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Development of a Robust Star Identification Technique for Use in Attitude Determination of the ACE Spacecraft

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ABSTRACT

The Advanced Composition Explorer (ACE) spacecraft is designed to fly in a spin-stabilized attitude. The spacecraft will carry 2 attitude sensors - a digital fine Sun sensor and a charge coupled device (CCD) star tracker - to allow ground-based determination of the spacecraft attitude and spin rate. Part of the processing that must be performed on the CCD star tracker data is the star identification. Star data received from the spacecraft must be matched with star information in the SKYMAP catalog to determine exactly which stars the sensor is tracking. This information, along with the Sun vector measured by the Sun sensor, is used to determine the spacecraft attitude.

Several existing star identification (star ID) systems were examined to determine whether they could be modified for use on the ACE mission. Star ID systems which exist for three-axis stabilized spacecraft tend to be complex in nature and many require fairly good knowledge of the spacecraft attitude, making their use for ACE excessive. Star ID systems used for spinners carrying traditional slit star sensors would have to be modified to model the CCD star tracker. The ACE star ID algorithm must also be robust, in that it will be able to correctly identify stars even though the attitude is not known to a high degree of accuracy, and must be very efficient to allow real-time star identification.

The paper presents the star ID algorithm that was developed for ACE. Results from prototype testing are also presented to demonstrate the efficiency, accuracy, and robustness of the algorithm.

I. INTRODUCTION

The Advanced Composition Explorer (ACE) spacecraft will be launched in August 1997. The spacecraft will be placed into a spin-stabilized attitude. The spacecraft will carry a pair of Adcole two-axis digital Sun sensors and a Ball Aerospace CT-631 series charged-coupled device (CCD) star tracker. Telemetry data from these sensors will be downlinked to allow spacecraft attitude determination at the NASA Goddard Space Flight Center (GSFC). Both spin rate and spin axis attitude will be open-loop controlled by ground commanded hydrazine thruster firings.

Following launch, GSFC personnel will design and execute a series of trajectory maneuvers to transfer ACE from a low earth orbit to a Lissajous orbit about the Sun-earth L1 libration point. The following constraints are levied on the spacecraft attitude by the mission design:

1) The spin axis (the spacecraft +Z axis) must be maintained within 20° of the spacecraft-Sun line for power, thermal, and science instrument safety reasons

2) The spacecraft high-gain antenna boresight, which is along the spacecraft -Z axis, must be maintained with 3° of nadir to allow sufficient link margin for radio frequency (RF) communications with the Deep Space Network (DSN) ground stations

3) The spacecraft spin rate must be maintained to 5.0 ± 0.1 RPM.

II. ALGORITHM DESCRIPTION

General Description of Algorithm

In general, stars are identified by processing data obtained while the star tracker is tracking stars, such as intensities and positional information, and comparing these data with similar data in a star catalog. The star catalog, which is usually a subset of the SKYMAP Master Catalog created for specific missions, is searched until a "match" of the data is found, indicating a successful star identification. For ACE, a mission-specific star catalog will also be created. The creation of this catalog is discussed in more detail later in this section. The star ID algorithm will search the catalog using the following criteria: star magnitude, and the angle between the star vector and the Sun vector. The Sun vector will be propagated in the spacecraft body coordinate frame to the time of each star angle measurement. Propagating the Sun vector in body coordinates has one major advantage over transferring the Sun vector to GCI coordinates; knowledge of the attitude is not required to do the former since the Sun's location with respect to the stars is relatively the same in either the body frame or the GCI frame. This allows the star ID algorithm to be much more robust. The major concern of taking this approach is the propagation of the Sun vector, which is discussed later.

Sensor Overview

A brief overview of the attitude sensors onboard ACE is appropriate at this stage to help explain the functionality of the star ID algorithm. Sensor data will be telemetered to the ground every major frame cycle (16 seconds) for 2-3 hours daily during the spacecraft's only pass.

Each of the two sets of Sun sensors has a ±64° field of view (FOV). One Sun sensor boresight is parallel with the spacecraft spin axis while the other is canted down 120°. This allows for the pair of Sun sensors to have complete hemispherical coverage. This is important to note, not because they are needed to get a fix on the spacecraft attitude, but because generating a Sun pulse is necessary for propagating the Sun vector with respect to time. The Sun sensor can operate in two modes: normal mode and high rate mode. In normal mode, the sensor mimics a slit Sun sensor, generating a time-tagged Sun pulse once per spin period (every 12 seconds). In high rate mode, the sensor is operated as a three-axis sensor, yielding time-tagged angles along the x and y axes. The Sun sensor takes 11 measurements per second in high rate mode.

