.g. Zeiss Stereo-planigraph, Wild A-5, later A-7 and A-9). The main characteristics of these "triangulation instruments" are base-in/base-out settings, b_y and b_z components, redirection of optical path to left and right projectors, and prisms for image rotation. Thus there was no longer a physical restriction on the length of the strips, commonly referred to as "aeropolygons", except perhaps limitations in the b_z-range because of earth curvature. Several procedures have been devised to overcome this, most notably "aero-levelling", which keeps the strip straight by introducing a small Φ rotation between each model to counteract the earth curvature.

The measured strip coordinates were then fitted onto the ground control by graphical or mechanical interpolation in adherance to the principle that "photogrammetry is the science without mathematics".

As you all know, this changed drastically with the advent of electronic digital computers. Even earlier, computations became more dominant (Brandenberger). In the 1950's and 60's, when strip triangulation was at its peak, numerical strip adjustments became very popular.

Based on theoretical work on transfer errors at the ITC in Delft, Netherlands (Vermeir) and on statistical studies into double summation (Gotthardt; Roelofs), a number of polynomial interpolation adjustment formulations were developed and widely used. One of these appeared in Schwidefsky's book, others were developed at the US Coast and Geodetic Survey (Harris, Keller, Tewinkel), the National Research Council of Canada (Schut), and the British Ordnance Survey, to mention a few. By sequentially adjusting one strip onto another, a block formation could be obtained.

With the digital computer gaining in prominence, this analogue procedure was recreated by analytical means, i.e. analytical relative orientation, absolute orientation strip formation, strip adjustment and finally block adjustment with strips. This fully analytical approach utilizes photo coordinates (image coordinates) observed with a stereo (or mono) comparator.

Unlike research centres and universities, comparators are not usually available to the mapping industry. Therefore analogue plotters were used for model formation, followed by analytical strip formation and strip adjustment. This semi-analytical approach has gained immense popularity and continues to be favoured, although now in conjunction with a rigorous simultaneous block adjustment.

Block Triangulation was already quite common with planimetric template layouts of the 1950's, which provided visible evidence of the internal strength of a photogrammetric block. Theoretical studies (Ackermann; Jerie) confirmed this, and the digital computer technology had progressed by the mid 1960's, such that the huge numbers of data and unknowns involved in a rigorous simultaneous block adjustment could be tackled. By the early 1970's a series of rigorous block adjustment programs became available, using either photocoordinates (bundle blocks) or model coordinates (independent model blocks) as input. Since these approaches are nowadays used worldwide, this workshop will concentrate on block adjustments.

Analogue - Semi-analytical - and Analytical Aerial Triangulation

In order to avoid confusion, I would like to clearly state the relationships between photogrammetric data collection and computational procedures for analogue, semi-analytical, and analytical aerial triangulation.

In analogue aerial triangulation, a "1st order" plotter is used to perform relative and (at least approximate) absolute orientation of the first model plus cantilever extension (dependent pair relative orientation plus scale transfer). The resulting strip coordinates are subsequently entered into a strip adjustment and/or a block adjustment with strips.

In semi-analytical aerial triangulation, a precision plotter (e.g. Wild A-8, A-10; Kern PG2; Zeiss, Oberkochen, Planimat; Zeiss, Jena Stereometrograph) or a "1st order" plotter is used to perform relative orientation only for each individual model (only base-in mode required). The resulting model coordinates are then processed on the computer. A rigorous, simultaneous independent model block adjustment is most suited for this, which sometimes causes people to consider the terms "semi-analytical" and "independent models" as interchangeable. Occasionally the models are combined into larger units (e.g. triplets) followed by a rigorous block adjustment.

Finally, independent models can be linked together analytically to form strips which are then subjected to strip adjustment and/or block adjustment with strips.

In analytical aerial triangulation, a comparator (stero-or mono plus point transfer device) is used to measure the image coordinates of each individual photograph. A bundle block adjustment is best suited for the evaluation. However, independent models can be obtained by simply performing analytical relative orientations thus providing the proper input data for an independent model block adjustment, and of course, the section or strip route can be followed as well. It should be noted here, that if an analytical plotter is used for data collection, we are also dealing with analytical aerial triangulation, not only when using the instrument in comparator mode, but also when independent models, or even strips are measured, because the effective readings remain photocoordinates, and whether they are processed internally via the control computer or externally does not matter.

After this general overview, I would like to deal with specific issues in the following sessions.

SESSION II: INDEPENDENT MODEL BLOCKS

Basic Concept

As the name suggests, the basic computational unit is the photogrammetric model, measured in its own aribitrary independent model coordinate system. In the course of the independent model block adjustment, many such models are connected together, while each individual model system has to be transformed into the common ground coordinate system. Since a photogrammetric model is similar to the terrain, this is best achieved with a spatial similarity transformation (7-parameter transformation). Thus the fundamental equation for independent models is:

$$\begin{bmatrix} X_i - X_o \\ Y_i - Y_o \\ Z_i - Z_o \end{bmatrix} = \lambda . R \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \qquad (2.1)$$

where

(X_i, Y_i, Z_i)	are the ground coordinates of point i.
(X_i, Y_o, Z_o)	are the ground coordinates of the origin of the model coordinate system.
λ	is the scale factor between model - and ground coordinate systems.
R	is a (3 x 3) rotational matrix defining the space rotation of the model system in respect to the ground system.
(x_i, y_i, z_i)	are the model coordinates of point i.

The 7 unknown transformation parameters are the coordinates (X_o, Y_o, Z_o) of the origin of the model coordinate system, the scale factor λ and the three rotation angles (ω, Φ, κ) which are implicit in the rotational matrix R.

Anblock

If only planimetric X,Y coordinates are required (i.e. for cadastral purposes), and if the photography is near vertical, as for virtually all aerial photogrammetric missions, then a planimetric similarity transformation (4-parameter transformation) suffices. In this case, only x/y model coordinates and X/Y ground coordinates are required.

$$\begin{bmatrix} X_i - X_o \\ Y_i - Y_o \end{bmatrix} = \lambda R \begin{bmatrix} x_i \\ y_i \end{bmatrix} \qquad (2.2)$$

While the spatial similarity transformation is non linear and needs to be linearized via Taylor's expansion, thus requiring an iterative solution, the planimetric transformation is linear and yields a direct solution.

In longhand, equation (2.2) becomes

$$X_i - X_o = \lambda(x_i \cos \kappa - y_i \sin \kappa)$$
$$Y_i - Y_o = \lambda(x_i \sin \kappa + y_i \cos \kappa) \qquad (2.3)$$

with X_o, Y_o, λ and κ representing the four unknown parameters. With $a = \lambda\cos \kappa$, and $b = \lambda\sin \kappa$, this equation becomes

$$X_i - X_o = ax_i - by_i$$
$$Y_i - Y_o = bx_i + ay_i \qquad (2.4)$$

This represents the basic set of linear equations for a planimetric adjustment (Anblock).

Thus it is very convenient to use independent models for planimetry, as this approach does not require any vertical control, which is a significant economic factor (see Session V).

The Use of Projection Centres

As demonstrated for template layouts, a planimetric block is internally strong and fairly rigid. The common area between models extends along the length of each model, and the overlap between strips is again along their long dimension. Thus there is very little chance of a rotational effect (κ). In the third dimension however, the situation is quite different.

In the strip direction for instance, the overlap between models is commonly of the order of 20%, which means that small transfer errors are extrapolated, resulting effectively in a Φ-rotation.

Similarly, a "hinge" effect between adjacent strips may occur. The latter cannot be eliminated within the block and thus is largely responsible for the higher density of vertical control points required for the adjustment (dense cross-chains of vertical control points, see Session V).

The uncertainty in Φ in strip direction however, is controlled internally by introducing the projection centres as model points into the block adjustment. Due to their large z-values, a small rotation manifests itself as a large x-difference at the affected projection centre. Therefore, the two projection centres have to be coordinated for each independent model in its model coordinate system.

Determination of Projection Centre Coordinates

For some precision plotters (e.g. all Wild instruments) the projection centres remain stationary in model space during relative orientation. It is thus not necessary to determine their model coordinates for each individual model, provided that all driving mechanisms remain engaged to the recording or reading systems (ideally no free-hand motions!).

The model coordinates of both projection centres are routinely determined at regular intervals (e.g. each morning), as a safeguard against accidental changes. In other instruments (e.g. Kern PG2, Zeiss Oberkochen, Planimat) the model coordinates of the projection centres change during relative orientation and thus have to be determined for each individual model. This is usually simplified on these instruments by providing for a direct observation of the projection centre coordinates (e.g. using autocollimation).

Generally, the projection centre coordinates have to be determined from grid measurements. Monocular grid measurements in two well separated planes (the difference in projection distance between these planes has to be read) provide the model coordinates for both projection centres by simple space intersections. Space resections can be utilized as well. In this case, the grid coordinates are measured in one z-level. With the known grid coordinates and the calibrated focal length, the projection centre coordinates can then be compiled. Rather than using special grid plates, the observations are often carried out with the fiducial crosses of the plate carriers.

Another, rather unique and interesting approach uses stereo-grid measurements. Here grid plates are needed and subjected to a relative orientation prior to the measurements. Thus a "true grid model", defined by the grid width "a" and the mean calibrated focal length "c" is transformed onto the measured stereo-grid via similarity transformation. This method has the advantage of providing instrumental accuracy from the residuals of the model coordinates of the grid points, obtained by using the same measuring procedures as for the actual model observations. Furthermore, available independent model software can be used directly in a "one model block adjustment", which provides the model coordinates of both projection centres.

Independent Model Measurements

The actual measurements of the independent models are quite straight forward:

- interior orientation (proper centering of photos plus introduction of the correct camera constant)
- relative orientation (κ_L - κ_R - Φ_L - Φ_R - ω)
- reading and recording of x, y, z model coordinates at predetermined points (pass-, tie-, control- and any other points of interest).

It should be noted here, that all points need to be uniquely numbered, which together with their proper identification, forms part of the preparation stage performed prior to the measurements, with the aid of positive prints of the photography. At this stage, proper overlap and sidelap configurations as well as photographic quality are also checked.

An extensive study on the most economical use of an analogue precision plotter in aerial triangulation revealed, that it is best used in "stereo-comparator" mode. Rather than performing a relative orientation, x, y, z and ω are read for each point. Photocoordinates for both images can be easily derived (p_x is inherent in z, and p_y in ω). This is then followed by analytical relative orientation, which requires very little computer time, and thus is more economical because of the plotter time saved. There is no significant difference in accuracy between this method and the conventional one.

The model coordinates provide the input into independent model block adjustment.

Software

A major reason for the worldwide popularity of independent model block adjustments is the program package PAT-M43, developed at Stuttgart University (Ackermann et al, 1973). Knowing the potential of independent model blocks and realising the need for such a program within the international mapping community, Professor Ackermann channelled the initial research and development efforts of his institute into the development of PAT-M (Program for Aerial Triangulation with Independent Models). Within the last decade or so, this program has been purchased and is being applied on every continent. It is therefore most appropriate to deal with it in more depth.

Utilizing the basic equation for independent models (2.1), the following non-linear set of observation equations is obtained:

$$\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}_{ij} = -\lambda_j R_j \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{ij} - \begin{bmatrix} X_o \\ Y_o \\ Z_o \end{bmatrix}_j + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_i \qquad (2.5)$$

where

$(x, y, z)^T_{ij}$	=	vector of model coordinates of point i in model j
$(X, Y, Z)^T_i$	=	vector of ground coordinates (usually unknown) of point i
$(v_x, v_y, z)^T_{ij}$	=	vector of corrections associated with the transformed point i in model j
$(X_o, Y_o, Z_o)^T_j$	=	origin of the model coordinate system of model j
λ_j	=	scale factor for model j
R_j	=	orthogonal rotation matrix for model j (function of the rotations ω, Φ, κ)

For the rotational matrix R, a modified version of the Rodrigues-Caylay matrix is used:

$$R_j = \frac{1}{K} \begin{bmatrix} 1 + 1/4(a^2 - b^2 - c^2) & -c + 1/2ab & b + 1/2\ ac \\ c + 1/2\ ab & 1 + 1/4(-a^2 + b^2 - c^2) & -a + 1/2\ bc \\ -b + 1/2\ ac & a + 1/2\ bc & 1 + 1/4(-a^2 - b^2 + c^2) \end{bmatrix} \qquad (2.6)$$

where $K = 1 + 1/4(a^2 + b^2 + c^2)$

and a, b, c = three independent rotational parmaters.

Thus equation (2.5) contains the following 7 parameters per model: $a, b, c, \lambda, X_o, Y_o, Z_o$.

The observed model coordinates can be weighted according to the following weight factor matrix, scaled to terrain units:

$$Q_{(ij)(ij)} = \begin{bmatrix} Q_{xx} & Q_{xy} & 0 \\ Q_{yx} & Q_{yy} & 0 \\ 0 & 0 & Q_{zz} \end{bmatrix} \qquad (2.7)$$

Planimetry and heights are treated as uncorrelated, and so they are treated as different "independent" models, thus:

$$Q_{(ij)(kl)} = 0$$

Since it is not practical to weight each individual model point, one set of weight coefficients is used for all model points, except for the projection centres.

The ground control points are treated as observations, as their accuracy varies, and it is not statistically justified to keep their coordinates fixed and adjust the photogrammetric block onto them. They provide an additional set of observation equations, which are linear:

$$\begin{bmatrix} V_x^c \\ V_y^c \\ V_z^c \end{bmatrix} = - \begin{bmatrix} X^c \\ Y^c \\ Z^c \end{bmatrix}_i + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_i \qquad (2.8)$$

where

$(X_c, Y_c, Z_c)_i^T$ = vector of ground coordinates of control point i (given)

$(X, Y, Z)_i^T$ = vector of ground coordinates of (control) point i (as in equation 2.5)

$(V_x^c, V_y^c, V_z^c)^T$ = vector of corrections associated with the ground coordinates of control point i

The ground control coordinates are also weighted according to equation (2.7). However, since it is often necessary to assign different weights to different control points, PAT-M permits the use of ten different weight matrices of the form (2.7).

Two special cases should be mentioned here, namely the null matrix (zero weight), which automatically makes the particular point a check point, and a weight matrix with very large diagonal terms (infinity), which effectively holds the geodetic control fixed.

As mentioned before, the major set of observation equations (2.5) is non-linear. Linearization by Taylor's series at approximate values (use zero for the rotations, i.e. perfect vertical photography and known flight direction), leads to:

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix}_{ij} = \begin{bmatrix} 0 & -z & y & -x \\ z & 0 & -x & -y \\ -y & x & 0 & z \end{bmatrix}_{ij} \begin{bmatrix} da \\ db \\ dc \\ d\lambda \end{bmatrix}_j - \begin{bmatrix} dX_o \\ dY_o \\ dZ_o \end{bmatrix}_j + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_i - \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{ij} \tag{2.9}$$

where da, db, dc, $d\lambda$, dX_o, dY_o, dZ_o represent increments to the approximate values for these unknowns.

These provide for better approximations for the next iteration, in which the measured model coordinates are replaced by newly transformed model coordinates.

The program PAT-M7 is based on equation (2.9) and provides a rigorous simultaneous solution for the 7 parameters. However, since planimetry and height are only slightly correlated (in terrestrial systems they are frequently referred to different datums) and since the non-linearity of equations (2.5) requires an iterative solution thereby virtually nullifying any residual effect of correlation, sequential horizontal (4 unknown parameters) and vertical (3 unknown parameters) adjustments are performed in PAT-M 43. This not only provides significant savings in computing cost (to solve for 3n plus 4n unknowns is far cheaper than for 7n), but also facilitates an Anblock adjustment without three dimensional control and iterations.

The horizontal block adjustment utilizes the following linear observation equations:

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix}_{ij} = - \begin{bmatrix} x & -y \\ y & x \end{bmatrix}_{ij} \begin{bmatrix} d \\ e \end{bmatrix}_j - \begin{bmatrix} X_o \\ Y_o \end{bmatrix}_j + \begin{bmatrix} X \\ Y \end{bmatrix}_i - \begin{bmatrix} x \\ y \end{bmatrix}_{ij} \tag{2.10}$$

for model observations, and

$$\begin{bmatrix} V_x^c \\ V_y^c \end{bmatrix} = - \begin{bmatrix} X^c \\ Y^c \end{bmatrix}_i + \begin{bmatrix} X \\ Y \end{bmatrix}_i \tag{2.11}$$

for ground control points.

The parameters d and e provide directly the unknowns c and λ in equation (2.5):

$$\lambda = (d^2 + e^2)^{1/2}$$

$$c = \frac{2(\lambda - d)}{e} \qquad (2.12)$$

For the vertical adjustment, the linearized model observation equations are:

$$(V_z)_{ij} = (-y \quad x)_{ij} \begin{bmatrix} da \\ db \end{bmatrix}_j - (dZ_o)_j + Z_i - z_{ij} \qquad (2.13)$$

At this stage, the projection centres enter the computation, providing the following linearized observation equations:

$$\begin{bmatrix} V_x^{PC} \\ V_y^{PC} \\ V_z^{PC} \end{bmatrix} = \begin{bmatrix} 0 & -z \\ z & 0 \\ -y & x \end{bmatrix}_{ij} \begin{bmatrix} da \\ db \end{bmatrix}_j - \begin{bmatrix} 0 \\ 0 \\ dZ_o \end{bmatrix}_j + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_i - \begin{bmatrix} x \\ y \\ z \end{bmatrix}_{ij} \qquad (2.14)$$

The ground control equations are:

$$(V_z^c) = -(Z^c)_i + Z_i \qquad (2.15)$$

The program PAT-M 43 starts with a horizontal adjustment [equations (2.10) and (2.11)], which requires no approximation, and provides d, e, X_o, Y_o for each model. Subsequently all horizontal coordinates of each model are transformed with these parameters, while the heights are corrected for scale.

These "corrected model" coordinates are entered into the vertical adjustment, utilizing equations (2.13), (2.14) and (2.15). This provides increments (da, db, dZ_o) for each model to update the transformation parameters, which are then used in a rigorous spatial similarity transformation.

Each iteration repeats the plan-height sequence of adjustment until sufficient convergence is reached. This normally occurs after two steps with a third as check. The final terrain coordinates for the unknown points are computed together with residuals at tie and control points.

Among other features, the program contains a powerful sort routine with the point number providing the proper linkage. Thus crossflights can be incorporated, and no specific input sequence for the models is required.

In addition to PAT-M-7, there are a number of other programmes for a simultaneous seven parameter solution [e.g. ALBANY (Erio, 1975)], some of which are quite popular, such as SPACE-M, developed at the

Topographical Survey Directorate of the Canadian Department of Energy, Mines and Resources (Blais, 1977). Just prior to his retirement, G. Schut of the National Research Council of Canada produced a simultaneous rigorous independent model block adjustment (Schut, 1980).

In the 1960's, Schut's polynomial adjustments of strips and blocks (Schut, 1968) formed analytically from independent models had gained worldwide recognition and application.
Following a strip formation program, an iterative polynomial strip adjustment is performed, similar to the polynomial interpolation of analogue strips. The program is relatively simple, has few unknowns (the coefficients of the polynomials for each strip) and thus can fit onto a smaller computer. Similar programs were utilized at the IGN in France and the British Ordnance Survey.

Many are still used today for preprocessing and data cleaning to reduce or avoid costly computer runs when blunders are present in the data.

References

Ackermann, F., et al (1973). "Block Triangulation with Independent Models", Photogrammetric Engineering, Vol. 39.

Blais, J.A.R., (1977). "Program SPACE-M: Theory and Development", Surveys and Mapping Branch, Dept. of Energy, Mines and Resources, Canada.

Crehange, A., (1964). "Etat actuel de l'Aerotriangulation Analytique a l'Institut Geographique National", Societe Francaise de Photogrammetrie, Bulletin 15-16.

Erio, G. (1975). "Three Dimensional Transformation of Independent Models", Photogrammetric Engineering and Remote Sensing, Vol. 41.

King, C.W.B., (1967). "A Method of Block Adjustment", The Photogrammetric Record, Vol. 5.

Schut, G.H., (1968). "Formation of Strips from Independent Models", Photogrammetric Engineering, Vol. 34.

Schut, G.H., (1980). "Block Adjustment of Models", The Canadian Surveyor, Vol. 34.

Van den Hout, C.M.A., (1966). "The Anblock Method of Planimetric Block Adjustment: Mathematical Foundation and Organization of its Practical Application", Photogrammetria, Vol. 21.

SESSION III: BUNDLE BLOCKS

Basic Concepts

The basic computational unit is the bundle of rays, which originate at the exposure station and pass through the image points. Bundle block adjustment means the simultaneous least squares adjustment of all bundles from all exposure stations to all measured image points, as well as the simultaneous recovery of the orientation elements of all the photographs, and the adjustment of the object points.

The fundamental equation describing the bundle in both image and object spaces, often called "single photo orientation", is:

$$\begin{bmatrix} x_i \\ y_i \\ 0 \end{bmatrix} - \begin{bmatrix} x_o \\ y_o \\ c \end{bmatrix} = \lambda_i R \begin{bmatrix} X_i - X_o \\ Y_i - Y_o \\ Z_i - Z_o \end{bmatrix} \qquad (3.1)$$

where

$(x_i, y_i, 0)^T$	is the vector of measured photo coordinates of point i
$(x_o, y_o, c)^T$	are the photo coordinates of the exposure station
λ_i	is the scale factor of point i (i.e. the length difference between the vectors along one ray in image and object spaces).
R	is a (3 x 3) rotational matrix, defining the space rotation of the photo system in respect to the ground system.
$(X_i, Y_i, Z_i)^T$	are the ground coordinates of point i
$(X_o, Y_o, Z_o)^T$	are the ground coordinates of the exposure station.

Being faced with an individual scale factor for each point in each bundle is rather awkward. Therefore λ_i is eliminated by dividing the first and second equations of (3.1) respectively by the third one.

With

$$R = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}$$

we thus obtain the collinearity equations.

$$F_x = x_i - x_o + c \frac{m_{11}(X_i - X_o) + m_{12}(Y_i - Y_o) + m_{13}(Z_i - Z_o)}{m_{31}(X_i - X_o) + m_{32}(Y_i - Y_o) + m_{33}(Z_i - Z_o)}$$

$$F_y = y_i - y_o + c \frac{m_{21}(X_i - X_o) + m_{22}(Y_i - Y_o) + m_{23}(Z_i - Z_o)}{m_{31}(X_i - X_o) + m_{32}(Y_i - Y_o) + m_{33}(Z_i - Z_o)} \tag{3.2}$$

These fundamental equations of analytical photogrammetry simply state that image point, exposure centre and object point are located along a straight line. These equations contain 6 unknowns per bundle, namely the ground coordinates (X_o, Y_o, Z_o) of the exposure station and the three rotation angles (ω, Φ, κ) which are implicit in the rotational matrix R. In the basic bundle approach, x_o, y_o, c are considered to be known (e.g. from camera calibration). As we shall see in the next session (Session IV), this assumption is not quite correct. A minimum of three ground control points is required (together with the geometry) to solve for the six unknowns per bundle, which are then used to compute the unknown ground coordinates of the other measured image points.

Development of a Mathematical Model for Bundle Block Adjustments

Since the measured photo coordinates contain random errors, F_x and F_y may differ from zero. Thus the collinearity condition has to be included into the adjustment. The collinearity equations are non-linear, and need to be linearized by Taylor's expansion at an approximate value.

