14th Congress of the International Society for Photogrammetry
Hamburg 1980
Presented Paper for Commission III, Working Group 1

DIGITAL DIFFERENTIAL RECTIFICATION OF AIR-BORNE MSS DATA FOR GEOTHERMAL MAPPING

By

Mitsuru Nasu

Kohei Shimamoto

Hiroaki Kano

Masataka Fuchimoto

Asia Air Survey Company, LTD.
Tokyo, Japan

ABSTRACT

An analytical positioning system for scanner remote sensing imagery using a DTM for relief information has been developed. The fundamental geometric model in the system is a collinearity condition of scanner data. The system is presently being used practically--mainly for geothermal mapping of mountainous areas. Accuracy studies of the analytical positioning system have been carried out with experimental as well as practical MSS strip data. The test results show an accuracy of about 3 pixels in standard deviation of residual errors after exterior orientation of MSS strips. Conformity of the orientation polynomial model has been checked using the experimental MSS strips. The results indicate that uncompensated pitching and/or aircraft ground speed change are primary sources of the strip deformation. Adjustment using square sections MSS strips as a unit is most practical for better fitting of lower degree orientation polynomial models. Non-linear image distortion along scan line, which disturbs the conformity of the collinearity model was observed in the film printed MSS data at the ground processing station. Comparative study of the film printed data and the direct digital conversion data indicated the fact that the non-linear image distortion was introduced by the film printer, probably in the process of the scan angle correction. The residual errors in the exterior orientation were reduced substantially by correcting such non-linear image distortion. Preparation of DTM data still remains the most time consuming and tedious work in the digital differential rectification system. Further study and development are required in this field. Since relief information is given by DTM in this system, further utilization of the DTM related information is expected to produce more advanced processing of the MSS remote sensing data.

1. INTRODUCTION

Geometrical aspects of remote sensing data, especially of scanner data are fundamental and primitive in remote sensing data analyses and operation. However, not much attention has been paid to this problem until recently when more operational aspects and uses of remote sensing have begun to be emphasized. Such needs became clearer when repetitive coverage and/or multitemporal remote sensing started to be used for monitoring purposes. Accuracy requirements also increased in time and precise positioning of remote sensing data were needed.

In Asia Air Survey Company, a Japan-made thermal scanner, IRA-301 manufactured by Fujitsu Co., LTD., was first introduced in July 1972, followed by a Deadalous DS-1250 MSS in December 1974. Numerous operational and semi-operational remote sensing activities have been performed in various fields of applications since 1972. Aerial remote sensing studies of geothermal resources and volcanic activities are examples of such operational application fields. In the beginning, analogue analysis of the data, i.e. density slicing of thermal imagery on a Color Data System (CDS 1200) with color display, was commonly performed and the results were manually transferred onto base maps. Digital treatment of the scanner data was then started when a drum scanner photo microdensitometer and later a direct digital data conversion capability from a FM tape were introduced into the data analysis system, while requirements for stricter positioning of scanner data increased.
A digital rectification system of air-borne scanner data combined with digital terrain model analyses was developed to meet such requirements. The system has been in operation for more than two years. This paper reports on the system and the results of accuracy analyses on experimental and practical bases. An example of the digital differential rectification is also given in the paper.

2. DIGITAL RECTIFICATION SYSTEM

2.1 SCANNER DATA AND ITS PROCESSING SYSTEM

Deadalous DS-1250 MSS is a normal scanning type MSS and records the data on a FM tape. Photo-like imagery is produced on 120 mm film in a DS-1850 ground data processing station from the FM data. Geometrical scan angle correction is made in a analogue/digital mode in the DS-1850 processor. The film recorded data, which is produced from the original FM data taken with a very high overlapping mode (usually 80 scan lines/sec.), can be used conveniently for overall evaluation of the data and for easy identification of points to be measured. When it is necessary, the density of the film data can be measured and stored on CCT utilizing a drum scanner photo microdensitometer. The original FM data can also be directly converted to CCT form through an analogue-to-digital converter, that is an ASCOT-100 connected to an Image-100 image processing system. The entire flow chart of the data processing system is shown in Fig. 1.

