

7. Image Navigation and Registration

The GOES N-P image navigation and registration (INR) system provides accurate earth location knowledge and control for each imager and sounder picture element (pixel). Image navigation refers to supplying knowledge of pixel earth locations in earth coordinates (latitude and longitude). Image registration refers to using that knowledge to actively control the pixel earth locations so that they are aligned to a predetermined fixed earth grid. The INR system produces images that are accurately mapped to earth coordinates and that overlay precisely from one image to the next without interpolation of the radiometric data.

The basic INR process originated on GOES I-M. The system has been upgraded on N-P to improve performance and extend operational coverage. The essential elements of the INR process are:

- A ground computer that determines orbit and attitude solutions
- The spacecraft attitude control system (ACS) that points the Imager and Sounder instruments toward earth
- Instrument mirror servos that scan the imaging detectors across the earth
- A mirror pointing compensation system in which the ACS generates correction signals to the mirror servos to adjust for the effects of orbit and attitude motion

Fundamental Basis for INR Approach

INR requirements are noted in Section 19.

The concept of an ideal image is fundamental to the INR system approach (Figure 7-1). The ideal image is that which would be achieved if:

- Spacecraft position conformed to a perfect geosynchronous orbit
- Instrument attitude was perfectly aligned to the orbit
- Instrument scan mirror control was perfect

The ideal image is characterized by a fixed one-to-one correspondence between earth locations (latitude and longitude) and commanded instrument scan angles (E-W and N-S mirror gimbal angles). In a real situation, of course, the orbit varies from the ideal due to eccentricity, inclination and longitude drift. The instrument attitude deviates

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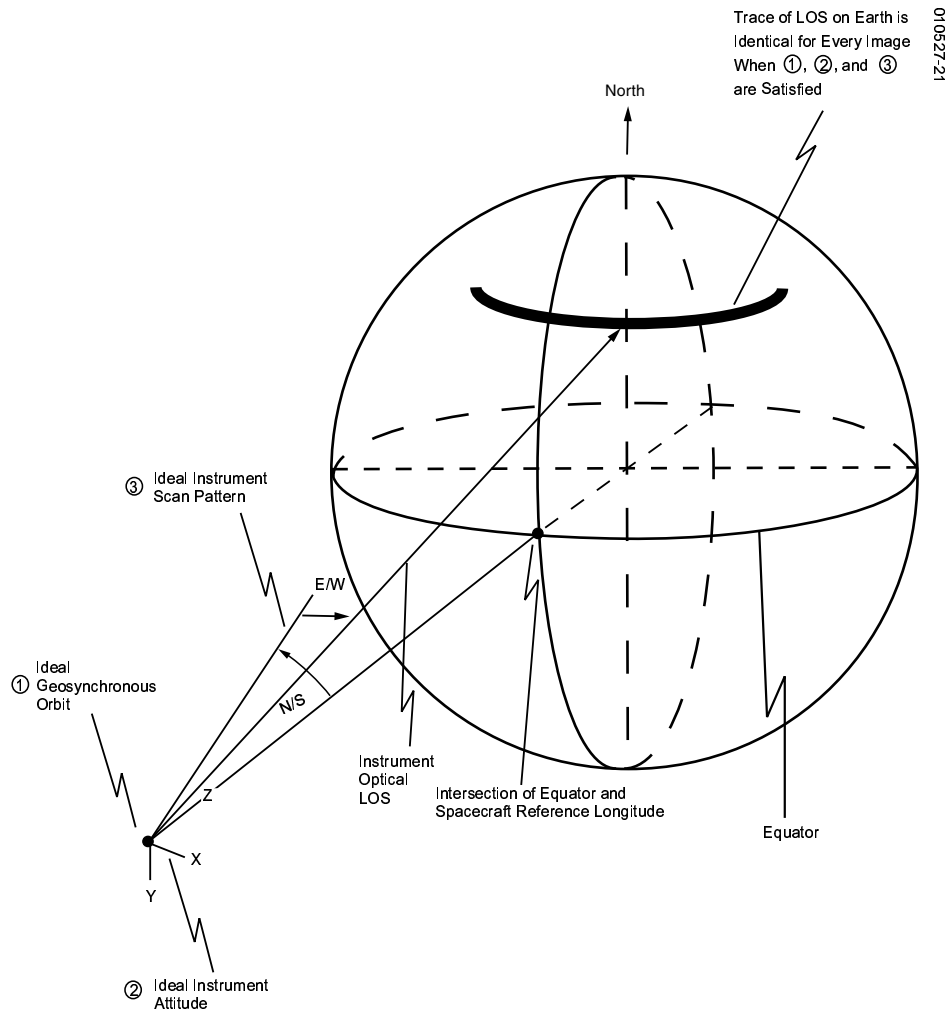


