Geostationary Operational Environmental Satellite (GOES) Gyro Temperature Model*

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Abstract

The Geostationary Operational Environmental Satellite I/M (GOES I/M) series of spacecraft are geostationary weather satellites that use the latest in weather imaging technology. The inertial reference unit package onboard consists of three gyroscopes measuring angular velocity along each of the spacecraft's body axes. This digital integrating rate assembly (DIRA) is calibrated and used to maintain spacecraft attitude during orbit delta-V maneuvers.

During the early orbit support of GOES-8 (April 1994), the gyro drift rate biases exhibited a large dependency on gyro temperature. This complicated the calibration and introduced errors into the attitude during delta-V maneuvers. Following GOES-8, a model of the DIRA temperature and drift rate bias variation was developed for GOES-9 (May 1995). This model was used to project a value of the DIRA bias to use during the orbit delta-V maneuvers based on the bias change observed as the DIRA warmed up during the calibration. The model also optimizes the yaw reorientation necessary to achieve the correct delta-V pointing attitude. As a result, a higher attitude accuracy was achieved on GOES-9 leading to more efficient delta-V maneuvers and a propellant savings.

This paper will summarize the

- Data observed on GOES-8 and the complications it caused in calibration

- DIRA temperature/drift rate model

- Application and results of the model on GOES-9 support

Introduction

The GOES I/M series of spacecraft are the new generation of geostationary weather satellites. The first two spacecraft of this series have been launched (GOES-8 on April 13, 1994 and GOES-9 on May 23, 1995) and are operational. The third, GOES-K, is currently planned for launch in March 1997. A summary of the characteristics of the GOES spacecraft, mission profile, and flight dynamics experience during the orbit-raising support of GOES-8 is given in References 1 and 2. The present paper expands on the topic of DIRA calibration that was introduced in Reference 1, and discusses calibration results from GOES-9.

Figure 1 shows the GOES spacecraft in its configuration during the orbit-raising phase of the mission with the solar array partially deployed. The roll, pitch, and yaw axes are indicated, along with the locations of the main satellite thruster (MST) on the –X face and the DIRA on the –Y face.

Partially Deployed
Solar Array

Trim Tab
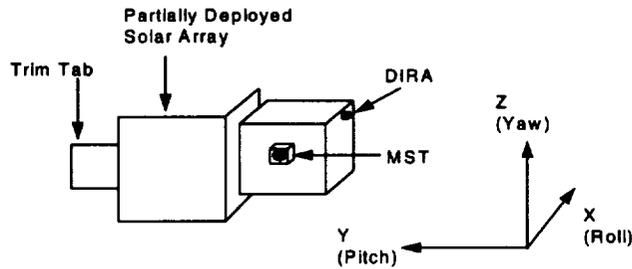
DIRA

Z
(Yaw)

MST

X
(Roll)

Y
(Pitch)

Figure 1. GOES Transfer Orbit Configuration

For some of the GOES mission attitude control modes, the spacecraft is dependent on the DIRA to maintain accurate pointing. In particular, during orbit maneuvers the yaw axis DIRA is used for position control to maintain the spacecraft yaw attitude. Maintaining the delta-V pointing attitude as close as possible to the target allows for an efficient orbit transfer. This requires, however, that the rate bias of the DIRA be determined and then compensated in the onboard control system by uplinking the bias to the spacecraft. Because of the length of the burns, which can approach 100 minutes, any DIRA rate bias residual can accumulate over the length of the burn to produce a significant pointing error, resulting in excess expenditure of fuel.

It is because of this potential for a large error that the Flight Dynamics Facility (FDF) produces a calibration scheme for the DIRA. Under ideal conditions, the DIRA would be calibrated under attitude pointing conditions that would exist for the burn. Unfortunately, the mission does not allow for the ideal. A series of perigee-raising maneuvers are performed during the orbit-raising phase. During the half orbit before each of these maneuvers a sequence of events is executed that includes a yaw reorientation (reor) to cool the MST, DIRA calibration, uplink of the DIRA bias, switch of the control mode to put the yaw DIRA in the control loop, update of the DIRA bias uplink, and finally yaw and pitch reors to the maneuver attitude. During a practice of this sequence in the half orbit before the first apogee all of these steps are performed, except no actual maneuver takes place. The first maneuver is done on fourth apogee.

