3.3 Land-related Algorithms

3.3.1 LTSKG

Precise Geometric Correction Algorithm

A. Algorithm Outline

(1) Algorithm Code: LTSKG

(2) Product Code: PGCI

(3) PI names: A2GSJ005, T.Hashimoto

(4) Overview of algorithm

The accuracy of geometric correction is dependent much on the accuracy of the satellite position and attitude. In case of the former satellites (e.g. ADEOS), the accuracy of satellite position and attitude seems not sufficient for precise geometric correction. The algorithm developed here enables to determine the precise satellite position and attitude using ground control points (GCP). The rectification of original image is carried out using the results of the exterior orientation.

This work has the following objectives:

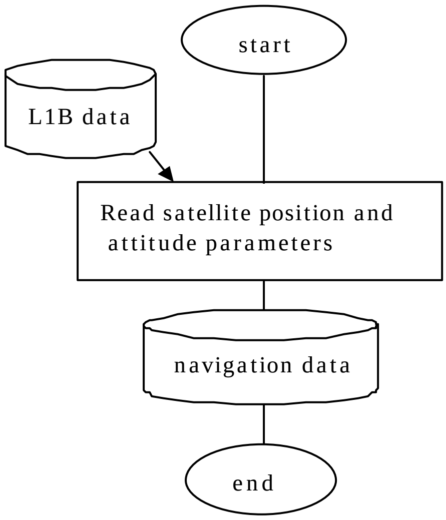
- To extract GCP automatically,
- To determine precise satellite position and attitude based on photogrammetry.
- To map rectified image.

B. Theoretical description

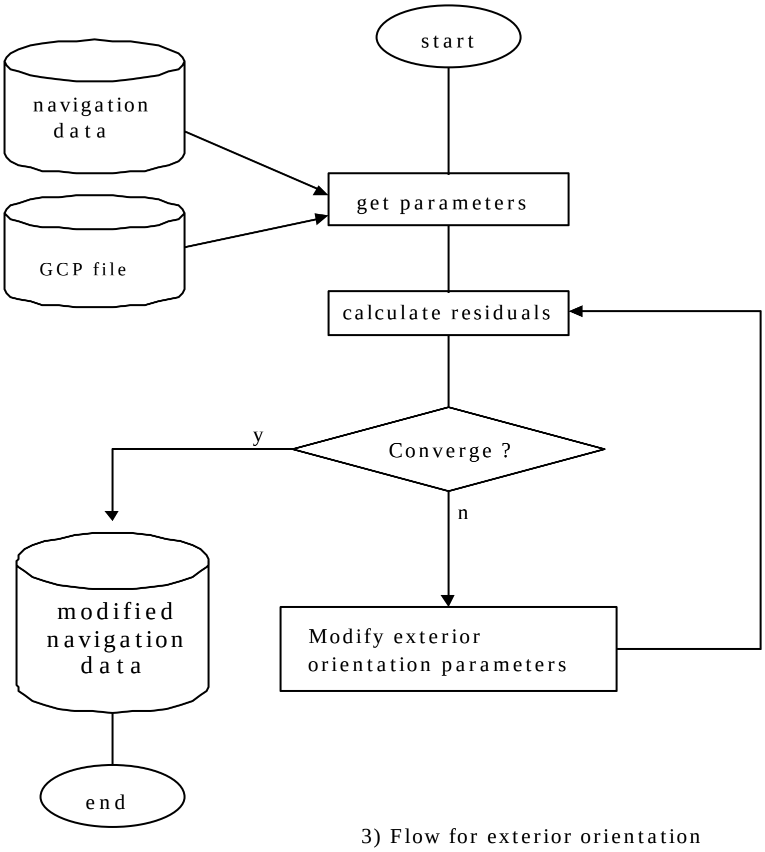
(1) Methodology and Logic flow

The methodology is realized by the following six softwares.

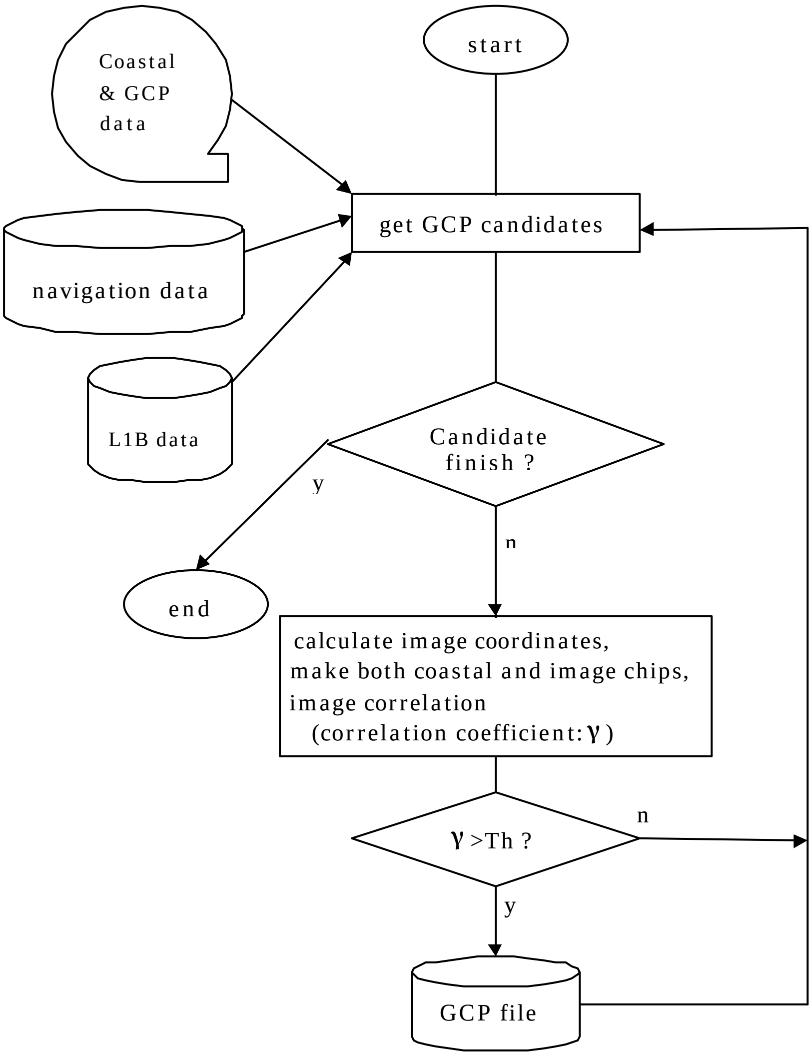
- To convert satellite position, velocity and attitude for one segment to navigation data.
- To determine precise satellite position and attitude utilizing GCPs based on the collinearity condition and get ground coordinates on the regular grids.
- To extract GCP automatically by image matching between image data and coastal line data.
- To get parameters to specify each scene.
- To modify orientation results for one segment to those for each scene.
- To map rectified image data and scan geometry data onto Latitude/Longitude coordinates or Polar Stereo Projection.