Figure 7-1. Ideal Image for Image Navigation and Registration

from the ideal due to short term spacecraft attitude control jitter and to longer term attitude variations driven by instrument and spacecraft thermal distortion. Finally, the instrument scan mirror servos are subject to various errors, both fixed pattern and dynamic errors. The goal of the INR system is to correct for or minimize all these various error sources to obtain images that are a close approximation to the ideal image.

The basic elements of the INR system design approach are:

- Orbit and attitude determination is performed periodically (may be performed more than once a day) in the spacecraft support ground system (SSGS) using spacecraft range and instrument star and landmark measurements. Predictions of daily orbit and attitude variations are generated in the SSGS and relayed to the spacecraft in parametric form via the image motion compensation (IMC) coefficient set.

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- The spacecraft ACS autonomously determines and controls the spacecraft bus attitude to a reference frame aligned to the orbit plane and the nadir direction. The ACS continuously senses bus attitude deviations induced by dynamic disturbances.
- The spacecraft ACS uses the IMC set to generate instrument scan mirror corrections for orbit and attitude variations. It uses the sensed bus attitude deviations to develop mirror corrections for short-term attitude variations (dynamic motion compensation [DMC]). Additionally, based on ground calibration data, the ACS generates mirror corrections for certain instrument fixed pattern errors (instrument systematic error compensation [ISEC]).
- The instrument scan mirror controllers execute commanded raster scan patterns while continuously applying the scan mirror corrections generated by the ACS.

Image Navigation

Image navigation solutions for the Imager and Sounder are produced in the SSGS. These solutions consist of predictions of orbit and attitude variations in parametric form. The IMC coefficient set is relayed to the spacecraft to enable image registration via mirror pointing compensation. Additionally, an equivalent set of coefficients, the orbit and attitude (O&A) set, is included in the navigation message embedded in the GOES variable (GVAR) format data stream. Thus, an end user of the GVAR data can accurately determine the earth locations of all image pixels whether IMC is turned on or off. The mode of INR system operation where IMC is turned off is called dynamic gridding mode. Only image navigation is supported in this mode. The mode of operation where IMC is turned on is called fixed gridding mode. This mode supplies images that are accurately navigated and registered to a fixed earth grid. Fixed or dynamic gridding mode may be selected independently for the imager and sounder.

Orbit and attitude determination is routinely performed in the SSGS every 24 hours. Orbit predictions are updated as needed during the course of the day to account for thruster momentum control maneuvers. With each firing of the thrusters there is generated a ΔV . Ranging data and imager landmark data are the observations used to determine the spacecraft orbit. Ranging measurements based on the round trip propagation time of the GVAR data stream are collected every 15 minutes. Imager landmark observations (scan angles corresponding to designated geographic features) are obtained from the GVAR data throughout the day. The typical landmark observation rate is about 100 landmarks per day, with visible channel data (1 km nadir resolution) used in daylight and IR channel data (4 km nadir resolution) used at night. Instrument star sense measurements, in conjunction with imager landmarks and, if available, sounder landmarks, are used to determine separate solutions for Imager and Sounder attitude. Typical star observation rates are four stars per half hour for each instrument.

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Image Registration

Image registration to a fixed earth grid (the “ideal” image) is provided when the onboard IMC correction for orbit and attitude variations is enabled. INR error sources include short term pointing errors, such as bus attitude control jitter and instrument servo errors, as well as errors in determining and applying the IMC correction. INR error sources will be discussed further below.

The effects of orbit and attitude variations on image registration determine the character of the IMC corrections. Over the course of a day, orbital motion causes two types of systematic error. The diurnal and secular variation of the subsatellite point causes image bias, meaning the center point of an image changes throughout the day in both E-W and N-S directions. Additionally, the changing perspective toward the earth produces image distortion, that is, earth location error that varies across an image with scan direction. Thermally induced attitude variations also have a diurnal cycle that can produce both image bias and image distortion. Thus, to provide properly registered images, the IMC corrections must possess a dynamic character with both time and scan angle dependence.

