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7.5 PHOTOGRAMMETRIC ASPECTS OF REMAPPING PROCEDURES*

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The presentation will discuss aspects specific to photogrammetry, particularly photogrammetric control generation. In order to avoid having this talk be more or less tutorial, I will, at the end of the talk, make the discussion relevant to remote sensing data reduction.

Referring to Figure 1, the outline, I will briefly go through several aspects of photogrammetry, including a classical definition of rectification which existed in photogrammetry for many years and then show how it changed to fit the context of what we do at present with remote sensing data. Since I was specifically asked to discuss triangulation, or at least ground control generation photogrammetrically, I'll be talking a little bit about that and then I will go into the MSS aircraft data work that we've been doing at Purdue at least in my area of engineering for over seven years. At the end, I hope to have time to offer some conclusions.

There are broad definitions for photogrammetry. However, as shown in Figure 2, I'm going to concern myself here with extracting information from photographs and images that are of metric quality. Fundamentally a photograph or an image, no matter which way it is acquired, is basically a two-dimensional representation of a three-dimensional space. This is shown schematically in Figure 3 for a frame photograph. If we do not take this fact into consideration, we are likely to have problems, and I'm sure many of us have had that.

In order to recover the information about the object, we basically are going in the direction from where the data was acquired back into the object, and the only way we can get the information correctly is to do one of two things. Either to assume that the object is an average plane like it was desired yesterday by Fred Billingsly, or we would have to have an external source of information about the object itself, such as having a digital elevation model as I will mention a little bit later.

Obviously an alternative to that, which is a typically photogrammetric solution, is to have more than one ray, and there was a question, at least one raised yesterday as to what the impact of having more than one image record is on the accuracy. I will show some results on that as well later on. Figure 4 is a schematic of three conjugate rays from three frame photographs.

Rectification, classically, was related specifically to a reprojection, and, in the context of a frame photograph, we assume that it is a perspective projection of a three-dimensional space, as shown in Figure 5, the original photograph was oriented not necessarily with the optical axis of the camera pointing downward. And what we would like to do is to get another equivalent vertical photograph through a transformation. The new equivalent photograph would represent a mean plane in the terrain itself. An extension to this is referred to as differential rectification in photogrammetry and requires having more than one photograph. Figures 6, 7 and 8 show schematics in which the terrain is represented with small segments, each of which is differential-

*Edited oral presentation.

ly rectified, that is to say, now parallel to the datum and then placed properly so that the elevation effect has been taken into account. This is the procedure that produces the orthophotos as is known in photogrammetry. The equivalent to that is to consider a single image, either a frame perspective photograph segmented into small patches or, in the case of the MSS imagery, to consider each of the pixels as if it were a segment. And if you have a digital elevation model, and if you want a full rectification in the photogrammetric sense, then you can merge these two together, and you can properly locate each one of those elements back relative to the terrain datum. I want to say that as far as map projection is concerned, that does nothing other than to change the frame of reference of the data. It has absolutely nothing to do with the fact that you are going either from three-dimensional to two-dimensional or multiple two-dimensional back to three-dimensional. The map projection is strictly a means of projecting the surface onto a map. So it's not the same thing at all.

Now, we move on to the triangulation, which is the procedure for getting control. There is quite a lot of detail that I should go through but I cannot, due to lack of time. There are different types of procedures for triangulation as shown in Figure 9. For our purposes here, the one most commonly used technique is analytical triangulation where a large number overlapping images can be simultaneously reduced in such a manner as to produce very high accuracy control. The idea is to have multiple rays for every point on the terrain for which you require the X, Y, and Z location, as shown in Figure 10, and for each of those rays, you write the proper equations. And then you reduce the entire set of multiple rays simultaneously in one analytical reduction method. Before you do that, you need to have at least estimates for the unknowns you sought for.

Figures 11 and 12 show situations which are rather idealized for a typical block of 20 aerial photographs, and the corresponding structure of normal equations used to derive supplementary control. The lower half of Figure 9 indicates that analytical triangulation has reached a very high degree of sophistication. Everything that enters the mathematical model is considered a stochastic variable including the ground control that is externally obtained by ground means. And you will enter the image coordinates as observable with their a priori known covariance matrices. All the possible systematic errors that occur are corrected according to the best models available. Control requirements are: for the horizontal control, you need it around the perimeter; for the vertical control, you need it well distributed through the block.

Figure 13 shows what are called the colinearity equations. Those are for frame photographs but can be modified for a continuous strip camera which is the exact equivalent of the pushbroom linear array; it can be modified for panoramic photographs and also for the multispectral scanner imagery.

So we have the mathematics to go from regular photogrammetric reduction to MSS reduction. In fact, we have done all that at Purdue, including the block adjustment of MSS data. I will show you some results if I have a chance at the end.

What do we do if we have several hundred photographs and for each of the photographs, there are six unknowns. We end up with a very large system of linear equations, actually they are originally nonlinear, but are linearized. We take advantage of the characteristics of the normal equation structure which is very sparsely populated by nonzero elements as shown in Figure 17. We also take advantage of techniques of folding parts of this matrix in such a way that we end up with only a subset of the unknowns, and it gives us a banded bordered structure of matrices which are relatively efficiently reduced.

So what do we get from the analytical triangulation scheme? Well, we will basically get X, Y and Z for all points of interest for which we had input image coordinates, based on a skeleton of control points around the perimeter and a few in the center. As regards accuracy, working with frame photography, and this of course may probably look out of context here, we can go down to three micrometers at the plane of the image for the control that we have obtained from aerial photography (Figure 9).

