6 Generation Of Geometric Correction Information

6.1 Overview

(1) Registration Correction

System correction method is applied basically for OCTS geometric correction map projection. OCTS scans by 10 elements for one scan and has tilting mechanism, these cause huge geometric distortion and discontinuity for raw images (Fig.6.1-1). For these reasons, system correction is not applied directly. Registration error between bands is also generated by different position assignment of detectors on focus plane for different bands. It is required to adjust registrations for bands when atmospheric correction is applied. Therefore, geometric correction is performed with registration correction at its previous stage. Registration correction should include registration correction between bands and also discontinuity correction between scan lines. After these corrections, normal system correction method is applied for further processing. Registration correction starts from the extracting of a pixel that is the closest to the most ideal position where ground track of OCTS optical axis is the ideal scanning position. The concept of registration correction is show in Fig. 6.1-2.

(2) System Correction

System correction is performed by the following procedure.

a) Generation of coordinate conversion function
Address for coordinates of output image (map projected image) which is corresponding to position of every pixel of input image (Level 1B image: image registration corrected) is determined by geometric model of the sensor, orbit, attitude data, model of the earth, map projections and so on. That is, the generation of coordinate conversion functions from the coordinates of input image to that of output image. Functions for this conversion are shown in Table 6.1 -1.

b) Calculation of geometric correction coefficients
At first, output image is divided to appropriate size blocks. Then, the address of grids points of the blocks is converted into input image address by convergence operation using functions for coordinate transformation mentioned in a) .

c) Resampling
Output image (map projected image) is generated by each pixel on map projection coordinates to be output by resampling each target pixel, performing liner interpolation on level 1B image address that corresponds grid points calculated in b). NN (Nearest Neighbor) method or BL (Bi-Linear) method is applied as resampling method for map projection. Conceptual drawing of System Correction is shown in Fig. 6.1 -3.

(3)　Sun and Satellite position information

It is required to the difference between get zenith angles of the sun and the satellite, and difference of azimuth angle between the sun and the satellite at each pixel for atmospheric correction.　For this calculation, the following procedure is adopted to reduce computation time for calculation at each pixel.　Divide raw image into blocks and calculate satellite zenith angle and azimuth angle by each grid points and perform liner interpolation within a block.　Registration corrected images is also divided into blocks and zenith of　the sun and azimuth angle at each grid points are calculated and liner interpolation is performed within a block.

(4)　Bin Processing

Bin products are generated for OCTS.　Bin is the blocked unit divided by longitude and latitude lines of the earth surface and the physical quantity generated from one scene image is gathered to one Bin unit.　And data for multiple scenes are gathered chronologically, then global data for the periods of day, week, month and year are generated.　For this purpose, it is required to calculate to identify which Bin each pixel of Level 2 (same as Level 1B image geometrically) belongs. This means that pixel address of Level 1B image needs to be converted to latitude and longitude.　For this, approximation method by Pseudo Affine Transformation method is also to be used to convert from image addresses at each block which is divided from Level 1B image to latitude and longitude of blocks.　Definition of Bin is shown in Fig. 6.1-4.

From the above,　coefficients to be calculated for geometric correction are as follows;

- Level 1B address to correspond crossing point on map projected image.
- Zenith and azimuth angles of the satellite corresponding to crossing points on raw image.
- Zenith and azimuth angles of the sun corresponding to crossing points on Level 1B image.
- Latitude and longitude corresponding to crossing points on level 1B.

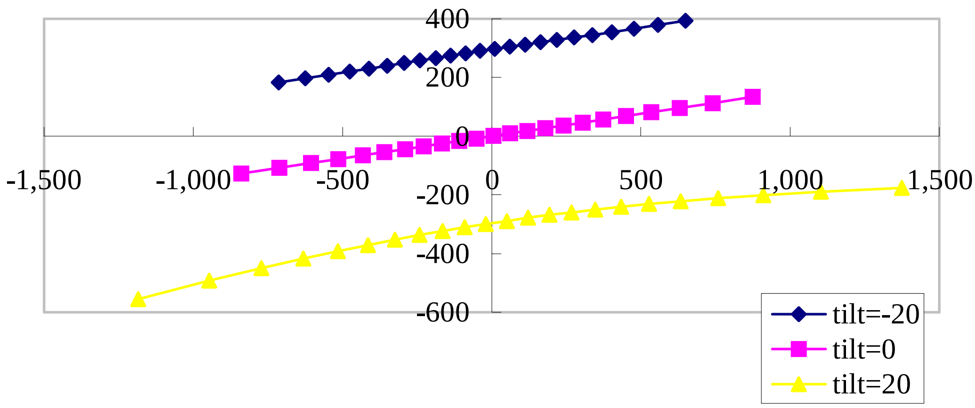
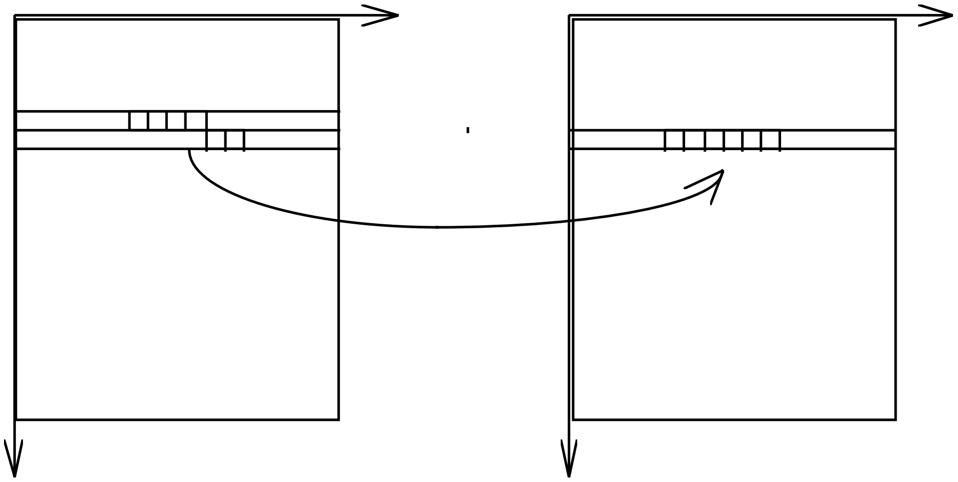


Fig. 6.1 -1 Conceptual Drawing Of OCTS Scanning



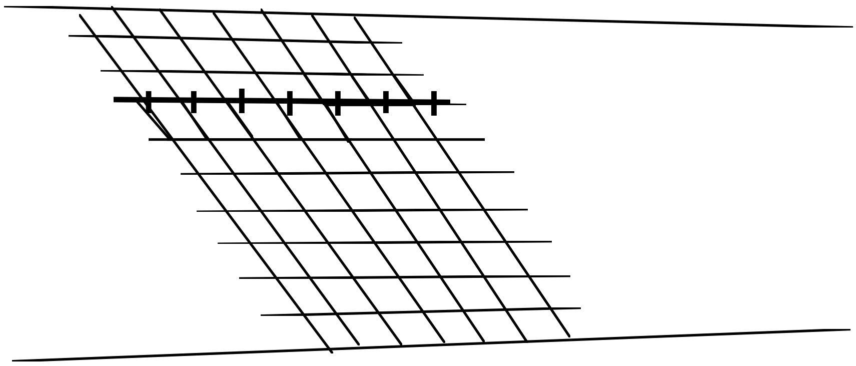


Fig. 6.1-2 Conceptual Drawing of Registration Correction

Table 6.1-1 Functions for Coordinates Conversion

No.	Abbreviation	Contents
1	F1	Conversion from Address of Level 1B image to EOR coordinates of imaging point
2	F2	Conversion from ECR Coordinates to Geodetic Latitude and Longitude
3	F3	Conversion from Geodetic Latitude and Longitude to Map Coordinates
4	F4	Conversion from Map Coordinates to Address of Map Projection image

