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An Analytic Correction Method for Satellite MSS Geometric Distortions

By employing satellite orbit and attitude data and sensor characteristics, a minimum of ground control points is required.

Abstract: *A new analytical method to correct the geometrical distortion in satellite multispectral scanner (MSS), and a production technique for composite color photographic maps from three band corrected images are described. This method is mainly intended to reduce the number of ground control points (GCP) and to provide more precise geometrical correction. Satellite orbit/attitude information and MSS scanning mechanism characteristics are employed sufficiently to make it possible to let the satellite image analytically correspond to topographic maps.*

Landsat MSS images are corrected, using the information stored on computer compatible tapes (CCT), as Scene Image Annotation Tape (SIAT). A precise correction method to reduce geometrical errors was developed, even when the SIAT data involve some measurement errors. A high speed calculation technique to accomplish geometric correction was also implemented.

Experimental results show that two or three GCP's are sufficient to correct the geometrical distortion to within one pixel accuracy and that produced satellite maps are confirmed to coincide with 1:200,000 scale maps. This analytical correction method can be applied to oceanic scenes without any GCP's.

Introduction

A new analytical correction technique was introduced to rectify the geometrical distortions of Landsat MSS images. A theoretically developed geometry of the scanner, the satellite, and the Earth, which simulates the MSS mechanism, models the total geometric distortions in the MSS system. A new method, which uses orbit elements and attitude information of the satellite as well as scanning characteristics, can make a picture element (pixel) of Landsat image correspond to a position on the Earth. Thus, a geometrically corrected image in a certain map projection was produced on film by a cathode-ray tube (CRT) film recorder. An effective correction experiment was accomplished using the Scene Image Annotation Tape (SIAT) data on computer compatible tape (CCT) distributed by EROS Data Center.

Several geometric correction techniques have been reported in the literature on both theoretical and experimental studies. NASA, for example, produced bulk MSS image data with respect to the Space Oblique Mercator (SOM) projection by

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employing an Electron Beam Recorder (EBR).[1] Distortion caused by the satellite attitude was only analyzed and corrected in film production. The SOM projection is not suitable for true scale along a specific meridian or parallel since it was designed for a different purpose.

Bernstein proposed a polynomial distortion model using ground control points (GCP)[2]. A computer program was developed to determine the coefficients of a best-fitting polynomial by the least-square approximation method. He discussed third and fifth order polynomials and their geometric accuracy with respect to the number of GCP's. In this case, GCP's should be identified as uniformly distributed as possible over the Landsat frame to minimize the total distortion error. Here, problems arise as to how to select GCP's and how much their identification procedure should cost. These interfere with the automatic correction system design. Sometimes there are few GCP's in the frame because of cloud cover or marine area.

This paper presents a new geometric correction experiment[3] to attain the limiting correction error in the Landsat MSS image data with the minimum number of GCP's. A mathematically derived technique was employed to model the geometric distortions. For this purpose, nominal values of the satellite attitude and orbit elements do not have sufficient geometric fidelity. More accurate information regarding the satellite attitude and orbit elements can be obtained using the Scene Image Annotation Tape (SIAT) and two or three GCP's. A Landsat frame was processed to have sufficient accuracy with less than one pixel error. A newly developed film recorder was found to be very effective in producing photographic maps.

Mathematical Formulation of Geometrical Distortion

Analytical Model of Geometrical Distortion

In this section, the geometrical configuration of the Earth, a satellite, and its scanner is described. Then the relationship is solved with respect to the direction vector of the observed point, whose origin is at the Earth's center. Finally, the direction vector is expressed using the geocentric coordinate system, with sequential coordinate transformations.

Let r, $\vec{\mathbf{a}}$, $\vec{\mathbf{R}}$ and $\vec{d}$ be the local Earth radius, direction vector of the observed point, radius vector of the spacecraft, and direction cosine of the scanner, respectively (Figure 1). The geometrical configuration is expressed by

$$\frac{\vec{\mathbf{R}} - r\,\vec{\mathbf{a}}}{|\vec{\mathbf{R}} - r\,\vec{\mathbf{a}}|} = -\vec{d}.$$