This leads to:

$$\begin{aligned}
V_{xij} &+ \left(\frac{\delta F_x}{\delta \omega_j}\right)^{\circ} \Delta\omega_j + \left(\frac{\delta F_x}{\delta \Phi_j}\right)^{\circ} \Delta\Phi_j + \left(\frac{\delta F_x}{\delta \kappa_j}\right)^{\circ} \Delta\kappa_j + \\
&+ \left(\frac{\delta F_x}{\delta X_{oj}}\right)^{\circ} \Delta X_{oj} + \left(\frac{\delta F_x}{\delta Y_{oj}}\right)^{\circ} \Delta Y_{oj} + \left(\frac{\delta F_x}{\delta Z_{oj}}\right)^{\circ} \Delta Z_{oj} + \\
&+ \left(\frac{\delta F_x}{\delta X_i}\right)^{\circ} \Delta X_i + \left(\frac{\delta F_x}{\delta Y_i}\right)^{\circ} \Delta Y_i + \left(\frac{\delta F_x}{\delta Z_i}\right)^{\circ} \Delta Z_i + F_x^{\circ} = 0 \\
V_{yij} &+ \left(\frac{\delta F_y}{\delta \omega_j}\right)^{\circ} \Delta\omega_j + \left(\frac{\delta F_y}{\delta \Phi_j}\right)^{\circ} \Delta\Phi_j + \left(\frac{\delta F_y}{\delta \kappa_j}\right)^{\circ} \Delta\kappa_j + \\
&+ \left(\frac{\delta F_y}{\delta X_{oj}}\right)^{\circ} \Delta X_{oj} + \left(\frac{\delta F_y}{\delta Y_{oj}}\right)^{\circ} \Delta Y_{oj} + \left(\frac{\delta F_y}{\delta Z_{oj}}\right)^{\circ} \Delta Z_{oj} + \\
&+ \left(\frac{\delta F_y}{\delta X_i}\right)^{\circ} \Delta X_i + \left(\frac{\delta F_y}{\delta Y_i}\right)^{\circ} \Delta Y_i + \left(\frac{\delta F_y}{\delta Z_i}\right)^{\circ} \Delta Z_i + F_y^{\circ} = 0
\end{aligned} \tag{3.3}$$

or

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix}_{ij} + \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} & b_{16} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} & b_{26} \end{bmatrix} \begin{bmatrix} \Delta\omega \\ \Delta\Phi \\ \Delta\kappa \\ \Delta X_o \\ \Delta Y_o \\ \Delta Z_o \end{bmatrix}_j +$$

$$+ \begin{bmatrix} b_{17} & b_{18} & b_{19} \\ b_{27} & b_{28} & b_{29} \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}_i = \begin{bmatrix} -F_x^{\,o} \\ -F_y^{\,o} \end{bmatrix} \tag{3.4}$$

where the partial derivatives are denoted as:

$$\left(\frac{\delta F_x}{\delta \omega_j}\right)^{o} = b_{11} \; ; \; \left(\frac{\delta F_x}{\delta \Phi_j}\right)^{o} = b_{12} \; ; \; \ldots . \; \left(\frac{\delta F_x}{\delta Z_i}\right)^{o} = b_{19}$$
$$\left(\frac{\delta F_y}{\delta \omega_j}\right)^{o} = b_{21} \; ; \; \left(\frac{\delta F_y}{\delta \Phi_j}\right)^{o} = b_{22} \; ; \; \ldots . \; \left(\frac{\delta F_y}{\delta Z_i}\right)^{o} = b_{29} \tag{3.5}$$

According to Brown's notation (Brown, 1969), equation (3.4) is compressed to

$$\underset{(2x1)}{V_{ij}} + \underset{(2x6)}{\dot{B}_{ij}} \; \underset{(6x1)}{\dot{\Delta}_j} + \underset{(2x3)}{\ddot{B}_{ij}} \; \underset{(3x1)}{\ddot{\Delta}_i} = \underset{(2x1)}{e_{ij}} \tag{3.6}$$

where the superscript "one dot" denotes the corrections to the exterior orientation parameters, and "double dot" denotes the corrections to ground coordinates.

As in PAT-M, given ground control is no longer treated as fixed, which means that the same set of observation equations is included here also

$$\begin{bmatrix} V_x^{\,c} \\ V_y^{\,c} \\ V_z^{\,c} \end{bmatrix}_i = - \begin{bmatrix} X^c \\ Y^c \\ Z^c \end{bmatrix}_i + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_i \tag{3.7}$$

[also eq. (2.8)]

or using approximations

$$\begin{bmatrix} V_x^{\,c} \\ V_y^{\,c} \\ V_z^{\,c} \end{bmatrix}_i - \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}_i = \begin{bmatrix} X^o - X^c \\ Y^o - Y^c \\ Z^o - Z^c \end{bmatrix}_i \tag{3.8}$$

which again is simplified to

$$\underset{(3x1)}{\ddot{V}_i} - \underset{(3x1)}{\ddot{\Delta}_i} = \underset{(3x1)}{\ddot{C}_i} \qquad (3.9)$$

Let us now consider a block of m photographs with n measured points, of which r are coordinated ground control points. For simplicity's sake, let us assume that all n points are imaged in all m photos. It is a simple matter of ignoring the ficticious observations during the computation phase and generate equations only for the parameters associated with actual measurements.

This leads to the following set of equations for point i:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ V_m \end{bmatrix}_i + \begin{bmatrix} \dot{B}_1 & & & & & & \\ & \dot{B}_2 & & & & & \\ & & \dot{B}_3 & & & & \\ & & & \cdot & & & \\ & & & & \cdot & & \\ & & & & & \cdot & \\ & & & & & & \dot{B}_m \end{bmatrix}_i \begin{bmatrix} \dot{\Delta}_1 \\ \dot{\Delta}_2 \\ \dot{\Delta}_3 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \dot{\Delta}_m \end{bmatrix} + \begin{bmatrix} \ddot{B}_{1,i} \\ \ddot{B}_{2,i} \\ \ddot{B}_{3,i} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \ddot{B}_{m,i} \end{bmatrix} \ddot{\Delta}_i = \begin{bmatrix} e_{1i} \\ e_{2i} \\ e_{3i} \\ \cdot \\ \cdot \\ \cdot \\ e_{mi} \end{bmatrix} \qquad (3.10)$$

or in short notation

$$\underset{(2mx1)}{V_i} + \underset{(2mx6m)}{\dot{B}_i} \underset{(6mx1)}{\dot{\Delta}} + \underset{(2mx3)}{\ddot{B}_i} \underset{(3x1)}{\ddot{\Delta}} = \underset{(2mx1)}{e_i} \qquad (3.11)$$

Each point gives rise to one equation (3.11):

$$\begin{bmatrix} V_1 \\ V_2 \\ \cdot \\ \cdot \\ \cdot \\ V_n \end{bmatrix} + \begin{bmatrix} \dot{B}_1 \\ \dot{B}_2 \\ \cdot \\ \cdot \\ \cdot \\ \dot{B}_n \end{bmatrix} \dot{\Delta} + \begin{bmatrix} \ddot{B}_1 & & & & & \\ & \ddot{B}_2 & & & & \\ & & \cdot & & & \\ & & & \cdot & & \\ & & & & \cdot & \\ & & & & & \ddot{B}_n \end{bmatrix} \begin{bmatrix} \ddot{\Delta}_1 \\ \ddot{\Delta}_2 \\ \cdot \\ \cdot \\ \cdot \\ \ddot{\Delta}_n \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \\ \cdot \\ \cdot \\ \cdot \\ e_n \end{bmatrix} \qquad (3.12)$$

or in short notation

$$\underset{(2mnx1)}{V} + \underset{(2mnx6m)}{\dot{B}} \underset{(6mx1)}{\dot{\Delta}} + \underset{(2mnx3n)}{\ddot{B}} \underset{(3nx1)}{\ddot{\Delta}} = \underset{(2mnx1)}{e} \qquad (3.13)$$

The set of observation equations for ground control points is now to be added:

$$\begin{bmatrix} \ddot{V}_1 \\ \ddot{V}_2 \\ \cdot \\ \cdot \\ \cdot \\ \ddot{V}_n \end{bmatrix} - \begin{bmatrix} \ddot{\Delta}_1 \\ \ddot{\Delta}_2 \\ \cdot \\ \cdot \\ \cdot \\ \ddot{\Delta}_n \end{bmatrix} = \begin{bmatrix} \ddot{C}_1 \\ \ddot{C}_2 \\ \cdot \\ \cdot \\ \cdot \\ \ddot{C}_n \end{bmatrix} \quad (3.14)$$

or

$$\underset{(3n\times1)}{\ddot{V}} - \underset{(3n\times1)}{\ddot{\Delta}} = \underset{(3n\times1)}{\ddot{C}} \quad (3.15)$$

If, as for independent models, any parameter of exterior orientation is measured or known (i.e. exposure station, or tilts, denoted with superscript "c") a further set of observation equations is needed, namely

$$\begin{bmatrix} V_\omega \\ V_\Phi \\ V_\kappa \\ V_{X_o} \\ V_{Y_o} \\ V_{Z_o} \end{bmatrix}_j - \begin{bmatrix} \Delta\omega \\ \Delta\Phi \\ \Delta\kappa \\ \Delta X_o \\ \Delta Y_o \\ \Delta Z_o \end{bmatrix}_j = \begin{bmatrix} \omega_o - \omega^c \\ \Phi_o - \Phi^c \\ \kappa_o - \kappa^c \\ X_o - X^c \\ Y_o - Y^c \\ Z_o - Z^c \end{bmatrix}_j \quad (3.16)$$

or in short

$$\underset{(6\times1)}{\dot{V}_i} - \underset{(6\times1)}{\dot{\Delta}_j} = \underset{(6\times1)}{\dot{c}_j} \quad (3.17)$$

For all m photographs, this becomes

$$\begin{bmatrix} \dot{V}_1 \\ \dot{V}_2 \\ \cdot \\ \cdot \\ \cdot \\ \dot{V}_m \end{bmatrix} - \begin{bmatrix} \dot{\Delta}_1 \\ \dot{\Delta}_2 \\ \cdot \\ \cdot \\ \cdot \\ \dot{\Delta}_m \end{bmatrix} = \begin{bmatrix} \dot{c}_1 \\ \dot{c}_2 \\ \cdot \\ \cdot \\ \cdot \\ \dot{c}_m \end{bmatrix} \quad (3.18)$$

or

$$\underset{(6m\times1)}{\dot{V}} - \underset{(6m\times1)}{\dot{\Delta}} = \underset{(6m\times1)}{\dot{c}} \quad (3.19)$$

Combining all observation equations, we get

$$
\begin{aligned}
V \quad + \quad \dot{B}\dot{\Delta} \quad + \quad \ddot{B}\ddot{\Delta} \quad &= e \\
\dot{V} \quad - \quad \dot{\Delta} \quad &= \dot{c} \\
\ddot{V} \quad - \quad \ddot{\Delta} \quad &= \ddot{c}
\end{aligned}
\tag{3.20}
$$

or in matrix notation

$$
\begin{bmatrix} V \\ \dot{V} \\ \ddot{V} \end{bmatrix} + \begin{bmatrix} \dot{B} & \ddot{B} \\ -1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \dot{\Delta} \\ \ddot{\Delta} \end{bmatrix} = \begin{bmatrix} e \\ \dot{c} \\ \ddot{c} \end{bmatrix} \tag{3.21}
$$

compressed to

$$\bar{V} + \bar{B}\,\bar{\Delta} = \bar{C} \tag{3.22}$$

Least squares treatment leads to

$$(\bar{B}^T\,\bar{W}\,\bar{B})\,\bar{\Delta} = \bar{B}^T\,\bar{W}\,\bar{C} \tag{3.23}$$

where $\bar{W}$ is a weight matrix.

The solution becomes

$$\bar{\Delta} = (\bar{B}^T\,\bar{W}\,\bar{B})^{-1}\,\bar{B}^T\,\bar{W}\,\bar{C} \tag{3.24}$$

In equation (3.23) the weight matrix $\bar{W}$ appears. This matrix consists of a series of submatrices assigned to the observed parameters, which must be organized in exactly the same manner as the $\bar{V}$-matrix.

Since the weight is inversely proportional to the variance of a measurement, we have

$$W_i = \frac{\sigma_o^2}{\sigma_i^2}$$

where σ_o^2 is the variance of unit weight. The variance - covariance matrix for a pair of measured photo coordinates (x_{ij}, y_{ij}) can be written as:

$$\Sigma_{ij} = \begin{bmatrix} \sigma^2_{x\,ij} & \sigma_{xy\,ij} \\ \sigma_{xyij} & \sigma^2_{y\,ij} \end{bmatrix} \tag{3.25}$$

The corresponding weight matrix is then

$$W_{ij} = \sigma_o^2 \begin{bmatrix} \sigma^2_x & \sigma_{xy} \\ \sigma_{xy} & \sigma^2_y \end{bmatrix}^{-1}_{ij} = \begin{bmatrix} q_{11} & q_{12} \\ q_{21} & q_{22} \end{bmatrix} \tag{3.26}$$

Thus, the weight matrix W for point i in all photos becomes:

$$\underset{(2m\times 2m)}{W_i} = \begin{bmatrix} W_{i1} & & & & \\ & W_{i2} & & & \\ & & \cdot & & \\ & & & \cdot & \\ & & & & \cdot \\ & & & & & W_{im} \end{bmatrix} \tag{3.27}$$

and for all n points:

$$\underset{(2mn\times 2mn)}{W} = \begin{bmatrix} W_1 & & & & \\ & W_2 & & & \\ & & \cdot & & \\ & & & \cdot & \\ & & & & \cdot \\ & & & & & W_n \end{bmatrix} \tag{3.28}$$

Similarily:

$$\underset{(6\times 6)}{\dot{\Sigma}_j} = \begin{bmatrix} \sigma_\omega^2 & \sigma_{\omega\Phi} & \cdot\ \cdot\ \cdot & \sigma_{\omega Z_o} \\ \cdot & & & \\ \cdot & & & \\ \cdot & & & \\ \sigma_{Z_o\omega} & \cdot\ \cdot & \cdot\ \cdot\ \cdot & \sigma^2_{Z_o} \end{bmatrix}_j \tag{3.29}$$

and

$$\dot{W}_j = \sigma_o^2\ \dot{\Sigma}_j^{-1} \tag{3.30}$$

If the photographs are assumed to be uncorrelated, the leads to

$$\underset{(6m\times 6m)}{\dot{W}} = \begin{bmatrix} \dot{W}_1 & & & & \\ & \dot{W}_2 & & & \\ & & \cdot & & \\ & & & \cdot & \\ & & & & \cdot \\ & & & & & \dot{W}_m \end{bmatrix} \tag{3.31}$$

Also

$$\underset{(3\times 3)}{\ddot{\Sigma}_i} = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_y^2 & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_z^2 \end{bmatrix} \tag{3.32}$$

and

$$\ddot{W}_i = \sigma_o^2\ \ddot{\Sigma}_i^{-1} \tag{3.33}$$

as well as

$$\underset{(3n\times 3n)}{\ddot{W}} = \begin{bmatrix} \ddot{W}_1 & & & \\ & \ddot{W}_2 & & \\ & & \cdot & \\ & & & \cdot \\ & & & & \ddot{W}_n \end{bmatrix} \tag{3.34}$$

and finally

$$\bar{W} = \begin{bmatrix} W & & \\ & \dot{W} & \\ & & \ddot{W} \end{bmatrix} \qquad (3.35)$$

Equation (3.23) can be simply expressed as

$$\underset{(6m+3n)\times(6m+3n)}{N} \cdot \underset{(6m+3n)\times 1}{\Delta} = \underset{(6m+3n)\times 1}{K}$$

which requires the simultaneous solution of 6m + 3n equations. This is computationally expensive and impractical, even for small blocks. By sequential substitution, this has been partitioned into:

$$\left[\begin{array}{cccc|cccc} \dot{N}_1 + \dot{W}_1 & & & & \bar{N}_{11} & \cdots & \cdots & \bar{N}_{1n} \\ & \dot{N}_2 + \dot{W}_2 & & & \vdots & & & \vdots \\ & & \ddots & & \vdots & & & \vdots \\ & & & \dot{N}_m + \dot{W}_m & \bar{N}_{m1} & & & \bar{N}_{mn} \\ \hline \bar{N}_{11}^T & \cdots & \cdots & \bar{N}_{m1}^T & \ddot{N}_1 + \ddot{W}_1 & & & \\ \vdots & & & \vdots & & \ddots & & \\ \vdots & & & \vdots & & & \ddots & \\ \bar{N}_{1n}^T & \cdots & \cdots & \bar{N}_{mn}^T & & & & \ddot{N}_n + \ddot{W}_n \end{array}\right] \left[\begin{array}{c} \dot{\Delta}_1 \\ \dot{\Delta}_2 \\ \vdots \\ \dot{\Delta}_m \\ \hline \ddot{\Delta}_1 \\ \vdots \\ \vdots \\ \ddot{\Delta}_n \end{array}\right] = \left[\begin{array}{c} \dot{K}_1 - \dot{W}_1\dot{C}_1 \\ \vdots \\ \vdots \\ \dot{K}_m - \dot{W}_m\dot{C}_m \\ \hline \ddot{K}_1 - \ddot{W}_1\ddot{C}_1 \\ \vdots \\ \vdots \\ \ddot{K}_n - \ddot{W}_n\ddot{C}_n \end{array}\right] \qquad (3.36)$$

where

$$\dot{N}_j = \sum_{i=1}^{n} \dot{B}_{ij}^T \; W_{ij} \; \ddot{B}_{ij}$$

$$\bar{N}_{ij} = \dot{B}_{ij}^T \; W_{ij} \; \ddot{B}_{ij}$$

$$\ddot{N}_i = \sum_{j=1}^{m} \ddot{B}_{ij}^T \; W_{ij} \; \ddot{B}_{ij}$$

$$\dot{K}_j = \sum_{i=1}^{n} B_{ij}^T \; W_{ij} \; e_{ij}$$

$$\ddot{K}_i = \sum_{j=1}^{m} B_{ij} \; W_{ij} \; e_{ij} \qquad (3.37)$$

Equation (3.36) provides some insight into the structure of the normal equation matrix, which, of course, is a symmetric matrix.

In the upper lefthand corner, there is a string of 6 x 6 submatrices, one for each photograph, along the main diagonal, while all other elements are zero. Similarily, there is a diagonal band of 3 x 3 submatrices in the lower right hand corner, one for each point.

Furthermore, the contribution of each individual observation equation can be directly identified within the normal equation matrix. Thus the normal equation matrix is directly computed by adding the influence of each individual observation equation to the respective elements.

In order to avoid having to invert the whole normal equation matrix, especially since this is an iterative process, different algorithms have been developed to avoid this and still provide a rigorous solution. Some of the better known ones are recursive partitioning (Brown, 1967; Elphingstone, 1972), Cholesky elimination with hypermatrices (HYCHOL) used in PAT-M as well as in PAT-B (Ackermann et al, 1972), and block successive over-relaxation (Carlson, 1972).

Measurement of Photo-coordinates

Photocoordinates, which form the basic input into bundle adjustments, are usually measured on a comparator (mono or stereo comparator), but can also be obtained on an analytical plotter operated in comparator mode. While the latter provide an accuracy of about 3 to 5µm in the photograph, precision stereo comparators (e.g. Zeiss, Oberkochen PSK, Wild STK-1, Zeiss, Jena Stecometer, OMI - TA3/P) and monocomparators (e.g. DBA-700, Kern MK-2, K&E Mono, OMI - TAI/P, Zeiss, Oberkochen P.K.) all have a least count of 1µm and thus give 1 - 3µm accuracy (standard deviation). The Zeiss, Jena Asco-record goes even higher, with a least count of 0.1µm, which however exceeds the accuracy inherent in photography.

Measurement of individual photocoordinates or photocoordinates and parallaxes is straightforward. It is advisable to observe each point at least twice and not to forget to include the fiducial marks. When using a monocomparator, it is usually necessary to transfer points from one image to another, unless the points are targeted on the ground. Most photogrammetric instrument manufacturers offer stereotransfer instruments, e.g. Wild PUG, Kern PGM, Zeiss, Oberkochen PM, Zeiss, Jena Transmark, which either drill or burn a well defined hole into the emulsion.

Software Developments

Unlike independent model block developments, where the software originated primarily in Europe, bundle adjustment packages were first developed in North America with D.C. Brown playing a leading role, first with military agencies in the U.S.A, where he worked along with H.H. Schmid (1955), later with his own companies (Brown 1958, 1967).

Other early developments were carried out at the US Coast and Geodetic Survey (Keller & Tewinkel, 1967). These early bundle block adjustments were solely based on the idea that the photogrammetric measurements contain random errors only. Thus the comparator measurements were subjected to an "image refinement" procedure, which corrected the image coordinates for all known systematic effects utilizing camera calibration values (either from laboratory or test field calibration), refraction models and the like (Keller & Tewinkel, 1965).

Since the remaining "random" photo-residuals are of the order of a few micrometres, the expected theoretical accuracy of bundle blocks is higher than that expected for independent model blocks. However, practical results showed a large discrepancy between predicted theoretical accuracy and actually obtained accuracy. In fact, practical results showed no significant improvement when using bundles, sometimes they were even worse (Ackermann, 1975; Ebner, 1973). This indicates the continued presence of systematic errors, even after image refinement, which leads us to the topic of Session IV, namely the procedures applied to model these systematic effects.

References:

Ackermann F.E. (1975) "Results of Recent Test in Aerial Triangulation" Photogrammetric Engineering and Remote Sensing, Vol.41

Ackermann F.E., Ebner H., Klein H. (1973) "Block Triangulation with Independent Models" Photogrammetric Engineering, Vol.39

Brown D.C. (1958) "A Solution to the General Problem of Multiple Station Analytical Stereotriangulation" RCA Data Reduction, Technical Report No. 43

Brown D.C. (1967) "The Simultaneous Adjustment of Very Large Photogrammetric Blocks" Symposium on Computational Photogrammetry, Syracuse, N.Y.

Carlson E. (1972) "BLSOR Iterative Method for Solving Large Photogrammetric Equations" The Photogrammetric Journal of Finland, Vol.6.

Ebner H. (1973) "Comparison of Different Methods of Block Adjustment" OEEPE, Official Publications No.8.

Elphingstone G.M. (1972) "An Efficient Computer Technique for Recursive Partitioning" Photogrammetric Engineering, Vol.38

Keller M, Tewinkel G.C. (1965) "Aerotriangulation: Image Coordinate Refinement" USCGS, Technical Bulletin No.25

Keller M, Tewinkel G.C. (1967) "Block Analytic Aerotriangulation", ESSA Technical Report C&GS No.35

Schmid H.H. (1955) "An Analytical Treatment of the Problem of Triangulation by Stereophotogrammetry, Ballistic Research Laboratories, Report No. 961.

SESSION IV: ADDITIONAL PARMATERS AND SELF CALIBRATION

Introduction

The difference between expected accuracy for bundle adjustments and practical results is primarily caused by uncompensated systematic errors. Thus the mathematical model of ideal central projection as described by the collinearity equations has to be improved by expressing the actual physical situation, which deals with a lightpath from object point via lens to image plane that is not straight, due to influences such as atmospheric refraction and lens distortion. Furthermore, the image position is distorted because of deformations within this plane (film flatness) as well as during processing and storage of the film.

The mathematical model is improved by introducing "additional parameters" into the collinearity equations:

$$x - x_o + \Delta X_p = -c \frac{(X - X_o)m_{11} + (Y - Y_o)m_{12} + (Z - Z_o)m_{13}}{(X - X_o)m_{31} + (Y - Y_o)m_{32} + (Z - Z_o)m_{33}}$$

$$y - y_o + \Delta Y_p = -c \frac{(X - X_o)m_{21} + (Y - Y_o)m_{22} + (Z - Z_o)m_{32}}{(X - X_o)m_{31} + (Y - Y_o)m_{32} + (Z - Z_o)m_{33}} \qquad (4.1)$$

where ΔX_p and ΔY_p are functions of several unknown parameters and are adjusted simultaneously with the other unknowns in the equations.

Under certain conditions, a complete recovery of all parameters, including x_o, y_o and c, is possible without the requirement for additional ground control points. Therefore this approach is often referred to as "self calibration".

Mathematical Modelling

Two general principles have to be considered when applying additional parameters, namely:

- the number of parameters should be as small as feasible to avoid over-parameterization and to keep the additional computational effort small.

- the parameters are to be chosen such that their correlations with the other unknowns are negligible. Otherwise the normal equation matrix becomes ill-conditioned or singular.

Since for most photogrammetric projects the same stable aerial camera is used to photograph the whole block in one flight mission under stable atmospheric conditions, the parameters can be assumed to be the same for all photographs. This leads to the so called "block-invariant" approach (Brown, 1974) which is most favourable for computational economy.

If, however, different cameras are used or if other conditions change (i.e. reflying of a strip) then a "block variant" approach has to be applied, where the parameters are valid for only a group of photographs (Ebner, 1976). In the extreme case (e.g. when using non-metric cameras, as in close-range photogrammetry) a "photo variant" approach is needed, which means new additional parameters have to be determined for each individual photograph.

Although many sets of additional parameters have been proposed - each of which has advantages and disadvantages, the functions are basically set up to either model the causes or the effects of image deformation. Since neither is fully known, the actual formulations vary, but most are quite efficient.

Modelling of causes of image deformation

As an example of this type of modelling, I would like to briefly present the additional parameters of UNBASC (Moniwa, 1977). This program was originally written as a calibration program for non-metric cameras and subsequently generalized to a bundle block adjustment with self calibration. It utilizes the well-known odd polynomial for radial (symmetric) distortion, Brown's decentering distortion model (Brown, 1966), and an affinity model derived to cover film shrinkage and non-perpendicularity of the comparator axes (Moniwa, 1977).

Thus:

$$\Delta X_p = dr_x + dp_x + dg_x$$

$$\Delta Y_p = dr_y + dp_y + dg_y \qquad (4.2)$$

where the radial distortion is expressed as:

$$dr = K_1 r^3 + K_2 r^5 + K_3 r^7$$

or in x and y components

$$dr_x = \frac{(x - x_o)}{r} dr = [K_1 r^2 + K_2 r^4 + K_3 r^6] (x - x_o)$$

$$dr_y = \frac{(y - y_o)}{r} dr = [K_1 r^2 + K_2 r^4 + K_3 r^6] (y - y_o) \qquad (4.3)$$

It should be noted here, that the linear term of dr ($K_o r$) has been omitted as it is 100% correlated with c, which in self calibration is regarded as unknown. The decentering distortion model is:

$$dp_x = p_1[r^2 + 2(x - x_o)^2] + 2p_2 (x - x_o) (y - y_o)$$

$$dp_y = p_2[r^2 + 2(y - y_o)^2] + 2p_1 (x - x_o) (y - y_o) \qquad (4.4)$$

which is the first term of Brown's polynomial (Brown, 1966).