INR Functional Configuration

The INR system comprises elements on the spacecraft and ground (Figure 7-2). The major functional components are:

- Imager/Sounder mounting plate
- Stellar inertial attitude control system
- Instrument scan mirror servo
- Orbit and attitude prediction
- Instrument mirror pointing compensation: IMC, DMC, and ISEC
- Diagnostic and quality monitoring capabilities

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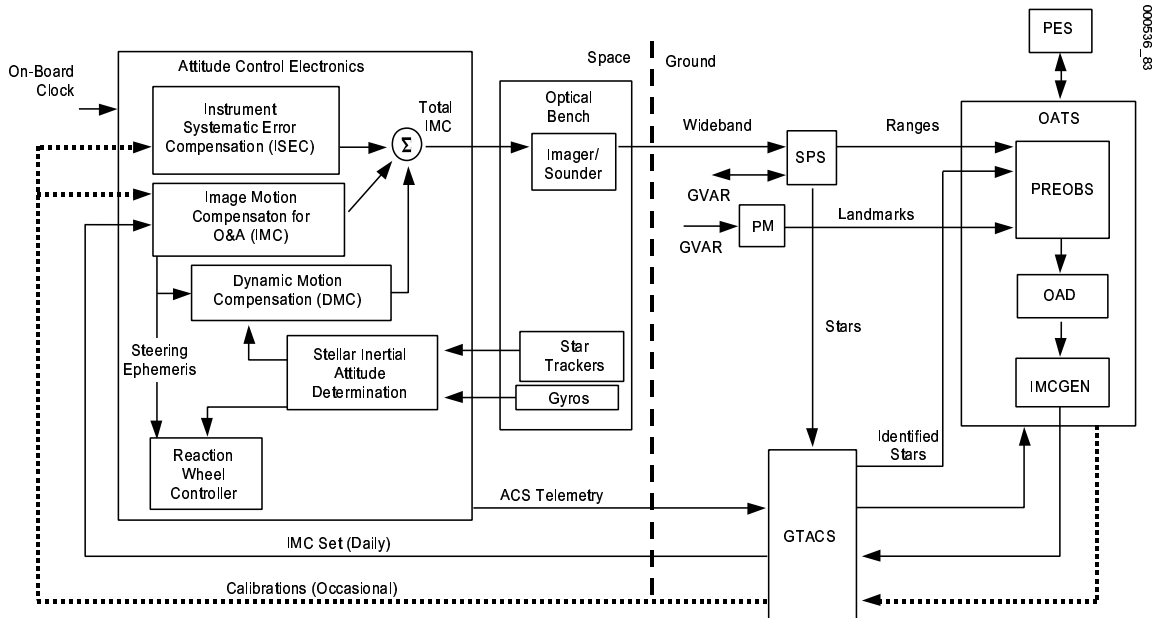


Figure 7-2. Image Navigation and Registration Functional Block Diagram

Imager/Sounder mounting plate. The imager and sounder are collocated with the spacecraft attitude sensors (star trackers and gyros) on a rigid structure that is highly resistant to thermal distortion. This structure provides a stable alignment between the ACS sensors and the payload instruments.

Stellar Inertial Attitude Control System. The ACS autonomously determines spacecraft orientation relative to the fixed stars. Data from multiple star trackers is compared to an onboard star catalog to update the onboard attitude estimate in a Kalman filter implementation. Data from a three-axis gyro set is used to propagate the attitude solution between star measurements. The flight software transforms from inertial coordinates to the desired earth reference coordinate frame using orbital predictions determined by the ground system and a time reference provided by a precision onboard clock. The bus attitude is controlled by a three-axis zero momentum system consisting of four canted reaction wheels. Bandwidth limitations on the bus controller prevent direct compensation for some dynamic disturbances. DMC uses the high data rate gyro output to sense bus dynamic disturbances and generate a mirror compensation signal that is passed to the instruments.

Instrument Servo. Each instrument contains a two-axis gimbaled scan mirror to point the optical line of sight (LOS). High bandwidth servos featuring inductosyn sensors and direct drive motors control the positioning of each gimbal axis.

