

## ANALYSIS OF EARTH ALBEDO EFFECT ON SUN SENSOR MEASUREMENTS BASED ON THEORETICAL MODEL AND MISSION EXPERIENCE\*

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Analysis of flight data from previous missions indicates that anomalous Sun sensor readings could be caused by Earth albedo interference. A previous Sun sensor study presented a detailed mathematical model of this effect. The model can be used to study the effect of both diffusive and specular reflections and to improve Sun angle determination based on perturbed Sun sensor measurements, satellite position, and an approximate knowledge of attitude. The model predicts that diffuse reflected light can cause errors of up to 10 degrees in Coarse Sun Sensor (CSS) measurements and 5 to 10 arc sec in Fine Sun Sensor (FSS) measurements, depending on spacecraft orbit and attitude. The accuracy of these sensors is affected as long as part of the illuminated Earth surface is present in the sensor field of view. Digital Sun Sensors (DSS) respond in a different manner to the Earth albedo interference. Most of the time DSS measurements are not affected, but for brief periods of time the Earth albedo can cause errors which are a multiple of the sensor least significant bit and may exceed one degree.

This paper compares model predictions with Tropical Rainfall Measuring Mission (TRMM) CSS measurements in order to validate and refine the model. Methods of reducing and mitigating the impact of Earth albedo are discussed. The CSS sensor errors are roughly proportional to the Earth albedo coefficient. Photocells that are sensitive only to ultraviolet emissions would reduce the effective Earth albedo by up to a thousand times, virtually eliminating all errors caused by Earth albedo interference.

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## INTRODUCTION

All Sun sensors are designed based on the assumption that only one bright object, i.e., the Sun, is present within the sensor field of view (FOV). Current Sun sensors cannot distinguish the effect of a single light source if several bright objects are simultaneously visible (discounting pattern recognition schemes that would not be practical for a relatively simple sensor). Therefore, it is expected that Earth albedo interference will degrade the accuracy of Sun Sensors. An analysis of Solar Maximum Mission flight data<sup>1</sup> provided indications that Fine Sun Sensor (FSS) measurements were affected by Earth albedo, but not a definite proof. Many other questions were also left unanswered. Is the accuracy of all Sun Sensors reduced by the Earth albedo interference? Is it possible to model and accurately quantify the effect of illuminated Earth on Sun Sensor measurements? A subsequent study by one of the authors<sup>2</sup> attempted to answer these questions by providing a detailed theoretical model of the Earth albedo effect on Coarse Sun Sensors (CSS), Digital Sun Sensors (DSS), and FSS. That study shows that all types of Sun sensors are adversely affected by the Earth albedo interference and predicts the accuracy degradation based on spacecraft, Earth and Sun positions, sensor boresight orientation, and sensor design data. For Coarse Sun Sensors (CSS), which are affected most, the theoretical model predicts measurement errors of up to 10 degrees.

The model has been tested before only for a few Sun, Earth, and spacecraft geometries. The goals of this study are to thoroughly test the model using Tropical Rainfall Measuring Mission (TRMM) flight data and then to determine whether the model could be used to increase the accuracy of CSS measurements. Coarse Sun Sensors were chosen as a benchmark due to their simplicity (their behavior can be predicted without a detailed knowledge of proprietary sensor design data) and significant response to Earth albedo interference. These CSS characteristics facilitate the testing of the model and the establishing of a procedure for improving the accuracy of CSS measurements. After being validated by application to the CSS, the procedure can be modified to include other Sun sensor types.

## MODELING THE EARTH ALBEDO EFFECT

The theoretical model of Earth albedo effect on CSS is discussed briefly here. For more details and for modeling other Sun sensors see Reference 2. The Earth albedo effect has to be determined numerically for each individual CSS eye. The Earth surface is divided into a set of area elements using a map-like grid (see Figure 1). An Earth surface element increases the intensity of the electric current produced by a CSS eye whenever the element is located on the illuminated side of the Earth, within the sensor FOV, and not beyond the spacecraft horizon. Surface elements with these characteristics will be called *active* (see Figure 2).

Define the model frame of reference as the Earth centered frame with axes parallel to the CSS eye axes. Mathematically, the three conditions that define an active element (the  $j^{\text{th}}$  element) can be expressed as follows:

$$X_j \cdot X_{Sun} + Y_j \cdot Y_{Sun} + Z_j \cdot Z_{Sun} \geq 0 \quad (\text{surface element is illuminated})$$

$$(X_j - X_c)^2 + (Y_j - Y_c)^2 - (Z_j - Z_c)^2 \tan^2 \left( \frac{FOV}{2} \right) < 0 \quad (\text{surface element within the FOV})$$

$$X_j \cdot X_c + Y_j \cdot Y_c + Z_j \cdot Z_c \geq R_{Earth}^2 \quad (\text{surface element is not beyond horizon})$$

