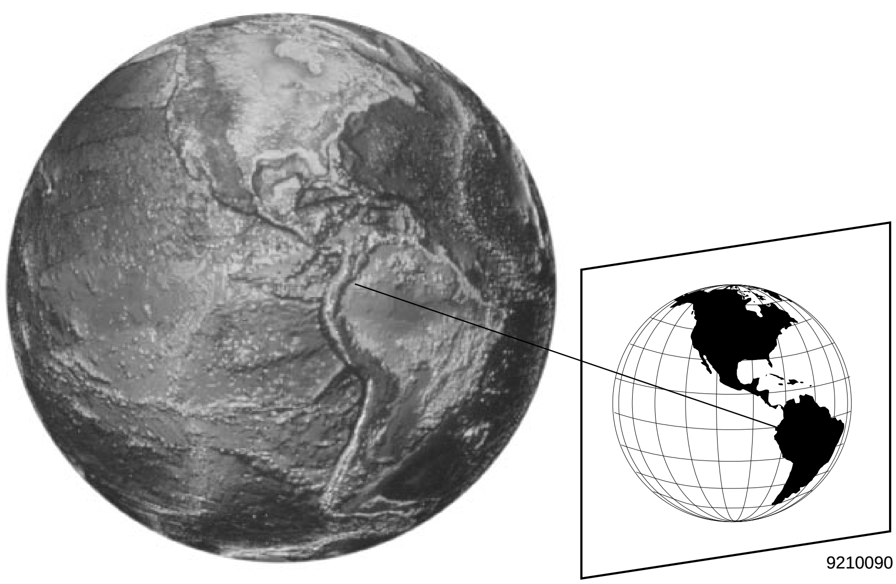
Image Navigation and Registration

In addition to the acquisition of imaging and sounding data, the GOES I-M system is capable of registering to a high degree of accuracy the earth's latitude and longitude locations of each picture element (pixel) within an image. This accurate determination of pixel location is accomplished by a ground computer in the operations ground equipment (OGE), which processes star and landmark data obtained by the Imager and Sounder. Working in conjunction with the spacecraft attitude and orbit control electronics (AOCE), the process maintains pointing of the pixels.

The accurate location and pointing of each pixel is a two-part process. The first part, image navigation, determines the location of a pixel within an image relative to an earth-referenced latitude and longitude. The second part, registration, entails maintaining the location of the pixels within an image and between repeated images to their earth-referenced latitude and longitude. This unique process, image navigation and registration (INR), yields daily imaging and sounding data on a precisely located, fixed-earth coordinate grid without ground interpolation.

Image Navigation/Registration with Fixed Earth Projection



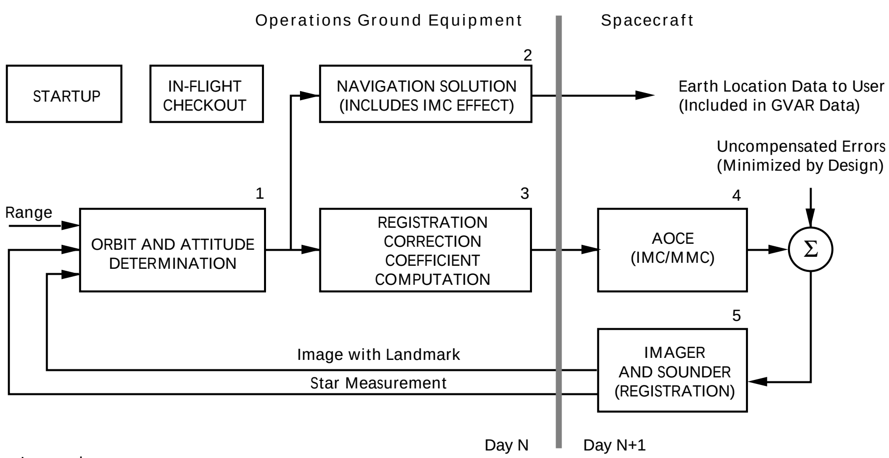
Fundamental Basis for INR Approach

Ideally, if the spacecraft were truly geostationary and the optical axes of the imaging instrument were to be held fixed relative to a geocentric coordinate frame, corresponding pixels of successive images would have the same earth longitude and latitude. In reality, however, orbital motion of the spacecraft and perturbations in the attitude of the optical axes, cause varying image motions over time. The purpose of the INR system is to correct for such motions at the source (the scan mirror) so that the apparent pixel shift due to these effects is compensated for in real-time, and the resulting earth projection remains fixed in the scan coordinate frame.