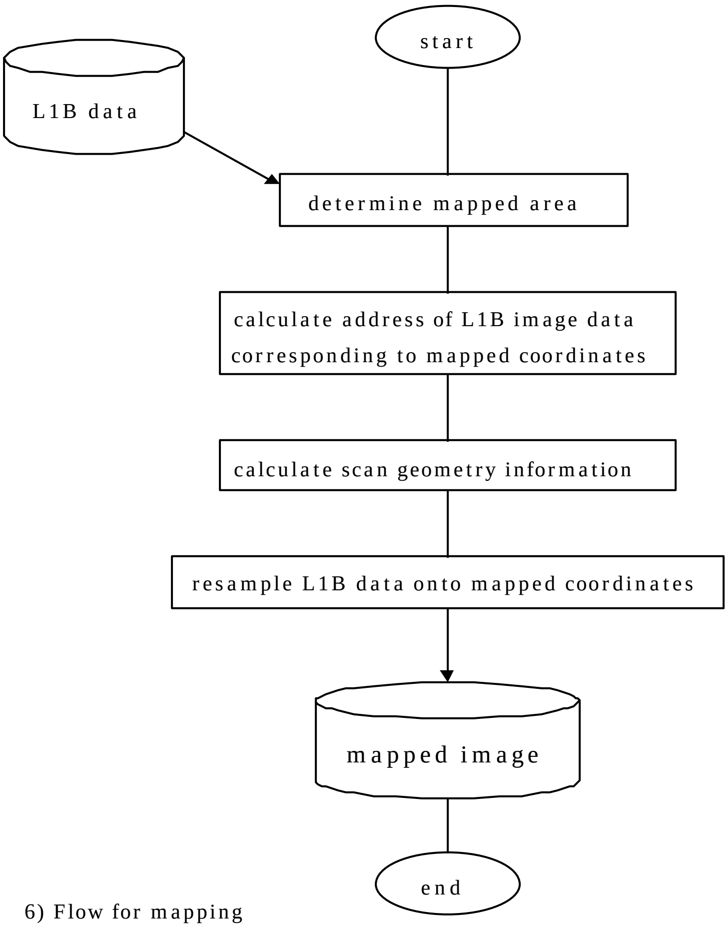
1) Flow for getting navigation data



3) Flow for exterior orientation



2) Flow for extrcting GCP



6) Flow for mapping

(2) Physical and Mathematical aspects of the algorithm

First of all, the coordinates systems used here are defined as follows ;

- (X,Y,Z): ECR(Earth Center Rotation) coordinates where the origin is the gravity center of the Earth, X axis is Greenwich Meridian at the equator, Z axis is North along the spin axis, Y is defined by right-handed rotation,
- (x, y, z): Orbital Coordinates where the origin is the gravity center of the satellite, z axis is nadir, y axis is defined by the outer product of z axis and velocity vector, x is defined by right-handed rotation.

1)Coordinate transformation[1,2,3,4]

The satellite position and velocity will be given in ECR coordinates in a standard product. The transformation between orbital coordinates and ECR coordinates is expressed using satellite position $\mathbf{P}_s = (X_o, Y_o, Z_o)$ and velocity $\mathbf{V}_s = (V_{xr}, V_{yr}, V_{zr})$ in ECR as follows.

let $\mathbf{n} = (x_e, y_e, z_e)$:unit vector of $\mathbf{P}_s$, $\mathbf{u} = (u_x, u_y, u_z)$:unit vector of $\mathbf{V}_s$,

$$\text{then, } \begin{pmatrix} X_r \\ Y_r \\ Z_r \end{pmatrix} = \mathbf{P}_2 \bullet \begin{pmatrix} X_e \\ Y_e \\ Z_e \end{pmatrix} = \begin{pmatrix} x_k & x_m & x_n \\ y_k & y_m & y_n \\ z_k & z_m & z_n \end{pmatrix} \begin{pmatrix} X_e \\ Y_e \\ Z_e \end{pmatrix} \qquad (1)$$

where (X_r, Y_r, Z_r) : any vector in ECR

(X_e, Y_e, Z_e) : any vector in orbital coordinates

$\mathbf{m} = \mathbf{n} \times \mathbf{u} = (x_m, y_m, z_m)$: directional vector for Y_e axis (in ECR)

$\mathbf{k} = \mathbf{m} \times \mathbf{n} = (x_k, y_k, z_k)$: directional vector for X_e axis (in ECR)

