GOES-NEXT NAVIGATION OPERATIONS

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ABSTRACT

The next generation of Geostationary Operational Environmental Satellites, GOES-I through -M (hereafter referred to as GOES-Next), begins a new era in the operation of weather satellites by the National Oceanic and Atmospheric Administration (NOAA). With a new spacecraft design, three-axis attitude stabilization, new ground support equipment, and improved methods of image navigation and registration that use on board compensation techniques to correct images for satellite motion, NOAA expects improved performance over the current series of dual-spin spacecraft. To meet these expectations, planning is currently underway for providing the complex and intensive operational environment that will meet the challenge of operating the GOES-Next spacecraft. This paper describes that operational environment.

1.0 INTRODUCTION

The Geostationary Operational Environmental Satellites-I through -M (hereafter referred to as GOES-Next), expected to be first launched in the early 1990s, will continue the GOES tradition as our Nation's primary weather monitoring system. It will have a different attitude stabilization system, a new ground support system, and improved image-processing techniques over its ancestors. This paper presents an overview of the National Oceanic and Atmospheric Administration's (NOAA's) current plans for providing navigational support for the operations of GOES-Next. It describes the GOES-Next mission, the GOES-Next ground equipment, and the operational requirements for the mission. It also provides an overview of the navigation and image navigation and registration (INR) support that will be provided, which includes orbit and attitude determination, star measurements, data monitoring, stationkeeping, housekeeping, and image motion compensation (IMC), which is the method used to correct image pixels for satellite motion.

1.1 MISSION DESCRIPTION

The purpose of the GOES mission is to provide meteorological, scientific, and communications services. Its meteorological services include providing visible and infrared images of clouds and of the Earth's surface. It also obtains water vapor field data and soundings of the Earth's atmosphere. Scientifically, the GOES-Next mission measures solar X-rays in 2 bands, low-energy particle flux in 14 bands, and high-energy flux of protons and alpha particles. The GOES-Next communication services include a data collection platform service to relay environmental data to the ground, a weather facsimile service to relay weather-related data, and a search-and-rescue service to relay data from emergency transmitters.

Figure 1 shows the spacecraft configuration. The structure consists of a main body that houses the instruments and the attitude and orbit control system, a solar array connected to the south face of the main body, and a solar sail connected to the north face of the main body. The primary instruments are the imager and the sounder, which are located on the Earth-pointing face of the main body. The imager provides 4 infrared channels and 1 visible channel for images of the Earth; the sounder provides 18 infrared channels and 1 visible channel for soundings of the Earth's atmosphere. The imager and the sounder provide the data for the meteorological services of the GOES mission.

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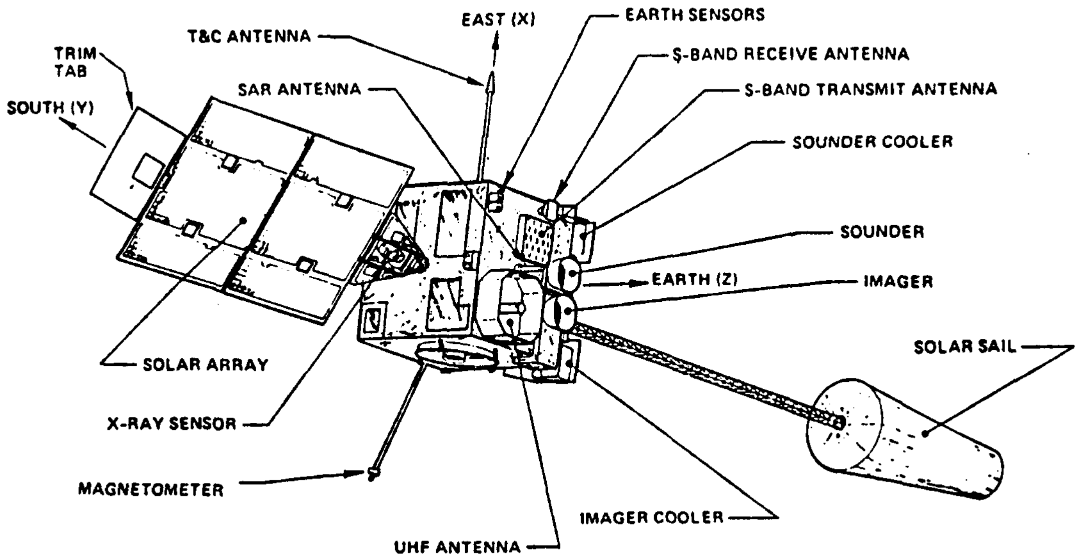

Figure 1. GOES-Next Spacecraft Configuration

There are six types of sensors and five types of actuators on the spacecraft (Figures 1 and 2) that are used for attitude and orbit control. The sensors include two sets of coarse analog Sun sensors (CASSs), redundant digital Sun sensors (DSSs), redundant Digital Integrating Rate Assemblies (DIRAs), redundant Earth sensors, a magnetometer, and two Sun analog sensors (located on the solar array yoke). The CASS orients the spacecraft with respect to the Sun during transfer orbit. The DSS calibrates the DIRA during the transfer orbit. The DIRA is a system of three mutually perpendicular rate integrating gyros that monitors attitude drift throughout the transfer orbit and during stationkeeping maneuvers. The Earth sensor provides pitch and roll data and is the primary sensor for on-orbit attitude control. The magnetometer senses the ambient magnetic field in the space environment. The Sun analog sensors provide information about the Sun's position relative to the solar array.