To accomplish this purpose the design of the INR system is based on three basic approaches:

- Spacecraft range data (altitude) together with star and landmark observation data (angles) are used in the spacecraft orbit and attitude determination process (block 1) in the OGE.
- The star and landmark data are obtained through the Imager (Sounder) itself (block 5); therefore all long-term effects are “zeroed out,” that is, the long-term effects are the same for each pixel as they are for stars and landmarks.
- Once long-term effects are modeled to compute registration correction coefficients (block 3), the mirrors of the Imager and Sounder are biased in east / west (E / W) and north / south (N / S) directions by the AOCE to compensate for those effects (block 4). The remaining error in navigation

Closed-Loop Image Navigation and Registration System



Legend

AOCE	Attitude and Orbit Control Electronics	IMC	Image Motion Compensation
GVAR	GOES Variable	MMC	Mirror Motion Compensation

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(block 2) and registration of each pixel (block 5) is primarily due to errors in attitude modeling, spacecraft stability, and scanner repeatability errors, which are minimized by design.

The real-time image motion compensation (IMC) and mirror motion compensation (MMC) of the INR system on board the spacecraft compensate for the orbit and attitude variations of the instruments to obtain images and soundings with a fixed-earth projection.

Image Navigation

Pixel navigation for the Imager and Sounder is independently established by orbit and attitude determination of each unit's optical line of sight. This computation, performed every 24 hours, is based on ranging data, landmark observations, and star observations made by each instrument. Orbit determination is accomplished primarily from range data and landmark observations. The ranging measurements are obtained by using the processed data relay (PDR) link and computing the round trip propagation time of the GOES variable (GVAR) format data bit stream. Attitude of the line of sight is based on star sensing through the Imager and Sounder optics and landmark observations; the star sense data are based on at least three different stars from both instruments and obtained about every 30 minutes. Hourly landmark data points are taken during the daylight intervals.

The spacecraft attitude is maintained and controlled with respect to the earth by means of an infrared earth sensor (ES), which provides the reference, and a momentum bias system with two skewed momentum wheels (MWs) for pitch and roll control. The spacecraft attitude control provides the short-term stability.

After accumulating the above line-of-sight information over a 24-hour period, the OGE models pixel drift experienced as a result of the long-term spacecraft motions due to both orbital effects and structural thermal distortion. The OGE then derives a set of compensation coefficients to be applied to the servo drives of the Imager and Sounder mirrors. These image motion compensation coefficients are uplinked daily to the spacecraft via the Command and Data Acquisition (CDA) Station, processed by the AOCE, and applied in the registration portion of the INR process.

Image Registration

The approach to registration is based on neutralizing the deterministic errors by applying a compensating signal to the scan mirror servo drive to correct the apparent pixel shifting. This shifting is caused by spacecraft motions, including long-term orbital and thermal effects and short-term effects due to the mechanical interaction of one instrument's mirror upon the other. The scan mirror is driven in such a way that the resulting image remains fixed in the scan coordinate system, thus achieving the required registration accuracy and fixed grids over a 24-hour period. The onboard correction compensates for mirror and image motions:

- IMC corrects for the long-term thermal distortions of the spacecraft, Imager and Sounder instruments, and Earth Sensor, as well as from spacecraft yaw and orbital deviations.
- MMC corrects for spacecraft short-term rigid body disturbances caused by mirror motion such as normal scan, retrace, blackbody and star sense.

