# VALIDATING GOES INSTRUMENT THERMAL DEFORMATIONS[1]

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## ABSTRACT

Comparison of GOES instrument thermal model predictions with on-orbit data shows that the models capture the observed temperature and misalignment trends. Lack of precise knowledge as to spacecraft pointing precludes such comparison with instrument pointing predictions. Based on the models, thermally induced instrument attitude variation will dominate GOES N-Q Image Motion Compensation (IMC). Errors due to day-to-day changes in the attitude profiles are predicted to be under 10 microradians except for rapid scans where disturbances may reach 30 microradians.

## THE VALIDATION PROBLEM

The ITT Industries Imager and Sounder are scanning multi-channel imaging instruments flown on the Geostationary Operational Environmental Satellites (GOES). To ensure that the line-of-sight points in the desired direction, nominal scan mirror orientation is adjusted to compensate for predicted instrument pointing and gimbal misalignment errors. This is called Image Motion Compensation (IMC) and ideally avoids the need for image adjustments on the ground. When there is a problem, it usually comes about because the pointing and misalignment predictions used to compute IMC are not correct.

On the current GOES I-M momentum-bias spacecraft built by Space Systems Loral (SSL), pointing errors come not only from instrument thermal deformations but also from the Earth sensors used to control spacecraft attitude. Upcoming GOES N-Q three-axis-stabilized spacecraft being built by Boeing Satellite Systems (BSS) control spacecraft attitude using star trackers and gyros. This approach is expected to leave instrument thermal deformation as the primary source of pointing error.

The archive of GOES IMC sets provides instrument pointing and misalignment profiles for every day of the year. Although instrument misalignment is spacecraft-independent, instrument pointing includes spacecraft attitude. Obtaining pure instrument pointing from the IMC set requires precise knowledge of spacecraft attitude. Unfortunately, it is the instruments themselves that provide the most accurate observations of spacecraft attitude, and no way has been found to distinguish between instrument pointing and spacecraft attitude effects.

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If there were a way to propagate spacecraft pointing either kinematically or dynamically, it would be possible to remove spacecraft pointing from the IMC pointing. Propagation accuracy, however, would have to be on the order of one-tenth the maximum IMC or about 100 microradians over 24 hours. Unfortunately GOES I-M gyro propagation is not this accurate. GOES I-M does provide relatively accurate actuator telemetry, but 100 microradians out of the daily 360° pitch rotation is only one part in fifty thousand, and knowledge of the spacecraft inertia is not that accurate.

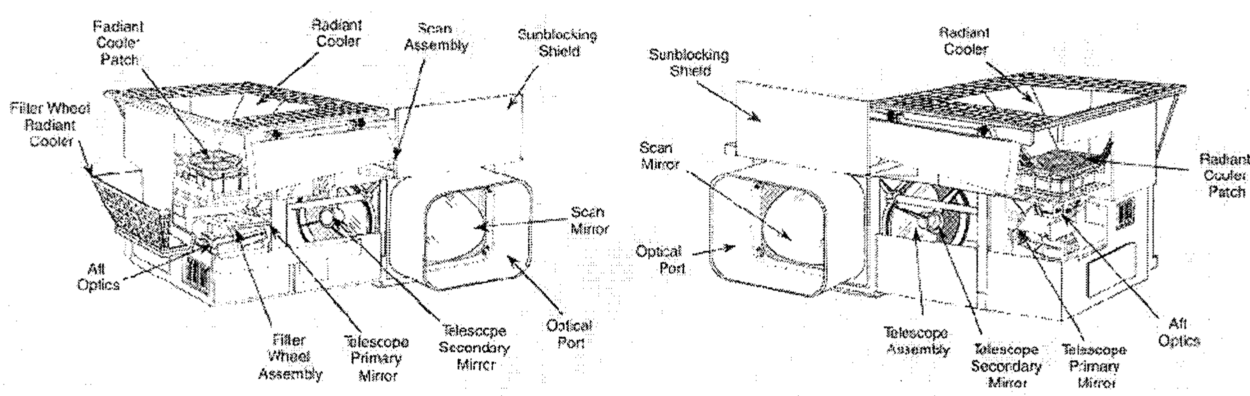
To determine instrument pointing and misalignment, ITT, SSL and BSS developed detailed thermal, structural and optical models for the instruments. The thermal model simulates electronic and solar heating plus reradiation and then computes temperatures at hundreds of instrument points. From these temperatures, the expansion of instrument parts is computed. The new dimensions are fed into a structural model that computes the movement of thousands of instrument points. Deflections and rotations of four critical optical points are then extracted and transformed to pointing and misalignment errors.

## INSTRUMENT MODELS

The Imager and Sounder are similar in construction. The optical components consist of a flat scanning mirror, a Cassegrain telescope made up of parabolic primary and secondary mirrors plus a detector array. These are housed in an aluminum box having an optical port for incoming light, cooling louvers above the scan mirror and radiant coolers above the detector array. Light from the Earth enters the optical port, is reflected at the scan mirror and enters the telescope and detector. The baseplate at the back of the instruments is attached to the spacecraft and is heated to keep its temperature above 12° C. Figure 1 shows the structure of the two instruments.

The instruments are insulated everywhere except over the optical port, radiant cooler and louver. At midnight (local solar time), the optical points toward the Sun. This is the time of greatest thermal loading and deformation. For much of the year, the Sun crosses the instrument field-of-view and around the equinoxes is eclipsed by the Earth. This intense heating interrupted by sudden cooling causes the most rapid thermal pointing and misalignment disturbances of all. Because Sun shining into the coolers reduces their effectiveness, 180° yaw maneuvers are planned for equinox to keep the coolers pointing away from the Sun.

