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A Simple Method for Verifying the Deployment of the TOMS-EP Solar Arrays

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Abstract

The Total Ozone Mapping Spectrometer-Earth Probe (TOMS-EP) mission relies upon a successful deployment of the spacecraft's solar arrays. Several methods of verification are being employed to ascertain the solar array deployment status, with each requiring differing amounts of data. This paper describes a robust attitude-independent verification method that utilizes telemetry from the coarse Sun sensors (CSSs) and the three-axis magnetometers (TAMs) to determine the solar array deployment status—and it can do so with only a few, not necessarily contiguous, points of data.

The method developed assumes that the solar arrays are deployed. Telemetry data from the CSS and TAM are converted to the Sun and magnetic field vectors in spacecraft body coordinates, and the angle between them is calculated. Deployment is indicated if this angle is within a certain error tolerance of the angle between the reference Sun and magnetic field vectors. Although several other methods can indicate a non-deployed state, with this method there is a 70-percent confidence level in confirming deployment as well as a nearly 100-percent certainty in confirming a non-deployed state. In addition, the spacecraft attitude (which is not known during the first orbit after launch) is not needed for this algorithm because the angle between the Sun and magnetic field vectors is independent of the spacecraft attitude. This technique can be applied to any spacecraft with a TAM and with CSSs mounted on the solar array(s).

Introduction

The TOMS-EP will be launched into a 340.5 x 964.9 km polar orbit with an inclination of 99.3 degrees. The final mission orbit will be at 955 km after a series of orbit-raising maneuvers. Upon being inserted into its initial preliminary orbit, the TOMS-EP spacecraft (Fig. 1) is to unfold its solar arrays and begin generating power from the incoming solar radiation. Since the spacecraft does not have an indicator in telemetry for solar array deployment, ground solutions to verify the status have been developed by the TOMS-EP Flight Support Team (FST). These solutions were originally divided into three verification paths: a power path (looking at battery voltage and current), a gyro path (looking at the change in spacecraft rotation due to solar array deployment), and a coarse Sun sensor path (using CSS to calculate Sun vector to determine array status). Of particular interest to the authors was the coarse Sun sensor path.

Any method of verifying deployment with the CSSs requires knowledge of the array and CSSs' geometry. The axis of the solar arrays are aligned along the spacecraft pitch (Y) axis. They are rotated, however, into a paddle wheel configuration with the offset being 45 degrees. This was done to maximize energy gathering over the entire orbit. The CSSs are physically attached to the arrays in a manner such that their boresights are 45 degrees off the plane of the arrays. The result is that the boresights are perpendicular to the roll (X) axis and 45 degrees away from the pitch (Y) and yaw (Z) axes (Figure 2). If the arrays are fully deployed, the Sun can be detected in two adjacent CSS; in one CSS, if the Sun is directly aligned with the boresight; or no CSS if the Sun is perfectly aligned with positive or negative roll axis. Consequently, this means that the Sun cannot be detected by CSS2 and CSS4 at the same time, nor CSS1 and CSS3. The sensors, in effect, are domes reporting the

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angle of the Sun up from the base of the dome. With this angle, a circle of solutions are identified which is a circle parallel with the base of the

