

GOES I-M IMAGE NAVIGATION AND REGISTRATION*

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ABSTRACT

Image Navigation and Registration (INR) is the system that will be used on future Geostationary Operational Environmental Satellite (GOES) missions to locate and register radiometric imagery data. It consists of a semiclosed loop system with a ground-based segment that generates coefficients to perform image motion compensation (IMC). The IMC coefficients are uplinked to the satellite-based segment, where they are used to adjust the displacement of the imagery data due to movement of the imaging instrument line-of-sight. This paper describes the flight dynamics aspects of the INR system in terms of the attitude and orbit determination, attitude pointing, and attitude and orbit control needed to perform INR. It discusses the modeling used in the determination of orbit and attitude, the method of on-orbit control used in the INR system, and various factors that affect stability. It also discusses potential error sources inherent in the INR system and the operational methods of compensating for these errors.

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INTRODUCTION

The Geostationary Operational Environmental Satellites (GOES) I through M (I-M) will begin a new era in the monitoring of the Earth's meteorological environment by the National Oceanic and Atmospheric Administration (NOAA). This monitoring is done through the collection and distribution of environmental images and soundings of the Earth's surface and atmosphere. NOAA will use the Image Navigation and Registration (INR) System to navigate and register these images accurately. Image navigation is the process of determining the Earth latitude and longitude of each pixel in an image. Image registration is the process of maintaining the relative pixel-to-pixel pointing within an image and the relative pointing of a particular pixel from image to image. This paper introduces and describes the GOES I-M INR system and illustrates the intimate connections between the new concept of INR and concepts that are more familiar to flight dynamics specialists, namely, the concepts of orbit and attitude determination and control.

The images and soundings for GOES I-M are acquired by two instruments, the imager and the sounder, which are located on the Earth-pointing face of the spacecraft main body. Figure 1 shows these instruments and the other major components of the spacecraft. More detailed descriptions of the spacecraft are presented in the literature listed in the Bibliography.

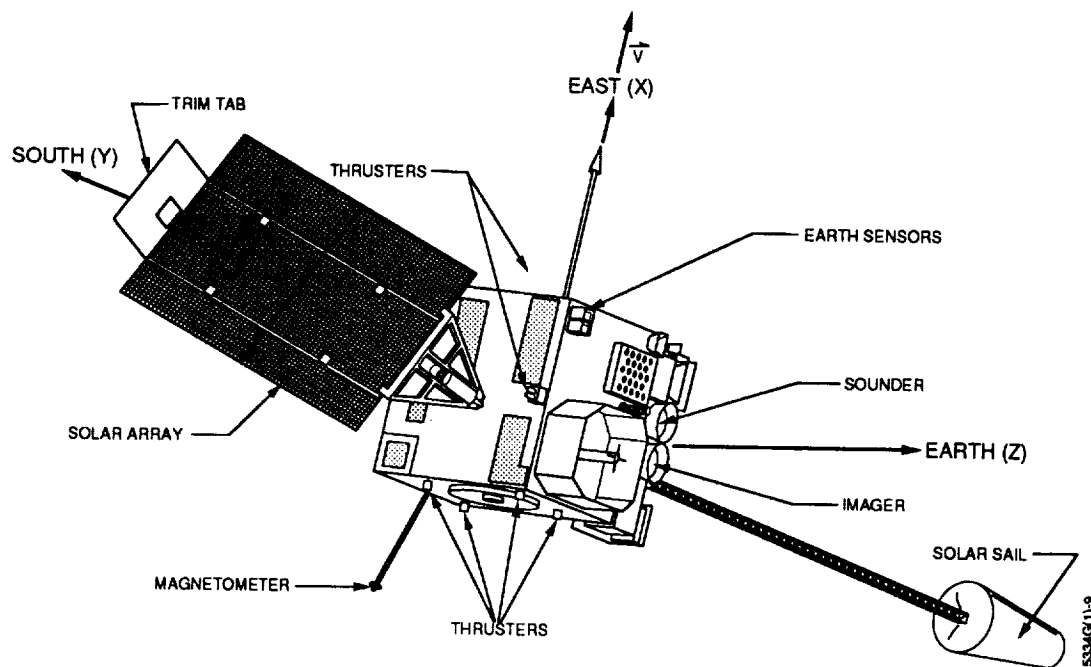


Figure 1. GOES I-M Spacecraft Configuration

To maintain proper positioning and pointing for the imager and sounder, two operational GOES I-M spacecraft will be positioned in geostationary orbits with a nominal attitude. These two operational spacecraft are located along the Equator at geostationary positions

of 75 and 135 degrees West longitude (Figure 2). At these locations, meteorological environmental images and soundings will be provided for much of the Western Hemisphere. Nonoperational spacecraft will be positioned in geostationary orbits at longitudinal locations safely away from the operational satellites. A nominal three-axis attitude is also sustained to provide proper pointing for the imager and sounder. This nominal attitude, shown in Figure 3, has the yaw axis pointing at nadir (the Earth), the pitch axis pointing along negative orbit normal, and the roll axis pointing along the velocity vector. Taken together, these geostationary locations and nominal attitude form the reference orbit and attitude for GOES-East and GOES-West, respectively.