Figure 1. Imager and Sounder Structure




For purposes of Image Navigation and Registration (INR), the instruments are characterized by three pointing and two internal misalignment angles which are collectively called the instrument attitude. The roll ($\phi$), pitch ($\theta$) and yaw ($\psi$) pointing angles are defined with respect to the orbital coordinate system x-, y- and z-axes respectively. In the upright orientation, orbital coordinates coincide with nominal instrument coordinates. In the inverted orientation, the instrument x- and y-axes coincide with the orbital minus x- and minus y-axes. This means that the same deformations in instrument coordinates imply opposite roll and pitch pointing in the upright and inverted orientations.

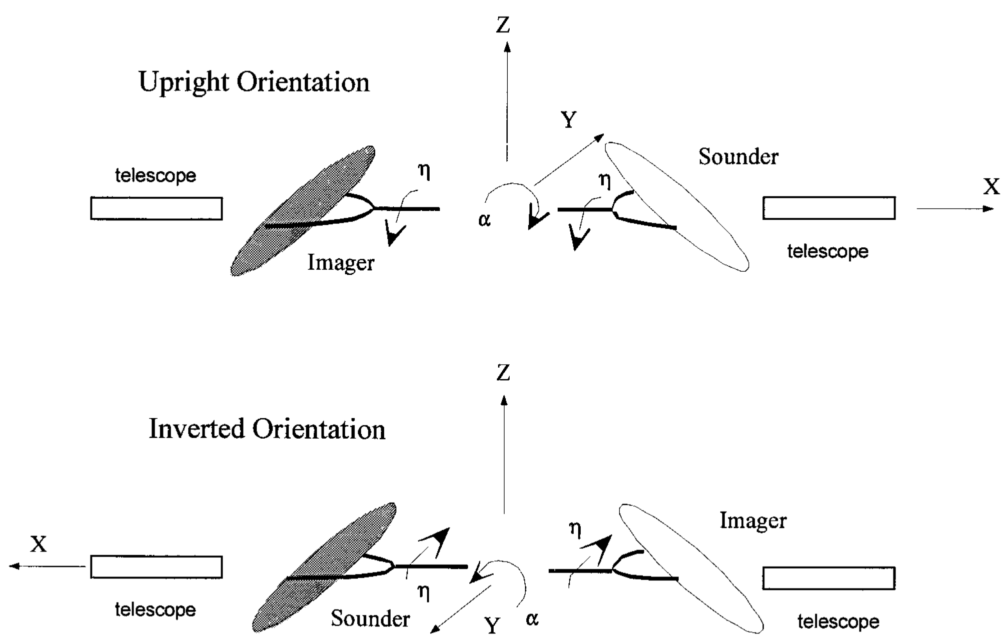
Misalignments are those of the outer scan mirror gimbal axis with respect to the Cassegrain telescope axis. Roll misalignment ($\phi_{ma}$ )and pitch misalignment ($\theta_{ma}$ ) are not tied to body coordinates as might be expected but are yaw-dependent. This is done to make the misalignments correspond to roll and pitch in either yaw orientation. Neither are the polarities the same for Imager and Sounder. This is done to make the upright Imager look like an inverted Sounder. The directions of positive misalignment rotation are indicated in Table 1.

Table 1. Misalignment Sign Conventions

| | | Upright | Inverted |
|---|---|---|---|
| Imager | $\phi_{ma}$ | -z_axis | z_axis |
| | $\theta_{ma}$ | -y_axis | y_axis |
| Sounder | $\phi_{ma}$ | z_axis | -z_axis |
| | $\theta_{ma}$ | -y_axis | y_axis |

Instrument observations are east-west (E) and north-south (N) scan angles derived from the scan mirror inner and outer gimbal angles $\alpha$ and $\eta$. The zero position for $\alpha$ is such that the mirror normal makes a 45°. angle with the outer gimbal axis. The zero position for $\eta$ is such that the mirror normal lies in the x-z plane. Unlike the misalignment angles, these angles are fixed in instrument coordinates along the positive body y– and x-axes respectively. This is Figure 2 shows this schematic INR model for the two instruments.

Figure 2. INR Instrument Model



The magnitude of the η angle corresponds approximately to the north-south scan angle (N), but the magnitude of the α angle is approximately half the east-west scan angle (E). Because the gimbal angles are defined with respect to instrument coordinates, however, the signs change with yaw orientation. If *yf* equal to +1 indicates the upright orientation and –1 indicates the inverted orientation and *is* equal to +1 indicates the Imager while *is* equal to –1 indicates the Sounder, the dependence of scan angle errors on pointing and misalignment for all four cases can be represented by the following pair of equations

$$\Delta E \approx \begin{pmatrix} 0 & -C_N & -S_N & -is \cdot yf \cdot S_N & 0 \end{pmatrix} \cdot \begin{pmatrix} \phi_n & \theta_n & \psi & \phi_{ma} & \theta_{ma} \end{pmatrix}^T \tag{1}$$

$$\Delta N \approx \begin{pmatrix} -1 & -S_N T_E & C_N T_E & 1 - \frac{C_N}{C_E} & \frac{S_N}{C_E}(S_E + is \cdot yf) \end{pmatrix} \cdot \begin{pmatrix} \phi_n & \theta_n & \psi & \phi_{ma} & \theta_{ma} \end{pmatrix}^T \tag{2}$$