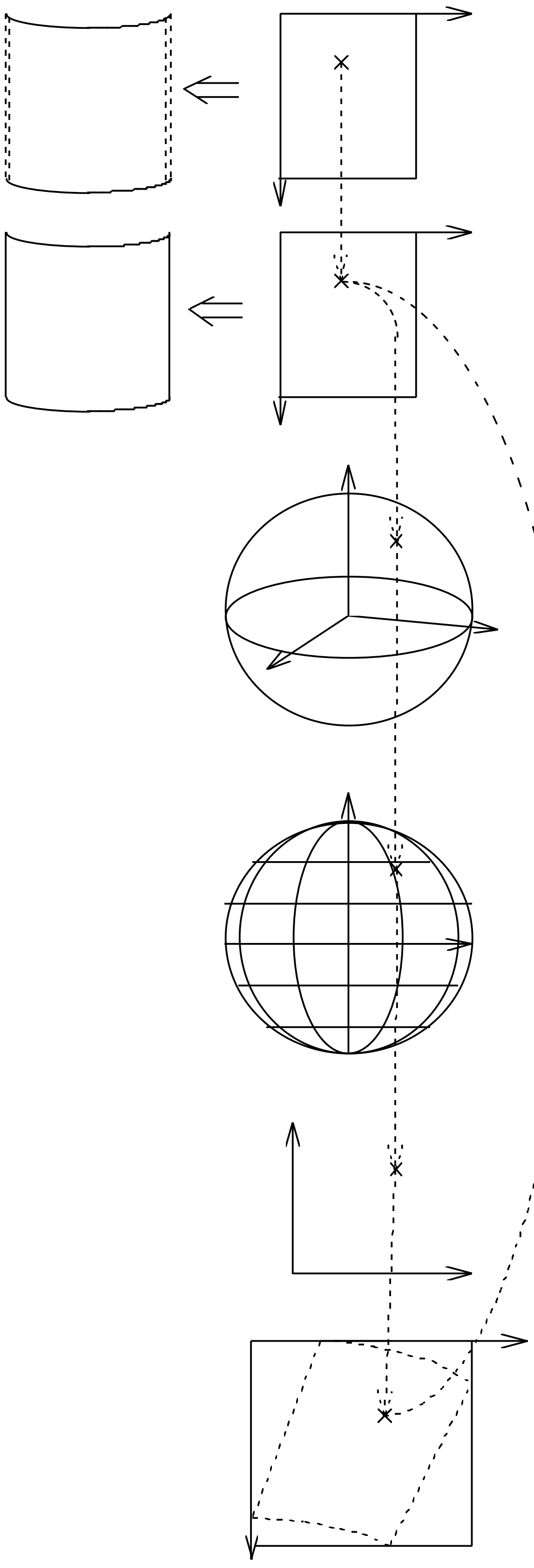


Fig. 6.1-3 Conceptual Drawing of System Correction

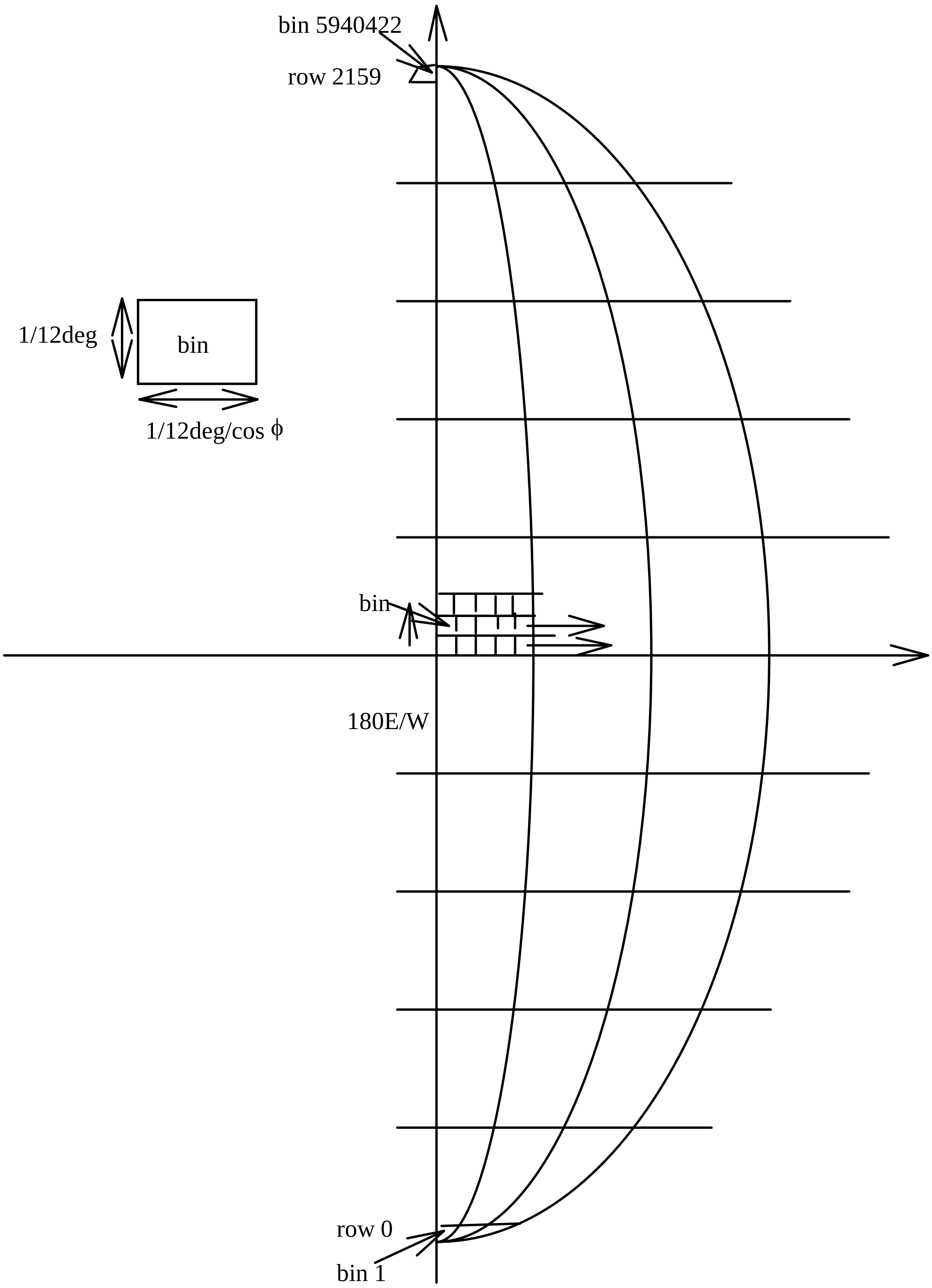


Fig. 6.1-4 Definition of Bin

6.2 Geometric Model

6.2.1 Definition Of Model

(1) Definition of Coordinate Systems

Definition of Coordinates to describe OCTS Geometric Model is shown in Table 6.2-1.

Table 6.2-1 Coordinates used for OCTS Geometric Mode

No.	Coordinates	Coordinate System Definition
1	OCTS Standard	Determined by side on which OCTS frame is installed. Coordinate Axes correspond to Satellite Coordinate system excepting Alignment error.
2	OCTS System	Determined by Alignment Mirror on OCTS frame. Coordinate Axes correspond to Satellite Coordinate system excepting Alignment error. Coordinates for each alignment measurement. Correlation with OCTS Standard Coordinates is measured.
3	Optics (detector segment)	Determined by Alignment Mirror of Optics. Coordinate Axes correspond to OCTS standard Coordinate system except Alignment error.
4	Scanning Mechanism	Coordinate Axes correspond to OCTS standard Coordinate system except Installation error.

(2) Coordinate Conversion

Coordinate conversion between OCTS Coordinate Systems is performed by rotation of Euler angle. Revolution of coordinates around (X,Y,Z) axes is shown in the following matrices;

$$R_X(\phi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix}$$

$$R_Y(\theta) = \begin{pmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{pmatrix} \qquad (6.2\text{-}1)$$

$$R_Z(\psi) = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Revolving of directional vector around (X,Y,Z) axes is shown in the following matrices;

$$\breve{\mathbf{R}}_{\mathbf{X}}(r)=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos r & -\sin r\\ 0 & \sin r & \cos r\end{pmatrix}$$

$$\breve{\mathbf{R}}_{\mathbf{Y}}(p)=\begin{pmatrix}\cos p & 0 & \sin p\\ 0 & 1 & 0\\ -\sin p & 0 & \cos p\end{pmatrix} \qquad (6.2\text{-}2)$$

$$\breve{\mathbf{R}}_{\mathbf{Z}}(r)=\begin{pmatrix}\cos y & -\sin y & 0\\ \sin y & \cos y & 0\\ 0 & 0 & 1\end{pmatrix}$$

a) Conversion from optics unit coordinate system to OCTS standard coordinate system.

The conversion from the optics coordinate system to OCTS standard coordinate system is a conversion on the alignment errors in optics. Analytical data for measured values of alignment angles at ground test and self-weight distortion are used for this conversion.

When there are discrepant angles around X, Y, or Z axes between optics coordinate system and OCTS standard coordinates based on the results of alignment measurement, are $\psi_{OC1},\psi_{OC2},\psi_{OC3}$ respectively, and self-weight distortion around each axis at the time of alignment measurement is expressed as $\psi_{OG1},\psi_{OG2},\psi_{OG3}$,

$$\mathbf{P_C}=\tilde{\mathbf{R}}_{\mathbf{Z}}(\psi_{OC3}-\psi_{OG3})\tilde{\mathbf{R}}_{\mathbf{Y}}(\psi_{OC2}-\psi_{OG2})\tilde{\mathbf{R}}_{\mathbf{X}}(\psi_{OC1}-\psi_{OG1}) \qquad (6.2\text{-}3)$$

directional vector by optics coordinate system x_O is converted to the vector X by OCTS standard coordinate system as follows:

$$\vec{X}=\mathbf{P_C}\vec{x}_O \qquad (6.2\text{-}4)$$

b) Conversion from Scanning Mechanism coordinate system to OCTS Standard Coordinate System

The conversion from Scanning Mechanism coordinate system to OCTS standard coordinate system is a conversion on the alignment error of the Scanning Mechanism. Analytical data for measurement value of alignment angles at ground test and self-weight distortion are used for this conversion.

If alignment measurement angles around X, Y, Z axes for OCTS reference coordinates of Scanning Mechanism are $\psi_{SC1},\psi_{SC2},\psi_{SC3}$, and Euler angle on self-weight distortion are expressed as $\psi_{SG1},\psi_{SG2},\psi_{SG3}$, then

$$\mathbf{Q_C}=\tilde{\mathbf{R}}_{\mathbf{Z}}(\psi_{SC3}-\psi_{SG3})\tilde{\mathbf{R}}_{\mathbf{Y}}(\psi_{SC2}-\psi_{SG2})\tilde{\mathbf{R}}_{\mathbf{X}}(\psi_{SC1}-\psi_{SG1}), \qquad (6.2\text{-}5)$$

directional vector x_S by Scanning Mechanism coordinate system x is converted to the vector by OCTS Standard coordinate system as follows.

$$\vec{X}=\mathbf{Q_C}\vec{x}_S \qquad (6.2\text{-}6)$$

C) Conversion from OCTS standard coordinate system to Satellite Coordinate System

Conversion from OCTS standard coordinate system to satellite coordinate system I_s the conversion on OCTS alignment. If RX3,RY3,RZ3 are alignment angles around X-Axis, Y-Axis and Z-Axis respectively and

$$\mathbf{P_B} = R_Z(-RZ3)R_Y(-RZ3)R_X(-RZ3) \quad (6.2\text{-}7)$$

is determined, directional vector $\vec{X}$ by OCTS standard coordinates is converted to directional vector $\vec{X}_B$ by satellite coordinates by the following equation.

$$\vec{X}_B = \mathbf{P_B}\vec{X} \quad (6.2\text{-}8)$$

d) Conversion from Satellite Coordinate System to Orbit Coordinate System

This is the conversion on altitude angle of the satellite. If RX1,RY1,RZ1 are roll, pitch and yaw angles respectively, by the following equation,

$$\mathbf{P_O} = R_Z(-RZ1)R_Y(-RZ1)R_X(-RZ1) \quad (6.2\text{-}9)$$

the directional vector $\vec{X}_B$ is converted to the directional vector $\vec{X}_O$ by orbit coordinate system as follows.

$$\vec{X}_O = \mathbf{P_O}\vec{X}_B \quad (6.2\text{-}10)$$

e) Conversion from Satellite Coordinate (ECR) System

As defined in Section 1.4, orbit coordinates are coordinates which define Z axis from the satellite's center of gravity to the center of the earth, and Y axis, which shows the opposite direction from orbit side vector. Satellite position and velocity vectors in ECR are used for conversion from orbit coordinates to ECR coordinates. Unit vectors in the direction of X, Y and Z axes by orbit coordinate are expressed as x, y, z by earth frames; equations are as follows.

$$\mathbf{z} = \frac{\mathbf{X_E}}{|\mathbf{X_E}|}$$

$$\mathbf{y} = \frac{-\mathbf{X_E}\times\mathbf{V_E}}{|\mathbf{X_E}\times\mathbf{V_E}|} \quad (6.2\text{-}11)$$

$$\mathbf{x} = \mathbf{y}\times\mathbf{z}$$

Therefore, if conversion of these vectors as row vectors is expressed as follows,

$$\mathbf{P_E} = (\mathbf{x} \quad \mathbf{y} \quad \mathbf{z}) \quad (6.2\text{-}12)$$

directional vector $\vec{X}_O$ by orbit coordinates is converted to directional vector $\vec{X}_\mathbf{E}$ by the following equation.

$$\vec{X}_\mathbf{E} = \mathbf{P_E}\vec{X}_O \quad (6.2\text{-}13)$$

Relationship between orbit coordinates and ECR is shown in Fig. 6.2-1.

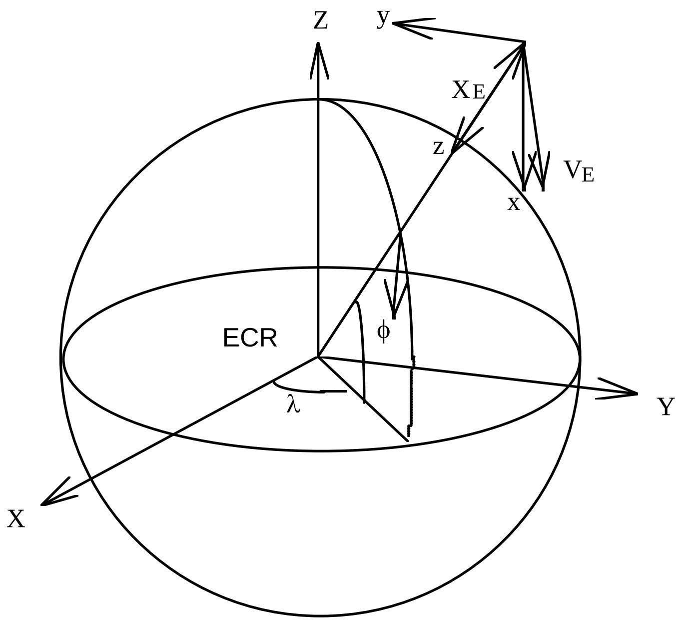


Fig. 6.2-1 Orbit Coordinates and ECR

(3) Definition of Tilting Rotation Angle and Scanner Rotating Angle

The following Coordinate system is defined in order to define tilting angle and scanner rotating angle.

A. Scanning Mechanism Coordinates

X-Axis is in the direction of scanning axis, and the axis perpendicular to scanning axis, on the plane in which normal vector of scan mirror and scanning axis are included, is Y-Axis. Y-Axis is located in the direction of Z x X. This coordinate system revolves along scanning mirror. However, Tilting axis is defined as Y-Axis of the Scanning mechanism coordinate system . However, this coincides with the scanning axis coordinate system when scanning rotating angle is zero. The redirection of normal vector of scan mirror is expressed with the following coordinate system.

$$\mathbf{n}_A = \begin{pmatrix} \sin\left(-\frac{\pi}{4}+\varepsilon\right) \\ \cos\left(-\frac{\pi}{4}+\varepsilon\right) \end{pmatrix} \qquad (6.2\text{-}14)$$

Here, ε is error angle in installing scanning mirror.