The affinity model was derived from geometric considerations as:

$$dg_x = A(y - y_o)$$

$$dg_y = B(y - y_o) \qquad (4.5)$$

with

$$r = [(x - x_o)^2 + (y - y_o)^2]^{1/2}$$

The unknown additional parameters are then K_1, K_2, K_3, p_1, p_2, A, B, which means that there are 16 unknown parameters per image (6 for exterior orientation, 3 for basic interior orientation, and 7 additional parameters).

This approach has the disadvantage that there are correlations between these parameters as well as between them and the basic orientation unknowns. Furthermore, irregular image deformation, likely a result of a combination of unpredictable components, is not modelled and thus may not be efficiently detected or compensated.

<u>Modelling of image deformation</u>

In this case, the combined effect of all systematic errors is modelled by an orthogonalized system of functions. Brown's formulation (Brown, 1976) and El Hakim's spherical harmonics model (El Hakim, 1979) are presented here as examples.

Brown expressed the combined effect of all systematic errors by orthogonalized functions as

$$\begin{aligned}
\Delta X_p = {} & a_1 x + a_2 y + a_3 xy + a_4 y^2 + a_5 x^2 y + a_6 xy^2 + a_7 x^2 y^2 + \\
& \frac{x}{c} [a_{13}(x^2 - y^2) + a_{14} x^2 y^2 + a_{15}(x^4 - y^4)] + \\
& x[a_{16}(x^2 + y^2)^2 + a_{17}(x^2 + y^2)^4 + a_{18}(x^2 + y^2)^6] \\
\\
\Delta Y_p = {} & a_8 xy + a_9 x^2 + a_{10} x^2 y + a_{11} xy^2 + a_{12} x^2 y^2 + \\
& \frac{y}{c} [a_{13}(x^2 - y^2) + a_{14} x^2 y^2 + a_{15}(x^4 - y^4)] + \\
& y[a_{16}(x^2 + y^2) + a_{17}(x^2 + y^2)^4 + a_{18}(x^2 + y^2)^6]
\end{aligned} \tag{4.6}$$

These formulae assume that $x_o = y_o = 0$, therefore, generally x should be replaced by $(x - x_o)$, and y by $(y - y_o)$.

El Hakim utilized three-dimensional spherical harmonics to derive

$$\begin{aligned}
\Delta X_p &= (x - x_o)T \\
\Delta Y_p &= (y - y_o)T
\end{aligned} \tag{4.7}$$

where

$$\begin{aligned}
T = {} & a_{00} + a_{11} \cos\lambda + b_{11} \sin\lambda + a_{20} r + a_{22} r \cos^2\lambda + \\
& + b_{22} r \sin 2\lambda + a_{31} r^2 \cos\lambda + b_{31} r^2 \sin\lambda + \\
& + a_{33} r^2 \cos 3\lambda + b_{33} r^2 \sin 3\lambda + \ldots
\end{aligned} \tag{4.8}$$

and

$$\lambda = \tan^{-1} \frac{y - y_o}{x - x_o} \qquad (4.9)$$

Again the parameters of the harmonic functions are not correlated with each other.

Modelling the effects has been far more popular and is most widely used. A comparison between El Hakim's and Moniwa's formulations using test field photography showed a consistently higher accuracy when using the harmonic function formulation, although both types of additional parameters provided improvement over a straight bundle adjustment (El Hakim, 1979).

Additional Parameters with Independent Models

Since the systematic image deformations manifest themselves as model deformations, it follows logically that additional parameters should improve independent model blocks as well. As modelling of the causes would be rather difficult and cumbersome because of the additional step of relative orientation, only the effect is being modelled in this case (Ebner, 1976; Schut, 1980). The results, presented later in this session confirm an accuracy improvement, but have to be seen from a practical point of view. For the test cases, independent models were formed analytically using photo coordinates measured ith comparator accuracy. However, for virtually all production work, the independent models are measured on an analogue plotter where the reading accuracy is less by a factor of 10 or so. Experience has shown that the distribution of residual parallaxes over the whole model during relative orientation is sufficient for this accuracy level and that the introduction of additional parameters is not justified. A series of tests using different sets of additional parameters (Faig and Atilola, 1984) confirmed this.

Other Calibration Models

Since systematic image deformation, the difference between physical situation and mathematical model, has led to the use of additional parameters, some efforts have been directed improving camera calibration to obtain better values for image refinement. However, even when photographing a targeted test field before and after the actual mission, the testfield calibration remained unreliable (Grun, 1978) and the results were definitely inferior to the ones obtained with self calibration using the same photographic data.

Another technique was developed in France (Masson d'Autume, 1972), where systematic error corrections are applied after block adjustment. In this method, the residuals of the tie points are analyzed, and systematic errors are reduced using second degree polynomials. Afterwards, the observed model or image coordinaters are corrected and the block adjustment is repeated. Several iterations may be required until no more significant systematic errors are detected.

While this technique appears to be superior to testfield pre- or post-calibration, it still does not reach the accuracy obtained with self calibration (Haug, 1976).

Mikhail and Kraus (1972) also carried out studies on the residuals after block adjustment and proved that correlated residuals may exist on the control points, thus requiring interpolation at the tie- and pass points. Using an a-priori variance-covariance matrix for the correlated components, least squares collocation can be applied. While the method is theoretically sound, the difficulty in obtaining a valid variance-covariance matrix has virtually prohibited its practical use.

Accuracy Improvement when using additional parameters

Bauer and Muller (1972) first demonstrated practically the accuracy improvement when using their BAP (Bundle adjustment with Additional Parameters) program. Since then, numerous studies have been carried out, all of which show some improvement. The following table, collected in (El Hakim, 1979) is presented as a representative sample:

	Control		Block Parameters				without additional parameters			with additional parameters			improvement factors		
Method Ref.)	H i	V j	Scale	Size	P%	a%	σ_0	μ_{xy}	μ_z	σ_o	μ_{xy}	μ_z	σ_o	μ_{xy}	μ_z
B.A. (Selmenpera et al)	4	4	4000	94	60	60	5.4	4.5	8.2	5.1	3.4	7.8	1.05	1.33	1.05
I.M.	2	4	28000	104	60	60	7.6	9.9	14.7	6.0	6.3	14.1	1.30	1.57	1.04
(Ebner)	4	8	"	"	"	"	7.5	13.4	19.0	6.0	6.6	17.1	1.30	2.03	1.11
	11	25	"	"	"	"	7.3	22.1	65.0	5.9	7.7	26.7	1.25	2.87	2.43
B.A. (Grün)	2	4	"	"	"	"	5.3	8.8	15.8	3.3	5.2	12.2	1.61	1.69	1.30
B.A. (Moniwa)	4	2	7200	15	60	30	8.3	10.0	87.5	8.3	42.0	58.3	1.00	2.62	1.50
I.M. (Schilcher)	2	4	7800	112	64	28	6.2	6.8	13.4	5.5	5.3	13.6	1.20	1.28	0.99

TABLE 1: Effect of systematic errors compensation

(I.M.: Independent Models, B.A.: Bundle Adjustment, i: No. of perimeter base lengths between control, j: No. of base lengths between chains of vertical control, P: overlap, q: sidelap, μ_{xy} and μ_z = RMS of check point discrepancies).

- all μm units in photo scale.
- all wide-angle cameras.

For fully controlled blocks, an improvement factor in the range of 1.3 to 1.6 in planimetry was achieved for independent models (analytically formed from photo-coordinates), and 1.3 to 2.6 for bundles. The height accuracy did not change significantly for independent models, but improved for bundles by a factor ranging from 1.3 to 1.5.

Obviously, self calibration yields greater improvements in cases of poorer control. The absolute accuracy achieved when using self calibration has reached a level that can compete with conventional terrestrial surveying. Apart from the Edmunston Block, where the object points were not targeted and the accuracy of the ground control though suitable for large scale mapping is unknown, accuracies of 3 - 5 µm in planimetry, and 8 - 12 µm in height were achieved for bundle block adjustments with additional parameters. Similar results were achieved elsewhere. This clearly indicates that analytical photogrammetry is approaching the accuracies inherent in photography, provided that the collinearity model is supplemented with additional parameters.

References

Bauer, H. and Muller, J. (1972). "Height Accuracy of Blocks and Bundle Adjustment with Additional Parameters", XIIth International Congress for Photogrammetry, Ottawa.

Brown, D.C. (1966). "Decentering Distortion of Lenses", Photogrammetric Engineering, Vol. 32.

Brown, D.C. (1976). "The Bundle Adjustment - Progress and Prospects", XIIIth International Congress for Photogrammetry, Helsinki.

Ebner, H. (1976). "Self Calibrating Block Adjustment", Bildmessung und Luftbildwesen, Vol. 4/76.

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

El Hakim, S.F. and Faig, W. (1977). "Compensation of Systematic Image Errors Using Spherical Harmonics", ASP Fall Technical Meeting, Little Rock.

Faig, W. (1975). "Calibration of Close-Range Photogrammetric Systems: Mathematical Formulation", Photogrammetric Engineering and Remote Sensing, Vol. 41.

Faig, W. and Atilola, O. (1984). "Aerotriangulation Using Data from Analogue Plotters", XVth International Congress for Photogrammetry, Rio de Janeiro.

Grun, A. (1978). "Experience with Self-Calibrating Bundle Adjustment", ASP Annual Meeting, Washington, D.C.

Haug, G. (1976). "Analysis and Reduction of the Systematic Image and Model Deformations of the Aerial Triangulation - Test Oberschwaben", XIIIth International Congress for Photogrammetry, Helsinki.

Masson d'Autume, G. (1972). "Le Traitement des Erreurs Systematiques dans l'Aerotriangulation", XIIth International Congress for Photogrammetry, Ottawa.

Mikhail, E.M. and Kraus, K. (1972). "Linear Least Squares Interpolation", Photogrammetric Engineering, Vol. 38.

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

Salmenpera, H., Anderson, J.M. and Savolainen, A. (1974). "Efficiency of the Extended Mathematical Model in Bundle Adjustment", Bildmessung und Luftbildwesen, Vol. 6/74.

Schilcher, M. (1976). "Some Practical Examples of Systematic Errors of Stereo-Models", XIIIth International Congress for Photogrammetry, Helsinki.

Schut, G.H. (1980). "Block Adjustment of Models", The Canadian Surveyor, Vol. 34.

SESSION V: CONTROL REQUIREMENTS; AUXILIARY CONTROL

Introduction

Regardless of geometric and stochastic conditions, any unit composed of two or more overlapping photographs needs to be absolutely oriented to the ground coordinate system. Whether this unit consists of one model, a section, a strip or a block, the commonly applied spatial similarity transformation has 7 unknown parameters and thus requires at least 7 known ground coordinates. Thus the absolute minimum ground control requirement are 2 horizontal (x/y) plus 3 vertical control points.

This, of course does not take into account any disturbing influences, such as those caused by transfer errors as well as extrapolation beyond the controlled area. Therefore the theoretical minimum is practically unrealistic.

Ground Control Requirements

Theoretical and practical investigations have led to a general acceptance of the following control requirements for:-

- planimetry: horizontal ground control along the perimeter of the block
- height: relatively dense chains of vertical control points across the block (normal to the strip direction).

While planimetric control in just the four corners of a block has provided acceptable results for some mapping purposes, a spacing of planimetric control points along the perimeter at 8 - 10 baselengths is commonly used. By expressing the control point separation in terms of base lengths, this number is independent of the photoscale and thus generally applicable. Similarly, for vertical control, dense cross-chains (every 2nd strip at least) at both ends and at 6 - 8 baselengths in between are recommended together with one additional perimeter point each between the cross-chains.

While this control configurations satisfies the needs for regular mapping, it will not provide the highest possible accuracy.

Based on Professor Ackermann's theoretical investigations for the Anblock method (Ackermann, 1966), dense perimeter control at every two base lengths produces the same accuracy inside the block regardless of the size of the block, which means that the block is fully controlled in this manner.

Gyer and Kennefick (1970) reached the same conclusion. Ebner (1972) found that for dense perimeter control (i.e. every two baselengths) the standard deviation increases only with the logarithm of the number of models per strip, which was confirmed by an independent study by Meissl (1972).

For vertical control, Ebner (1972) suggested a relatively dense net of points within the block (once every 2 baselengths normal to the strip direction, and every 4 baselengths along strip direction). Similar conclusions were reached earlier by Jerie (1968).

Although this configuration in planimetry and height should be maintained for highest accuracy, it is possible to reduce the number of points when changing the flight parameters (El Hakim, 1979).

The use of 60% sidelap, instead of the customary 20% improves the planimetric accuracy by a factor 1.25. Thus it is possible to reduce the photoscale by 25% without accuracy loss. This in turn increases the baselength, thus reducing the actual number of control points.

Multiple coverage has a similar effect, as a block covered twice will have an accuracy improvement factor of 1.4 It should be noted however, that a 40% reduction in photoscale may create point identification problems. Thus the mentioned improvement is valid only if there are no systematic errors (both in photo- and ground coordinates) and if the point identification does not suffer.

Recent studies at the ITC (Molenaar, 1984) indicate, that under certain circumstances, perimeter control may not be totally acceptable now that photogrammetric accuracies are often in the same class as terrestrial ones. If the terrestrial survey was laid out solely to establish perimeter control (e.g. by a ring traverse) it may lead to a weak geometric configuration, which in turn affects the absolute accuracy. Some cross-connections would then strengthen the geometry and thus the absolute accuracy significantly.

While this is a valid warning, it may loose its significance with the increasing use of satellite positioning techniques for control establishment.

Auxiliary Control

The use of perimeter control for planimetry has led to a drastic reduction in required terrestrial work, however, the cross-chains for vertical control demand additional surveys. Therefore any auxiliary data which can reduce the need for ground control surveys most notably vertical control, appear to be more than welcome. While the topic of auxiliary vertical control appears off and on in photogrammetric literature, their limited practical application is somewhat surprising, considering the great savings in vertical control that can be achieved.

Some Remarks on the History of Auxiliary Control

The utilization of directly measured exterior orientation data in aerotriangulation dates back more than half a century.

The most important instruments used, were (Zarzycki, 1972):-

- statoscope, which provides the z coordinate of the exposure station via differential altimetry (metric differences between aircraft path and isobaric surface).
- horizon camera, which provides rotational angles, referred to the horizon.
- solar periscope, which also provides rotations but with respect to the sun's location.

With the exception of statoscope, these instruments gained little practical acceptance. After the 2nd World War, airborne ranging methods were developed for determining the horizontal positions of the camera stations (Shoran, Hiran, Shiran) to support the airborne determination of large horizontal geodetic networks (Corten, 1960). For accuracy and economy reasons, they are not used any longer.

In the 1960's the Airborne Profile Recorder (APR) was developed and utilized extensively in Canada. The instrument consists of a statoscope or similar device to monitor the movements of the aircraft with respect to an isobaric surface plus a continuous record of the clearance profile between terrain and aircraft. Thus by correlating identificable features in photography and profile (e.g. horizontal water bodies) it became possible to derive ground elevations for a number of features along the flight path.

A new version of PAT-M was written in the early 1970's, which directly incorporates statoscope and APR data into the rigorous block adjustment. In addition, lake levelling was utilized (Ackermann et al, 1972). The latter makes use of the condition, that points along the shoreline of a lake have the same (though unknown) elevation. This is especially useful in areas like Northern Canada and thus has also been incorporated into SPACE-M (Blais, 1976).

Thus in conjunction with independent models, statoscope and lake levelling is used in practice (Brown, 1979; Faig et al, 1977), although not as much as it could be. The additional scale information obtained from APR-readings does not merit the extra cost of the equipment, as the statoscope, which is only part of it provides the major additional vertical information. Thus the use of APR has diminished in recent years.

Early attempts to determine the exterior orientation parameters for each aerial camera station utilizing gyroscopes were not very successful, mainly because of accuracy limitations (Corten, 1976). However, advances in inertial and satellite positioning technology as well as in airborne ranging have again focussed some attention to the subject. Flight navigation systems have been proposed which will assess the position and attitude of camera and carrier in real time during the flight. They are rather expensive and utilized for navigation and pin-point photography. However, these data can be utilized as auxiliary control during the block adjustment phase.

Positioning data (for x/y and/or z) are more effective than attitude data (ω, Φ, κ) as the latter still imply a summation of errors that affect the final coordinates (Ackermann, 1984).

In the future, it may even by possible to obtain accuracies of about 10cm in position and better than 1 second of arc in attitude thus greatly simplifying photogrammetric restitution and perhaps even make aerotriangulation obsolete.

Mathematical Modelling of Auxiliary Control

The method of integrating auxiliary control into a photogrammetric block adjustment is relatively simple and does not create serious numerical problems. The auxiliary information provides additional observation equations which, after proper weighting, are adjusted together with the other equations.

Ackermann (1984) provides the observation equations for the independent model block adjustment with PAT-M as follows:

- Statoscope: $$V_j^{stat} = Z_j^{PC} - Z_j^{stat} - (a_0 + a_1 x_j + ..)$$

- APR: $$V_j^{APR} = Z_i - Z_i^{APR} - (b_0 + b_1 x_j + ..)$$

- Horizontal positioning: $$V_j^x = X_j^{PC} - X_j^{NaV} - (c_0 + c_1 x_j + ..)$$
$$V_j^y = Y_j^{PC} - Y_j^{NaV} - (d_0 + d_1 x_j + ..)$$

- Attitude: $$V_j^{\omega} = \omega_j - \omega_j^{NaV} - (e_0 + e_1 x_j + ..)$$
$$V_j^{\Phi} = \Phi_j - \Phi_j^{NaV} - (f_o + f_1 x_j + ..)$$
$$V_j^{\kappa} = \kappa_j - \kappa_j^{NaV} - (g_0 + g_1 x_j + ..)$$

The latter three equations may be obtained after a preliminary transformation and linearization. This type of observation equations can be adapted to bundle adjustments as well.

The observation equation for lake levelling affects ground points and thus is similar to the vertical observation equation (Ackermann et al, 1972) in PAT-M (l is the lake index):

$$[V_z]_{ijl} = - [y\ x]_{ijl} \begin{bmatrix} da \\ db \end{bmatrix}_j - [dZ_o]_j - [Z]_l - [z]_{ijl}$$

Blais (1984) provides some equations for SPACE-M.

<u>Results</u>

Rather than presenting a great amount of numerical data, I would like to quote D.C. Brown (1979) "The dual and contemporaneous developments of generating effective airborne control by means of optimally reduced statoscopic observations and of generating optimally distributed ground control by satellite Doppler positioning ideally complement each other; in combination, they can render economically feasible the mapping of huge areas that might otherwise be prohibitively expensive....". He said this after reporting on a 1:25,000 mapping project where only 24 fully controlled points were used to control a block of about 3,000 photos. These points were separated by some 20 to 30 baselengths along the strips, and by 4 to 8 baselengths across the strips.

Ackermann (1974) reported on tests in a more controlled environment, where statoscope data adequately covered a block of 60km length without the need for interior vertical control.

Studies performed at the University of New Brunswick (El Hakim, 1976, Faig, 1976, 1979; Faig et al, 1977) were based both on test and production blocks flown either for the Topographical Survey Directorate, Department of Energy, Mines and Resources in Canada or for the 1:10,000 resource mapping program conducted by the Maritime Land Registration and Information Service.

Overall it became quite obvious that drastic savings can be realized with auxiliary vertical control for medium and small scale mapping. In particular, the following conclusions were drawn:

(1) The effect of lakes becomes significant when the bridging distance is more than 10 base lengths and the rate of improvement increases rapidly with increasing bridging distances. Lakes if well distributed can replace about 75% of vertical control points without sacrificing accuracy.

(2) The use of statoscope, particularly with some lake information, can completely satisfy vertical control requirements within a block for mapping with 5 m contours. With a vertical control chain at each end of the block plus perhaps one additional perimeter point on either side, statoscope data provide sufficient vertical control, even for bridging distances of up to 56 models.

Even the loss of one or two strips of statoscope readings due to malfunction does not significantly degrade the accuracy.

(3) With longitudinal APR, the accuracy decreases very little with increasing bridging distance, and virtually remains constant when cross flights with APR are introduced.

Based on these results plus some further investigations of their own, the Maritime Land Registration and Information Service requires the use of statoscope for all their photogrammmetric work and has changed the cross-chain separation for vertical control to 15 base lengths with excellent practical results. All lakes are measured as an additional bonus as it does not increase the cost significantly.

Ackermann (1984) reported on an experiment "Bodensee 1982" using flight navigation data as auxiliary control in block triangulation. The test demonstrated that the requirements for horizontal control can be substantially reduced for small scale mapping. He states: "The positive experience gained previously with statoscope and APR concerning vertical auxiliary data can certainly be extended to horizontal camera positioning data. Further research is required, especially when extending to inertial - or GPS navigation systems and to attitude data".

References

Ackermann, F. (1966). "On the Theoretical Accuracy of Planimetric Block Triangulation". Photogrammetria, Vol. 21.

Ackermann, F. (1974). "Accuracy of the Statoscope Data - Results from the OEEPE-test Oberschwaben", ISP Symposium, Comm. III, Stuttgart.

Ackermann, F. (1984). "Utilization of Navigation Data for Aerial Triangulation", Invited Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Ackermann, F., Ebner, H., Klein, H. (1972). "Combined Block Adjustment of APR-Data and Independent Photogrammetric Models", The Canadian Surveyor, Vol. 26.

Blais, J.A.R. (1976). "SPACE-M: Spatial Photogrammetric Adjustment for Control Extensions Using Independent Models", Presented Paper, Comm. III, ISP Congress, Helsinki.

Blais, J.A.R. (1984). "The Use of Auxiliary Data in Photogrammetric Block Adjustments of Stereo Models", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Brown, D.C. (1979). "Establishment of Photogrammetric Control by Satellite Doppler Positioning", Proceedings of the International Symposium on Current Trends in the Development, Execution and Use of Aerial Triangulation, Brisbane, Qld.

Corten, F.L. (1960). "Survey Navigation and Determination of Camera Orientation Elements", Photogrammetria, Vol. 15.

Corten, F.L. and Heimes, F.J., (1976). "Integrated Flight and Navigation System", Invited Paper, Comm. I, ISP Congress, Helsinki.

El Hakim, S.F. (1976). "The Utilization of Auxiliary Vertical Control in Aerotriangulation with PAT-M", M.Sc.E. thesis, Department of Surveying Engineering, University of New Brunswick.

El Hakim, S.F. (1979). "Potentials and Limitations of Photogrammetry for Precision Surveying", Ph.D. dissertation, Department of Surveying Engineering, University of New Brunswick, also UNB-SE Technical Report No. 63.

Ebner, H. (1972). "Theoretical Accuracy Models for Block Triangulation", Bildmessung und Luftbildwesen, 1/72.

Faig, W. (1976). "Independent Model Triangulation with Auxiliary Vertical Control", Presented Paper, Comm. III, ISP Congress, Helsinki.

Faig, W. (1979). "Canadian Experiences in the Adjustment of Large Photogrammetric Blocks with Auxiliary Vertical Control", Proceedings of the International Symposium on Current Trends in Aerial Triangulation, Brisbane, Qld.

Faig, W., El Hakim, S.F., Mathew, T. (1977). "Vertical Control for Independent Model Blocks", Journal of the Surveying and Mapping Division, American Society of Civil Engineers, Vol. 103.

Gyer, H.S. and Kennefick, J.F. (1970). "Propagation of Errors in Blocks", Photogrammetric Engineering, Vol. 36.

Jerie, H.G. (1968). "Theoretical Height Accuracy of Strip and Block Triangulation with and without Use of Auxiliary Data", Photogrammetria, Vol. 23.

Kure, J. (1974). "APR-Experience and Application", ITC Journal 73/74.

Meissl, P. (1972). "A Theoretical Random Error Propagation Law for Anblock Networks with Constrained Boundary", Osterreichische Zeitschrift fur Vermessungswesen.

Molenaar, M. (1984). "The Connection of Aerotriangulation Blocks and Ground Control Reconsidered", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Zarzycki, J.M. (1972). "The Use of Auxiliary Data in Aerial Triangulation", Invited Paper, Comm. III, ISP Congress, Ottawa.

SESSION VI: COMBINED ADJUSTMENT OF SURVEYING OBSERVATIONS AND PHOTOGRAMMETRIC DATA

Introduction

Historically, the adjustment of photogrammetric and geodetic measurements has been treated as two separate problems. In such a two-step solution, the terrestrial surveys are first adjusted to give a unique set of coordinates plus perhaps a variance-covariance matrix for the ground control points which are then used as input data into the photogrammetric solutions. This, of course, requires that all points can be coordinated from surveying data alone.

In the previous session it was illustrated how APR observations were adjusted simultaneously with photogrammetric observations, thus replacing a two step solution with a rigorous simultaneous approach. The same principle can be applied to conventional surveying observations. This also provides a more realistic approach to error analysis and weighting of the observations.