The CT-631 CCD star tracker has a 20° x 20° FOV and is capable of tracking up to 5 stars simultaneously. The CCD star tracker can also operate in both normal and high rate mode and will retain information on the brightest stars observed. In normal rate mode, one set of star tracker data is transmitted every fourth major telemetry frame. This set consists of up to 4 star observations. These observations are all obtained in the same spin revolution and each pertains to a different star. In high rate mode, every major frame consists of one set of star tracker data. This set of data consists of up to 10 unique observations from the same spin period. The star tracker is mounted on the side of the spacecraft, its boresight 90° from the primary Sun sensor boresight. All star observations will contain a vertical angle measurement, taken as each star crosses the center of the FOV of the sensor (i.e. when the horizontal angle is zero). The tracker will be capable of determining a predicted spacecraft spin rate as it tracks stars through its FOV. The star tracker uses a "picket fence" algorithm to search for star observations. This algorithm partitions the band which is swept out by the star tracker FOV into hundreds of "pickets", each of which is .4° wide and 20° high. During each full spacecraft revolution, the star tracker views every 8th picket and searches for stars within those pickets. The "picket fence" search is advanced one picket during subsequent revolutions. This pattern continues for 8 complete revolutions (nominally 96 seconds), at which time the entire FOV band has been searched. Once a star is observed it continues to be tracked until it leaves the FOV.

Creation of Star Catalog

A star catalog must be created in order to test the star ID prototype. There are no scientific constraints on ACE which require it to target any particular star or set of stars. This will allow the creation of a star catalog which is more conducive to the star identification process. The main goal was to generate a star catalog which contained few enough stars to promote quick identification and enough stars that at least 4-6 would be observed every spacecraft revolution. Limiting the magnitude of stars in the mission specific catalog to 3.5 reduces the number of calculations performed in the star ID algorithm and still contains enough stars to assure that there will be several to identify each spin period. The SKYMAP Master Catalog contains approximately 300 stars of magnitude 3.5 or brighter. Uniform distribution suggests a star population of about one every 12-square degree section of the celestial sphere. This star density will yield approximately 50 stars in any band swept out by the star tracker FOV during a revolution. Using the "picket fence" algorithm previously discussed means that about 6 stars will be observable during each revolution. These predictions corroborate the findings of Ball Aerospace (reference 1) regarding the number of stars available for observation during each revolution of ACE.

An additional element driving the creation of the star catalog is the fact that CCD star trackers are most sensitive at red passbands when measuring star magnitudes. The SKYMAP Master Catalog does not contain red passband data for many stars. The star catalog analysis section at Computer Sciences Corporation (CSC) has developed the Instrumental Red Magnitude Prediction System (reference 2). This system is capable of predicting red passband magnitude data for SKYMAP stars that do not have observed values. The accuracy of the predicted values is within .25 magnitude for fairly bright stars but decreases to as much as 2.5 magnitudes for dim stars, which is another advantage of using stars that are 3.5 magnitude or brighter. The stars being used for the mission specific catalog will be run through the Instrumental Red Magnitude Prediction System before being placed in the catalog; however, this was not done for the testing of the star ID prototype since the sensor models used to generate test data did not emulate sensitivity in the red passband.

Sensor Models

Modeling both Sun sensor and star tracker data was necessary to verify that the star ID algorithm was properly identifying stars. Simplified models were developed to help conserve time. Running the sensor models enabled more accurate predictions of how the identification process would work, in addition to providing test data for the algorithm itself. The Sun sensor model generates time dependent x and y angles. The star tracker model generates a list of all stars in the FOV band for a user specified attitude. This list is then trimmed down to include only the 5 or 6 brightest stars. A pseudo measurement file is constructed from the resulting Sun sensor and star tracker observations. The sensor models are capable of simulating nutation. Nutation will be discussed in later sections.

Algorithm Steps

Obtain Sun Vector

The Sun vector in the sensor frame is determined using the standard conversion from α and β (which are the angle measurements between the Sun vector and the projections of the Sunline onto the *X-Z* and *Y-Z* planes, respectively) as follows:

$$\hat{S}_{SS} = \frac{1}{(1 + \tan^2\alpha + \tan^2\beta)^{1/2}} \begin{bmatrix} \tan\alpha \\ \tan\beta \\ 1 \end{bmatrix}$$

which is translated into body coordinates as follows:

$$\hat{S}_B = M_{BSS}\hat{S}_{SS}$$

where M_{BSS} is the alignment matrix which describes the transformation from the Sun sensor coordinate frame to the body coordinate frame.