The experience on GOES-8 showed variations in the determined DIRA rate biases from the time of calibration and uplink to the time of the maneuver. The major cause of this was found to be variable DIRA temperatures combined with a strong, but not consistent, dependence of the rate bias on the temperature. The temperature vartiations were caused by the changing spacecraft-Sun geometry throughout the premaneuver period. Thus it became desirable to create a model to account for these variations and predict an accurate DIRA rate bias for a future time.

DIRA Temperature and Bias Characteristics

The temperature of the DIRA varies during the course of calibration and the orbit maneuver because of the changing Sun angle. Figure 2 shows as an example the history of the DIRA temperature during the GOES-9 apogee maneuver firing (AMF)-1 activities. This behavior may be understood by considering Figures 3 and 4, which illustrate the orbit and attitude geometry, respectively, during this period.

Figure 3 illustrates the geometry looking into the orbit plane. The −X axis points generally toward the Sun, and the Z-axis toward the Earth. Figure 4 is an edge-on view of the orbit plane looking from the direction of apogee back toward the Earth to illustrate the yaw attitude geometry. The quiescent attitude [Figure 4(a)] has the Sun on the −X axis, and is intended to maximize power on the solar array during orbits without maneuvers. At the start of the DIRA calibration (time = 0 in Figure 2), the Earth is captured with the Earth sensor, followed by a yaw reor to

move the Sun as far as possible off the –X axis. This yaw reor was not in the initial GOES mission design, but was added during the GOES-8 support when a thermal problem in the MST caused the first maneuver to be aborted. Yaw is controlled with the digital Sun sensor (DSS) at this time, and the mounting of the DSS forces the yaw reor to be in the direction shown in Figure 4(b). While keeping the MST cool, this reor has the effect of allowing the Sun to hit the DIRA mounted on the –Y face, so its temperature increases. This increase continues until the yaw reor to the AMF attitude [Figure 4(c)], where the DIRA is in shadow again and begins to cool down. This yaw reor occurs at time = 3 hr in Figure 2.
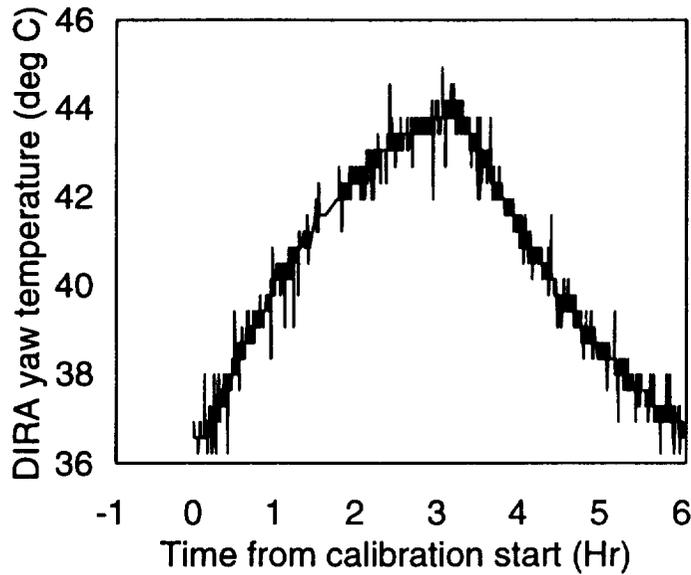
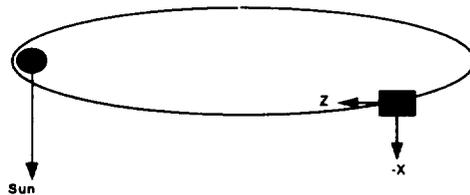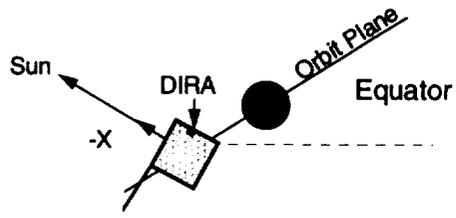