The configuration of the actuators is shown in Figure 2. The actuators include six redundant pairs of 5-pound thrusters, two momentum wheels, a reaction wheel, two magnetic torquer coils (not shown in the figure), and a solar array trim tab panel. The thruster pairs are located on the east, south, and west faces of the spacecraft. They are used by the onboard Attitude and Orbit Control System (AOCS)

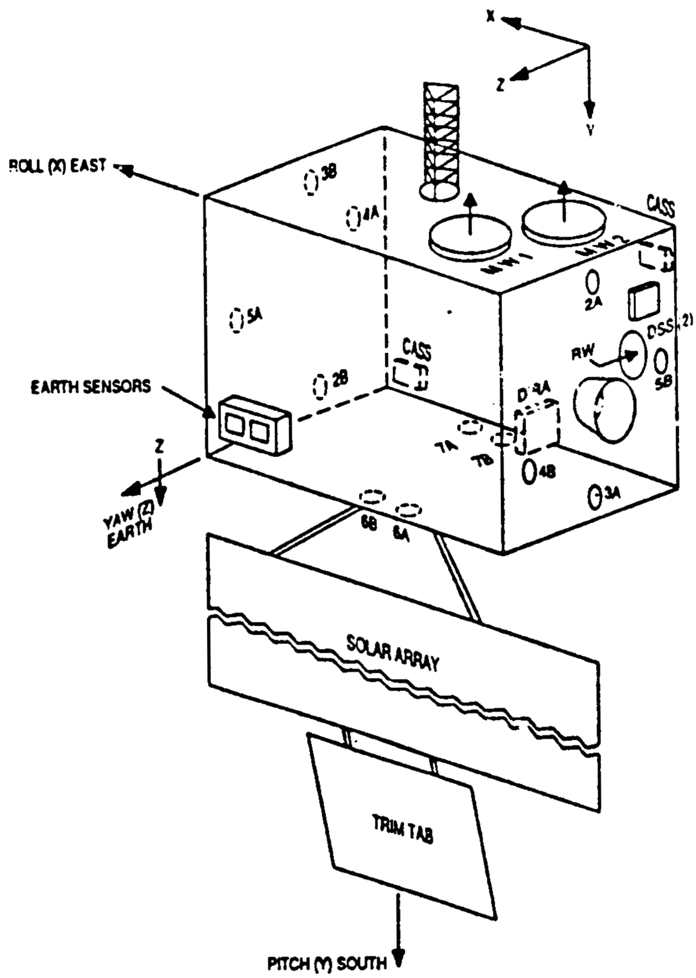

Figure 2. GOES-Next Attitude and Orbit Control System

for autonomous attitude control and by ground command for orbit control. The momentum wheels are used for primary attitude stabilization, with the reaction wheel as a backup. The magnetic torquer coils are located on the anti-Earth and east faces of the spacecraft; they are used for yaw control. The trim tab panel is located at the end of the solar array and is used for compensating the solar radiation torque on the solar array. The solar array is continuously rotated by a stepper motor to expose all solar cells to the Sun.

The two operational GOES-Next spacecraft will fly in geosynchronous orbit with designated stations of 75 degrees and 135 degrees west longitude. Their nominal