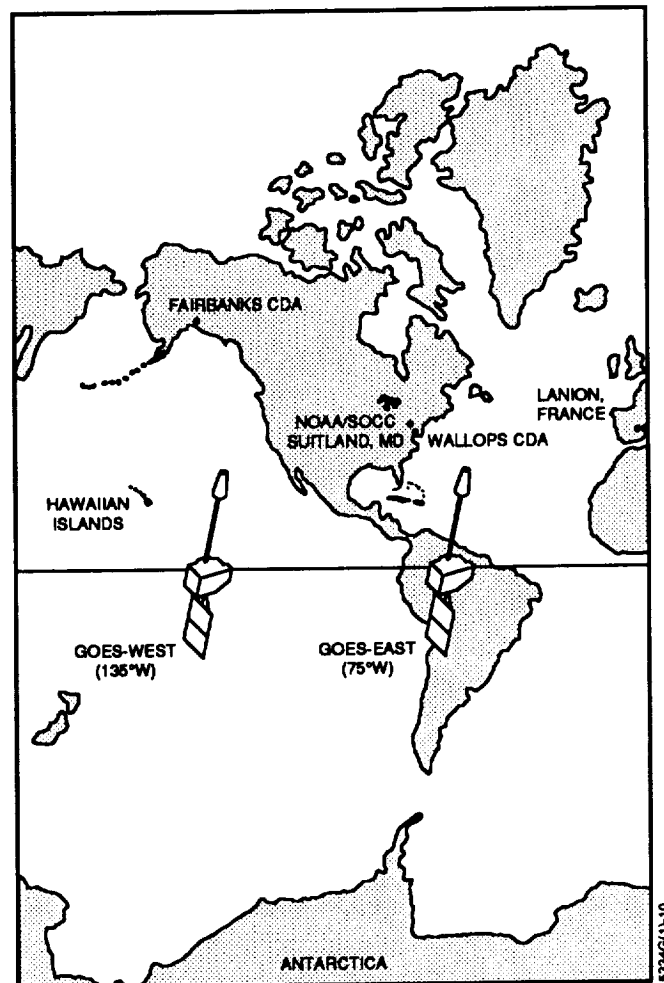


Figure 2. Nominal GOES Stations

Because they are fixed in an Earth-pointing direction, the imager and sounder use independent two-axis gimballed mirror scan systems to generate their respective images and soundings. Figures 4 and 5 show typical scan patterns for the imager and sounder detector arrays, respectively. The imager detector array consists of one visible and four IR channels, as shown in Figure 4. The sounder has 18 IR channels and 1 visible channel,

all of which are configured as shown in Figure 5. During a typical scan line, the mirror will continuously move along the scan line to a new position. At each new position, radiometric data are taken. At the end of a line, the mirror steps in the north/south direction to a new scan line. Both instruments act as their own star sensors, slewing away from the Earth to view stars.

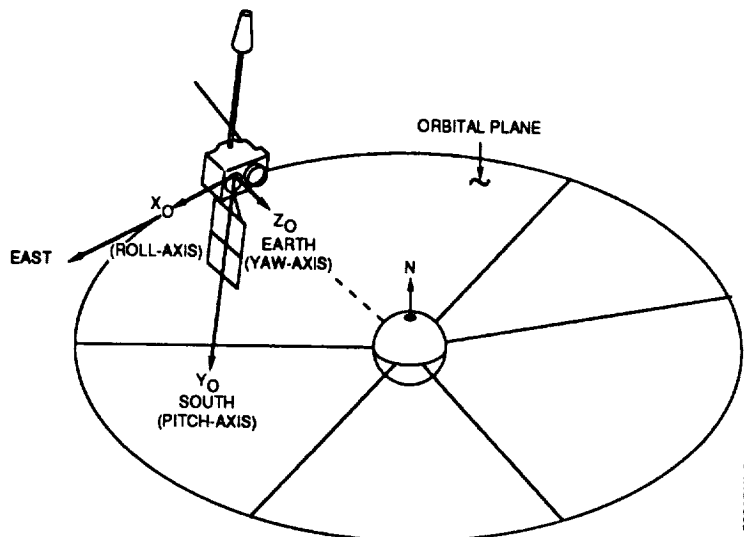
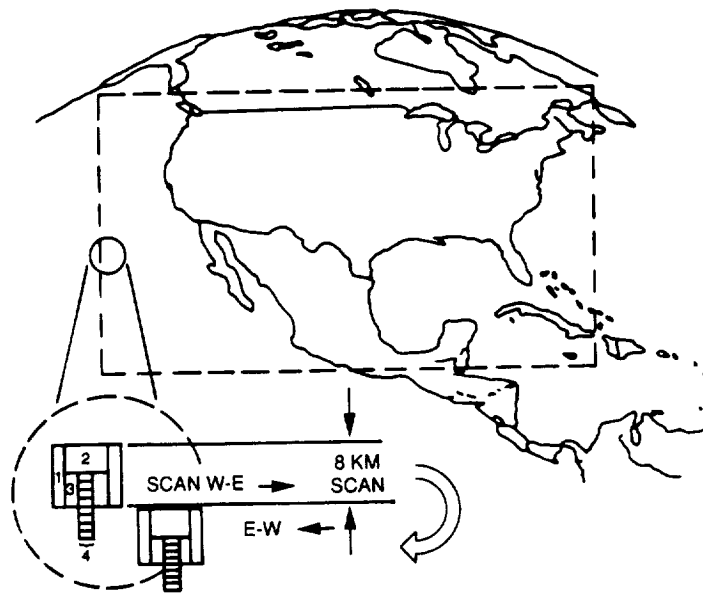


Figure 3. Nominal GOES I-M Orientation

The line-of-sight pointing for these instruments is not truly fixed. There are pointing errors that also move the line of sight. These errors are caused by orbit and attitude drifts, spacecraft thermal distortions, instrument servo errors, attitude control system noise, and dynamic interactions between the instruments and the spacecraft. The INR system is designed to remove or minimize these errors.