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Orbit and Attitude Prediction. The orbit and attitude tracking system (OATS) within the SSGS processes observations of landmarks, instrument star sightings, and spacecraft range to fit parametric models of orbit and instrument attitude in a batch least squares implementation. The processing consists of three phases. The observation preprocessing function (PREOBS) corrects for certain systematic effects in the measurements and then computes residuals of the measurements relative to expected values. The orbit and attitude determination function (OAD) solves for orbit and attitude state variables. Finally, the IMC generation function (IMCGEN) produces the set of orbit and attitude model coefficients (the IMC set) that model the future orbit and attitude variation.

Instrument Mirror Pointing Compensation: IMC, DMC and ISEC. The spacecraft attitude control electronics (ACE) generates precision-timed analog signals to correct mirror pointing for the effects of orbit and long-term attitude variations (IMC), short-term attitude variations (DMC), and certain instrument fixed pattern errors (ISEC). The processing sequence begins in flight software with the evaluation of the time dependent orbit and attitude models defined by the IMC coefficient set. The software processing continues with scan angle dependent computations that yield E-W and N-S mirror pointing adjustments for IMC, DMC, and ISEC. A multichannel high speed signal interface supplies the ACE with the necessary scan angle information from the instruments. Finally, the flight software products are metered to high resolution ramp generation and digital-to-analog conversion electronic circuitry to produce the analog mirror compensation signals.

Diagnostic and Quality Monitoring Capabilities. The operational INR system is supplemented by spacecraft diagnostic data and off-line software tools that can be used to monitor and analyze INR system performance.

- *IMC Check.* An assessment of IMC implementation error may be performed in OATS using instrument IMC signal telemetry extracted from the GVAR data stream. The spacecraft telemetry is compared to expected values based on a ground software emulation of the flight IMC algorithm.
- *Dynamic Interaction Diagnostic (DID).* Analysis tools are available on the DID workstation to perform assessments of structural interactions on the spacecraft bus and within the instruments using angle displacement sensor (ADS) data and instrument servo error data contained in the multi-use data link (MDL) data stream. The DID has data interface with the MRS&S but not the SPS.
- *ACS Telemetry.* Routine spacecraft telemetry collected and archived on the GOES telemetry and command system (GTACS) may be used to verify basic ACS functioning. Additionally, dwell telemetry mode enables frequent sampling of designated ACE memory locations related to stellar inertial attitude determination, bus attitude control, and mirror compensation signal generation.
- *OATS Measurement Residuals.* Star, landmark, and range measurement residuals are routinely plotted in OATS to monitor INR performance trends. Landmark residuals are used to compute overall INR system performance metrics.

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- INR Performance Evaluation System (PES).** PES is a computer simulation of the INR system that may be used to conduct diagnostic studies of INR performance based on on-orbit data for individual error sources. PES contains analytical models of all INR error sources and simulates INR processes and operations on the ground and spacecraft. System impact assessments for anomalous error sources and the selection of optimum operational parameters to adjust for actual on-orbit performance characteristics are potential applications of the PES during the operational phase. PES is used only as an analytical tool.

INR System Operations and Data Flow

INR system support operations at the satellite operations and control center (SOCC) are characterized by a routine 24 hour cycle that accommodates the daily thruster firings for spacecraft momentum control. Additional INR support activities are undertaken for special operational periods and for maintenance of system calibrations.

Normal Operations. The daily cycle of INR support operations, illustrated in Figure 7-3, features the following sequence of events.

- OAD is performed once per day shortly before the end of the INR cycle.
- An IMC coefficient set and a table of imager and sounder star sense commands are generated from the OAD solution, uploaded to the spacecraft and then, at the start of the new cycle, enabled.