From this vector equation, direction vector $\vec{\mathbf{a}}$ is given by

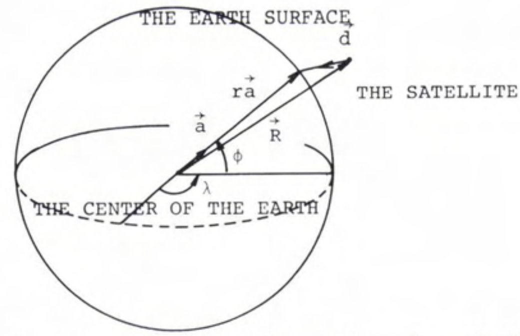

Fig. 1. Configuration of the satellite and the Earth.

$$\vec{\mathbf{a}} = \frac{1}{r}\left[\vec{\mathbf{R}} - \vec{d}\ \left\{(\vec{\mathbf{R}}\cdot\vec{d}) + \sqrt{\mathbf{r}^2 - \mathbf{R}^2 + (\vec{\mathbf{R}}\,\vec{\mathbf{d}})^2}\right\}\right]$$

where one possible root is selected from the quadratic equation. The relation between the direction vector $\vec{a} = (a_x, a_y, a_z)$ and the geodetic coordinates (latitude ϕ, longitude λ) is expressed as follows:

$$\phi = \sin^{-1}(a_z),\ \lambda = \tan^{-1}(a_y/a_x).$$

The Bessel ellipsoid is adopted for the Earth model in Japan. The geoid surface is defined as the mean water level of Tokyo Bay. The local Earth radius is approximately given by

$$r = r_0(0.99832706 + 0.001676 \cos 2\phi^* - 0.00000352 \cos 4\phi^*)$$

where ϕ^* and r_0 are local latitude and the Earth equatorial radius, respectively, and the value of r_0 is 6378.160 km. (This formula can be found in *Scientific Anallen*, edited by the Tokyo Astronomy Institute.)

The orbital coordinate system is defined as follows: its x and z directions are the spacecraft flight direction and the Earth center direction, respectively (Figure 2). The y direction is defined so as to form a right hand system with the x and z direc-

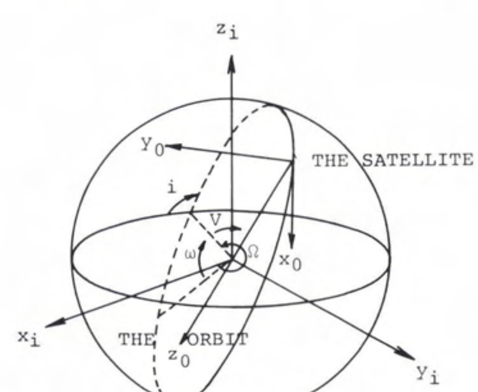

Fig. 2. The inertial and the orbit coordinate systems.

tions. The satellite orbit vector, $\vec{\mathbf{R}}$, is obtained from the spacecraft height, h, and from r as follows:

$$\vec{\mathbf{R}} = \begin{pmatrix} 0 \\ 0 \\ -(r+h) \end{pmatrix}$$

in the orbital coordinate system. The direction cosine, $\vec{d}$, is calculated from the formula

$$\vec{d} = \frac{1}{\sqrt{1 + \tan^2\psi\,(J) + \tan^2\theta\,(I)}} \begin{pmatrix} \tan\psi\,(J) \\ \tan\theta\,(I) \\ 1 \end{pmatrix}$$

where $(\theta(I), \psi(J))$ is a line-of-sight angle of pixel (I, J) in the scanner coordinate system (Figure 3).

The components of the direction cosine, $\vec{d}$, and orbit vector, $\vec{\mathbf{R}}$, are given in the scanner coordinate system and in the orbit coordinate system, respectively. In order to obtain the components of the direction vector, $\vec{\mathbf{a}}$, in the geocentric coordinate system, it is necessary to transform the components of vectors $\vec{\mathbf{d}}$ and $\vec{\mathbf{R}}$ to the geocentric coordinate system.

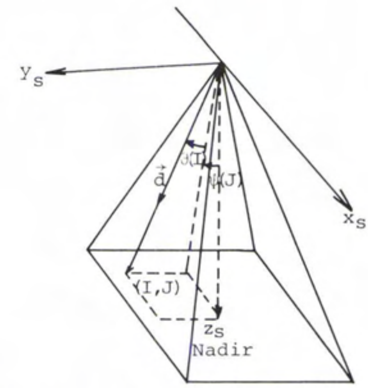

FIG. 3. Direction cosine $\vec{d}$ and line-of-sight angles $(\theta(I), \psi(J))$ for the pixel (I, J).