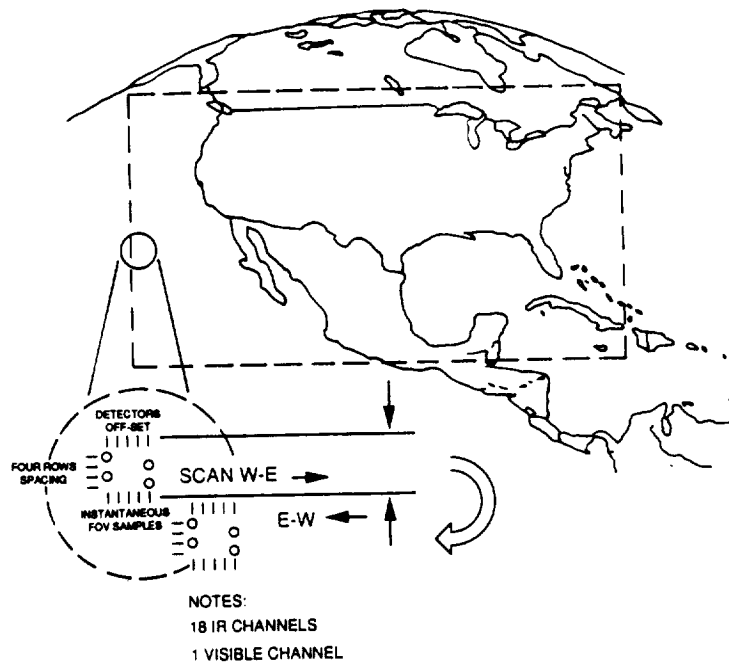
The GOES I-M INR system is a cyclical system, as represented in Figure 6. In this system, the imager and sounder gather star and landmark observations as part of their daily operations. These observations are sent to the Operations Ground Equipment (OGE), where they are used in conjunction with range data to perform orbit and attitude determination. Over the course of a day, an orbit and attitude profile is developed, from which a set of image motion compensation (IMC) coefficients are generated. These IMC coefficients are uplinked to the spacecraft, where they are used by the onboard computer to correct the pointing of each pixel for drifts caused by predicted, systematic errors such as orbit and attitude drifts and predictable thermal distortions. However, random errors also affect pixel pointing during the imaging period when these compensations are being made. These random errors are reflected in the new star and landmark observations that are taken and used for subsequent orbit and attitude determination. The goal of the INR system is to remove or minimize these errors to within acceptable values. Table 1 lists the specifications for these acceptable values. During orbit day, visible imagery data are used for INR; during orbit night, infrared imagery data are used.



NOTES:

- 1 = ONE 8-KM IR CHANNEL FOR 6.5- TO 7.00-MICROMETER WATER VAPOR
- 2, 3 = THREE 4-KM IR CHANNELS FOR 3.8- TO 4.00-MICROMETER NIGHT CLOUDS
10.2- TO 11.2-MICROMETER SURFACE TEMPERATURE
11.5- TO 12.5-MICROMETER SEA SURFACE TEMPERATURE
AND WATER VAPOR
- 4 = ONE 8-KM VISIBLE CHANNEL FOR 0.55- TO 0.75-MICROMETER CLOUD COVER

Figure 4. Typical Imager Scan Pattern



NOTES:

- 18 IR CHANNELS
- 1 VISIBLE CHANNEL

Figure 5. Typical Sounder Scan Pattern

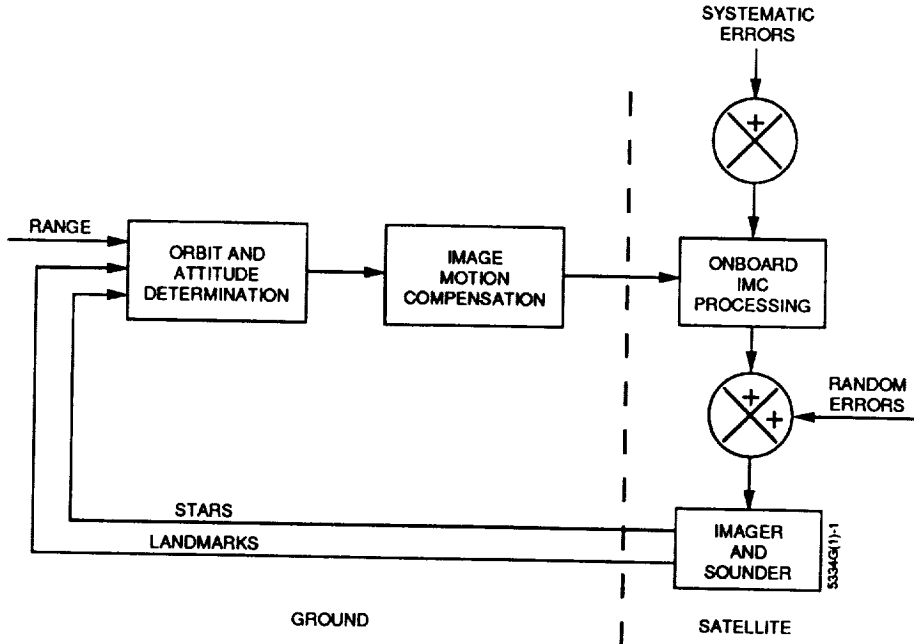


Figure 6. GOES I-M INR System

Table 1. INR Specifications

| PARAMETER | ORBIT NOON ±8 HOURS | | ORBIT MIDNIGHT ±4 HOURS | |
|--|---------------------|--------------|-------------------------|--------------|
| | KILOMETERS* | MICRORADIANS | KILOMETERS* | MICRORADIANS |
| IMAGER | | | | |
| IMAGE NAVIGATION (AT NADIR) | 4 | 112 | 6 | 168 |
| IMAGE REGISTRATION WITHIN A 25-MINUTE IMAGE | 1.5 | 42 | 1.5 | 42 |
| IMAGE REGISTRATION BETWEEN REPEATED IMAGES TAKEN WITHIN 90 MINUTES | 3 | 84 | 3.75 | 105 |
| IMAGE REGISTRATION BETWEEN REPEATED IMAGES TAKEN WITHIN 24 HOURS | 6 | 168 | 6 | 168 |
| SOUNDER | | | | |
| IMAGE NAVIGATION (AT NADIR) | 10 | 280 | 10 | 280 |
| IMAGE REGISTRATION WITHIN A 120-MINUTE SOUNDING | 3 | 84 | 4 | 112 |
| IMAGE REGISTRATION BETWEEN SOUNDINGS TAKEN WITHIN 24 HOURS | 10 | 280 | 10 | 280 |

*NOTE: AT GEOSYNCHRONOUS ALTITUDE, 28 MICRORADIANS SUBTENDS 1 KILOMETER ON THE GROUND.

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IMAGE NAVIGATION

Determining the location on the Earth at which a pixel is pointing requires a knowledge of the position and orientation of the pixel. This is equivalent to knowing the spacecraft orbit and the spacecraft and instrument attitudes. Consequently, orbit and attitude determination play a major role in image navigation.