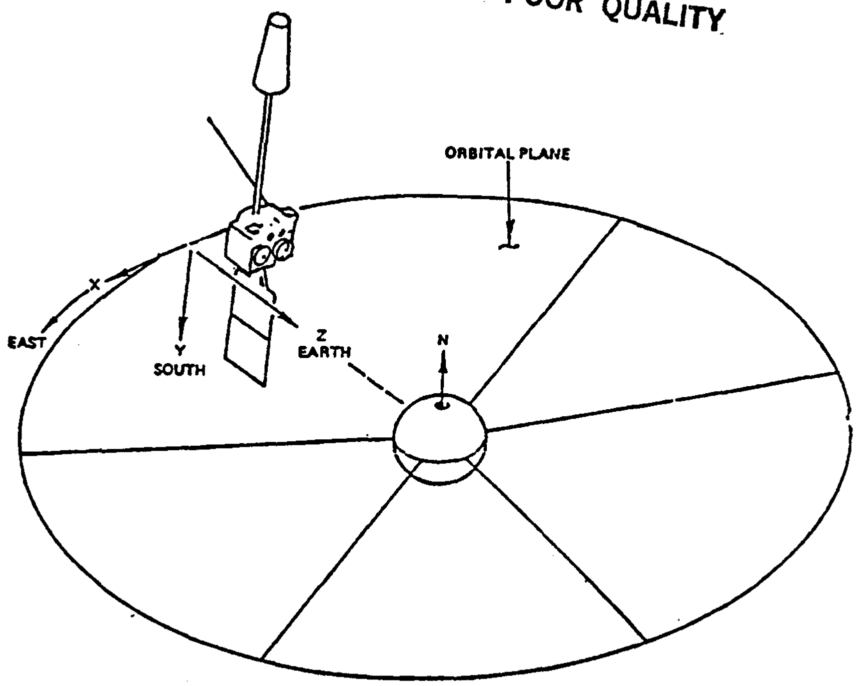

Figure 3. Nominal GOES-Next Orientation

inclination is ±0.1 degree about the Equator. Their attitude is three-axis stabilized, spinning at one revolution per orbit to maintain Earth pointing for the imager and the sounder. Figure 3 shows the nominal GOES-Next attitude orientation.

1.2 OPERATIONS GROUND EQUIPMENT (OGE) DESCRIPTION

On-orbit ground support for the GOES-Next spacecraft will be provided by the Operations Ground Equipment (OGE) located at the Satellite Operations Control Center (SOCC) (currently in Suitland, Maryland) and at a command and data acquisition (CDA) station at Wallops Island, Virginia. The OGE components at the SOCC include the Product Monitor (PM) and the Orbit and Attitude Tracking System (OATS). The PM performs data quality monitoring, system troubleshooting, landmark identification, and image navigation and registration (INR) data capture and distribution. The latter two functions are performed in support of the OATS, which is the key tool for navigation operations. The CDA station OGE components include the OGE Data Acquisition and Patching Subsystem (ODAPS), the Sensor Processing System (SPS), the OGE Input Simulator (OIS), and the PM. The ODAPS performs demodulation, bit synchronization, and patching functions. The SPS performs processing of imager and sounder raw data. The OIS simulates data in support of OGE integration and testing and serves as a diagnostic tool. During mission operations, the OIS will be a backup for the OATS. The PM at the CDA station is used for backup quality monitoring and testing. Figure 4 is a diagram of the OGE at both locations.

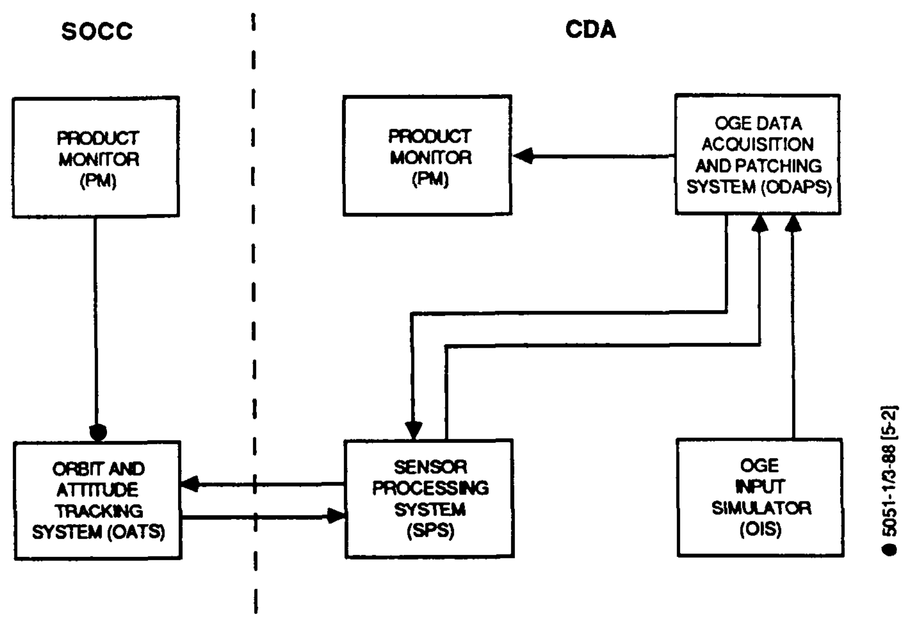

Figure 4. OGE Components at SOCC and CDA Station

The OATS is the primary tool for performing all the navigation operations functions. It is composed of both hardware and software. The hardware includes a Gould CONCEPT 32/6751 central processing unit (CPU) with a 4-megabit (Mb) random access memory (RAM) and a hardware floating-point accelerator as the central processor. There are also two 160-Mb disk drives, one 800/1600-bit-per-inch (bpi) magnetic tape drive, seven input/output (I/O) devices, and two communication multiplexers. The system software includes a Gould MPX-32 Operating System, a macro assembler, a FORTRAN 77+ compiler, control software, and analysis and planning software. The control software provides a multitasking environment and support for multiple spacecraft for the analysis and planning software.