Mathematical Modelling

The first major development in this area was the program SAPGO (Simultaneous Adjustment of Photogrammetric and Geodetic Observations), developed at the University of Illinois (Wong and Elphingstone, 1972). Laplace azimuths, straight-line distances, geodetic azimuths, horizontal angles, elevation differences, latitudes, longitudes and elevations are accepted as input into SAPGO, together with photocoordinates. The photogrammetric model is the bundle adjustment without additional parameters, while classical geodesy forms the basis of the geodetic model, treating horizontal and vertical adjustments separately. The horizontal adjustment is performed on the surface of a reference ellipsoid as a function of longitude and latitude, while the vertical adjustment is based on mean sea level elevations. In order to combine these geodetic models with the photogrammetric one (based on a spatial rectangular coordinate system) the geodetic observation equations had to be modified. This means that the terms $d\Phi$, $d\lambda$ and dh of the classical geodetic equations need to be replaced by dX, dY, dZ as:

$$d\Phi = \left(\frac{\delta F_{\Phi}}{\delta X}\right) dX + \left(\frac{\delta F_{\Phi}}{\delta Y}\right) dY + \left(\frac{\delta F_{\Phi}}{\delta Z}\right) dZ$$

and similarily for $d\lambda$ and dh.

Unfortunately, there is no explicit functional relationship between Φ, λ, H and X, Y, Z. Therefore the partial derivatives were obtained in SAPGO by a numerical method, using the following approach:

If $g = f(X, Y)$ and $g_{\Delta X} = f(X + \Delta X, Y)$

then $$\frac{\delta g}{\delta X} = \frac{g - g_{\Delta X}}{\Delta X}$$

and similarily $$\frac{\delta g}{\delta Y} = \frac{g - g_{\Delta Y}}{\Delta Y}$$

This does not provide a rigorous solution, and the accuracy depends on the values chosen for ΔX and ΔY.

At the University of New Brunswick, the program system GEBAT (General Bundle Adjustment Triangulation) was developed (El Hakim, 1979; El Hakim and Faig, 1981). This system is a bundle adjustment with additional parameters using a harmonic function to compensate for the effect of systematic errors. The geodetic observations (slope distances, vertical angles, horizontal directions, astronomic azimuths, elevation differences, astronomic latitude and longitude) are based on modern three dimensional geodesy and rigorously combined with the photogrammetric adjustment. The stochastic model can be further improved by taking the correlation between the observations into account and applying least squares collocation.

After formulating observation equations for each type of observation, the following combined system was obtained for the least squares adjustment:

$$F_p(\hat{X}_1, \hat{X}_2, L_p) = 0 \qquad \text{for photogrammetric observations}$$

$$F_g(\hat{X}_2, \hat{X}_3, L_g) = 0 \qquad \text{for geodetic observations}$$

these are linearized to

$$W_p + A_{p1}\hat{X}_1 + A_{p2}\hat{X}_2 + B_p\hat{V}_p = 0$$

$$W_g + A_{g1}\hat{X}_2 + A_{g2}\hat{X}_3 + B_g\hat{V}_g = 0$$

where X_1 is the vector of photo orientation elements and additional parameters

X_2 is the vector of object coordinates

X_3 is the vector of orientation, refraction unknowns and astronomic coordinates

$Wp = Fp(X_1^o, X_2^o, Lp)$ is the photogrammetric misclosure vector for the initial value X_1^o and X_2^o.

$Wg = Fg(X_2^o, X_2^o, Lg)$ is the geodetic misclosure vector

Vp and Vg are the vectors of residuals for photocoordinates and geodetic observations respectively, and

A_{p1}, A_{p2}, B_p, A_{g1}, A_{g2}, B_g are the design matrices, obtained for instance as:

$$A_{p1} = \left.\frac{\delta F_p}{\delta \hat{X}_1}\right|_{X_1^o,\, X_2^o,\, L_p} \qquad \text{etc.}$$

The variation function is then:

$$\Phi = \hat{V}_p^T P_p \hat{V}_p + \hat{V}_g^T P_g \hat{V}_g + \hat{X}_1^T P_1 \hat{X}_1 + \hat{X}_2^T P_2 \hat{X}_2 + \hat{X}_3^T P_3 \hat{X}_3 +$$

$$+ 2\hat{K}_p^T (W_p + A_{p1}\hat{X}_1 + A_{p2}\hat{X}_2 + B_p\hat{V}_p) +$$

$$+ 2\hat{K}_g^T (W_g + A_{g1}\hat{X}_2 + A_{g2}\hat{X}_3 + B_g\hat{V}_g) = \text{minimum}$$

where P_p and P_g are the weight matrices for the observations; P_1, P_2, P_3 the weight matrices for the unknowns, and K_p and K_g are estimates for the vectors of Lagrange multipliers:

The normal equations become

$$\begin{bmatrix} P_p & 0 & B_p^T & 0 & 0 & 0 & 0 \\ 0 & P_g & 0 & B_g^T & 0 & 0 & 0 \\ B_p & 0 & 0 & 0 & A_{p1} & A_{p2} & 0 \\ 0 & B_g & 0 & 0 & 0 & A_{g1} & A_{g2} \\ 0 & 0 & A_{p1}^T & 0 & P_1 & 0 & 0 \\ 0 & 0 & A_{p2}^T & A_{g1}^T & 0 & P_2 & 0 \\ 0 & 0 & 0 & A_{g2}^T & 0 & 0 & P_3 \end{bmatrix} \begin{bmatrix} V_p \\ V_g \\ K_p \\ K_g \\ X_1 \\ X_2 \\ X_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ W_p \\ W_g \\ 0 \\ 0 \\ 0 \end{bmatrix} = 0$$

and provide the following results:

$$\hat{X}_2 = - [P_2 + N_{p22} + N_{g11} - N_{g12} (P_3 + N_{g22})^{-1} N_{g21} -$$

$$- N_{p21} (P_1 + N_{p11})^{-1} N_{p12}]^{-1} . [U_{p2} + U_{g1} -$$

$$- N_{g12} (P_3 + N_{g22})^{-1} U_{g2} - N_{p21} (P_1 + N_{p11})^{-1} U_{p1}]$$

and

$$\hat{\Sigma}_{xx} = - \hat{\sigma}_0^2 [P_2 + N_{p22} + N_{g11} - N_{g12} (P_3 + N_{g22})^{-1} N_{g21} -$$

$$- N_{p21} (P_1 + N_{p11})^{-1} N_{p11}]^{-1}$$

where

$$\hat{\sigma}_0^{\,2} = \frac{\hat{V}^T P \hat{V} + \hat{X}_1^T P_1 \hat{X}_1 + \hat{X}_2^T P_2 \hat{X}_2 + \hat{X}_3^T P_3 \hat{X}_3}{df}$$

The degree of freedom (df) equals the number of observations, since all unknowns are weighted.

The following abbreviations were used:

$$N_{pij} = A_{pi}^{T} [B_p P_p^{-1} B_p^T]^{-1} A_{pj}$$

$$N_{gij} = A_{gi}^{T} [B_g P_g^{-1} B_g^T]^{-1} A_{gj} = A_{gi}^{T} P_g A_{gi}$$

$$U_{pi} = A_{pi}^{T} [B_p P_p^{-1} B_p^T]^{-1} W_p$$

$$U_{gi} = A_{gi}^{T} [B_g P_g^{-1} B_g^T]^{-1} W_g$$

At the National Research Council of Canada, this basic program was subsequently optimized and expanded to include gross-error detection (data snooping) (El Hakim, 1984).

Available Software

Depending on the area of application, several GEBAT versions can now be used, such as GEBAT-D (which is designed for using distance observations only with photogrammetry) or GEBAT-V (a close-range version for non-metric cameras with photo variant additional parameters) (Faig and El Hakim, 1982).

In addition to SAPGO and GEBAT, there are a number of programs available at present for simultaneously adjusting geodetic and photogrammetric data [e.g. Anderson (1983), Elassal (1983)]. Ebner (1984) has summarized those developments.

While this approach has gained more acceptance in close-range photogrammetry, where a number of programs are now in use, numerical and computational problems have affected large blocks.

By including geodetic observations into the block adjustment, the normal equation matrix is of a more general nature. In order to keep the computational effort within reasonable limits, measures have to be taken to obtain a more favourable structure. Ebner (1984) presents a number of alternatives, based on specific arrangements as reported by Roşculeţ (1980), Duppe (1984), Larsson (1983), Kruck (1984) as well as his own which uses equations similar to a free adjustment (Schmid, 1980).

With conventional geodetic networks being coordinated frequently by satellite positioning (e.g. Doppler, GPS) the distinction betweeen control points and auxiliary control data is slowly disappearing, and thus the separation of these topics becomes marginal.

By integrating the different approaches for coordinating points, including photogrammetry, it is possible to achieve a solution even though any one of the systems alone can be under-determined, as later illustrated with an example in Session VIII.

Before leaving the subject of control, I would like to mention the capability of photogrammetry to utilize line features rather than points for control. Just as a horizontal plane (i.e. lake level) can provide vertical strength, a well defined line that can be clearly identified in both object and image spaces can successfuly serve as control even though there is no direct one-to-one relation between specific ground- and photo-points (Masry, 1981; Luguano and Souza, 1984).

References

Anderson, J.M. (1982). "A Combined Photogrammetric and Doppler Adjustment", Dept. of Photogrammetry, Royal Institute of Technology, Stockholm, Report 2:46.

Duppe, R.D. (1984). "Kombinierte Ausgleichumg in der Photogrammetrie: Programmkonzeption und Beispiele", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Ebner, H. (1984). "Combined Adjustment of Photogrammetric and Non-Photogrammetric Information", Invited Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Elassal, A.A. (1983). "Generalized Adjustment by Least Squares (GALS)", Photogrammetric Engineering and Remote Sensing, Vol. 50.

El Hakim, S.F. (1979). "Potentials and Limitations of Photogrammetry for Precision Surveying", Ph.D. Dissertation, Dept. of Sureying Engineering, University of New Brunswick, Fredericton.

El Hakim, S.F. (1984). "On the Detection of Gross and Systematic Errors in Combined Adjustment of Terrestrial and Photogrammetric Data", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

El Hakim, S.F. and Faig, W. (1981). "A Combined Adjustment of Geodetic and Photogrammetric Observations", Photogrammetric Engineering and Remote Sensing, Vol. 48.

Faig, W. and El Hakim, S.F. (1982). "The Use of Distances as Object Space Control in Close-Range Photogrammetry", Proceedings, Symposium on Precision and Speed in Close-Range Photogrammetry, York.

Kenefick, J.F. (1978). "Bridging with Independent Horizontal Control", Photogrammetric Engineering and Remote Sensing, Vol. 45.

Kruck, E. (1984). "Ordering and Solution of Large Normal Equation Systems for Simultaneous Geodetic and Photogrammetric Adjustment, Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Larsson, R. (1983). "Simultaneous Photogrammetric and Geodetic Adjustment - Algorithms and Data Structures", Dept. of Photogrammetry, Royal Institute of Technology, Stockholm, Report 2:48.

Lugnani, J.B. and Souza, F.C.B., (1984). "Control Features - An Alternative Source for Urban Area Control", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Masry, S.E. (1981). "Digital Mapping Using Entities - A New Concept", Photogrammetric Engineering and Remote Sensing, Vol. 48.

Roşculeţ, D. (1980). "Recursive Methods for the Simultaneous Adjustment of Photogrammetric and Geodetic Observations in Analytical Aerotriangulation", Presented Paper, Comm. III, ISP Congress, Hamburg.

Schmid, H.H. (1980). "Vom freien zum gelagerten Netz", Institut fur Geodasie und Photogrammetrie, ETH Zurich, Mitteilung 29.

Torlegard, K. (1983). "Combined Geodetic and Photogrammetric Mensuration - Problems and Possibilities", FIG Congress, Paper 501.2, Sofia.

Wong, K.W. and Elphingstone, G. (1972). "Aerotriangulation by SAPGO" Photogrammetric Engineering, Vol. 39.

SESSION VII: ACCURACY, PRECISION AND RELIABILITY; CAPABILITY AND LIMITATIONS OF NUMERICAL PHOTOGRAMMETRY.

Introduction

The main purpose of aerial triangulation is the determination of ground coordinates for a large amount of terrain points using as few control points as possible. Compared to terrestrial surveying methods, aerial triangulation is generally more restricted as far as the number of over-determinations for individual points is concerned, and requires the simultaneous solution for a huge amount of unknowns. Thus it is economically not feasible to compute a full variance-covariance matrix which would provide the standard deviations for each coordinate of each point. It is therefore necessary to provide some other indication for the quality of aerial triangulation.

While the functional models for aerial triangulation are highly sophisticated, the stochastic modelling has been rather simplified, which means that we obtain coordinate values but often do not know "how good" they are.

The quality of the results has a different meaning for different people, and includes terms like "accuracy, precision and reliability". The term "accuracy" basically describes how close the results are to the true values (i.e. position or location), while the term "precision" deals with scatters as expressed by the variance. Both are affected by bias and thus by blunders and outliers. If only random errors exist, the relationship between accuracy and precision will be within certain limits, e.g. at the 95% confidence level, the accuracy should not exceed 1.96 times the standard deviation, assuming normally distributed residuals. This assumption however is not valid for aerotriangulation. Thus, the root mean square error between adjusted coordinates and known check point coordinates is a better indication of accuracy than the standard deviation, provided that the accuracy of the check points is known (Parsic, 1984). This is the case for a number of specially designed test areas, which have been used to evaluate the accuracy of various aerial triangulation procedures. In practice, however, this directly contradicts the purpose of aerotriangulation, namely to work with a minimum of ground control.

Therefore, the relationship between RMS-value and standard deviations is established for a certain procedure via test blocks and then applied to production blocks executed in a similar manner.

As mentioned earlier, it is generally too expensive to provide the variance-covariance matrix and thus the individual standard deviations. Thus the use of the standard error of unit weight (σ_0) as the sole indication of precision is commonly accepted in practical aerotriangulation.

Provided that the bias is kept within tolerable limits (i.e. by modelling systematic errors with additional parameters), this quality measure is quite valid, though often somewhat optimistic.

Blunders, which remain in the adjustment, disturb this relationship, thus it is important to consider the reliability of the adjustment. Reliability is directly related to the number of over-determinations, both for the whole adjustment as well as for individual points. Unique solutions, i.e. points imaged in two photographs only, are statistically unreliable and have to be avoided. During the last few years, great efforts in photogrammetric research have been directed towards blunder detection and elimination to improve the aerotriangulation accuracy. (Ackermann, 1984; Kubik et al, 1984; Molenaar, 1984). Some of these approaches will be discussed later in this session.

Accuracy Evaluation with Test Blocks

Various test blocks have been photographed and adjusted in every conceivable measure to evaluate different methods of aerotriangulation, control point configuration, auxiliary vertical control, self-calibration, lake levelling etc. etc. (e.g. Ackermann, 1974; Brown, 1976; Ebner & Grun, 1979; Faig, 1979; Kilpela & Salmenpera, 1979).

Rather than giving individual results, it can be stated, that bundle block adjustments with additional parameters and ideal control (i.e. perimeter control at every 2 base lengths for planimetry plus dense cross chains of vertical control every 4 base lengths) can provide an accuracy at photoscale of 2 - 5μm in planimetry and 5 - 10μm in height. Analytical independent models are only slightly less accurate. If, however, the independent models are measured on an analogue instrument, an accuracy of 20 - 30μm is more realistic. The area of blunders still needs to be considered.

Blunder Detection in Aerotriangulation

Since the computations involved with a photogrammetric block adjustment are quite expensive, it is desirable to detect and eliminate blunders in steps, some of them prior to performing the block adjustment. Therefore, pre-adjustment error detection procedures are extensively used. These may be in form of on-line checks, the formation of models, sections, such as triplets or quadruplets, or of strips with automatic check of the residuals and elimination or identification of questionable observations (Jacobson, 1984).

During the iterative adjustment process, observations can be eliminated based on their residuals or else have weights assigned such that bad observations have little or no influence in the final result ("Danish Method").

A statistical test ("Data Snooping") generally leads to best results with respect to the localization and detection of small gross errors.

As pointed out in (Forstner, 1984) when evaluating a test on gross error detection, observations should be corrected if the error can be identified. In most tests, the size of the error is usually incorrectly estimated. If the error cannot be located, then the point should be removed from the adjustment or else properly identified as unreliable.

The "Danish Method"

In this method, originally proposed by T. Krarup, (Krarup et al, 1980), the blunder detection uses the residuals plus σ_o from the previous iteration as weight for the present one. Unfortunately, gross errors do not necessarily show among the largest residuals, which led to the following three-step approach (Juhl, 1984):

1. Run 2 - 3 iterations of a normal bundle adjustment.

2. A drastic weight function is introduced, assuming that 10 - 25% of all observations contain blunders. This provides a better chance to find the actual blunders. Due to the lower weight, the residuals will increase in size, a process that will accelerate while iterating. This, however, happens only for blunders, while the major part of the weight reduced residuals will only slightly increase, despite having a weight smaller than one. Two to three iterations are used.

3. In the third step a softer new weight function is introduced, which reduces the weight of only ½ - 2% of all observations. This brings all observations with reduced weight in step 2 that have no blunder back into the usual least squares adjustment while keeping observations with blunders at a low weight.

The method usually requires 3 - 5 iterations. This basic approach, which is an application of "robust estimators" (Jorgensen et al, 1984), has for instance been incorporated into PAT-M (Klein & Forstner, 1984).

The approach of robust estimators can detect more than one blunder in the same adjustment, but may be insensitive to smaller blunders.

<u>"Data Snooping"</u>

This statistical method was first developed by Baarda (1967; 1968) for testing geodetic networks. The following null-hypotheses are being tested:

$$H_{oi} = E(V_i) = 0$$

by using the statistics

$$W_i = \frac{|V_i|}{\sigma_{vi}} \qquad \text{with } \sigma_{vi} = \sigma_0 \sqrt{q_{vi\,vi}}$$

If H_{oi} is true, then W_i has a student's t - distribution (Mikhail, 1979).

The problem lies in computing σ_{vi}, i.e. the diagonal elements $q_{vi\ vi}$ of the variance-covariance matrix Q_{vv} of the residuals.

Since the latter is directly derived from the variance-covariance matrix of the unknowns via the covariance law, it is desirable to avoid its full computation in aerotriangulation for economical reasons. Thus various alternatives have been proposed (Grun, 1979), which invariably leads to reliability. The latter depends on random errors, considered to be normally distributed and unbiased, which in turn could imply the absence of both systematic errors or blunders. Assuming that systematic errors have been properly modelled, reliability provides a means of dealing with blunders.

The reliability studies related to data snooping can be used in two ways, namely to design the block such that the tests become very sensitive and can detect even small errors with a high probability (system with "high internal reliability"), or such that undetected errors do not cause serious deformations ("high external, or global, reliability").

While the average diagonal term of Q_{vv} P can serve as a global reliability measure, the $q_{vi\,vi}$ - values have a strong relation to local reliability measures. The latter are mainly influenced by parameters such as

- number of rays determining a point
- type of point (control point or not), and to a lesser extend
- number and distribution of image points and of control points
- camera parameters.

Thus the computation of a reliability number is quite helpful in data snooping (El Hakim, 1981; 1984).

Due to correlation between residuals, usually only one blunder can be detected in one adjustment. Furthermore, σ_o is influenced by blunders thus perhaps reducing the efficiency of the test. However, data snooping leads to the best results in blunder detection (Ackermann, 1984). Schwarz and Vaessen (1984) provide results for data snooping with independent model blocks.

Pre-analysis for Photogrammetric Block Adjustments

In spite of many theoretical investigations into photogrammetric accuracy (Ackermann, 1966; Jerie, 1968; Talts, 1968; Kubic, 1971; Ebner, 1972), empirical tests with test blocks have been providing the main tool for estimating expected accuracy. El Hakim (1979) proposed a pre-analysis method much along the lines commonly used in geodesy and precision surveying.

Assuming random errors only, the accuracy of the resulting coordinates is given by the covariance law:

$$\Sigma_{xx} = J_{xl}\,\Sigma_{ll}\,J_{xl}^{T}$$

where Σ_{xx} is the covariance matrix of the adjusted vector of coordinates X, Σ_{ll} the covariance matrix of the observations $\bar{l}$, and

$$J_{xl} = \frac{\delta \bar{X}}{\delta \bar{l}}$$ is the Jacobian matrix of $\bar{X}$ with respect to $\bar{l}$.

For pre-analysis purposes, the rotation angles are assumed to be zero, and the elevation differences $(Z_o - Z_i)$ as equal to the flying height H. This leads to the following variance-covariance matrix for bundles:

$$\Sigma_{xx} = \begin{bmatrix} nc^2 & 0 & c\sum_{i=1}^{n} x_i \\ 0 & nc^2 & c\sum_{i=1}^{n} y_i \\ c\sum_{i=1}^{n} x_i & c\sum_{i=1}^{n} y_i & \sum_{i=1}^{n}(x_i^2 + y_i^2) \end{bmatrix}^{-1} \cdot H^2\sigma^2$$

where n is the number of photos in which the point appears, c is the camera constant, x_i/y_i are observed photo coordinates, assumed to be uncorrelated, and σ is the standard deviation of photocoordinate observations.

The following conclusions can be drawn from this equation:

- points at the edge of the block (appearing only twice for 30% sidelap) have a lower accuracy than points inside the block. Thus it is advisable to extend a block beyond the area of interest.

- increasing the sidelap to 60% improves the accuracy as the points appear on more photographs.

- multiple coverage improves the accuracy by m, where m is the number of flights at the same photoscale.

- for wide angle photography, z is less accurate than x or y, because

$$\sum_{i=1}^{n} (x_i^2 + y_i^2) < nc^2$$

For superwide angle photography, the z accuracy would improve relative to x and y, but only if the photoscale remains the same.

The same procedure can be applied to independent models, leading to

$$\Sigma_{xx} = \begin{bmatrix} \frac{\sigma_x^2 H^2}{n^2 c^2} & 0 & 0 \\ 0 & \frac{\sigma_y^2 H^2}{n^2 c^2} & 0 \\ 0 & 0 & \frac{\sigma_z^2 H^2}{n^2 c^2} \end{bmatrix}$$

This proves that the accuracy is directly related to the measuring accuracy of the model coordinates.

The effect of sidelap, multiple coverage and location of point within the block is similar to the bundle case. However, the use of superwide angle cameras has theoretically no effect on the accuracy as long as the H/c ratio and the measuring accuracy remain the same.

References

Ackermann, F. (1966). "On the Theoretical Accuracy of Planimetric Block Triangulation". Photogrammetria No. 21.

Ackermann, F. (1974). "Accuracy of Statoscope Data; Results from the OEEPE Test 'Oberschwaben' ", ISP Comm. III Symposium, Stuttgart.

Ackermann, F. (1984). "Report of the Activities of Working Group III/1 During 1980-84", Invited Paper, Comm. III ISPRS Congress, Rio de Janeiro.

Baarda, W. (1967). "Statistical Concepts in Geodesy", Netherland's Geodetic Commission, Vol. 2, No. 4.

Baarda, W. (1968). "A Test Procedure for Use in Geodetic Networks", Netherland's Geodetic Commission, Vol. 2, No. 5.

Brown, D.C. (1976). "The Bundle Adjustment - Progress and Prospects", Invited Paper, Comm. III, ISP Congress, Helsinki.

Ebner, H. (1972). "Theoretical Accuracy Models for Block Triangulation", Bildmessung und Luftbildwesen 1/1972.

Ebner, H. and Grun, A. (1979). "Accuracy Aspects of Bundle Adjustment Applications to Cadastre and Network Densification", Aerial Triangulation Symposium, Brisbane.

El Hakim, S.F. (1979). "Potentials and Limitations of Photogrammetry for Precision Surveying", Ph.D. Dissertation, Dept. Of Surveying Engineering, University of New Brunswick, Canada.

El Hakim, S.F. (1981). "A Practical Study of Gross-Error Detection in Bundle Adjustment", The Canadian Surveyor, Vol. 35.

El Hakim S.F. (1984). "On the Detection of Gross and Systematic Errors in Combined Adjustment of Terrestrial and Photogrammetric Data", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Faig, W. (1979). "Canadian Experiences in the Adjustment of Large Photogrammetric Blocks with Auxiliary Vertical Control", Aerial Triangulation Symposium, Brisbane.

Forstner, W. (1984). "Results of Test 2 on Gross Error Detection of ISP WG III/1 and OEEPE", Invited Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Grun, A. (1979). "Gross Error Detection in Bundle Adjustment", Aerial Triangulation Symposium, Brisbane.

Jacobsen, K. (1984). "Experience in Blunder Detection for Aerial Triangulation", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Jerie, H.G. (1968). "Accuracy of Aerial Triangulation", ITC Publications, No. A47.

Jorgensen, C., Frederiksen, P., Kubik, K., Weng, W. (1984). "Ah, Robust Estimation!", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Juhl, J. (1984). "The "Danish Method" of Weight Reduction for Gross Error Detection", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Kilpela, E. and Salmenpaera, H. (1979). "Analytical Block Triangulation in Finland, Theory, Practice and Results", Aerial Triangulation Symposium, Brisbane.

Klein H. and Forstner, W. (1984). "Realization of Automatic Error Detection in the Block Adjustment Program PAT-M43 Using Robust Estimators", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Krarup, T., Juhl, J., Kubik, K. (1980). "Gotterdammerung over Least Squares", Presented Paper, Comm. III. ISP Congress, Hamburg.

Kubik, K. (1971). "The Effect of Systematic Image Errors in Block Triangulation", ITC Publications, No. A49.

Kubick, K., Weng, W., Frederiksen, P., (1984). "Oh, Gross Errors!", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Mikhail, E.M. (1979). "Review and Some Thoughts on the Assessment of Aerial Triangulation Results", Aerial Triangulation Symposium, Brisbane.