(2) $\mathbf{T}_o^i$; the transformation from the orbit coordinate system to the inertial coordinate system (Figure 2).

The transformation is given by

$$T_o^i = \begin{pmatrix} -\sin(\omega+V)\cos\Omega - \cos(\omega+V)\cos i\sin\Omega & -\sin i\sin\Omega & -\cos(\omega+V)\cos\Omega + \sin(\omega+V)\cos i\sin\Omega \\ -\sin(\omega+V)\sin\Omega + \cos(\omega+V)\cos i\cos\Omega & \sin i\cos\Omega & -\cos(\omega+V)\sin\Omega - \sin(\omega+V)\cos i\cos\Omega \\ \cos(\omega+V)\sin i & -\cos i & -\sin(\omega+V)\sin i \end{pmatrix}$$

The coordinate transformation is sequentially performed by matrix multiplication as follows:

$$\mathbf{T}_s^g = T_i^g\, T_o^i\, T_b^o\, T_s^b$$

where subscripts and superscripts g, i, o, b, and s indicate the geocentric, inertial, spacecraft orbit, body, and scanner coordinate systems, respectively. The coordinate transformation is taken from the lower coordinate system to the upper one.

These intermediate coordinate transformations are described as follows. Here, the inverse coordinate transformation is equal to the transposed one.

(1) $\mathbf{T}_i^g$; the transformation from the inertial coordinate system to the geocentric coordinate system (Figure 4).

Earth rotation angle γ_e is given by the equation

$$\gamma_e = \text{Gha} + \omega_e \cdot t$$

where Gha, ω_e, and t are the Greenwich hour angle, Earth rotation angular velocity, and relative scanning time for the pixel (I, J), respectively. Then, the following is obtained:

$$\mathbf{T}_i^g = \begin{pmatrix} \cos\gamma_e & \sin\gamma_e & 0 \\ -\sin\gamma_e & \cos\gamma_e & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

where i, Ω, ω, and V are the orbital elements inclination, ascending node, argument of perigee, and true anomaly, respectively. The transformation from the orbit system to the geocentric one is condensed to

$$\mathbf{T}_o^g = \mathbf{T}_i^g\, \mathbf{T}_o^i.$$

The spacecraft body coordinate system is defined by using the orbital coordinate system; its x,

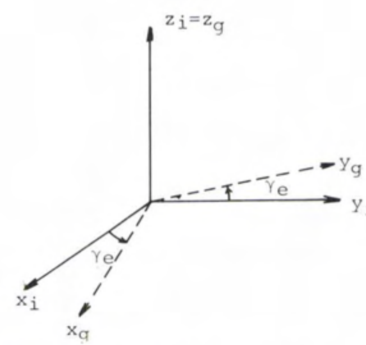

FIG. 4. The inertial and the geocentric coordinate systems.

y, and z directions are obtained from the orientation angles roll, pitch, and yaw based on the orbital coordinate system.

(3) $\mathbf{T}_o^b$; transformation from the orbit coordinate system to the spacecraft body coordinate system (Figure 5).

A 1-2-3 system rotation is carried out with angles of roll, α, pitch, β, and yaw, γ.

$$\mathbf{T}_o^b = \begin{pmatrix} \cos\beta\cos\gamma & \sin\alpha\sin\beta\cos\gamma + \cos\alpha\sin\gamma & -\cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma \\ -\cos\beta\sin\gamma & -\sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \cos\alpha\sin\beta\sin\gamma + \sin\alpha\cos\gamma \\ \sin\beta & -\sin\alpha\cos\beta & \cos\alpha\cos\beta \end{pmatrix}$$

(4) T_b^s; transformation from the spacecraft body coordinate system to the scanner coordinate system (Figure 6).

The transformation is a rotation of azimuth angle, ψ_s, and zenith angle, θ_s. Therefore,

$$T_b^s = \begin{pmatrix} \cos\psi_s & \sin\psi_s & 0 \\ -\sin\psi_s\cos\theta_s & \cos\psi_s\cos\theta_s & \sin\theta_s \\ \sin\psi_s\sin\theta_s & -\cos\psi_s\sin\theta_s & \cos\theta_s \end{pmatrix}.$$

APPLICATION TO LANDSAT

The mathematically derived transformation technique leads to an efficient analytical model which can transform from Landsat MSS pixels to geographical coordinates. This analytical model is applied to the Landsat project.