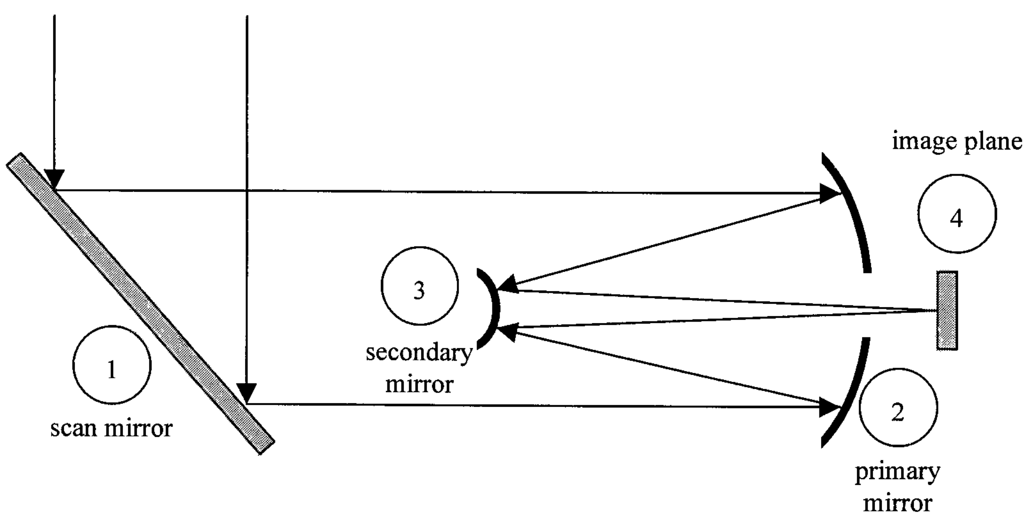
Here, $C$ and $S$ denote the cosine and sine of the subscript angles, and $\phi_n$ and $\theta_n$ are the modified roll and pitch used in the GOES Orbit and Attitude Tracking System (OATS)

$$\phi_n \equiv \phi + \phi_{ma} \tag{3}$$

$$\theta_n \equiv \theta + \theta_{ma} \tag{4}$$

Although the thermal and structural models predict deformations for thousands of instrument points, the optical model requires the three displacements and three rotations of only four points [1, 2, 3, 4, 5]. As shown in Figure 3, these four points are the centers of the scan mirror, primary mirror, secondary mirror and detector. Their twenty-four coordinates are multiplied by an Optical Sensitivity Matrix (OSM) that is specific for each instrument in each of the two possible yaw orientations. No deformations of the optical components are considered.

Figure 3. Four-Point Optical Model




## GOES I-M MODEL VALIDATION

Over the years since 1987 when the ITT instrument model was first developed, it has been repeatedly compared to ground test or on-orbit data and against general purpose modeling software. Temperature predictions have been checked to test the thermal model. Natural vibration frequency predictions have been checked to test the structural model. Pointing and misalignment predictions have been checked to test the optical model. When necessary, the model has been corrected or enhanced.

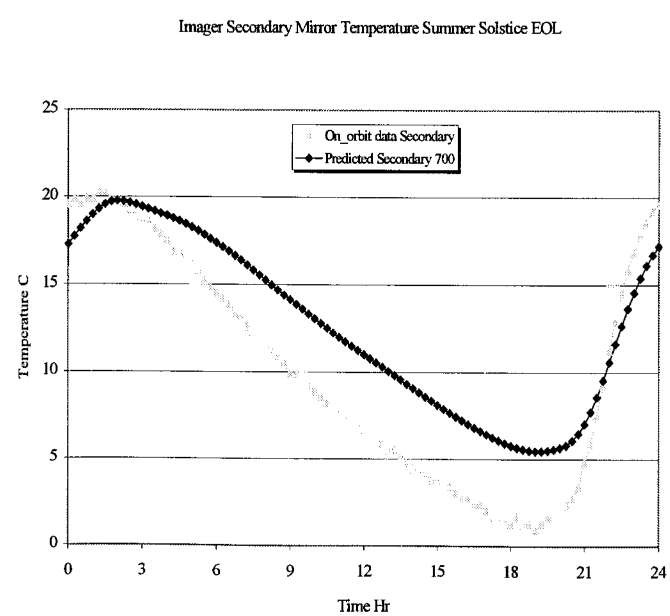
Thermal modeling is the first step in the simulation process, and predicted temperatures have been compared to both ground test and on-orbit telemetry data. In 1994, Harter showed that temperature predictions matched test data and predicted INR performance [6]. In 1995, Zurmehly showed that predicted temperatures matched GOES-8 on-orbit temperatures [7]. In 1996, Ghaffarian and Sprunger predicted that secondary mirror temperatures would exceed operating limits and verified their predictions with GOES-8 thermistor data [8].

Structural models relate temperatures to deformations. In 1997, Harter validated the structural model by successfully predicting instrument natural vibration frequencies [9]. He also showed that uniform temperature gives minute pointing errors as expected. In 1998, he identified the contributions of various instrument sub-assemblies by setting coefficients of thermal expansion to zero for all but the components under consideration [10]. In this way, Harter showed that roughly three-fifths of INR errors came from deformations of the instrument housing and one third came from deformations of the scan assembly.