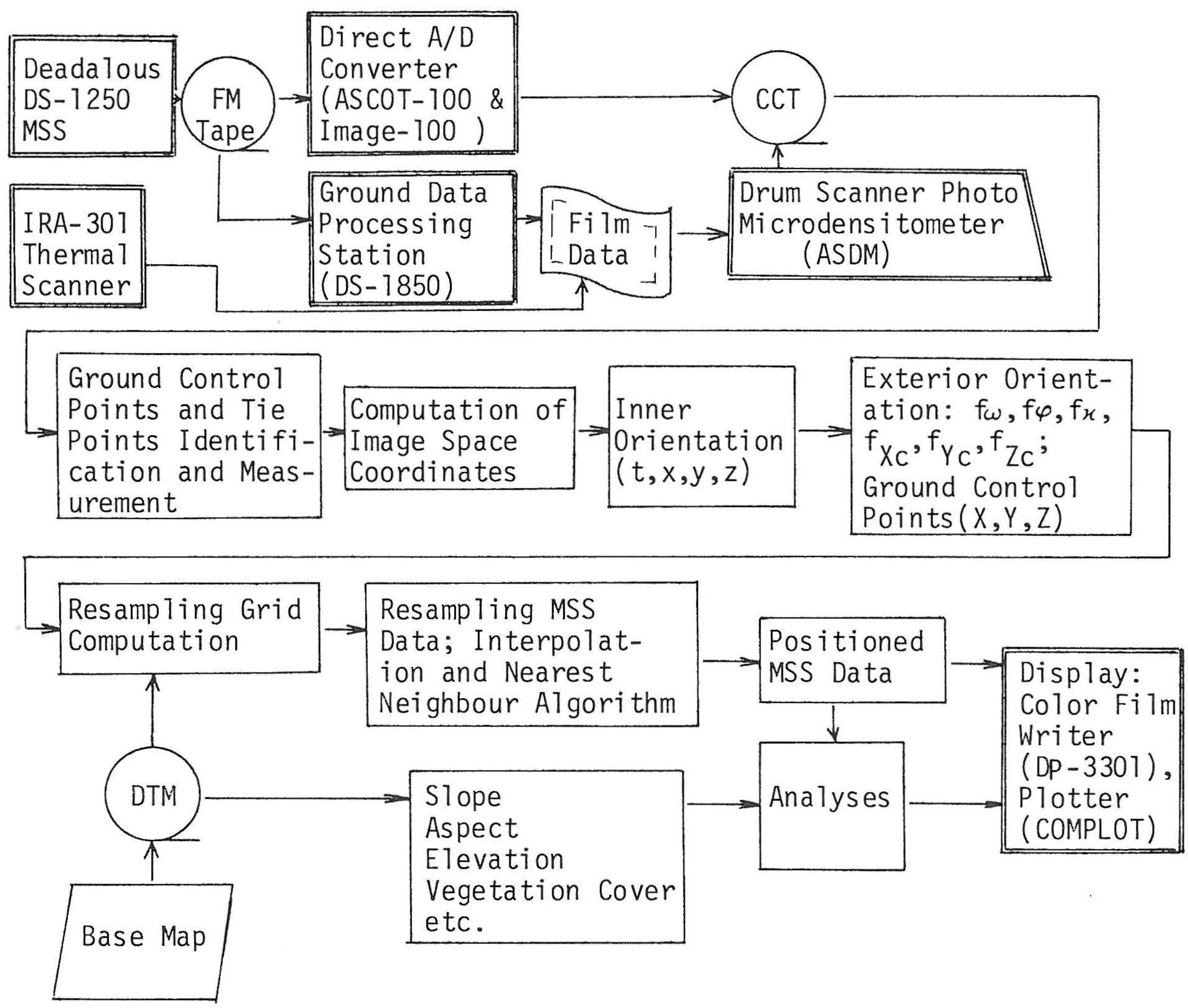


Fig. 1. Data Processing System for Digital Differential Rectification of MSS Remote Sensing Data.

2.2 MATHEMATICAL MODEL FOR SCANNER DATA

A basic mathematical model employed in digital differential rectification is the so-called collinearity condition model which may be written as follows:

$$Fx_j = x_j - z_j \frac{A\,(X_j - Xc) + B\,(Y_j - Yc) + C\,(Z_j - Zc)}{D(X_j - Xc) + E\,(Y_j - Yc) + F\,(Z_j - Zc)} = 0$$

$$Fy_j = y_j - z_j \frac{A'(X_j - Xc) + B'(Y_j - Yc) + C'(Z_j - Zc)}{D(X_j - Xc) + E\,(Y_j - Yc) + F\,(Z_j - Zc)} = 0 \qquad \ldots.(1)$$

where x_j, y_j, z_j are image space coordinates of point j; X_j, Y_j, Z_j the object space coordinates; A, B, C, ..., F the coefficients of orientation matrix in which the exterior orientation parameters are ω, φ, and κ; and Xc, Yc, Zc the positional exterior orientation parameters of scanner. The exterior orientation parameters, ω, φ, κ, Xc, Yc, and Zc of an image point can be approximated by utilizing polynomial equations in which the time space coordinate is a parameter ((1), (2)). The polynomial equations may have the functional form as follows:

$$\begin{aligned}
\omega &= \omega_o p_o(t) + \omega_1 p_1(t) + \ldots.. + \omega_n p_n(t)\\
\varphi &= \varphi_o p_o(t) + \varphi_1 p_1(t) + \ldots.. + \varphi_n p_n(t)\\
\kappa &= \kappa_o p_o(t) + \kappa_1 p_1(t) + \ldots.. + \kappa_n p_n(t)\\
Xc &= X\overset{o}{c} p_o(t) + X\overset{1}{c} p_1(t) + \ldots.. + X\overset{n}{c} p_n(t)\\
Yc &= Y\overset{o}{c} p_o(t) + Y\overset{1}{c} p_1(t) + \ldots.. + Y\overset{n}{c} p_n(t)\\
Zc &= Z\overset{o}{c} p_o(t) + Z\overset{1}{c} p_1(t) + \ldots.. + Z\overset{n}{c} p_n(t)
\end{aligned} \qquad \ldots\ldots(2)$$

where t is the time space coordinate; p_o, p_1, ..., p_n the coefficients of the orientation polynomials; and ω_o, ω_1, ..., $Z\overset{n}{c}$ the unknown orientation parameters to be estimated by the adjustment computation. Assuming smooth variation of the exterior orientation parameters, any kind of polynomials can be used to approximate the behavior of the orientation parameters during the remote sensing operation. Harmonic polynomials, orthogonal polynomials and ordinary polynomials were tested as optional ones. The ordinary polynomials are currently used in the system under study althrough other models may have advantageous points.