The Landsat orbital parameters are semi-major axis, 7286 km, inclination, 99.1 degrees, and eccentricity, 0.0006. As the orbit is sun-synchronous, all equatorial crossings occur at the same local time. Spacecraft roll and pitch are controlled within 0.4 degrees and measured by Attitude Measurements Sensor (AMS), which is an Earth horizon sensor with better than 0.07 degrees of accuracy. The yaw is measured by a rate-gyrocompass whose accuracy is better than 0.6 degrees.

The Multispectral Scanner (MSS) of the Landsat consists of an oscillating mirror. Six scan lines are simultaneously swept in four spectral bands by using 24 detectors. The MSS characteristics are given in the *Users' Handbook*.[1] The instantaneous field-of-view is 0.086 milliradians, the mirror oscillation frequency is 13.62 Hz, the crosstrack field-of-view is 11.56 degrees, and the sampling interval of detector output is 9.95 microseconds. One Landsat frame consists of approximately 3240 by 2340 pixels. This image covers an area of about 185 by 185 km. Using this information, sensor direction angles and relative time to the image center can be modeled.

For an arbitrary picture element (I, J) in the coordinate system of a Landsat image, the scan mirror angles (θ_I, ψ_J) can be determined from

$$\theta_I = \left\{1 - \frac{1}{I_{\max} - 1} \times (I - 1)\right\} \times \theta$$

$$\psi_J = \left[-\frac{5}{2} + \left\{J - \left[\frac{J-1}{6}\right] \times 6\right\}\right] \times \psi$$

under the condition that the mirror has a constant rate of rotation, where ψ is the instantaneous field-of-view and 2θ is the total field-of-view. A nonlinear rate of the mirror motion, however, is considered after a slight modification in calculations according to the CCT manual.[4]

Relative time, $t(I, J)$, to the image center can be obtained from the formula

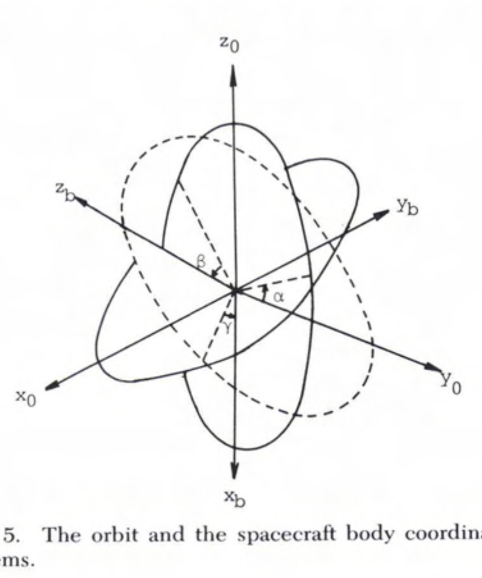

Fig. 5. The orbit and the spacecraft body coordinate systems.

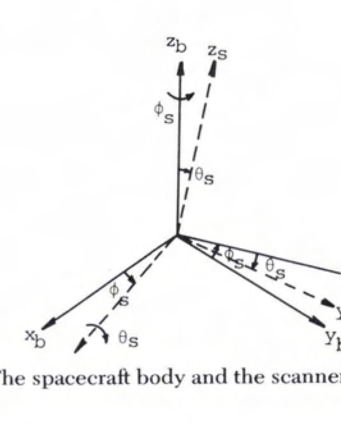

Fig. 6. The spacecraft body and the scanner coordinate systems.

$$t(I,J) = T_m + \left[\frac{J-1}{6}\right] \times T_{cy} + (I-1) \times T_s$$

where T_m is the duration time from the image center to the starting point (1, 1) of the image, T_{cy} is one period of the scanning mirror, and T_s is the sampling interval of the detector output. These constants are easily computed from the given MSS characteristics.

This vector is also represented by the geodetic latitude, ϕ, and longitude, λ, as

$$\begin{pmatrix} \cos\phi\cos\lambda \\ \cos\phi\sin\lambda \\ \sin\phi \end{pmatrix}.$$

Since these two vectors are equal, the following equations are derived:

$$\begin{aligned}
\cos\phi\cos\lambda &= \cos(\omega+V)\cos(\Omega-\gamma_e) - \sin(\omega+V)\cos i\sin(\Omega-\gamma_e) \\
\cos\phi\sin\lambda &= \cos(\omega+V)\sin(\Omega-\gamma_e) + \sin(\omega+V)\cos i\cos(\Omega-\gamma_e) \\
\sin\phi &= \sin(\omega+V)\sin i
\end{aligned}$$