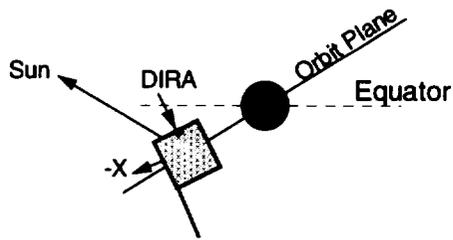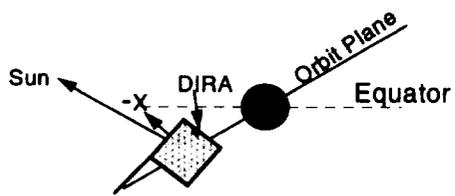Figure 2. DIRA Temperature During GOES-9 AMF-1

Figure 3. GOES Orbital Geometry

(a)

(b)

(c)

Figure 4. GOES Attitude Geometry

This temperature variation by itself would not be a problem, except that during the DIRA calibration activities for the GOES-8 mission, a temperature dependence of the DIRA rate bias was detected. A linear variation of the rate bias with temperature was measured, as shown in Figure 5. To further complicate the problem, the slope and intercept were not consistent from one maneuver to the next. On GOES-8, the rate of change of rate bias ranged from 0.12 to 0.24 deg/hr/deg C and the bias at constant temperature up to 2 deg/hr. The requirement for attitude control during the AMFs is 1.57 deg, so the variations noted in Figure 5 have a significant effect. As a result of this, and in spite of attempts to project the best value of bias to use, attitude errors during the orbit maneuvers on GOES-8 were as large as 0.6 deg.
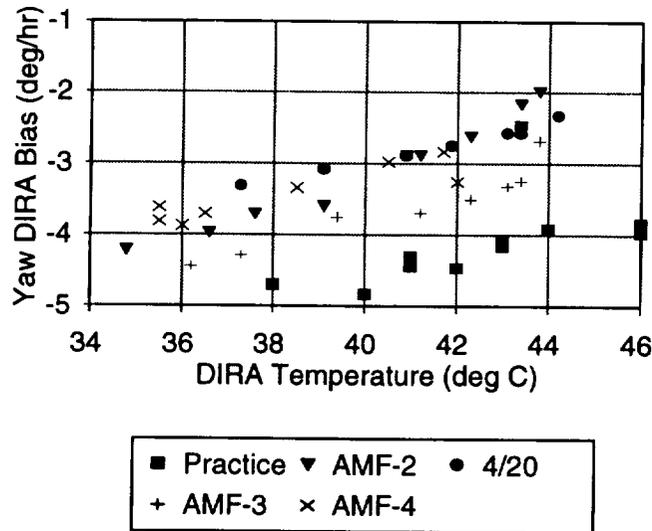

Figure 5. DIRA Biases for GOES-8

The ideal situation is to have the attitude constant at the target value during the entire AMF, because this is the way the maneuver software models the burn. However, the continuously varying DIRA temperature produces a continuously varying bias, and hence a continuously varying yaw attitude when the DIRA is used to control the attitude. Only a constant value of the bias can be uplinked, and so the attitude rate can be made zero only at one point. Thus, selection of an uplink rate bias value is at best a compromise. The compromise chosen was to make the attitude rate zero at the midpoint of the burn, and then a target for the reor was chosen such that the attitude is correct at the midpoint of the burn.

Two models were actually developed: one to describe the DIRA rate bias variations and one to describe the resulting yaw attitude variations. These are discussed in the next section.

Model Development

From the data collected during the early mission support of GOES-8, a model for the temperature profile and the rate bias behavior was developed to serve as the basis for the GOES-9 calibration procedure. Review of the GOES-8 DIRA temperature histories indicated a consistent pattern of temperature increasing at an average rate of 2.8 deg/hr until the AMF yaw reor, and then decreasing at an average rate of 4.0 deg/hr afterward, as illustrated schematically in Figure 6. In particular, the ratio, K, of the slopes was found to be nearly constant from maneuver to maneuver at an average value of -1.43. The small exponential variation evident in Figure 2 was neglected.