Figure 1 - TOMS-EP Spacecraft

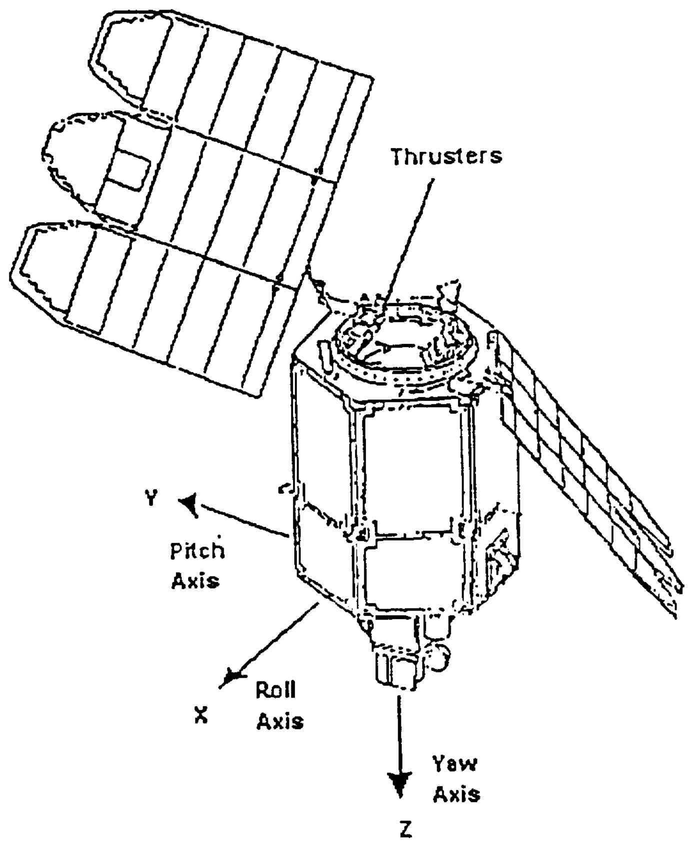
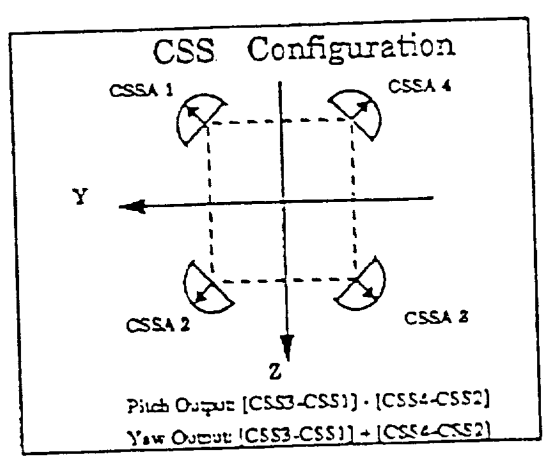


Figure 2 - CSS Numbering and Alignment



dome. By using the reported angles from two coarse Sun sensors, the circles of solutions will intersect in two places, thereby creating an ambiguity. This ambiguity will be discussed as it relates to determining the deploy and non-deploy status of the solar arrays.

The coarse Sun sensor path initially developed for the mission has several levels of verification that can be employed. The initial check just uses the aforementioned knowledge of the CSS and solar array geometry to determine if the panels are stowed. The second level of verification utilizes a Sun vector solution which relies on two CSSs having Sun presence. Within a certain accuracy, it can determine the solar array status for the fully stowed and four partially deployed cases. The fully deployed case must rely upon TAM or power data to obtain a deterministic solution. This method, however, needs approximately 7 to 8 minutes of CSS data to converge on a solution with a 95% success rate for the stowed and partial configurations. This necessity of a significant span of data at the very first pass was the impetus for the authors to search for a verification method that needed fewer data points.

This solution capitalizes on the attitude independent relationship between the Sun vector and the magnetic field vector. The Sun vector can be computed by using CSS measurements while the magnetic field vector is obtained from the TAM. Both measurements are resolved in the body coordinate system so the angle between the vectors can be computed using their dot products. This angle can then be compared to the angle between the corresponding reference Sun and magnetic field vectors. Though the reference vectors are in Geocentric Inertial Coordinates (GCI), the angle between them is independent of the specific coordinate system. The reference angle and observed angle can then be compared. Within a specified error tolerance, it can be ascertained whether the solar arrays are deployed or not.

Operational Scenario

Shortly after TOMS-EP's separation from the Pegasus, and the spacecraft processor (SP) wake-up, the stored commands for solar array panels deployment are activated. As noted earlier, there is no indicator available in the to directly verify panel deployment. Additionally, since the spacecraft is in shadow, there is no Sun position data available from the coarse Sun sensors (CSS) which are located on the outer corners of the solar panels. Since the verification method utilizes the Sun data from the CSSs, it is not until the spacecraft exits the shadow and telemetry data from the CSSs becomes available that the procedure can be performed. The first ground contact opportunity for the spacecraft becomes available approximately twenty minutes after insertion. This pass over the McMurdo ground station lasts for nearly 12 minutes. Depending on the day of the year when the launch takes place, the spacecraft could still be in the shadow for at least a portion of the contact period at McMurdo. The verification will be performed again at the Indian Ocean-Seychelles (IOS) pass which occurs approximately forty six minutes after orbit insertion. If the data from this method and the other paths do not indicate proper deployment with a high degree of confidence, the onboard computer (OBC) can be commanded to the redundant side to reattempt the solar array deployment process.