Molenaar, M. (1984). "The Present Status of the Theory for the Evaluation of the Quality of Photogrammetric Point Determination", Invited Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Parsic, Z. (1984). "Investigation of the Accuracy of a Block Adjustment According to the Bundle Method", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Schwarz, P.G., and Vaessen, E.M.J. (1984). "FOTEF: Experiences with Data Snooping in Photogrammetric Production", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Talts, F. (1968). "On the Theorectical Accuracy, of Rigorous Block Adjustment in Planimetry and Elevation", Presented Paper, Comm. III. ISP Congress, Lansanne.

SESSION VIII: APPLICATION OF AERIAL TRIANGULATION OTHER THAN CONTROL EXTENSION AND MAPPING CONTROL - WRAP-UP

Introduction

In this closing session, I would like to accomplish two things, namely to provide you with a broader perspective on where aerotriangulation may be used in practice, and secondly to impress on you that aerotriangulation is not a closed and established subject but that there is still room for expansion and development.

Applications of Aerial Triangulation

Equivalent to a travel slogan "everybody talks about the weather - we don't", I would like to skip the areas of control extension and mapping control determination by aerotriangulation. They are well known and commonly accepted.

There appears to be a need to draw the attention towards additional applications, which may perhaps open new doors for photogrammetrists in other fields requiring measurements. Since the users are often not aware what photogrammetrists can offer, it is essential that photogrammetrists educate the users thus generating new markets for their expertise and products.

While the surveying profession has long been involved with photogrammetry, many of its members regard it as a mapping tool only. Thus aerial triangulation has not really gained acceptance in cadastral surveying. One of the main arguments that often arise is accuracy limitation. While several studies (i.e. Ackermann, 1974; Brown, 1976) have clearly demonstrated that aerotriangulation can provide very competitive absolute accuracies, there appears to be a hang-up on relative accuracies. Since photogrammetric accuracy is independent of point separation, relative accuracy is a poor measure, as it would be unacceptably low for points very close together (the point of contention), and incredibly high for points far apart (a clever argument used sometimes in marketing to give the appearance of superiority of photogrammetry). If neighbouring accuracy is important, directly measured short distances could be included into the photogrammetric adjustment thus eliminating the problem. With this, aerial triangulation becomes a powerful tool for large area cadastral surveys (El Hakim, 1981).

By applying aerotriangulation procedures to industrial projects, even perhaps at close-range, many three-dimensional measuring tasks can be successfully tackled.

Since the accuracy is a direct function of photoscale, photogrammetry can provide three-dimensional accuracies which are very difficult if not impossible to obtain by conventional surveying means. As an example, I would like to mention a project where an industrial network of points had to be coordinated to millimetre accuracy. Using a phototheodolite elevated for approximate vertical photography, the area of about 200 m^2 was covered by a small block of four photographs and the points were successfully coordinated thus saving the factory's survey crew days, perhaps weeks of angular measurement (Faig, 1981; Faig and El Hakim, 1982).

Another example from my own experience is in the area of mining subsidence determination where aerotriangulation procedures were directly applied to evaluate movements. With proper control, this can be done with two separate missions evaluated independently, however, practical problems often prevent this. Thus modifications were made to overcome control problems and directly obtain movement vectors as described in Faig (1984).

While "the sky is the limit", I would urge photogrammetrists to look back "down to earth" and apply their expertise to the varied measurement problems which face our society, and then perhaps look the other way and "reach for the moon" a as mapping object or whatever. The tools are there, use them!

Wrap-up

In presenting the subject area of aerial triangulation in such a condensed manner, there remain developments which are not properly treated or not even mentioned. This should not be taken as a value judgement, which is why I now want to draw your attention to developments such as online triangulation and the use of analytical plotters, e.g. Kratky, 1984a & b; Grun, 1984; Jacobsen, 1984; Heikkila and Kilpela, 1984; Dowideit, 1979) VLBA (Very Large Block Aerial Triangulation) (Andrade et al, 1984), the use of minicomputers in aerotriangulation (Klein, 1978; Dorrer, 1982; Julia, 1984), and the use of sections consisting of several photographs or models (Mikhail, 1979; Torlegard, 1984). They and others were simply left out because of the time limitations.

Finally, the subject is by no means closed and established, although many photogrammetrists are led to believe this at various times in their career. When I graduated in the early 1960's, the subject was "just about completed", and in the early 1970's I was told in the U.S. that the "final development is just being written up, thus wrapping-up the subject". It was interesting to hear Professor Ackermann at the 1979 Brisbane Symposium saying that he was told the same thing when he was a student and several times since. Yet the field is as vigorous as ever, which is evident by the fact the Commission III required two volumes for the proceedings at this year's Congress in Rio de Janeiro. Aerotriangulation is and remains a challenging field for years to come!

References

Ackermann, F. (1984). "Photogrammetric Densification of Trigonometric Networks - The Project Appenweier", Bildmessung und Luftbildwesen, 6/1974.

Andrade, J.B., Rosier, F.A., Olvas, M.A.A. (1984).. "Very Large Block Aerial Trangulation", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Brown, D.C. (1976). "The Bundle Adjustment - Progress and Prospects" Invited Paper, Comm. III, ISP Congress, Helsinki.

Dorrer, E. (1982). "APL - Modernes Hilfsmittel fur Geodasie und Photogrammetrie", von Siemens - Stiftung, address, Nymphenburg.

Dowideit, G.R. (1979). "A Real Time Bundle Block Adjustment for Analytical Plotters", Aerial Triangulation Symposium, Brisbane.

El Hakim, S.F. (1982). "Results from a Precise Photogrammetric Densification of an Urban Control Network", The Canadian Surveyor, Vol. 36.

Faig, W. (1981). "Close-Range Precision Photogrammetry for Industrial Purposes", Photogrammetria, Vol. 36.

Faig, W. (1984). "The Use of Photogrammetry for Mining Subsidence Determination", The Australian Journal of Geodesy, Photogrammetry and Surveying, (in print).

Faig, W. and El Hakim, S.F. (1982). "The Use of Distances as Object Space Control in Close-Range Photogrammetry", Symposium on Precision and Speed in Close Range Photogrammetry, York.

Grun, A. (1984). "Algorithmic Aspects in On-Line Triangulation", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Heikkila, J. and Kilpela, E. (1984). "Aerial Triangulation by Analtyical Plotter", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Jacobsen, K. (1984). "Data Collection for Bundle Block Adjustment on Analytical Plotters", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Julia, J.E. (1984). "A General Rigorous Method for Block Adjustment with Models in Mini and Microcomputers", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Klein, H. (1979). "Block Adjustment Program for Minicomputers", ISP Comm. III Symposium, Moscow.

Kratky, V. (1984a). "Report on Activities of Working Group III-2 in 1980-1984 (On-Line Photogrammetric Triangulation)", Invited Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Kratky, V. (1984b). "On-Line Triangulation Performance of the NRC Anaplot", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

Mikhail, E.M. (1979). "Comparative Results from Block Triangulation with Different Units", Aerial Triangulation Symposium, Brisbane.

Torlegard, K. (1984). "Multi-Models to Increase Accuracy - Summary of an Experiment", Presented Paper, Comm. III, ISPRS Congress, Rio de Janeiro.

SECTION 2: DIGITAL MAPPING

SESSION I: DIGITAL MAPPING: WHAT IS IT, AND WHAT TYPE OF EQUIPMENT IS NEEDED?

The Scope of Digital Mapping

Digital Mapping, automated cartography, computerised cartography, are just some of the terms frequently used when talking about the utilization of computer technology in the field of topographic and/or thematic mapping. Unfortunately, they apppear to have different meanings for different people and are often confused with terms like "Computer Graphics, Computer Aided Draughting, or CAD/CAM (Computer Assisted Design/Computer Assisted Manufacturing).

While I am not trying to define Digital Mapping, I would like to provide you with the framework into which Digital Mapping fits. In my opinion, it is the process of collecting spatial (topographic) information, converting it into digital form, then combining it with other relevant data and finally represent it in different combinations in graphical and/or alpha-numeric form. Digital Mapping thus goes beyond computer aided photogrammetric stereocompilation (i.e. analytical plotters, or stereoplotters with encoders and subsequent computer plotting), which can be considered a subset of Digital Mapping, but stops short of Land Information Systems, as it deals with the spatial/graphic aspects of these. In fact, some Land Information Systems emphasise other aspects, thereby unfortunately neglecting the graphical, positional information and thus being limited in scope and usefulness.

Digital Mapping then deals with two types of information, namely graphics (Images) and Attribute Data, related to the Graphics. Both have to be in a computer compatible form (i.e. digital). This form permits easier detection of change and facilitates rapid updating.

The main operations in a digital mapping environment are:

- data collection (input)
- formation of clean data files (editing) for a data base
- maintenance of the data base (updating)
- utilization of the data base (data analysis, production of maps, graphs, reports etc. - output).

Digital Mapping thus tackles the main problems of conventional mapping, namely:

- incompatibility of data from different sources
- lack of data revision
- lack of efficient procedures for data analysis.

Elements of a Digital Mapping System

A digital mapping system consists of three major parts, namely:

- input system
- storage and data management system
- retrieval, analysis and display system.

The input system has to be capable of handling spatial elements (points, lines, area elements) which usually are provided in analogue form (i.e. on maps or aerial photographs), as well as alpha-numeric (names and numbers) and symbolic elements.

The storage and data management system has to assemble data files in certain data structures (either vector - or raster based) and combine graphic and alpha-numeric data into a spatial data base, such that for each graphic element all corresponding thematic and semantic elements can be found and vice versa. Such a system should include software that provides:

- simultaneous and fast access to more than one user
- fast retrieval, update, and data revision
- non-redundant data storage
- data security and integrity.

The retrieval, analysis and display system has to provide for data retrieval according to spatial or thematic aspects, should include spatial analysis functions (geometric calculations, statistical evaluations, overlays, windows etc) and apply computer graphics for display purposes. Then the desired result is sent to various output devices, such as plotters and printers.

Hardware Components for Digital Mapping

The central piece of hardware is a computer - usually referred to as CPU (Central Processing Unit) and has a certain size (number of cells) which are available for logic and for core memory. The size of a CPU is measured in "words".

A word is a collection of bits (i.e. 16 bits, 32 bits); medium and small computers usually have 16 bit words.

A "bit" represents either 0 or 1, and a byte consists of two bits. For instance, the DEC (Digital Equipment Corp.) PDP 11/60 has 128k words.

The information contained in one mapsheet however is about 400k words. Thus it cannot be handled in core, and auxiliary memory is necessary.

Disk storage is equivalent to a phonograph record with information on one or both sides. A disk is reasonably sensitive to contamination, such as dust. Usually about 11 mapsheets can be stored on one standard disk. Dispacks may have 2 to 8 disks.

Magnetic Tape is less sensitive than a disk, and has more storage capacity (about 3 dispacks fit onto one tape), however, reading from tape is much slower than from a disk.

Magnetic tapes are commonly 2400 ft long (800 m). Depending on the tape drive, they can store 800 bits per inch (350 bits/cm) for the old standard, and 1600 bits per inch (700 bits/cm) for the new standard.

The shelf life of a frequently used tape is somewhat over one year, while it lasts nearly indefinitely, when it is not used. Therefore, it is normal practice to recreate the magnetic tapes yearly (copy plus verify).

Diskette storage is too small for map information and thus not used. Occasionally, a Winchester Disk is used, which is sealed and cannot be removed from the disk drive (to avoid contamination). It has a very high recording density.

The interaction between the human operator and the CPU is normally achieved with the aid of a terminal.

There are 4 basic types of terminals, namely:

- alpha-numeric (letters and numbers)
- printer (like alpha-numeric plus hard copy capability)
- graphics (draws pictures)
- colour graphics.

Alpha-numeric terminals are common in virtually all aspects of electronic data processing. Some only print characters and permit typing input, while other ("smart") terminals can highlight characters, underline, have different size texts and black and white reversal. Normally, a terminal can accommodate 24 lines with 80 characters each, although some have 132 characters per line to match the printers.

Alpha-numeric terminals may be interfaced with a printer or a graphics terminal instead of with the computer.

A printer terminal is similar to an alpha-numeric terminal but prints on paper with a fixed line length of 132 characters. The printer may be of the impact type (ribbon is hit) or of a non-impact type which either burns the characters into the paper or else ejects ink. The latter operate quietly.

Older types have formed characters like a typewriter, where newer ones operate with a dot-matrix (7 x 9 resp. 33 x 18 dots).

The printing speed varies from to 10 to 150 characters per second.

Graphic terminals have commonly a 19 inch (48 cm) screen whose surface consists of a raster of dots (4096 x 3120 dots for black and white; 1280 x 1024 dots for colour).

A line is represented by a sequence of turned-on dots, which explains the lower line quality of colour terminals.

The dots are activated by an electron gun.

A black and white graphics terminal has one elctron gun and usually operates as a storage type, i.e. once turned on, the dots stay on. When turning off, the whole screen is flooded.

A colour terminal has three electron guns (blue, green, red), and the dot stays on for a very short time. Similarly to an alpha-numeric terminal, it has to be reprinted 60 times per second.

Another major input device is the digitizing table. It consists of a stand that can be tilted and rotated plus a cursor tablet with cross hair and digitizing buttons.

Digitizing is performed either in point mode (press button, record) or in stream mode, where the computer samples while the cursor moves along a curvilinear feature. The speed of the digitization is computer controlled, the resolution is usually 1000 points per inch, or 400 points per centimetre. Either absolute coordinates are stored or else incremental differences.

It should be noted that older digitizers lose their origin once the cursor is lifted from the table; modern solid state ones retain it.

For mass-digitizing of maps, a raster scanning system is preferable. A high speed scanner will produce a raster image of a map which is then transformed into vector mode by sophisticated software. Here pattern recognition techniques are applied as well to handle alpha-numeric characters and symbols.

While scanners are efficient, they are also very expensive (in the vicinity of $1/2 million), and thus beyond the reach for many organizations involved in Digital Mapping.

Computer plotters provide the means of obtaining hard copies of the graphical information. Drum plotters, are fast (~ 42 inches per second, or 105 cm/s) but have problems with ink and pen when rolling back and forth.

Flatbed plotters are of highest accuracy and can be used for scribing as well, but are much slower (~ 10 inches per second, or 25 cm/s).

Concluding Remarks

By now it should be evident that digital mapping is not replacing conventional mapping (at least initially) but rather complements and expands it. A large amount of its input information is drawn from conventional mapping products and will continue as such for the near future.

As the users prefer graphical hard copy maps, their production will continue, although via the digital route, which is causing significant changes in the mapping industry.

While it is sometimes necessary to build specific hardware components for a digital mapping system, it is advisable to keep this to the absolute minimum and use "off the shelf" components as they are readily being serviced by the vendors. Hardware maintenance is a most critical aspect of any electronic data processing venture.

SESSION II: BASIC SOFTWARE REQUIREMENTS

To start this session, I would like to emphazise, that it is impossible to cover digital mapping software in detail within the frame of a workshop like this. Most systems contain an investment of several man-years of programming, system analysis etc. As with hardware, "off the shelf" routines and commercially marketed programs are included in most digital mapping systems. Often the development of specific software is done by, for, or in cooperation with the hardware manufacturers.

The operating system for a specific central processing unit forms the foundation as it provides for interface between user and hardware, real time operations, multi-use, utilities (e.g. text editor, word processor, archiving) etc.

Furthermore, user societies and similar organizations are good software sources as they provide information on program libraries, special interest groups, symposia etc. (e.g. DECUS (Digital Equipment Corp. Users' Society). And finally, there are software catalogues available where software is marketed (e.g. Midcam).

As mentioned earlier, the main steps are:

Collection of Data (Input)
Editing
Maintenance of Data Base (Updating)
Utilization of Data Base

Input

The most expensive operation in digital mapping is data collection. Basically two types of data are encountered, namely graphical data and attribute data. The latter are usually keyed in using a simple alpha-numeric terminal in a time sharing operation, or else they are extracted from existing files.

There are a number of different sources of the graphical data, each of which requires different treatment.

At present, the most common source for graphical data are existing maps. Digitization is normally carried out manually with table digitizers. In point mode, planimetric coordinates of a point are measured by pressing a button on the cursor. A straight line vector is defined by the coordinates of the end points.

In stream digitization, coordinates are sent continually.

It is necessary that these coordinates are stored in conjunction with at least one identifying attribute.

Since there is a limited number of functions required for manual digitization, this mode of input is usually menu-driven. This is easily implemented by selecting a certain branch of a screen menu or a field of a software-keyboard (i.e. a graphic menu on a digitizing tablet). It is important to ensure efficient registration (basically a planimetric orientation) to the overall ground system.

As mentioned, mass digitizing of maps is performed most quickly with a raster scanning system, where a raster image of the map is produced. This type of equipment has to be supported by a comprehensive software system in order to convert the raster information into vector mode for further processing. It also has to have pattern recognition capabilities for properly identifying symbols and alpha-numeric characters.

More recent mapping information is likely to be derived from aerial photography.

Rather than plotting a line map from a stereo-model, the photogrammetric operator digitizes directly from the stereomodel via encoders on the stereoplotter. In this case, three-dimensional coordinates are obtained. Again, the software needs to efficiently convert the model coordinates into the ground system, which may mean an analytical absolute orientation or an update of it. Often specialized software of this type is available with the plotter, especially with analytical plotters. Depending on the degree of sophistication of the photogrammetric software, single photograph digitization is also possible.

Another data source are conventional surveying field data. They may be entered via alpha-numeric terminal from field notes (angles, distances, elevation differences etc). Modern electronic systems (e.g. electronic theodolites combined with EDM instruments) can generate an automatic data flow via radio- or telephone transmission.

The software thus has to contain an efficient least squares adjustment routine for the solution of various geodetic problems, complete with statistical testing and error rejection for the transformation data.

Last, but not least, the graphical data may have been stored as coordinates on magnetic tape or disk, collected for other purposes.

In order to make them compatible with the system at hand, software is needed to perform coordinate transformations.

There are also a number of general requirements for all input data which have to be addressed in context with the software. The most important one is the spatial accuracy of the data, others are the resolution of the input device and the information content at the source.

Since most input is done in an interactive mode, the software has to provide feedback to the user for all actions. In many instances, this will consist of displaying the movement of the cursor on the screen. In others, it may be a text message. The graphical display should always contain a scale indicator (divided and annotated scale line and/or the numerical scale fraction).

Thus the input control usually provides for a spatial window for grapical display, a text window (e.g. for error messages), and a menu space on the terminal.

Good communication at the input phase is most essential.

The software for data input has to be user friendly, such that it requires minimum training and qualifications for the operator.

It is also extremely important to keep data loss to a minimum by providing back-up on command from the digitizer.

Mixing of digitizing and editing functions should be avoided, as this can cause loss of data as well as misinterpretation. Editing should be kept as a separate secondary step, designed to correct or modify the data.

The input system has to be able to enforce tolerances dictated by the system manager (e.g. closing tolerances, speed tolerances). Automatic checks are to be performed to meet the specifications. This in turn reduces the amount of editing that is required.

All these considerations hold for any CAD/CAM system as well. However, for digital mapping purposes, the input software needs efficient routines and procedures for fast input of polygonal data, which is very clumsy on CAD/CAM systems based on more regular features.

Therefore, I would like to say a few words on polygonal input.

Polygons represent a basic input unit to a digital mapping system, as all property boundaries are closed polygons. The input thus consists of:

(1) Coordinates of each boundary (<u>once!</u>) in any desired sequence.

(2) The positions of one point within each polygon (for attribute purposes). The system then should rapidly perform the following operations:

  - find the boundaries of each polygon (parcel of land)

  - find the (two) parcels bordering each boundary

  - find the area of each parcel as a by-product

  - find the length of each boundary

  - detect errors in the data, especially:

    missing boundaries
    missing labels

- allow the user to:

  edit and correct errors
  input cartographic parameters
  and attributes

It should be noted here, that semantic attributes need to be clearly and uniquely defined. The label "road" for instance has different meanings to different users depending on its type etc.

Editing

As mentioned before, digital mapping software requires semi-automatic editing and data checking in order to arrive at a clean data base.

Some of the main examples would be:

- edge matching
- validity checks on attributes
- double digitizing
- missing elements

Of course, editing requires interactive human effort in order to obtain clean data files for the data base. For this purpose, a small subset of the data base is brought into the workspace and displayed at the terminal. Editing involves the addition or deletion of graphical and/or attribute information.

Maintenance of Data Base (Update)

The process of updating has many similarities with editing, in fact, editing can be considered as an initial update.

Whenever new data are available that either complement or replace existing information, it is necessary to find out the present status of the data base.

Again, a small subset is brought into the working space and queried. If the information is not found in the workspace, then the data base is searched, and the required material is transferred to the workspace for graphical and/or textual display. Now the information can be viewed and edited as well as updated (additions to and deletions from the graphical and textual information that is being displayed).

Unlike the procedures for editing, usually a record is kept of all updating files, thus preserving the change in the information, which means that information deleted from the current data base is not lost.

Updating and the subsequent analysis and utilizing the data base are not suitable for menu techniques because of a large amount of options, modifiers and analysis functions. Thus the software for this part is based on a command language. This provides greater flexibility at the expense of increased training, even though, the command language should exist of as few explicit modes as possible in order to avoid confusion. However, if there are very few modes, then the number of commands on the screen at one time could become excessive. Thus a reasonable compromise must be reached in grouping commands into modes.

Explicit modes have to be invoked by the users, by changing from another mode with an explicit command, and the user must always be aware of what mode is in use.

Utilization of the Data Base

In order to use a digital mapping system as an information system, it has to have an efficient data structure. This is the foundation of all digital information systems and affects all aspects of operation and thus dictates the flexibility and range of applications in other words, the scope of the system. I shall address data structures in more detail at the next session.

The operational part of the utilization of a (graphical) data base is handled by a software package, referred to as a Data Base Management System.

By now it should be obvious, that we no longer deal with simple data files (i.e. strings of homogeneous information), but with a series of different and interlinked data files, which are either graphic files or attribute files.

It should also be stressed again, that there is a huge volume of data, with usually much more graphical data than attribute data. A 1:50,000 map sheet for instance may contain 15 Mbytes of information, while a 1:10,000 sheet has 3 - 5 Mbytes.

Data bases have to handle the interrelationship between data files. The most common type is the hierarchial data base, consisting of a hierarchy of levels with an arbitrary number of items in each level. It is most suitable for alpha-numeric data, and graphical information that occurs naturally in hierarchial form. Data from any one root may be recovered rapidly by search through the branches.

Hierarchial systems break down, when it becomes necessary to recover related information from many leaf modes, as each must be located and queried individually, which is a rather slow process.

Network data bases are rather complex, but permit the fast recovery of related information, provided the relationships have been built into the network and the path of navigation through it is known. It is difficult to modify them, and thus they are frequently used as components within a larger system.

Relational data bases consist of three elements, namely relations, domains and tuples. Usually, the relation represents the type of object, the domain, the attribute of the object, and the tuple, the example or occurrance. In general, domain and tuples may consist of numbers and symbols, unrelated to physical quantities. The strength of a related data base is that it may be indexed to link relations to one another in ways that are easy to visualize. It is theoretically possible, though impractical, to index every item to everything else.

Once a system of indexing is set up, the recovery of related information is very fast.

For the application and utilization of the data bases, specialized software is required. Again usually these software systems are accessed via the command language. The operation is interactive via the graphics terminal and perhaps an image processing system.

Once the product is ready for output, the information is sent to the respective plotters and printers. Normally their software is device dependent.

All this, of course, is founded on the data structure which is extremely important but usually kept secret. In the next session, I shall try to provide some insight to this fundamental aspect.

SESSION III: INTRODUCTION TO DATA STRUCTURES

The flexibility and range of applications depend on an efficient data structure. For digital mapping, this structure has to include data compaction and allow fast retrieval for processing, i.e. editing, updating, information retrieval, polygon formation.

The main question - usually not answered by software developers - is how to put the data into the system?

When dealing with topographic information, we have huge numbers of data, e.g. 1/2 million points for one medium scale map sheet, and it is desirable to complete a search in less than 2 seconds. An unstructured list would require a search of 1 1/2 hours on a main frame computer. A general CAD/CAM system would take 3 days of operation on an IBM mainframe to search through the 15 Mbytes of information contained in a 1:50,000 map sheet. Why? because its structure is not designed for topographical mapping.

When dealing with topographical data structures, we have to accommodate data that locates, identifies and describes topographic features and their attributes. These features consist of points, lines and areas (polygons). Furthermore, there are some topological facts which describe the relationship between these feature elements. For instance, an area carries reference to the arcs (lines) which delimit it as well as to the nodes (points) in which these lines intersect.

The basic topographic components are quite simple:

- point: identifier (name or numerical code)
  locator (set of coordinates)
  description and attributes

- line: identifier (line code)
  list of coordinate sets (points)
  description and attributes

- area: identifier
  set of lines (or of area elements)
  description and attributes

There are other types of basic structures which are not solely related to points. The information from a rasterized map for instance, can be condensed by "run-length" encoding. When, in row by row scanning, a certain type of area element (pixel) is first encountered, that pixel receives an opening flag. If a number of pixels with identical properties is encountered sequentially, they are counted, and a closing flag is given to the last one. Thus only the locations and codes of the flagged pixels plus the count is stored.