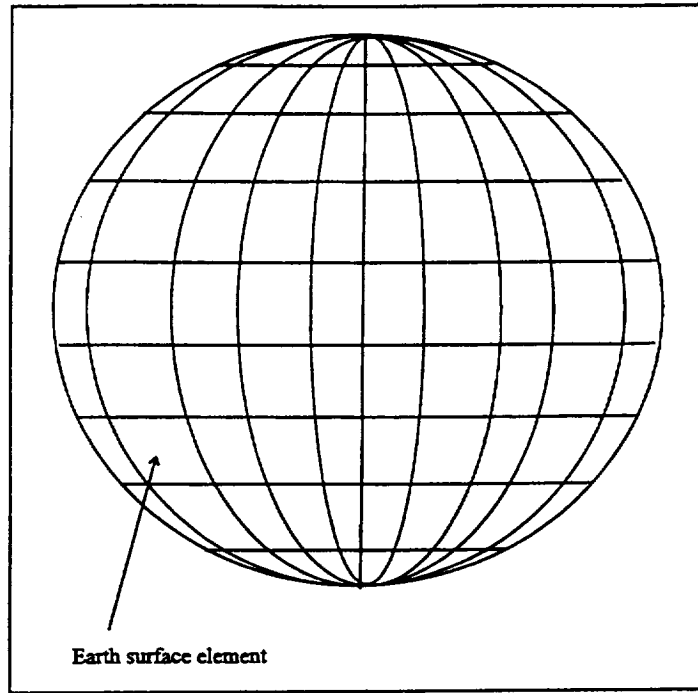


Figure 1. Surface Grid

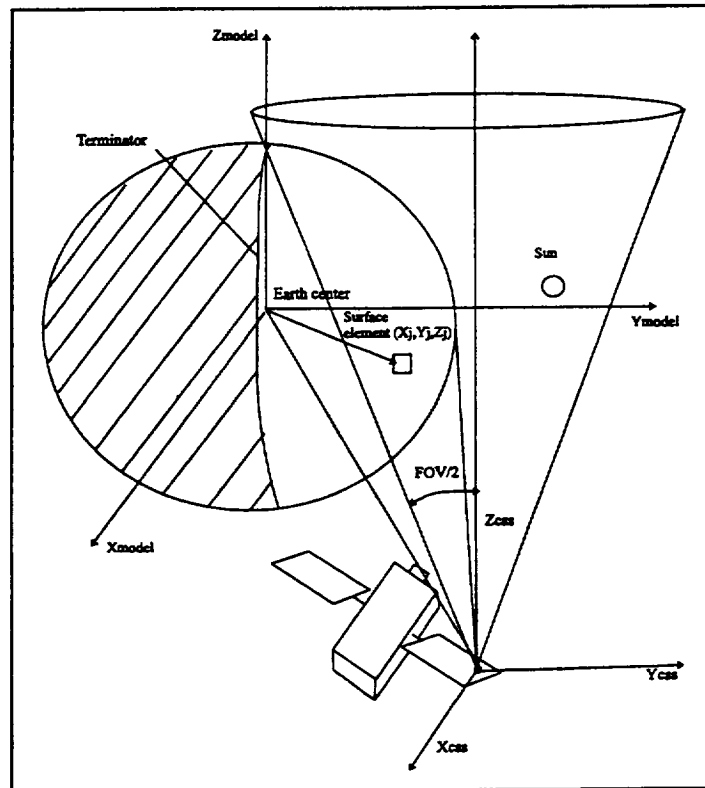


Figure 2. Spacecraft, Earth, and Sun geometry

where  $(X_c, Y_c, Z_c)$  is the CSS eye position,  $(X_{Sun}, Y_{Sun}, Z_{Sun})$  is the Sun vector, and  $(X_j, Y_j, Z_j)$  is the position of the  $j^{th}$  element, all in the model frame. The CSS FOV is a 160 deg cone.

Neglecting specular reflections, the light flux reflected by the  $j^{th}$  active element,  $\delta\phi_j^{(r)}$ , is given by

$$\delta\phi_j^{(r)} = A_j \phi_s S_j \cos u_j \quad (1)$$

where  $A_j$  and  $S_j$  are the albedo coefficient and surface area of the active element, respectively,  $\phi_s$  is the incident solar flux, and  $u$  is the angle between the normal to the surface element and the Sun direction. This light is reflected within a solid angle of  $2\pi$  steradians (half-sphere). The perturbation flux due to the  $j^{th}$  active element,  $\delta\phi_j$ , is given by

$$\delta\phi_j = \frac{\delta\phi_j^{(r)}}{2\pi[(X_c - X_j)^2 + (Y_c - Y_j)^2 + (Z_c - Z_j)^2]} \quad (2)$$

In general, the electric current,  $I$ , produced by a bright object in the sensor FOV is

$$I = K\phi \cos \alpha \quad (3)$$

where  $K$  is a sensor constant,  $\phi$ , is the light flux detected by the solar sensor and  $\alpha$  is the angle between the sensor boresight and the bright object direction. So, the perturbation flux produces a perturbation current,  $I_j$ , given by

$$I_j = K\delta\phi_j \cos \alpha_j \quad (4)$$

where,  $\alpha_j$  is the angle between the eye boresight and the area element direction. Therefore, the maximum current expected from the CSS eye photocell,  $I_0$ , is

$$I_0 = K\phi_s \quad (5)$$

Based on Eq. (3), the current due to the Sun can be expressed as

$$I_s = K\phi_s \cos \alpha_s \quad (6)$$

where  $\alpha_s$  is the Sun angle (i.e., the angle of interest between the boresight and Sun direction).