Solar Array Deployment Verification Algorithm

As mentioned previously, the solar array deployment verification algorithm uses the fact that the angle between two vectors is independent of the reference coordinate system. It does require, however, that the sensors measurements be resolved in the same coordinate system. The procedure for this algorithm is very simple but that is essential to its inherent robustness and versatility.

The algorithm begins by computing the reference angles (in GCI coordinates) between the Sun vectors and the Earth's magnetic field vectors for the time span in question. For this application, it would be the span of the McMurdo pass. These Sun vectors are obtained by using the Solar, Lunar, Planetary (SLP) ephemeris tables. The magnetic field vectors are computed with an 8th order estimate of the Earth's magnetic field using a spacecraft ephermeris as input. A simple dot product calculation determines the GCI reference angle as a function of time.

$$\theta_{ref} = \operatorname{acos}(\hat{S}_I \bullet \hat{B}_I)$$

where:

$\hat{S}_I$ = reference Sun vector

$\hat{B}_I$ = reference magnetic field vector

In a similar manner, telemetered observations of the solar array mounted CSS and the body mounted TAM are used to calculate the observed angle between the Sun vector and Earth's magnetic field (in spacecraft body coordinates). It should be noted that the computation of the observed Sun vector in spacecraft body coordinates has a built in assumption that the solar arrays have deployed properly.

$$\theta_{obs} = \operatorname{acos}(\hat{S}_B \bullet \hat{B}_B)$$

where:

$$\hat{S}_B = \begin{bmatrix} \sqrt{1 - \frac{1}{255^2}(I_1^2 + I_2^2 + I_3^2 + I_4^2)} \\ \frac{1}{255\sqrt{2}}(I_1 + I_2 - I_3 - I_4) \\ \frac{1}{255\sqrt{2}}(-I_1 + I_2 + I_3 - I_4) \end{bmatrix}$$

and

I_i = CSS cell currents for i = 1 to 4 (0 < I < 255)

$\hat{B}_B$ = unitized measured magnetic field vector (computed from TAM data)

Differences between the observed and reference angles which are greater than an expected tolerance indicate that the solar arrays have not deployed properly. The tolerance is a function of sensor accuracy, spacecraft position errors, timing errors etc...

$$\theta_{obs} - \theta_{ref} < \varepsilon$$

The following section addresses the above errors as well as the interpretation of the algorithm results.

Interpretation of Solar Array Deployment Algorithm Output

In performing the angular separation comparison between the reference and observed vectors, error in the observation must be considered. Therefore, the angular separations should not be expected to be exactly the same, but should differ within some error tolerance. The total error is relatively large, which significantly affects the interpretation of the results. There are several error sources that are considered for this solar array deploy check method: the measurement uncertainty for the CSS and the TAM, the error associated with the magnetic field model, time variations between TAM and CSS readings, as well as in the orbit arc, and finally the error associated with the true spacecraft orbit.

The dominant error source is the measurement uncertainty for the CSS, which is 10 degrees. This value is conservative as it results mostly from a "Sunrise" effect. This "Sunrise" effect, or time just after end of shadow, has been shown to create an error as large as 5 degrees for currently flying spacecraft with a similar orbit and CSS. However, only 2 seconds later , this effect shrinks to a value on the order of 0.1 degrees.

The measurement uncertainty for the TAM, which includes all biases and misalignments, is assumed to be 2 degrees. The uncertainty in the reference magnetic field is 1 degree.

The error associated with time corresponds to the fact that there could be a 4 or 5 second error in the Flight Dynamics Facility's (FDF) time correction as well as a 13 second time error in the CSS current data (the observed Sun vector/TAM vector/clock time may be separated by up to 13 seconds). Furthermore, at McMurdo, 1 degree of orbit arc error corresponds to roughly 2° of magnetic field error; at IOS, which is far from the poles, there is about 1.5 degree of magnetic field error for every 1 degree of orbit arc error. The spacecraft moves roughly 1 degree of orbit arc in 18 seconds and 0.5 degrees in 9 seconds. Resultingly, the error at McMurdo could be 2 degrees while at IOS it could be 1.5 degrees.