Yaw AMF
Reor Midpoint
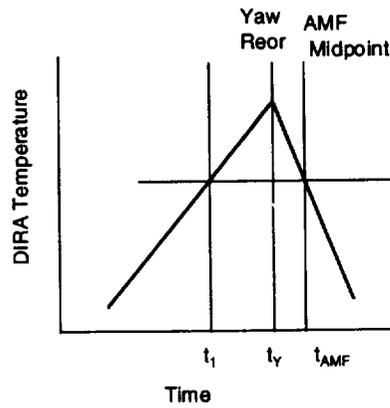
DIRA Temperature

t_1 t_Y t_{AMF}

Time

Figure 6. Typical DIRA Temperature Profile

Although the temperature dependence of the DIRA bias changed from maneuver to maneuver on GOES-8, the dependence was always linear. Thus, we expect the DIRA bias at t_1 , the time where the DIRA temperature is the same as it is at t_{AMF} (the midpoint of the AMF), to be the same as the DIRA bias at t_{AMF}, and this along with K being constant forms the basis of the model. The time t_1 can be found given K, the AMF midpoint time, t_{AMF}, and the yaw reorientation time t_Y.

$$t_1 = t_Y + K(t_{AMF} - t_Y)$$

Note that the validity of this model depends on K being constant from maneuver to maneuver (which was in fact observed on GOES-8) and on the reor and burn occurring on the times in the script. The actual bias and time rate of change of the bias are determined for each maneuver and thus need not be constant from maneuver to maneuver.

During the DIRA calibration period, 20-minute sliding batch-least squares solutions are obtained and a linear function of time fit to these measurements. Typically, the first DIRA bias uplink is required before t_1 is reached, so the fit is actually extrapolated to this time. The fit also has the effect of smoothing the scatter in the 20-minute solutions.

At a time t_P (after the first bias uplink), the spacecraft is put into a mode where the yaw attitude is controlled by the yaw DIRA. At a later time t_u , an updated bias of value B_u is uplinked. This value is obtained from the fit as before, but it now covers a longer period of time such that t_1 is within the period of the fit. Also, any effects from orbit rate coupling are included in this uplink. The orbit rate coupling effect occurs because of nonzero yaw and pitch attitude during the time the spacecraft rotates about the yaw axis at the orbit rate. This uplink is followed by the reor to the maneuver attitude at time t_Y , and finally by the maneuver itself, with time of midpoint t_{AMF} .

Because the temperature is a linear function of time and the bias is a linear function of temperature, the bias, B, will be a linear function of time

$$B(t) = B_0 + \dot{B}(t - t_0) \quad \text{for } t < t_Y$$

where B_0 and $\dot{B}$ are obtained from the linear fit of bias versus time as described above. Because the bias is a linear function of the temperature, the ratio of the rates of change of the bias before and after the yaw reor will also be equal to K, so

$$B(t) = B_0 + \dot{B}(t_Y - t_0) + K\dot{B}(t - t_Y) \quad \text{for } t \geq t_Y$$

K is found from the slopes of temperature versus time before and after the yaw reorientation. After the event is over, K is found and used on the next event. In general, the yaw attitude rate is given by the following:

$$\dot{Y} = B_c - B(t)$$

where B_C is the commanded DIRA drift rate bias, and the yaw attitude by

$$Y = Y_0 + \int_{t_0}^{t} \dot{Y} dt$$

The above equations may be evaluated to predict Y, keeping in mind that B_C has one value at t_P and another at t_U. The value of the orbit rate coupling is added to B at the time of the pitch reor. The initial yaw attitude is Y_0 at t_P as determined from attitude solutions; the value at t_Y is incremented by a step of the amount of the yaw reorientation. In actual use, the size of the yaw reorientation is adjusted, and the model is run in an iterative fashion until the best approximation to the target maneuver attitude is obtained.

