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Celestial Referenced Attitude Determination of Galileo Spacecraft

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An entirely autonomous attitude determination algorithm has been developed for the dual-spin Galileo spacecraft in its mission to Jupiter. A batch mode process is established which identifies three stars within the scanner's field-of-view based on the criteria of intensity and geometry. This is followed by a continuous star acquisition procedure which provides star transit times and a spacecraft spin rate estimate. A least-squares estimator then sequentially determines the spacecraft's attitude from successive star crossings by minimizing an error derived using the necessary condition of star and scanner slit normal orthogonality. Simulation results are presented, showing successful star identification and attitude convergence in the presence of nutation and star transit time uncertainty.

I. Introduction

THE main objective of the Galileo mission to Jupiter is to conduct intensive scientific investigations of Jupiter's atmosphere, magnetosphere, and satellites. The dual-spin configured Galileo spacecraft, scheduled for launch in 1985, will undergo many phases of operations such as launch, trajectory-correction maneuvers, Jupiter orbit insertion, as well as various modes of science acquisitions. Thus the attitude information of the spacecraft is essential to both spacecraft maneuvering and normal attitude sustenance (Earth tracking), and is vital to the success of the mission.

One innovative feature of the attitude determination (AD) system onboard the Galileo spacecraft is its capability to determine the absolute spacecraft attitude with respect to a fixed celestial-referenced frame by onboard processers without explicit prior attitude knowledge. There are several reasons for the requirement of autonomous AD in Galileo. The mission demands complex modes of spacecraft maneuvers and frequent trajectory corrections which require accurate attitude information of the spacecraft. Time constraints are tight owing to the spacecraft's enormous distance from Earth, thereby rendering any ground support impractical. (One-way light time from Jupiter to Earth is 45 min.) Furthermore, sun-referenced or open-loop AD cannot provide sufficient accuracy for navigation among the Jovian satellites. The principal requirement imposed on the Galileo's star-scanner/AD system is to achieve a spacecraft attitude estimate to within an accuracy (3σ) of 0.5 mrad for high gain antenna pointing and scan platform pointing control.

The concept of the star-mapping technique aboard a spin-stabilized vehicle for AD has been designed and successfully implemented in various Earth-orbiting satellites. In an early application for the Project Scanner, the onboard process was not entirely autonomous, but required manual sorting of star transit time pairs.[1] Other systems such as the Applications Technology Satellite (ATS-C), Orbiting Solar Observatory (OSO),[2-4] and the NASA Multimission Modular Spacecraft (MMS)[5] use a wide variety of instruments, reticle designs and attitude determination software implementations. An autonomous onboard star identification technique was devised for planetary exploration spacecraft and constitutes the basic approach for the design in Galileo.[6]

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The Galileo spacecraft configuration is shown in Fig. 1. The spinning section (rotor) carries the high gain antenna, two radioisotope thermoelectric generators (RTG's), and a magnetometer boom. The despun section (stator) provides pointing capability for the articulated scan platform. Accurate inertial pointing is aided by a pair of gyros located on the scan platform.

There are two major aspects of attitude determination as defined here: identification of selected stars through correlation of their angular separations and intensities with cataloged values, and estimation of spacecraft attitude through the use of sensor geometry and the star transit time history. The paper is organized as follows: In Sec. II, the overall attitude determination and functional interface and the celestial sensor hardware are described. The batch and sequential star identification algorithms are then described in Sec. III. A formulation of the attitude estimator is presented in Sec. IV. Computer simulation results of the entire attitude determination scheme from star-scanner data are presented in Sec. V, and finally, conclusions are given in Sec. VI.

II. Attitude Determination Overview

A significant difference between Galileo's AD system and that of previous missions is that ground processing of star data is not required. The onboard processes, along with a 200-star catalog, is capable of determining from star data the absolute spacecraft attitude from any orientation, with respect to a fixed celestial-referenced frame without explicit prior attitude knowledge.

Two basic modes of operation pertaining to Galileo's attitude determination can be defined: cruise and inertial. The former implies that the spacecraft attitude is evaluated onboard, using stars as references. In the latter mode, inertial reference relies on gyro sensing, while intermittently being updated by star data. A star scanner mounted on the rotor serves as the celestial sensor. Two dual-axis gyros mounted on the scan platform are used to measure integrated rates about three orthogonal axes defined in the gyro reference frame. This paper addresses only that portion of the attitude determination algorithms that use the star-scanner data.