Compensation for the mirror interaction effects is computed by the spacecraft AOCE and an analog mirror motion compensation signal is superimposed on the IMC signal prior to its application to the Imager and Sounder drives. The IMC coefficients are derived by the OGE.

INR Functional Configuration

Near real-time image navigation and registration are accomplished by implementing the various INR aspects on board the spacecraft and in the OGE at the SOCC and the CDA Station, all guided by the basic approach described above. The major functions of the INR system are:

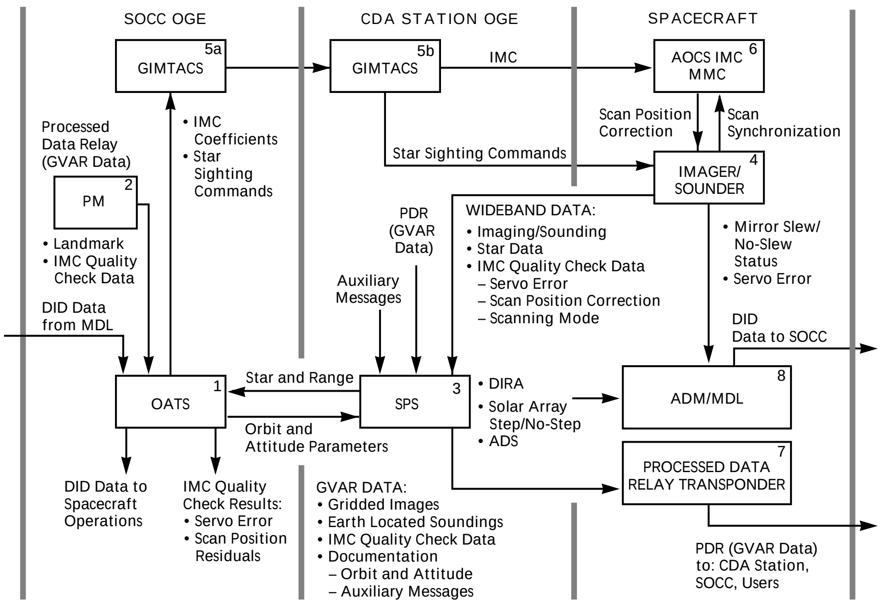
- Determination of spacecraft orbit and Imager and Sounder attitudes
- Generation of star sighting command data
- Landmark observation and ranging
- IMC and MMC
- Provision of real-time earth location information for users
- IMC quality check
- Dynamic interaction diagnosis

Orbit and Attitude

Spacecraft orbit and Imager/Sounder attitudes are determined in the orbit and attitude tracking system (OATS, block 1 of the following diagram) of the OGE at the Satellite Operations Control Center (SOCC). The product monitor (PM, block 2) sends to OATS data consisting of landmark longitude and latitude and corresponding instrument coordinates for the various landmarks while the sensor processing system (SPS, block 3) sends star data observed by the Imager/Sounder (block 4) and spacecraft range measured at the SPS. The off-line OATS determines spacecraft orbit and Imager/Sounder attitude parameters from spacecraft range, star, and landmark data and transmits the parameters to the SPS for gridding and inclusion in the GVAR data stream to users.

The OATS also generates star sighting command data issued directly to the Imager/Sounder via the GOES I-M telemetry and command system (GIMTACS, block 5), and periodically updates IMC coefficients for transmission to the onboard AOCE (block 6) through GIMTACS. The SPS provides the necessary

Functional Configuration - Image Navigation and Registration System



Legend

ADM	Attitude Data Multiplexer	IMC	Image Motion Compensation
ADS	Angular Displacement Sensor	MDL	Multiuse Data Link
AOCS	Attitude and Orbit Control Subsystem	MMC	Mirror Motion Compensation
DID	Dynamic Interaction Diagnostic	OATS	Orbit and Attitude Tracking System
DIRA	Digital Integrating Rate Assembly	PDR	Processed Data Relay
GIMTACS	GOES I-M Telemetry and Command System	PM	Product Monitor
GVAR	GOES Variable	SOCC	Satellite Operations Control Center

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data averaging, threshold detection, signal peak or midpoint determination, and time tagging of star sense data required as input to OATS.