The satellite movement can be also expressed using the distance between the Earth center and the satellite center (R), the longitude of ascending node(Ω), the inclination(i), the latitude argument from ascending node on the orbital plane(u) as follows.

$$\begin{pmatrix} X_r \\ Y_r \\ Z_r \end{pmatrix} = \mathbf{P}_3 \bullet \begin{pmatrix} X_e \\ Y_e \\ Z_e \end{pmatrix} = \begin{pmatrix} \cos\Omega & \sin\Omega & 0 \\ \sin\Omega & -\cos\Omega & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sin i & -\cos i \\ 0 & \cos i & \sin i \end{pmatrix} \begin{pmatrix} -\sin u & 0 & \cos u \\ 0 & 1 & 0 \\ \cos u & 0 & \sin u \end{pmatrix} \begin{pmatrix} X_e \\ Y_e \\ Z_e \end{pmatrix}$$

$$= \begin{pmatrix} -\cos\Omega\sin u - \sin\Omega\cos i\cos u & \sin\Omega\sin i & \cos\Omega\cos u - \sin\Omega\cos i\sin u \\ -\sin\Omega\sin u + \cos\Omega\cos i\cos u & -\cos\Omega\sin i & \sin\Omega\cos u + \cos\Omega\cos i\sin u \\ \sin i\cos u & \cos i & \sin i\sin u \end{pmatrix} \begin{pmatrix} X_e \\ Y_e \\ Z_e \end{pmatrix} \qquad (2)$$

The equation (1) and (2) are absolutely same each other. To compare both equations, the parameters(Ω, i, u) are calculated from the satellite position and velocity as;

$$\Omega = -\tan^{-1}\left(x_m / y_m \right), \quad i = \cos^{-1}(x_m), \quad u = \tan^{-1}\left(z_n / z_k \right). \qquad (3)$$

And the R is expressed by the satellite position as;

$$R = \sqrt{\left(X_o^{\,2} + Y_o^{\,2} + Z_o^{\,2} \right)}. \qquad (4)$$

Both $(\mathbf{P}_s, \mathbf{V}_s)$ and (R, Ω, i, u) are time dependent. The variation ratios of the former are bigger than those of the latter, especially at the equator or the polar regions. So the latter is suitable for the expression of satellite position and velocity. In this work, the parameters for satellite movement are expressed by the polynomials of line number (L) as ;

$$P = P_0 + P_1 \cdot L + P_2 \cdot L^2 + \Lambda, \qquad P = (R, \Omega, i, u, w, f, k). \qquad (5)$$

The coefficients of polynomials for (R, Ω, i, u) and attitude are determined by the regression analysis using the satellite motion(position, velocity) and attitude in a standard product, respectively

2)Exterior orientation[2]

The view vector at the aperture (corresponding to the satellite coordinates) can be defined by the optical-mechanical system of GLI. The view vector in the satellite coordinates are transformed into the orbital coordinates using the attitude, (roll, pitch, yaw)=(ω, ϕ, κ), as follows.

$$
\begin{pmatrix} Bx_e \\ By_e \\ Bz_e \end{pmatrix} = \mathbf{P}_1 \bullet \begin{pmatrix} Bx_s \\ By_s \\ Bz_s \end{pmatrix} = \begin{pmatrix} \cos\kappa & -\sin\kappa & 0 \\ \sin\kappa & \cos\kappa & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\phi & 0 & \sin\phi \\ 0 & 1 & 0 \\ -\sin\phi & 0 & \cos\phi \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\omega & -\sin\omega \\ 0 & \sin\omega & \cos\omega \end{pmatrix} \begin{pmatrix} Bx_s \\ By_s \\ Bz_s \end{pmatrix}
$$

$$
= \begin{pmatrix} \cos\phi\cos\kappa & -\cos\omega\sin\kappa + \sin\omega\sin\phi\cos\kappa & \sin\omega\sin\kappa + \cos\omega\sin\phi\cos\kappa \\ \cos\phi\sin\kappa & \cos\omega\cos\kappa + \sin\omega\sin\phi\sin\kappa & -\sin\omega\cos\kappa + \cos\omega\sin\phi\sin\kappa \\ -\sin\phi & \sin\omega\cos\phi & \cos\omega\cos\phi \end{pmatrix} \begin{pmatrix} Bx_s \\ By_s \\ Bz_s \end{pmatrix} \qquad (6)
$$

where (Bx_s, By_s, Bz_s) : view vector in satellite coordinates

(Bx_e, By_e, Bz_e): view vector in orbital coordinates.

Applying equation (6) to equation (2), the view vector is transformed into ECR as follows.

$$
\begin{pmatrix} Bx_r \\ By_r \\ Bz_r \end{pmatrix} = P_3 \bullet P_1 \bullet \begin{pmatrix} Bx_s \\ By_s \\ Bz_s \end{pmatrix}, \qquad (7)
$$

where $(Bx_r,\ By_r,\ Bz_r)$: view vector in ECR.

Since a ground object point $\mathbf{P} = (X, Y, Z)$, satellite position $\mathbf{S} = (X_o, Y_o, Z_o)$ and image point $\mathbf{Q} = (x, y)$ exist on one line (or a bundle), it satisfies the collinearity equation as follows.