Linear features may be stored in a "strip tree" for data compaction. A rectangle is computed which encloses all line points, parallel to the straight line connecting the end points of the line. Then the largest orthogonal offset to this line is computed. If it lies within a given tolerance, the line is considered to be straight between the endpoints. If not, two enclosing rectangles are computed. This is continued and results in a tree structure, where different tolerance limits represent different levels in the tree, which is very helpful for generalization.

An equivalent procedure applied to raster imagers is the "quad tree". Here the image is divided into sections with rows and columns in integral numbers of two. A section is then quartered and checked for homogeneity of pixels. If it is, it is stored as one unit. if not it is quartered again.

The basic topological relationships are:

- connectivity of vectors (e.g. individual roads are connected)

- connectivity and adjacency of areas (e.g. neighbouring polygons)

- intersection (e.g. roads and streams to recover culverts)

- proximity (e.g. what type of timbers are within 1 km of a highway?)

Without going into detail, I would like to mention that topological relationships are handled mathematically using linear graph theory, because three-dimensional topographic information is mapped onto a plane. Connectivity graphs, which may be a distorted abstraction (e.g. sub-urban train station map of the network) consist of nodes (points of intersection) and of arcs (lines between the points) to represent linear features. Areas (polygons) are modelled by incidence - and adjacency graphs. An incidence graph is like a line graph, where the arcs represent the boundaries between adjacent polygons, and the nodes or vertices represent points where three or more polygons meet. Thus the degree of the vertices (number of polygons that meet there) can be used for checking whether all polygons are closed. An adjacency graph looks like an incidence graph, but is reversed such that a vertex represents a polygonal area, and an arc a pair of adjacent polygons.

Graph theory basically provides mathematical tools to answer specific questions and is thus very useful in digital mapping, as it can speed up searches.

Now, I would like to provide a bit more detail on data structures, using as specific examples some elements of the data structure of CARIS (Computer Aided Resource Information System), developed jointly by members of the Department of Surveying Engineering, University of New Brunswick and of Universal Systems Ltd. of Fredericton N.B., Canada.

Data structure causes a system to be "boxed in" or "open ended". For digital mapping it has to be flexible and open ended, thus cannot be hard wired. Let me give you a simple example:

Many professionals and business men "collect" business cards with telephone numbers. The simplest way of storage is to throw them into a desk drawer which thus represents an unorganized sequential structure. It is easy to add new data - by just throwing them on top of the pile, however a search is cumbersome and time consuming.

It would be much better to have them in alphabetical order, but how do we know how many spaces to save for each letter? In computer terms, we want to minimize storage requirements as well as search time. This can be accomplished with the use of specific pointers:-

Example: the unsorted pile of business cards in sequential order is as follows:

Head of List = 11

1	Merrill, A.		12	
2	Jones, B.		1	
3	Turner, K.		*	
4	Thompson, N.		3	
5	Harris, H.		2	
6	Boone, T.		8	
7	Dable, R.		10	
8	Brown, K.		7	
9	Perry, R.	→	4	14
10	Doak, A.		5	
11	Astle, L.		6	
12	Miles, G.	→	9	13

The right hand column provides the pointers, e.g. in alphabetical order "Jones" would follow "Harris", thus "Harris (#5) points to "Jones" (#2). The list starts with "Astle" (#11) and ends with "Turner". Now let us add two cards, namely

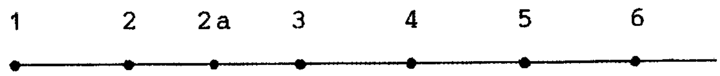
13	Miller	9
14	Smith	4

This requires an update (shown with arrows above) for the pointers taken up by the new data.

A similar approach applies to topographical data.

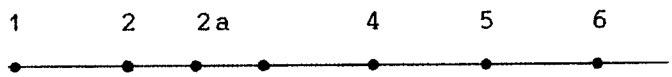
Let us assume, we have a line, defined by points 1 to 6

Now we want to insert a point (point 2a)



It requires lots of time to move the whole file around.

What about deleting a point? (point 3, as it lies on a straight line from 2a to 4)



deleted point --- wasted storage!

Of course, we could squeeze the data, again requiring lots of time.

The problem is that we want all points of a line together in sequence. A solution would be to break it into segments and use pointers to connect the segments. In this case, we can always allocate a fixed amount of points per line segment.

This allows us to utilize any empty spaces for extending a line, and similarily create empty spaces when chipping a line. Even though the latter may be in the middle of a file, they are not wasted as they can be filled up again when using a pointer.

The search is further accellerated by utilizing a description file. The description file contains bounding rectangles (one for every 100 points).

Since the placement of the crosshair on the terminal is approximate, a first step is to compare the crosshair coordinates against the bounding rectangle by searching the description file. Afterwards only part of the data file has to be searched.

In the CARIS-system, geometric data for lines can be in absolute coordinates or compressed with directional coding using eight discrete directions. All the transformation parameters between the file coordinate system and the ground coordinate system is stored with the map files.

Even with compression, most lines are so long that each will need thousands of words to store. In order to permit in-core processing, each line is segmented into pieces that can fit into a core-buffer. These line segments represent the basic logical element of the graphics data structure. It is composed of a descriptor record and a data record (DAD - Description and Data). Each descriptor, and thus each DAD has a unique identification, called graphics description number.

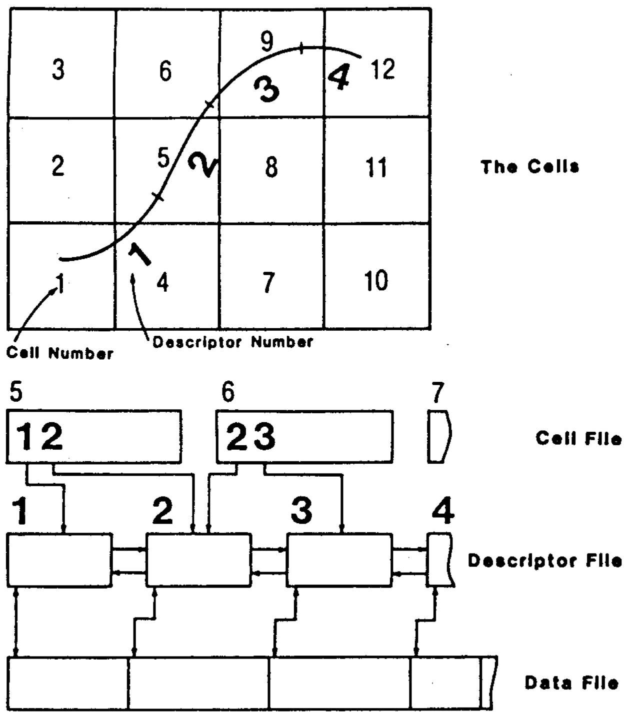


FIGURE 3.1: CARIS Graphics Data Structure

The data record stores the information that is required for plotting the graphic entity, e.g. for a line it contains coordinates, while for a name it contains location, slope and ASCII record of each character in the string.

The descriptor record stores a geometric summary of the entity (e.g. bounding rectangle) together with attribute data such as feature code and source number.

The feature code is an alpha-numeric code chosen by the user to identify or name the feature.

The source number is a signed integer ranging from - 32,768 to 32,767 and serves as additional identifier (e.g. to identify the survey docuement from which the feature was compiled).

Since a continuous line may consist of a number of DAD's scattered all over the disk, pointers are also kept in the description record to link them together.

The descriptor records are of fixed size with identical format for each type of graphics, while data records vary in length and format. A data code in the descriptor identifies the type of graphics for proper interpretation of the associated data record.

As descriptor record and data record are fundamentally different, they are stored in different files (descriptor file and data file respectively). This requires another set of pointers in the descriptor record to point to its data record.

All pointers are doubly linked to provide maximum search speed and to reduce the risk of loosing data because of corrupted pointers.

In addition to these two levels of files in the CARIS hierarchy, there is a third level above the descriptor file which is the cell file.

Each map is divided into square cells, each of which has a record in the cell file. The entries in the cell record are descriptor numbers of the graphics elements within or passing through the cell. This makes it possible to localize most search operations to a limited number of cells and also helps in the design of efficient algorithms for polygon processing.

For archiving, an interchange format is adapted, the cell file dropped, descriptor - and data files merged, and pointers inactivated. They will be reconstructed when being converted back again into the active edit format.

The topological data structure concerns itself primarily with arc-to-polygon relationships (how the lines are related to polygons) and with polygon-to-polygon relationships. In order to better manipulate the lines, their extent is restricted from one node to another, where a node is simply the meeting point of two or more lines.

Being a line, an arc is a collection of DAD's. A special arc descriptor is created to store specific information about an arc, such as length, bounding rectangle and pointers to relate this arc to polygons. This arc descriptor is linked to the start of the first graphics descriptor of the line forming the arc.

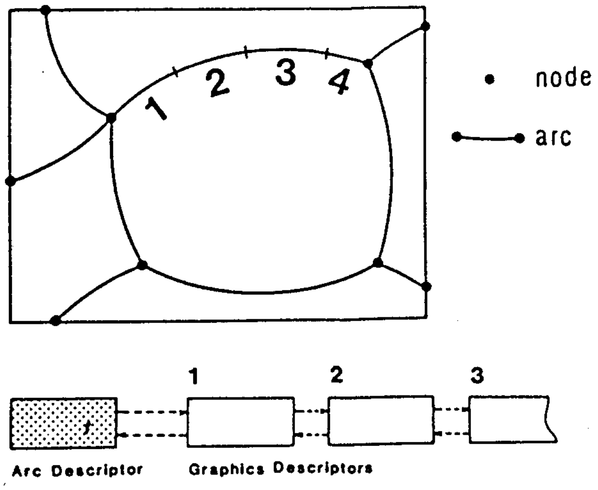


FIGURE 3.2: CARIS Arc and Graphics Descriptors

In the CARIS data structure, each arc descriptor contains two polygon pointers and two arc pointers.

The polygon pointers point to the left and right neighbouring polygons.

The arc pointers point to the next arc (in counter-clockwise direction) at the start and end nodes of the arc (see Figure 3.3).

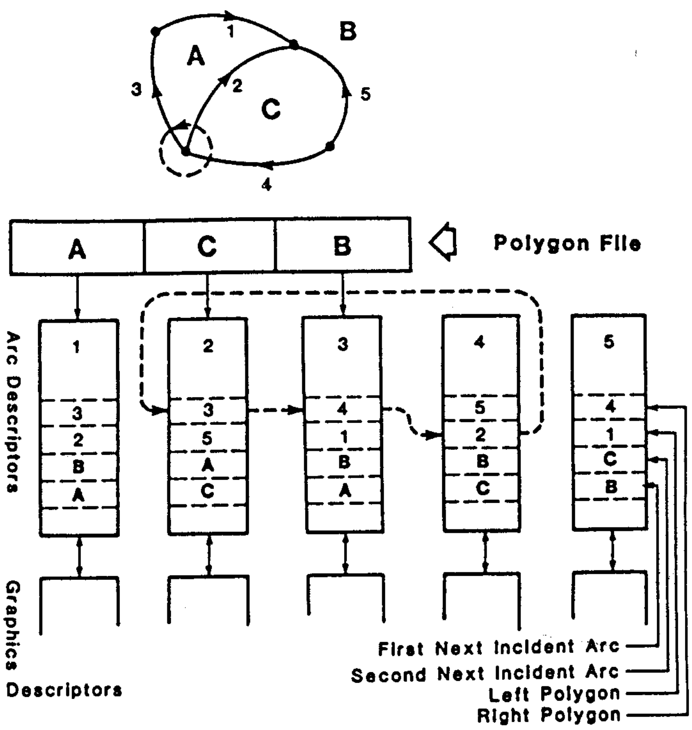


FIGURE 3.3: CARIS Topological Data Structure

A further file (the polygon file) is used to store polygon related information (area, label, interior point, bounding rectangle, pointer to one of its arcs, pointers to attribute record, as well as that relating to polygon to polygon relationship, such as enclosing polygon and islands).

The capabilities of a digital mapping data structure become evident in the algorithms used to process polygons. There are two types, namely those designed to build the data structure from the raw file (type A), and those designed to retrieve information from the clean data base (type B). A type A algorithm would for instance associate a label with its polygon. It has the following steps:

1. Determine the cell enclosing the polygon interior point.

2. Of the four orthogonal directions to the border of the map (up, down, left, and right), pick the shortest path.

3. Extend a finite half line from the interior point to the closest border along the shortest path.

4. If there is no arc pointed to by the current cell record, move over one cell in the direction of the finite half line and repeat this step.

5. If there are arcs pointed to by the current cell record, determine if any of these intersects the finite half line. If an intersection is found, the enclosing-polygon problem is solved since the left and right polygons are known for each arc. If no intersection is found, move over to the next cell in the direction of the finite half line and repeat from step four.

An enclosing polygon will eventually be found for a point unless the point is outside the map.

A type B algorthim would for instance retrieve the arcs of a polygon as follows:

1. From the polygon record, read the first component arc of the polygon.

2. Read the arc descriptor record of the first component arc. Note which side the polygon in question is related to this arc.

3. If the polygon is to the left of the arc, use the first next incident arc pointer to get to the next component arc. If the polygon is to the right, use the second next incident arc pointer.

4. Read the descriptor record of the next component arc and pick the other component arcs using the same rules as in step three.

5. Exit if the first component arc is again reached.

This algorithm always collects arcs of a polygon in a clockwise sequence.

Some applications may be quite difficult and time consuming without a data structure designed specifically for digital mapping. Thus, when testing a system one should carefully examine the following types of operations.

- test with response time, but be aware that hardware manipulations may speed up the process.

- test by adding a large size file (i.e. a 1:50,000 map sheet with approximately 15 Mbytes information), then ask questions like:

  . how efficient is the data collection?

  . what and how many of overlays, unions and intersections can be produced using several sets of data?

  . retrieve and show me all sewer lines with a diameter of 20 cm maintained in 1980.

  . what is the search time for distantly related facts within the system?

  (i.e. show me the waterbodies that flow through municipally owned park land)?

It is possible to get a feel for the capability of the data structure and thus of the system by comparing flexibility, response time, capability of mixing overlay information etc.

Then it is easier to make a decision on what to adopt for your purposes.

SESSION IV: REASONS FOR DIGITAL MAPPING

After the previous sessions, which concentrated on technical aspects of digital mapping, let us look at the reasons for using computers in mapping.

From the previous discussions it is quite clear, that digital mapping is presently based to a large extent on existing maps. This leads to questions like: why bother and waste all that money? Wouldn't it be just as fast to plot a map than to digitize from a stereomodel? Why not go with automated orthophoto production?

These aspects are difficult to dispute if the topographic map is seen as the final end product of the mapping exercise.

This is true for conventional mapping, where the published map sheet is most definitely one end product which is used by a variety of users for a variety of purposes. They extract from this analogue map whatever they need (e.g. distances between points, slopes etc.).

In digital mapping, however, the map sheet is merely a by-product. The actual information sits in the data base. And, what is most important, this topographical information is in digital form and thus can be readily manipulated on a computer. There is no more need to use a ruler, protractor or planimeter to extract information from the map, and thus no secondary loss in accuracy. Since the actual "map" is the data base, and since it is in digital form, it can easily be changed and updated whenever new information is available. Map revision thus becomes an instantaneous procedure rather than a time consuming work intensive effort.

Furthermore, digital mapping has to be seen in the context of larger information systems based on spatial (topographic) data. Mapping is no longer an end in itself, but a significant component of land information systems, dealing with virtually any aspect of human living related to land.

Digital mapping has a number of advantages over conventional mapping when viewed from this perspective.

The economical value is still very difficult to assess. There is not yet enough experience to have actual cost-benefit studies. The benefits are long term; while the costs are initially very high (hardware + software), they will become significantly lower at the operational level.

The mapping and revision speed is commonly used to justify some of the costs, but the real benefit lies in the information content that is readily available for further computerized evaluation.

While a multitude of users benefit, very few of them can justify the cost. It is thus up to government bodies to pay for it, just as they look after conventional mapping and many other aspects of benefit to the community as a whole (e.g. what is the advantage to having a public library? who pays for that?).

There are other reasons for digital mapping as well, such as the maintenance of the initial accuracy of the data - and therefore the need to specify it at the input level. In resource management, digital mapping is most useful. Using digital overlaying techniques we can combine a variety of themes, such as soil map, minerals, land use patterns etc.

It is possible to merge several attribute files or several graphical files to produce new files of interest. The latter works, even if different map projections are used, since transformations can be applied prior to the merger.

The whole area of generalization and production of maps of different scales from the same base can be performed digitally.

Furthermore, data from other agencies can be merged with data from other agencies (e.g. add contours to your plan of sewer lines).

Retrieval can be accomplished by using both attributes and graphics. This is something that has not been possible with conventional maps, as it requires the search of other files as well. For example, "highlight all properties assessed at more than $10,000 that were sold in 1980" requires not only a search of the property and assessment files, but also the changes in ownership, and of course the spatial positions of the properties.

With digital mapping it is also possible to retrieve a rather selective set of data, within a window of interest (that can be irregular in shape) or according to a specific type.

The possibilities are endless, and it is easy to get carried away. The technology is there, it is now up to the authorities in charge to use it sensibly by establishing systems for their needs with the capability of data exchange between them.

SESSION V: EXAMPLES OF DIGITAL MAPPING SYSTEMS: INTERGRAPH AND CARIS

After dedicating the first day of the workshop to providing you with a general idea on digital mapping, I would now like to present you with some specific examples. As you are well aware, there are numerous interactive computer graphics systems in various stages of development, ranging from concept to prototype to fully operational.

Many systems have been developed for engineering design purposes and are being utilized in mapping as well. Others were developed - though not necessarily exclusively - for topographic and thematic mapping. Both Intergraph and CARIS belong into this category. They were selected as examples, because the Intergraph system is best known for mapping around the world, and I personally know CARIS better than other systems, since it was developed within my Department of Surveying Engineering at the University of New Brunswick.

While it is impossible to provide a detailed impression of such complicated systems within a short time, I shall try to summarize the main features.

Intergraph has applied interactive computer graphics to topographical mapping since 1973 by supplying hardware and software tools to the mapping community. The Intergraph system records spatial information in a dual fully integrated data base.

The graphic elements are contained in the files of the "Interactive Graphics Design Software" (IGDS), while the attribute data are contained in the files of the "Data Management and Retrieval System" (DMRS). The latter employ a network data structure together with storage facilities for data compression.

By integrating the IGDS/DMRS files, a comprehensive digital map data base is obtained where graphic elements are linked with the related attributes.

The central processing unit is either a PDP 11/44, PDP 11/70 or VAX 11/780 from DEC (Digital Equipment Corporation), complete with high performance tape drive and magnetic disk drives. Graphic workstations usually consist of dual-screen graphics terminal and keyboard.

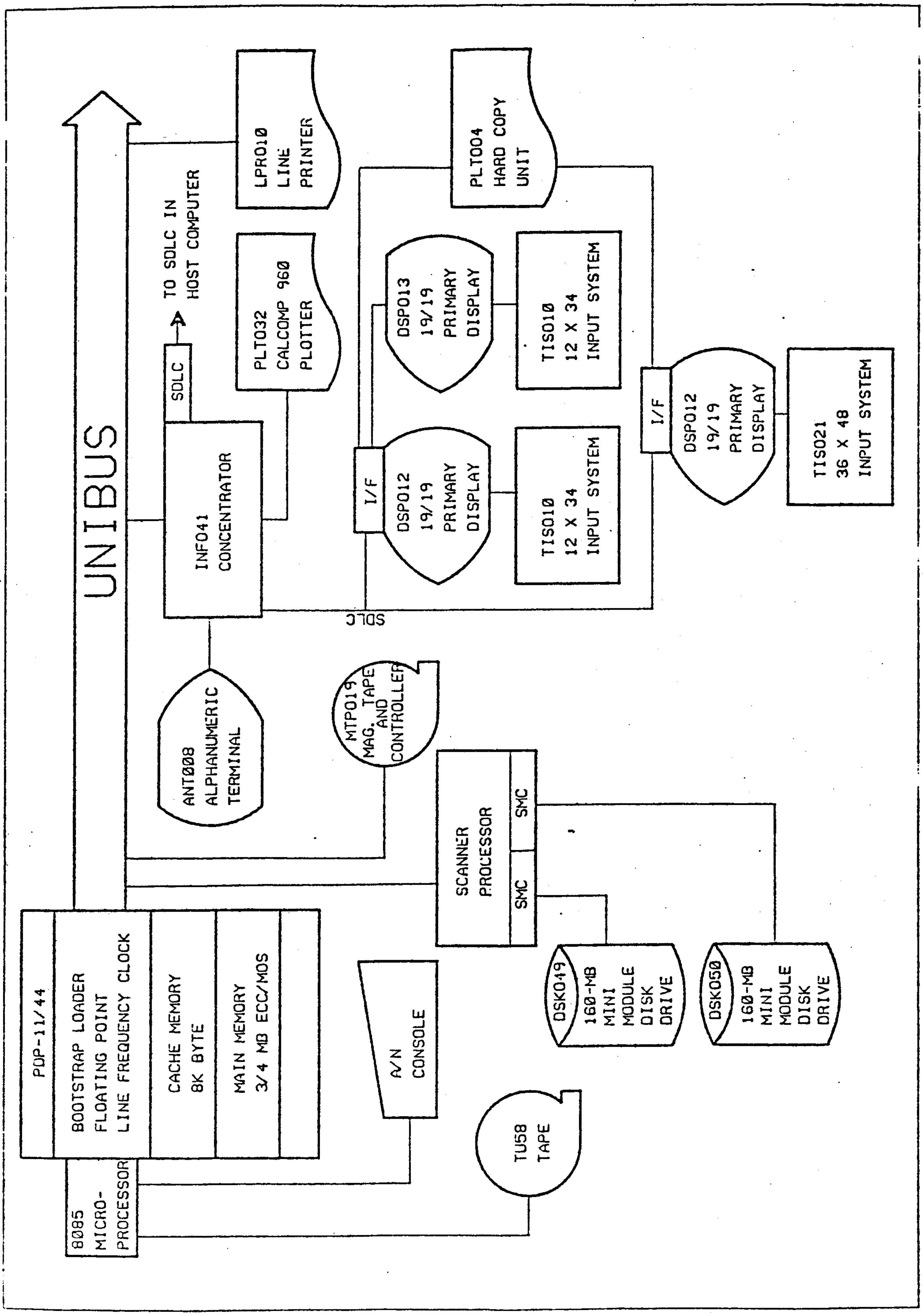


FIGURE 5.1: Typical Hardware Configuration for IGDS/DMRS

In addition to the terminal interface (graphics, as well as alpha-numeric), data collection and input is via table digitizers (menu-driven), stereoplotter digitizing, raster scanning as well as from existing magnetic tapes.

Hardcopy output is normally obtained on a line printer and/or plotter, which could be a Hewlett Packard pen plotter, a Versatec electrostatic colour plotter, or a Gerber photoplotter. The latter plots map manuscripts onto photographic film.

The heart of the Intergraph system is the software and interfaces developed for digital mapping.

The IGDS software is designed to run under the DEC RSX-11M PLUS operating system with PDP-11 computers or the VAX/VMS operating system with VAX 11/780 computers. These operating systems provide for standard input/output and file control services.

It goes beyond the scope of this workshop, to deal with the operating system in detail. Figure 5.2 illustrates the IGDS Software/Hardware Structure.

In order to properly utilize the different types of <u>input</u>, the Intergraph system has conversion software and interfaces for these sources of data. In particular, the following should be emphazised:

- ETS (Electronic Theodolite System) and ICSA (Interactive COGO Systems) which provide for the computation of geodetic coordinates from digital field data, such that they are compatible with IGDS/DMRS.

- the Stereodigitizing-Intermap work station for digitizing stereomodels from photogrammetric plotters. This system features superimposition of digitized line work onto the aerial photo as it appears in the stereoviewer and has an optional Voice Recognition Module.

- Feature code matrix menu for efficient manual digitizing.

- the Data Scan Capture System derives raster images from maps which later can be converted to vector format.

- SIF (Standard Interchange Format) and IGES (Initial Graphics Exchange Specification) for graphics, which translate all existing digital data into the Intergraph format.