The last section of this talk briefly covers work we did at Purdue. Three papers, listed as references, will briefly be discussed. Figure 14 shows the detailed outline for the first paper, essentially a survey paper giving the mathematical models we use when we actually deal with MSS images as if they were photogrammetric blocks of photographs. The idea is that for each one of the locations of the sensor you would have nominally six parameters describing its location and attitude. This would lead to six parameters per pixel if we treat the problem in a vigorous manner, which would lead to a very large number which would be impossible to reduce (see Figure 15). For the case of the pushbroom scanner, we have six parameters for each line. For practical purposes we segment the image, and consider each segment as if a photograph had six elements (X_c, etc.). We then consider each of those elements as if it were a function of time. There is a large number of possibilities with which we actually model the exterior element and I have several of those already mentioned in those papers. There are two basic techniques: either to specifically model everything we know about the sensor, or to use some interpretive technique in order to get the information.

Another important aspect is to consider whether we want to work with only single images which have the limitation of considering only horizontal (or X, Y) information, or we will work with the block adjustment which then gives us also the Z. In consideration of the Z, there are two ways of looking at this problem: either using the remote sensing data for mapping purposes, or for the purpose of merging the MSS information to other sources of data, which would require only rectification. You want to rectify it but not use it for mapping as such. So everything Roy Welch said yesterday was to meet map accuracy standards as if the MSS or its equivalent (whatever the sensor used) actually does the topographic mapping at appropriate scale. What I am saying here is related to the need to rectify the data so that you may derive other types of information from it.

Figure 16 shows the single coverage results. One of the things that we did is to take a strip of MSS imagery and segment it, write constraints between segments so that continuity is preserved. As the number of segments increases, the check, or what ever measures you have for accuracy, would improve up to a certain point and after that, of course, it levels off because the degrees of freedom are reduced (see Figure 17). Using real data from three sidelapping strips, the Z is indeed recoverable (see Figure 18). I don't know if the gentleman who asked the question yesterday regarding the use of stereo is here or not but he was wondering what would happen if you use overlapping imagery.

This not only produces the Z but it also improves the recovery of horizontal coordinates by 40 and 60% as shown in Figure 19. There are other aspects of this work, namely that you could adapt techniques from the block adjustment of photographs to be used with MSS. Notably, we have used geometric constraints such as points lying on straight lines (e.g., roads). The use of such constraints can replace the need for control, or if used in addition to control, can lead to improved accuracy.

In conclusion, we feel, in photogrammetry, that we were not really heeded as much as we ought to have been; there's a wealth of information, a wealth of technology that is useable with remote sensing imagery. Everything I've said here, of course, relates to aircraft MSS data which is the one thing I had continued to work with. We have not the equivalent thing with Landsat for obvious reasons It was a tremendous jump to go from the micrometer level to the 80-meter resolution, so I stayed with the aircraft.

I feel that I have just scratched the surface as far as the actual remapping topic. However, I hope that this with reference papers will give you a good idea of what can be gained when photogrammetric technology is considered when rectifying and/or registering remote sensing data.

Bibliography

E.M. Mikhail and J.C. McGlone, "Current Status of Metric Reduction of (Passive) Scanner Data", Invited Paper, Commission III (WG III-1) 14th Congress of the International Society for Photogrammetry, July 13-25, 1980, Hamburg, FDR.

J.C. McGlone and E.M. Mikhail, "Accuracy, Precision and Reliability of Aircraft MSS Block Adjustment", paper submitted for publication in _Photogrammetric Engineering and Remote Sensing_, 1982.

C.J. McClone and E.M. Mikhail, "Geometric Constraints in Multispectral Scanner Data", paper to be presented at the 1982 Annual Convention of the American Society of Photogrammetry.

OUTLINE

- INTRODUCTION
  * Photogrammetry
  * Rectification
- PHOTOGRAMMETRIC TRIANGULATION
  * Purpose
  * Procedures
  * Analytical Triangulation
  * Adaptation to MSS
- METRIC REDUCTION OF SCANNER DATA
  * Mathematical Models
  * Applications to Spacecraft Data
  * Applications to Aircraft Data
- CONCLUSIONS