2.3 INNER ORIENTATION

The inner orientation of the scanner imagery consists of: (1) the reduction of measured image point coordinates to an image space system;

(2) the reduction of time coordinates; (3) determination of an appropriate projection distance. Image space coordinates, (t_{ij}, x_{ij}, y_{ij}, and z_{ij}), of point P, for which line and pixel coordinates are (i,j), may be written as follows:

$$\begin{aligned} t_{ij} &= (i-1)\cdot t_s + j\cdot t_r \\ x_{ij} &= 0 \\ y_{ij} &= C\cdot \tan(\gamma\cdot(j-N/2)) \\ z_{ij} &= -C \end{aligned} \qquad \ldots\ldots (3)$$

where C is an imaginary projection distance; γ the angle between adjacent scan pixels; N the total number of pixels per scan line, i.e. j= 1, 2,.., N; t_s the time period for one line scanning; and t_r the time for an instantaneous aperture (See Fig. 2). The time space coordinate is determined in order to correlate independently defined three dimensional image space coordinate systems for individual image points. The projection distance C can be set at an arbitrary number assuming a projection plane. When film printed imagery, in which scan angle correction already has been applied, is available, the image space coordinates can be directly measured on the film imagery. And, the projection distance is assigned to the data so as to hold the specified scan geometry.

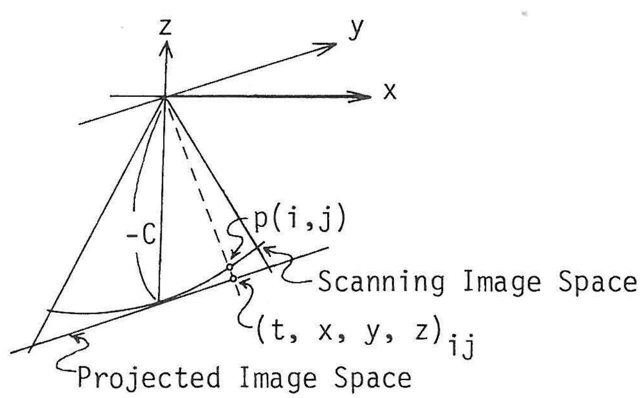


Fig. 2. Scanner's Inner Geometry.

2.4 EXTERIOR ORIENTATION

Based on the collinearity condition model and orientation polynomial models, a computer program has been developed in order to find the scanner's exterior orientation parameters, (ω, φ, κ, Xc, Yc, and Zc), through the least squares adjustment scheme. The computer program employs the general least squares adjustment method. Weight procedure for the observation equations is formed in such a way that any weight is assignable to the observation data (image point coordinates, object point coordinates, and exterior orientation parameters) and arbitrary constraints can be enforced for the adjustment parameters. Employing these functions of the program, appropriate orientation parameters for the exterior orientation can be selected based on the geometric strength of the subjected MSS strip, which is governed by the scanning mode and ground control point distribution. For the normal scanner, pitching (φ) is indeterminable, therefore it should be given as an appropriate value, i.e. $\varphi=0$.

2.5 DIGITAL TERRAIN MODEL

The plan position of the image point is found by making the correction for the relief displacement. In the digital mapping system under study, digital terrain model (DTM) is formed for relief displacement correction. Knowing the exterior orientation parameters of the MSS strip, the mapped image coordinates of the DTM points, which are located coherently in a grid-like configuration, can be determined by the inverse transformation of the collinearity equation (Equation 1). The amount of data required for construction of a DTM increases in proportion to the accuracy requirement for the terrain model. Furthermore, as Makarovic (4) suggested, accuracy of the reconstructed terrain surface from the sample points seems to rely on the sampling density rather than on the interpolation method used. Thus, selection of an optimum sampling point density which fulfills both the accuracy and storage requirements is important. However, it seems no definite and practical algorithm is presently available. Sampling interval is therefore determined from the practical view point considering available base map and terrain undulation of the mapping areas. Typical sampling interval for practical uses is 50 to 100 m depending on the base map scale and scanner's ground altitude.

2.6 COMPUTATION OF RESAMPLING GRIDS

With the knowledge of the exterior orientation parameters of the MSS strip, the mapped image coordinates of the DTM grid points can be determined by the inverse transformation of the collinearity equations. The equations for the inverse transformation are non-linear and need to be linearized for the iterative solution. Good initial estimates of the image and time coordinates are required to reduce computation time. Fairly good initial estimates of these coordinates can be obtained from the given exterior orientation polynomials and object point coordinates of the sample point. The approximate value of the time coordinate t^{oo} can be obtained as follows:

$$t^{oo} = (X_c^1 \cdot X_p - X_c^o \cdot X_c^1 - Y_c^o \cdot Y_c^1 + Y_c^1 \cdot Y_p)/(X_c^1 \cdot X_c^1 + Y_c^1 \cdot Y_c^1) \quad \ldots\ldots (4)$$

where X_c^o, X_c^1, Y_c^o, and Y_c^1 are coefficients of the orientation polynomials; and X_p, Y_p the object point coordinates of sample point P. When yawing of the MSS strip is large, the initial approximate value t^{oo} should be corrected in terms of the yawing to yield better approximation. Using the previously defined notations as well as that given in Fig. 3, correction Δt for t^{oo} can be obtained as follows:

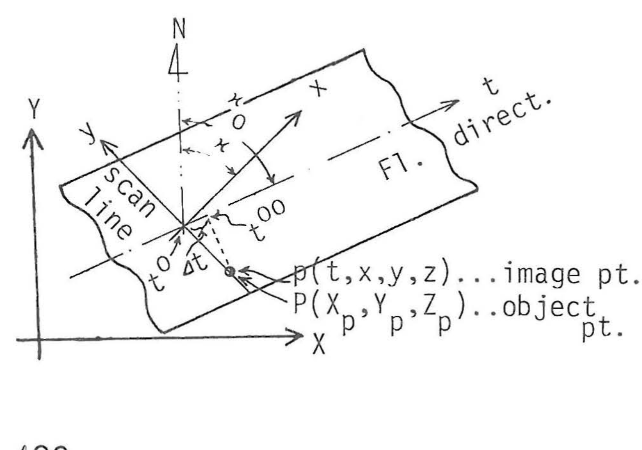
$$\Delta t = \frac{\Delta L}{\Delta D}, \text{ and}$$
$$t^o = t^{oo} - \Delta t \quad \ldots\ldots (5)$$

where $\Delta L = L \cdot \tan\Delta\kappa$; $\Delta D = (X_c^1 \cdot X_c^1 + Y_c^1 \cdot Y_c^1)^{1/2}$; $L = ((X_p - Xc)^2 + (Y_p - Yc)^2)^{1/2}$; $\tan\Delta\kappa = (\tan\kappa_o - \tan\kappa)/(1 - \tan\kappa_o \cdot \tan\kappa)$; $\tan\kappa_o = Y_c^1/X_c^1$; and finally $Xc = X_c^o + X_c^1 \cdot t^{oo}$ and $Yc = Y_c^o + Y_c^1 \cdot t^{oo}$. Then, initial approximation of y coordinate y^o is obtained as follows:

$$y^o = -z \cdot \frac{-\sin\kappa \cdot (X_p - Xc) + \cos\kappa \cdot (Y_p - Yc) + \omega \cdot (Z_p - Zc)}{\omega \cdot \sin\kappa \cdot (X_p - Xc) - \omega\cos\kappa \cdot (Y_p - Yc) + (Z_p - Zc)} \quad \ldots\ldots (5)$$

where orientation parameters κ, Xc, Yc, and Zc are evaluated substituting the time coordinate t^o into the orientation polynomials; projection distance z is a constant. Starting from these initial approximates, iterative computation is required to solve the collinearity condition equation for the image space coordinates of t and y. It should be noted that x coordinate is zero for all pixels on a scan line in the case of a single line scanner. The computed time and y coordinates are further transformed into the line and pixel coordinate system of the MSS strip.

Fig. 3. Geometric Configurations of Initial Approximation of Time Coordinate t^o for Inverse Solution of Resampling Grid Points.



2.7 INTERPOLATION AND RESAMPLING OF MSS DATA

With the line and pixel coordinates of the grid-like sample points which are previously obtained, finer resampling position of the designated cell is computed using an ordinary affine transformation with a cross term. Resampling of the digital MSS data is made by applying the so-called nearest neighbor algorithm. The final product of the digital rectification system is a uniformly spaced matrix of pixels of the digital MSS data.

2.8 ANALYSIS AND DISPLAY

The geometrically corrected MSS data are subjected to analysis and evaluation in various disciplines. So far, the developed digital rectification system has mostly been applied to geothermal mapping such as volcano observations and geothermal energy exploitations in mountainous areas. In such cases, the digital count of the MSS thermal data is converted to the corresponding surface temperature of the ground by employing the internal and external references (thermal control points). Radiometric corrections are also applied in some cases in the data processing. The surface temperature map is usually displayed in a color coded form using a drum type film writer. Furthermore, geothermal data are analysed in terms of distribution, pattern, temperature, etc. for specific purposes. In case of volcano observation, the distribution pattern of the surface temperature is most important, while exploitation of the geothermal reservoir is the primary purpose of the geothermal mapping.

3. ACCURACY ANALYSES

Governing factors of the mapping accuracy in the digital differential rectification system may be pointed out as follows:

1) Conformity of the collinearity condition model,
2) Conformity of the orientation polynomial model employed,
3) Accuracy of point identification and image coordinates measurements,
4) Accuracy of inner and exterior orientation, and
5) Accuracy of relief information given by DTM.

Among these factors, 1) and 2) above are fundamental problems in geometric aspects of remote sensing data. While 3), 4) and 5) above are operational problems in the system. Considering these factors, accuracy analyses of the mapping system under study have been made utilizing experimental MSS strips taken over an undurating terrain where many natural and man-made objects can be located as ground control points. The experimental results were further verified by the practical application of the digital mapping system.