B. Scanning axis coordinate system

With scanning direction X-Axis, this coordinate system has Y-Axis in the plane including scanning axis and tilt axis. Rotation angle from scanning coordinate system to scanning mirror coordinates system is defined as scanner rotating angle. However, scanning angle zero on resolver is defined in the negative pitch direction of normal vector of scan mirror, scanning angle 0 here is in the direction of the nadir (Z-Axis). Coordinate conversion from scanning mirror coordinates to scanning axis coordinates are determined by the following equation.

$$\vec{X}_B = \tilde{\mathbf{R}}_{\mathbf{X}}(\omega)\vec{X}_A \tag{6.2-15}$$

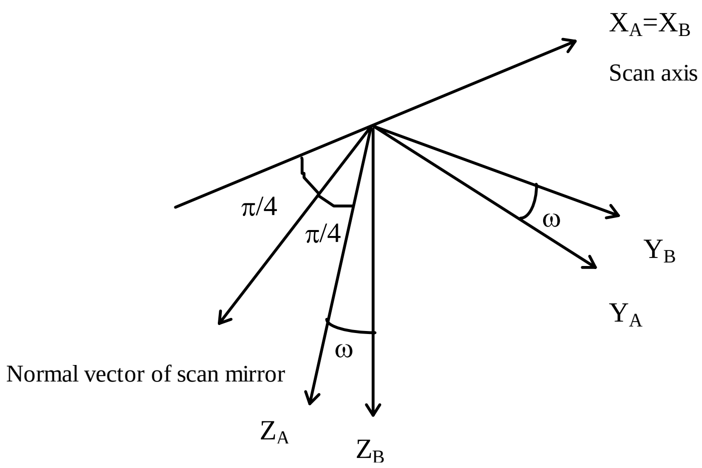


Fig. 6.2-2 Definitions of Scanning mirror coordinates and Scanning axis coordinates

C. Tilt Axis coordinates

With tilting direction Y-Axis, this coordinate system has Y-Axis in the plane including scanning axis and tilt axis. This revolves with tilt and coincides with scanning axes coordinates except for installation error of scanning axis. Coordinate conversion from scanning axis coordinates to tilting axis coordinates is expressed with the following equation.

$$\vec{X}_C = R_Z(\delta)\vec{X}_B \tag{6.2-16}$$

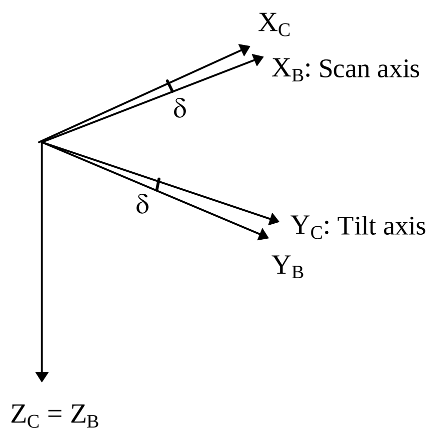


Fig. 6.2-3 Scanning Axis Coordinates and Tilt Axis Coordinates

D. Tilt Coordinates

These coordinates define tilt axis direction as Y-axis when tilt angle is 0. Revolving angle to tilt axis coordinates is tilt revolving angle. Conversion from tilt axis coordinates to tilt coordinates is expressed by the following equation.

$$\vec{X}_D = \tilde{\mathbf{R}}_Y(\theta)\vec{X}_C \qquad (6.2\text{-}17)$$

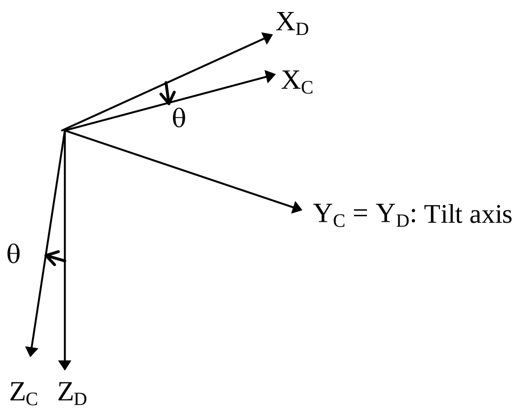


Fig. 6.2-4 Tilt axis coordinates and tilt coordinates

Conversion from tilt coordinates to scan mechanism coordinates is pertaining to installation error angle of scanning mechanism, and when error angle around X, Y and Z axis is SA1, SA2 and SA3 respectively, by stating that

$$\mathbf{Q_A} = \tilde{\mathbf{R}}_\mathbf{Z}(SA3)\tilde{\mathbf{R}}_\mathbf{Y}(SA2)\tilde{\mathbf{R}}_\mathbf{X}(SA1) \qquad (6.2\text{-}18)$$

conversion is expressed as the following.

$$\vec{X}_S = \mathbf{Q_A} \vec{X}_D \tag{6.2-19}$$

Tilting angle is positive rotation angle around tilting axis (Y Axis) of scanning axis of scanning mirror, and tilting angle coincides with the principal axis when the tilting angle is zero. The effective tilting angle is twice of tilting rotation angle (due to mirror reflection).

Direction of scanning axis of scanning mirror at zero tilting angle is defined as X-Axis of Scanning Mechanism Coordinates. The scanning rotation angle is positive rotation angle around tilting axis (X-Axis) of the scanning mirror, and the principal axis reflected by scanning mirror at zero tilting rotation angle crosses ZX plane of the scanning mechanism. The effective scanning angle is the rotation angle around X-Axis of reflected principal axis, and it does not coincide with scanning rotation angle at tilting.

Fig.6.2-5 shows the definitions of Tilting rotation angle ω and Scanning rotation angle θ.

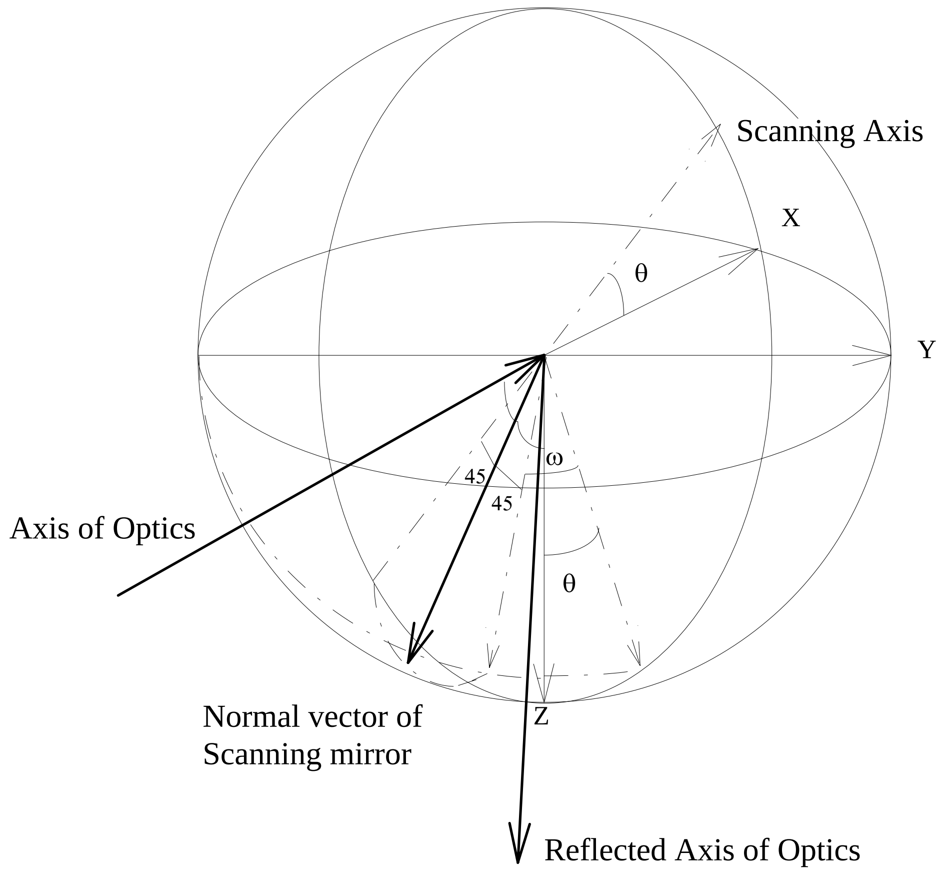


Fig. 6.2-5 Tilting rotation angle and Scanning rotation angle

6.2.2 Calculation Of Line-Of-Sight Vector

In order to perform geometric correction of image, it is necessary to be able to determine OCTS line-of-sight vector as a function of image pixels and line numbers of each pixel. In Level 1A images (except GAC), the pixel number is a sample number in OCTS raw data. The remainder of the line number after division by 10 is the detector number, and its quotient is the scan number. Pixel position coincides with scanning axis track of ideal line-of-sight vector as defined by a certain method. Also, since registration correction is performed during sub sampling input, GAC is already a registration-corrected image equivalent to level 1B at the level 1A stage.

(1) Line-of-sight vector in the optics unit

Line-of-sight vector in the optics unit is expressed as follows by optics coordinate system;

$$\mathbf{a}(m,n) = \frac{\mathbf{a}'}{|\mathbf{a}'|}$$

$$\mathbf{a}'(m,n) = \begin{pmatrix} 1 \\ \Delta \cdot (m + dm) \\ \Delta \cdot (n + dn) \end{pmatrix} \qquad (6.2\text{-}20)$$

In this equation, (m,n) is the normalized coordinates on focal plane, and it describes ideal position of detector element on focal plane. dm, dn express element alignment error and optics aberration. Δ corresponds to IFOV and it is expressed as follows using interval of the elements d and focal distance f ;

$$\Delta = d \,/\, f \qquad (6.2\text{-}21)$$

The conceptual drawing for line-of-sight vector in optics is shown in Fig.6.2-6. For generating level 1B image with registration correction, it uses directional vector in the optics direction as line-of-sight vector in order to determine ideal imaging point to be used as reference. It is expressed as follows in the coordinates in optics;

$$\mathbf{a} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad (6.2\text{-}22)$$

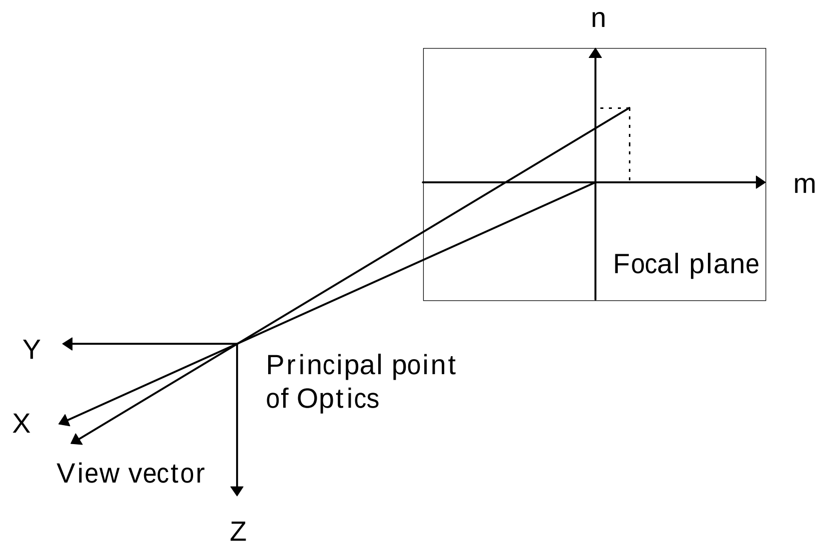


Fig.6.2-6 Line-of-sight Vector in Optics

Element allocation on focal plane is when in Fig.6.2-7. Value m that corresponds to each value is as follows;

Band	1	2	3	4	5	6	7	8	9	10	11	12
m	0.5	-6.5	7.5	14.5	-9.5	-2.5	4.5	11.5	-14.5	-6.5	0.5	7.5

n value that corresponds to each detector is expressed as $n_j = j - 5.5$ ($j = 1,....10$)