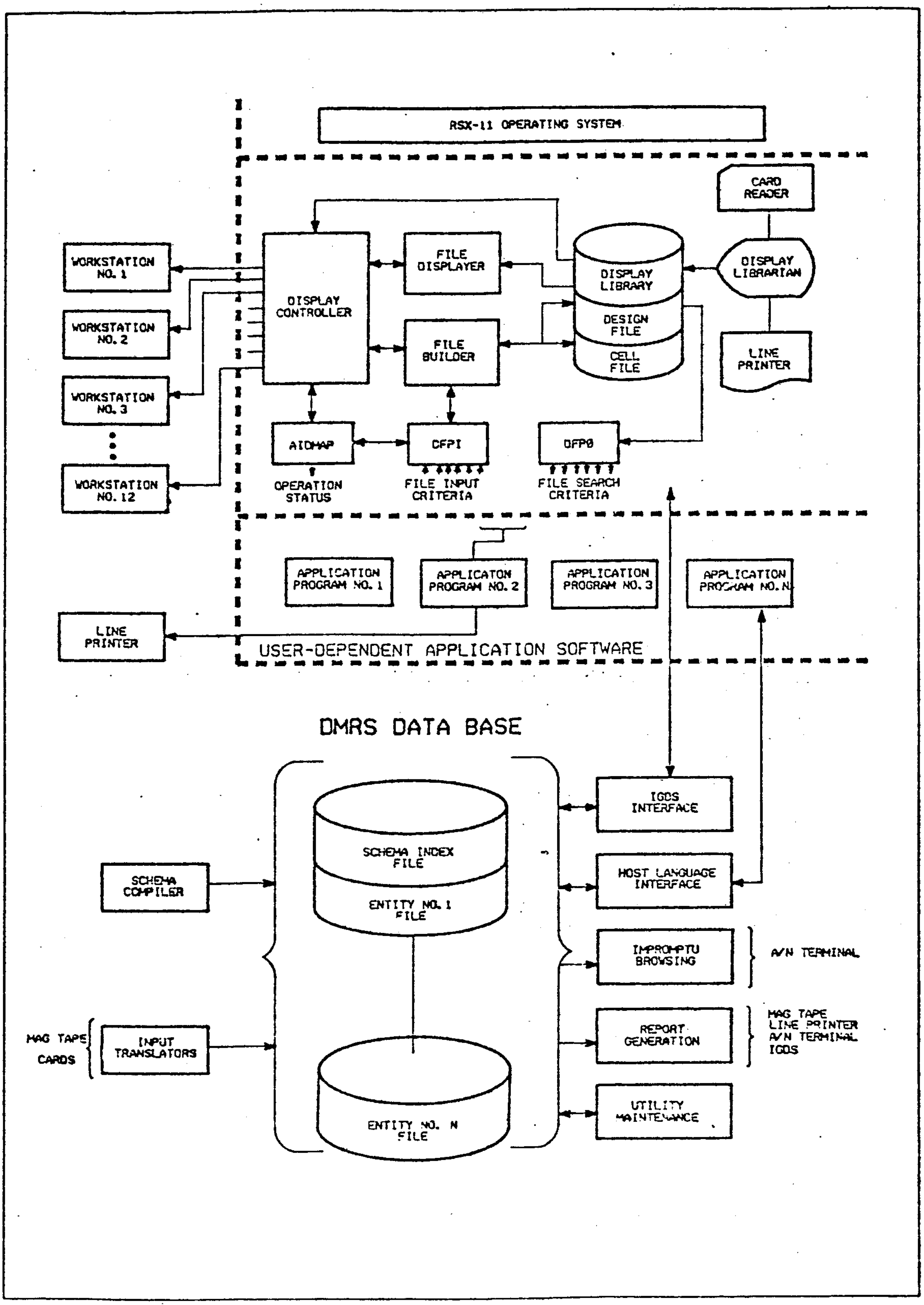


FIGURE 5.2: IGDS Software/Hardware Structure

Once the data are in the Intergraph format, a number of transformations can be applied to merge a variety of map segments of different size and scale into a single continuous digital map. EBSALS (Elastic Body/Small Angle/Least Squares) uses a mathematical fit to remove distortions, while EDGE looks after proper edge matching. WMS (World Mapping System) converts data from different map projections into latitude/longitude values, from which coordinates in a variety of commonly used map projections can be subsequently computed.

The editing stage is primarily based on interactive map display. Map information is stored in data base files containing up to 63 levels which can be displayed in any combination. Symbols are stored in tabular form and applied to map displays only if required.

Up to 256 colours can be displayed simultaneously to represent individual map elements. Furthermore, there are some special features, such as:

- Raster Colour Fill (colours in raster displays of polygons)

- Hidden Line Suppression (this is for perspective views, which are further enhanced by surface shading)

- Patterning and Cross-hatching.

Using the graphical display, editing is done interactively with a cursor and menu commands.

The system also contains routines, checking automatically the polygon closures. Finally, proof plots of the maps can be obtained at the digitizing scale for comparison with the source document.

Once a clean data base is established, it has to be updated whenever new information becomes available. DMRS descriptors are readily updated from a graphics workstation or an alpha-numeric terminal, while graphical input is accepted from any of the associated input devices. The Distributed Graphics Software (DGS) provides for the coordination and synchronization of the various inputs into the system. It allows extraction, updating and posting back of any position of the data base, while fully protecting the system against invalid or unauthorized modifications.

The Drawing Management System (DMS) offers the indexing of mapping information by sheet name rather than coordinates - an interesting option.

There are numerous applications of the digital mapping data bases in addition to map production via the plotter output. Graphical displays in various combinations aid in the analysis of the maps. Specialized software has been developed for specific user needs. I would like to briefly mention some of the more prominent ones:

- FIDS (Facilities Interactive Graphics and Data Management System) is tailored to the needs of utilities.

- TES/EMPS (Terrain Edit System/Elevation Matrix Processing System) provides digital elevation models and displays them in various perspectives.

- GPPU (Graphics Polygon Prcessing Utilities) utilizes polygon topology for a variety of purposes, especially in land use and resource mapping.

Other applications are in related fields, such as superimposing census and statistical data on spatial information, using the already mentioned ICS (Interactive COGO System) in transportation engineering design together with Digital Terrain Modelling, utilizing exploration and seismic data, as well as geological information, interfacing the Dipix digital image analysis system for remote sensing purposes and others.

The development, improvement and expansion of the system is often triggered by user requests and is a continuing process. This is the case for virtually all software systems.

The development of CARIS (Computer aided Resource Information System) started in the early 1970's at the Department of Surveying as a logical follow-up of research into image correlation techniques and digital data collection from photogrammetric stereo models. Soon the development work exceeded the capabilities and the realm of university research, and a major portion of the work was taken over by Universal Systems Ltd. of Fredericton, N.B.

The system has been operational for a number of years and an eight workstation CARIS for topographical mapping has been installed at the Land Registration and Information Service of the Council of Maritime Premiers a bit over a year ago.

Being developed initially at a university, the system is based on "off the shelf" hardware, which helps with the maintenance. Figure 5.3 provides an overview of the CARIS environment, which is based on the PDP-11/70 host computer.

The only piece of specialized hardware is the CARIS Controller, consisting of 3 microcomputers and control electronics which make the electronics of the input devices compatible with the host computer.

Due to the fact that CARIS was developed at UNB where numerous programmes for geodetic coordinate computations exist, the input is restricted to geodetic coordinates and attributes (via magnetic tape or keyboard) plus data collection from map sheets and from photogrammetric stereomodels.

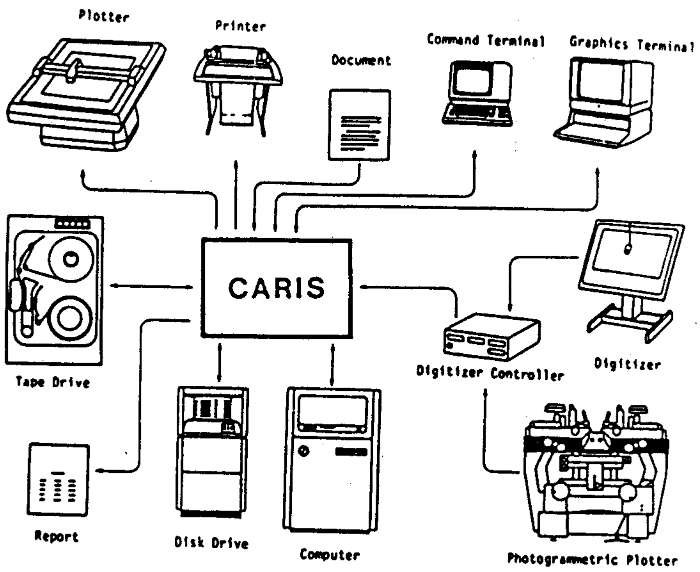


FIGURE 5.3: Configuration of CARIS with Distributed Processing Approach

As figures 5.4 and 5.5 show, both follow a similar path.

Data collection from map sheets is accomplished with the aid of table digitizers (solid state or encoder type). This can be done in point mode or stream mode. The system permits data compaction of convoluted lines (e.g. contours) collected in steam mode and allows a storage of up to 700 points per inch (280 points per centimetre) of a digitized line at map scale. The exact number can be prescribed by the user depending on his requirements.

The system separates between the data collection operation and their interactive editing and cartographic enhancement. At the digitization stage, minimum interactive editing functions are allowed. Highlights of the input functions are:

- Provision for entry of main header data for map being digitized. This includes map projection system (7 different map projections are provided for), date of digitization, date of survey, number of map, section of map, etc. This header can be edited any time before digitization is completed.

- Least squares adjustment computations of the transformation parameters from digitizer coordinates to ground coordinates. These parameters are used in real-time transformation of digitizer coordinates with continuous display of ground coordinates. (Transformation and display of as many as 40 points per second is possible).

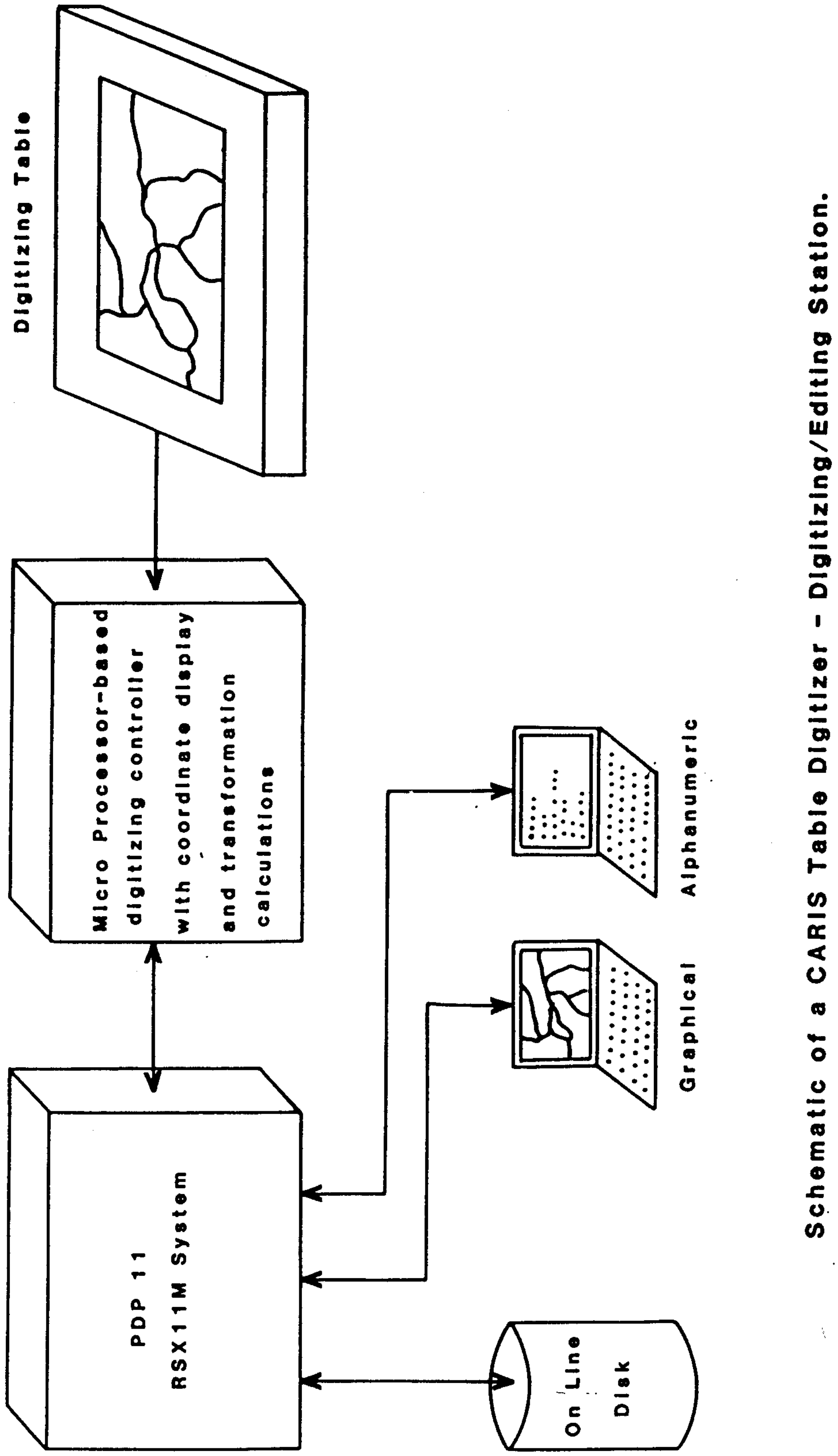


FIGURE 5.4: Schematic of a CARIS Table Digitizer - Digitizing/Editing Station

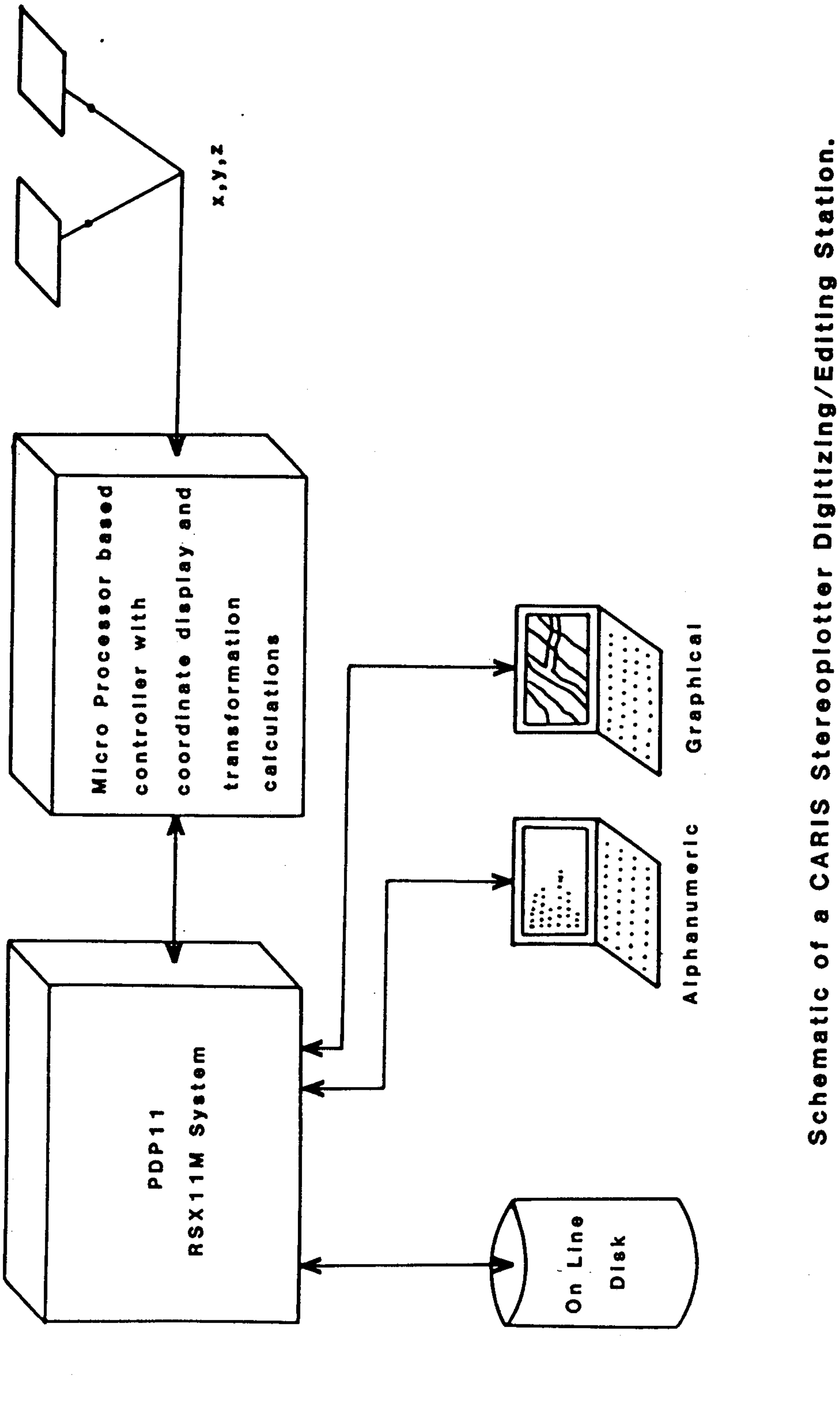


FIGURE 5.5: Schematic of a CARIS Stereoplotter - Digitizing/Editing Station

- Provision for checking of accidental movement of document or breakdown of digitizer at any time during the digitization.

- Provision for removal of document and continuation of work at a later stage.

- Provision for addition of data from other document sources to the same file. (The data structure allows that data from 32 000 sources can be integrated into the same file. The data can be separated later according to their source numbers).

- Filtering of any minor irregularities (at the resolution level of the digitizer) which may be caused by the hand shakiness or by the digitizer itself (such as in the case of motor driven types).

- Communication with operator using different sound tones or a voice synthesizer.

- Provision for automatic tagging of a feature or a group of features with a code (other than the usual identification code). Such codes proved useful in later processing of these features and in the creation of and retrieval from data bases.

- Provision for automatic display of digitized data on the graphics terminal, if desired. Features can be displayed automatically in different colours according to their feature codes.

- Provision for entry of a weight indicating the confidence in an observed spot height (of particular use in photogrammetric digitization).

- Facilities for speeding of data input which include: automatic adjustment of angles between lines to 90^{o} (for buildings), automatic generation of parallel lines (parallel lines may have different codes or the same code), automatic closure of features, and fast repetition of a feature code.

As mentioned, data collection can also be carried out from analogue stereoplotters provided with encoders via a microprocessor-based controller, designed and built for this purpose. The same controller can be used for data collection from analytical stereoplotters.

Absolute orientation is carried out using a least squares adjustment on observed model points. Partial control points (x, y only, or z only) and/or full control points (x, y, z) can be used in the adjustment. The operator enters the instrument settings then observes each control point and enters its identification number. The ground coordinates of the points are then retrieved automatically from the control file via their identification number. Upon completion of the observations, the adjustment is carried out and the residuals to the solution are displayed. A special display is also provided which allows the operator to better judge the effect of removal or addition of control points. Points can be rejected or re-observed, and additional points can be observed. The adjustment is repeated until it is accepted. If accepted, the program lists the new settings for the operator to speed up the procedure. It should be noted here that, if desired, absolute orientation can be performed only analytically. The program utilizes in that case all the transformation parameters in computing the ground coordinates. This is useful in the generation of digital terrain models and the compilation of planimetric detail (when no contour compilation is required).

The digitization is essentially similar to the case of map sheets in that the highlights of the digitizing and editing functions are also available. All the editing functions are available at the photogrammetric plotter station. It is interesting to note that, in relation to the separation between digitization and editing operations, a number of mapping organizations which have been involved in photogrammetric data collection for some time, follow a similar approach.

Common to the data collection from maps and stereomodels, the symbology can be imposed onto the final map through a separate program using a symbology table which can be modified. The symbolized map can be viewed and edited using a graphics display prior to the final plotting. Also, check plots can be obtained on CALCOMP or ZETA drum plotters.

At the interactive <u>editing</u> stage, some of the widely used interactive function available are:

- Flexible placement of names along convoluted features. (A character may be individually moved). Names can also be stretched, rotated, and shrunk.

- Safety feature to prevent accidental deletion of features from a file being edited.

- Provision for clipping or extending the end of a line, deleting a segment of a line or a whole line, and shift points of a line.

- Semi-automatic edge matching of cartographic features.

- Addition of information via the graphical CRT cross hairs or the digitizer's cursor.

- Manipulation of points of a digital terrain model for selective display of points (of particular use in a dense digital terrain model).

- Provision for attaching to each digital terrain point additional information in the graphical file itself. This is of particular use when the display of a point is different from its actual location, as well as in hydrographic and municipal applications.

- Provision for modification of all descriptive information of any feature.

- Selective display of features which satisfy certain codes and/or belong to a particular source.

- Provision for recording a summary of all commands which took place in an editing session and which affect the data base (of particular use for a person in charge of a data base).

Implementation of the handling of polygonal maps by CARIS was based on the requirements of some agencies involved in resource management in Canada's Maritime Provinces. It may be relevant to note that the data structure allows mixing of polygons and cartographic features in the same file.

Since I used CARIS as an example when discussing data structures, there is no need to repeat the details here.

The sequence of operations of data input are outlined in Figure 5.6. This sequence allows the operator to digitize the arcs in an arbitrary manner. That means that the arcs defining a polygon do not have to be digitized one after the other and that the digitization is performed as clockwise or anti-clockwise only once. Also, there is practically no limitation on the number of points entered per arc since the system allows data compaction of convoluted lines. The operator also digitizes one point within each polygon in any desired sequence. The linking of the arcs defining each polygon and the detection of any topological errors are done automatically and separately from the digitization. (The errors can be corrected using the interactive graphics editor). The organization of the data in CARIS is such, that such linking can be completed quite rapidly.

As shown in Figure 5.6, entry of the attribute data is done separately from the digitization of the arcs and requires only an alpha-numeric terminal. A special software package is used for the entry of the attribute data. The fields defining an attribute record can be designed beforehand and the operator is prompted to enter the correct field.

Attribute data can be retrieved, based on criteria of the attribute fields and statistical reports with different formats generated. The highlights of the facilities provided for the manipulation of attribute data are:

- Find the attribute file for the task.

- Arrange the attribute data for job specification.

- Train the user with a "guide mode" which is a "hand-holding" tutorial feature that takes him through the command sequences.

- Produce formatted reports which provide the attribute data in a readable form.

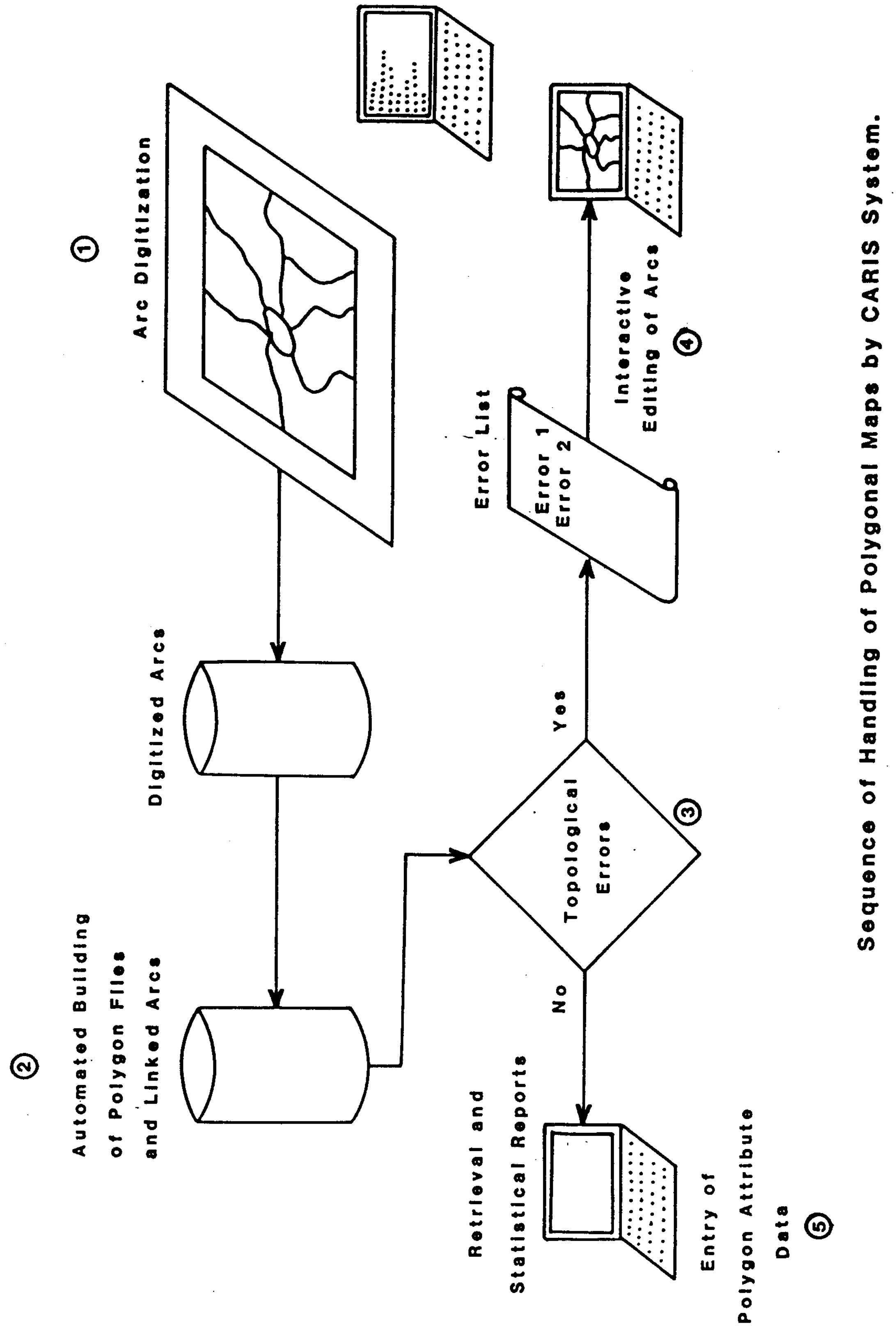


FIGURE 5.6: Sequence of Handling of Polygonal Maps by CARIS

- Update (modify) attribute data

- Create new fields of the attribute data.

