5. IMAGE NAVIGATION

Navigation refers to the procedure for determining the earth-location (latitude-longitude) of each satellite image pixel and the three angles which define the observation geometry, namely the satellite and solar zenith angles at the earth surface and the relative azimuth angle between the sun-Earth and Earth-satellite directions. Fig. 5.1 defines these angles. Note that relative azimuth, φ, in B3 data is defined as used in radiative transfer calculations; conventional relative position azimuth (η) is given by 180 - φ. The value of φ is reported in the range of 0 to 180 degrees. In this section, we describe the information provided by the satellite operators and SPCs used for navigation, the general techniques for calculating the five quantities (Θ = latitude, λ = longitude, μ_o = cosine of solar zenith angle, μ = cosine of satellite zenith angle, and φ = relative azimuth), quality control procedures, and estimates of the accuracy obtained.

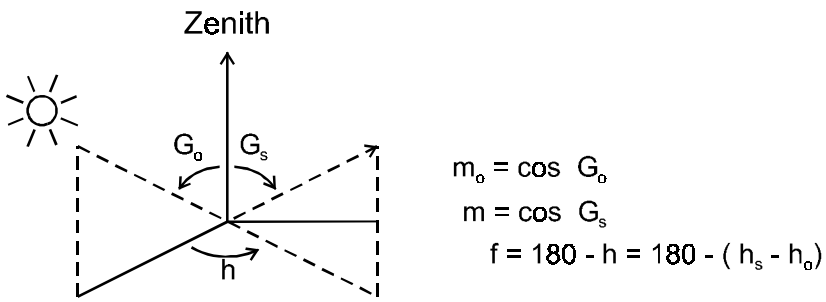

Figure 5.1. Definition of viewing geometry angles.

5.1. INFORMATION PROVIDED

The satellites participating in ISCCP provide two types of navigation information. The METEOSAT and NOAA systems provide direct earth-location information (i.e., Θ and λ) for every image pixel and indicate the subsatellite point in the image. This information, when combined with knowledge of spacecraft orbital altitude and the solar position (given by the date and time of the observation), allows calculation of μ_o, μ, and φ. METEOSAT image processing routinely reprojects all images into a standard viewpoint as if the satellite were always at precisely the same altitude above the same earth location, namely (0,0).† METEOSAT orbital altitude is taken as 35,793 km. The time GMT (Greenwich Mean Time or Universal Time, Coordinated, UTC) at the beginning of the image is provided. Each subsequent scan line starts 600 msec after the preceding line; thus the time of each observation is known. (INSAT provides navigation infromation similar to METEOSAT.) NOAA provides the time GMT of each scanline and the earth location of every fourth pixel along a scan line (every eighth pixel in the original 4-km data is labeled) starting with the subsatellite point. Thus, even though the viewpoint is constantly changing for the polar orbiter data, the same combination of information is available as for METEOSAT. NOAA orbital altitude is taken to be 848 km (NOAA-7), 834 km (NOAA-8), 857 km (NOAA-9), 820 km (NOAA-10), 853 km (NOAA-11), 824 km (NOAA-12) and 856 km (NOAA-14).

The GOES and GMS satellites provide coordinates which describe the space-craft orbit, the spacecraft attitude, and the relationship between image pixel position and the spacecraft geometry. (The GOES-NEXT series provides information similar to METEOSAT.) The spacecraft orbital data (time, date, semi-major axis, eccentricity, orbital period and inclination, longitude of the ascending node, argument of the perigee and mean anomaly) allow calculation of spacecraft orbital position in celestial coordinates at the time of the observation. The spacecraft attitude and geometry information allow calculation of the direction that the radiometer points at each time. These results, together with the known position of the earth and sun in celestial coordinates, lead to calculation of Θ, λ, μ_o, μ, φ. All of the supplied parameter values used to navigate ISCCP images are recorded in each image header on the data tape.

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† All earth positions will be described by the ordered pair (Θ,λ) where $-90 \le \Theta \le 90$ and $0 \le \lambda \le 360$ degrees. Negative latitudes are in the southern hemisphere; longitude is always positive and increases eastward from the Greenwich meridian.