The analysis and planning software includes modules that perform the major functions for navigation operations. It estimates the spacecraft orbit state and the spacecraft attitudes for the imager and the sounder. It generates predictions of star availability, sensor conflicts, eclipses, and the spacecraft ephemeris. Using the orbit and attitude states, it generates coefficients for uplink to the spacecraft that will be used to compensate the images for orbit and attitude motion. It also generates orbit and attitude parameters that are used for gridding and Earth location. It uses star availability predictions to generate commands for uplink to the spacecraft to view stars. It also generates commands for changing the trim tab angle and for calibrating the DIRA. It plans stationkeeping maneuvers and generates the thruster firing commands for these maneuvers. It also analyzes thruster firing telemetry for calibrating the thrusters and for monitoring fuel use.

1.3 OPERATIONAL REQUIREMENTS

The primary purpose of navigation operations is to monitor and maintain the accuracy of image navigation and registration (INR). Image navigation is the process of determining the Earth longitude and latitude corresponding to each pixel in an image. Image registration is the process of maintaining the image so that each pixel points to the same corresponding Earth location. The INR accuracy requirements are currently being defined. They are stated in terms of Earth location and image registration accuracy. Furthermore, all images and soundings taken within a 24-hour period must meet the Earth location accuracy requirements with reference to a common grid.

The Earth location accuracy requirements apply to the instantaneous geometric field of view for every pixel in any image. The central Earth angle is the angle between the subsatellite point at the center of the image and the pixel that is being Earth located.

Image registration requirements are specified in three categories: image registration between pixels in the same image, image registration between corresponding pixels in any two images taken within a 90-minute period not interrupted by a disturbance interval, and image registration between corresponding pixels in any two images taken within a 24-hour period interrupted by up to three 10-minute housekeeping intervals.

Maintaining the attitude and geostationary orbit constraints is also the responsibility of navigation operations. The orbital requirements are a spacecraft inclination in the range of ± 0.1 degree and a spacecraft longitude maintained within ± 0.5 degree of its nominal station.

Navigation operation activities focus on providing INR support for maintaining the INR requirements and on maintaining the spacecraft orbit and attitude through stationkeeping and housekeeping support.

2.0 INR SUPPORT

Navigation operation activities that support the effort of maintaining the INR requirements include orbit and attitude determination, star measurements, IMC coefficient generation, and data monitoring. All these activities are performed using the OATS.

2.1 ORBIT AND ATTITUDE DETERMINATION

The orbit and attitude determination process for GOES-Next uses range, star, and landmark data to obtain the best estimate of the spacecraft orbit and attitude. The estimated orbit and attitude states are then used to generate IMC coefficients to be uplinked to the spacecraft. These coefficients are used on board to correct each pixel in the image corresponding to the true orbit and attitude to produce an image corresponding to the ideal orbit and attitude.

Spacecraft range measurements are the primary observable for orbit determination and are taken from the CDA station. Landmark observations are primarily obtained by the imager visible channel. Each operational spacecraft has a separate landmark list, although several landmarks are common to both operational spacecraft. Star observations are performed by the imager and the sounder with commands generated by the OATS for observing them. Star measurements are discussed in detail in the next section.

The orbit and attitude determination process involves the nonlinear estimation of the orbit and attitude state vectors such that the weighted sum of the squares of the residual errors of the observables,

$$\sum_i \delta \vec{M}^T \bullet W \delta \vec{M} \tag{1}$$

is minimized. The data weighting matrix, W, is the inverse of the covariance matrix for measurement noise and $\delta\vec{M}$ is the residual error.

The observation data used are the slant range and star and landmark scan angles. The slant range is the distance from the CDR tracking station to the spacecraft. The scan angle observables, E and N (designated in Figure 5), are transformed from raw star and landmark observations. E is the complement of the angle between the instrument X_B axis and the line of sight to the star or landmark, $\hat{S}$, in the scan plane. This is approximately in the east-west direction. N is the angle between the instrument X_B-Z_B plane and the scan plane. This is approximately in the north-south direction.