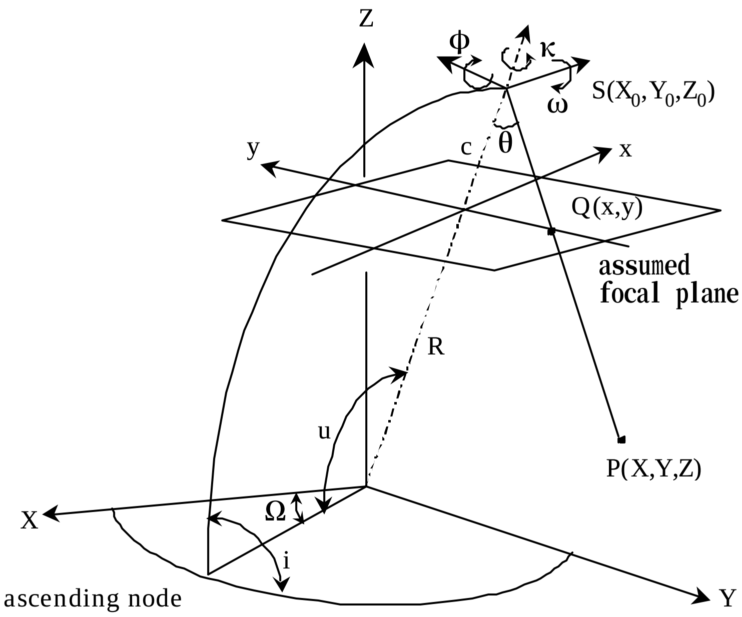
$$
F_x = -x - c\frac{Bx_s}{Bz_s} = -x - c \cdot \frac{a_1(X - X_o) + a_2(Y - Y_o) + a_3(Z - Z_o)}{a_7(X - X_o) + a_8(Y - Y_o) + a_9(Z - Z_o)} = 0
$$

$$
F_y = -y - c\frac{By_s}{Bz_s} = -y - c \cdot \frac{a_4(X - X_o) + a_5(Y - Y_o) + a_6(Z - Z_o)}{a_7(X - X_o) + a_8(Y - Y_o) + a_9(Z - Z_o)} = 0 \qquad (8)
$$

where $\begin{pmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{pmatrix} = (\mathbf{P}_3 \bullet \mathbf{P}_1)^T = \mathbf{P}_1^T \bullet \mathbf{P}_3^T$, c : assumed focal length.

$$
\begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} = \begin{pmatrix} \cos\Omega\cos u - \sin\Omega\cos i\sin u \\ \sin\Omega\cos u + \cos\Omega\cos i\sin u \\ \sin i\sin u \end{pmatrix} \cdot R
$$

$$
\Theta \begin{pmatrix} Bx_s \\ By_s \\ Bz_s \end{pmatrix} = k \cdot \begin{pmatrix} x \\ y \\ -c \end{pmatrix} \text{ : parallel }, \qquad \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -c \cdot Bx_s / Bz_s \\ -c \cdot By_s / Bz_s \end{pmatrix}
$$



In the equation (8), the parameters (R, Ω, i, u) and (ω, ϕ, κ) are unknown. As the equation (8) is not linear, it is be approximated by Taylor development around the unknown parameters as;

$$F^{\circ}{}_x + ?_x - \frac{\P F_x}{\P R} dR - \frac{\P F_x}{\P O} dO - \frac{\P F_x}{\P i} di - \frac{\P F_x}{\P u} du - \frac{\P F_x}{\P ?} d? - \frac{\P F_x}{\P f} d f - \frac{\P F_x}{\P ?} d? = 0$$
$$F^{\circ}{}_y + ?_y - \frac{\P F_y}{\P R} dR - \frac{\P F_y}{\P O} dO - \frac{\P F_y}{\P i} di - \frac{\P F_y}{\P u} du - \frac{\P F_y}{\P ?} d? - \frac{\P F_y}{\P f} d f - \frac{\P F_y}{\P ?} d? = 0 \qquad (9)$$

where the notation ‘ ^{0} ‘ means the approximation and (v_x, v_y) is residuals.

If the observed satellite position is accurate and the unknown parameters are only satellite attitude (it is the circumstances of ADEOS satellite), the equation (9) will be simplified as ;

$$F^{\circ}{}_x + ?_x - \frac{\P F_x}{\P ?} d? - \frac{\P F_x}{\P f} d f - \frac{\P F_x}{\P ?} d? = 0$$
$$F^{\circ}{}_y + ?_y - \frac{\P F_y}{\P ?} d? - \frac{\P F_y}{\P f} d f - \frac{\P F_y}{\P ?} d? = 0 \qquad (10)$$

In the equation (10), differential coefficients are expressed as ;

$$\frac{\partial F_x}{\partial w} = -c\frac{Bx_s' Bz_s - Bx_s Bz_s'}{Bz_s^2}, \quad \frac{\partial F_y}{\partial w} = -c\frac{By_s' Bz_s - By_s Bz_s'}{Bz_s^2},$$

$$\begin{pmatrix} Bx_s' \\ By_s' \\ Bz_s' \end{pmatrix} = \begin{pmatrix} 0 & \sin\omega\sin\kappa + \cos\omega\sin\phi\cos\kappa & \cos\omega\sin\kappa - \sin\omega\sin\phi\cos\kappa \\ 0 & -\sin\omega\cos\kappa + \cos\omega\sin\phi\sin\kappa & -\cos\omega\cos\kappa - \sin\omega\sin\phi\sin\kappa \\ 0 & \cos\omega\cos\phi & -\sin\omega\cos\phi \end{pmatrix} \mathbf{P}_3^T \begin{pmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{pmatrix}$$

$$\frac{\partial F_x}{\partial f} = -c\frac{Bx_s' Bz_s - Bx_s Bz_s'}{Bz_s^2}, \quad \frac{\partial F_y}{\partial w} = -c\frac{By_s' Bz_s - By_s Bz_s'}{Bz_s^2}, \qquad (11)$$