Due to the Earth albedo effect, the total current provided by the CSS eye photocell,  $I_{total}$ , is

$$I_{total} = I_s + \sum_{j=1}^n I_j \quad (7)$$

where  $n$  is the total number of active elements. Equations (4), (6), and (7) show that

$$I_{total} = K \left( \phi_s \cos \alpha_s + \sum_{j=1}^n \delta\phi_j \cos \alpha_j \right) \quad (8)$$

Assuming the only bright object present within the sensor FOV is the Sun, Eqs. (5) and (6) show that the Sun angle is given by

$$\alpha_s = \text{acos}\left(\frac{I_s}{I_0}\right) \quad (9)$$

Unfortunately, Eq. (9) is always used to calculate the Sun angle, even when other bright objects are present within the field of view. Therefore, the angle  $\alpha'_s$  calculated using  $I_{total}$  is not the true Sun angle but a perturbed value:

$$\begin{aligned} \alpha'_s &= \text{acos}\left(\frac{I_{total}}{I_0}\right) = \text{acos}\left(\frac{K\left(\phi_s \cos \alpha_s + \sum_{j=1}^n \delta\phi_j \cos \alpha_j\right)}{K\phi_s}\right) \\ &= \text{acos}\left(\cos \alpha_s + \sum_{j=1}^n \frac{A_j S_j \cos u_j \cos \alpha_j}{2\pi[(X_j - X_c)^2 + (Y_j - Y_c)^2 + (Z_j - Z_c)^2]}\right) \end{aligned} \quad (10)$$

The difference,  $\delta\alpha_s$ , between the true Sun angle and the CSS eye measurement thus is given by

$$\delta\alpha_s = \alpha_s - \alpha'_s = \alpha_s - \text{acos}\left(\cos \alpha_s + \sum_{j=1}^n \frac{A_j S_j \cos u_j \cos \alpha_j}{2\pi[(X_j - X_c)^2 + (Y_j - Y_c)^2 + (Z_j - Z_c)^2]}\right) \quad (11)$$

According to the above theoretical model, Eq. (10) should accurately predict the Earth-induced current whenever the albedo coefficient of each active element is known. However, the local albedo coefficients are strongly dependent on weather conditions over large regions (but not so large that a global average is sufficient). Even using advanced weather monitoring and prediction systems, creating and maintaining a database of local albedo coefficients would be a formidable undertaking. The simplest approach is to replace the local albedo coefficient everywhere with a constant value,  $a$ , and replace Eq. (10) with

$$\begin{aligned} \alpha'_s &= \text{acos}\left(\frac{I_{total}}{I_0}\right) \\ &= \text{acos}\left(\cos \alpha_s + a \cdot \sum_{j=1}^n \frac{S_j \cos u_j \cos \alpha_j}{2\pi[(X_j - X_c)^2 + (Y_j - Y_c)^2 + (Z_j - Z_c)^2]}\right) \end{aligned} \quad (12)$$

Then the Sun angle error is approximately

$$\delta\alpha_s = \alpha_s - \alpha'_s \approx \alpha_s - \text{acos}\left(\cos \alpha_s + a \cdot \sum_{j=1}^n \frac{S_j \cos u_j \cos \alpha_j}{2\pi[(X_j - X_c)^2 + (Y_j - Y_c)^2 + (Z_j - Z_c)^2]}\right) \quad (13)$$

The average albedo coefficient of active areas and the average albedo coefficient of the entire Earth<sup>3</sup> (i.e., 0.30) can be quite different. Therefore, model predictions based on the average Earth albedo can be quite inaccurate. Nonetheless, the model was tested by comparing TRMM flight data with predictions based on Eq. (12) using the average Earth albedo coefficient. The following sections present more detail.

## THE TROPICAL RAINFALL MEASURING MISSION

TRMM is one of a series of National Aeronautics and Space Administration (NASA) missions designed for the study of the Earth as a dynamical system. TRMM is a joint project between NASA and the National Space Development Agency (NASDA) of Japan. The TRMM instruments will determine the rate and total amount of rainfall occurring over the tropics and subtropics (from latitude 35 S to 35 N).