Figure 1. Remapping Procedures Overview

- PHOTOGRAMMETRY

  * Metric Information From Photographs and Images

  * Image is 2-Dimensional Representation of 3-Dimensional Object Space

  * Recovery of 3-Dimensional Object From a Single Image is Not Possible

    Unless: 1) Assumptions Made About Object

    2) Additional Object Information Available

  * Recovery of 3-Dimensional Object From Two or More Overlapping Images

- RECTIFICATION

  • Transformation of One Frame Photo to Another

  • Differential Rectification

    * Single Photo and DTM

    * Overlapping Photos → Orthophoto

  * Considerations for Remote Sensing Images

Figure 2. Introduction

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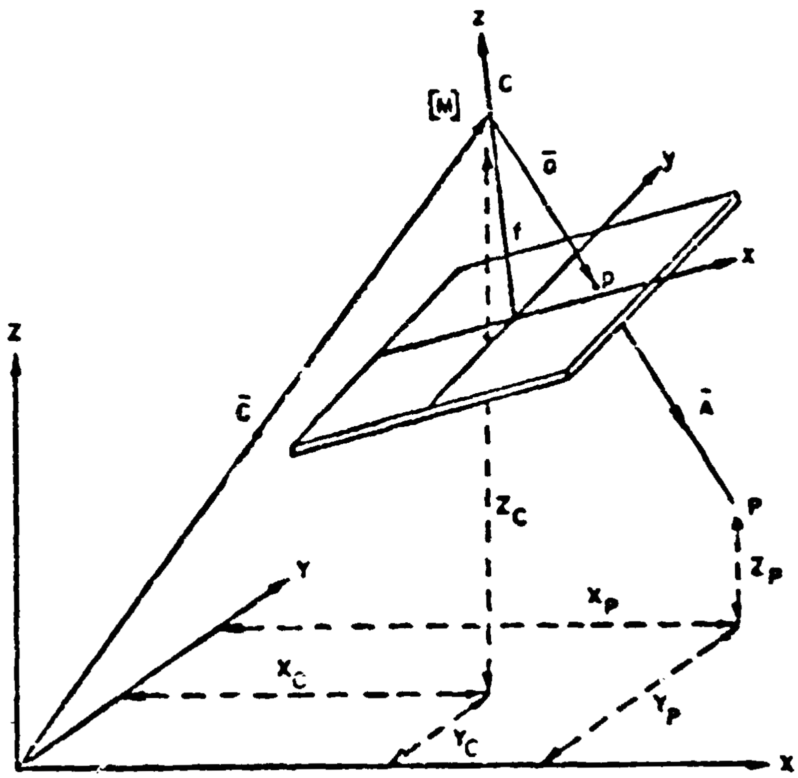

Figure 3. Object Space and Exterior Orientation

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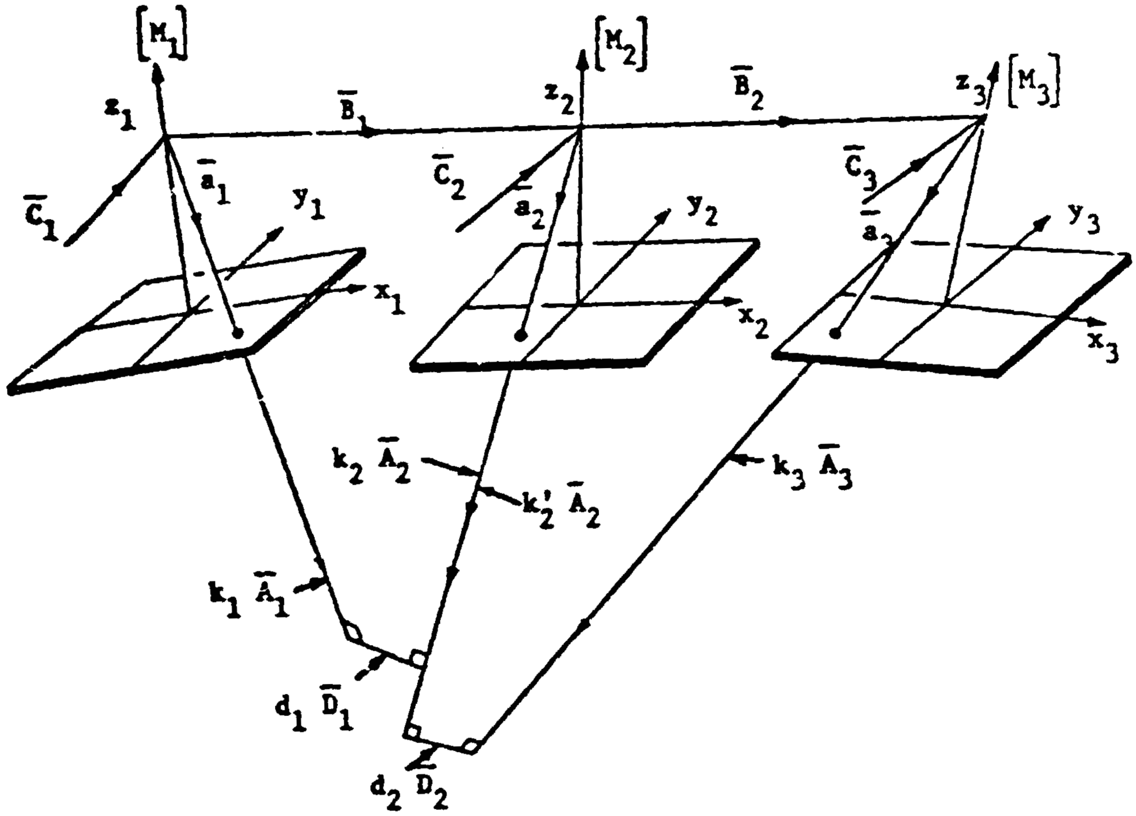