3.1 EXPERIMENTAL MSS DATA

Two 6 km-long MSS strips were acquired using a Deadalous DS-1250 MSS from the ground altitude of 1,100 m over a moderately undulating test area during day time. The tape recorded MSS data was processed in a Deadalous DS-1850 ground processing station. The outputs from the processor were film-recorded thermal IR imagery. Well-defined natural features and objects whose map coordinates and elevations could be determined on 1:2,000 topographic maps were selected as ground control points for the exterior orientation of the MSS strips. Image coordinates of these points were directly measured on the film data using a digitizing table. The smallest reading unit of the coordinates was 10 micrometers. The measured image coordinates were reduced for the inner orientation and the scanner's image space coordinates were defined for each point.

3.2 SCAN STRIP DEFORMATION

Conformity of the collinearity condition and orientation polynomial models can be evaluated through the analyses of the residual errors in the adjustment computation of the exterior orientation. Fig. 4 and Table 1 show the results of the exterior orientation made for the experimental strips. Fig. 4 shows residual profiles in the strip direction. Configuration of ground control points used are also shown for Strips 1 and 2 in Fig. 4. AS shown in Table 1, configurations of these strips are 6 km in strip length and 1.8 km in scan width, which corresponds to 500 mm x 122 mm MSS film strip. Among coefficients of the exterior orientation polynomials, the parameters recovered were constant terms of yawing (κ), and constant and linear terms of the positional parameters of MSS (X_c^0, X_c^1, Y_c^0, Y_c^1, Z_c^0, and Z_c^1), which are shown in the form of 0-0-1-2-2-2 for the parameters of ω-φ-κ-Xc-Yc-Zc. All other terms were fixed at zero value by assigning large weights to the observation equations. Results of the exterior orientation showed that the standard deviations of the residuals were 6.8 pixels (d.f.=93) and 6.2 pixels (d.f.=89) for Strips 1 and 2, respectively (See Table 1). The residual profiles in Fig. 4 clearly indicate that the strip deformations are in third or higher order in nature. This trend is distinct in x image coordinate, i.e. in the strip direction. Combined effect of un-

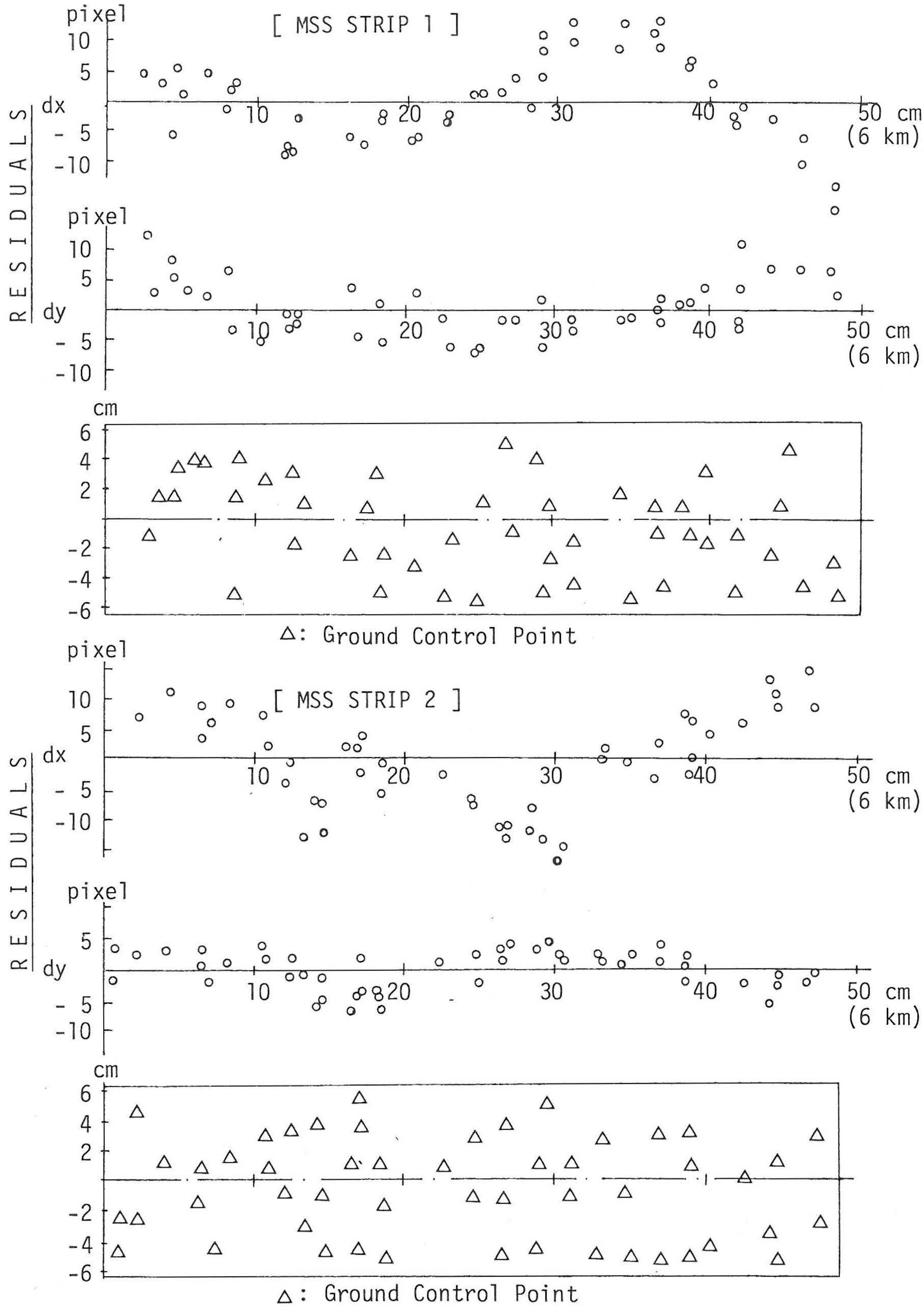


Fig. 4. Residual Profiles along the Strip Direction after Exterior Orientation of MSS Strips (Experimental Data, Day Time Imagery).