The TRMM spacecraft was launched on November 27, 1997 onboard a NASDA H-II launch vehicle. The nominal orbit is circular with an altitude of 350 km and an inclination of 35 deg. The attitude is three-axis stabilized and Earth-pointing. Primary attitude sensors include a Barnes static Earth sensor, a Kearfott inertial reference unit, two Adcole digital Sun sensors, and two three-axis magnetometers. The nominal attitude determination accuracy is 0.2 deg per axis ( $3\sigma$ ). The required control accuracy is 0.4 deg ( $3\sigma$ ) with stability of 0.1 deg/sec.

TRMM is equipped with eight CSS eyes.<sup>4</sup> Two eyes (numbers 1 and 2) are located on solar panel 1; another two (numbers 5 and 6) are on solar panel 2. The boresight directions of eyes 1, 2, 5, and 6 in the solar panel frame of reference are given in Table 1. The other eyes are located on the body and their boresights in the body frame are given in Table 2.

**Table 1. Boresight directions of CSS eyes located on solar panels**

CSS eye number	1	2	5	6
Boresight unit vector	0.773372 -0.168597 -0.6111227	-0.2820903 -0.6468678 -0.7085105	-0.2796423 0.8598846 -0.42708166	0.7697018 0.3757137 -0.5161380

**Table 2. Boresight directions of CSS eyes located on the satellite body**

CSS eye number	3	4	7	8
Boresight unit vector	0.7625562 0.5507738 -0.3393467	-0.96013227 0.27954134 -0.00163112	0.3369986 -0.8775453 -0.3410957	-0.96013227 0.27954134 -0.00163112

## BIAS ESTIMATION

Before comparing measured and predicted CSS output currents, some account must be made for sensor calibration errors. In particular, separate biases need to be determined for each CSS eye. Systematic sensor errors can arise from a number of physical causes. A bias in the measured current shifts the cosine of all angles by the same amount; whereas, an error in the maximum current,  $I_0$ , is a scale error that changes the cosines all by the same fraction. A misalignment will show up as a shift in the angles that depends on the location of the Sun in the field of view.

A simplification occurs for the CSS eyes that are mounted on the solar array panels. For these eyes, the Sun remains at nearly a constant angle throughout the sunlit part of the orbit. In this case, all the calibration parameters can be absorbed into a single bias; separate bias, scale factor, and misalignment parameters cannot be distinguished without observing the Sun over a range of angles in the CSS frame. This study analyzes these solar panel mounted eyes only.

For each eye, a bias was determined using only data from that part of the orbit where the predicted Earth albedo interference was less than 0.02 deg. These measurements have essentially no Earth interference so the difference between the measured and the expected CSS current can be attributed to sensor bias. Table 3 shows the biases obtained by averaging this difference over all points where the Earth interference is negligible. The fourth column in Table 3 indicates the scatter of observations. This scatter contributes an angular uncertainty proportional to the bias standard deviation divided by  $\sin \theta$ . (Angular sensitivity is worst when observing near the boresight.) At  $\theta = 45$  deg, an error of 0.006 corresponds to an angular uncertainty of about 0.5 deg.

Table 3 shows bias values obtained using a data set consisting of one orbit from Feb. 22, 1998. Biases recalculated using another data set from Mar. 10, 1998 differ by less than 0.02  $I_0$ .

**Table 3. TRMM CSS Biases for Selected Solar Array Mounted Eyes**

CSS Eye	Number of Points	Bias ( $\Delta I / I_0$ )	Std. Dev. of Bias
1	245	-0.0743	0.00662
5	77	-0.0895	0.0230
6	355	-0.0707	0.00643

## EVALUATION OF ERRORS

Tests with different grid sizes (see Figure 1) were performed. The total number of grid cells ranged from 7200 to 7,372,800 in these tests. The grid selected for the TRMM analyses had 115,200 cells. This discretization leads to numerical errors of no more than 0.00004  $I_0$ .

The measurement residual,  $r$ , which is the sensor error after compensating for bias and predicted Earth albedo effect, is

$$r = \alpha'_s - \alpha_{m,c} \quad (14)$$

where  $\alpha_{m,c}$  is the measured sensor output corrected only for bias, and  $\alpha'_s$  is the predicted CSS output corrected for albedo interference.

Uncompensated for Earth albedo, the sensor error is

$$e = \alpha_{m,c} - \alpha_{ref} \quad (15)$$

where  $\alpha_{ref}$  is the reference Sun angle, uncorrected for bias or Earth interference. The residual  $r$  and error  $e$  are displayed in the plots presented below as sensor errors either corrected or uncorrected for Earth albedo interference; the measured angle in both cases is  $\alpha_{m,c}$  so both  $r$  and  $e$  are corrected for sensor bias.

## NUMERICAL APPROACH

Based on TRMM telemetry, Sun and spacecraft position vectors in the geocentric inertial reference frame (GCI) were calculated every other second using a set of MATLAB 4.2 scripts. These vectors were rotated from GCI into the model frame using another MATLAB script. A FORTRAN code was then used to determine the reference Sun angle and predicted CSS output every other second. CSS biases and resulting statistics were calculated using MathCAD 6.0.