- Format selected fields of attribute data for display together with the graphical files.

A separate software package of the CARIS system allows merging of mapping data files. These files can be in different map projections and the user selects the projection in which the merged output file will be. The user can also select multi-sided windows of interest. The output file will then consist of the data within or surrounding these windows. Figure 5.7 provides a general overview of the CARIS software modules.

As mentioned earlier, the data structure of CARIS was designed particularly for mapping applications and allows a relatively fast retrieval and the processing of large files (e.g. search time for one feature or symbol of a 1:50,000 map in a 4 Mbytes data file is of the order of 2 seconds!). The system is flexible enough to allow for future expansion to accommodate new demands in mapping. Applications in topographic, hydrographic and polygonal maping have been operational for several years. Extensions, such as 3D-modelling, digital terrain model viewing from different directions, line of sight applications in real time and satellite imagery evaluations are presently being incorporated.

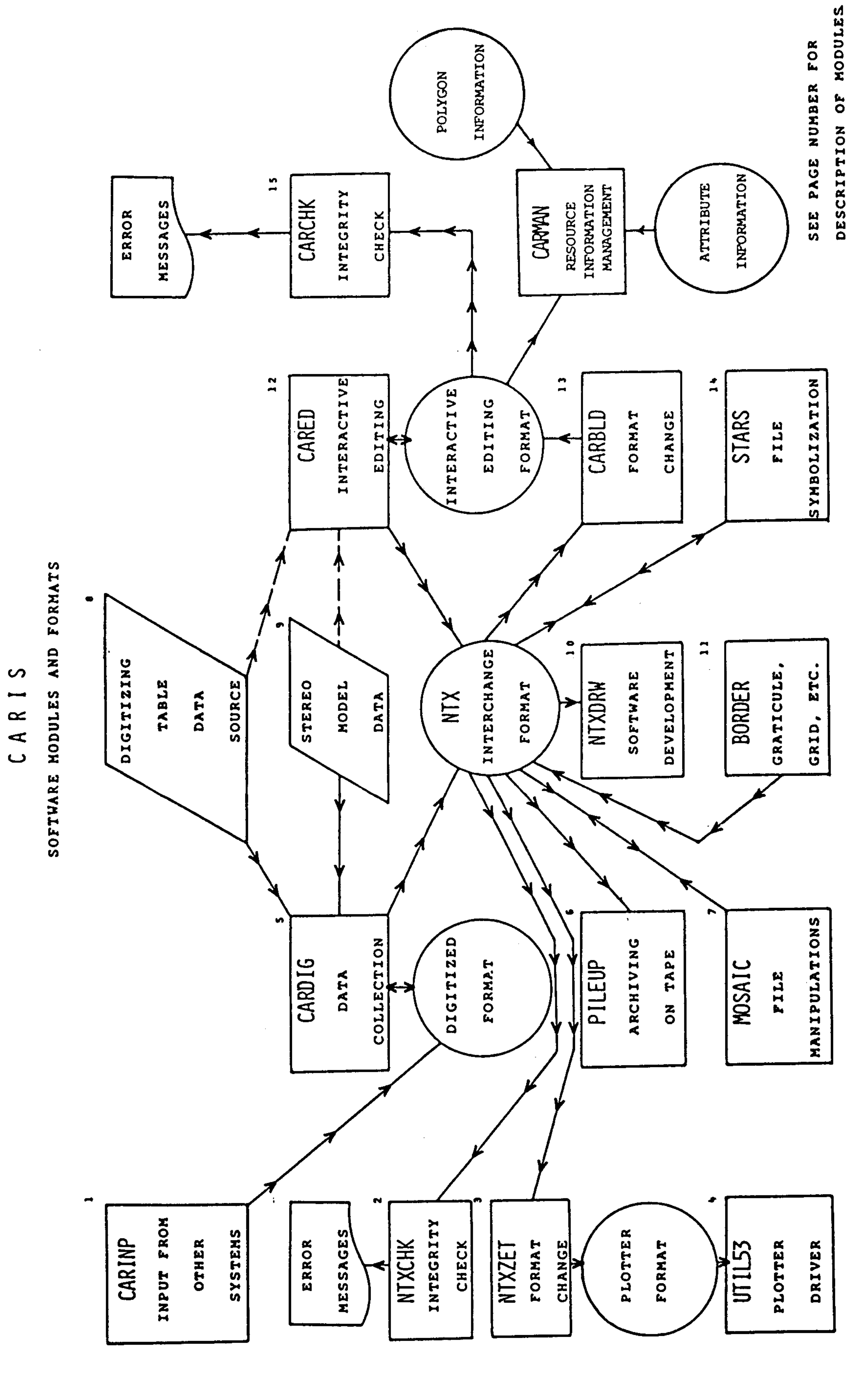


FIGURE 5.7: CARIS: Software Modules and Formats

SESSION VI: DIGITAL MAPPING WITHIN LAND INFORMATION SYSTEMS IN SYDNEY

Of the many applications of digital mapping at different levels within Metropolitan Sydney, I would like to highlight three systems operating within a land information context. Having had the opportunity to obtain a demonstration for each, I would like to briefly discuss the systems of the Australian Gas Light Company, the Sydney City Council and the Metropolitan Water, Sewerage and Drainage Board, concentrating of course, on the digital mapping component of each system. When considering these systems, it becomes very obvious that digital mapping is in fact not an end in itself, but rather a (quite important) component of a much larger space-related information system.

<u>The AGL - Mapping System</u> is tailored to specifically meet the needs of AGL, namely providing maps where gas distribution lines and related information (e.g. valves, syphons etc.) are shown together with street boundaries and identification information, such as street names and house numbers.

Since the company also has a need for engineering design - and business graphics, a more general CAD/CAM system was purchased in 1979 from Autotrol in Denver, Colorado. While the system lacks some of the features specifically useful for topographic mapping, it was selected because the vendor offered the best field support.

The system is based on a 16 bit word Univax with CDC disk drives as the central processing unit and supports four work-stations with Opec 10 digitizer (Auto-trol) plus graphics terminal. A flatbed plotter produces the final hard copy maps.

As with all such systems, there is a certain amount of development required for each individual set-up. Software problems (e.g. U.S. imperial units) and proliferation of work caused a rather inefficient operation for the first two years (only 40 map sheets completed).

This has improved drastically with a management change three years ago, leading to the formation of an integrated CAD-group which initially concentrated on <u>one</u> project only, namely mapping.

The company's installations are covered by approximately 2000 maps at 1:2000 scale (Metropolitan Sydney, Wollongong, Newcastle, Canberra, Hunter Valley).

A four year plan was set out for the completion of the task, and after 2 1/2 years it is right on target with approximately 900 - 1000 completed.

Unlike the systems mentioned earlier, the mapping is "quick and dirty", practical (for AGL) but not fancy. All topographic information comes from the CMA 1:4000 (1:2000 in places) maps with no other input, such as coordinates, as AGL does not have in house surveying capabilities. Thus the accuracy is totally dependent on the quality of maps and digitization. From the CMA base maps, street boundaries are digitized, which takes an average 2 - 3 hours per map sheet. Then several steps follow, carried out on the graphics work-stations in an assembly-line type operation. These add mainly gas line and attribute information, e.g. lines, valves, syphons, distances of lines from street boundaries etc., but also street names and house numbers, but no property lines within blocks.

There are 12 levels of overlay information, each of which is checked and edited separately. The final output is a metric 1:2000 map sheet, drawn on a flatbed plotter.

The total operator time required for one map is 20 to 25 hours.

While the hard copy map is the working copy, the actual digital map remains as the data base in the system. Updates are entered into the system whenever new information becomes available. The changes may be done manually on the map as well. Once a certain amount of changes have occurred to a particular map sheet, a new one is plotted.

Now that the mapping operation is running very smoothly and meets all of AGL's requirements, other capabilities of the CAD/CAM system are being utilized. A low level engineering design package for piping has been introduced, which provides dimensioned work and construction plans with material lists and related information.

At present, the CAD system is used to about 50% for mapping, 30% for piping, and 20% for business graphics used for public relations and management purposes.

The Sydney City Council Land Information and Management System is for public enquiry and internal use. In 1972 an action study commenced for the design and implementation of an Information System for the City Planning Department. This study was adopted by Sydney City Council in 1974. In 1975 the broader functions of the Council's organization, including financial and engineering applications were identified and integrated into an overall management concept. The development and application of the Data Management System commenced in 1976 and was substantially completed by 1980.

The system was developed by Council and International Computers (Australia) Pty Ltd (ICL) as one of the world's most advanced Land and Financial Management Systems. A computing centre was established by ICL at Town Hall House and encompasses within an integrated data base, the accounting, engineering, planning and general information requirements of the Council.

The system is supported by two main frame computers and has 33 display units (mostly alpha-numeric) plus five hard copy printers.

As the system is geared for planning purposes the graphics (mapping) part is presently its weakest link. This is caused by differences in interest between planners on one side, and engineers and surveyors on the other, but also by the graphics software which again was not developed for topographical mapping.

According to the planners, spatial representation provides no problem, as the margin of graphical errors is acceptable to them. Thus 1:1000 urban property maps are digitized to an accuracy of 0.5 m. Apparently, this serves the Council's planning needs, as the map base is established and tied to the integrated survey grid and amalgamations are by far outnumbering subdivisions.

The engineering section looks at the situation somewhat differently, as it is envisioned to eventually show all utilities on the map displays. Thus the engineers and surveyors are hoping for improved software from ICL that can support more than just one level. It is planned to improve the positional accuracy to 0.1 metre (engineering standard) at the 2nd stage, and eventually reach the surveying standard of 5 mm for properties at the third stage of systems development. To this end, some cooperation with the Municipal Water, Sewerage and Drainage Board has been initiated.

At present, horizontal surveying control is being upgraded by in-house surveyors. Furthermore, polygon areas are being fitted mathematically onto existing control using affine transformations. Working from larger polygons to smaller ones appears to be quite successful.

Until at least the utilities are included into the data base, the graphical display - and thus digital mapping - plays a rather minor role confined to the planning process. Its use is limited to displays and possibly subsequent plotting of polygon areas, representing certain planning elements, including proximity considerations (e.g. show all terrace houses within 200 m of a certain intersection). Thus a response time of 30 seconds is not considered to be detrimental.

It would be interesting to see whether the digital mapping capabilities of the system will eventually catch up to the efficiency of the rest of the land information system which handles a huge amount of data, accessed by street address and property key (parcel numbers). 30 - 40 inquiries per hour are routinely handled by systems like BAS (Building Activity System) VOSS (Valuation, Ownership, Sales System), PCON (Planning Controls System), DABA (Development Applications and Building Application System), DEPS (Data Extraction and Presentation System), which are all cross-referenced.

All this, of course is only part of the overall system, which includes the whole financial and accounting operation of the Council as well.

The Metropolitan Water, Sewerage and Drainage Board is presently setting up IFIS (Installed Facilities Information System). In 1983 a 15 month pilot study was approved and commenced, after the completion of a 3 months' feasibility study. This pilot project, which was completed last September, involved the following:

- identification of numerous requirements based on discussions with the users
- determination, with the user areas, of applications for development in the study
- determination, with the user areas, of the manner in which information is to be displayed
- reconfiguration of the general software packages provided by IBM to suit the Board's mapping- and related property and facility data input and output requirements

  (IBM had provided IGGS (Interactive Geo-facilities Graphics Support) and GDBS (Geo-facilities Data Base Support))
- installation of GPG (Graphics Programme Generator) to replace IGGS and resolution of problems found in the new package
- detailed systems and data base design
- software development for unique applications of the Board
- software development for map conversion and updating
- interface programming to access information from other computer systems
- education and training of IFIS team
- demonstration of all applications to the user areas
- monitoring of system performance
- documentation

The pilot project was used to identify the major requirements of the system, which are:

- Cadastral display (property information)
- Watermain display (similar to existing record maps)
- Sewer display (similar to existing sewer reference)
- Stormwater display (as for sewer references)
- Drainage area display (hydraulic survey record maps)

- Data base (direct access and authorization)
- IFIS entry options (different levels of user participation)
- Board's interests display (land, easements, facilities)
- Subdividor/developer action display (areas under dvelopment)
- Other authorities' display (related information)
- Main tracing (connectivity, networking)
- Real estate mapping (hard copy real estate maps)
- Plan drawing, watermains (for construction and report plans)
- Billing data base (direct access of IFIS information)
- R.P. Assets Register (IFIS identification of Board's land).

This list shows, that digital mapping is the fundamental component of the system, which was recognized by IBM when IGGS was upgraded to GPG.

The hardware consists of a mainframe computer (IBM 3081) with 12 workstations containing an IBM 3277 Alpha Screen, a Tektronix 618 Graphics Terminal, a Digitizing Table with menu plates and cursor, plus a Tektronix 4611 Hardcopy Printer (which might be shared by several workstations). The final map product is obtained off-line via a flatbed plotter.

The input information is mainly from 1:475 scale (60 links/inch) occupation plans, which were continued by MWSDB (after Public Works terminated their production) until the mid-seventies. New plans are in 1:1000, often with photographic enlargement to 1:500 for plotting of individual houses. These plans are in a Cassini/Soldner Projection and then transformed to the ISG coordinates.

Other input may be bearings and distances or coordinates in digital form. Only planimetric data are included, although sewer depths are listed as attributes.

It is planned to convert all maps into the digital data base within 3 years (i.e. 1.9 million parcels, which is 63% of all NSW properties).

Each line carries an accuracy attribute ranging from A (super accuracy; B is 1st order geodetic control) to Z (lowest accuracy), each category being again numerically subdivided. At present, the accuracy lies by 0.1 m for urban areas and may disintegrate to 10 m in rural back country.

The system operates in vector mode, although raster terminals and colour enhancement (e.g. with IBM Personal Computer) is being considered.

Straight lines are stored via two end points, curves as circular arcs with beginning and end points plus one point in between.

The data base is multi-layered with parcel number providing the identification key.

Eventually, it is planned to decentralize the system, to 5 regional offices. This may cause some delays in response time because of Telecom linkage. However, this could be overcome with the use of stand alone mini-computers with a partial data base at the regional office which would be updated periodically from the main office.

This brief overview of IFIS was supplemented by a presentation from a member of the IFIS Group at the beginning of the next session.

The example of IFIS which is being implemented by the Metropolitan Water, Sewerage and Drainage Board, emphazises the value of a digital mapping data base with high positional accuracy. The establishment of such a data base and its maintenance is very expensive, and thus other agencies are interested in purchasing some of these data. This is similar to conventional mapping, where a few agencies collect the data and produce the map. This map in turn is purchased by users who then extract information to meet their needs. Since many users nowadays need information in digital form, it would be ideal, if digital mapping data bases (or parts of it) could be purchased in digital form ready for direct use.

The prime benefit of digital mapping lies in the reduction and possible elimination of duplication of effort between agencies.

Present reality however is that many agencies are using different digital mapping systems, which often are incompatible. This of course is fuelled by hardware vendors because of stiff competition.

There is definitely a need to interchange data if the full economic benefits to society are to be realized.

Data interchange requires at the very least reformatting, and almost all systems provide software for it. In digital mapping we have basically three types of data, namely:

- graphics e.g. lines, symbols
- topological data e.g. polygons, networks
- attributes e.g. ownership, land use, utilities, assessment

each of which may cause different problems with data exchange.

I would like to just give you a few examples.

1. Problems with graphical data

(a) Feature code matching:

e.g. "road" RRRD (LRIS)
2000 (EMR)

In Canada, the Maritime Land Registration and Information Service (LRIS) uses 4 letters as feature code for roads, while the Federal Department of Energy, Mines and Resources (EMR) uses a four digit number.

(b) Classes of features:

While provincial highway departments have road classifications of up to 50 types, LRIS and EMR recognize 20 types each (which are not quite the same), while other systems have as few as 2 (paved and unpaved).

(c) Campatibility between computers.

The word length is most critical, e.g.

computers	No. of bits per word
PDP	16
VAX	32
IBM	32
UNIVAC	36

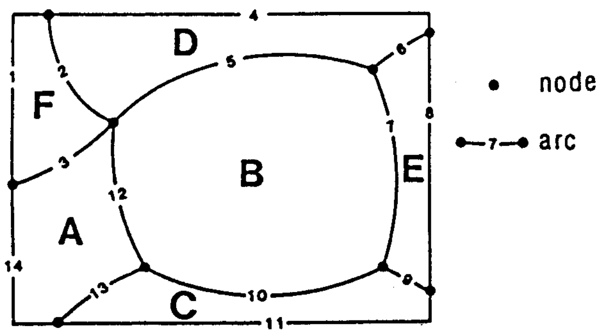
2. Problems with topologica data:

Different data structures utilize different pieces of information and thus have different limitations.

(a) limits on nesting polygons

(b) ability to handle complex islands

(c) neighbourhood relationships between polygons may be based on arcs or on nodes.



Polygon	Arc List
A	3, 12, 13, 14
B	5, 7, 10 12
C	9, 10, 11, 13
D	2, 4, 5, 6
E	6, 7 8, 9
F	1, 2, 3

FIGURE 7.1: Polygons Represented by Arc Lists

Figure 7.1 illustrates some polygons and their representation by arc lists. It is obvious, that the neighbours of polygon B are A, C, D, E and F. However, the arc list described in the figure does not readily reveal F as a neighbour of B.

3. Problems with attribute data:

Data base management systems use various file structures and the vendors of these systems are highly secretive about the format of these data bases. Since, as previously stressed, the data structure is the heart of a digital mapping system, commercial companies are very reluctant to give any details about formats and internal data flow. Thus it is often impossible to directly interchange attribute data.

Graphical data are the simplest and easiest to exchange. The time required to develop interchange software depends on:

- complexity of the formats

- availability and quality of the documentation of formats

- whether existing routines can be used

- whether other data exchange programs exist.

In order to facilitate efficient data interchange, a state - or better - a national standard for interchange of digital data is required. Thus a straight forward format that can be readily adapted by all agencies has to be agreed upon.

Concluding, I want to emphasize again, that data interchange is not as simple as it may seem, depending on what is being exchanged.

In order to reap even greater benefits from digital mapping, it is essential to quickly move towards a national standard for the interchange of digital data, and some large government agency has to assume leadership in this venture. Only then can we really justify the high costs of digital mapping.

SESSION VIII: DIGITAL MAPPING SKILLS: HOW DO CARTOGRAPHERS FIT IN?

There is a general fear that digital mapping will replace cartography and thus the need for cartographers. In my opinion, this is not true at all. Let me perhaps indicate how I see cartography as a profession. Cartography is the art and science dedicated to represent three dimensional topographic and thematic information in a two dimensional graphical form, such that the representation is not only positionally and thematically accurate but also easy to evaluate and pleasant to look at.

I specifically did not say anything on how this is accomplished because mankind has continually upgraded its tools, and cartography is no exception in this case. It is perhaps worth mentioning, that early maps were engraved into stone plates for printing. Scribing sheets and photographic production of printing plates came later and have not adversely affected the cartographic profession, although cartographers did have to obtain some proficiency in different skills, such as photography.

Since digital data processing is merely a tool, I would like to think that cartographers can make good use of it rather than letting the tool take over the profession.

It is true that computer plots can be obtained without the involvement of cartographers - but are these maps?

Years of experience after solid training and education have provided the cartographers with the knowledge on <u>how</u> to display complicated spatial information on a sheet of paper. This unique ability remains in demand in spite of the drastic change in production methods.

Users will require hard copy maps for years to come and they want good, easy to understand products.

I am sure that all of you have noticed the significant decline in the popularity of orthophoto maps. Their production is virtually automatic with very little human intervention, and very little cartography. The information content of the photographic image is extremely high - yet the user requests different products. He wants cartographic enhancement, someone to interpret the information for him, discard what is of little importance and highlight other aspects. This has resulted in orthophotos being overprinted with simple line maps, and many users find even that too cluttered and complicated.

This should serve to illustrate my point. It is however obvious that many of the manual skills are not needed any longer and have to be replaced with expertise in interacting with the computer. Thus a certain amount of retraining and redirection is most definitely required.

A cartographic draughtsman for instance no longer requires draughting and lettering skills - the latter have already been replaced by stick-on lettering. Instead he has to be able to position and place information, letters and symbols on a graphics terminal. He should be thoroughly familiar with digitizing, data input and editing procedures. He then is able to cover the data collection input phase up to producing clean data files. Line matching, matching of classifications, polygon closures, assignment and checking of attributes as well as placing symbols and names are some of the digital mapping tasks that he would be most suitable to perform.

Senior cartographers would require knowledge of the command language in order to utilize the data base. This would be in addition to the terminal operation. Their expertise in representing spatial information would be directed towards the design of the various maps. They would have to overlay different sets of information and find their union or intersection, depending on the user requirements. Once they have combined the different levels of data, it is their job to optimally display them. They have to generalize, i.e. select and emphazise important information, suppress other information to obtain a reasonably clear map without loss of necessary data. Here their knowledge of scale and how much can be displayed at a certain scale, the need to displace features in order to fit in symbols such as double lines for a highway, line weights etc. is invaluable.

Furthermore, they have to add symbols, place names in the correct size for a specific scale as well as superimpose grids, neat lines and legend.

If the map display is pleasant and ready for reproduction, cartographers have to decide on colours, provide colour separations, masks and line work as a basis for subsequent printing. Again, all manual tasks such as scribing are taken over by the computer. Thus the work is faster, which means that the productivity of each cartographer increases, thus facilitating faster revision cycles and more up-to-date maps.

There is lots of work to be done, and I believe it is essential for the cartographic profession to add computer operating skills (programming is often not even necessary) to its basic knowledge requirements and to take digital mapping into its domain, rather than let it slip away to computer experts, whose lack of mapping experience often leads to inferior map products.

Just as the photogrammetric plotter operators followed the change from pencil map manuscript via directly plotter scribed sheets to stereo-model digitizing with terminal control, while still retaining his unique claim on stereo-evaluation based on experience in stereovision and plotter orientations, the cartographer has to adapt his work to the most advanced technology without sacrificing his position within the mapping field. If he is willing to incorporate modern technology into his field of expertise rather than back away from it, his future will be bright.

REFERENCES

Adamec, A. and Lee, H. H. (1984). "Computer Mapping with Dated Equipment". International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV, Rio de Janeiro.

Australian Major Water Supply & Sewerage Authorities (1984). "Conference Report, Facilities Information Systems", Sydney.

——— (1984). "Conference Papers, Facilities Information Systems", Sydney.

Cannafoglia, C. and Catalani, L. (1984). "The Analytical Stereoplotter for the Creation and the Updating of a Numerical Cadastral Survey Cartography". International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV, Rio de Janeiro.

Caprioli, M. A. (1984). "Application of Direct Digitization on Stereoplotting Instruments for Original Mapping Systems". International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV., Rio de Janeiro.

Collins, S. H.., Moon, G. C., Lehan, T. (1984). "Advances in Geographic Information Systems". International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV, Rio de Janeiro.

Council of the City of Sydney (1975). "Planning Information System", Action Study 5, Sydney.

——— (1980). "1980 City of Sydney Strategic Plan", Sydney.

Ehlers, M. (1984). "The Automatic DISCOR-System for Rectification of Space Borne Imagery as a Basis for Map Production". International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV, Rio de Janeiro.

Ellis, J. (1984). Personal Communication.

Furuya, H. (1973). "Automating the Marine Chart Production Process", Cartographica Monograph, No. 9.

Harris, R. (1985). Personal Communication.

Huebel, K. (1984). Personal Communication.

IBM. (1984). "The Winds of Change: CAD at the S. C. C.", IBM Quarterly, December 1984.

Intergraph Corp. (1982). "Mapping and Earth Sciences". Publication # DGC007B0.

——— "Mapping Overview". Publication # DGC01140.

Kainz, W. (1984). "An Information System for the Geo-Sciences". International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV, Rio de Janeiro.

Lands Directorate, Environment Canada (1973). "The Canadian Geographic Information System", Geographica Monograph No. 9.

Leatherdale, J.D. & Keir, K.M. (1980). "Digital Map Production", International Archives of Photogrammetry, Vol. XIII, Comm. IV, Hamburg.

Lee, Y.C. (1983). "A Data Structure for Resource Mapping with CARIS". Proceedings of the Sixth International Symposium on Automated Cartography.

M & S Computing Inc. (1980). "Interactive Graphics Design System", Report 80-077.

Makarovic, B. (1984). "Procedures and Structures for Extraction and Sampling Geo-information from Images". International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV, Rio de Janeiro.

Makkonen, K. (1984). "Modelling a Dynamic Geodata Base". Internatinal Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV, Rio de Janeiro.

Masry, S.E. (1982). "CARIS, a Computer Aided Resource Information System: An Overview". Paper presented at the Institute for Modernization of Land Data Systems, Georgetown University Law Center, Washington, D.C.

Nash, K. (1984). Personal Communication.

Satharanond, V. (1984). "New Data Structure Model for Digital Geographic Data Base". International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV, Rio de Janeiro.

Slade, L.O. and Adamec, A. (1984). "Computer-Assisted Generalization". International Archives of Photogrammetry and Remote Sensing, Vol. XXV, Comm. IV, Rio de Janeiro.

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