Figure 4. Scale Restraint Equation

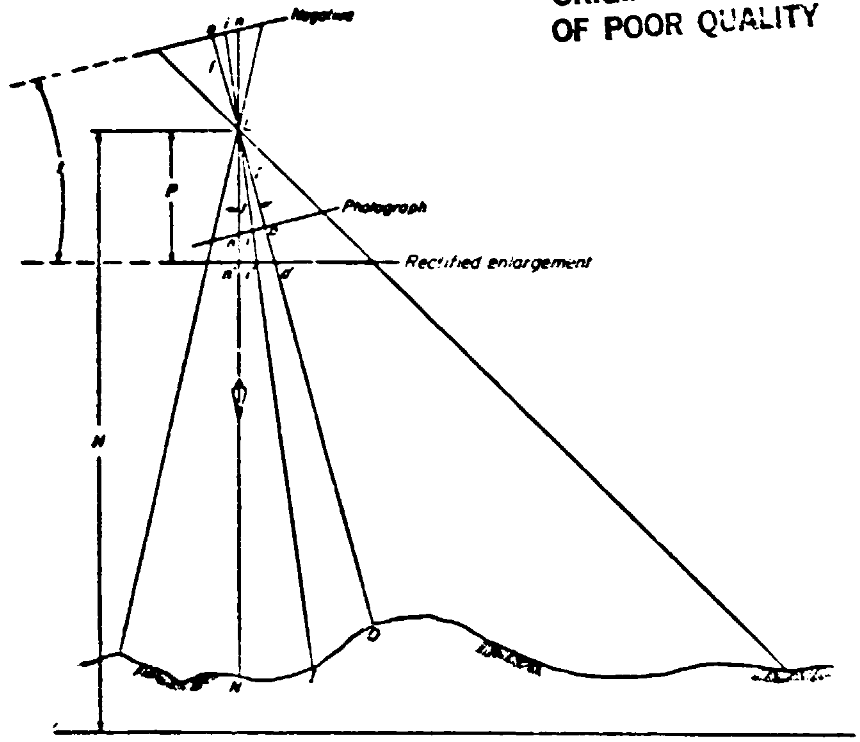

Figure 5. Tilted photograph and rectified enlargement.

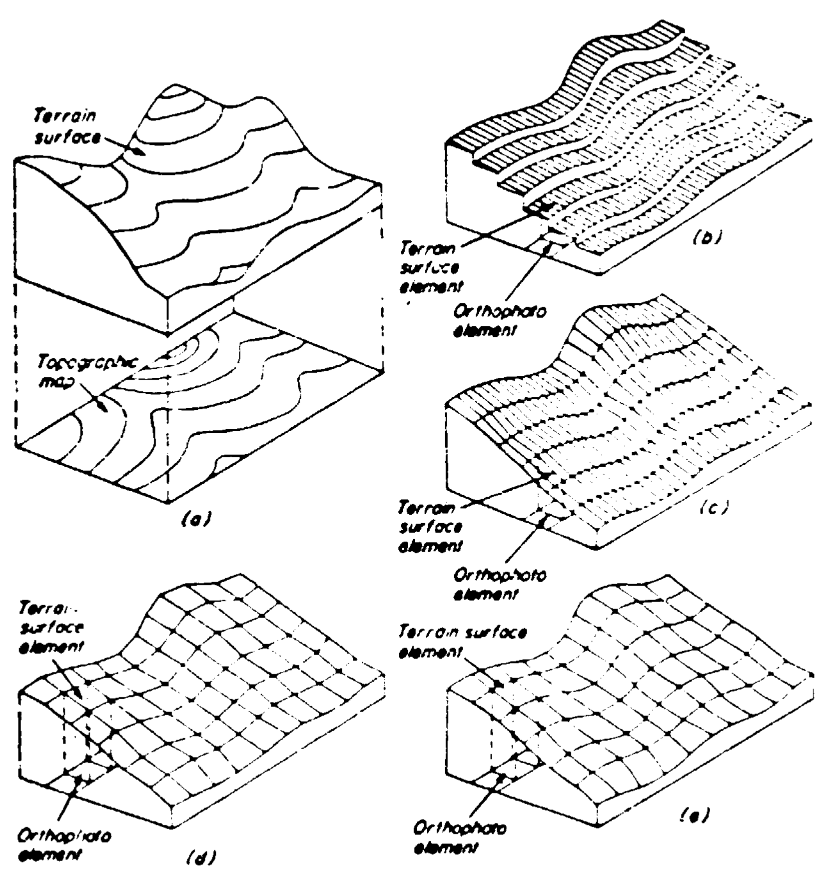

Figure 6. Methods of differential rectification (a) Terrain and corresponding contour map (b) Fixed line element strip rectification (c) Rotating line element strip rectification (d) Plane area element rectification (e) Curved area element rectification. After Edmond, Bendix Technical Journal, Vol. 1, No. 2, 1968.

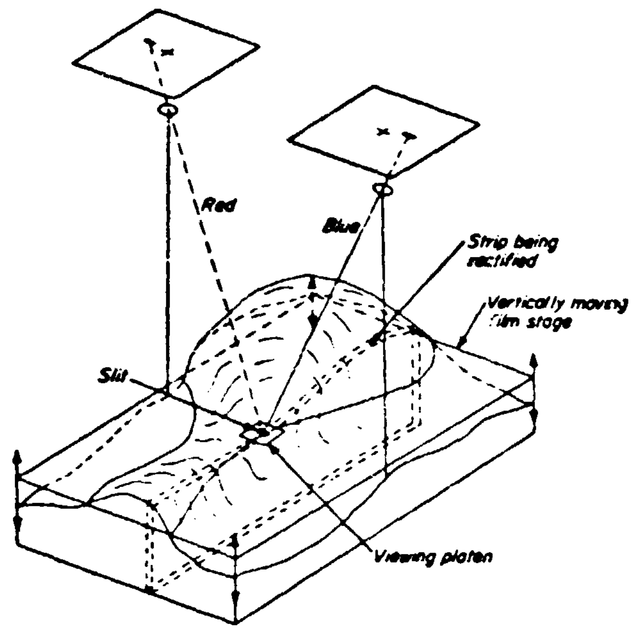

Figure 7. Fixed line element rectification.