Table 1. Residual Errors of Exterior Orientation (Experimental Strips, Day Time Imagery).

Strip Name	Strip Length km^2	No. of GCP	No. of Parameters in Orientation Polynomials for ω- φ- κ-Xc-Yc-Zc*	No. of Unknowns	Residual Errors (St. Dev.),Pixels** Sxy (No Correct.)***	d.f.	Sxy (With Correct.)***	d.f.
1	1.8 x 6	50	0--0--1--2--2--2	7	6.8	93	--	--
Sub-section 1-1	1.8 x 2	38	0--0--1--2--2--2	7	4.8	69	3.7	69
			0--0--1--3--3--3	10	--	--	3.7	66
Sub-section 1-2	1.8 x 2	38	0--0--1--2--2--2	7	4.2	69	3.4	69
			0--0--1--3--3--3	10	--	--	3.5	66
Sub-section 1-3	1.8 x 2	44	0--0--1--2--2--2	7	4.2	81	2.3	81
			0--0--1--3--3--3	10	--	--	2.3	78
2	1.8 x 6	48	0--0--1--2--2--2	7	6.2	89	--	--
Sub-section 2-1	1.8 x 2	39	0--0--1--2--2--2	7	5.0	71	4.8	71
			0--0--1--3--3--3	10	--	--	3.3	68
Sub-section 2-2	1.8 x 2	45	0--0--1--2--2--2	7	3.7	83	3.1	83
			0--0--1--3--3--3	10	--	--	3.1	80
Sub-section 2-3	1.8 x 2	47	0--0--1--2--2--2	7	4.2	87	3.3	87
			0--0--1--3--3--3	10	--	--	3.2	84

* Coefficients of Orientation Polynomials:
0 term(s) ..... No recovery
1 " " ..... Constant term only
2 " " ..... Constant and first degree terms
3 " " ..... Constant, first, and second degree terms.

** 1 pixel = 200 micrometers on 120 mm-wide MSS film strip.

***Correction for non-linear image distortion along scan line.

compensated pitching and ground speed variation of the scanner may be the primary source of such strip deformation, and larger deformation can result in day-time MSS data due to atmospheric turbulence. On the other hand, rolling compensation can be made in the Deadalous MSS system by employing a rate gyro within a total $\pm$ 10 degree correction range. Although the strip deformation in these long MSS strips is quite large, mapping with shorter strip length is common in practice. In order to draw more practical figures of the strip deformation, the experimental strips were divided into three sections. Six 2 km-long and 1.8 km-wide MSS strips were obtained in this manner, and additional ground control points were selected so that each sub-section included 40 to 50 ground control points to evaluate geometric fidelity of the data. As shown in Table 1, residual errors of 4.4 pixels in average were obtained for these sub-sections (See "Residual Errors, Sxy(No Correction)" in Table 1). These residuals are slightly larger than that summarized by Konecny (1).

3.3 DISTORTION ALONG SCAN LINE

Analysis and correction of image distortion along scan line are needed to improve the conformity of the collinearity condition model. This kind of distortion may be analysed from the residual errors in the adjustment computation of short strips. Fig. 5 shows the residual errors in y coordinate plotted along scan line, and asymmetric image distortion can be observed along scan direction. To investigate the primary source of such systematic image distortion, direct digital conversion of FM data was performed, and photo-like imagery was produced from the digital data after scan angle correction in the film writer. Comparison of corresponding image points on the ground station's film data and the film data from direct digital data clearly showed the fact that such distortion was introduced in the ground data processing station. The distortion curve which was obtained in the analysis is represented by a solid line in Fig. 5. Reduction of such non-linear image distortion substantially improved the conformity of the collinearity condition model and reduced the residual errors about 25 %, from 4.4 pixels to 3.4 pixels in the average standard deviation. The results of distortion corrected data are shown under the title of "Sxy(With Correction)" in Table 1. Improvement of the fitness by the second order orientation polynomials was not remarkable excepting sub-section 2-1 in which the residuals were reduced from 4.8 pixels to 3.3 pixels. Residuals of 3.2 pixels in average were obtained for the experimental data adjusted by the second order orientation polynomials of 0-0-1-3-3-3.