Three types of observations are used in determining the orbit and attitude: range, landmark, and star data. Range data are normally acquired from NOAA's Command and Data Acquisition (CDA) station located at Wallops, Virginia. Occasionally, the NASA Deep Space Network (DSN) is also used. Landmark and star data are obtained by the imager and sounder. Landmarks are obtained during each instrument's normal imaging operation. Each operational satellite has a reference set of landmarks (Figure 7). The landmark is a well-defined land point, usually at a boundary between land and water. Figure 8 shows an example landmark for the GOES-West satellite. Visual landmarks are used during day, and infrared landmarks are used during night. Star observations are also obtained by the imager and sounder. After completion of an image, the scan mirror slews to a position just ahead of an expected star crossing. The mirror remains fixed while the normal orbital motion of the spacecraft allows the star to sweep across the mirror and be detected. The imager and sounder are capable of observing stars down to the sixth magnitude.

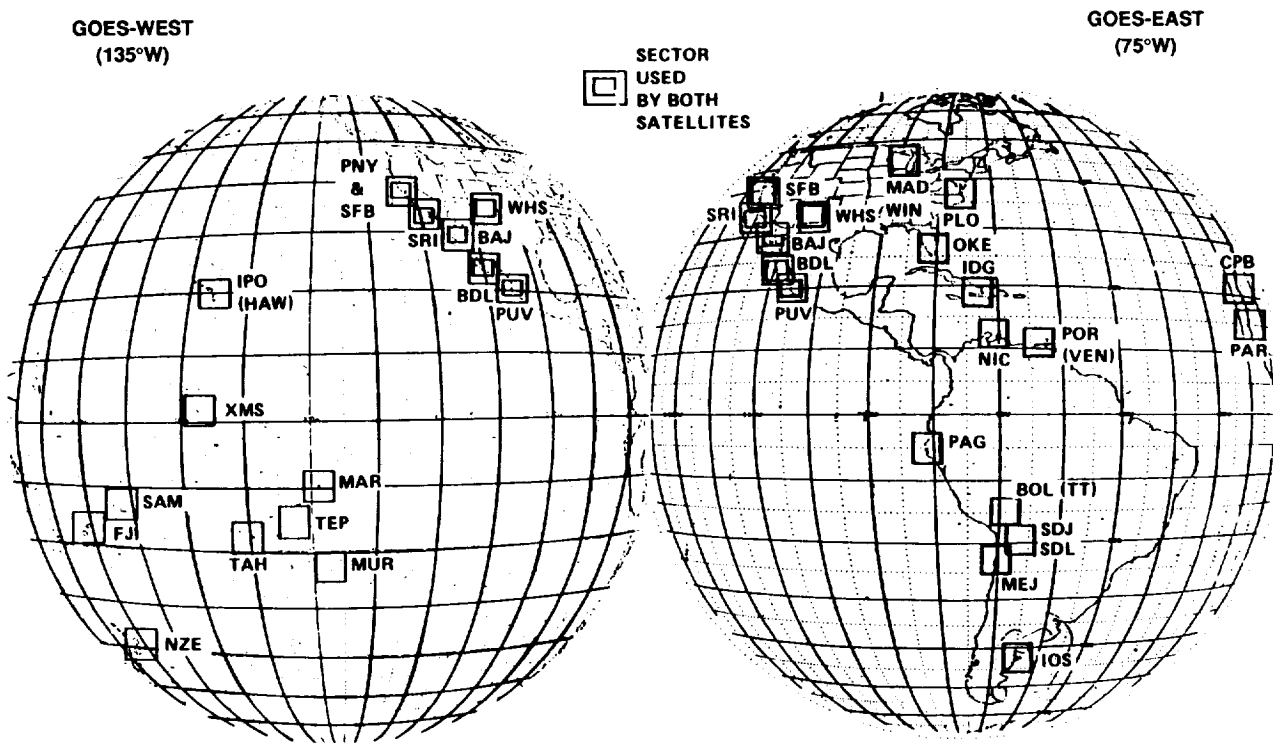


Figure 7. GOES Reference Landmark Locations

Once the observations are recorded, they are corrected for known physical effects and processed into observables. Range data are corrected for atmospheric refraction, polar