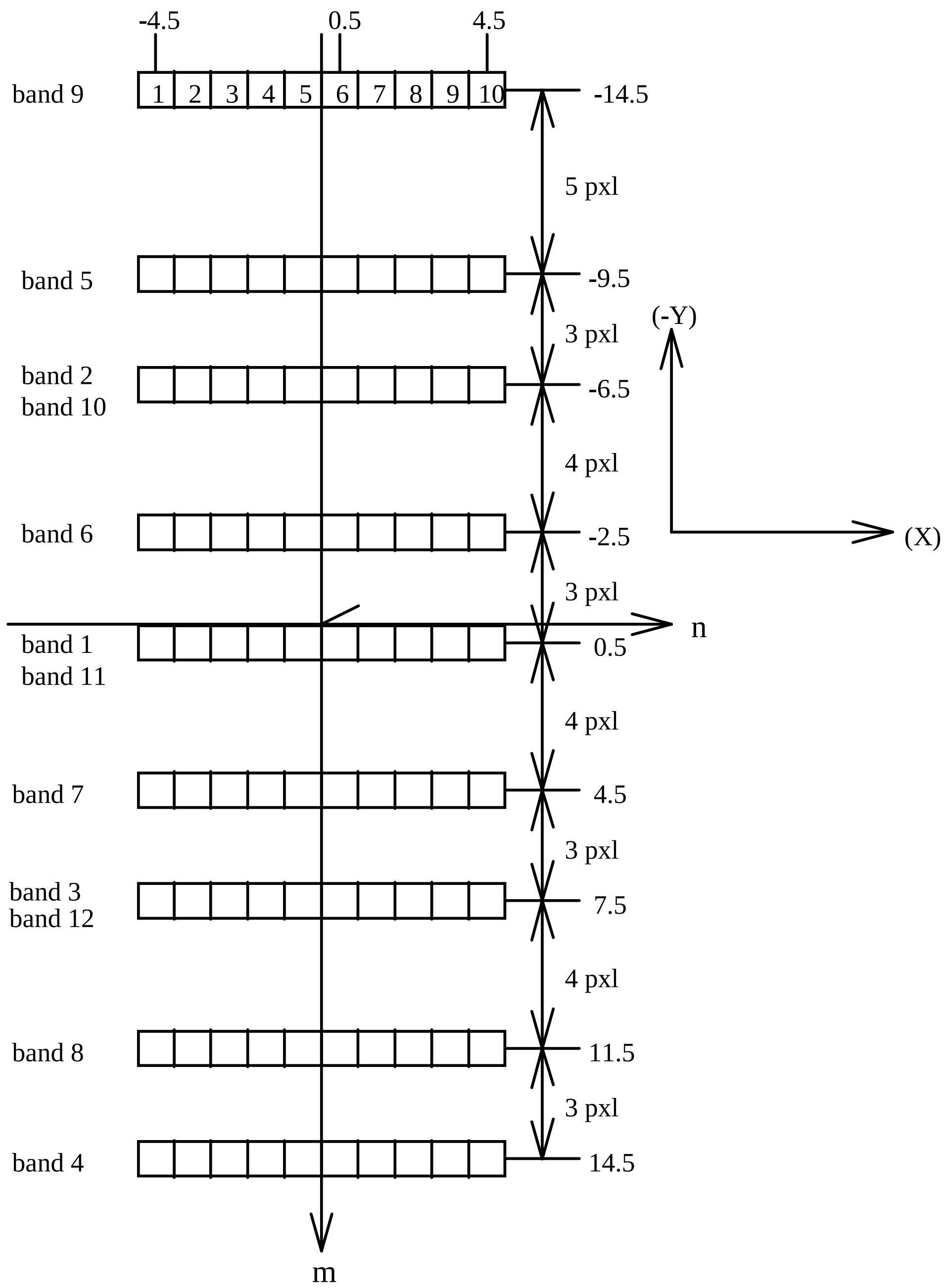


Fig. 6.2-7 Element allocation

(2) Line-of-sight vector a in the OCTS reference coordinate system

The line-of-sight vector in optics calculated in above (1) is converted to OCTS reference coordinate system. According to equation (6.2-4), the line-of-sight vector $\mathbf{a_0}$ in OCTS reference coordinates is calculated by the following equation from the line-of-sight vector $\mathbf{a}$ by coordinates in optics:

$$\mathbf{a_0} = \mathbf{P_C a} \tag{6.2-23}$$

(3) Calculation of Normal Vector of Scanning Mirror

a) Calculation of Tilting Angle

Tilting angle is calculated from telemetry data of rotation angle (output value of the resolver). The output value of the resolver θ'' is converted to the true tilting angle θ,using the correction table generated from ground test data.

b) Calculation of Rotating Angle of Scan

The scanning rotation angle is not telemetered. It is detected by scan resolver, and pixel data is sampled by at certain rotation angles.

One scanning period is divided by $2^{18}/30$ in the inside of OCTS. Also, sample number is counted from minus pitch direction, and ground surface imaging data corresponds to 5443 to 7664 by this sample number. Therefore, nominal value at ω'(n) of scanning rotation angle for number n pixel (n = 0 to 2221) obtained from the following;

$$\omega'(n) = 2\pi \frac{5443 + n}{2^{18}/30} - \frac{3}{2}\pi \tag{6.2-24}$$

The tilting angle calculated by above equation does not coincide with actual tilting angle due to resolver error and installation error. True scanning rotation angle is corrected by using the scanning rotation angle correction table by ground test data. However, in real operation, imaging of 10 detectors are not performed simultaneously since there is variation in sample time. So, scanning rotation angle is expressed as follows.

$$\omega'(n) = 2\pi\left(\frac{5443 + n}{2^{18}/30} + \frac{P_d}{P_s}k\right) - \frac{3}{2}\pi - \alpha \tag{6.2-25}$$

In this equation,

$\alpha(n)$: Correction value of resolver

P_s: Scanning period (0.905sec)

P_d: Detector imaging period (9.33 x 10-6sec)

k: Detector number (0 - 9)

In case of a level 1B image (pixel position is reference scanning position for registration correction) it is assumed that the ideal line-of-sight vector is sampled within a certain range of scanning angle in a nominal sampling rate. That is, scanning rotation angle is calculated after assigning level 1B pixel number to level 1A sample numbers , using equation 6.2-24.

As level 1A image becomes greater, scan range on the ground that corresponds to sample range increases; therefore, in the case of tilt 0 and -20 degrees, pixels out of effective scan range may be included at both ends among all 2222 pixels. For this reason, the number of pixels are determined for level 1B images so that images can be generated within a range that doesn't include excluded domain.

Level 1A sample numbers that correspond to level 1B pixel numbers are indicated as follows.

$$n = n' + \frac{1}{2}(2222 - N) \qquad \text{(for LAC)}$$

$$n = (n' + 0.5) \cdot r_{ss} - 0.5 + \frac{1}{2}(2222 - N \cdot r_{ss}) \qquad \text{(for GAC)} \qquad (6.2\text{-}26)$$

In this equation,

n' : Level 1B pixel number (0 ~ N-1)
N : Number of level 1B pixels
r_{ss} : GAC subsampling rate (column direction)

c) Calculation of Normal Vector of Scanning Mirror

If Matrices to express Vector rotation around X-Axis, Y-Axis and Z-Axis are expressed as follows;

$$\mathbf{n}(\theta,\omega) = \mathbf{Q_A}\breve{\mathbf{R}}_\mathbf{Y}(\theta)\breve{\mathbf{R}}_\mathbf{X}(\omega)\mathbf{n_A} \qquad (6.2\text{-}27)$$

In this equation, since installation error δ is negligibly small and below the level of random variation, it is ignored here.

(4) Normal Vector of Scanning Mirror in the OCTS Standard Coordinate System

Normal vector of scanning mirror in the scanning mechanism coordinate system $\mathbf{n}(\theta,\omega)$ is converted to vector $\mathbf{n_0}(\theta,\omega)$ in the OCTS reference coordinate system with SMA alignment data by equation (6.2-6);

$$\mathbf{n_0} = \mathbf{Q_C}\mathbf{n} \qquad (6.2\text{-}28)$$

(5) Calculation of OCTS Line-of-sight Vector

The line-of-sight vector b as OCTS line-of-sight vector in the OCTS reference coordinate system can be obtained from normal vector of scanning mirror and optical line-of-sight by the following equation. (mirror reflection)

$$\mathbf{b} = \mathbf{a_0} - (2\mathbf{a_0} \bullet \mathbf{n_0})\mathbf{n_0} \qquad (6.2\text{-}29)$$

(6) Calculation of Line-of-sight Vector in the satellite coordinate system

Line-of-sight vector in the OCTS reference coordinate system is converted to that of satellite coordinate system with OCTS alignment data by the equation.

$$\mathbf{b_B} = \mathbf{P_B}\mathbf{b} \qquad (6.2\text{-}30)$$

(7) Calculation of Line-of-sight Vector in the orbit coordinate system

Line-of-sight Vector in the satellite coordinate system is converted to that of in the orbit coordinate system by the equation.

$$T_{ijk} = Ts_i + \Delta T_i + Ps \cdot \left(j + 5443 \right) \cdot r_s + Pd \cdot k \qquad (6.2\text{-}31)$$

In this equation,

- i : Scan number
- j : Pixel number (0 - 2221)
- k : Detector number (0 -9)
- Ts_i : Satellite time (corrected)
- ΔT_i : OCTS scan time offset
- Ps : Scan (0.905sec) period
- r_s : Sean rate per pixel ($\frac{1}{2^{18}/30}$)
- Pd : Detector imaging rate (9.33×10^{-6} sec)

However, due to accuracy problem of ΔT data, time calculated by the above equation generates error. Therefore, in real operation, interpolation is performed on scanning rather than on time. That is, an expanded scan number is calculated for each pixel and interpolated. Scan number s is calculated by the following equation.

$$s = i + \left(j - j_0 \right) \cdot r_s \qquad (6.2\text{-}32)$$

In this equation, j_0 is scan number which corresponds to nadir direction. Scan time is converted from frame time measured to the time when nadir is scanned from frame time measured in the minus pitch direction in preprocessing. Lagrange interpolating is applied to the orbit and attitude of that time. A section related to detector imaging period is ignored due to its negligible size. Pixel number j_0 to scan nadir direction is as follows.

$$j_0 = \frac{3}{4} \cdot \frac{1}{r_s} - 5443 \qquad (6.2\text{-}33)$$

For line-of-sight vector (registration correction in the direction of reference scanning direction)), scanning time for pixel numbers and line number are defined as follows:

$$s = \left(l - 4.5 \right) / 10 + \left(j - j_0 \right) \cdot r_s \qquad \text{(for LAC)}$$

$$s = \left(l - 0.5 \right) / 2 + \left(j - j_0 \right) \cdot r_s \qquad \text{(for GAC)} \qquad (6.2\text{-}34)$$

In this equation, j is a value obtained by converting p to corresponding level 1A pixel number by equation 6.2-26.

Linear interpolation is performed to scan numbers calculated above in order to calculate orbit and attitude data for each pixel as follows. That is, if y_i is orbit data or attitude data of scanning i , data interpolated by scanning s is shown in the following equation.

$$y(s) = \left(1 - r \right) y_i + r \cdot y_{i+1} \qquad (6.2\text{-}35)$$

$i = [s]$ (round off to the nearest whole number)

$r = s - i$

(8) Calculation of Line-of-Sight Vector in Orbit Coordinate System

Line-of-sight vector in orbit coordinate system is converted to line-of-sight vector in orbit coordinate system by the equation (6.2-10) from attitude angle calculated by interpolation of each pixel by (7).

$$\mathbf{b_O} = \mathbf{P_O b_B} \qquad (6.2\text{-}36)$$

(9) Calculation of Line-of-Sight Vector in the ECR Coordinate System

Line-of-sight vector in earth frame is converted to line-of-sight vector in ECR from satellite position and velocity vector in ECR calculated from interpolation of each pixel by (7).

$$\mathbf{b_E} = \mathbf{P_E b_O} \qquad (6.2\text{-}37)$$

6.3 Coordinate Conversion Function

In order to perform geometric corrections, the correspondance between the pixel positions in the uncorrected image and those in the image to be generated must be calculated. When this calculation is carried out, categorized coordinate conversion functions are used for convenience, as follows. Coordinate functions used for the geometric correction for OCTS are shown in Table 6-3-1

Table 6.3-1 Coordinate conversion functions

No.	Abbriviation	Description
1	F1	Conversion from raw image (or Level 1B image) address to ECR coordinates of Imaging points
2	F2	Convert ECR coordinates to Geodesic Lat-Lon coordinates
3	F3	Convert Geodesic Lat-Lon to Map coordinates
4	F4	Convert Map coordinates to Map Projection image address

6.3.1 Function F1

The Function Fl converts addresses on level 1A image or level 1B image to ECR coordinates of imaging points. Imaging points are calculated as the intersection with earth ellipsoid (semi spheroid of each earth model) which is an extension from satellite position to line-of-sight vector. For this purpose, scanning rotation angle, tilting angle, satellite position/velocity data and attitude angle should be determined from image address and, using these OCTS line-of-sight vectors in ECR, coordinates are calculated. Refer to 6.1.2 " Calculation of line-of-sight vector " for this procedure.