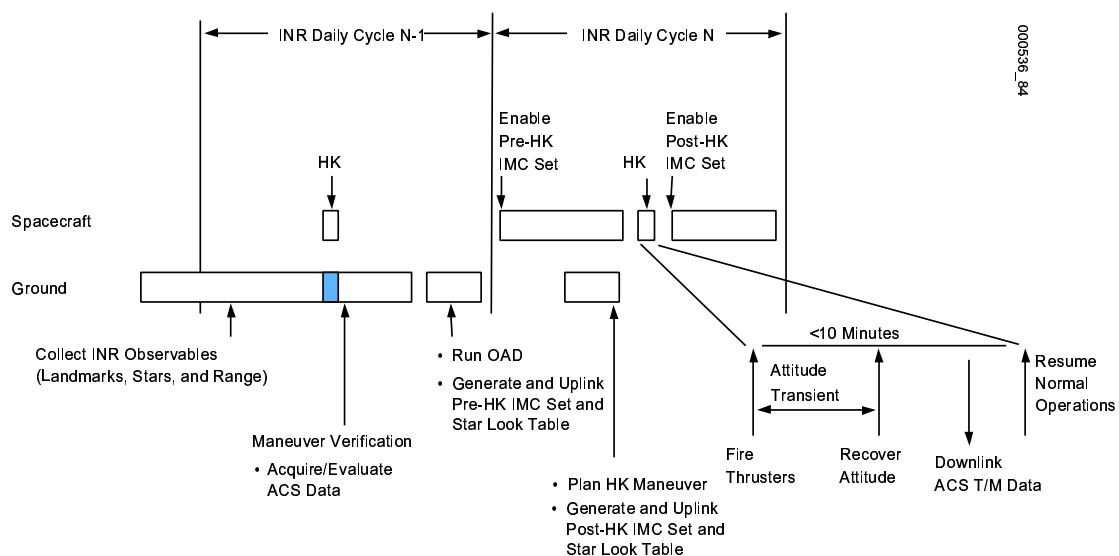


Figure 7-3. Image Navigation and Registration Sequence for Normal Operations

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- A new IMC set and star table are generated and uploaded shortly before the daily housekeeping maneuver. The pre-maneuver attitude prediction remains unchanged in the new IMC set, while the orbit prediction is modified in accordance with the anticipated maneuver ΔV .
- The stellar inertial ACS autonomously recovers from thruster induced attitude transients within the allowed 10 minute housekeeping interval. Normal INR operations resume with the new INR commands immediately after the housekeeping period.

Special Operations. The INR system operates during eclipse, post-yaw flip, and post-stationkeeping periods, generally with somewhat reduced performance levels compared to normal operations. Ground support activities are modified for these special periods by the addition of special OAD and IMC set generation runs.

Periodic Calibrations and Maintenance. The INR system requires minimal maintenance effort aside from generating the daily IMC set and star sense commands. Thruster calibration is periodically performed in the SSGS using spacecraft telemetry and OAD solutions. This off-line function provides more accurate maneuver ΔV predictions. ISEC parameters are also calibrated in off-line SSGS processing using stored star residual measurements.

INR System Data Flow. INR-related data flows between the spacecraft and SSGS components located at the command and data acquisition station (CDAS) and SOCC are illustrated in Figure 7-4. Major SSGS components and their functions for INR operations are listed below.

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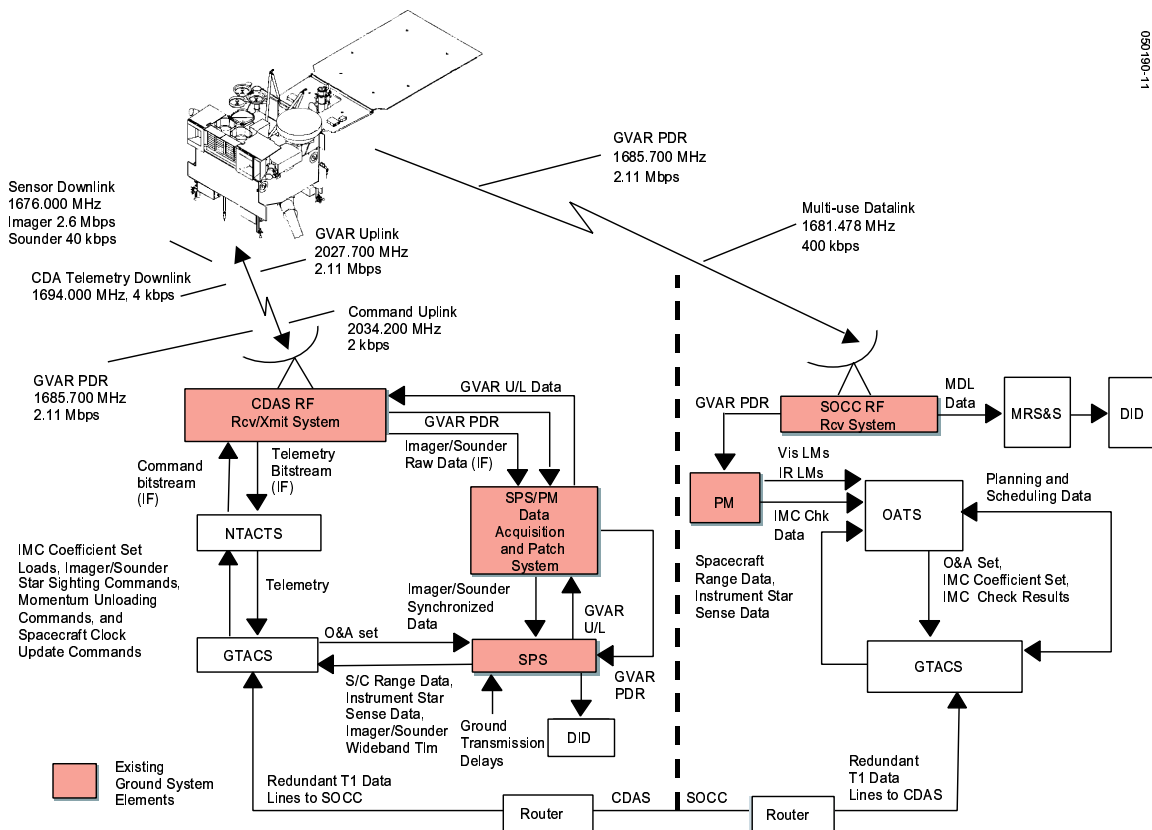