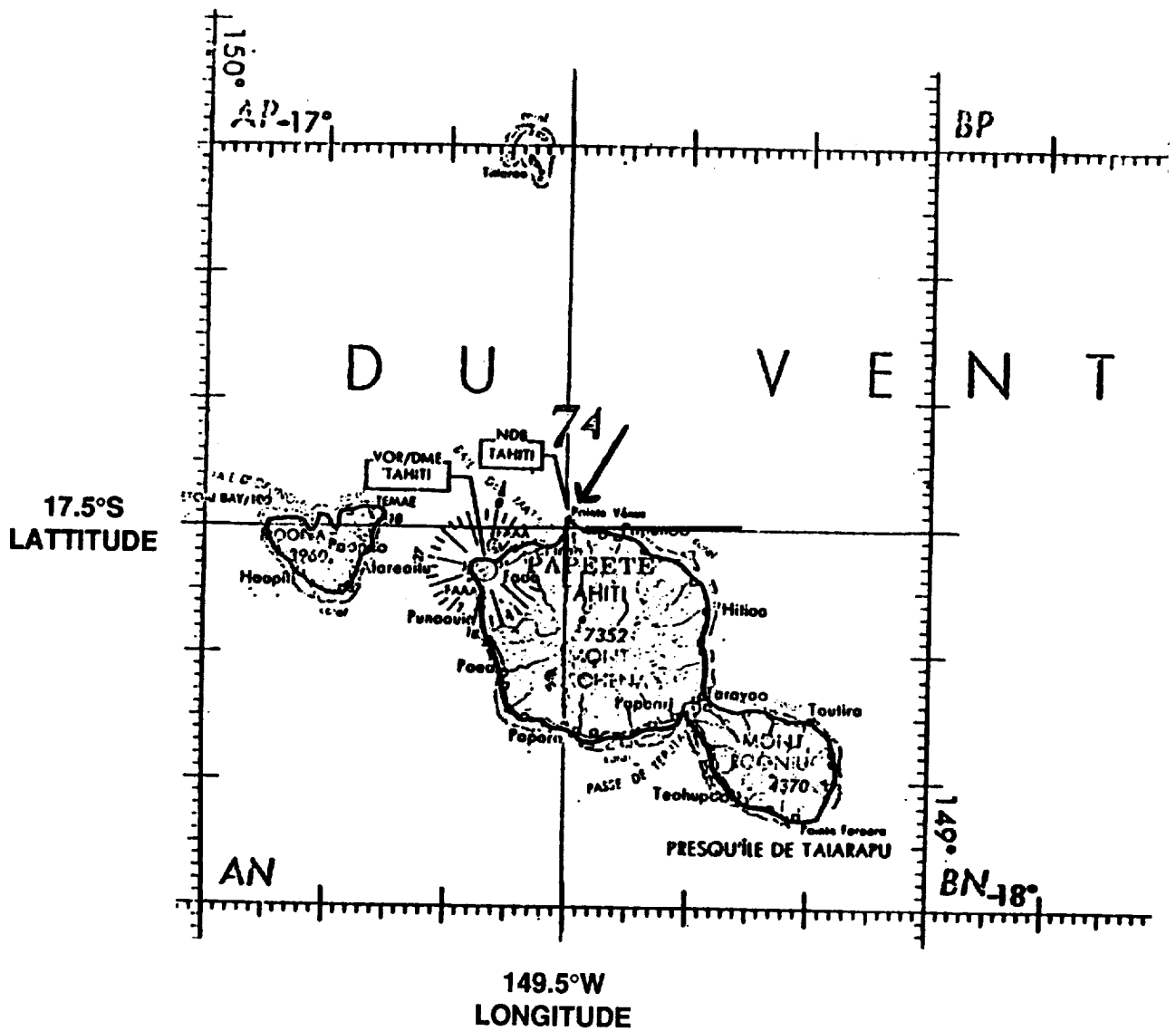
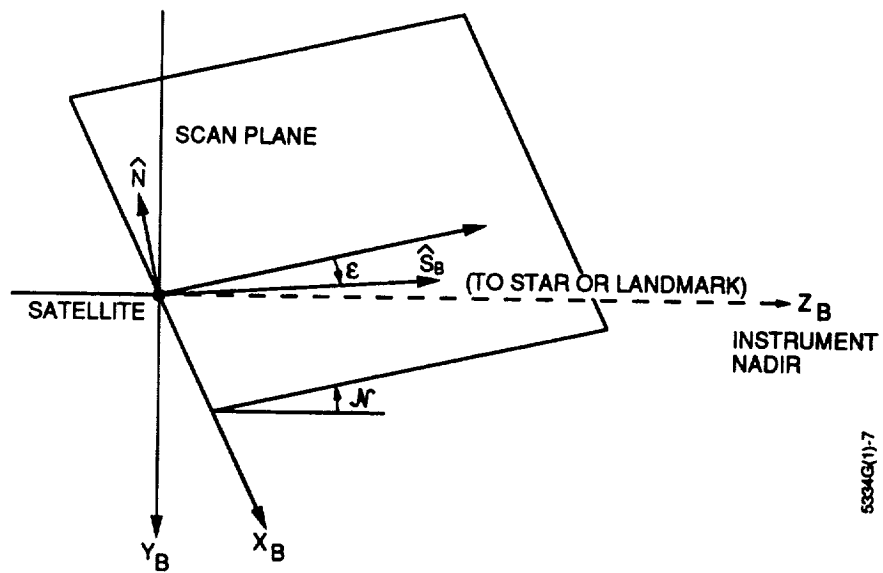


Figure 8. Example GOES Landmark—Tahiti

wander, and electronics delays. A predetermined station clock bias and range bias are then added to the range data to produce a slant range observable.

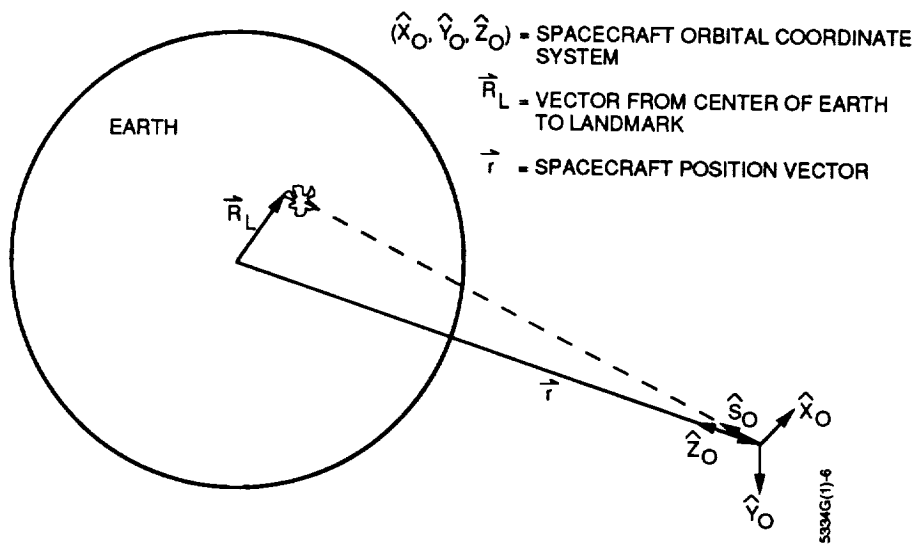
Star observations are corrected for proper motion, stellar aberration, and parallax; landmark observations are corrected for satellite orbital motion aberration. Additional corrections due to instrument characteristics such as image rotation and misalignments are also included in star and landmark observation corrections. Because of the orientation of the scan mirror with respect to the detector at a particular north/south scan angle, the projection of the image will be rotated as shown in Figure 9. This phenomena is known as image rotation. Mounting misalignments cause a constant systematic bias. Detector misalignment is caused by thermal distortions between other components of the spacecraft and the instrument. One additional correction is made on landmark observations. Because the onboard computer applies IMC shifts to pixels on the Earth, the landmark



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(X_B, Y_B, Z_B) = INSTRUMENT BODY COORDINATE SYSTEM

Figure 10. Scan Angle Observables in Instrument Body Coordinate System



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Figure 11. Scan Angle Measurement

orbit and attitude in terms of a state vector, generating partials of the measurement model with respect to the state vector, and estimating the orbit and attitude. Equations (1) and (2) form the basis for the first step—developing the measurement model for the scan angle observables—since these observables are components of \hat{S}_B in the instrument body coordinate system ($\hat{x}_B, \hat{y}_B, \hat{z}_B$). The measurement model for the slant range, ρ , is illustrated geometrically in Figure 12 and mathematically by

$$\rho \text{ (slant range)} = |\vec{r} - \vec{R}_e| + \text{range bias} \quad (3)$$