5.2. CALCULATION TECHNIQUES

5.2.1. TECHNIQUE WHEN Θ AND λ ARE KNOWN

Fig. 5.2 illustrates the situation and defines several quantities. In this case, since (Θ,λ) are known for the paricular image pixel **and** the subsatellite image pixel, the geocentric angle, ψ, is easily calculated:

$$\cos\psi = \cos(\Theta - \Theta_s)\cos(\lambda - \lambda_s) \tag{5.1}$$

here (Θ,λ) and $(\Theta,\lambda)_s$ are the earth coordinates of the particular image pixel and the subsatellite pixel, respectively. The law of cosines leads directly to μ, viz.,

$$\mu = \cos\Gamma_s = \left(\frac{a+h}{s}\right)\cos\psi \tag{5.2}$$

where

$$s^2 = a^2 + (a+h)^2 - 2a(a+h)\cos\psi \tag{5.3}$$

with a = 6371 km and h = 848 km (NOAA-7), etc. (Using constant average values of h and a only causes an error in μ < 0.2%).

The solar zenith angle is obtained from the solar declination, δ, and right ascension or the "hour-angle", t_h:

$$\mu_o = \sin\Theta\sin\delta + \cos\Theta\cos\delta\cos t_h \tag{5.4}$$

Using equations from Paltridge and Platt (1976), the solar declination angle (in radians) is given by

$$\begin{aligned}\delta = {} & 0.006918 - 0.399912\cos(D_o) + 0.070257\sin(D_o) - 0.006758\cos(2D_o) \\ & + 0.000907\sin(2D_o) - 0.002697\cos(3D_o) + 0.001480\sin(3D_o)\end{aligned} \tag{5.5}$$

where $D_o = {}^{2\pi d}/_{365}$ and d is the day of year minus 1. The hour angle is given by

$$t_h = \zeta + \left(\frac{\pi}{180}\right)\left(\frac{LMT - 720}{4}\right) \text{ (radians)} \tag{5.6}$$

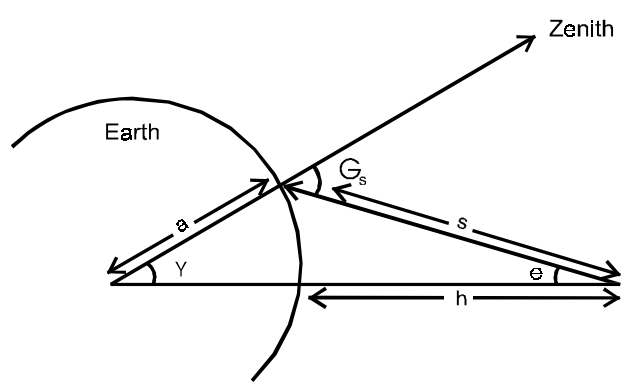

Figure 5.2. Geometry of satellite observations.

where LMT is the local mean time in minutes. For λ in degrees

$$\mathrm{LMT} = \mathrm{GMT} + 4\,\lambda \tag{5.7}$$

and

$$\begin{aligned}\zeta = {} & 0.000075 + 0.001868\cos(D_o) - 0.032077\sin(D_o) \\ & - 0.014615\cos(2D_o) - 0.040849\sin(2D_o)\end{aligned} \tag{5.8}$$

These formulae are used to calculate the zenith angle of the center of the solar disk observed through a non-refracting atmosphere. Together with the much smaller errors in the series expansions used, the estimated error in calculating the solar zenith angle is <0.5° (Paltridge and Platt 1976).

The difference in position azimuths can be obtained from the law of cosines for the two spherical triangles formed by (Θ,λ), $(\Theta,\lambda)_s$ and the north pole and by (Θ,λ), $(\Theta,\lambda)_o$ and the north pole:

$$\cos\eta_s = \frac{\sin\Theta_s - \sin\Theta\cos\psi}{\cos\Theta\sin\psi} \tag{5.9}$$

$$\cos\eta_o = \frac{\sin\delta - \sin\Theta\cos\Gamma_o}{\cos\Theta\sin\Gamma_o} \tag{5.10}$$

where $\varphi = 180 - \eta = 180 - (\eta_s - \eta_o)$, and $\mu_o = \cos\Gamma_o$, and the coordinates (Θ,λ), $(\Theta,\lambda)_s$ and $(\Theta,\lambda)_o$ are the latitude and longitude of the observed point, the subsatellite point and the subsolar point, respectively. (Note that the sides of the triangles involve $90 - \Theta$, $90 - \Theta_s$ and $90 - \delta$.) The above expressions include two quantities, $\sin\psi$ and $\sin\Gamma_o$, which have not been calculated in previous steps. For reasons of computational efficiency, φ is found from evaluating $\tan(\eta_s - \eta_o)$ which does not involve these two quantities because of the ratio involved:

$$\tan(\eta_s - \eta_o) = \frac{\sin\eta_s\cos\eta_o - \sin\eta_o\cos\eta_s}{\cos\eta_s\cos\eta_o + \sin\eta_s\sin\eta_o} \tag{5.11}$$

$$\sin\eta_s = \frac{-\cos\Theta_s\sin(\lambda_s - \lambda)}{\sin\psi} \tag{5.12}$$

$$\sin\eta_o = \frac{-\cos\delta\sin t_h}{\sin\Gamma_o} \tag{5.13}$$

$$\phi = 180 - \tan^{-1}(\eta_s - \eta_o) \tag{5.14}$$

The function $\tan^{-1}(\eta_s - \eta_o)$ is undefined whenever μ or μ_o is nearly 1; when this occurs φ is given the previous value in that scan line.