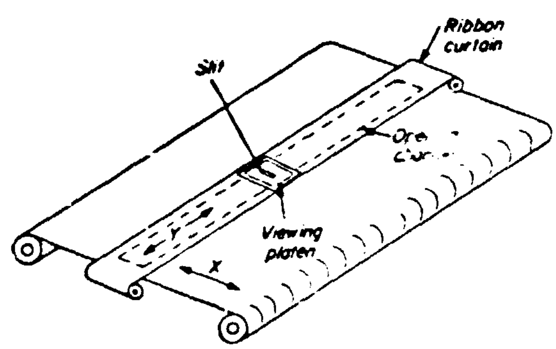

Figure 8. Curtain used to cover film exposure in line element rectification.

- PURPOSE: To Generate Extensive Control Net From Overlapping Photographs and a Few Control Points

- PROCEDURES: Analog Semi-Analytical Analytical

  Choice: Accuracy Requirements
  Photography Characteristics
  Equipment

- ANALYTICAL TRIANGULATION

  * Most Sophisticated

  * Can Reduce Large Number of Photos Simultaneously

  * Need:
    * Image Coordinates - Their Σ
    * Models For Corrections For Systematic Errors
    * Approximations For Unknowns
    * Horizontal Control Along Block Perimeter
    * Vertical Control Distributed Throughout Block

  * Method:
    * Use Unified Least Squares Where all Variables are Considered Stochastic

  * Result:
    * All Sensor Parameters - Their Σ
    * All Ground Coordinates - Their Σ

  * Extension:
    * Extended Mathematical Models For Self-Calibration
    * Use of Geometric Constraints

  * Accuracy:
    * Fraction of Flying Height (H/20,000 and Better)
    * Given σ at Photo Scale (Down to 3 μm)

- ADAPTATION OF TRIANGULATION TECHNIQUES TO MSS

Figure 9. Photogrammetric Triangulation

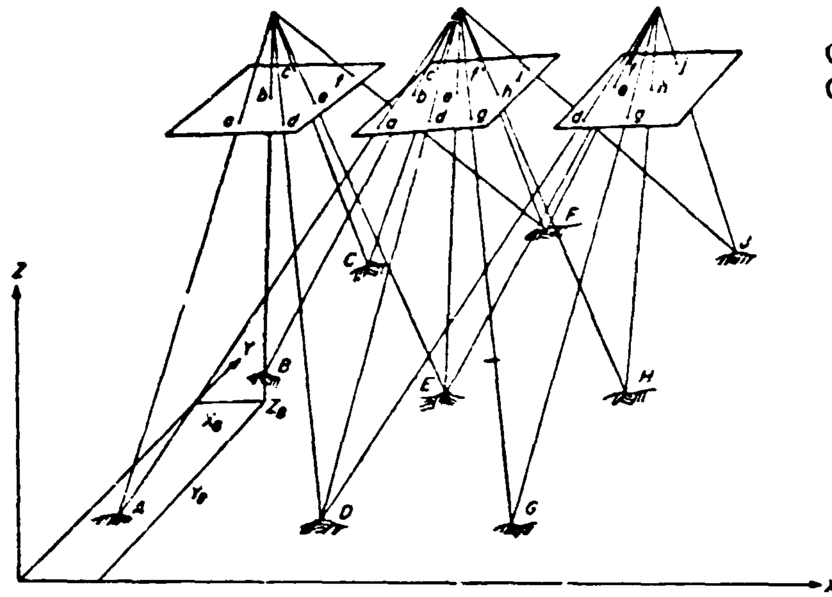

Figure 10. Numerical models to be numerically joined by analytic aerotriangulation.