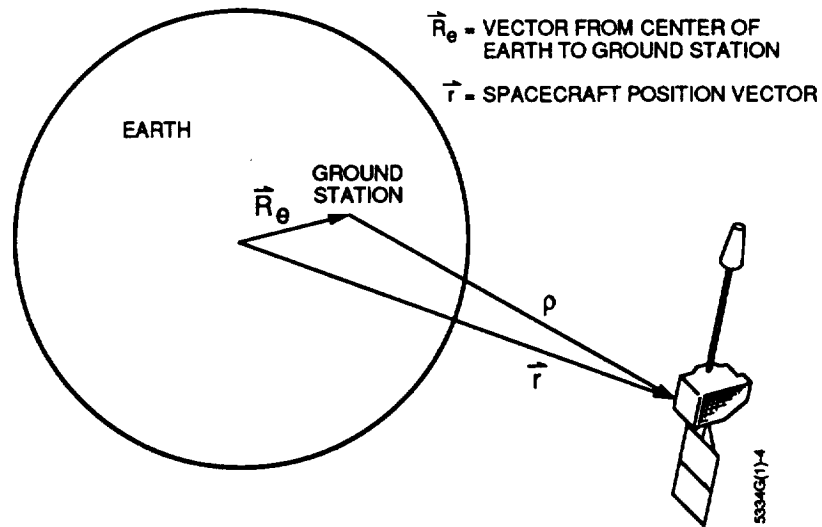


Figure 12. Range Measurement

The orbit model in the state vector is parameterized in terms of equinoctial elements that are used to avoid singularities for zero or near-zero inclination and zero or near-zero eccentricity orbits. The equinoctial elements are listed below in terms of the more familiar Keplerian elements.

| <u>Equinoctial Elements</u> | <u>Keplerian Elements</u> |
|--|---|
| $a_f = e \cos (\Omega + \omega)$ | $e = \text{eccentricity}$ |
| $a_g = e \sin (\Omega + \omega)$ | $\Omega = \text{right ascension of ascending node}$ |
| $n = \left(\frac{\mu}{a^3} \right)^{1/2}$ | $\omega = \text{argument of perigee}$ |
| $(\mu = \text{gravitational constant})$ | $a = \text{semimajor axis}$ |

| Equinoctial Elements | Keplerian Elements |
|--|---------------------------|
| $L = \Omega + \omega + M$ | $M = \text{mean anomaly}$ |
| $\chi = \frac{\sin i \sin \Omega}{1 + \cos i}$ | $i = \text{inclination}$ |
| $\psi = \frac{\sin i \cos \Omega}{(1 + \cos i)}$ | |

The attitude model in the state vector is a linear combination of basis functions representing each of the five attitude angles: roll (ϕ), pitch (θ), yaw (ψ), roll misalignment (ϕ_{ma}), and pitch misalignment (θ_{ma}). The basis function consists of Fourier, exponential, and monomial sinusoid functions denoted by subscripts F, E, and MS, respectively:

$$\beta^i(t) = \beta_F^i(t) + \beta_E^i(t) + \beta_{MS}^i(t) \quad i = (1, \dots, 5) \text{ corresponding to} \quad (4)$$

$$(\phi, \theta, \psi, \phi_{ma}, \theta_{ma})$$

The attitude can be expressed by up to three basis function sets. A Fourier series

$$\beta_F^i(t) = \sum_{j=0}^n C_{1j}^i \cos(j\omega t + a_j^i) \quad (5)$$

is used to model the nominal daily attitude behavior. Exponential functions

$$\beta_E^i(t) = C_{E1}^i e^{-t/C_{E2}^i} \quad (6)$$

are included to model the deviations in attitude that usually occur around eclipse. Monomial sinusoid functions

$$\beta_{MS}^i(t) = \sum_{j=1}^4 C_{1j}^i (t - C_{3j}^i)^{D_j} \cos(O_j \omega t + C_{2j}^i) \quad (7)$$

are available to model attitude deviations that cannot be modeled by Fourier or exponential functions.

The solve-for parameters in the orbit model are the equinoctial elements at epoch, σ_0 ; in the attitude model, they are the coefficients (c_{ij}^k , a_j^i , D_j , and O_j) in the basis function set

modeling the attitude. Consequently, the partial matrix of the measurement model, \vec{M} , contains elements that are chain rule partial derivatives of these solve-for parameters:

$$\frac{\partial \vec{M}}{\partial \vec{\sigma}_0} = \frac{\partial \vec{M}}{\partial(\vec{r}, \vec{v})} \frac{\partial(\vec{r}, \vec{v})}{\partial \vec{\sigma}} \frac{\partial \vec{\sigma}}{\partial \vec{\sigma}_0} \quad (\text{orbit partials}) \quad (8)$$

$$\frac{\partial \vec{M}}{\partial \vec{c}} = \frac{\partial \vec{M}}{\partial \vec{\beta}} \frac{\partial \vec{\beta}}{\partial \vec{c}} \quad (\text{attitude partials}) \quad (9)$$

These partials are used in a linearized least-squares estimation to determine the orbit, attitude, and attitude misalignments.

IMAGE REGISTRATION

To maintain the relative pixel-to-pixel pointing within an image and between images, it is necessary to control the orbit and attitude of the spacecraft. For GOES I-M, orbit control is performed through manual ground commands, and attitude control is performed autonomously on the spacecraft.

To meet the INR requirements listed in Table 1, the geosynchronous GOES orbit must be controlled in both inclination (north/south excursion from the Equator) and longitude (east/west excursion from nominal longitude). The inclination is maintained to within 0.1 degree of the Equator, and the longitude is maintained to within 0.5 degree on either side of its nominal longitude.

Solar and lunar gravity are the primary perturbations that cause the inclination drift away from the Equator. This drift causes an inclination maneuver approximately every 2.8 months. The tesseral harmonic terms of the Earth's gravitational potential are the principle contributors to longitudinal drift. This drift causes a longitude maneuver approximately every 2.5 months.