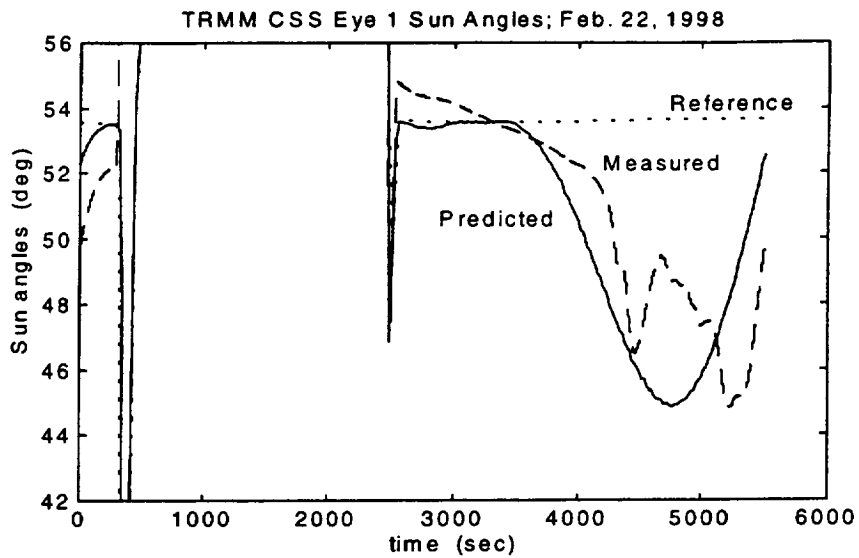
## RESULTS AND DISCUSSION

The CSS eyes that were analyzed are those subject to Earth interference for extended periods of time. These were eyes 1, 5, and 6. Figure 3 shows the reference  $\alpha_{ref}$  (dotted line), predicted  $\alpha'_s$  (solid line), and measured sensor output  $\alpha_{m,c}$  (dashed line) for eye 1 based on the Feb. 22, 1998 data set. The predicted sensor output was calculated using the average Earth albedo coefficient. The value of  $\alpha_{ref}$  is nearly constant since the CSS eye is mounted on the solar array which follows the Sun.

A large discrepancy between the measured and predicted angles is apparent in Figure 3 from  $t = 300$  to 600 seconds. This occurs because the model in this prototype version of the code does not take into account Sun occultations by the Earth.

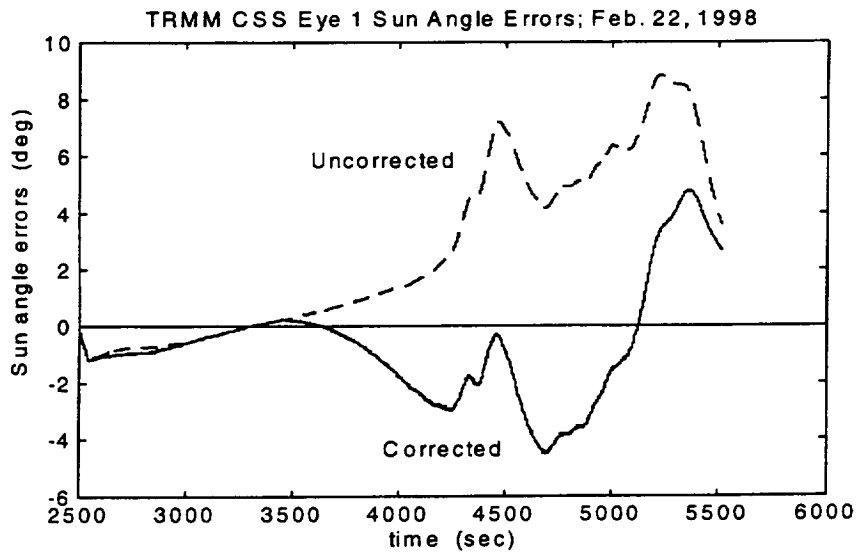
Differences between the reference Sun angle and the measured sensor output seen in Figure 3 are due to Earth albedo interference. The sensor output and the reference angle agree within the measurement uncertainty due to bias scatter (roughly 1 deg) except from 0 to 250 sec and from 3500 to 5500 sec. These are the time intervals when the Earth interference is significant and are accurately predicted by the model. For these intervals, the predicted curve is smooth while the measured curve shows abrupt changes. This qualitative difference is due to using Eq. (12) instead of (10), i.e., assuming a constant albedo coefficient. In reality this coefficient varies from one Earth area to another; the local albedo coefficient can vary from 0.05 to 0.6.<sup>3</sup> As a consequence, the predicted and measured output differ by up to 5 deg (at  $t = 4700$  sec). Nevertheless, the predicted and measured angles show similar overall trends. According to both measured and predicted CSS output, Earth albedo interference causes errors of up to 10 deg (from 4500 to 5500 sec).