Figure 7-4. Image Navigation and Registration System Data Flow

- **N-Q Telemetry Acquisition and Command Transmission System (NTACTS).** Interfaces between GTACS and RF systems for spacecraft command transmission and telemetry receipt.
- **GTACS.** Generates spacecraft command schedules, formats commands and processes and archives spacecraft telemetry.
- **OATS.** Principal ground unit supporting INR. Solves for orbit and instrument attitude. Generates IMC sets and instrument star commands. Performs INR calibrations. Monitors INR performance. Supports maneuver planning and commanding.
- **MDL Receive System and Server (MRS&S).** Ingests, processes, and archives data from the MDL data stream.
- **DID.** Provides analysis tools for assessing spacecraft dynamic interactions using MDL data.

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- *Sensor Processing System (SPS)*. Performs preprocessing on raw spacecraft range and instrument star sense data. Generates GVAR data stream including insertion of image navigation message.
- *Product Monitor (PM)*. Performs landmark measurement extraction from the GVAR data.

INR Dynamic Environment

The INR system is subject to a broad spectrum of disturbance sources ranging from high frequency structural vibrations to slowly varying thermal distortion. Figure 7-5 provides an overview of the INR dynamic environment including disturbance sources, sensors and compensation methods.

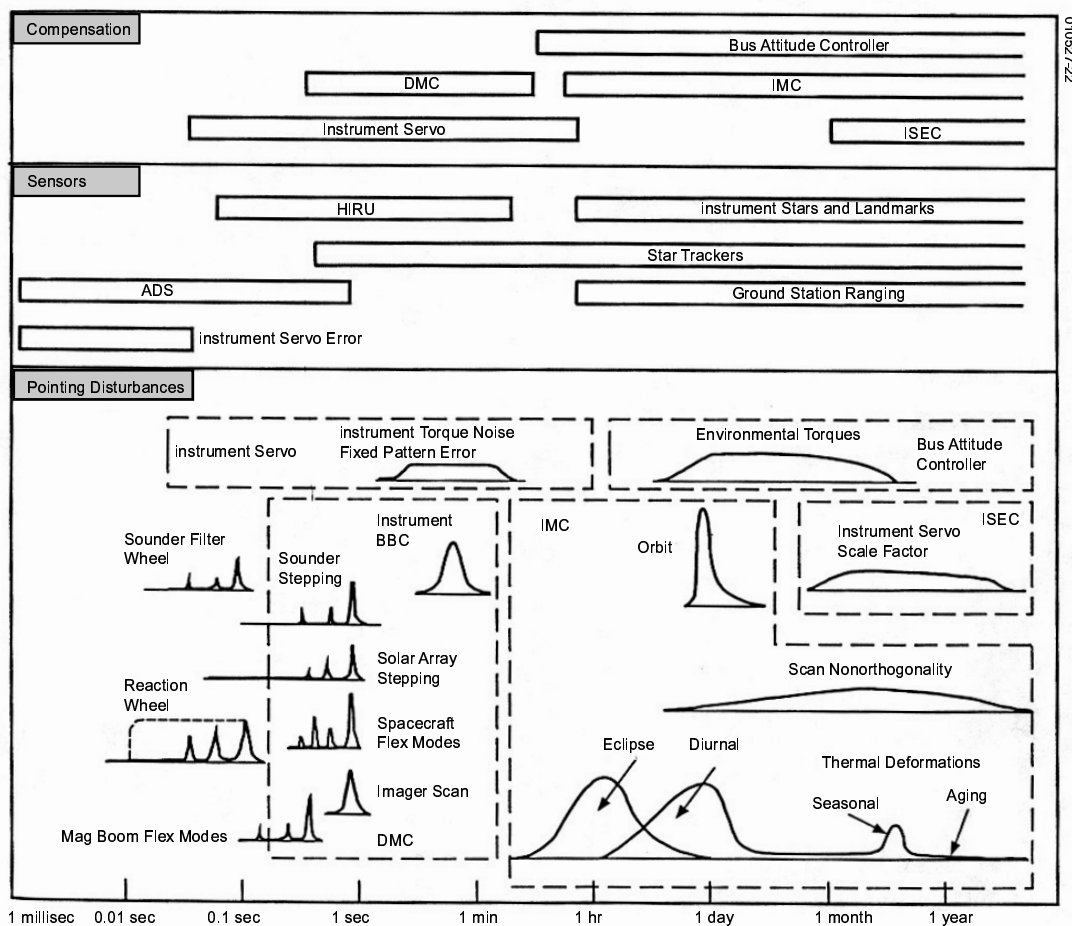


Figure 7-5. Image Navigation and Registration System Dynamic Characteristics

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Instrument Servo Errors. Instrument scan mirror control is subject to various dynamic disturbances including gimbal bearing noise, drive motor torque noise and structural interactions. Fixed pattern errors, meaning systematic errors that vary with scan direction, arise from gimbal encoder errors and internal optics misalignments. Some instrument fixed pattern errors may be calibrated with ground processing of instrument star measurements and corrected via ISEC on the spacecraft. Servo dynamic error, the difference between commanded and encoder-sensed gimbal angles, is recorded onboard and included in the MDL data stream for diagnostic purposes.