Landsat operational information is recorded on the CCT as a Scene Image Annotation Tape (SIAT). The SIAT contains six records of the sensor characteristics and satellite orbit and attitude data for the period when the image is scanned. The sixth record of the SIAT is used for the geometrical correction of MSS data. Spacecraft orbit information is not given in an explicit form, but is given as altitude, nadir longitude, and latitude of 11 points for each image. The orbit elements are derived from this information in an inverse solution. The attitude information is given in terms of roll, pitch, and yaw for nine points per image. These attitude angles can be approximated by third order polynomials with respect to scanning time. The constant parts of the roll, pitch, and yaw angles are updated by employing two or three GCP's for the precise correction.

Since Landsat is a three-axis controlled satellite, its orbit should be observed more accurately and stably than its attitude. A new proposal to construct a precise MSS model is that attitude information and associated errors be totally corrected by updating attitude values by using GCP's and the SIAT orbit information, as well as scan mirror characteristics.

The Landsat orbit parameters given in the manual[1] are not sufficient for accurate geometrical correction, because they indicate only rough values which contain errors. The least-square approximation method is applied to obtain orbit elements in the neighborhood of the image center by employing SIAT orbit information.

Let T_o^g be the transformation matrix from the orbit system to the geocentric coordinate system. The direction from the nadir to the satellite is given by (0, 0, −1) in the orbit system. It is expressed in the geocentric coordinate system as follows:

The spacecraft orbit equation is

$$R = \frac{a(1-e^2)}{1+e\cos V}$$

where a is the semi-major axis and e is eccentricity.

These four equations are linearized to apply the least-square method. The orbital elements, except the true anomaly, are assumed to be fixed, because on Landsat image scanning period is about 30 seconds. The true anomaly is sampled for 11 different times and shown by $\{V(n)\colon n = \pm5, \pm4, \ldots, \pm1, 0\}$, because the orbital information is given for these times.

The orbital initial values and their minute values are denoted by zero indexes and δ prefixes, respectively. Then these orbital elements are shown by

$$a = a_0 + \delta a,\ e = e_0 + \delta e, \ldots, V(n) = V_0(n) + \delta V(n), \quad (n = \pm5, \pm4, \ldots, 0).$$

These parameters are simbolized by ρ such as

$$\rho = (a, e, i, \ldots, V(-5), V(-4), \ldots, V(5)).$$

Then, $\rho = \rho_0 + \delta\rho$.

A set of the Taylor expanded equations with respect to independent variables $\delta\rho = (\delta a, \delta e, \delta i, \ldots, \delta V(-5), \delta V(-4), \ldots, \delta V(5))$ are obtained. These 16 linearized equations are solved simultaneously to obtain a set of $\{a, e, i, \Omega, \omega\ V(-5), V(-4), \ldots, V(5)\}$ which satisfy the least-square criteria.

Attitude information is updated to compensate for the difference between the GCP latitude/longitude and values calculated from the MSS analytical model with corrected orbit elements. The spacecraft roll, pitch, and yaw are approximated third order polynomials by using the SIAT data.

$$T_o^g \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix} = \begin{pmatrix} \cos(\omega+V)\cos(\Omega-\gamma_e) - \sin(\omega+V)\cos i\sin(\Omega-\gamma_e) \\ \cos(\omega+V)\sin(\Omega-\gamma_e) + \sin(\omega+V)\cos i\cos(\Omega-\gamma_e) \\ \sin(\omega+V)\sin i \end{pmatrix}$$

The update procedure is carried out to refine time-invariant factors. Let k GCP's be

$$\{I(k), J(k), \phi(k), \lambda(k); k = 1, 2, \ldots, K\}$$

where I, J, ϕ, and λ are the pixel coordinate values of the scanner system, latitude, and longitude, respectively. Let $(\phi'(k), \lambda'(k))$ be a calculated latitude/longitude for point $(I(k), J(k))$ by employing the analytical model with corrected orbit information. The bias parts of the difference set

$$\{\phi'(k) - \phi(k) ; k = 1, 2, \ldots, K\}$$
$$\{\lambda'(k) - \lambda(k) ; k = 1, 2, \ldots, K\}$$

are denoted with $\Delta\phi$ and $\Delta\lambda$. Let $(\alpha_0(t), \beta_0(t), \gamma_0(t))$ be the attitude of the SIAT and $(\delta\alpha, \delta\beta, \delta\gamma)$ be a minute attitude compensation factor to be added for correction. The following simultaneous equations are derived by decomposing these bias parts into latitude and longitude parts with inclination, i.