**Figure 3. Reference, predicted, and measured Sun angles for CSS eye 1; Feb. 22, 1998 (albedo coefficient = 0.30)**

The eye 1 errors before and after compensating for predicted Earth albedo effect are shown in Figure 4. For this orbit, model predictions based on the average Earth albedo coefficient provide a significantly better CSS accuracy. After compensating for the Earth albedo effect, the average CSS error is 0.5 deg with a RMS of 2.1 deg. Without compensation, the average error is 2.6 deg with a RMS of 3.9 deg. The maximum error is reduced from 9 deg to 5 deg.



**Figure 4. CSS eye 1 errors for Feb. 22, 1998, corrected and uncorrected for Earth interference (albedo coefficient = 0.30)**

Figure 5 shows the reference, predicted, and measured Sun angles for eye 5. The same February 22 data set was used here as for Figures 3 and 4. Again, the model accurately predicts the time intervals when the CSS eye is exposed to Earth albedo interference (i.e., roughly from 0 to 100 seconds and from 2600 to 5500 seconds); the overall shape of the predicted sensor output also is approximately correct. The predicted and measured outputs differ by up to 2 deg.

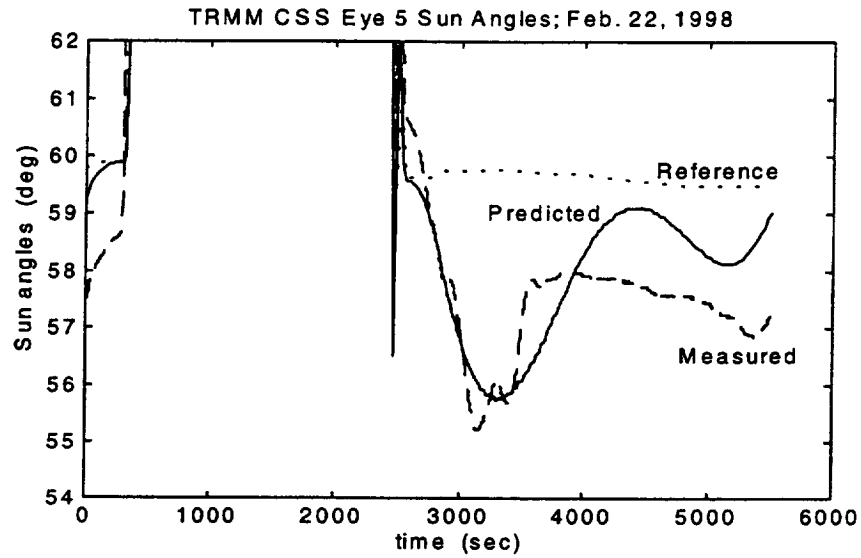


Figure 5. Reference, predicted, and measured Sun angles for CSS eye 5; Feb. 22, 1998 (albedo coefficient = 0.30)

The eye 5 errors before and after applying the model corrections are shown in Figure 6. Using the average Earth albedo, the model reduces the CSS average error from 2.0 deg to 0.49 deg and the RMS error from 2.3 to 1.0 deg. The maximum error is reduced from 5 to 2 deg.

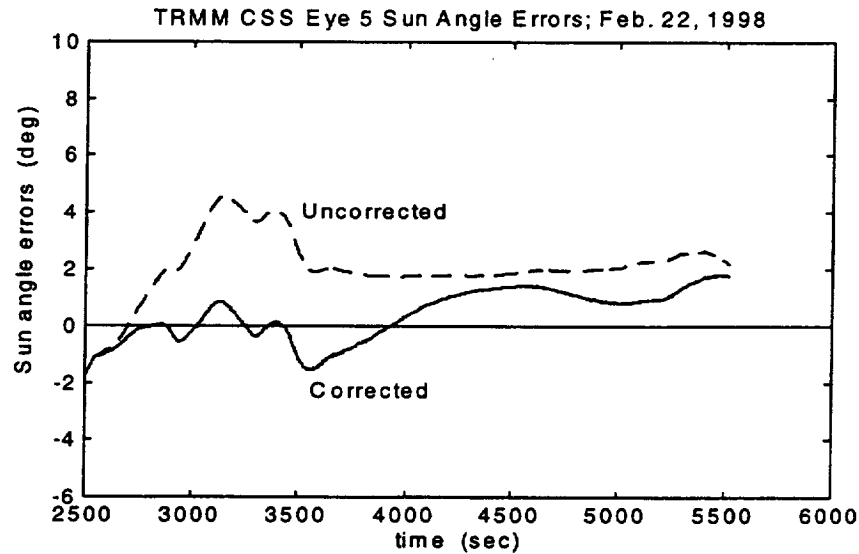


Figure 6. CSS eye 5 errors for Feb. 22, 1998, corrected and uncorrected for Earth interference (albedo coefficient = 0.30)

For eye 6, the reference, predicted, and measured Sun angles are shown in Figure 7. As before, the model and reference angles differ at the start of the Sun occultation period. Eye 6 is affected by the Earth albedo from 0 to about 100 seconds and from 3800 to 5500 seconds. The Earth interference periods are accurately predicted. The predicted sensor response again is only qualitatively correct because the average Earth albedo coefficient is used. The eye 6 errors before and after accounting for the Earth albedo interference are shown in Figure 8. The model reduces the maximum error from 7 to 4.0 deg. The average error decreases from 1.7 deg to 0.67, and the RMS decreases from 3.0 to 1.8 deg.