Finally, there is an error associated with uncertainty in the spacecraft ephemeris. The ephemeris generated for TOMS-EP is based on the insertion vector supplied by the launch site; hence the accuracy of the predicted orbit depends on the accuracy of the insertion vector. Off nominal injections, of course, would yield much larger errors. If there is no data available from the launch vehicle, FDF will know ahead of time, and will consequently know that this check is not at all accurate. Analysis indicates that TOMS-EP may see a maximum of 1 degree along track error in the predicted ephemeris. Using the computation mentioned in the above paragraph, this would mean an additional error of 2 degrees in the magnetic field model at McMurdo and 1.5 degrees at IOS.

The error budget associated with the solar array deploy verification is shown in Table 1 with total error being 17 degrees. The interpretation of the absolute difference between the observed and reference angles as it applies to the solar array deploy status is explored in the ensuing sections.

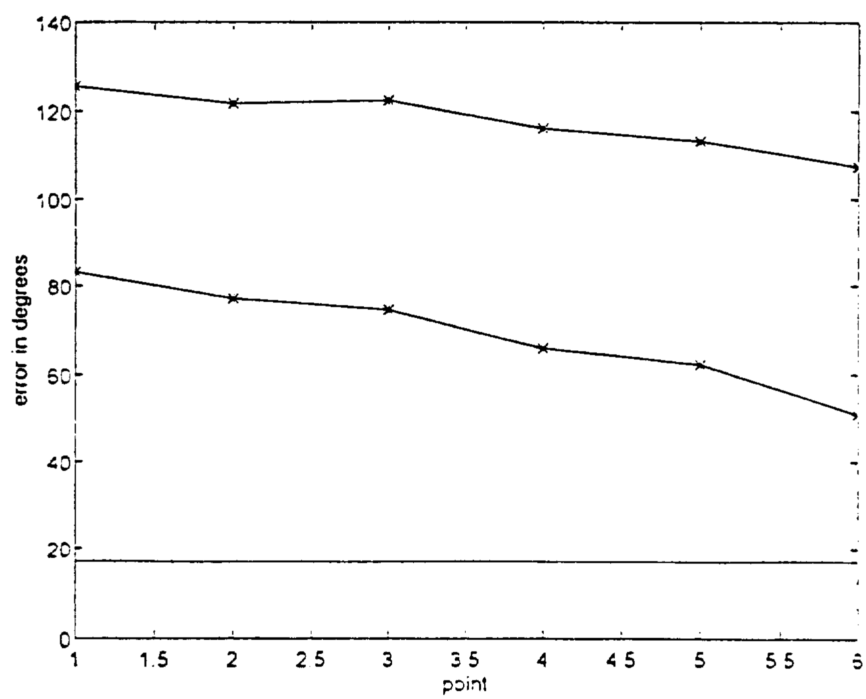
VERIFYING A NON-DEPLOY

If one or more of the sampled observations minus the expected, for both sets of sets of angles (noting the ambiguity in the CSSs), lies outside the 17 degree error budget, the solar arrays cannot be fully deployed (Figure 3). It is important to note which CSSs are reporting that they see the Sun. By nature of their fully deployed configuration, two, one, or none CSSs can see the Sun at any given time. If more than two see the Sun then the arrays are not fully deployed. If two, and only two, see the Sun throughout the pass, and the error is outside the 17 degree budget, then a non-deploy can only be reported for the solar panel, or portions of both panels that houses those CSSs. The complete picture can be determined if all 4 CSSs see the Sun (in sets of two) during the pass. If samples fall outside the error budget for each pair of CSSs, neither of the arrays deployed completely.