$$\begin{pmatrix} Bx_s' \\ By_s' \\ Bz_s' \end{pmatrix} = \begin{pmatrix} -\sin\phi\cos\kappa & \sin\omega\cos\phi\cos\kappa & \cos\omega\cos\phi\cos\kappa \\ -\sin\phi\sin\kappa & \sin\omega\cos\phi\sin\kappa & \cos\omega\cos\phi\sin\kappa \\ -\cos\phi & -\sin\omega\sin\phi & -\cos\omega\sin\phi \end{pmatrix} \mathbf{P}_3^T \begin{pmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{pmatrix}$$

$$\frac{\partial F_x}{\partial k} = -c\frac{Bx_s' Bz_s - Bx_s Bz_s'}{Bz_s^2}, \quad \frac{\partial F_y}{\partial w} = -c\frac{By_s' Bz_s - By_s Bz_s'}{Bz_s^2},$$

$$\begin{pmatrix} Bx_s' \\ By_s' \\ Bz_s' \end{pmatrix} = \begin{pmatrix} -\cos\phi\sin\kappa & -\cos\omega\cos\kappa - \sin\omega\sin\phi\sin\kappa & \sin\omega\cos\kappa - \cos\omega\sin\phi\sin\kappa \\ \cos\phi\cos\kappa & -\cos\omega\sin\kappa + \sin\omega\sin\phi\cos\kappa & \sin\omega\sin\kappa + \cos\omega\sin\phi\cos\kappa \\ 0 & 0 & 0 \end{pmatrix} \mathbf{P}_3^T \begin{pmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{pmatrix}$$

The equation (10) is re-written by using a matrix as ;

$$\begin{pmatrix} ?_x \\ ?_y \end{pmatrix} - \begin{pmatrix} a_5 & a_6 & a_7 \\ b_5 & b_6 & b_7 \end{pmatrix} \cdot \begin{pmatrix} d? \\ d f \\ d? \end{pmatrix} = \begin{pmatrix} -F^{\circ}{}_x \\ -F^{\circ}{}_y \end{pmatrix}$$
$$\text{whrere} \quad \begin{pmatrix} a_5 & a_6 & a_7 \\ b_5 & b_6 & b_7 \end{pmatrix} = \begin{pmatrix} \frac{\P F_x}{\P ?} & \frac{\P F_x}{\P f} & \frac{\P F_x}{\P ?} \\ \frac{\P F_y}{\P ?} & \frac{\P F_y}{\P f} & \frac{\P F_y}{\P ?} \end{pmatrix} \qquad (12)$$

It is simplified as ;

$$\nu - \alpha\ \delta = F^{\circ} \qquad (13)$$

The unknown parameters can be solved using GCPs by least square method.

3)Ground coordinates

A position vector $\mathbf{G} = (X_g, Y_g, Z_g)$ of the scanned point is expressed with the satellite position, the view vector and the distance from the scan point to the satellite (D) as;

$$\begin{pmatrix} X_g \\ Y_g \\ Z_g \end{pmatrix} = \begin{pmatrix} X_o \\ Y_o \\ Z_o \end{pmatrix} + D \bullet \begin{pmatrix} Bx_r \\ By_r \\ Bz_r \end{pmatrix}. \tag{14}$$

Assuming that the scanned position is located on the surface of reference ellipsoid, it satisfies the following equation.

$$\frac{X_g^{\ 2} + Y_g^{\ 2}}{Ra^2} + \frac{Z_g^{\ 2}}{Rb^2} = \frac{X_g^{\ 2} + Y_g^{\ 2}}{Ra^2} + \frac{Z_g^{\ 2}}{Ra^2(1-e^2)} = 1 \quad . \tag{15}$$

where Ra : equatorial radius, Rb : polar radius, e : eccentricity of the Earth.

Applying the equation (15), the equation (14) can be re-written as;

$$a \cdot D^2 + 2b \cdot D + c = 0$$

$$\left[\begin{aligned} a &= \frac{Bx_r^{\ 2} + By_r^{\ 2}}{Ra^2} + \frac{Bz_r^{\ 2}}{Ra^2(1-e^2)} \\ b &= \frac{Bx_r X_o + By_r Y_o}{Ra^2} + \frac{Bz_r Z_o}{Ra^2(1-e^2)} \\ c &= \frac{X_o^{\ 2} + Y_o^{\ 2}}{Ra^2} + \frac{Z_o^{\ 2}}{Ra^2(1-e^2)} - 1 \end{aligned}\right. . \tag{16}$$