The optical model transforms the three translations and three rotations for each of the four optical points into three pointing and two misalignment angles. Predictions have been compared with on-orbit IMC sets by Harter in 1991, Walker in 1996, Hampton in 1997, and Harter in 1997, but agreement was weak due to the overriding effect of Earth sensor errors [11, 12, 13, 14]. From the 1997 study, Harter found that structural translations and rotations corresponding to an instrument rigid body rotation wrongly produced optical internal misalignments. He also discovered that the OSM predicted results of the wrong sign for the Sounder. In 1999, Harter revised the Imager OSM and created a distinct OSM for the Sounder [15]. In 2000, Harter and Wickholm showed that the corrected OSM matched results obtained with the Code V optics modeling program [16].

GOES instrument thermal models are important for day-to-day operations as well as INR prediction. The instrument is susceptible to overheating, and operators avoid scanning close to the Sun rather than risk damage. The cost of this caution is lost images. So, there is motivation to predict temperatures as accurately as possible. Current models capture trends and actual temperatures within several degrees. Figure 5 shows typical agreement between predicted and observed Imager secondary mirror temperatures for GOES-10 at summer solstice.

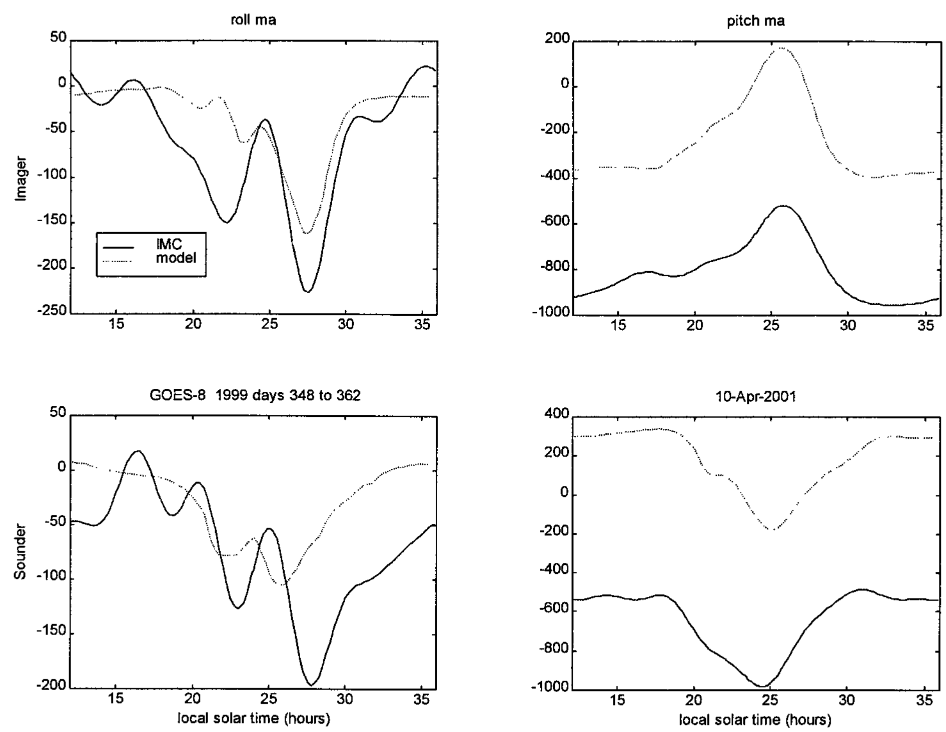
Figure 5. Predicted and Observed Mirror Temperatures



Unfortunately, there are no strain gauges or other devices to measure deformations on-board. So, structural predictions cannot be checked. The next level of on-orbit instrument validation possible is that of instrument attitude. As mentioned earlier, attitude is available from the GOES I-M IMC sets but is not ideal. Pointing includes Earth sensor errors, and misalignment observability is often poor. To minimize the effect of day-to-day variability, the IMC values in the following plots were averaged over fifteen days.

Figure 5 shows predicted and observed misalignments for winter solstice. The pointing curves show little agreement. When the shapes of the predicted and observed misalignment curves are compared, they are almost identical. Roll misalignment values are within the uncertainty of the IMC profiles. The larger pitch misalignment bias may be due to unmodeled effects either in the thermal or INR models. Lower bounds on the pitch misalignment estimate standard deviation are 10 microradians, and the misalignments are not among the most highly correlated of the solved-for state variables.

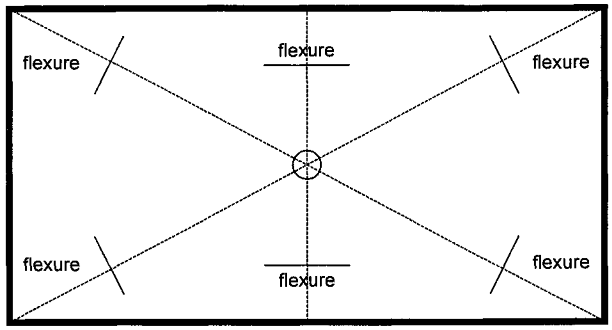
Figure 5. Predicted and Observed Misalignment