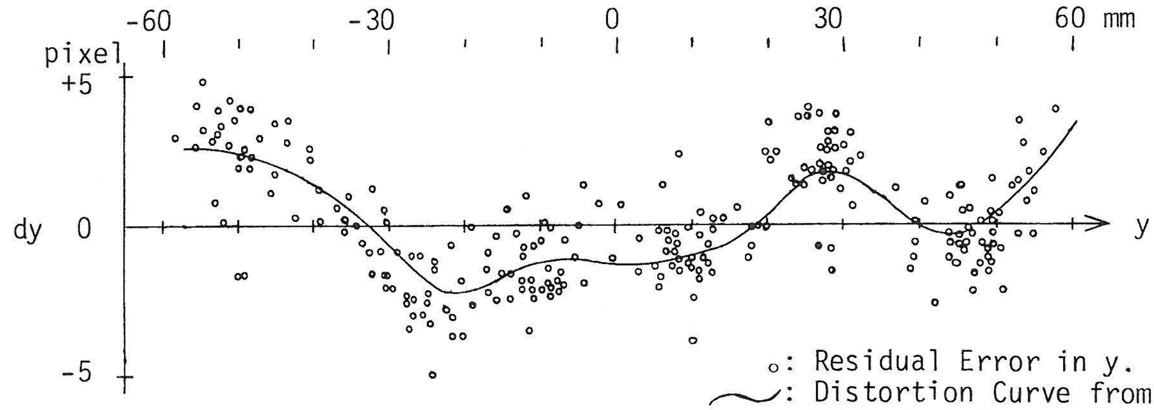


Fig. 5. Image Distortion Along Scan Line.

3.4 PRACTICAL RESULTS

Table 2 shows some results of exterior orientation obtained in operational remote sensing projects. All of these data were night time imagery. Therefore, better fitting of the orientation polynomials were expected. However, the number of well-defined ground control points were limited in mountainous areas. Typical natural objects used for ground control points were intersections and corners of roads, trails, rivers, agricultural fields, deforested open areas, houses, etc. As shown in Table 2, residuals range from 2 to 4 pixels with an average standard deviation of 3.4 pixels. With the present system, this magnitude of residual error is a typical accuracy figure. The final positioning accuracy is primarily governed by exterior orientation. However, through study and experience it has been found that the establishment of well-defined ground control points is essential for further improvement of the exterior orientation. To solve this problem, a special panel using aluminum foil has been tested and found to be very successful in practical thermal mapping projects.

4. DIGITAL DIFFERENTIAL RECTIFICATION RESULT

An example of the digital differential rectification result is shown in this section. The test data were taken over Mt. Mihara, a famous volcanic mountain located on Oshima Island, 100 km south of Tokyo, using a Deadalous DS-1250 MSS from a ground altitude of 1300 m above the crater. Thermal channel data recorded on a FM tape was directly converted into digital form and recorded on a CCT by ASCOT-100 and Image-100. An original black and white thermal imagery written by a DP-3301 film writer with aperture size of 100 micrometers is shown in Fig. 6. A DTM was prepared from 1:2,500 base map with the mesh interval of 25 m for 1.3 x 1.3 km^2 area, in which topographic elevation ranges from 440 to 750 m. A perspective view of the DTM is shown in Fig. 8, and distorted DTM meshes in the image space are shown in Fig. 6. Only meshes of 100 m interval are shown in Fig. 6. Within the 25 x 25 m^2 unit mesh, 10 x 10 finer meshes were automatically generated and the original digital data was resampled at the denser mesh points using the nearest neighbour algorithm. The final result of the digital differential rectification is shown in a photo-like imagery in Fig. 7. A color coded thermal distribution map is one of the products of the thermal mapping project.

Table 2. Residual Errors of Exterior Orientation (Practical Data, Night Time Imagery)

MSS Strip	Strip Length km^2	No. of GCP	Residual Errors(St. Dev.), Pixels		Remarks
			S_{xy}	d.f.	
1	4x4.5	33	4.1	59	Volcanic mountain; Natural objects as GCP; Base map scale 1:10,000; Orientation polynomials: 0-0-1-2-2-2.
2	4x5.3	31	3.4	55	
3	4x5.0	38	3.7	69	
4	4x4.9	28	2.9	49	
5	4x4.8	25	3.3	43	
6	4x6.2	25	4.3	43	
7	4x7.2	37	2.8	67	
8	3x2.1	12	1.8	18	
9	3.5x2.5	16	3.8	25	

Fig. 6. Original Thermal Scanner Imagery (Mt. Mihara Volcano), Mesh Interval 100 m.

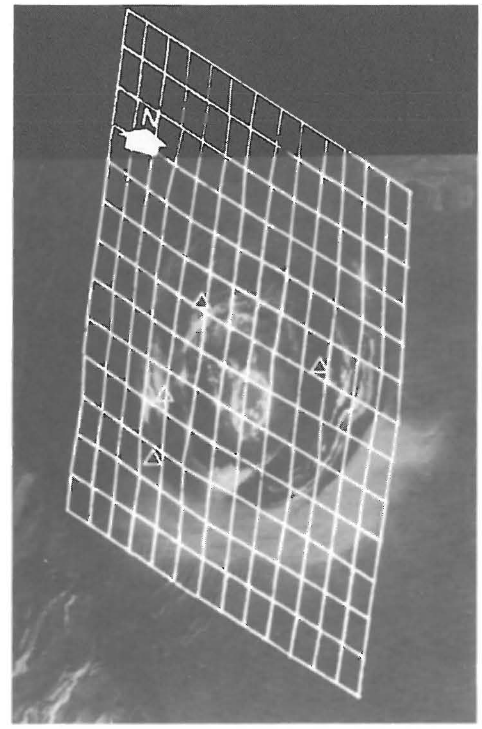


Fig. 7. Result of Digital Differential Rectification of Thermal Scanner Imagery, Mesh Interval 100 m.