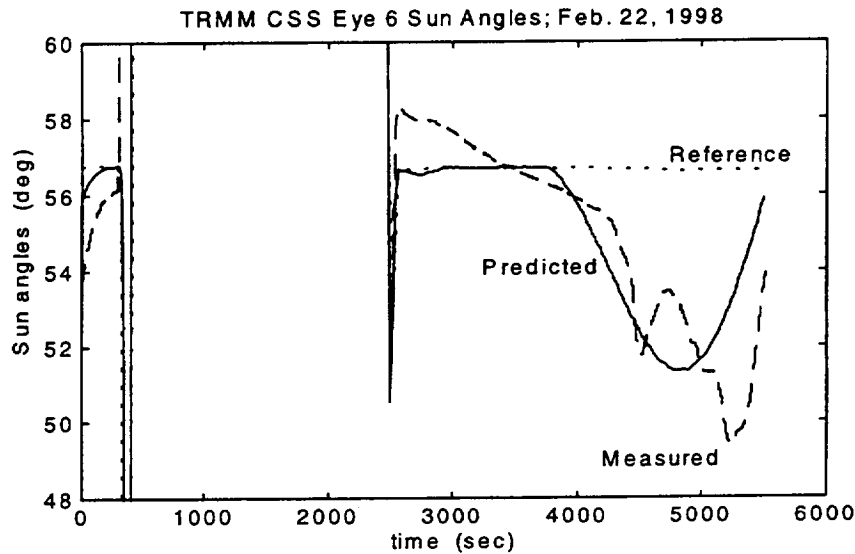


Figure 7. Reference, predicted, and measured Sun angles for CSS eye 6; Feb. 22, 1998 (albedo coefficient = 0.30)

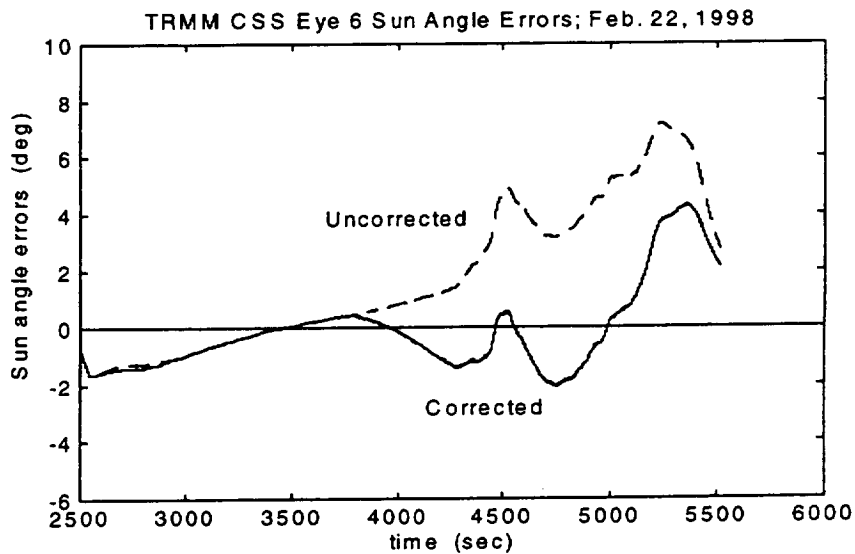
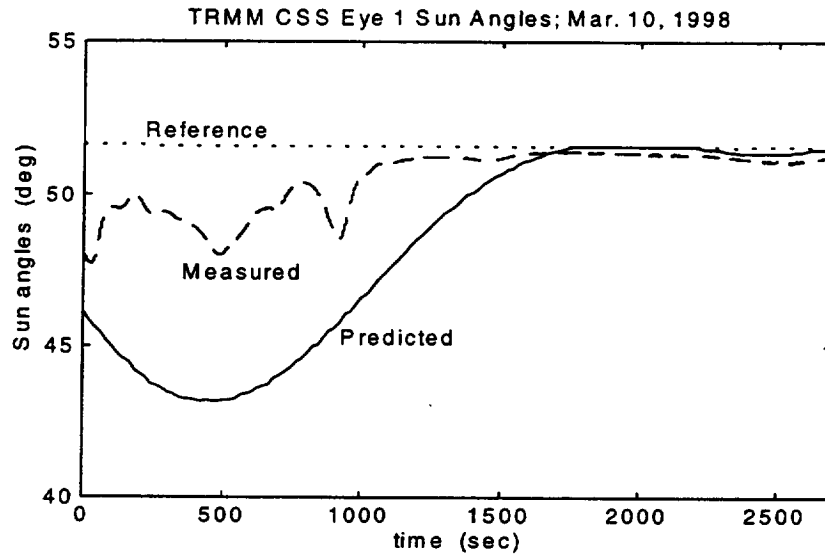