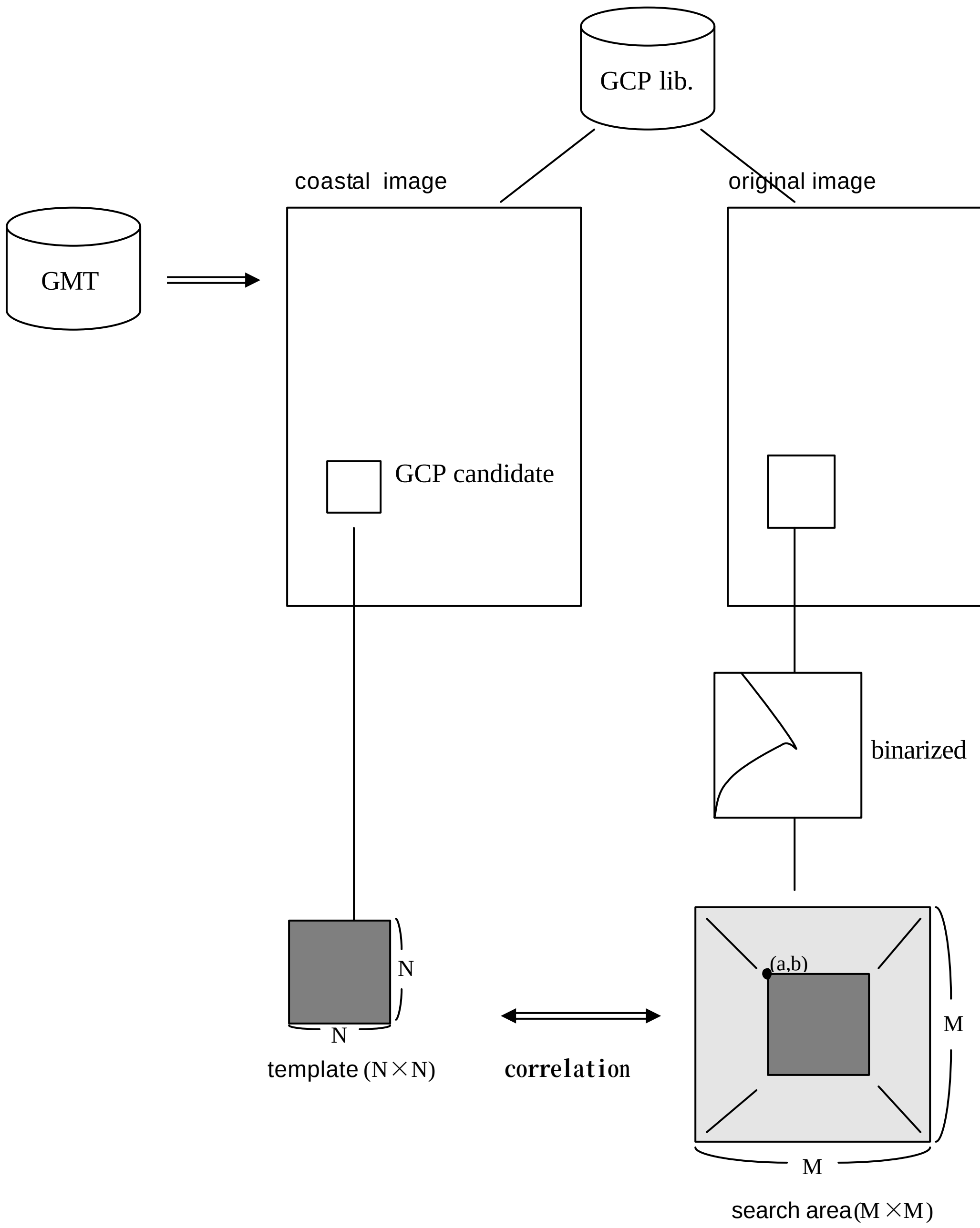
Solving for D in the equation (16) and applying the D to the equation (14), the ground position in the ECR can be obtained. The ground position is transformed into geodetic coordinates $(j, \cdot l, H)$ = (Latitude, Longitude, Elevation) by the following equation.

$$\begin{pmatrix} X_g \\ Y_g \\ Z_g \end{pmatrix} = \begin{pmatrix} (N+H)\cos j \cdot \cos l \\ (N+H)\cos j \cdot \sin l \\ \{(N(1-e^2)+H\}\sin j \end{pmatrix}, \qquad N = Ra \Big/ \sqrt{1 - e^2 \sin^2 j} \tag{17}$$

4)GCP collection

Sufficient numbers of GCPs are necessary for exterior orientation. Conventionally, the GCP collection has been conducted by human interpretation. Such procedure is very time consuming and not proper for daily process. In this work, the GCP collection is realized by the template matching.

In the following figure, two image patches contain coastal lines. One (a) is a template from the Generic Mapping Tool (GMT) coastal data prepared in advance, another (b) is a reference image made by the binarization of the original image. The template (a) is selected as a GCP candidate from the GCP library which have to be prepared. In this work, the sizes of both patches are determined as m=32 and n=16 through some experiments.



(a) coastal line patch (b) original image patch

Since both patches to be matched have to be in the same coordinate system, the GMT coastal data in geodetic coordinates is transformed into the uncorrected image coordinates. The transformation from $(j ,\cdot l , \mathrm{H})$ to (L,P) = (Line, Pixel) is realized as follows. Firstly, the $(j ,\cdot l , \mathrm{H})$ is transformed to (Xg, Yg, Zg) in the ECR by the equation (17). Then the (Xg, Yg, Zg) is transformed to (x,y) in the image coordinates. In order to carry out this transformation, the collinearity equation (8) is developed around (L,P) as follows.

$$
\begin{aligned}
F^{\circ}{}_{x} + ?_{x} - \frac{\P F_x}{\P L} dL - \frac{\P F_x}{\P P} dP &= 0 \\
F^{\circ}{}_{y} + ?_{y} - \frac{\P F_y}{\P L} dL - \frac{\P F_y}{\P P} dP &= 0
\end{aligned}
\tag{18}
$$

$$
\frac{\partial F_x}{\partial L} = -c \frac{Bx_s' \, Bz_s - Bx_s Bz_s'}{Bz_s^{\;2}}, \qquad \frac{\partial F_y}{\partial L} = -c \frac{By_s' \, Bz_s - By_s Bz_s'}{Bz_s^{\;2}},
$$

$$
\begin{pmatrix} Bx_s' \\ By_s' \\ Bz_s' \end{pmatrix} = \left[\frac{\partial}{\partial \omega}\left(\mathbf{P}_1^{\,T} \bullet \mathbf{P}_3^{\,T}\right)\frac{\partial \omega}{\partial L} + \frac{\partial}{\partial \phi}\left(\mathbf{P}_1^{\,T} \bullet \mathbf{P}_3^{\,T}\right)\frac{\partial \phi}{\partial L} + \frac{\partial}{\partial \kappa}\left(\mathbf{P}_1^{\,T} \bullet \mathbf{P}_3^{\,T}\right)\frac{\partial \kappa}{\partial L} + \frac{\partial}{\partial \Omega}\left(\mathbf{P}_1^{\,T} \bullet \mathbf{P}_3^{\,T}\right)\frac{\partial \Omega}{\partial L} \right.
\tag{19}
$$