Spacecraft Attitude Control Errors. Dynamic disturbances to bus attitude include environmental torques, solar panel stepping, reaction wheel noise, instrument mirror motion and structural interactions. Thruster activity is always constrained to periods when the INR system is not operational. Stellar inertial system error sources include star tracker fixed pattern errors, random noise and gyro drift. The Kalman filter processing provides significant attenuation of high frequency star tracker errors. The ACS comprises two complementary compensation loops. Bus attitude control using reaction wheels is limited in bandwidth capability by bus structural modes. However, DMC exploits the considerably higher bandwidth capabilities of the instrument mirror servos to effectively extend the bandwidth of the spacecraft attitude control system. High frequency spacecraft motion is measured by an ADS unit (which measures angular rate) mounted adjacent to the instruments on the mounting plate; the data is included in the MDL data stream for diagnostic purposes.

Thermal Distortion Errors. Diurnal thermal variations induce distortion within the instruments and the spacecraft Imager/Sounder mounting structure. The resulting slowly varying pointing errors are sensed directly through the instruments using star and landmark observations. Compensation for thermal distortion is determined via attitude estimation on the ground and implemented via IMC on the spacecraft.

Orbit Errors. Orbital motion produces slowly varying pointing errors with both drift and periodic components. The orbital motion is sensed by instrument landmark and spacecraft range measurements. Compensation for orbital motion is determined via orbit estimation on the ground and implemented via IMC on the spacecraft. Compensation for the orbit perturbation from daily thruster maneuvers is determined via maneuver prediction on the ground using thruster calibration data and implemented via IMC.

Mirror Compensation Implementation Errors. Generation of the analog mirror compensation signals for IMC, DMC and ISEC is subject to flight software numerical and timing errors and to D-to-A converter nonlinearity and quantization errors. The resulting IMC implementation error behavior includes both random noise and scan angle dependent errors. Diagnostic data for the mirror compensation signal is available in imager/sounder telemetry at the SPS or at a reduced data rate at the PM. Sampled compensation signal data from the spacecraft bus side of the ACE-to-instrument interface is also available in the MDL data stream.

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