A. Attitude Determination Overview

The star-scanner generated data are being used by two distinct onboard algorithms to provide the spacecraft attitude in inertial coordinates, specifically, the Earth-Mean-Equatorial system of 1950 (EME50). These algorithms are the Star Identification Algorithm (SID) and the Attitude Estimator (AE). Their functional interfaces with other AD algorithms are depicted in Fig. 2.

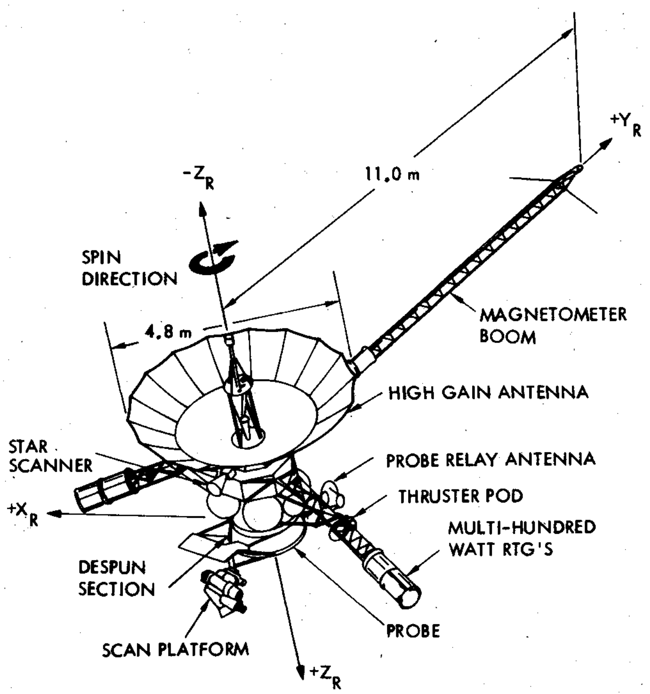

Fig. 1 Galileo spacecraft (deployed configuration).

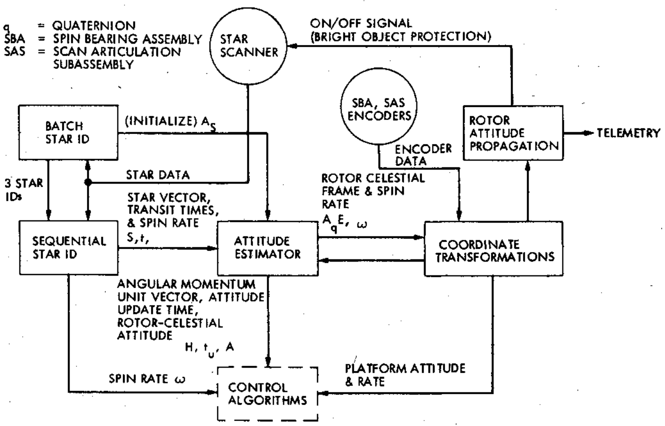

Fig. 2 Block diagram of Galileo attitude determination from star data.

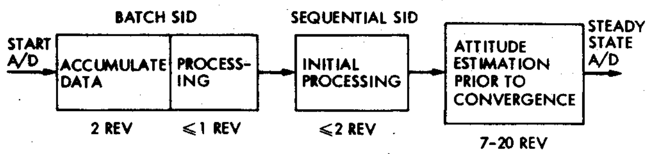

Fig. 3 Sequence of initial attitude determination.

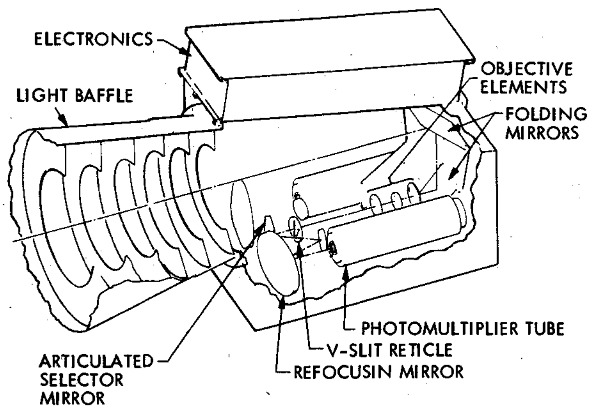

Fig. 4 Bendix Galileo star-scanner assembly.