(1) Calculation of ECR coordinates of imaging point

The line-of-sight vector of a pixel in the ECR coordinates is denoted as b_E and the satellite position at that time is denoted x_E. The position vector of imaging point p is expressed as follows: (see Fig.6.3-1)

$$\mathbf{p} = \mathbf{x_E} + \delta\,\mathbf{b_E}$$

The coordinates of an imaging point are found if we can determine δ, if we denote elements of $\mathbf{p}$ as $\mathbf{p}$ = (x,y,z), and if we can express the earth shape as spheroid. We can then obtain the following equation.

$$\frac{(x-\Delta x)^2}{a^2}+\frac{(y-\Delta y)^2}{a^2}+\frac{(z-\Delta z)^2}{b^2}=1 \qquad (6.3\text{-}1)$$

where a is the semi-major axis of the spheroid, b is semi-minor axis, and $(\Delta x, \Delta y, \Delta z)$ is the origin offset of the spheroid. $\mathbf{b_E}$ element is denoted as (u, v, w) and $\mathbf{x_E}$ as (x_E, y_E, z_E), this equation is obtained,

$$\left(\frac{u^2}{a^2}+\frac{v^2}{a^2}+\frac{w^2}{b^2}\right)\delta^2+2\left(\frac{(x_E-\Delta x)u}{a^2}+\frac{(y_E-\Delta y)v}{a^2}+\frac{(z_E-\Delta z)w}{b^2}\right)\delta$$
$$+\frac{(x_E-\Delta x)^2}{a^2}+\frac{(y_E-\Delta y)^2}{a^2}+\frac{(z_E-\Delta z)^2}{b^2}-1 = 0 \qquad (6.3\text{-}2)$$

Then, δ is also obtained as follows;

$$\delta=\frac{-B-\sqrt{B^2-AC}}{A} \qquad (6.3\text{-}3)$$

where,

$$A=\frac{u^2}{a^2}+\frac{v^2}{a^2}+\frac{w^2}{b^2}$$

$$B=\frac{(x_E-\Delta x)u}{a^2}+\frac{(y_E-\Delta y)v}{a^2}+\frac{(z_E-\Delta z)w}{b^2}$$

$$C=\frac{(x_E-\Delta x)^2}{a^2}+\frac{(y_E-\Delta y)^2}{a^2}+\frac{(z_E-\Delta z)^2}{b^2}-1$$

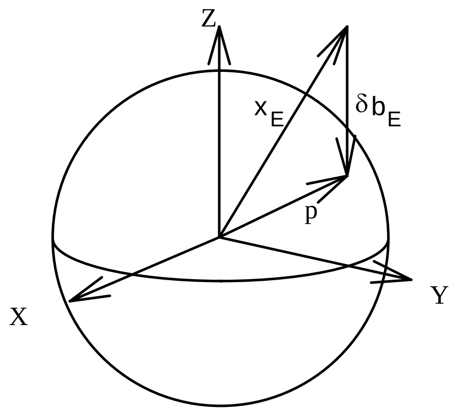


Fig. 6.3-1 the position vector of imaging point

6.3.2 Function F2

Function F2 converts values on earth frames (ECR) to geodetic latitude and longitude. It is necessary to consider the discrepancy between ECR and origin in cases such as a reference ellipsoid like Tokyo Bessel, which is used for local area map projections, or as an earth ellipsoid used for geodetic latitude and longitude. (refer to Fig,6,3-2). If coordinates on ECR are (x,y,z) and if the ECR origin is moved in parallel to the ellipsoid origin, then its coordinates on the coordinate system of the ellipsoid is (x', y', z')

$$\begin{cases} x' = x - \Delta x \\ y' = y - \Delta y \\ z' = z - \Delta z \end{cases} \tag{6-3-4}$$

where $(\Delta x, \Delta y, \Delta z)$ is offset of origin of reference spheroid. Geodetic latitude-longitude coordinates are written from the above;

$$\phi = \begin{cases} \arctan\left(\dfrac{\tan\varphi}{1-e^2}\right) & \cdots (x'^2 + y'^2 \neq 0) \\ \dfrac{\pi}{2} & \cdots (x' = y' = 0, z' > 0) \\ -\dfrac{\pi}{2} & \cdots (x' = y' = 0, z' < 0) \end{cases}$$

$$\tan\varphi = \frac{z'}{\sqrt{x'^2 + y'^2}} \qquad \cdots (x'^2 + y'^2 \neq 0)$$

$$
\lambda = \begin{cases} \dfrac{\pi}{2} - \arctan\left(\dfrac{x'}{y'}\right) & \cdots (y' > 0) \\ -\dfrac{\pi}{2} - \arctan\left(\dfrac{x'}{y'}\right) & \cdots (y' < 0) \\ 0 & \cdots (x' \geq 0, y' = 0) \\ \pi & \cdots (x' < 0, y' = 0) \end{cases} \qquad (6.3\text{-}5)
$$

where, e is eccentricity of reference earth ellipsoid

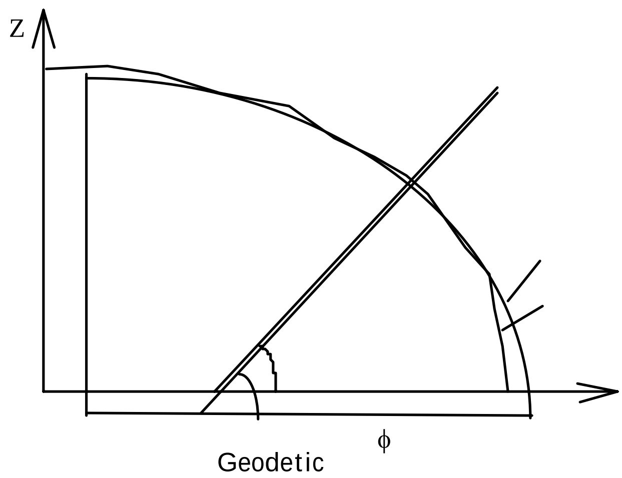


Fig. 6.3-2 ECR and Reference earth ellipsoid

6.3.3 Function F3

Function F3 converts geodetic latitude and longitude into map coordinates. For OCTS, there are Mercator projection, LCC (Lambert Coformal Conic) projection and PS (Polar Stereo) projection which can be applied.

(1) Function F3 for Mercator Projection

The Mercator Projection is rectangular longitudinal and cylindrical projection, and its parallels and meridians are orthogonal. Map coordinates (x,y) can be calculated from Geodetic latitude ϕ and longitude λ by the following equation;

$$\begin{cases} x = a\cos\phi_0 \cdot \lambda \\ y = a\cos\phi_0 \cdot \log\left(\tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \cdot \left(\frac{1 - e \cdot \sin\phi}{1 + e \cdot \sin\phi}\right)^{\frac{e}{2}} \right) \end{cases} \tag{6.3-6}$$

where a the equatorial radius of the earth and e is eccentricity, and É” 0 is the reference latitude.　The conceptual drawing of Mercator coordinate system is shown in Fig. 6.3-1.

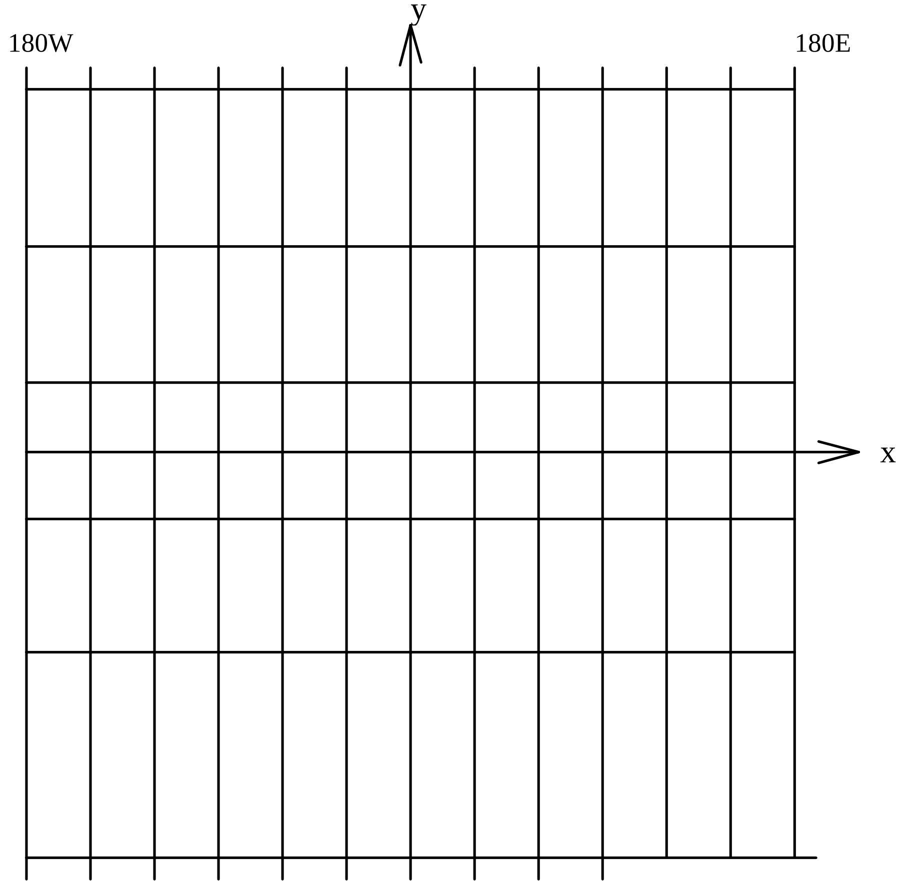


Fig. 6.3-1 Mercator coordinate system

(2) Function F3 for LCC Projection

The LCC (Lambert Conformal Conic) Projection is rectangular, longitudinal and has two standard parallel projection. On a map, parallels are expressed as concentric circles around the pole, and on the two standard parallels, distance is projected equally. In this projection, geodetic latitude and longitude (ϕ, λ) are converted to the radius of development radius ρ and zenith angle θ from the pole and zenith angle, then converted to the map coordinates (x, y) as the orthogonal coordinate system. Conversion equation is expressed as follows,

$$\begin{cases} x = \rho \cdot \sin\theta \\ y = -\rho \cdot \cos\theta \end{cases} \quad \text{(North pole)}$$

$$\begin{cases} x = \rho \cdot \sin\theta \\ y = -\rho \cdot \cos\theta \end{cases} \quad \text{(South pole)} \qquad (6.3\text{-}7)$$

but, $$\begin{cases} \rho = K \cdot \tan^{\mu} \dfrac{\xi}{2} \\ \theta = \mu \cdot (\lambda - \lambda_0) \end{cases}$$

where,

$$\tan\frac{\xi}{2} = \tan\left(\frac{\pi}{4} - \frac{\phi}{2}\right) \cdot \left(\frac{1 + e \cdot \sin\phi}{1 - e \cdot \sin\phi}\right)^{\frac{e}{2}}$$

$$\mu = \frac{\log(\cos\phi_1 / \cos\phi_2) + \log(N_1 / N_2)}{\log\left(\tan\frac{\xi_1}{2} \Big/ \tan\frac{\xi_2}{2}\right)} \qquad (6.3\text{-}8)$$

$$K = \frac{N_1 \cdot \cos\phi_1}{\mu \cdot \tan^{\mu} \frac{\xi_1}{2}} = \frac{N_2 \cdot \cos\phi_2}{\mu \cdot \tan^{\mu} \frac{\xi_2}{2}}$$

$$N_1 = \frac{a}{\sqrt{1 - e^2 \cdot \sin^2 \phi_1}} \quad N_2 = \frac{a}{\sqrt{1 - e^2 \cdot \sin^2 \phi_2}}$$

(In the case of the southern hemisphere, for ϕ, ϕ_1, ϕ_2, codes are reversed.)

Where, ϕ_1, ϕ_2 are reference latitudes and λ_0 is reference longitude for projection. e is eccentricity and a is equatorial radius. When true north is designated, reference longitude takes longitude of scene center and when map north is designated, as default, reference longitudes are as shown as Table 6.3-1.

Conceptual drawing of coordinates by LCC Projection is shown in Fig. 6.3-2.