## GOES N-Q MODEL VALIDATION

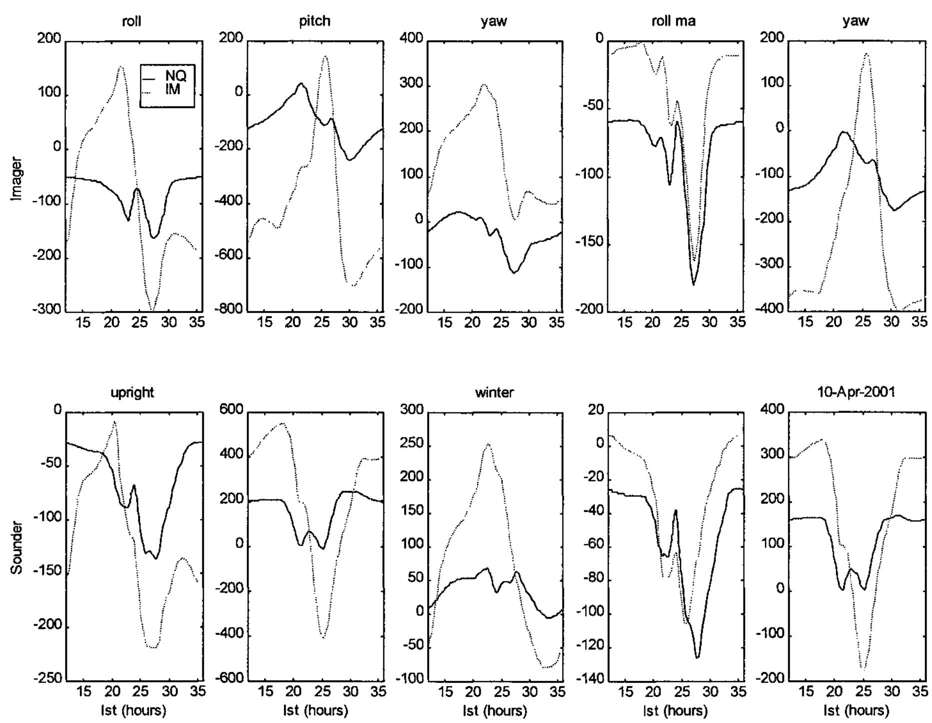
The preceding comparisons with on-orbit data were made against the GOES I-M model, but it is primarily the GOES N-Q models that are of interest now. Without GOES N-Q temperatures or IMC sets for comparison, the N-Q models can still be checked for reasonableness. The N-Q models are qualitatively similar to those for GOES I-M. The primary differences are the attitude stability of the spacecraft and the instrument mounting. Thin metal strips called *flexures* attach the instrument to the bench. This holds the instrument in place but allows it more freedom to expand and contract. As shown in Figure 7, the instrument is mounted using six flexures whose normal vectors intersect at the center of the instrument footprint.

Figure 7. Flexure Mounting




Harter identified flexures in 1998 as a way to reduce pointing and misalignment errors without redesigning the instrument [11]. As shown in Figure 8, the GOES N-Q predictions are generally smaller than those for GOES I-M. Pointing improvement may be due in part to the GOES N-Q bus attitude stability, but misalignment improvement is due to the flexures. Pitch misalignment is greatly reduced while roll misalignment variation is only slightly reduced. The results for summer and equinox are similar.

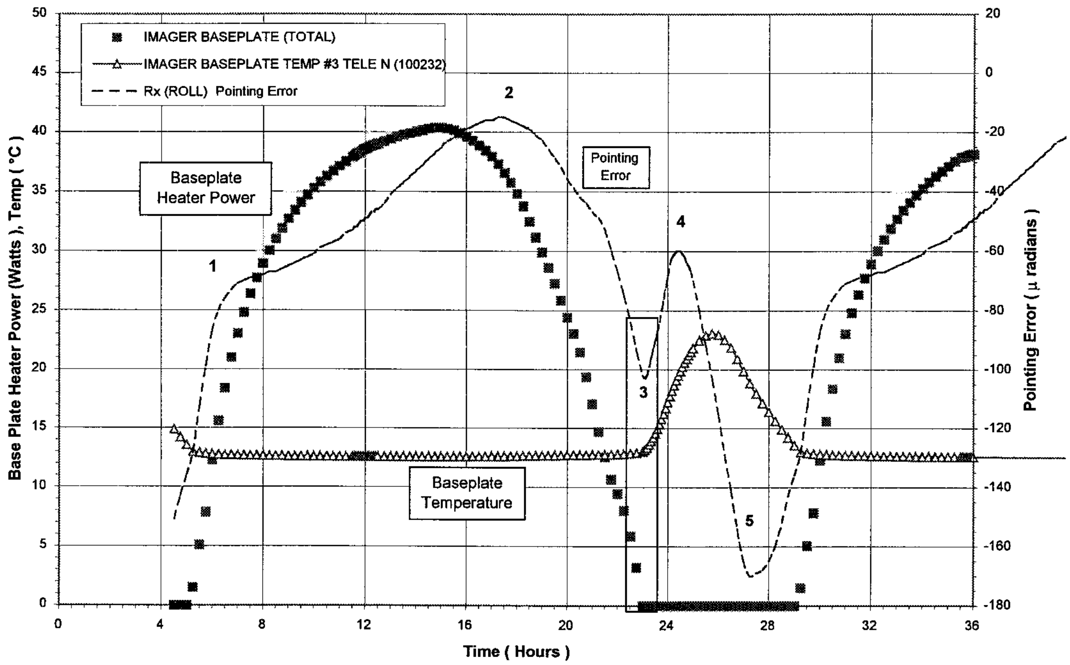
Figure 8. GOES I-M / N-Q Model Comparison




The strange shape of some of the GOES N-Q predicted curves, particularly the double peaks, raised concern that the GOES N-Q model might not be consistent with real instrument behavior. To resolve that question, GOES I-M IMC sets were checked to see if double peaks had been seen in operations and temperature predictions were checked for anything that could cause the double peaks. . In addition, special simulations were run holding the spacecraft at a uniform temperature and holding the instrument at a uniform temperature in order to isolate the contributions of the spacecraft alone and the instrument alone.