Spacecraft range is determined at SPS from the time difference between uplinking the GVAR data stream from the SPS to the spacecraft and receiving the retransmitted GVAR downlink. The determined range and associated statistics are transmitted to OATS via GIMTACS. The range residual is calculated in OATS and used to estimate the spacecraft orbit and attitude. The ranging error due to noise is about 10 meters (33 feet).

Earth landmark data are essential to separate the orbit and attitude effects; landmarking is a manual task using the PM. Landmarks can be obtained from the visible detectors in the Imager (1-kilometer or 0.6 statute mile resolution) that are primary data, visible detectors in the Sounder (10-kilometer resolution) that are backup, and IR detectors in the Imager (4-kilometer resolution) that are also backup.

Image and Mirror Motion Compensation

In the IMC / MMC system, the spacecraft AOCE processor receives updated IMC coefficients from OATS and scan synchronization signals from the Imager and Sounder. With these data, the AOCE generates and sends to the Imager and Sounder servos mirror scan compensation signals, which are the sum of the IMC and MMC adjustments. These compensation signals are then converted to the proper scan adjustments in the Imager and Sounder, producing images and soundings with a fixed-earth projection.

The SPS receives wideband data from the spacecraft and generates in real-time GVAR formatted data consisting of gridded images, earth-located soundings, IMC quality check data, and documentation data (orbit and attitude parameters, auxiliary messages). The GVAR data stream is transmitted in real-time from the SPS to the spacecraft (block 7) and retransmitted in real-time to users, the CDA Station, and the SOCC. The SPS uses the received GVAR data for range measurements.

INR Quality

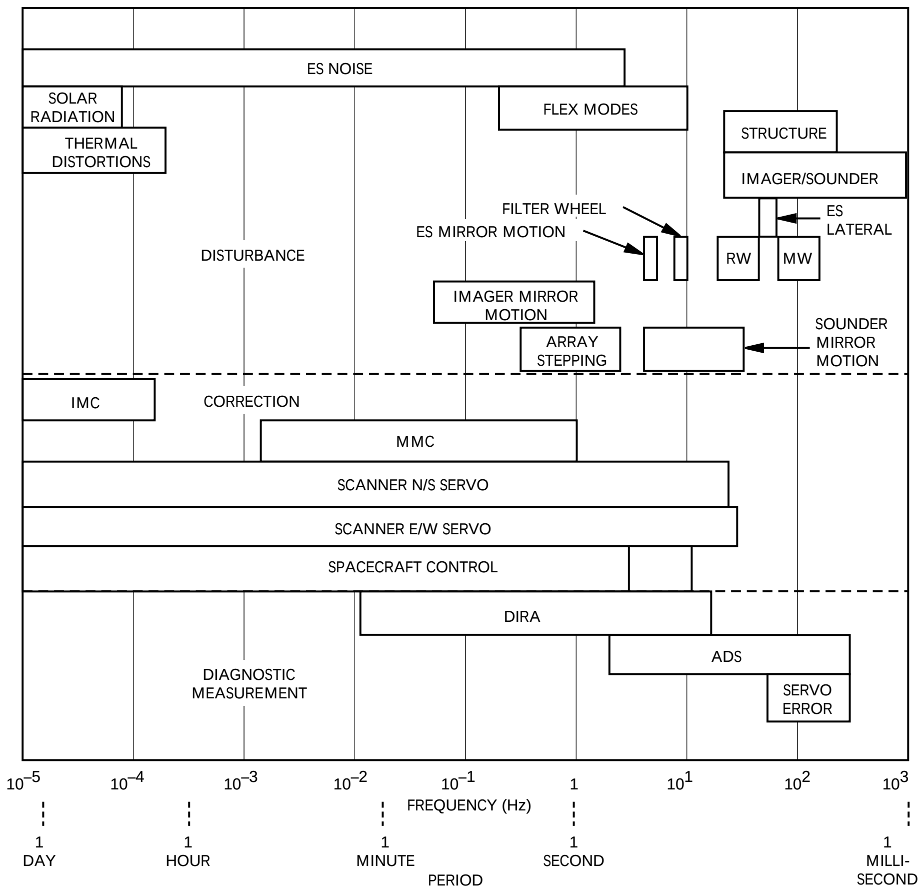
IMC quality check data consists of mirror position, compensation signal in effect, and status of the Imager and Sounder mirrors. Quality data are removed from the wideband data by the SPS, translated into the GVAR format, extracted from the GVAR downlink by the PM, and routed to OATS. The OATS then determines the IMC quality check results that are servo errors and mirror scan position residuals for both the Imager and Sounder. These results should be within prescribed limits for proper IMC operation; such limits are in the OATS data base. In addition to the above, monitoring of star, landmark, and range residuals by the OATS operator provides another source of data for verifying INR system operation.