$$
\left. + \frac{\partial}{\partial i}\left(\mathbf{P}_1^{\,T} \bullet \mathbf{P}_3^{\,T}\right)\frac{\partial i}{\partial L} + \frac{\partial}{\partial u}\left(\mathbf{P}_1^{\,T} \bullet \mathbf{P}_3^{\,T}\right)\frac{\partial u}{\partial L} \right] \begin{pmatrix} X - X_o \\ Y - Y_o \\ Z - Z_o \end{pmatrix} + \left(\mathbf{P}_1^{\,T} \bullet \mathbf{P}_3^{\,T}\right) \begin{pmatrix} X - \dfrac{\partial X_o}{\partial L} \\ Y - \dfrac{\partial Y_o}{\partial L} \\ Z - \dfrac{\partial Z_o}{\partial L} \end{pmatrix}
$$

$$
\frac{\partial}{\partial L}\begin{pmatrix} X_o \\ Y_o \\ Z_o \end{pmatrix} = \frac{\partial}{\partial L}\begin{pmatrix} \cos\Omega \cos u - \sin\Omega \cos i \sin u \\ \sin\Omega \cos u + \cos\Omega \cos i \sin u \\ \sin i \sin u \end{pmatrix} \cdot R + \begin{pmatrix} \cos\Omega \cos u - \sin\Omega \cos i \sin u \\ \sin\Omega \cos u + \cos\Omega \cos i \sin u \\ \sin i \sin u \end{pmatrix} \cdot \frac{\partial R}{\partial L}
$$

The coefficients $\dfrac{\partial F_x}{\partial P} = \dfrac{\partial F_x}{\partial x} \cdot \dfrac{\partial x}{\partial P} = \dfrac{\partial x}{\partial P}$ and $\dfrac{\partial F_y}{\partial P} = \dfrac{\partial F_y}{\partial y} \cdot \dfrac{\partial y}{\partial P} = \dfrac{\partial y}{\partial P}$ are determined by the optical-mechanical system of GLI. The image point (x,y) is expressed as a function of a pixel number. If a polynomial is adopted, the function is expressed as follows.

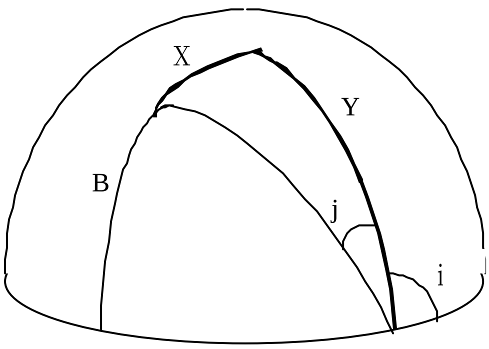
$$
\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -c \cdot \dfrac{Bx_s}{Bz_s} \\ -c \cdot \dfrac{By_s}{Bz_s} \end{pmatrix} = \begin{pmatrix} a_0 + a_1 \cdot P + a_2 \cdot P^2 + \Lambda \\ b_0 + b_1 \cdot P + b_2 \cdot P^2 + \Lambda \end{pmatrix}
\tag{20}
$$

So the coefficients $\dfrac{\partial x}{\partial P}$ and $\dfrac{\partial y}{\partial P}$ are also expressed by the polynomials.

$$
\begin{pmatrix} \dfrac{\partial x}{\partial P} \\ \dfrac{\partial y}{\partial P} \end{pmatrix} = \begin{pmatrix} a_1 + 2a_2 \cdot P + \Lambda \\ b_1 + 2b_2 \cdot P + \Lambda \end{pmatrix}
\tag{21}
$$

In solving the equation (18), the initial approximates of (L,P) are necessary. The approximates are obtained by trigonometry as the equation (22) under the assumption that the satellite orbit is circular and the Earth shape is globe. The values of (L,P) are derived easily from (X, Y).

$$
\begin{aligned}
\sin X &= -\sin j \sqrt{1 - \cos^2 B \cos^2 dL} \\
\sin Y &= \cos B \cos dL \big/ \cos X
\end{aligned}
\tag{22}
$$



Sometimes miss matching will occur when the binarization results are not correct. The accuracy of template matching is evaluated by the correlation coefficient $C(a,b)$ as follows. If the correlation coefficient is bigger than a certain threshold, the matching result will be regarded as a GCP.

$$C(a,b) = \sum_{m=0}^{N-1}\sum_{n=0}^{N-1} \frac{\{I_{(a,b)}(m,n) - \bar{I})\}\{T(m,n) - \bar{T}\}}{\sqrt{I_{sab} \cdot T_s}} \tag{23}$$

$$\text{where} \quad \bar{I} = \frac{1}{N^2}\sum_{m=0}^{N-1}\sum_{n=0}^{N-1} I_{(a,b)}(m,n), \quad \bar{T} = \frac{1}{N^2}\sum_{m=0}^{N-1}\sum_{n=0}^{N-1} T(m,n),$$

$$I_{sab} = \sum_{m=0}^{N-1}\sum_{n=0}^{N-1}\{I_{(a,b)}(m,n) - \bar{I}\}^2, \quad T_s = \sum_{m=0}^{N-1}\sum_{n=0}^{N-1}\{T(m,n) - \bar{T}\}^2.$$

where (a,b) is the coordinates of upper left point of template, $T(m,n)$ is the coordinates of template and $I_{(a,b)}(m,n)$ is the coordinates corresponding image patch.