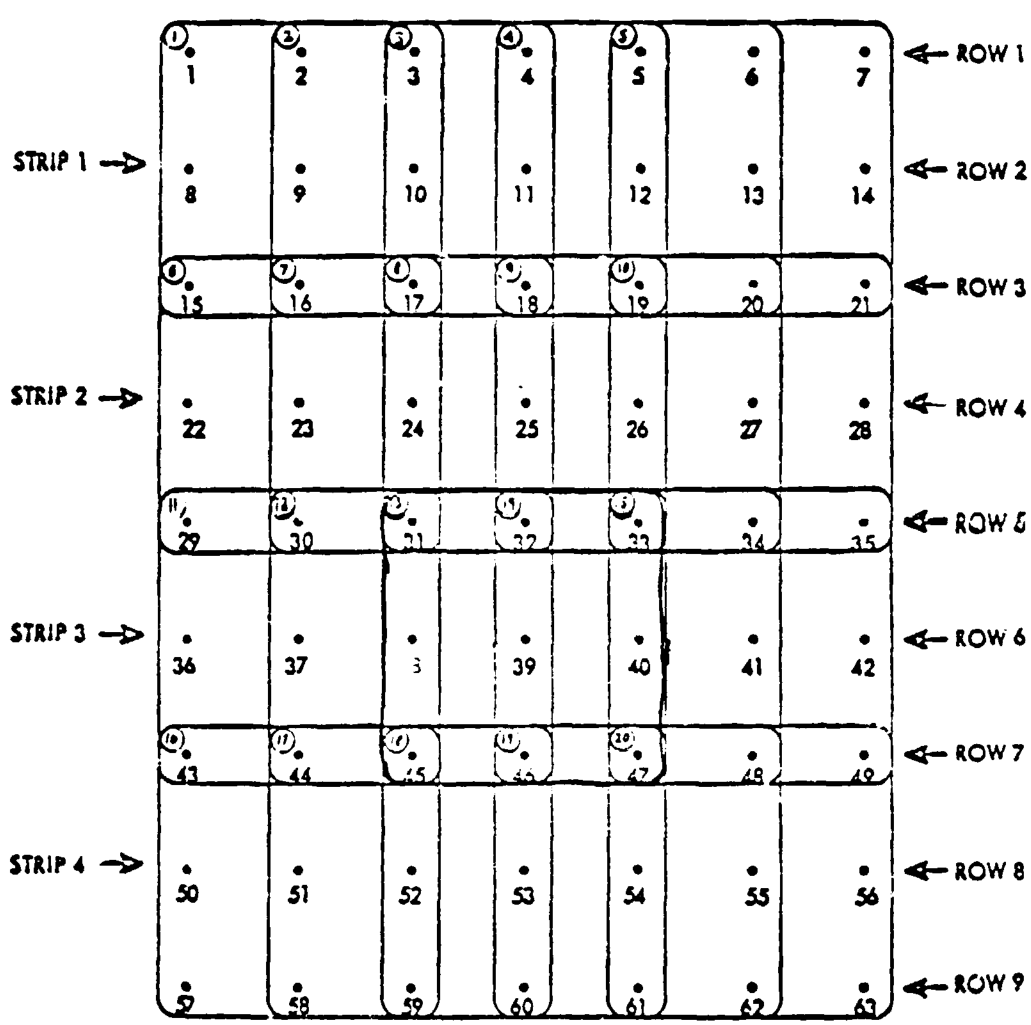

Figure 11. Arrangements of Points in Block of 4 Strips with 5 Photos Per Strip

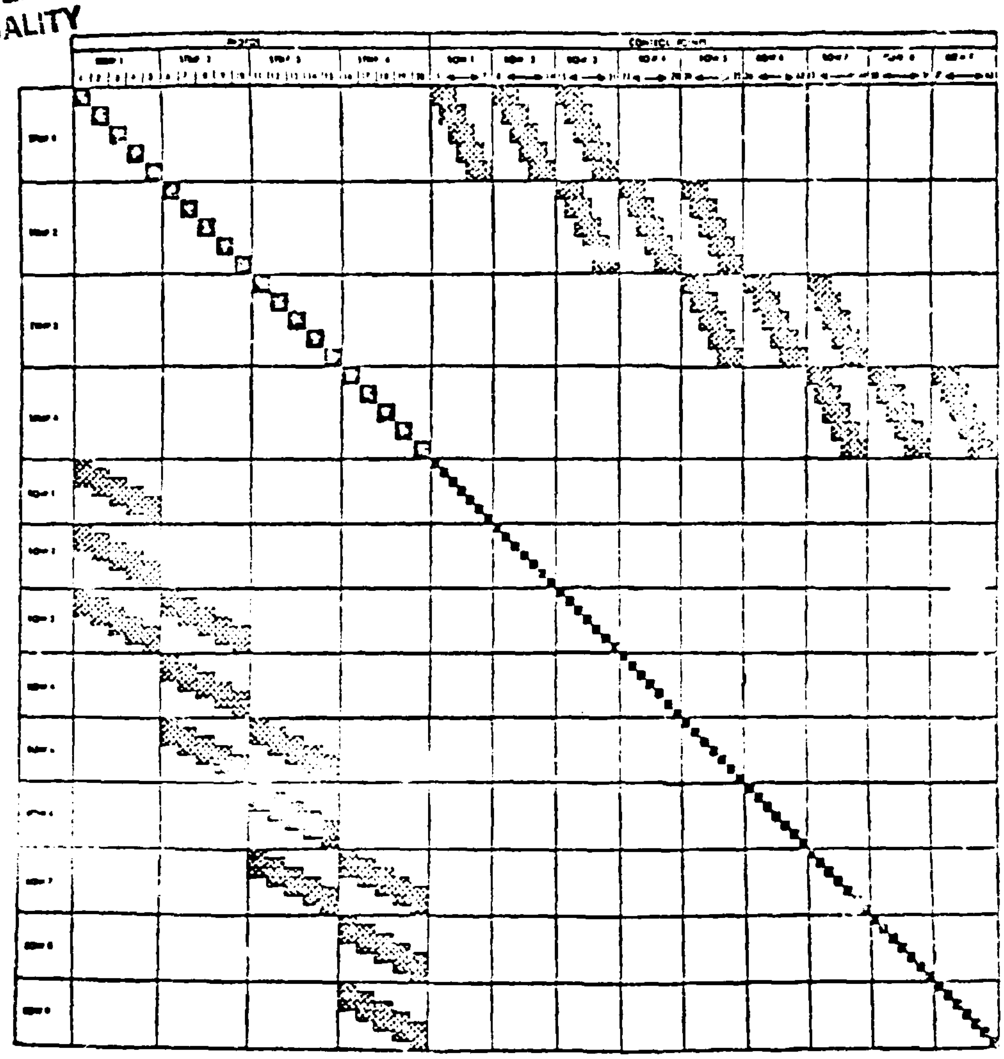

Figure 12. Normal Equation Matrix Arising From Application of Collinearity Equations to a 4 Strip - 20 Photo Block

$$\bar{a} = \left\{ \begin{array}{lll} (x_p - x_o) & = & k\left[m_{11}\,(X_P - X_C) + m_{12}\,(Y_P - Y_C) + m_{13}\,(Z_P - Z_C)\right] \\ (y_p - y_o) & = & k\left[m_{21}\,(X_P - X_C) + m_{22}\,(Y_P - Y_C) + m_{23}\,(Z_P - Z_C)\right] \\ -f & & k\left[m_{31}\,(X_P - X_C) + m_{32}\,(Y_P - Y_C) + m_{33}\,(Z_P - Z_C)\right] \end{array} \right.$$

$$(x_p - x_o) = -f\left[\frac{m_{11}\,(X_P - X_C) + m_{12}\,(Y_P - Y_C) + m_{13}\,(Z_P - Z_C)}{m_{31}\,(X_P - X_C) + m_{32}\,(Y_P - Y_C) + m_{33}\,(Z_P - Z_C)}\right]$$

$$(y_p - y_o) = -f\left[\frac{m_{21}\,(X_P - X_C) + m_{22}\,(Y_P - Y_C) + m_{23}\,(Z_P - Z_C)}{m_{31}\,(X_P - X_C) + m_{32}\,(Y_P - Y_C) + m_{33}\,(Z_P - Z_C)}\right]$$