The Sun vector can be calculated this way regardless of which mode the Sun sensor is in. If the sensor is in low-rate mode (operating as a slit sensor), α will be 0 and β will be the angle measured at the time $\alpha = 0$ occurs. The same measurements can be derived for the sensor when it is operating in high-rate mode as well. Normally, this mode yields values for both α and β at each measurement time.

Process Star Tracker Data

Convert the time-tagged star measurements to the body frame as follows:

$$\hat{U}_B = M_{BST}\hat{U}_{ST}$$

where

$$\hat{U}_{ST} = \frac{1}{(1 + \tan^2\theta)^{1/2}} \begin{bmatrix} 0 \\ \tan\theta \\ 1 \end{bmatrix}$$

and θ is the vertical angle measured when the horizontal position is 0. M_{BST} is the alignment matrix which describes the transformation from the star tracker coordinate frame to the body coordinate frame.

This vector will be calculated for each observed star.

Propagate Sun Vector

The most important part of the star ID algorithm is the propagation of the measured Sun vector in the body frame. Since the algorithm compares the angle between the Sun vector and the star vector, it is imperative that the distances between the Sun vector and the star vector be the same in both the GCI reference frame and the body frame. The only way to assure this is to propagate the measured Sun vector to the time the star measurement occurred. ACE is spinning at 5 rpm. This translates to a phase angle shift of 30° per second. At this rate, even small miscalculations will cause the calculation of the vector to be off by several degrees. Aside from the spin rate factor, there are additional sources of error which can affect the accuracy of the propagation. The Sun vector can be propagated as such:

$$\hat{S}'_B = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \hat{S}_B$$

where

$\phi = \omega \, \Delta t$
ω = spin rate
Δt = time between Sun measurement and star observation

The value of ϕ is directly dependent on these two variables. Decreasing Δt is one way to improve the calculation of ϕ. This can be accomplished by placing the sensors in high rate mode. In high rate mode, Sun sensor data is measured 11 times per second. At this high rate, if no propagation were done the error would still be only 1.36°. In low rate mode, more care must be taken to reduce the amount of error resulting from large values of Δt. High rate mode cannot be maintained for extended periods of time because or battery restrictions.

The calculation of ω may be the trickiest part. For testing purposes, it was assumed that the spin axis and the spacecraft +z axis are parallel. In reality, this will not be the case. Changes in the spacecraft center of mass and torque's applied to the spacecraft resulting from maneuver thrusts will alter the location of the spin axis. This will cause the +z axis to "wobble" about the angular momentum vector. This "wobble" is commonly referred to as nutation. Nutation will affect the calculation of the spacecraft spin rate (reference 3), which in turn, will affect the propagation of the Sun vector. The nutation angle will be determined as part of the ground processing of attitude data and can be fed back into calculations for adjusting the spin vector. It is yet to be determined how accurately the attitude ground support system will evaluate the nutation angle. Until that time, it is difficult to predict how much of an effect this will have on the actual propagation of the Sun vector. It may be desirable to place the spacecraft into high rate mode at the beginning of each pass until the ground system can come up to speed and assist in the calculation of such parameters as the spin rate. The star tracker will also downlink predicted values for the spin rate which can be utilized to help determine the actual spin rate.

It is assumed, for the purpose of testing the star ID algorithm, that nutation will be .25°, the spin rate is known to within the required .1 rpm, and the alignment on the Sun sensor is known to within .5°. Taking these sources into consideration, a 2° error in the propagated vector is more than sufficient to model the worst case scenario.

<u>Calculate Observed Sun Vector/Star Vector Angle</u>

The observed angle between the propagated Sun vector and the processed star vector is calculated using the standard dot product method:

$$\zeta_O = \cos^{-1}(\hat{U}_B \bullet \hat{S}'_B)$$

<u>Calculate Reference Sun Vector/Star Vector Angle</u>

For each star in the star catalog, the angle between the Sun vector and the star position vector must be calculated. This is most easily accomplished in the GCI reference frame since positional information in the star catalog is stored as GCI x, y, and z coordinates. The Sun vector in the GCI reference frame can be obtained from the Solar Lunar Planetary (SLP) ephemeris file. The SLP file will be available to the star ID software since it is used in other parts of the ACE attitude ground support system. The reference Sun vector/star vector angle is calculated for each star in the catalog as follows:

$$\zeta_R = \cos^{-1}(\hat{U}_{GCI} \bullet \hat{S}_{GCI})$$

where

$$\hat{U}_{GCI} = \begin{bmatrix} X_{GCI} \\ Y_{GCI} \\ Z_{GCI} \end{bmatrix}$$

is the position of the star in GCI coordinates obtained from the star catalog and $\hat{S}_{GCI}$ is obtained directly from the SLP file. These calculations should be processed in advance to save time during the real-time processing. The angles can be stored in a file and read in when needed for comparison. Since the catalog will contain only 300 stars the calculations of the angle between each star and the Sun vector will be done almost instantaneously. Calculation of the reference angle is independent of time. While it is true that the Sun moves in the GCI reference frame, the movement is minuscule during the time period in question. This implies that the Sun does not move relative to the stars in either the body frame or the GCI frame. This allows comparison of the two angles without any knowledge of the spacecraft attitude.

Match Star Information

For each star measured, loop through the star catalog using the matching criteria: the magnitude difference between the measured and reference star, and difference between the measured and reference Sun/star angle (ζ_O and ζ_R). Compare both criteria for every star in the catalog. If the absolute value of the differences between the measured and reference values is less than a predetermined tolerance then that particular observed star has been identified. This process is repeated for each observed star:

Do for each observed star ...

If $|Mag_{observed\ star} - Mag_{catalog\ star}| < \varepsilon_M$ and

If $|\zeta_O - \zeta_R| < \varepsilon_A$ then

Star identification completed, return time-tagged position of measured star and repeat process for next observed star

Else continue

<Process completed>

The tolerances are specified by the user. For testing the prototype the tolerances were set as follows:

$\varepsilon_M = .3125$

The accuracy of the Instrumental Red Magnitude Prediction System is .25 and the magnitude resolution of the ACE star tracker is .0625, so .3125 was chosen as a worst case value. Although CCD trackers are relatively new, several missions prior to ACE will fly the CCD star tracker, including SOHO and XTE. This experience should lead to a more refined calibration of the Instrumental Red Magnitude Prediction System which should reduce the .25 error somewhat.

$\varepsilon_A = 2.0$ degrees

This value is derived from possible errors resulting in the propagation of the Sun vector, which was previously discussed.

III. PROTOTYPING AND ANALYSIS

Verification of Results

Development of the star ID prototype has been completed and will become part of the ACE attitude ground support system once it has been fully tested. Testing continues at the writing of this paper. Final results of the testing phase will be reported at the FMET symposium in May, although preliminary results are discussed in the next section.

IV. SUMMARY AND CONCLUSIONS

Tests were run on the pseudo sensor measurement file and the results are very promising. The sensor models were run for several different spacecraft attitudes and Sun angles. The number of observed stars in the measurement file was between 26 and 40 stars for every case. This indicates that between 3 and 5 stars will be available during each revolution. The star observations are currently being checked against all other stars in the star catalog. Preliminary results show that most test cases yield a single star identification which is the desired result. For some cases there are at most 2 stars being identified, resulting in an ambiguous identification. This situation is undesirable if it occurs too often, although in this case, there is only one ambiguous identification occurring some of the time. One solution to this is to simply flag those star identifications as ambiguous and use the remaining star data. Therefore, at least 2 or more vectors will be available every revolution in addition to the Sun vector for attitude determination.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

1. Ball Aerospace and Communications Group, P93-801-80, Proposal for CT-631 Star Tracker for the ACE Spacecraft, (Volume 1), Ball Electro-Optics and Cryogenics Division, June 1993

2. Computer Sciences Corporation, CSC/TR-93/6124, SKYMAP Requirements, Functional, and Mathematical Specifications: Instrumental Red Magnitude Prediction Subsystem, (Volume 2), A. Miller and M. Slater, October 1993

3. NASA Goddard Space Flight Center, Optimal Attitude Maneuver Execution for the ACE Mission, (paper submitted for the Flight Mechanics/Estimation Symposium), M. Woodard and D. Baker, May 1995

4. J. R. Wertz, ed., Spacecraft Attitude Determination and Control, Dordrecht, Holland: D. Reidel, 1978

5. Computer Sciences Corporation, "Proposed Algorithm for Performing Star Identification for ACE", (memorandum), D. Rohrbaugh, September 1994