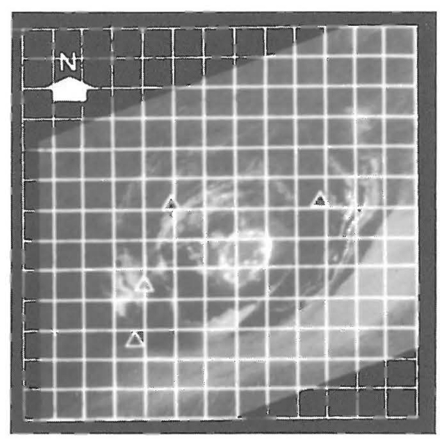
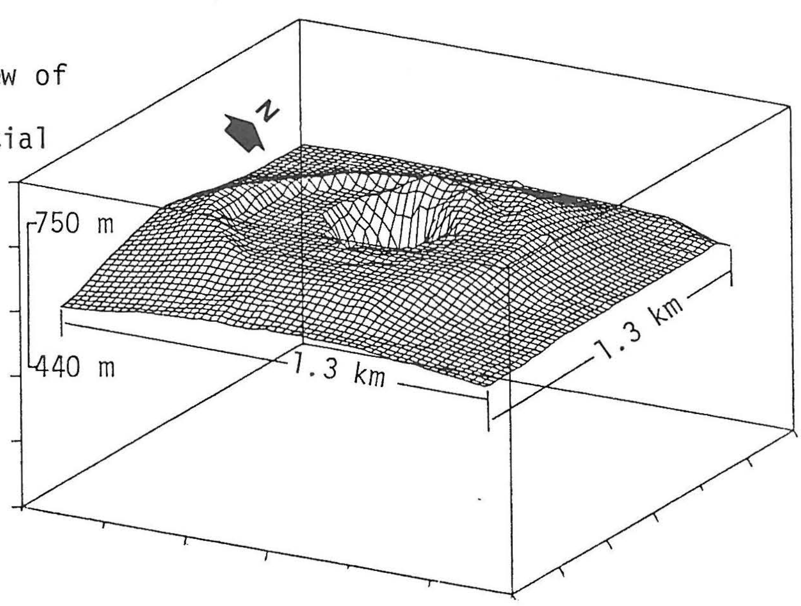


Fig. 8. A Perspective View of DTM used for the Digital Differential Rectification.



5. S U M M A R Y

The mathematical background and test results of the digital differential rectification system for air-borne MSS data have been discussed in this paper. The newly developed positioning system seems quite feasible. So far, it has been applied most effectively to geothermal mapping in mountainous areas. Practical test results showed that the accuracy of exterior orientation, indicated by the residual errors at the ground control points, was about 3 pixels in standard deviation. Conformity of the orientation polynomial model was analyzed and the results showed that primary sources of higher order strip deformation were pitching and/or ground speed variation of the aircraft. However, simple linear orientation polynomials are, in general, sufficient to obtain sufficient accuracy of 3 to 4 pixels for square section MSS strips. The use of the simplest possible orientation polynomials for the sub-section of a strip yields the most reliable results for mapping.

Non-linear image distortion along the scan line was found in the MSS film data processed in a ground station. Correction of such non-linear distortion reduced the residual errors in the exterior orientation by 25 %. The establishment of well-defined ground control points is essential to obtain reliable mapping results, since the final positioning accuracy is primarily governed by the exterior orientation of the MSS strip. Special panels made of aluminum foil have been used very successfully in practical thermal mapping projects.

Preparation of DTM data still remains the most time consuming and tedious work in the digital mapping system, although the size of the DTM is relatively small in most cases. Thus, further study and development are required in this field. Terrain relief information is already a part of this MSS data processing system. Further utilization of the DTM data is expected to produce more advanced data processing system of the MSS remote sensing data.

R E F E R E N C E S

(1) KONECNY, G. "Mathematical Models and Procedures for the Geometric Restitution of Remote Sensing Imagery." Invited paper for Commission III, XIII Congress of the International Society for Photogrammetry, Helsinki, Finland, July 1976.

(2) BAKER, J.R., and MIKHAIL, E.M. "Geometric Analysis and Restitution of Digital Multispectral Scanner Data Arrays." LARS Information Note 052875, Purdue University, West Lafayette, IND., 1975.

(3) MORI, Chuji; OKAMOTO, Atsushi; and HATTORI, Susumu. "Investigation of the Geometric Accuracies of Aircraft MSS Data with the Parametric Method." Journal of Japan Society of Photogrammetry, Vol. 18, No. 2, 1979.

(4) MAKAROVIC, B. "Information Transfer in Reconstruction of Data from Sampled Points." Photogrammetria, XXVIII, No.4, 1972, pp.111-30.

(5) NASU, Mitsuru. "Analytical Positioning of Remote Sensing Data for Digital Mapping." Journal of Japan Society of Photogrammetry, Vol. 15, No.2, 1976.

(6) NASU, Mitsuru. "Analytical Positioning of Thermal IR Imagery for Monitoring Volcanic Activity." Proceedings of the Twelfth International Symposium of Remote Sensing of Environment, Vol. II, April 1978, pp.1481-87.