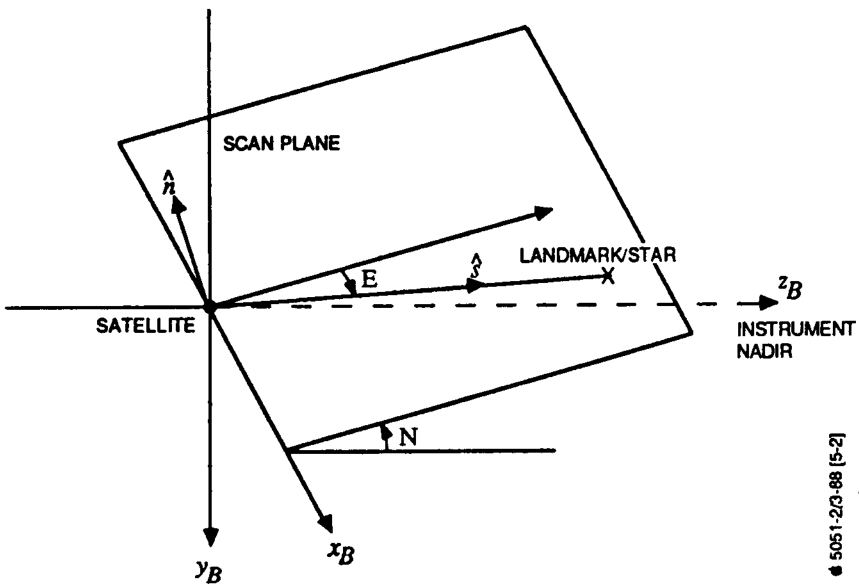

Figure 5. Scan Angle Observables

The scan angles are affected by detector misalignment and small attitude changes. Detector misalignment shifts the center of the image when the instrument is at an angle N in the north-south direction. This causes the following corrections in the scan angles:

$$\delta E = \Theta_{ma} \cos N + \Phi_{ma} \sin N \tag{2}$$

$$\delta N = \phi_{ma} \cos N - \Theta_{ma} \sin N \tag{3}$$

where Θ_{ma} and ϕ_{ma} are the pitch misalignment and roll misalignment, respectively. Small changes in roll, pitch, and yaw ($\delta\phi$, $\delta\Theta$, $\delta\psi$) also cause corrections to the scan angles:

$$\delta E = -\cos N\delta\Theta - \sin N\delta\psi \tag{4}$$

$$\delta N = -\delta\phi - \tan E \sin N\delta\Theta - \tan N \cos N\delta\psi \tag{5}$$

The observable model, $\vec{M}$, is a function of the state vector, $\vec{g}(\vec{\mu},\vec{\beta})$, which includes the orbital state vector, $\vec{\mu}$, consisting of the orbital elements, and the attitude/misalignment state vector, $\vec{\beta}$, which consists of the roll, pitch, and yaw attitude angles (ϕ, Θ, ψ) and the roll and pitch instrument misalignment angles (ϕ_{ma}, Θ_{ma}). The attitude model used is an empirical model that fits each angle with a linear combination of Fourier, exponential, and B-Spline basis functions:

$$\beta^k(t) = \sum_{j=1}^{n} C_j^k \, B_j(t)\text{: generalized attitude state vector} \tag{6}$$

where the superscript k indicates the attitude state vector angle (ϕ, Θ, ψ, ϕ_{ma}, Θ_{ma}) indexed from 1 to 5. $B_j(t)$ are the basis functions, and C_j^k are their associated coefficients. These coefficients are part of the solve-for parameters and are the IMC coefficients for attitude. From a finite element analysis, the expected attitude variation over one day is as shown in Figure 6. Caused mainly by instrument thermal distortions, this variation should be repeatable approximately every 24 hours, lending itself to a natural periodic fit with a Fourier series. Exponential basis functions are used to model the attitude during eclipse season. However, some erratic behavior in the attitude is expected even after the Fourier and exponential fit has been made. B-spline functions are available to fit this erratic behavior, if necessary.