Figure 13. Collinearity Equations

INTRODUCTION

BASIC MATHEMATICAL MODELS

PARAMETRIC MODELS

ORBIT MODELING FOR SPACECRAFT IMAGES

POLYNOMIAL MODELING

HARMONICS

AUTOREGRESSIVE MODELS

INTERPOLATIVE MODELS

USING GENERAL TRANSFORMATION

WEIGHTED MEAN

MOVING AVERAGES

MESHWISE LINEAR

LINEAR LEAST SQUARES PREDICTION

APPLICATIONS TO SPACECRAFT DATA

APPLICATIONS TO AIRCRAFT DATA

ADJUSTMENT OF MULTISERIES DATA

CONCLUSIONS

Figure 14. Current Status of Metric Reduction of (Passive) Scanner Data

PARAMETRIC MODELS

BASED ON LINEARIZED FORM OF COLLINEARITY EQUATIONS

EXCESSIVE NUMBER OF SENSOR/PLATFORM PARAMETERS

REPLACE SOME OR ALL OF THE SIX PARAMETERS

(X_c, Y_c, Z_c, ω, ϕ, κ per pixel, line, or segment)

BY FUNCTIONS.

FOR ORBITAL CASE: REPLACE X_c, Y_c, Z_c BY FUNCTIONS OF THE SIX ORBITAL PARAMETERS

OR USE A LINEAR SEQUENTIAL ESTIMATOR (KALMAN FILTER)

FOR AIRCRAFT CASE: REPLACE PARAMETERS BY POLYNOMIALS AND SEGMENT RECORDS - USE CONSTRAINTS

(COULD USE HARMONICS)

FOR EITHER CASE: USE AUTOREGRESSIVE MODEL (GAUSS-MARKOV PROCESS)

Figure 15. Basic Mathematical Models

INTERPOLATIVE MODELS

GENERAL TRANSFORMATION

- 4 - PARAMETER
- 6 - PARAMETER
- 8 - PARAMETER
- GENERAL POLYNOMIAL (RUBBER SHEET)

WEIGHTED MEAN

WEIGHT DECREASES AS DISTANCE BETWEEN POINT AND REFERENCE INCREASES (NEW PARAMETER ESTIMATION FOR EACH POINT)

MOVING AVERAGES

MESHWISE LINEAR

(TRIANGULAR OR RECTANGULAR MESHES - LINEAR ESTIMATION)

LINEAR LEAST SQUARES PREDICTION

(ESTABLISH COVARIANCE FUNCTION)

Figure 15. (continued)

METHOD	STRIP 1 X	STRIP 1 Y	STRIP 1 XY	STRIP 2 X	STRIP 2 Y	STRIP 2 XY	STRIP 3 X	STRIP 3 Y	STRIP 3 XY	STRIP 4 X	STRIP 4 Y	STRIP 4 XY
COL. 1 SEC.	1.57	2.03	1.80	2.70	2.19	2.45	7.33	9.66	8.58	4.10	4.24	3.90
" 2 SEC.	1.51	1.68	1.59	2.57	1.82	2.19	3.69	5.17	4.49	4.23	3.76	3.34
" 3 SEC.	1.42	1.36	1.39	2.70	1.37	2.04	2.89	3.08	2.99	4.16	4.01	3.63
P.POLY 1 SEC.	1.58	2.01	1.79	2.68	2.38	2.53	7.33	8.71	8.05	4.09	4.32	4.21
2 SEC.	1.51	1.69	1.60	2.57	2.18	2.37	3.66	4.74	4.24	4.18	3.16	3.71
3 SEC.	1.42	1.37	1.40	2.71	1.36	2.03	2.89	3.15	3.02	3.33	[illegible]	3.49
W. MEAN	1.56	1.23	1.41	3.27	1.52	2.55	3.05	4.44	3.81	3.75	2.91	3.36
M. AVG.	1.32	2.04	1.72	2.74	1.95	2.38	2.62	3.91	3.33	5.33	3.58	4.54
MESH. LINEAR	1.35	2.26	1.86	2.50	2.42	2.46	4.35	4.82	4.59	4.23	7.55	6.18
G. MARKOV, 1ST	1.18	1.44	1.32	2.05	2.33	2.20	2.43	2.80	2.62	3.66	3.77	3.72
	H=1500M, 0.006 RAD 1550 LINES 30 CONT PTS 60 CHK PTS			H=1500M 0.006 RAD 1400 LINES 23 CONT PTS 9 CHK PTS			H=900M, 0.006 RAD 1970 LINES 36 CONT PTS 35 CHK PTS			H=900M, 0.006 RAD 2700 LINES 26 CONT PTS 25 CHK PTS		

Figure 16. Single Coverage Data (E/M), Check Point RMSE (Pixels)