Table 6.3-1 Reference Longitudes of LCC Projection

Scene Center Longitudes (deg.)	Standard Longitude (deg.)
-22.5 - +22.5	0
-22.5 - +67.5	45
+67.5 - +112.5	90
+112.5 - +157.5	135
+157.5 - -157.5	180
-157.5 - -112.5	-135
-112.5 - -67.5	-90
-67.5 - -22.5	-45

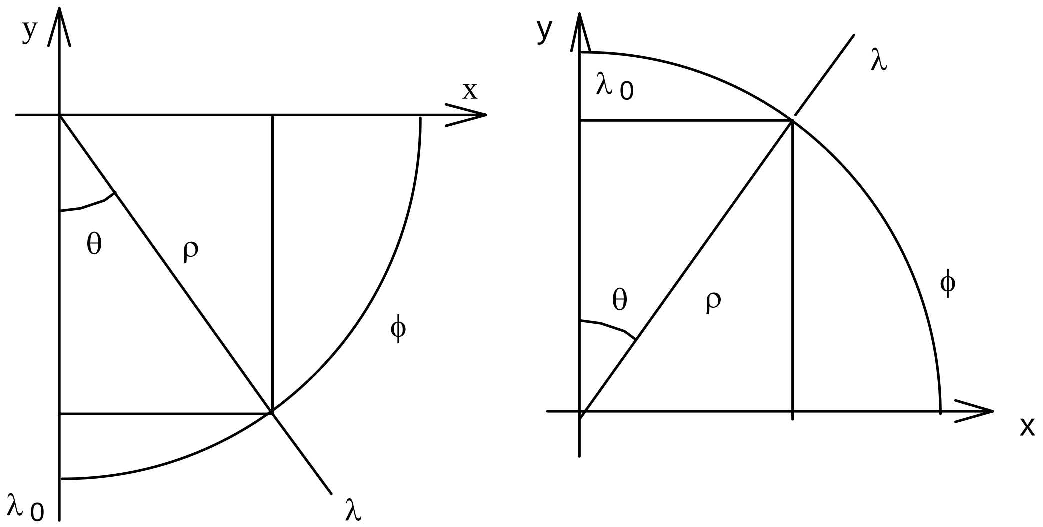


Fig. 6.3-2 Coordinates of LCC Projection

(3) Function F3 for PS Projection

The PS (Polar Stereo) Projection is conformal projection whose parallels are expressed as concentric circles around the pole, and meridians are expressed as radius from pole. If reference latitudes and longitudes are (ϕ_0, λ_0), arbitrary latitude and longitude are expressed by the following equation.

$$\begin{cases} x = \rho \sin(\lambda - \lambda_0) \\ y = -\rho \cos(\lambda - \lambda_0) \end{cases} \quad \text{(North pole)}$$

$$\begin{cases} x = \rho \sin(\lambda - \lambda_0) \\ y = \rho \cos(\lambda - \lambda_0) \end{cases} \quad \text{(South pole)} \qquad (6.3\text{-}9)$$

$$\rho = K\tan\left(\frac{\pi}{4}-\frac{\phi}{2}\right)\left(\frac{1+e\sin\phi}{1-e\sin\phi}\right)^{\frac{e}{2}}$$

$$K = \frac{N\cos\phi_0}{\tan\left(\frac{\pi}{4}-\frac{\phi_0}{2}\right)\left(\frac{1+e\sin\phi_0}{1-e\sin\phi_0}\right)^{\frac{e}{2}}} \qquad (6.3\text{-}10)$$

$$N = \frac{a}{\sqrt{1-e^2\sin^2\phi_0}}$$

(In case of the southern hemisphere codes ϕ and ϕ_0 are reversed.)

Where, a is major radius of the earth and e is eccentricity. λ_0 is reference longitude for projection. When true north is designated, reference longitude takes longitude of scene center and when map north is designated, as default, reference longitudes are as shown as Table 6.3-2.

Table 6.3-2 Reference longitude of PS Projection

Scene Center Longitudes (deg.)	Standard Longitude (deg.)
-22.5 - +22.5	0
-22.5 - +67.5	45
+67.5 - +112.5	90
+112.5 - +157.5	135

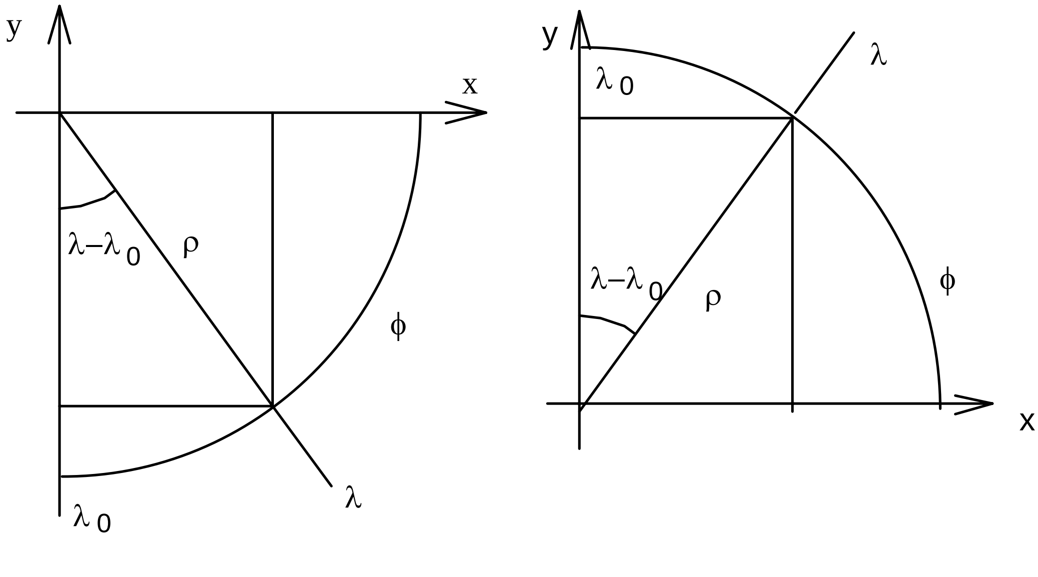


Fig. 6.3-3 Coordinates of PS Projection

6.3.4 Function F4

F4 function converts coordinates value on map coordinates into values on map projection image coordinates. Only scaling and isolation is involved in conversion and procedures for conversion are as follows. Directions on map are stored on projection image:

1. Eight points on level 1B image, p1 - p8 (four corners of the scene, the center of the first and last line and F1 to F3 on central line) are used to convert to map coordinates.

2. Using values at the eight points and spacing values, image size in the direction of column is calculated by the difference between the maximum value and minimum value. Line number is calculated by the difference between maximum value and minimum value in the y direction. Coordinates at the center of image are calculated by size; that is, if pixel spacing is δ and map coordinates of point pi are (Xi, Yi), image size in the column direction is C, and size of image in line direction is L, as follows;

$$
\begin{aligned}
C &= (\max(X_i) - \min(X_i))/\delta + 1 \\
L &= (\max(Y_i) - \min(Y_i))/\delta + 1
\end{aligned}
\qquad (6.3\text{-}11)
$$

   Map coordinates (X_0, Y_0) is as follows.

$$
\begin{pmatrix} X_0 \\ Y_0 \end{pmatrix} = \begin{pmatrix} (\max(X_i) + \min(X_i))/2 \\ (\max(Y_i) + \min(Y_i))/2 \end{pmatrix} \qquad (6.3\text{-}12)
$$

3. From the above, conversion from map coordinates (X, Y) to map projection coordinates (x, y) is expressed as follows;

$$
\begin{pmatrix} x \\ y \end{pmatrix} = \frac{1}{\delta} \begin{pmatrix} X - X_0 \\ -(Y - Y_0) \end{pmatrix} + \begin{pmatrix} C/2 \\ L/2 \end{pmatrix} \qquad (6.3\text{-}13)
$$

Fig. 6.3-4 shows the relationship between map coordinates system and map projection image coordinates system.

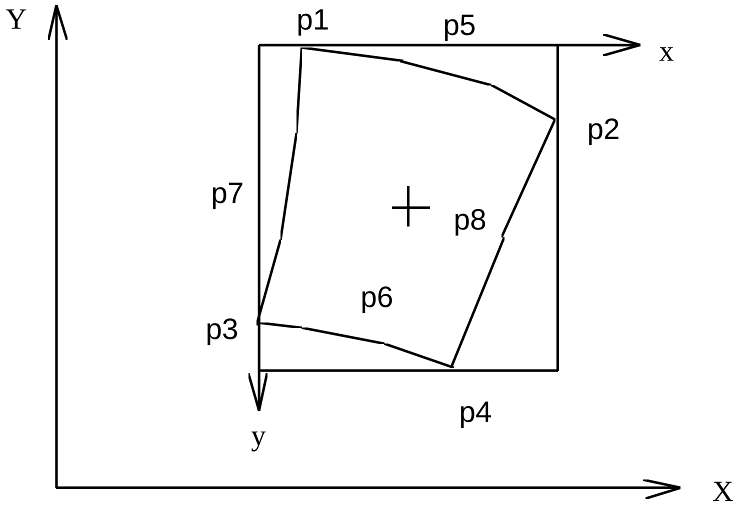


Fig. 6.3-4 The relationship between map coordinates system and map projection image coordinates system.

6.4 Generation Of Registration Correction Information

Images acquired by OCTS contain registration errors since imaging the position of one pixel with its pixel number varies band by band due to different position of detectors on the focal plane according to a band. It is necessary to apply registration correction when atmospheric corrections are performed. In addition, it is quite difficult to perform geometric corrections, as is, since the scanning method leads to heavily distorted images and discontinuities of pixel positions which are caused by the use of the 10 detector elements which are used for a single scan. Therefore, the correction for this discontinuity should be included in the registration correction.

For registration correction, data from all bands need to be resampled after determining reference ground scan position according to that position. The ground track of ideal line-of-sight vector that coincides with optical axis is used as a reference position. OCTS picks up images from 10 detector elements in a single scan. Since the ideal position referenced for registration correction eliminates discontinuities between scanning, it is defined as ideal line-of-sight vector, which scans 10 times in each 1/10 of a scan period. Refer to section 6.2 for details.

In registration correction, raw image pixels which are closest to ideal position by each band are extracted, and the value is determined as pixel value of that address of level 1B. (NN methods)

Registration correction is performed by calculating coordinates of ground scan point by using ideal line-of-sight vector, determining scan angle around roll axis and off-nadir around pitch angle and calculating pixel of each band and detector number that corresponds to its scan angle and off-nadir. During this process, since pixel and detector number are not calculated directly by scan angle and off-nadir, convergent operation is performed. Effective detector numbers are not necessarily calculated by the same scan number as is used for calculating reference position, calculation of the scanning should be performed before and after untill the effective number is found.

6.4.1 Calculation of Reference Scan Position

For ground scan position referenced for registration corrections, coordinates or ground imaging points are calculated by ideal line-of-sight vector in the optical light access direction, using line-of-sight vector calculation methods at ECR mentioned in "6.2.2 Calculation of line-of-sight vector," and using F1 function in 6.3.1. In order to simplify calculation, in registration correction, satellite is regarded as being still during a single scan. That is, normally the following equation 6.2-34 is used for calculation of scan number to interpolate orbit and satellite data.

$$s = (l - 4.5)/10 + (j - j_0)\cdot r_s \qquad \text{(In case of LAC)}$$
$$s = (l - 0.5)/2 + (j - j_0)\cdot r_s \qquad \text{(In case of GAC)}$$

Where l is a line number and j is a sample number. Instead of these use the following.

$$s = (l - 4.5)/10 \qquad \text{(In case of LAC)}$$
$$s = (l - 0.5)/2 \qquad \text{(In case of GAC)} \qquad (6.4\text{-}1)$$

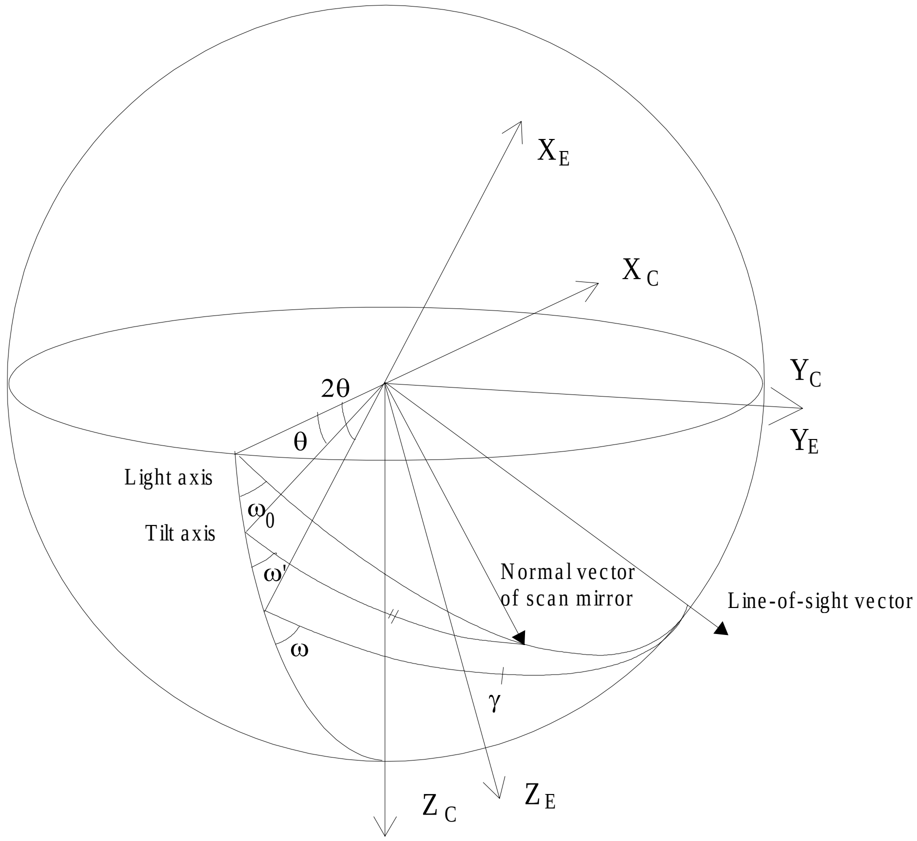
Scan rotating angle moves approximately 90 degrees during sampling 2222 pixels for a single scan and takes about 0.23 second. During this period, satellite moves 1.5 km, registration correction error can be ignored by ignoring satellite’s move during scanning when scan angle and distance is calculated for the next section.