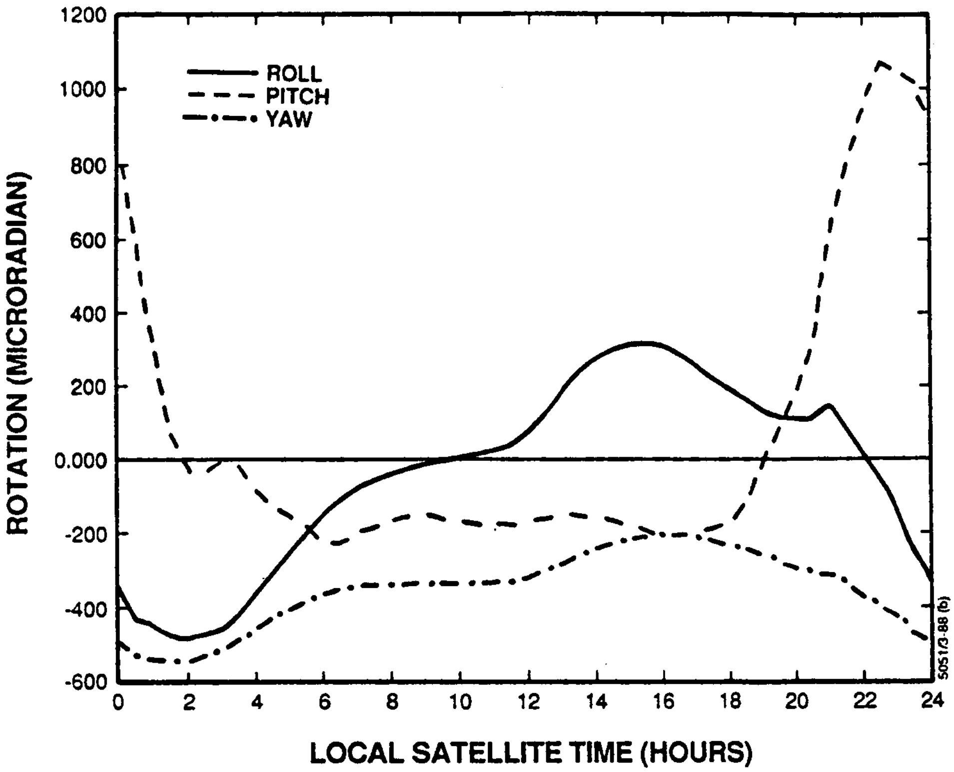

Figure 6. Expected Daily Attitude Variation

2.2 STAR MEASUREMENTS

Predicting star windows and generating star viewing commands are navigation operation functions that support the orbit and attitude determination process in OATS. The GOES-Next star catalog consists of approximately 500 stars of 6th magnitude and brighter, including some variable and multiple stars. Star observations are made in the imager and sounder fields of view around the Earth. Stars are selected for observation only if they are observed uniformly throughout the day and are separated geometrically within an image. It is currently planned to observe approximately three stars in the interval following each imaging interval (every half-hour). This provides approximately 150 stars per day for use in attitude determination. Navigation operation responsibilities include investigating and taking corrective action for anomalies such as missed star observations and large star measurement residuals.

2.3 IMAGE MOTION COMPENSATION

IMC is the process of correcting the pixels in an image for orbital and attitude motion effects and for instrument thermal distortions. This is performed in the attitude and orbit control electronics by the control system processor. The east-west and north-south shift in each pixel is based on the IMC coefficients that are computed in the OATS. As a result, the scan lines in the image seen by the user appear as a perfect image. Figure 7 is a diagram of the IMC system. The top of Figure 7 shows the scan lines that would result from no pixel shifts due to satellite motion. This would occur in an ideal orbit and attitude. However, in the actual motion of the satellite, scan lines trace a path that deviates from the ideal path (shown at the bottom of Figure 7). The IMC system will correct the azimuth and elevation of each image pixel so that the scan line seen by the user is ideal.

The field of view of the imager is 23 degrees in azimuth by 21 degrees in elevation. There are 1480 scan lines from top to bottom. Each visible scan line contains a series of pixel arrays that are 1 pixel wide by 8 pixels high. Individual pixels are 1 kilometer in both azimuth and elevation. The number of pixel arrays contained in an image depends on the scan field. Scan fields range from a full Earth scan down to an intensive region scan covering 1000 kilometers in both azimuth and elevation.

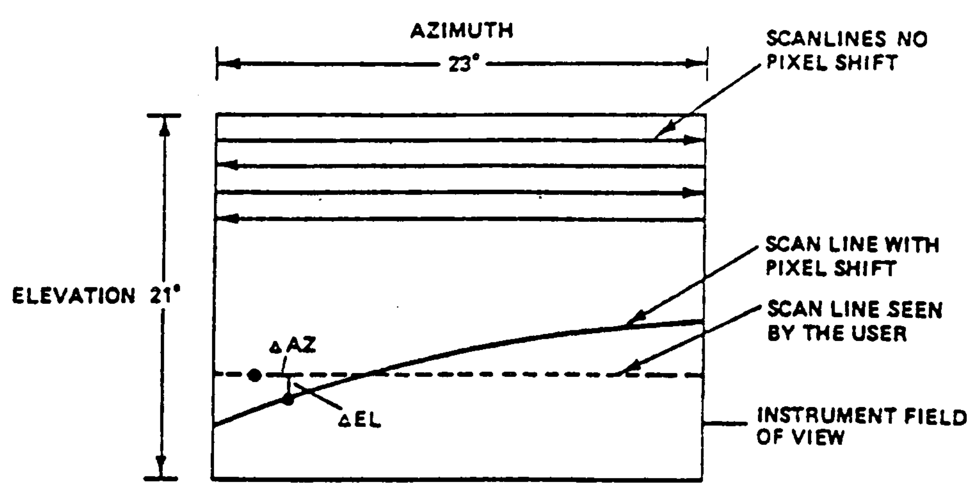

Figure 7. Image Motion Compensation (IMC) System

Orbital drift is caused mainly by the geopotential field (zonal and tesseral harmonic terms), solar and lunar gravity, and solar radiation pressure. The orbital effects on the image are a shift in azimuth due to the east-west drift of the spacecraft from its nominal station and a shift in elevation due to the nonzero inclination of the orbit. Attitude drift effects are caused primarily by solar radiation torques. Attitude effects on the image are on elevation shift due to roll drift, an azimuth shift due to pitch drift, and a combination of azimuth and elevation shifts due to yaw drift and instrument misalignments.