Checking IMC sets showed some days with and some without double peaks. That day-to-day variability may have been due to Earth sensor and estimation errors. So, other verification was still necessary. Given the success of the thermal model in capturing thermal variations, baseplate heater power and instrument temperatures were examined for features coincident with instrument attitude variations. The instrument temperatures checked were those of the baseplate, optical port sunshade, scan mirror gussets, north panel, primary and scan mirror. What was found were that the jogs in the INR profiles did correspond to instrument thermal events and that reradiation or *backloading* from the optical port sunshade was a significant source of heating. Figure 9 shows one such plot of roll overplotted on top of baseplate heater power [17].

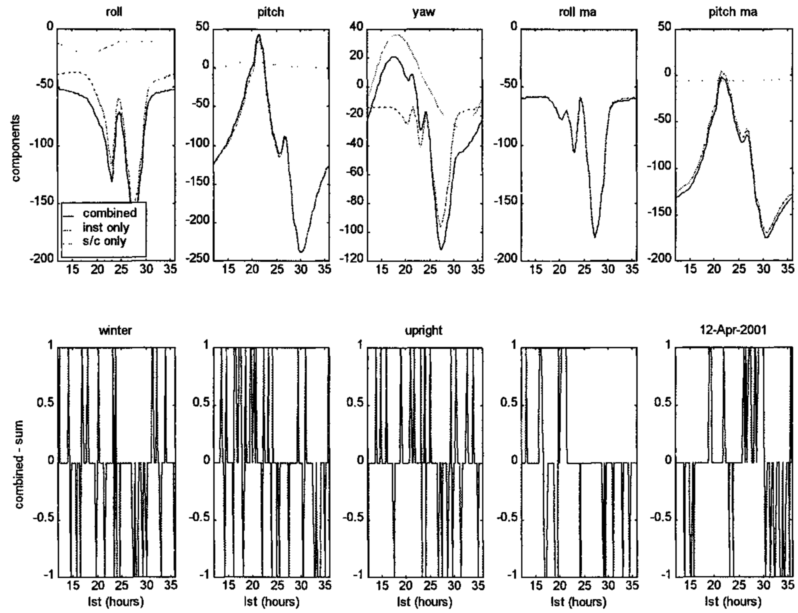
Figure 9. Roll and Baseplate Heater Power




The special simulations to separate instrument and spacecraft effects also suggested that the double peaks were due to the instrument. Figure 10 shows the original combined attitude profiles plus those for the instrument alone and spacecraft alone. The prediction for the instrument alone closely follows that for the spacecraft and instrument combination. Due to the spacecraft stability, the spacecraft-only profile is a small fraction of the combination. Also as expected, spacecraft thermal variation contributes very little to instrument misalignment.

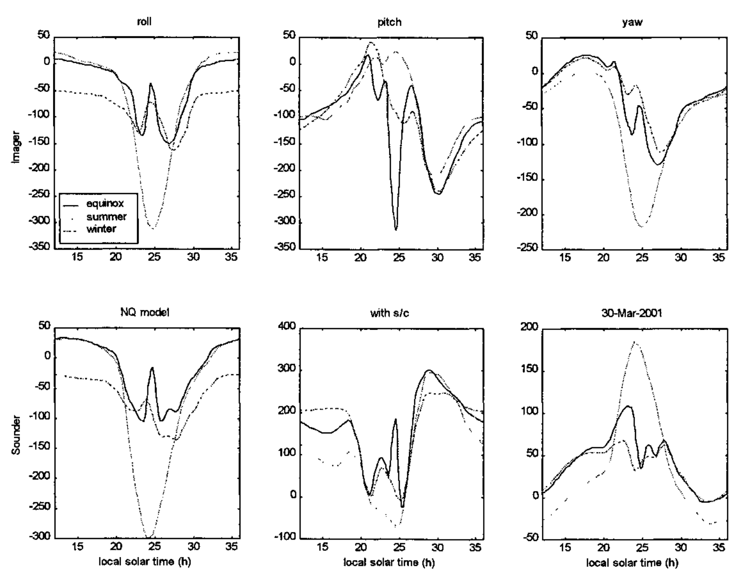
Underlying the interpretation of these simulations as the effect due to spacecraft alone and that due to the instrument alone is the assumption that the combined profile equals the sum of the individual profiles, i.e. that the spacecraft and instrument effects are independent of each other. Conceivably, there could be interactions between components of the spacecraft and instrument attitudes that would cause the individual profiles not to add up. When summed together, however, the spacecraft-only plus instrument-only profiles do match the combined profiles within one microradian. This agreement lends credence to the interpretation of the results as being spacecraft-only and instrument-only effects.