6.4.2 Calculation Of Scan Angle And Off-nadir

Registration correction is performed by calculating the actual level 1A pixel number after determining the ideal scan position of the line-of-sight vector of each level 1B pixel and calculating the 1A pixel number which actually scanned that reference position; however in order to calculate the pixel number from reference position (equivalent to reversed function of F1 function in section 6.3), the pixel number in the direction of line-of-sight from the satellite and reference position is calculated.

Although it is possible to calculate the line-of-sight vector direction from pixel number (section 6.2.2), it is analytically impossible to calculate the pixel number from a line-of-sight in reversed operation. Therefore, it is necessary to determine this reversed operation from the operation in the right direction by using some repeated process. In order to perform this reversed operation effectively, by using scan angle and off-nadir defined as follows, the pixel number is calculated by convergent operation by this scan angle and off-nadir. It is necessary to use quantities that have the closest linear relationship the pixel number (sample number and detector number). Scan angle off-nadir are defined in Fig. 6.4-1.

In the coordinate system of tilt axis, the scan axis is in the direction in which the tilt rotating angle is θ degrees rotated on ZX plane from the tilt angle (X_C axis) direction. In addition to this, the coordinate system that has X axis in the direction in which the tilt angle is 2θ degrees rotates in the direction where scan axis is θ degrees rotated in the same direction. (this is the $X_E Y_E Z_E$ coordinate) In registration correction, rotation angle from $Z_E X_E$ plane angle of line-of-sight vector by this coordinate system is defined as scan angle, and the rotating angle from $Y_E Z_E$ plane of line-of-sight vector is defined as off-nadir.



ω_0 : True scan angle
ω' : Scan rotating angle
ω : Scan angle used for registration calculation
γ : off-nadir used for registration calculation

Fig. 6.4-1 Definition of scan angle and off-nadir

(1) Scan angle and off-nadir correspond to reference position

If unit vector in the X_C axis direction is u = (1, 0, 0) unit vector in X_E direction is expressed in the coordinate system of tilt axis as follows:

$$\mathbf{x_E} = \tilde{\mathbf{R}}_{\mathbf{Y}}(2\theta)\mathbf{u} \tag{6.4-2}$$

If satellite position, velocity and attitude angle are determined, this can be converted to ECR coordinate system by the coordinate conversion in section 6.2.1.

$$\mathbf{x} = \mathbf{P_E P_O P_B Q_C Q_A x_E} \tag{6.4-3}$$

Likewise, if unit vector in Y axis direction is v and unit vector in Z axis direction is w , unit vector in Y_E axis direction and Z_E axis direction is expressed by ECR coordinates as follows;

$$\begin{aligned} \mathbf{y} &= \mathbf{P_E P_O P_B Q_C Q_A v} \\ \mathbf{z} &= \mathbf{P_E P_O P_B Q_C Q_A \tilde{R}_Y}(2\theta)\mathbf{w} \end{aligned} \tag{6.4-4}$$

Therefore, if the position vector of the registration reference scan position is p and the satellite position is s, the line-of-sight vector to reference position is c = s - p. Using this, scan angle • and off-nadir γ are expressed as follows;

$$\begin{aligned} \tan\omega &= \frac{-\mathbf{c}\cdot\mathbf{y}}{\mathbf{c}\cdot\mathbf{z}} \\ \tan\gamma &= \frac{\mathbf{c}\cdot\mathbf{x}}{\mathbf{c}\cdot\mathbf{z}} \end{aligned} \tag{6.4-5}$$

Satellite position, velocity and attitude angle are functions of the scan number; however, in this equation it is not assumed that satellite does not move, and orbit and attitude data at the center of scan is used. However, in cases where detector numbers of a 1A pixel that correspond to target 1B pixel are not searched within an efficient range (0 - 9), it is necessary to calculate the scan angle and off-nadir again before and after the scan. For OCTS there is the case where a level 1A pixel that corresponds to the level 1B pixel expands to three scannings after and before.

(2) Scan angle and off-nadir corresponding to level 1A pixel

The Scan angle and off-nadir that corresponds to each pixel of level 1A image is a function only of sample number and detector number and is calculated from the line-of-sight vector in OCTS reference coordinate system. The line-of-sight vector that corresponds to the pixel number is calculated in the equation (6.2-29) in section 6.2.2. Each coordinate axis of $X_E Y_E Z_E$ is considered to be the same as (1) in OCTS standard coordinates, they are expressed as the follows.

$$\begin{aligned} \mathbf{x_O} &= \mathbf{Q_C Q_A \tilde{R}_Y}(2\theta)\mathbf{u} \\ \mathbf{y_O} &= \mathbf{Q_C Q_A v} \\ \mathbf{z_O} &= \mathbf{Q_C Q_A \tilde{R}_Y}(2\theta)\mathbf{w} \end{aligned} \tag{6.4-6}$$

If the line-of-sight vector of the OCTS coordinate system is b, the scan angle and off-nadir are expressed in the following way,

$$\tan\omega = \frac{-\mathbf{b}\cdot\mathbf{y_O}}{\mathbf{b}\cdot\mathbf{z_O}}$$
$$\tan\gamma = \frac{\mathbf{b}\cdot\mathbf{x}}{\mathbf{b}\cdot\mathbf{z_O}} \qquad (6.4\text{-}7)$$

6.4.3 Calculation Of Pixel Number By Convergence Operation

The Reference ground scan position of each pixel is calculated in section 6.4.1 by the ideal scan vector that corresponds to each line l and pixel p of the level 1B image. From that reference scan position, scan angle ω and off-nadir γ are calculated as in (1) in section 6.4.2. Registration correction is performed by determining scan number i, sample number j and detector number k of the corresponding 1A image from ω and γ. However, since this conversion can not be directly calculated, using the calculation for scan angle and off-nadir the scan sample detector number in (2) in section 6.4.2., the sample detector number (and scan number) whose scan angle and off-nadir agree are searched by convergent operation. If conversion from the sample detector number to the scan angle and off-nadir is $(\omega, \gamma) = f(j,k)$ (in this equation, j and k that are independent from scan number are functions), then this reversed function is solved by convergent operation. In the convergent operation, it is efficient to use an equation that is as linear as possible to the sample detector number; scan angle ω is used as is, but $\Gamma = \tan\gamma$ is used for off-nadir γ. That is, $(\omega,\Gamma) = f(j,k)$ is used (since scan angle ω becomes scan -rotation angle and $\tan\gamma$ becomes focal plane element "n" in the first degree approximation).

(1) Simplified conversion method

In order to apply convergent operation, it is necessary to be able to calculate initial values and modified quantities of j and k which correspond to $\tan\gamma$ and ω. For this purpose, conversion from scan angle and off-nadir to sample number *j* and detector number *k* is represented by pseudo affine conversion as follows;

$$\begin{cases} j = a_0 + a_1\omega + a_2\Gamma + a_3\omega\Gamma \\ k = b_0 + b_1\omega + b_2\Gamma + b_3\omega\Gamma \end{cases} \qquad (6.4\text{-}8)$$

By substituting representative sample and detector numbers of four points and coefficients a_0 ~ a_3, b_0 ~ b_3 are determined

(2) Convergence operation

Sample detector numbers that correspond to scan angles and off-nadir are calculated by convergent operation. That is, by substituting the given scan angle and off-nadir into the pseudo affine conversion equation, the results are again converted by $(\omega,\Gamma) = f(j,k)$. Due to approximation error caused by pseudo affine conversion, this result does not coincide with original scan angle and off-nadir. If this difference is expressed $(\Delta\omega,\Delta\Gamma)$, a modified value for the sample detector number is calculated and this operation is repeated until the difference falls below a certain value. That is, the following calculation is performed.

$$\begin{cases} j_{(n)} = a_0 + a_1\omega_{(n-1)} + a_2\Gamma_{(n-1)} + a_3\omega_{(n-1)}\Gamma_{(n-1)} \\ k_{(n)} = b_0 + b_1\omega_{(n-1)} + b_2\Gamma_{(n-1)} + b_3\omega_{(n-1)}\Gamma_{(n-1)} \end{cases} \quad (6.4\text{-}9)$$

$$(\omega_{(n)}, \Gamma_{(n)}) = f(j_{(n)}, k_{(n)})$$

$$(\Delta\omega_{(n)}, \Delta\Gamma_{(n)}) = (\omega_{(n)}, \Gamma_{(n)}) - (\omega, \Gamma) \quad (6.4\text{-}10)$$

$$(\omega_{(n+1)}, \Gamma_{(n+1)}) = f(\omega_{(n)} + \Delta\omega, \Gamma_{(n)} + \Delta\Gamma)$$

$$\text{where} \begin{cases} \Delta\omega = (a_1 + a_3)\Delta\omega_{(n)} + (a_2 + a_3)\Delta\Gamma_{(n)} \\ \Delta\Gamma = (b_1 + b_3)\Delta\omega_{(n)} + (b_2 + b_3)\Delta\Gamma_{(n)} \end{cases} \quad (6.4\text{-}11)$$

6.4.4 Generation Of Registration Correction Information

In the the previous section, the sample detector number as extended to real number was calculated. The number obtained by rounding off becomes the target pixel number.

However, depending on the pixel position, regarding the same scan number as level 1B pixel number, there may be cases where the detector number is smaller than 0 or larger than 9. In this case, corresponding level 1A pixel does not exist. When it is smaller than 0, as to previous scan, scan angle and off-nadir are calculated again and the pixel number is also determined again. Calculation is repeated until it is within the range of an efficient detector number. Sometimes two efficient detective numbers are calculated for neighboring scan numbers. If this happens, the one closer to the original scan number is selected. If a gap is caused between scanning, an efficient pixel cannot be found by any scan number. If this happens, for GAC the closest pixel before and after the scan is selected. For non-GAC, a flag must be placed as out of scan.

In case of GAC, registration correction is performed during level 0 subsampling input. Subsampling table used for subsampling input is generated in the above procedures with sample detector number (and scan offset) by each pixel as a table. The table should be generated under nominal conditions (orbit, attitude and telemetry) before processing. (Refer to Chapter 3)

In case of non-GAC, a pixel number is calculated by each scan by referencing actual orbit, attitude and telemetry data during image processing. Since calculation of registration correction requires enormous operation volumes, it takes too much time to calculate each pixel. For this reason, sample detectors calculated as real numbers between grid points are linearly-interpolated by dividing level 1B image into blocks in the pixel direction and calculating by each grid point. Two lines in a single scan in the detector direction are calculated and likewise they are linearly-interpolated within the scan. If calculated pixel value after registration correction belongs to different scan, interpolation can not be performed. So regardless of whether a calculated pixel value's detector number falls in the range, calculation is performed by each scan offset and interpolation is performed to the same scan offset and as a result, that data is used whose detector range becomes efficient. Pixel number interpolated is rounded off and the difference from reference pixel number is output to file as registration correction information. Reference pixel number is defined by the following equation.

$$j = p + (S_j - S_p) \\ k' = l \tag{6.4-12}$$

Where p and l are level 1B pixel numbers (pixel and line) , j is level 1A sample number, k is level 1A line number ($k' = 10 \times i + k$) and S_j and S_p are number of pixels in the direction of level 1A, 1B pixels.

That is , values generated as registration correction information are as follows.

$$\Delta j = j - p - (S_j - S_p) \\ \Delta k = k' - l \tag{6.4-13}$$

In case where detector number is calculated by different scan number, detector number is regarded as the number to which scan offset multiplied by 10 has been added.

6.5 Calculation Of Geometric Correction Coefficients

The address of corresponding registration correction images (level 1B images) at grid points on map projection image coordinates are used for map projection as geometric coefficients. The latitude and longitude of grid points on the registration correction image is used for interpolation of space binning and atmospheric correction of earth observation data.

6.5.1 Generation Of Geometric Correction Coefficients For Map Projection

During map projection, which map projection image pixel correspond to which address of input image (in this case registration correction image) has to be determined. Conversion to determine coordinates on corresponding registration corrected image (input image) from coordinates (address) on map projection (output image) can be approximated by the following linear conversion (pseudo affine conversion).

$$\begin{cases} u = axy + bx + cy + d \\ v = exy + fx + gy + h \end{cases} \qquad (6.5\text{-}1)$$

where (x, y) : coordinates of output image (pixel, line)
(u, v) : coordinates of input image (pixel, line)
$a \sim h$: coefficients

At the map projection image coordinates, address of registration correction corresponding to its grid points is calculated by dividing into a rectangle area to the size for which this conversion can be performed with sufficient accuracy.