Nominal attitude control is performed using a horizon sensor and a pair of momentum wheels. The momentum wheels nominally run with a constant pitch angular momentum to maintain Earth pointing. The horizon sensor senses pitch and roll. Pitch errors cause a speed modulation in both momentum wheels to control pitch. Roll errors cause a differential modulation of the momentum wheel speeds to induce momentum along the yaw axis. Roll and yaw are coupled due to the rotation of the roll/yaw plane around an orbit. Periodically, momentum is dumped using thrusters to avoid saturation of the momentum wheels.

The primary environmental torque at geosynchronous orbit is due to solar radiation pressure force, which causes an inertial roll torque. Coarse control of this torque is done using the rigid solar sail located on the north face of the spacecraft and the movable trim tab panel located on the base of the solar array (Figure 1). Fine control is done using the magnetic torquer coils.

The control system also performs corrections to the instrument servos, preventing image disturbances in one instrument caused by the independent motion of the scanning mirror in the other instrument. This autonomous correction, known as mirror motion compensation (MMC), causes the mirror drive electronics to adjust the inertial pointing of the mirror to compensate for attitude disturbances caused by motion of the other instrument's mirror.

Certain circumstances cause pointing disturbances in the control system and consequently affect INR. Cloud and radiance gradient excursions and solar or lunar intrusions into the horizon sensor field of view are such circumstances. Cloud and radiance gradient excursions result in a deviation in the detected infrared threshold that produces an anomalous pitch or roll error. Sun and Moon intrusions result in a deviation in the Earth horizon limb detection that also produces an anomalous pitch or roll error. Either of these conditions can be identified by observing the residual errors of star and landmark observations from their predicted locations. Special ground operations minimize their effects. In these special operations, intermediate IMC coefficient sets, based on the observation data affected by these conditions, are uplinked and used to navigate and register the image until normal conditions resume.

Orbit maneuvers also cause significant postmaneuver disturbances. During an orbit maneuver, the attitude is autonomously controlled using the horizon sensor, three mutually perpendicular gyros, and thrusters. An attitude error sensed by the sensor or the gyros causes an automatic thruster firing, compensating for the error. When the orbit maneuver is completed, attitude control is resumed by the horizon sensor and momentum wheels. The thruster firings during the maneuver cause significant disturbances that do not immediately die down after the maneuver. The yaw error from these disturbances is not immediately sensed. Special ground operations are used to reduce the yaw attitude error after the maneuver. These operations consist of determining the yaw error using star observations and manually performing short thruster firings to remove most of the yaw error. Any residual yaw error remaining is removed by the magnetic torquer coils.

IMAGE MOTION COMPENSATION

IMC is the main component of the INR system. It is the process used by the onboard computer to correct the azimuth and elevation pointing of each image pixel, in real time, for deviations caused by orbit drift, attitude drift, misalignments caused by spacecraft thermal distortions, and other systematic errors.

In effect, IMC corrects the true pointing of the pixels in an image to the ideal pointing of the pixels. The ideal pointing of the pixel is defined with respect to an ideal, or reference, orbit and attitude. The true pointing of the pixel deviates from this ideal pointing due to deviations of the orbit, attitude, and attitude misalignments from this reference orbit and attitude.

This is illustrated in Figure 13. In this figure, \vec{R}_R represents the ideal pointing of a pixel in the reference orbit and attitude coordinate system ($\hat{x}_R, \hat{y}_R, \hat{z}_R$). This system defines the ideal, or reference, orbit and attitude. The reference coordinate system is one in which the spacecraft orbit and attitude are as follows:

- The spacecraft is always located at its reference longitude (75°W for GOES-East or 135°W for GOES-West).
- The spacecraft is always along the Equator in a zero inclination orbit.
- The spacecraft attitude is referenced with roll = pitch = yaw = 0 in the orientation shown in Figure 3.

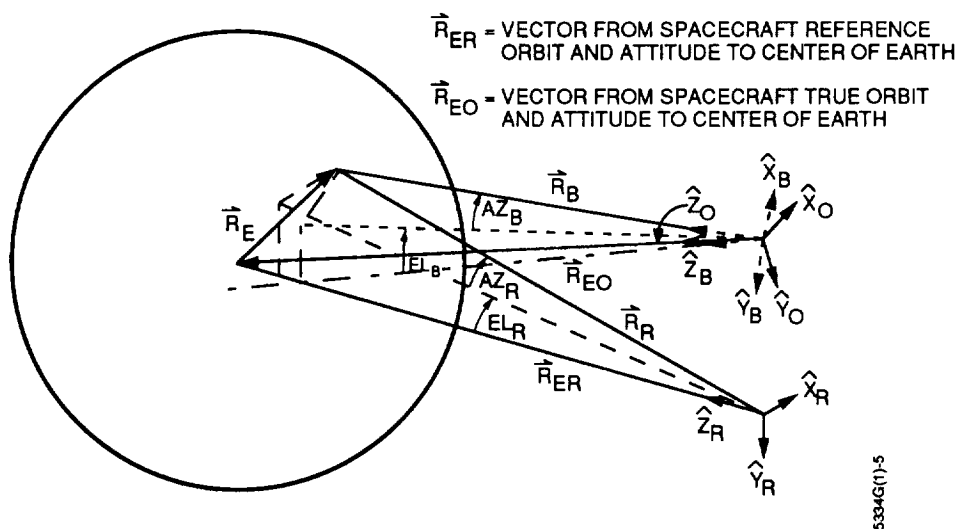


Figure 13. IMC Geometry

The true orbit deviation from the reference orbit is a function of the difference in longitude, λ_e , from the reference longitude; the nonzero inclination, i , of the true orbit; and the argument of latitude, u , of the spacecraft position in the nonzero inclination orbit. This is shown graphically in Figure 14. The 2-3-2 transformation, M_O , defines the relationship between the reference coordinate system, ($\hat{x}_R, \hat{y}_R, \hat{z}_R$), and the spacecraft orbital coordinate system, ($\hat{x}_O, \hat{y}_O, \hat{z}_O$). The geometries of these systems are shown in