Figure 10. Spacecraft versus Instrument Effects



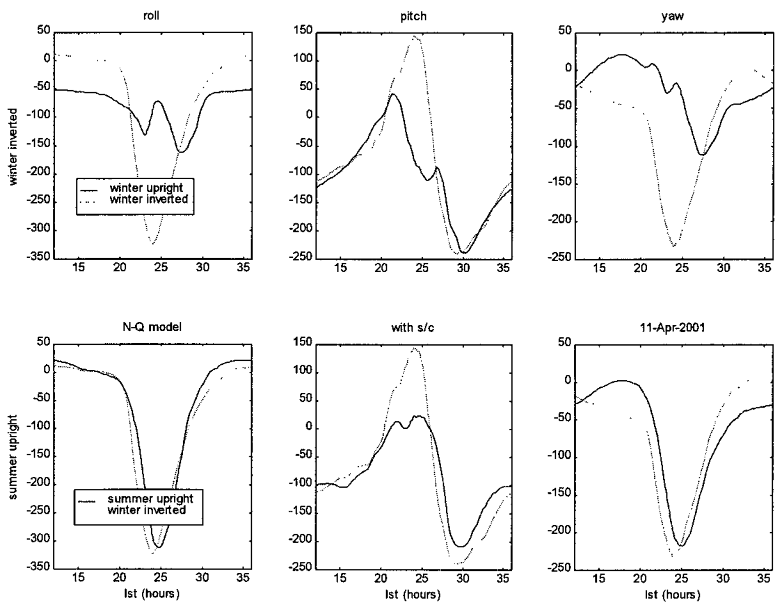

The variation of pointing and misalignment with season also provides insight into the thermal behavior of the instruments. Figure 11 shows predicted pointing for winter, spring and summer in the upright yaw orientation. At midnight, the summer Sun illuminates the north face of the instruments, shines into the louvers and heats the scan cavity. This causes the large long-lasting excursions that dominate the roll and yaw profiles. In contrast, the winter Sun illuminates the south face of the instruments and does not shine into the louvers. It does not cause the same large deformations at midnight. As expected, the equinox case is intermediate between the winter and summer cases for most of the day. At midnight, however, the Earth blocks the Sun, and the instruments cool down rapidly pushing the equinox profile in the winter direction.

Figure 11. Predicted Pointing for Different Seasons



The dominant effect of Sun coming into the louvers suggests that summer in the upright orientation should look more like winter in the inverted orientation than summer in the upright orientation. This is borne out in Figure 12 where the curves in the second row of plots are more similar than those in the first row. The differences between the summer upright and winter inverted curves may be due to the fact that the Sun travels in different directions with respect to the instrument and also to the greater distance from the Sun during summer.

Figure 12. Summer Upright ~ Winter Inverted



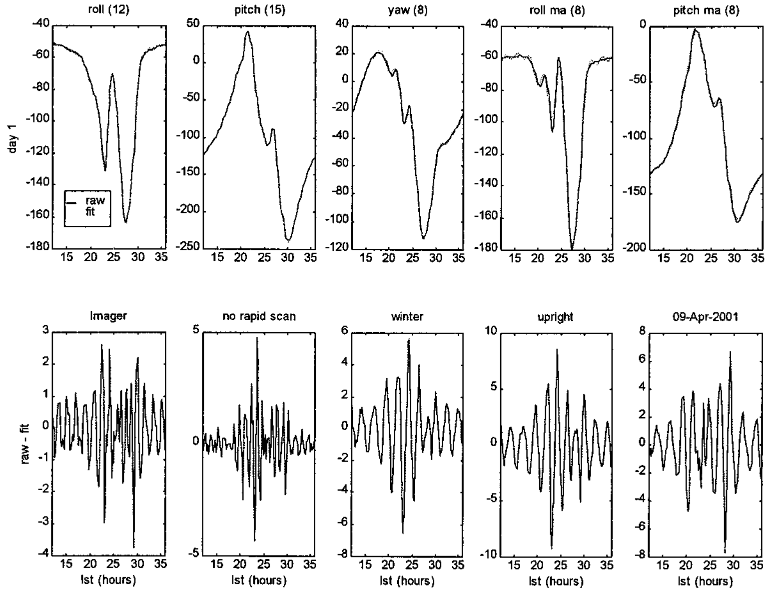

## INR PREDICTIONS

To ensure that GOES N-Q meets its INR requirements, day-to-day variations in the thermal profiles are specified to be under 10 microradians. The thermal model provides a means of predicting whether or not this requirement will be met. By fitting the day 1 profile to a Fourier series and comparing that fit to the raw profile for day 2, one can predict the day-to-day INR error. This error depends on season because the thermal profiles depend on season. Vernal and autumnal equinox are expected to be the worst cases, but special short span IMC sets will be used over the eclipse periods. The only case considered here is that of winter solstice which is in the normal season for upright yaw.

Rather than fit points at the same time as the next day's "observations", day 1 points were first interpolated to uniform 15 minute intervals staggered 7.5 minutes from the original points. Then the interpolated values were fit to Fourier series with the recommended [12 15 8 8 8] fit orders for the roll, pitch, yaw, roll misalignment and pitch misalignment. This was considered a better simulation of the random landmark observation spacing encountered in operations. As shown in Figure 13, fit errors range from 3 microradians for roll to 10 microradians for more jagged roll misalignment.