5.2.2. TECHNIQUE WHEN ORBIT/ATTITUDE ELEMENTS ARE KNOWN

Orbital elements are used to calculate the spacecraft position in its orbit at a particular time in celestial (Earth-centered) coordinates. The position is given by

$$\begin{aligned} X &= r\,[\cos\Sigma\cos w - \sin\Sigma\cos i\sin w] \\ Y &= r\,[\cos\Sigma\sin w + \sin\Sigma\cos i\cos w] \\ Z &= r\,\sin\Sigma\sin i \end{aligned} \tag{5.15}$$

where w is the longitude of the ascending node, i is the orbital inclination,

and

$$r = a\,(1-\varepsilon_2)\,/\,(1+\varepsilon\cos\Omega) \tag{5.16}$$

$$\Sigma = \Omega + \alpha \tag{5.17}$$

The orbital (radial) distance, r, is a function of the semi-major axis, a, the orbital eccentricity, ε, and the true anomaly; the angle Σ is the sum of the true anomaly, Ω, and the argument of the perigee, α. The true anomaly is calculated from the difference between the observation time and the time of periapsis passage (expressed as a function of the orbital period), m:

$$\Omega = m + (2\varepsilon - \varepsilon^3/4)\sin(m) + (5\varepsilon^2/4)\sin(2m) + (13\varepsilon^3/12\sin(3m)) \tag{5.18}$$

This position can also be expressed in terms of subspacecraft (Θ,λ); however, the particular image pixel which corresponds to $(\Theta,\lambda)_s$, remains to be determined. (Θ,λ) for all other image pixels must also be calculated.

To determine the pointing vector direction, the attitude of the space-craft spin axis is used to relate image pixels to a spacecraft-centered coordinate system. In addition, the angular relationship between the radiometer telescope and the spacecraft spin axis must be known (see Fig. 5.3). Spin axis attitude and instrument alignment must generally be determined after launch by comparing calculated (Θ,λ) values with the locations of recognizable landmarks. Indeed, this procedure must be used operationally to obtain accurate enough information. Thus, GOES and GMS navigation requires additional information on instrument alignment to adjust the spacecraft attitude to eliminate much of the remaining uncertainty.

The coordinate transformation from (x',y',z') to (x,y,z) to (X,Y,Z) is specified by the angular relations illustrated in Fig. 5.3 and determines the vector labeled "s" in Fig. 5.2. The length of this vector is calculated by finding its intersection with an ellipsoid centered on the Earth's position, defined by

$$\left(\frac{X}{a}\right)^2 + \left(\frac{Y}{a}\right)^2 + \left(\frac{Z}{b}\right)^2 = 1 \tag{5.19}$$

where a = 6378 km and b = 6357 km and (X,Y,Z) are celestial coordinates.

With lengths s, h and a known, the satellite zenith angle can be determined by the law of cosines:

$$\mu = -\cos(180 - \Gamma_s) = \frac{a^2 + s^2 - (a+h)^2}{2\,a\,s} \tag{5.20}$$

Solar zenith angle is determined exactly as described in (5.4) through (5.8).

The relative azimuth angle between the solar and satellite direction vectors can be found using the law of cosines for the spherical triangle formed by the image pixel point on the Earth's surface (Θ,λ), the subsatellite point $(\Theta,\lambda)_s$ and the subsolar point $(\Theta,\lambda)_o$. The latter two points are related directly to the satellite and sun positions specified by orbit position and Eqs. (5.5) and (5.6). The values of (Θ,λ) for a particular image pixel are obtained during the