$$\delta\alpha \cdot \sin(\pi - i) - \delta\beta \cdot \cos(\pi - i) = -\Delta\lambda/h$$
$$-\delta\alpha \cdot \cos(\pi - i) - \delta\beta \cdot \sin(\pi - i) = -\Delta\phi/h$$

These equations are solved with respect to $\delta\alpha$ and $\delta\beta$ as follows:

$$\delta\beta = \frac{1}{h}(-\Delta\lambda \cdot \sin i - \Delta\phi \cdot \cos i)$$

$$\delta\beta = \frac{1}{h}(-\Delta\lambda \cdot \cos i + \Delta\phi \cdot \sin i)$$

The corrected roll $\alpha(t)$ and pitch $\beta(t)$ are

$$\alpha(t) = \alpha_0(t) + \delta\alpha$$
$$\beta(t) = \beta_0(t) + \delta\beta.$$

The residual difference between latitude/longitude of the GCP and calculated values with these $\alpha(t)$, $\beta(t)$, and $\gamma_0(t)$ is the first degree factor only along the latitude direction. As the first degree function written with $\Delta r(I)$ is zero at the center of I_{max}, it is denoted as $\Delta r(I) = -\delta\gamma \cdot h \cdot \sin i \cdot \theta_I$. Under the condition that $\Delta r(I)$ is linear, θ_I may be considered as

$$\theta_I = c(I - 0.5 \cdot I_{max})$$

where c is a constant determined by the field-of-view; consequently,

$$\delta\gamma = -\Delta r(I)/h \cdot \sin i \cdot c(I - 0.5 \cdot I_{max}).$$

Assuming that $\Delta r(I)$ is linear, two or three GCP's are enough to determine the function since the constant factor is time invariant.

The fine correction after the attitude update makes it possible to attain accuracy within one pixel. Images can be similarly processed after the fine attitude correction, as the characteristics of scan mirror velocity are fixed. Images along a satellite orbit are corrected with GCP's on the swath, and the number of GCP's per image is then reduced. It is also possible to process marine area images where no GCP's can be collected, if there is some land area either before or after the sea area.

The efficiency of computer processing for the geometrical correction is characterized by short execution time, small memory capacity, high accuracy, and flexible algorithms for change of images. This analytical method can provide more accurate and flexible correction algorithms than the polynomial approximation method. An image of 1000 by 1000 points is corrected in about one hour by a large general purpose computer, even when the developed approximation formula for the analtyical model is applied. In producing photographic Landsat maps, the transformation computation from the geodetic coordinate system to the map projection system is indispensable. The amount of calculation is quite large, and the practical procedure is not direct but an approximation formula; the development power series for examples.

Polynomial approximation of the analytical model can solve the above problems. The developed analytical MSS model can compute geodetic coordinate in terms of latitude/longitude (ϕ, λ) for a given pixel (I, J). Then, the polynomial approximation of the analytical MSS model is carried out for several pixels $(I(k), J(k); k = 1, 2, \ldots, N)$ which are uniformly distributed in a frame and their latitude/longitude $(\phi(k), \lambda(k)$: $k = 1, 2, \ldots, N)$ is computed. A set of $(I(k), J(k), \phi(k), \lambda(k)$: $k = 1, 2, \ldots, N)$ is regarded as GCP's, and polynomials are approximated by the least-square method with these calculated GCP's. Uniformly distributed GCP's are sufficient to form the polynomial mapping from the MSS system to the geocentric system in a straight-forward manner. This mapping is a highly precise and efficient procedure, as the composite function of the analytical MSS model and the map projection polynomials can be similarly derived by the least-square method. Concrete map projection and approximation errors are located in the following section. This efficient procedure does not always require GCP collection.

When display equipment with random scan is not available, an inverse function from the geocentric system to the MSS system is required with resampling techniques. It is also possible to construct the inverse function successfully for the Landsat images.