Navigation operation responsibilities for IMC include generating the IMC coefficients and monitoring their uplink, quality assuring the IMC coefficients, and troubleshooting IMC anomalies. Residuals of computed IMC coefficients against the orbit and attitude solutions are monitored. Large residuals are investigated, and corrective action is taken before the coefficients are uplinked and made operational. IMC quality checking is also performed using the OATS. IMC data are received and checked for consistency with the IMC model.

2.4 DATA MONITORING

Data are monitored regularly to check INR accuracy requirements, stationkeeping requirements, and the health and safety of the spacecraft. Landmark observations are processed, and their residuals are computed based on the predicted orbit and attitude. Abnormally large numbers of landmark residuals above the threshold are investigated, and corrective action is taken. Star observations are also monitored, as discussed in Section 2.2.

3.0 NAVIGATION SUPPORT

Stationkeeping maneuvers are performed to control the inclination (north-south stationkeeping maneuvers) and subsatellite longitude (east-west stationkeeping and station change maneuvers). Maneuvers at the end of mission life are also performed to dispose of the spacecraft. Attitude reorientation is a continuous process controlled by the onboard attitude and orbit control system. Navigation support for this is provided through housekeeping operations.

3.1 NORTH-SOUTH STATIONKEEPING

The average inclination drift at geosynchronous altitude is approximately 0.86 degree per year. This requires north-south stationkeeping maneuvers approximately every 2.8 months to maintain a 0.1-degree inclination. Maneuver dates are predicted by periodically generating a spacecraft ephemeris in the OATS based on the current OATS orbit solution. Approximately 1 week before the projected maneuver date, the OATS is used to determine the thruster firings required to move the spacecraft orbit to its target. The target orbit is the orbit having an inclination at the opposite end of the inclination constraint box. This is achieved by a "node flip"; that is, the roll thrusters, pointing southward, are fired at the descending node such that it becomes the ascending node. Approximately 2 hours before the start of the maneuver, the DIRA is turned on and calibrated. This is discussed further in Section 3.3. Postmaneuver attitude instabilities can last for as much as 6 hours, causing a serious impact on normal imaging operations. Following each maneuver, thruster firing data and propellant system temperature and pressure data are collected. These data are used for calibrating the thrusters and managing propellant use.

3.2 EAST-WEST STATIONKEEPING

East-west stationkeeping maneuvers are performed to maintain or change the subsatellite longitude. Nominal stations for the operational GOES satellites are 75 degrees west longitude (GOES-East) and 135 degrees west longitude (GOES-West). Stored satellites will be positioned with regard to their intended use and the health status of the operational satellites. The direction and rate of drift of the subsatellite longitude depends on its position relative to a stable longitude node of 105.5 degrees west. For the operational spacecraft stations, east-west stationkeeping maneuvers occur approximately every 2.5 months. Station change maneuvers occur as required. Their frequency depends on the desired use for the spacecraft or on the health and safety of the spacecraft.

East-west stationkeeping maneuver dates are predicted by periodically generating a spacecraft ephemeris in the OATS based on the current OATS orbit solution. Maneuvers take place on or before the date on which the east-west stationkeeping constraint is violated. Maneuvers are planned such that the thruster firings provide an impulse to the spacecraft so that its east-west drift keeps it within its station longitude limits for the longest period of time. Similarly, station change maneuvers are planned such that the thruster firings provide an impulse to the spacecraft so that its east-west drift brings it to its desired station in a given period of time. Postmaneuver attitude instabilities can last for as much as 6 hours, causing a serious impact on normal imaging operations. Maneuver monitoring occurs in the same manner as for north-south maneuvers. Thruster data are collected after each east-west maneuver so that thruster calibration and propellant management can be performed.

3.3 DIRA CALIBRATION

Approximately 2 hours before the start of a maneuver, the DIRA is turned on so that roll, pitch, and yaw DIRA angle data can be collected by the OATS for DIRA calibration. Roll and yaw data are used to determine an average drift rate in those directions, pitch data, which include the orbital drift rate that maintains spacecraft Earth pointing, are also used to determine an average drift rate. These drift rates are used to calibrate the DIRA. DIRA angle data may be monitored during the process for unexpected attitude drift.