Application of the Model to GOES-9

Following is a summary of the results obtained on GOES-9 for the three cases (practice, AMF-1, and AMF-2) when the DIRA temperature variation occurred. Detailed results are shown for AMF-1, and the other events are summarized.

The DIRA temperature profile during the practice DIRA calibration showed a ratio of the rise and fall slopes to be approximately -1.0 rather than the -1.43 observed on GOES-8. Because of this, the predicted bias after the yaw reorientation did not match well with the actual bias. This was not a problem because no maneuver took place, and the goal of the practice calibration was in fact to refine the parameters of the model for use on AMF-1 and on AMF-2.

The DIRA yaw temperature variation for AMF-1 was shown in Figure 2. Note that the shape is not strictly linear (as assumed in the model) but has an apparent exponential component, as might be expected from thermodynamics. Modeling this may be a way to refine the model for the future. In any event, the fit of the DIRA drift rates as a function of time is shown in Figure 7. The peak-to-peak residual from the linear fit is about 0.2 deg/hr, which includes the effect of nonlinearity in the bias as well as scatter in the bias solutions. This is an indication of the size of the DIRA bias uncertainty.
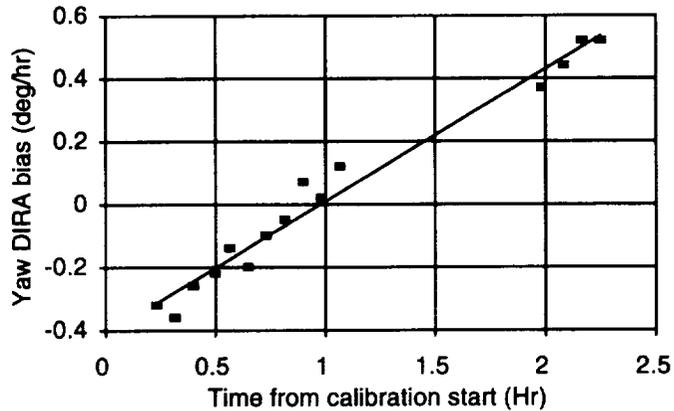
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Figure 7. Yaw DIRA Bias Versus Time for GOES-9 AMF-1

A 4-minute telemetry dropout occurred during the calibration period for AMF-1. This gap was too large to interpolate across accurately and hence affected the quality of the solutions. Therefore, biases were not computed for a period of 20 minutes on either side of the gap. Based on the fit before the gap, a DIRA yaw bias of 0.7 deg/hr was selected. The value was then updated to 0.5 deg/hr after the gap (the additional data reduced the slope slightly). This value inadvertently did not include the predicted orbit rate coupling of −0.16 deg/hr. The yaw reo was then planned, taking into account the fact that the orbit rate coupling had not been included in the bias uplink. Figure 8 shows predicted and observed yaw attitudes starting shortly after the yaw reor. The prediction was done at the time using the actual uplinks and modeling the effect of the orbit rate coupling given these uplinks. The horizontal line in this figure indicates the target attitude; the midpoint of the AMF occurs at the 4-hour mark.
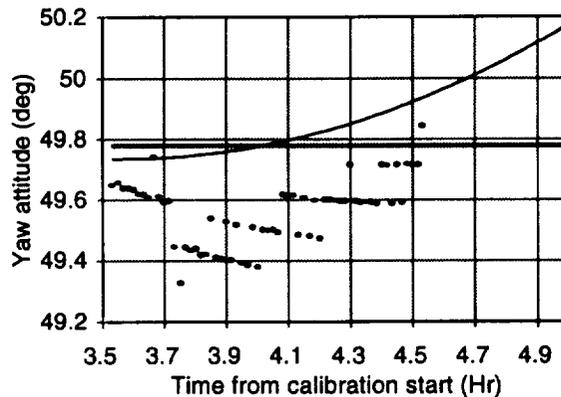

Figure 8. Predicted and Observed Yaw Attitude for AMF-1

Figure 8 indicates that the attitude should have been correct at the midpoint of the burn with a positive rate because the orbit rate coupling in the DIRA bias was not included. However, because of a negative yaw hangoff during AMF-1, the actual attitude was 49.6 deg on average, slightly less than the target of 49.78 deg. The actual attitude

rate was positive as expected. The yaw hangoff was neglected by prelaunch agreement with the flight operations team (FOT), because the value was uncertain before launch but expected to be well within the allowable yaw attitude error. In fact, AMF-1 turned out to be a very successful maneuver with the final inclination within 0.13 deg of the target.