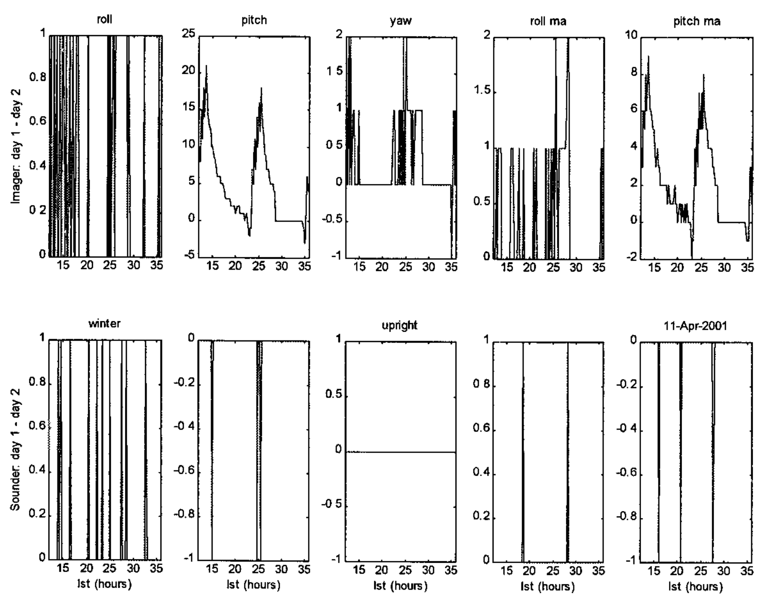
In addition to solar heating, another source of nonrepeatability is the rapid scan mode of operation used to image severe storms. Rapid scanning may heat and deform the instrument on one day but not necessarily the next day. To assess the impact on repeatability, rapid scans were simulated for the Imager on day 2 but not for the Sounder.

Figure 13. Curve Fit Error



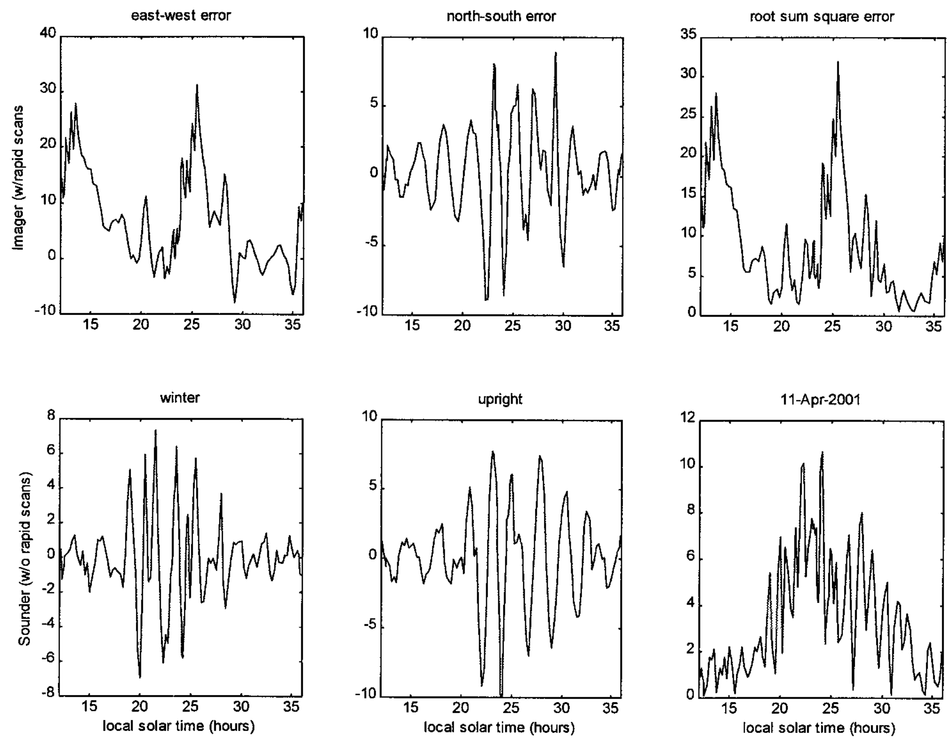

During rapid scanning, the servo motor generates more heat than usual. This alters the thermal deformation profiles and causes errors in the profiles predicted from the previous day. Figure 14 shows the error for the Imager which performs two rapid scans on day 2 and for the Sounder which does none. The error is greater at noon when the scan cavity is otherwise cool than at midnight when sunlight enters the optical port. Without rapid scans, repeatability differences are under one microradian (Sounder). With rapid scans (Imager), differences reach 20 microradians in pitch and 8 microradians in pitch misalignment. This exceeds the specification for day-to-day variation and requires special attention.

Figure 14. Repeatability



Although instrument pointing and misalignment have their own requirements, navigation error is the bottom line for INR. Scan angle errors can be computed using the equations (1-4) given earlier from instrument attitude and the scan angles themselves. Roll, pitch, roll misalignment and pitch misalignment effects depend weakly on scan angle, but yaw effects increase from zero at nadir to a maximum at the edge of the field of view. For a point on the Earth limb 8.3° to the north and east of nadir, the east-west, north-south angle and rss errors are as shown in Figure 15. Overall navigation error may be computed as the root sum square of the east-west and north-south scan angle errors. With rapid scans, navigation error reaches 30 microradians. Without rapid scans, navigation error is only 10 microradians.

Figure 15. Navigation Errors




## CONCLUSIONS

The GOES I-M Imager and Sounder thermal, structural and optical models have been shown to agree with on-orbit data. The GOES N-Q instrument models are derived from those for GOES I-M but predict smaller pointing and misalignment errors due to improved spacecraft attitude stability and stress-relieving instrument flexure mounts. In the absence of on-orbit GOES N-Q data for comparison, the instrument models have been shown to be reasonable and self-consistent.

The GOES N-Q models predict that the instrument itself will be the primary source of pointing and misalignment errors. In the absence of rapid scans, day-to-day pointing and misalignment repeatability are predicted to be 1 microradian at winter solstice. Curve fitting these profiles with the planned [12 15 8 8 8] order Fourier series introduces additional error on the order of 8 microradians. Rapid scanning heats the instruments and causes deformations that add 20 microradians to the nonrepeatable error. The resulting root sum square of the east-west and north-south errors is 30 microradians which is of concern.

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