Output of Geometrically Corrected Results

Let a mapping, f, be the analytical model of the geometrical distortion to calculate the geodetic coordinates from the Landsat coordinates with desired accuracy. It is necessary to project the Landsat image data into a certain map coordinate system in order to overlay the MSS image on the map. Letting the projection be g, the map coordinates (x, y) are obtained as follows:

$$(x, y) = g(\phi, \lambda) = g \cdot f(I, J).$$

Two output experiments for Landsat MSS images, one transforming to the Universal Transversal Mercator (UTM) projection and the other to the conformal conic map projection, were adopted. The UTM map projection was used to obtain an image which corresponded to the 1:200,000 topographic map area published by the National Geographical Survey Institute of Japan. The conformal conic projection with two standard parallels was selected to produce a whole map from the Landsat scene. The standard parallels of the 1:500,000 topographic map of Kanto-Koshinetsu Region was chosen for the output Landsat image of the Toukai and Kanto Districts.

The coordinate calculation program was successfully implemented, and results are stored in a magnetic tape to record latitude/longitude and projection coordinates. Each record consists of the starting and end points of the MSS for every scan line and increments for the intermediate points.

Calculated data for latitude/longitude, map projection coordinates and CCT Landsat image data are stored in a large capacity magnetic disk. The image data have a standard data format proposed by the Information Processing Society of Japan. Color display monitoring and film output are available in an experimental system.

Since conventional geometrical correction methods require resampling in the map coordinate (x, y) system, some difficulties in data quantity and data access interfere with practical applications. The proposed correction method needs no resampling when the image output is made on film. This method reduces computer time for image output, the buffer memory capacity, and software loading. The output apparatus requires random scanning such as that provided by a electron beam recorder (EBR) or a flying spot scanner (FSS). A newly developed FSS was used here as a film recorder. It was found to be suitable to output such a large image as Landsat images. This recorder has a high positioning accuracy, which is good for color synthesis.

For an arbitrary Landsat pixel (I, J), the projected coordinates (x, y) have been calculated as in the previous sections. Output coordinates of the film recorder are obtained by a certain transformation. The brightness of the output coordinates is fetched from CCT data at the (I, J) pixel and then recorded on film. The geometrically corrected result for an entire Landsat MSS image is produced by performing the above operation for all CCT (I, J) pixels. In order to obtain an image which corresponds with a map, the projection coordinates (x, y) or latitude/longitude coordinates (ϕ, λ) are limited by a predetermined region. A subimage projected to UTM coordinates, corresponding to the 1:200,000 topographic map "Kouhu," was produced. Experimental results show that this high precision FSS film recorder is suitable for the geometrical correction of Landsat

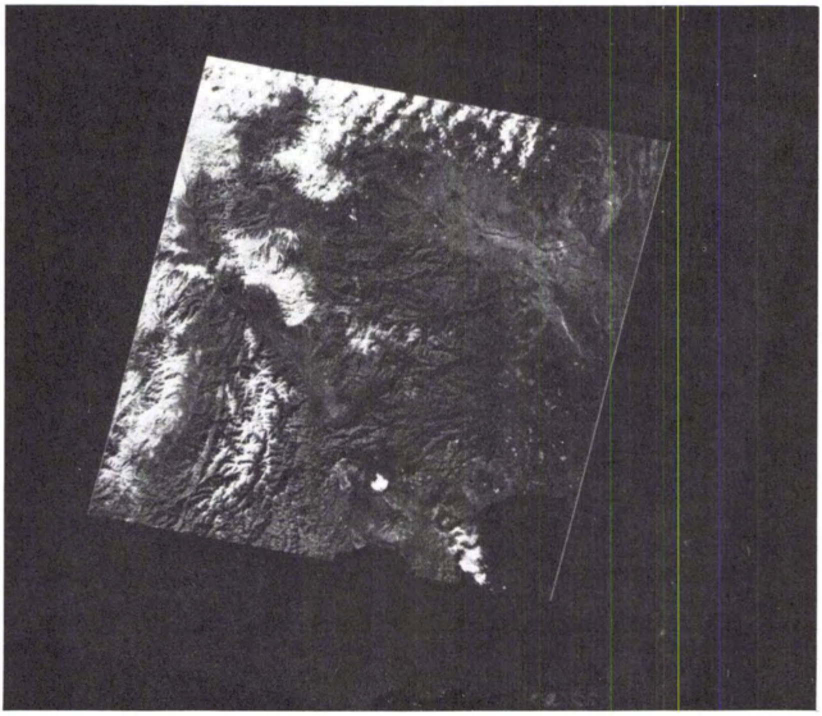

FIG. 7. Geometrically corrected result of "Toukai" (Landsat-1, 15 December 1972) projected to the conformal conic projection.