Figure 8. CSS eye 6 errors for Feb. 22, 1998, corrected and uncorrected for Earth interference (albedo coefficient = 0.30)

At other times, as shown by analyzing a March 10, 1998 data set, model predictions based on the average Earth albedo coefficient may over-correct the CSS, actually increasing the sensor error. Figure 9 shows reference, predicted, and measured angles for eye 1. The interference time spans are accurately predicted, as usual. Nevertheless, between 0 and 1000 seconds the predicted and measured sensor output differ by more than 7 deg, while the average uncorrected sensor error is less than 4 deg. Overall, the model correction based on the average Earth albedo coefficient increases the average eye 1 error from 1.0 to 2.0 deg and the RMS from 1.8 to 3.0 deg.



**Figure 9. Reference, predicted, and measured Sun angles for CSS eye 1; Mar. 10, 1998 (albedo coefficient = 0.30)**

This increased error is not due to an error in the model itself. Rather, the adverse effect is due the assumption that the average albedo of active areas and the average Earth albedo are equal. The altitude of TRMM is about 350 km, which means that during an entire orbit, a swath of about 16% of the entire Earth area is visible. This is a large area and therefore great albedo variations should be expected. The average error can be reduced to 0 by taking the average albedo for the active areas to be 0.105 instead of 0.30 (see Figure 10). The maximum error then is 1.5 deg and the RMS is 0.94 deg. Finding the optimum coefficient, i.e., the albedo coefficient that provides an average corrected error of 0, improves the maximum error and the RMS as compared to the correction based on a global average value of 0.30. This optimum value improves the CSS measurements at all times that were analyzed. The optimum albedo coefficient can be easily determined a posteriori. Unfortunately, a cost-effective and general method of determining it a priori, i.e., before the CSS measurements are made, is not available. For the most accurate results, Eq. (10) should be used. This method requires a detailed database containing the albedo coefficients of thousands of Earth surface elements that is frequently updated using accurate weather input. Such an approach would be difficult and expensive.

## CONCLUSIONS

The model presented here accurately predicts the time intervals when Earth albedo affects Sun sensor measurements. Regardless of the Earth albedo coefficient that is used, the model

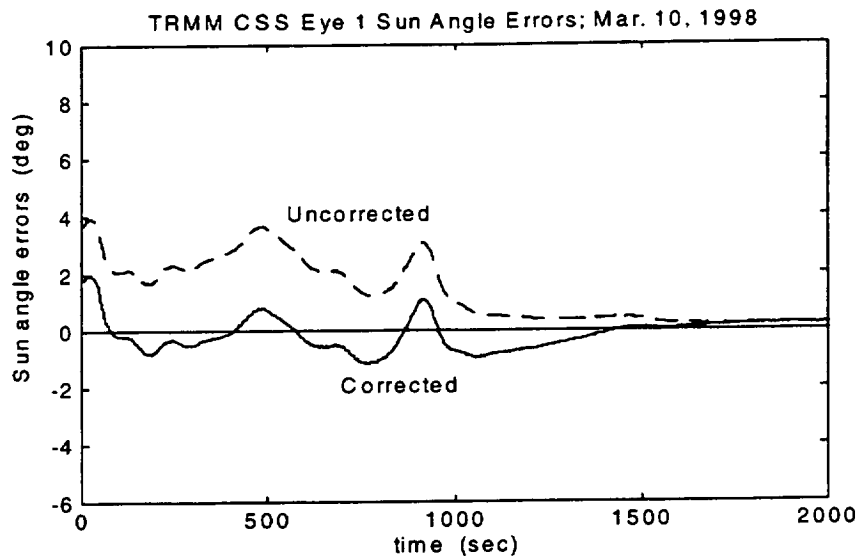


Figure 10. CSS eye 1 errors for March 10, 1998, corrected and uncorrected for Earth interference (albedo coefficient = 0.105)

provides a good qualitative prediction of Earth interference. In general, the model predictions based on the average Earth albedo coefficient increase the CSS accuracy. Nevertheless, there are times when this method severely over-corrects the sensor and reduces accuracy. The optimum albedo coefficient improves the accuracy of CSS measurements at all times, but it is not clear how to determine it a priori. The best Earth interference predictions could be made by maintaining a detailed database of local albedo values.

This study shows that the straightforward method of predicting Earth interference using a global mean albedo coefficient is insufficiently accurate. An albedo database adequate to improve matters is not readily available. A far more reasonable approach, as mentioned in previous studies,<sup>1</sup> is to reduce the effect of Earth interference in the first place by using a filter. Earth albedo is very low for several ranges of ultraviolet and infrared radiation. If the filter restricts the sensor sensitivity to such a range, the Earth albedo becomes negligible relative to the Sun. All types of Sun sensors could benefit from such a design modification.

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