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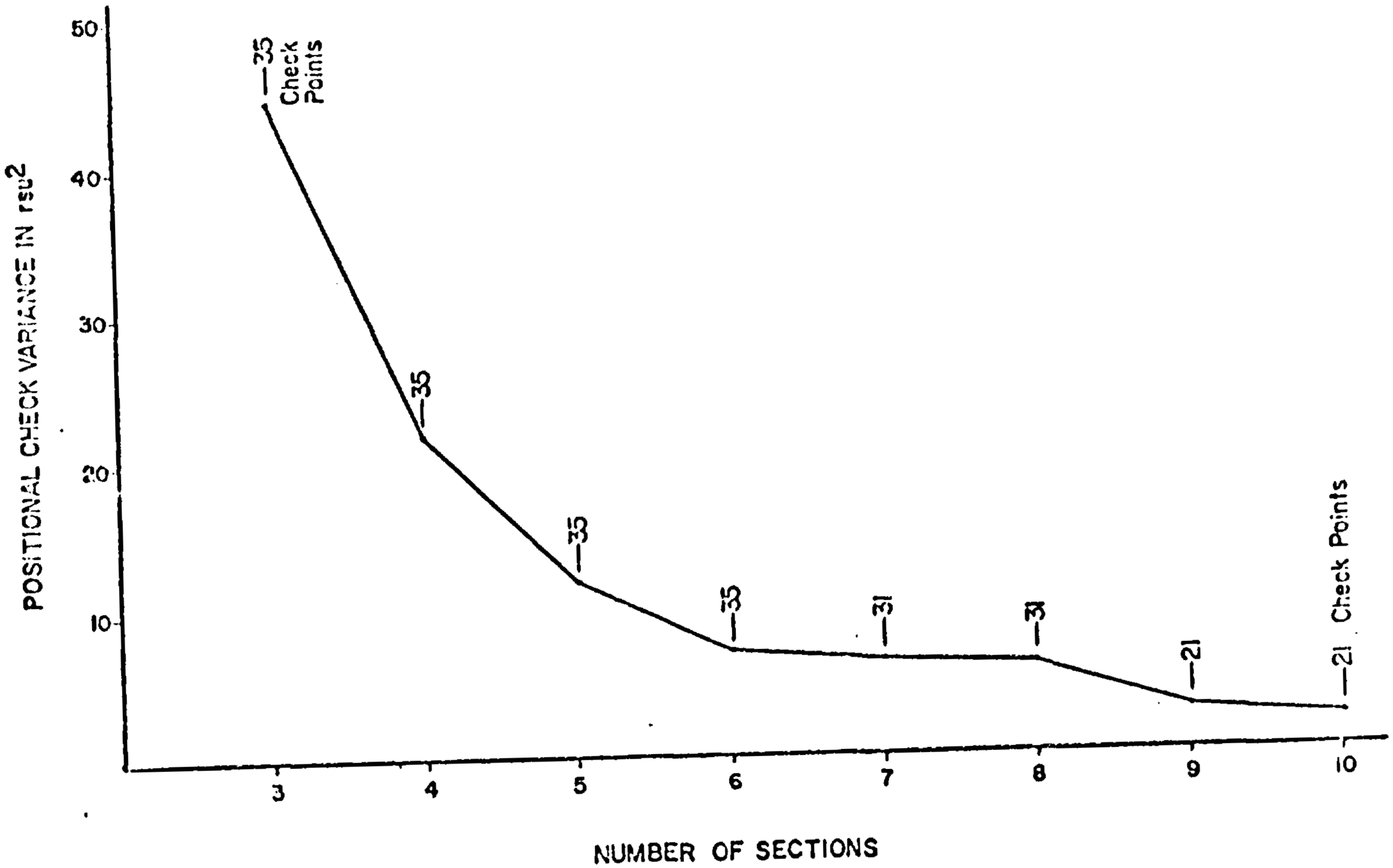

Figure 17. Positional Check Variance Vs. Number of Sections (Piecewise Polynomial Case P_2 Applied to Flight Penn 1.)

STRIP	1			2			3			4		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
1	24.4	31.6	-	25.0	17.7	-	21.6	13.1	-	16.1	12.9	-
2	16.2	24.2	-	16.6	19.4	-	14.4	13.3	-	14.3	11.4	-
3	16.1	23.6	-	11.6	24.5	-	10.0	24.0	-	9.7	23.9	-
POOLED	19.9	27.3	-	19.4	20.5	-	16.73	17.4	-	13.9	16.9	-
1 & 2	20.1	31.0	55.8	21.0	17.7	53.4	17.9	12.5	36.2	14.3	12.5	27.4
2 & 3	16.8	29.3	92.0	11.8	25.2	81.2	10.6	20.0	66.1	9.9	19.8	64.2
POOLED	18.7	30.3	77.2	17.5	21.3	67.1	15.1	16.2	54.2	12.6	16.1	50.4
1,2,3	18.6	29.2	69.2	17.5	18.5	53.5	15.2	13.7	36.4	11.9	14.9	37.5

CONTROL POINTS 44 X,Y 44 Z

CHECK POINTS 53 X,Y 25 Z

H = 3050 M, IFOV = 0.0025 RAD, 1450 LINES EACH

Figure 18. Single and Multiple Coverage Data (Mc/M), Checkpoint Root Mean Square Error (M), Number of Sections

NUMBER OF RAYS

NUMBER OF STRIPS	1		2			3		
	X	Y	X	Y	Z	X	Y	Z
1	16.7	17.4	-	-	-	-	-	-
2	17.3	16.5	11.5	15.8	54.2	-	-	-
3	18.8	14.4	10.3	12.8	41.3	8.9	11.5	27.3

Figure 19. Check Point Root Mean Square Error For Single and Multiple Ray Points