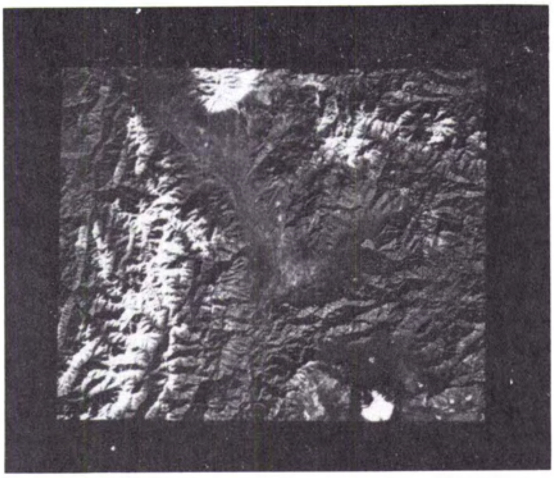

FIG. 8. Subimage projected to the projection UTM, corresponding to the 1:200,000 topographical map "Kouhu".

MSS images. This apparatus can perform random scan and needs no line buffer memory for resampling. The output was accomplished in about 10 μsec per pixel, which is approximately ten times faster than a drum scanner.

There are two ways to get a color output image; direct color negative production on film and photographic color composition from three monochrome negatives. The photographic color composition was adopted to obtain a Landsat photographic map in order to simulate the color combination freely.

Landsat MSS images denoted "Toukai" (Landsat-1, 15 December 1972) and by "Kanto" (Landsat-2, 29 July 1976) were corrected by this new method. Figure 7 shows a geometrically corrected result for "Toukai" projected to the conformal conic projection, Figure 8 shows a subimage projected by the UTM projection corresponding to the 1:200,000 topographic map "Kouhu," and Figure 9 shows that of "Kanto." Bands 4, 5, and 6 of Landsat MSS data were selected for the color composition. These experiments have revealed that this method can meet map production requirements.

CONCLUSION

Geometrical correction precision employing the analytical model is examined based on the practical experiments of the results of the "Toukai" test. The correction accuracy is limited to within about two pixels without any GCP's. Error estimation results are within one pixel—34.7 m (0.61 pixel) in the latitude direction and 35.4 m (0.45 pixel) in the longitude direction—under the condition that the nonlinear characteristics for scan mirror velocity are given by three GCP's and that 20 points are added for error estimation.

Further applications include the precise registration of many temporal images to detect changes in land use and to produce a mosaic. It will be extended to collect GCP's automatically from analytical correspondence between coordinates. A

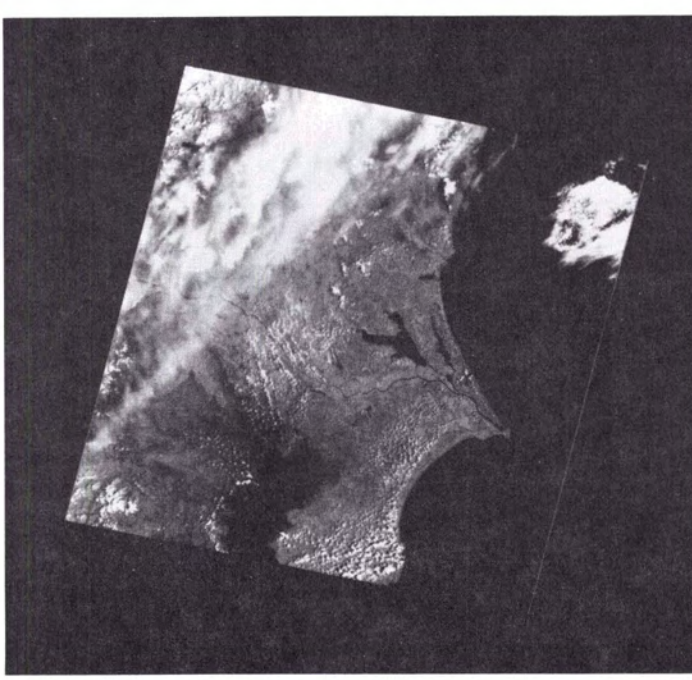

FIG. 9. Geometrically corrected result of "Kanto" (Landsat-2, 29 July 1976).

fully automatic system, using high precision geometrical correction, is now being started.

Acknowledgments

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Color composition using three monochrome negatives was carried out by the Asia Air Survey Co., Ltd.

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