Figure 13. The relationships between a pointing vector in the spacecraft orbital coordinate system can then be expressed with respect to the reference coordinate system as follows:

$$\vec{R}_O = M_O (\lambda_e, i, u) \vec{R}_R \quad (10)$$

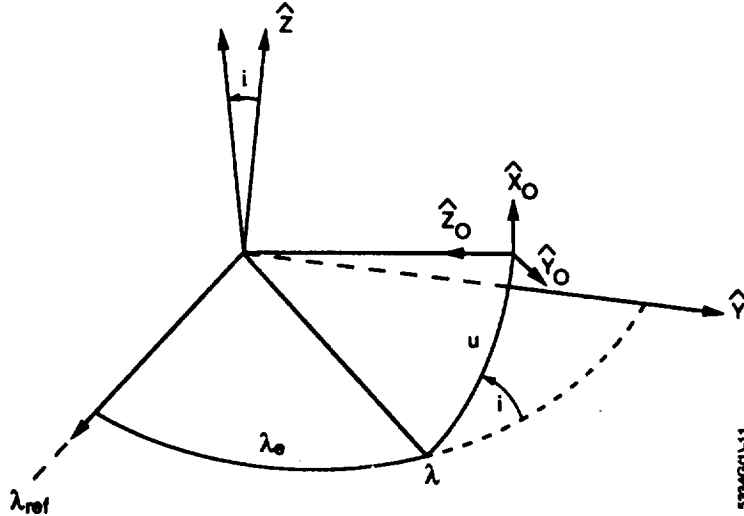


Figure 14. True Orbit Transformation Geometry With Respect to an Earth-Centered Coordinate System (\hat{x} , \hat{y} , \hat{z})

where M_O is the transformation matrix between the pointing vector, \vec{R}_R , in the reference coordinate system ($\hat{x}_R, \hat{y}_R, \hat{z}_R$) and the pointing vector, \vec{R}_O , in the spacecraft orbital coordinate system ($\hat{x}_O, \hat{y}_O, \hat{z}_O$).

Attitude deviations are functions of the spacecraft roll (ϕ), pitch (θ), and yaw (ψ) angles with respect to the reference attitude. They are represented by a 1-2-3 Euler transformation, M_E . When applied to the spacecraft orbital coordinate system, ($\hat{x}_O, \hat{y}_O, \hat{z}_O$), this transformation produces the instrument body coordinate system ($\hat{x}_B, \hat{y}_B, \hat{z}_B$), which is also shown in Figure 13. The equations

$$\vec{R}_B = M_E (\phi, \theta, \psi) \vec{R}_O \quad (11)$$

and

$$\vec{R}_B = M_E (\phi, \theta, \psi) M_O (\lambda_e, i, u) \vec{R}_R \quad (12)$$

show the relationships between the pointing vector, \vec{R}_B , in the instrument body coordinate system ($\hat{x}_B, \hat{y}_B, \hat{z}_B$) and the spacecraft orbital and reference coordinate system pointing vectors, \vec{R}_O and \vec{R}_R , respectively.

The IMC system uses these transformations and misalignment offsets of the scan angles in the instrument body scan plane (Figures 9 and 10). Misalignment deviations are any roll and pitch misalignments, ϕ_{ma} and θ_{ma} , of the instrument with respect to the spacecraft. These misalignments affect the scan angle observables, ϵ and \mathcal{N} , through offsets, $\delta\epsilon$ and $\delta\mathcal{N}$, in the instrument body coordinate system (see Figure 9). These offsets are dependent upon the elevation angle, \mathcal{N} , of the scan plane in the instrument body coordinate system (see Figure 10):

$$\delta\epsilon = \theta_{ma} \cos \mathcal{N} + \phi_{ma} \sin \mathcal{N} \quad (13)$$

$$\delta\mathcal{N} = \theta_{ma} \sin \mathcal{N} - \phi_{ma} \cos \mathcal{N} \quad (14)$$

The coordinate transformations and misalignment offsets from Equations (12) through (14) are used to correct the azimuth and elevation angles that define the pointing of an image pixel. Referring to Figure 13, these angles in the instrument body coordinate system are AZ_B and EL_B . However, in the reference coordinate system, these angles are AZ_R and EL_R . IMC changes the true pointing of the pixel by applying the following compensations:

$$\delta AZ = AZ_R - AZ_B \quad (15)$$

$$\delta EL = EL_R - EL_B \quad (16)$$

This is done by using the ground-determined orbit and attitude states in the form of IMC coefficients. The corrections due to orbit deviations are used by expressing the ground-computed orbit in terms of the following parameters:

- ΔR —difference in radial distance from the ideal radial distance
- $\Delta \lambda$ —difference in subsatellite longitude from the ideal subsatellite longitude
- ΔL —difference in subsatellite latitude from the Equator
- $\Delta \psi$ —difference in yaw caused by the orbit's inclination

The corrections due to attitude are computed by determining the attitude angles from the solve-for coefficients of the attitude determination process. As many as 550 coefficients are uploaded daily to determine these orbit and attitude corrections.

During scanning of the Earth, the onboard computer continually computes these corrections. The onboard flight model approximates the exact computation to provide high-speed calculations for real-time pixel corrections. Because the mirror is continually scanning during these computations, the onboard computer performs extrapolations to account for this motion. It also models the curvature of the Earth at the limb to avoid erratic behavior at the scanner turnaround point.

SUMMARY

This paper introduced and described the new system of navigating and registering meteorological environmental images—Image Navigation and Registration—that will be used on the GOES I-M spacecraft. It also demonstrated the deep-rooted connection between INR and orbit and attitude determination and control.

Before the expected launch of the spacecraft in the early 1990s, NOAA is working to resolve several issues dealing with the operational performance of this system. As with any new spacecraft system, a thorough checkout of each component must be accomplished once in orbit before it begins operation. NOAA and NASA INR specialists are currently working together to ensure that every component of the INR system undergoes complete ground testing so that the in-orbit checkout will be successful.

During the operation of the system, anomalous or degraded INR performance could occur due to some unforeseen circumstance. Once again, NOAA is preparing for such circumstances by investigating potential anomalous behavior and preparing operational procedures for dealing with their occurrence. The special operational procedures previously discussed in the section on image registration are examples of NOAA's preparation.

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