In the case of AMF-2, the DIRA temperature and DIRA drift rate bias as a function of time were similar to AMF-1. A yaw hangoff of –0.2 deg was included in the yaw reor command, based on the value at the end of AMF-1. The orbit rate coupling was negligible. The final attitude during AMF-2 was very close to the target (31.36 deg versus 31.29 deg), and predicted rates agreed well.

Temperature Dependence of DIRA Bias for GOES-9

On GOES-8 the temperature dependence of the DIRA biases varied in a nonsystematic way from event to event. The behavior on GOES-9 up through AMF-2 was much more consistent, as shown in Figure 9. The slope of the linear fit in Figure 9 is 0.18 deg/hr.
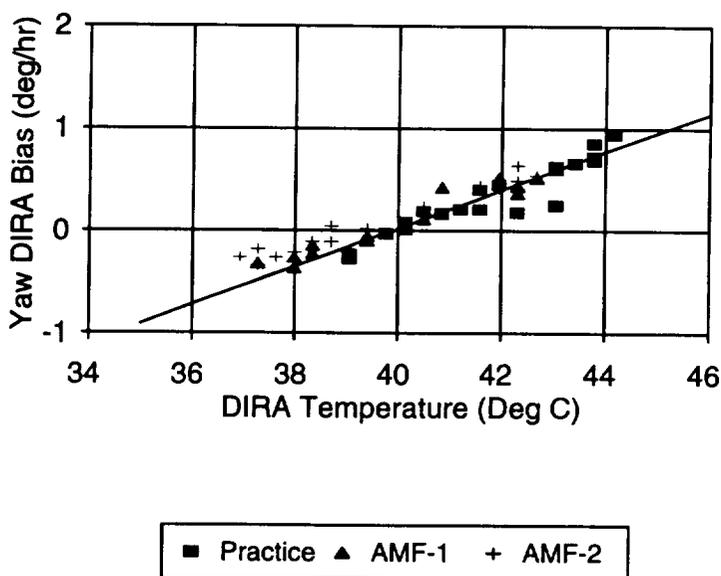

Figure 9. DIRA Biases for GOES-9

Conclusions

The experiences on GOES-8 and GOES-9 described in this paper provide an interesting case study of how real life in mission support is often different from what is expected before launch. The technique described here for estimating the DIRA draft rate biases and the yaw reorientation resulted in actual average yaw attitudes within 0.3 deg of the target attitude in the presence of changing DIRA temperatures and drift rates. This is a factor of two improvement over GOES-8. More importantly, mechanizing the procedure reduces greatly the chances of a much larger error occurring because of human error in trying to estimate a value of bias to use. Major sources of error in this technique include nonlinearity in the time dependence of the bias, uncertainty in the bias solutions, and variations in the actual times of reorientations and bias uplinks from those planned in the script. Modeling the nonlinearity might be a way to improve the results, but, considering that 0.3 deg is already much less than the requirement of 1.57 deg and that the other sources of error will still exist, the point of diminishing returns has probably been reached. However, a study of the actual and predicted yaw hangoffs for AMF-1 on GOES-8 and

GOES-9 might be useful to determine if a predicted yaw hangoff could reasonably be included in the AMF-1 planning for future GOES missions.

Acknowledgment

References

1. C. H. Noonan, et al., "Geostationary Operational Environmental Satellite (GOES)-8 Mission Flight Experience," presented at the Flight Mechanics/Estimation Theory Symposium, GSFC, May 16–18, 1995.

2. W. Forcey, et al., "Evaluation and Modeling of Autonomous Attitude Thrust Control for the Geostationary Operational Environmental Satellite (GOES)-8 Orbit Determination," presented at the Flight Mechanics/Estimation Theory Symposium, GSFC, May 16–18, 1995.