An independent diagnostic attitude measurement system monitors any unforeseen disturbances affecting INR, including spacecraft dynamic interactions. From the multiuse data link (MDL, block 8), the OATS receives and processes dynamic interaction diagnostic (DID) data consisting of attitude data from the digital integrating rate assembly (DIRA), angular displacement sensor (ADS) data, and servo error data from the Imager and Sounder. The processed DID data, provided to SOCC, assist spacecraft operators and analysts to initialize and monitor the INR system.

INR Dynamic Environment

The complete dynamic environment of the spacecraft for image navigation and registration includes the dynamic interaction disturbance sources that affect INR, approaches for correcting the effects of such disturbances, and the dynamic interaction diagnostic measurement system installed on the spacecraft. It also includes the frequencies associated with the minor disturbances, as well as the natural vibration frequencies of the various spacecraft elements.

Spacecraft Dynamic Environment for INR



Legend

ADS	Angular Displacement Sensor	IMC	Image Motion Compensation
DIRA	Digital Integrating Rate Assembly	MMC	Mirror Motion Compensation
ES	Earth Sensor	MW	Momentum Wheel
E/W	East/West	N/S	North/South
		RW	Reaction Wheel

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Disturbance Sources

Minor disturbances to the spacecraft on orbit are caused by moving elements and flexible appendages that could lead to jitter in the line of sight of the Imager, Sounder, and ES. Such disturbances are caused by residual static and dynamic imbalance of MWs/reaction wheel (RW), scanning mirror motions of the ES, Imager and Sounder, solar array stepping, and oscillations of flexible appendages (solar array, solar sail and boom, and magnetometer boom). Imager and Sounder line-of-sight pointing errors are also affected by variations in thermal distortions of and solar radiation pressure on the spacecraft.

Correction Approaches

The spacecraft design incorporates means for compensating to a large extent the effects of the dynamic environment on INR. The IMC system on board the spacecraft mainly compensates for orbit and attitude errors due to thermal distortion and solar radiation effects. The MMC system compensates for the effects on the rigid body portion of the Imager and Sounder mirror motions. These correction approaches are also supported from the ground through available commands which can select stepping profiles that prevent solar array stepping motions from sympathetically interacting with the flexible appendages and from causing resonance in the solar array.

The AOCS attenuates the ES noise effect on spacecraft motion by a factor of 29 (from 375 to about 13 µrad). The Imager and Sounder scanner servo errors (E/W and N/S) are minimized by design (for example, using a coherent error integrator for Imager E/W motion and an average error integrator for Imager and Sounder N/S stepping motions).

Diagnostic Measurement (GOES-I & K)

As noted above, the diagnostic attitude measurement system monitors unforeseen disturbances affecting INR. The attitude motions in frequencies from near zero to 300 Hz can be determined from DID data. The DIRA provides attitude data in the range from zero to 15 Hz, the ADS from 2 to 200 Hz, and the Imager and Sounder servo error telemetry scan mirror pointing data from 80 to 150 Hz. The star and landmark measurements provide information on the effects of thermal distortion and solar radiation on attitude.