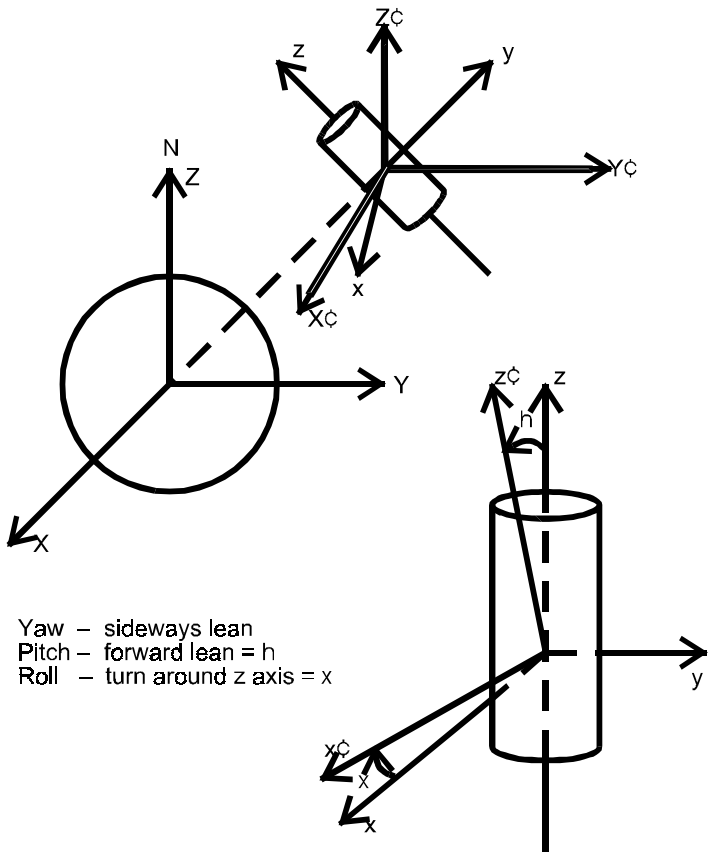

Figure 5.3. Coordinate transformations employed to relate image coordinates to spacecraft-centered coordinates and to celestial coordinates.

calculation of s by solving for the celestial coordinate of the intersection of the view-vector with the Earth's surface.

$$\cos(\eta_s - \eta_o) = \frac{\cos\psi' - \cos\psi_s \psi_o}{\sin\psi_s \sin\psi_o} \tag{5.21}$$

Then
where ψ', ψ_s and ψ_o are Earth-centered angles given by

$$\cos\psi_s = \cos(\lambda - \lambda_s)\cos(\Theta - \Theta_s) \tag{5.22}$$

$$\cos\psi_o = \cos(\lambda - \lambda_o)\cos(\Theta - \Theta_o) \tag{5.23}$$

$$\cos\psi' = \cos(\lambda_s - \lambda_o)\cos(\Theta_s - \Theta_o) \tag{5.24}$$

The relative azimuth, $\varphi = 180 - (\eta_s - \eta_o)$.

5.3. OUTPUT QUANTITIES

Five quantities are reported for each image pixel: latitude (Θ) and longitude (λ) of the image pixel, cosine of the satellite (μ) and solar (μ_o) zenith angles at the Earth's surface, and the relative azimuth angle (φ) between the sun-to-surface and surface-to-satellite vectors. Latitude (-90° to 90°) is measured in degrees from the equator to the poles (positive latitudes in the northern hemisphere); longitude (0° to 360°) is measured in degrees from the Greenwich meridian, positive eastward. (Coded longitudes on the data tape range between -360° and 360°, but the provided tape reading software converts these values to 0° to 360°. Both μ (0 to 1) and μ_o (-1 to 1) are dimensionless; negative values of μ_o indicate nightside data. φ (0° to 180°) is measured in degrees and is always positive.

In order to save space in the Stage B3 data, the navigation angles are coded in the form of coefficients for a second order polynomial fit to their variation along an image scan line. The fit parameters are reported at a variable number of locations along the scan line to maintain the error of the fit below prescribed limits. The maximum error allowed in each quantity is: 0.06° in Θ and λ, 0.01 in μ and μ_o and 0.5° in φ.

5.4. NAVIGATION ACCURACY

The GPC performs routine checks of the navigation for every month of data in two steps. The survey step checks every image in a crude way by checking for proper radiance contrasts across the terminator (solar channel only), the planet limbs (IR channel only), and coastlines (both channels). Any anomalous behavior is flagged for further inspection. The inspection step is performed on four complete days of images per month, even if no other images are flagged by the survey step. Each image (both channels) is displayed with continental outlines and angle contours superimposed. Manual inspection of the correspondence of the coastlines with visible landmarks is used to verify navigation accuracy. Also, the consistency of the angle distribution over the image is checked.

The accuracy of the image pixel locations varies depending on the procedure, but nominal estimates place the accuracy for all satellites at $\leq$ 20 km or approximately $\leq$ 0.18° (near nadir). The checks made on B3 data to monitor the accuracy verify the navigation accuracy to within one B3 pixel or about 24-30 km, 0.2-0.3°.