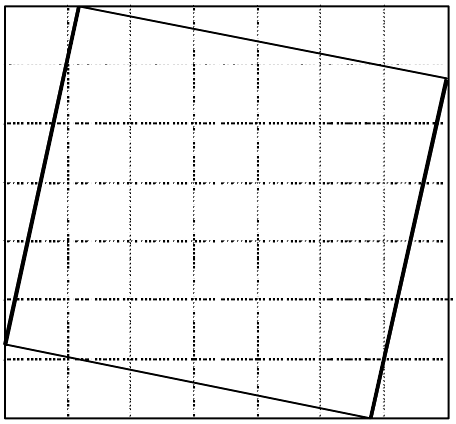
5)Mapping

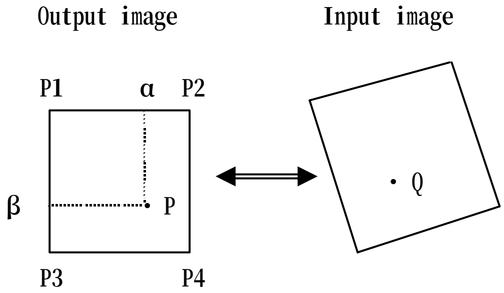
In general, the coordinates transformation for mapping is carried out as follows.

map coordinates (u,v) $\rightarrow$ ground coordinates (X,Y,Z) $\rightarrow$ image coordinates (L,P)

This transformation can be realized by the equation (18). But the transformation needs iteration and takes long times, so the calculation is carried out only on the grids with proper dimension and the image coordinates of the pixels on output image within the grids are calculated by bi-linear interpolation expressed in (24) utilizing the results of grids.

$$Q = Q_1(1-a)(1-b) + Q_2 a(1-b) + Q_3(1-a)b + Q_4 ab \tag{24}$$





In the work, two kinds of projection methods are adopted, Latitude/Longitude projection for middle and low latitude regions (60°N～60°S) and Polar Stereo projection for polar regions (90°N～50°N, 50°S～90°S). Both projections are expressed as follows.

Let map coordinate (u,v)=(horizontal, vertical), geographic coordinate (B,L)=(Latitude, Longitude) and S=scale factor.

a) Latitude/Longitude projection

$$\mathrm{u} = \mathrm{S} \cdot \mathrm{L} \qquad\qquad (25)$$

$$\mathrm{v} = \mathrm{S} \cdot \mathrm{B}$$

b) Polar Stereo projection

$$\mathrm{u} = \mathrm{S} \cdot \sin(L - L_0) \cdot \tan\left(\frac{p}{4} - \frac{\mathrm{B}}{2}\right)$$

$$\mathrm{v} = -\mathrm{NS} \cdot \mathrm{S} \cdot \cos(L - L_0) \cdot \tan\left(\frac{p}{4} - \frac{\mathrm{B}}{2}\right) \qquad\qquad (26)$$

$$\mathrm{B} = \mathrm{NS} \cdot \left(\frac{p}{2} - 2 \cdot \tan^{-1}\left(\frac{\sqrt{\mathrm{u}^2 + \mathrm{v}^2}}{S}\right)\right) \qquad\qquad (27)$$

$$\mathrm{L} = \mathrm{L}_0 - \mathrm{NS} \cdot \tan^{-1}\left(\mathrm{u}/\mathrm{v}\right)$$

L_0: Reference Longitude, NS=1: Northern Hemisphere, =-1: Southern Hemisphere

C. Practical Considerations

One scene defined in the GLI processing system is so small that it will often occur that no GCP can be extracted from one scene. To avoid such circumstances, the processes of the GCP collection and the exterior orientation should be carried out over one tilt segment. A large memory size is necessary for realizing such processes, as coastal line data and original image data for one tilt segment are stored on the main memory.

In the mapping process, a huge channels of image data as well as the scan geometry data (solar zenith and azimuth angles, satellite zenith and azimuth angles), cloud flag and L/O flag are rectified at a time, and they have the different record length. All of those input data should be stored on the main memory to accelerate the process time.

As mentioned above, the algorithm of 'LTSKG' can be realized only on a high performance computer with a large memory and disk volume and a fast clock time.

(1) Programming, Procedural, Running Considerations

Program Requirements: The following table shows information about the expected software generated from this algorithm

Program Memory	Large, as a huge amount of data is stored on the memory.
Program Size	Not so large.
Required Channels	Near infrared channel (TBD) for GCP matching. All channels of land for mapping.
Necessary/Ancillary Data	Generic Mapping Tool (GMT) coastal line data required. Ground Control Point (GCP) library has to be developed. DEM(GTOPO30) is necessary for the data with 250m resolution.
Expected Disk Volume	As big as possible.
Special Programs or Subroutines	Not so special.

(2) Calibration and validation

The validation of the geometric correction may be realized by the following schemes;

- To evaluate the accuracy of exterior orientation around GCPs,
- To evaluate the corrected image overlaid with coastal lines by human interpretation.

(3) Quality Control and Diagnostic Information (TBD)

(4) Exception Handling (TBD)

(5) Constraints, Limitations, Assumptions (TBD)

(6) Publications and Papers (TBD)

D. References

1. NOAA/NESDIS, *NOAA KLM User's Guide : Appendix I,* on WWW.
2. Hashimoto, H. and Murai, S., *Fast and Accurate Geometric Correction of NOAA AVHRR Imagery,* Archives of 17th ISPRS, 1992, 445-450.
3. Patt, F. S., et al, *Exact closed-form geolocation algorithm for Earth survey sensors,* Int'l Journal of Remote Sensing, 1994, Vol.15, No.18, 3719-3734.
4. Rosborough, G. W., et al, *Precise AVHRR Image Navigation,* IEEE Trans. On Geoscience and Remote Sensing, 1994, Vol.32, No.3, 644-657.