Table 1 - Error Budget

Source	Error (degrees)
CSS Measurement Uncertainty	10
TAM Measurement Uncertainty	2
Magnetic Field Model Error	1
Ground Telemetry Time Error	2
Spacecraft Ephemeris Error	2
Total Error	17

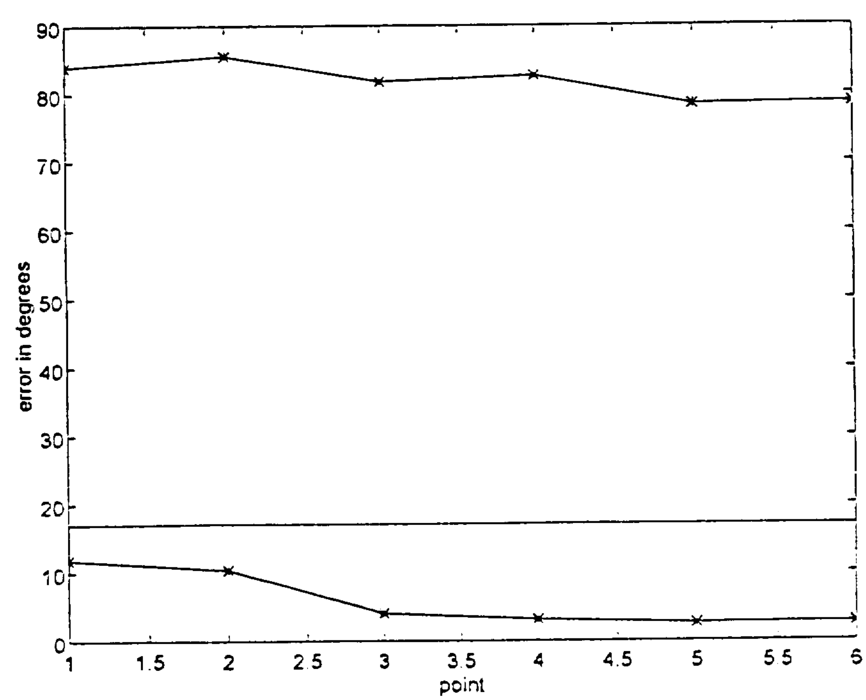
Figure 3 - Reference - Observed for Non-Deploy Case



VERIFYING A DEPLOY

Although the converse of the above section is not necessarily true, some conclusions can be drawn with some level of confidence. If all observations lie within the error budget, for one or both sets of angles (again, noting the ambiguity in CSSs), there is a good chance that the solar array(s) are deployed, again dependent on which CSSs are reporting Sun presence. Analysis has been performed to investigate when a likely non-deployed situation (includes one or more detonator failures) can look like a deploy, i.e. if the angle under consideration could still match the predicted within 17 degrees[2]. Even if it's the improper choice for ambiguity resolution, as there is no way to tell during this check, it would still falsely appear as a deploy. The investigation showed that a deploy can be correctly reported 70% of the time. These odds improve when several points can be taken throughout the pass and compared, and all lie within the 17 degree budget. Also, this study showed that if the spacecraft incurs a rate of rotation, which TOMS-EP is likely to have at injection, the likelihood of a non-deployed state reporting an error less than 17 degrees through the pass is more remote still.

Figure 4 - Reference - Observed for Deploy Case



Analysis and Simulation Results

The work performed by N. Tull [2] ran through a sphere of possible Sun and magnetic field vectors. These were input into the solar array deployment algorithm to not only determine the percentage of deploy and non-deploy confirmations, but also to gain confidence in the algorithm itself. In addition to this analysis to confirm the algorithm's performance, the deployment algorithm has been used in TOMS-EP simulations with success. Several minutes after the McMurdo pass was completed, the Flight Dynamics facility was able to determine, to a high degree of confidence, if the arrays were deployed. Through the simulations, the procedures for implementing the algorithm were tested and refined.

Summary

The solar array deployment algorithm was developed as a quick method for use with TOMS-EP. It is robust and will allow a quick determination of the solar array status. To recap. if one or more observed angles between the magnetic field and Sun line differ from the expected separation angle by more than the 17 degree error budget, one or both of the solar arrays are not fully deployed. This depends, though, on which CSS are giving data. If all of the observed angles differ from the expected by less than the error budget, a deployed state is known with 70 % likelihood for one or both solar arrays. These odds go up markedly with increased data points and when the spacecraft has a rotation rate, which is expected for the initial TOMS-EP orbit insertion.

References

1. T. Mendenhall, TRW Memorandum, "CSSA Function," March 21, 1994

2. N. Tull, Internal NASA Memorandum, "Predicting the Deployment of TOMS Solar Arrays Based on Solar and Magnetic Field Data," August, 1994