3.4 PLUME IMPINGEMENT

Before the start of a north-south stationkeeping maneuver, the solar array is placed in a park position to minimize roll thruster plume impingement. However, solar array heating still occurs. Consequently, there is a constraint limiting roll thruster continuous firing to 5 minutes, followed by a 5-minute cooling interval before the next firing. This constraint has a significant effect on the duration of north-south stationkeeping maneuvers; for example, a 0.4-degree inclination would require a 15-minute maneuver of which 10 minutes is actual burn time. Plume impingement and heating effects can be minimized by performing north-south stationkeeping maneuvers at optimum times around solstices.

3.5 CONTINGENCIES

Several contingencies are available to handle abnormal events that may occur during a stationkeeping maneuver. A standby communications link is ready in the event that communications are lost just before the start of a maneuver. If communications are lost during a maneuver, that maneuver is terminated. The effect of the completed part of the maneuver is determined, and the remainder is rescheduled and replanned if necessary.

If abnormal attitude changes occur during a stationkeeping event, there is the possibility of regaining attitude control by entering either Sun or Earth reacquisition mode in the AOCS.

4.0 HOUSEKEEPING SUPPORT

Housekeeping operations are part of the activities supported by the OATS. Housekeeping includes attitude control through unloading of angular momentum from the momentum wheels, trim tab positioning, and DIRA calibration. Housekeeping operations occur daily and are scheduled so as not to interfere with the imaging process.

4.1 ATTITUDE CONTROL

Nominal attitude control for GOES-Next will be performed by the two pitch momentum wheels (Figure 8). Both wheels operate to maintain Earth pointing throughout the orbit. Pitch is controlled by a speed modulation of both wheels. Roll and yaw are controlled by roll-yaw quarter-orbit coupling. Roll errors cause a differential modulation of wheel speed producing a yaw momentum increment. Attitude errors created during stationkeeping maneuvers are controlled by unloading roll and yaw momentum with thruster firings.

4.2 TRIM TAB POSITIONING

The trim tab is used to compensate the solar array for the solar radiation pressure torque. The trim tab angle can be stepped daily. The OATS determines the angle at which the trim tab is to be set based on the solar torque. The OATS also generates the commands for setting the trim tab angle.

4.3 DIRA CALIBRATION

The DIRA is composed of three mutually perpendicular rate integrating gyros. They are oriented along the roll, pitch, and yaw axes and are used to measure attitude changes in those directions.

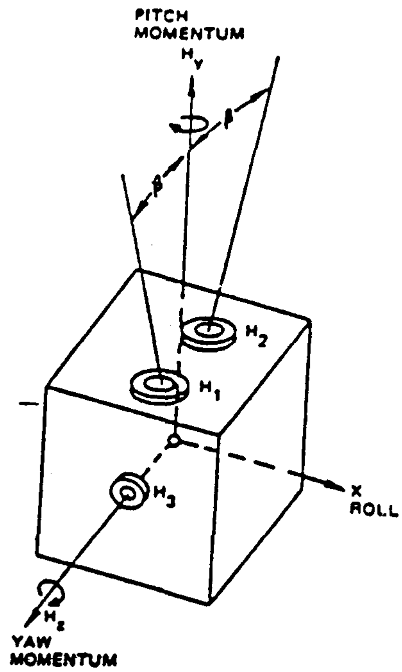

Figure 8. Momentum/Reaction Wheel Configuration

Following turn-on and warmup of the DIRA, the OATS collects at least 30 minutes of roll, pitch, and yaw DIRA angle data. The pitch data are corrected for the orbital rate. Each set of data are then curve-fit to produce an average drift rate in each direction. The OATs prepares commands for these drift rates to be uplinked to the spacecraft. Once they are uplinked, the DIRA is reset to initiate their use.

5.0 SUMMARY

The GOES-Next series of spacecraft will present a more demanding requirement on operations than the current GOES satellites. The new system of INR using image motion compensation for better imaging calls for daily generation of IMC coefficients based on orbital and attitude motions of the spacecraft and instrument thermal distortions. Three-axis attitude stabilization requires daily housekeeping activities that are not performed on the current dual-spin spacecraft. Potential impacts on normal imaging operations, such as those that will occur during stationkeeping maneuvers, also pose an operational problem. Consequently, NOAA is currently preparing for daily operations of these spacecraft. As part of this preparation, they are developing methods of reducing the impacts to imaging. An early mission evaluation period is also planned to evaluate spacecraft performance. Once this evaluation is complete, the GOES-Next system should provide improved and accurate weather forecasts into the next century.

ACKNOWLEDGMENTS

The authors wish to thank K. Kelly (NOAA), M. Suranno (NOAA), R. Johnson (Computer Sciences Corporation), and J. Dunham (Computer Sciences Corporation) for their thoughtful comments during preparation of this paper. They are also grateful to R. Pendley (Computer Sciences Corporation) and to the Technical Publications Department for their assistance in producing this paper.

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