(1) Block division

Address of grid points of a block is input from database. Block size is used which that is sufficient for liner approximation of coordinate conversion, .

(2) Calculation of Input image coordinates corresponding to grids

Conversion from output image coordinates to input image coordinates are reversed functions of coordinate conversion function F1 to F4. As it is difficult to calculate reversed function of F1 function, a simple conversion is substituted. The difference between this conversion value and one by true conversion using F1 - F4 function the difference is calculated by convergent operation. Pseudo affine conversion is used. If this conversion is used as is, work coordinates that absorb linearly in cross track direction are used since this may cause divergence in convergent operation due to linearity in cross track direction.

a) Calculation of Work coordinate system
Coordinates (u', v') verses input image coordinates (u, v) are defined as follows;

$$\begin{cases} u' = \dfrac{R}{\delta}\arcsin(\theta) \\ v' = v \end{cases} \tag{6.5-2}$$

However, $\theta = \dfrac{R+h}{R}\sin(\alpha)$

$\alpha = d\omega(u - u_0)$

R is earth radius and h is satellite altitude. Nominal values are used for these. u_0 is central pixel number in the column direction, δ is pixel size (varies from tilt angle) in the cross track direction at nadir point of satellite and $d\omega$ is scan angle per pixel at nadir point of satellite. By using the nominal scan model in the cross track direction shown in Fig. 6.5-1, pixel numbers in the column direction are converted to pixel position on ground orbit track. In actual operation, although scan angle does not change linearly according to pixel number (scan rotation angle), the difference is ignored. Conversion from work coordinates to input image coordinates is performed by the following equation.

$$\begin{cases} u = \dfrac{\alpha}{d\omega} + u_0 \\ v = v' \end{cases} \tag{6.5-3}$$

However, $\alpha = \arcsin\left(\dfrac{\sin\theta}{\sqrt{k^2 - 2k\cos\theta + 1}}\right) \qquad \left(k = \dfrac{R+h}{R}\right)$

$\theta = \dfrac{\delta}{R}u'$

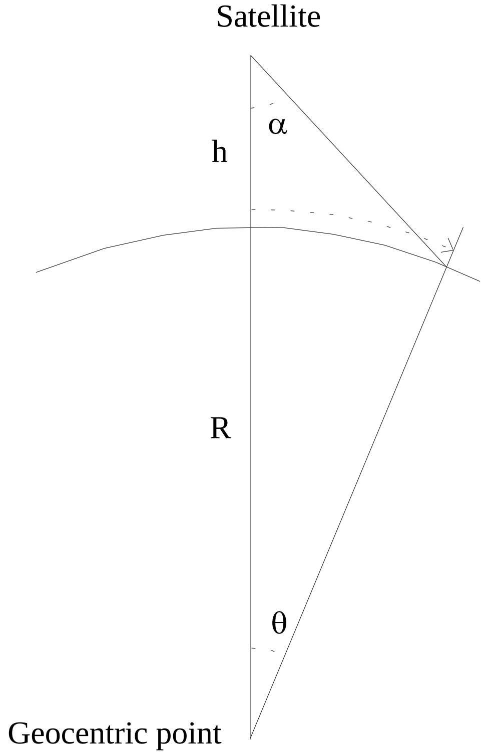


Fig. 6.5-1 Geometric model of work coordinate system

b) Calculation of pseudo Affine conversion coefficients

The following pseudo affine conversion is used for conversion from output image coordinates (x, y) to work coordinates (u', v').

$$\begin{cases} u' = a_0 + a_1 x + a_2 y + a_3 xy \\ v' = b_0 + b_1 x + b_2 y + b_3 xy \end{cases} \qquad (6.5\text{-}4)$$

By converting coordinates of selected four points on input image into work coordinates by equation (6.5-2) and converting coordinates of four points to output image coordinates using F1 to F4 function, coefficients of the above a_0 to a_3 and b_0 to b_3 are calculated for these four sets of dataset using simultaneous equation.

c) Determination of Input image address using convergent operation

Coordinate (u, v) of the point on input image corresponding to grid points (x, y) on output image is calculated with the above pseudo affine conversion by convergent operation. That is, the grid point address (x, y) is converted to work coordinates values (this conversion is defined as f) and coordinates obtained as the result of the conversion should be then converted to input image coordinates (this conversion is defined as g) according to equation (6.5-3) . This value is used as initial value for target coordinates.

$$\begin{aligned} (u_{(0)}, v_{(0)}) &= g\left(f(x, y) \right) \\ &= g(u'_{(0)}, v'_{(0)}) \end{aligned} \qquad (6.5\text{-}5)$$

These coordinates are converted to output image coordinates by F1 to F4 functions (this entire conversion is expressed as F). Ideally these coordinates should coincide with original (x, y) but may not do so due to approximation aberrance. If this aberrance is $(\Delta x, \Delta y)$, the following equation is obtained;

$$\begin{aligned} (x_{(n)}, y_{(n)}) &= F(u_{(n)}, v_{(n)}) \\ (\Delta x_{(n)}, \Delta y_{(n)}) &= (x_{(n)}, y_{(n)}) - (x, y) \end{aligned} \qquad (6.5\text{-}6)$$

Initial value is modified as follows by the above difference.

$$(u_{(n+1)}, v_{(n+1)}) = f(u'_{(n)} + \Delta u', v'_{(n)} + \Delta v') \qquad (6.5\text{-}7)$$

However, $\begin{cases} \Delta u' = (a_1 + a_3 y_{(n)})\Delta x_{(n)} + (a_2 + a_3 x_{(n)})\Delta y_{(n)} \\ \Delta v' = (b_1 + b_3 y_{(n)})\Delta x_{(n)} + (b_2 + b_3 x_{(n)})\Delta y_{(n)} \end{cases}$

For this modified value, ($u_{(n)}$, $v_{(n)}$) are target coordinates for which equation (6.5-5) is repeated to the point ($\Delta x_{(n)}$, $\Delta y_{(n)}$) becomes small enough.

Procedures for calculation of input image coordinates are shown in Fig. 6.5-2.

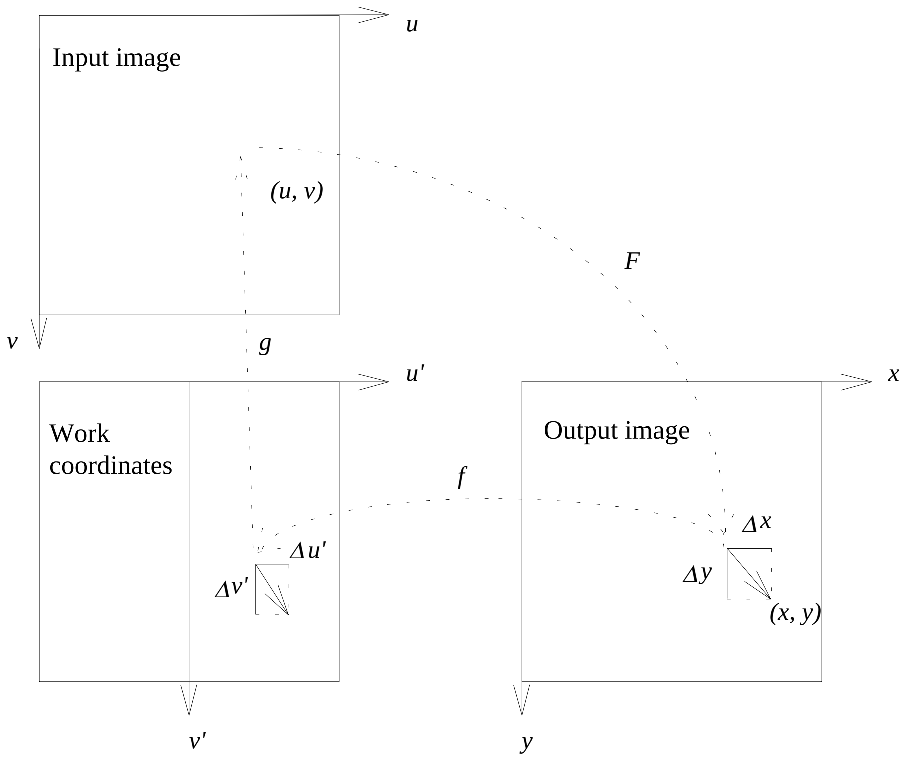


Fig. 6.5-2 Procedures for calculation of input image coordinates

6.5.2 Calculation Of Latitude-Longitude Conversion Coefficients

Latitude and longitude per grid points of block is calculated by dividing registration correction image (level 1B image) into blocks. Calculation of latitude and longitude are equivalent to F1 - F2 functions in 6.3 "Coordinate conversion function". See 6.2 "Geometric model" and 6.3 "Coordinate conversion function" for details.

6.6 Calculation Of Postition Calculation Coefficients For The Sun And The Satellite

It is necessary to calculate difference between zenith angle of the sun and satellite and azimuth of the sun and satellite by each pixel. Performing this calculation to each pixel involves a heavy work load. For this reason, for satellite position, zenith and azimuth angles of satellite by each grid point are calculated by dividing row images into blocks.

Likewise, as to the sun position, zenith and azimuth angles of the sun are calculated by each grid point by dividing level 1B image into blocks. Value of grid points are linearly interpolated within a block.

(1) Calculation of zenith angle of the sun

It is necessary to know imaging position in order to calculate solar angle. Latitude and longitude of imaging point can be calculated by using coordinate conversion function F1 and F2 in section 6.3. If calculated latitude and longitude are (ϕ, λ), direction vector that indicates the top of vertical line is expressed as follows.

$$\mathbf{n} = \begin{pmatrix} l \\ m \\ n \end{pmatrix} = \begin{pmatrix} \cos\phi\cos\lambda \\ \cos\phi\sin\lambda \\ \sin\phi \end{pmatrix} \qquad (6.6\text{-}1)$$

Therefore, if the positional vector at ECR coordinates of the sun is s = (X_s, Y_s, Z_s), the following equation is obtained.

$$\cos\eta = \frac{\mathbf{s}\cdot\mathbf{n}}{|\mathbf{s}||\mathbf{n}|} = \frac{X_s l + Y_s m + Z_s n}{\sqrt{(X_s^2 + Y_s^2 + Z_s^2)}} \qquad (6.6\text{-}2)$$

See 4.3 "Calculation of sun position vector".

(2) Calculation of the zenith angle of the sun

Perpendicular coordinates must be considered which take x axis in the north direction and y axis in the east direction and z axis as bottom vertical line on the plane that meets earth ellipsoid at imaging point. As to the zenith angle of the sun, if position vector of the sun is expressed in this coordinate system as (x, y and z) , the following equation is obtained.

$$\tan\theta = \frac{y}{x} \qquad (x <> 0) \qquad (6.6\text{-}3)$$

Therefore, x, y can be calculated.
If unit vector in x axis direction at ECR is l and one in y axis direction is m,

$$\mathbf{l} = \begin{pmatrix} -\sin\phi\cos\lambda \\ -\sin\phi\sin\lambda \\ \cos\phi \end{pmatrix}$$

$$\mathbf{m} = \begin{pmatrix} -\sin\lambda \\ \cos\lambda \\ 0 \end{pmatrix} \qquad (6.6\text{-}4)$$

By these, x and y are determined by the following equation.

$$\begin{aligned} x &= \mathbf{l}\cdot\mathbf{s} \\ y &= \mathbf{m}\cdot\mathbf{s} \end{aligned} \qquad (6.6\text{-}5)$$

(3) Calculation of Zenith angle and azimuth angle of the satellite

Imaging point of each pixel of each band can be calculated by using coordinate conversion function F1 in section 6.3. Latitude and longitude of image point is calculated using F2 function from ECR coordinates.
If latitude and longitude at imaging point are (ϕ,λ) position vector of imaging point at ECR is expressed as follows.

$$\mathbf{p} = \begin{pmatrix} N\cos\phi\cos\lambda \\ N\cos\phi\sin\lambda \\ (1-e^2)N\sin\phi \end{pmatrix} \qquad (6.6\text{-}6)$$

$$N = \frac{a}{\sqrt{1-e^2\sin^2\phi}}$$

Where major radius of the earth is "a" and eccentricity is "e".
Therefore, if positional vector or satellite is $\mathbf{x_B}$, directional vector of satellite from imaging point is expressed as follows.

$$\mathbf{x_B} - \mathbf{p} \qquad (6.6\text{-}7)$$

By performing the same process in (2) and (3) for directional vector of this satellite, zenith angle and azimuth angle of the satellite can be calculated.