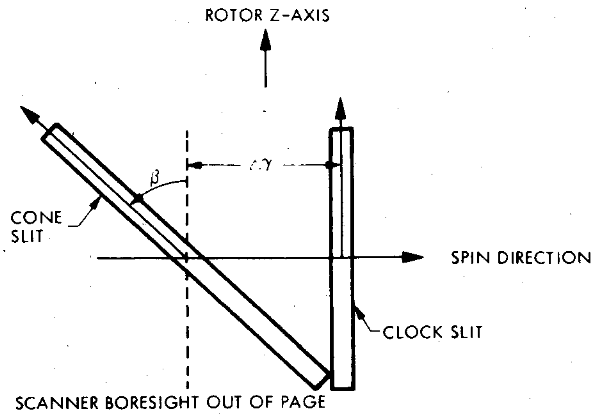

Fig. 5 Star-scanner slit configuration.

There are two modes to the SID algorithm: batch and sequential, which are designed to operate in sequence. The batch SID operates on the data to identify and define three reference stars by comparisons with data in a star catalog. A coarse spin rate estimate provided by the acquisition sun sensor is available for star vectors computation. Accurate spin rate will also be estimated from the periodic pattern of the star data recorded in the two revolutions. The function of the sequential SID is to continuously track the three reference stars defined in the batch mode. It operates on the principle of prediction and confirmation. A time range of the star crossing event is predicted, and the data within the predicted range is then processed to confirm the occurrence of the star.

The purpose of the AE is to sequentially determine the spacecraft attitude and angular momentum vector (***H***) in EME50 when each reference star crossing data set (star vector, clock/cone transit times) is confirmed by the sequential SID.

The spacecraft attitude information is needed for real-time onboard control algorithms such as high gain antenna pointing, spin rate control, initializing command turns, as well as scan platform pointing in the cruise mode (when gyros are off). A gyro integrator algorithm propagates the attitude of the scan platform in quaternions from the gyro's incremental position outputs, and also compensates for gyro drift rate. An onboard algorithm also updates the gyro drift rate compensation and gyro quaternion integration from celestial references, when available. This provides spacecraft attitude and enables inertial pointing of the scan platform even in the temporary absence of star-scanner data.

The time sequence of the AD execution is depicted in Fig. 3. Total time for initial attitude acquisition is approximately 4-8 min. The relative difficulties in interpreting the star data increase as the spacecraft motion deviates from pure spin. Combination of nutation and wobble effects will degrade the performance of the SID and the AE. Consequently, the attitude determination algorithms are executed only after these adverse dynamical effects have been damped or controlled.

B. Sensors

A rotor-mounted star scanner (Fig. 4) is being employed as the celestial sensing element for Galileo. It consists of a set of refractive optics which project the star field images onto a V-slit reticle (Fig. 5). One of the slits, known as the clock slit, will provide the clock positions of the stars detected in the spacecraft body frame. It is, in general, aligned tangentially to the meridian of a celestial sphere with the poles along the spin axis. The other, termed the cone slit, is slanted with respect to the former to provide the cone positions of the stars.

The scanner has a cone field-of-view (FOV) of ±5 deg and is sensitive to stars within the visual magnitude range of −1.46 to 4.79. A coincidence pulse pair is generated whenever a star is scanned through the V-slit detector. The magnitudes as well as the time of crossings correspond to a reference clock are recorded for processing. The time difference between pulses of a pair indicates the star cone angle, while the relative clock angle between any two stars can be evaluated from the difference between the two clock slit transit times. These computations require that spin rate information be available, which can be determined based on the repetitive star pattern over several revolutions. However, an a priori spin rate estimate from a different sensor, e.g., sun sensor or gyro, is still required for initialization.

III. Star Identification

The batch mode is executed when there is no a priori attitude information available. Three reference stars are identified based on various criteria for subsequent tracking by the sequential mode. The sequential mode will then continuously track the defined stars by confirming their occurrences within the time window predicted.

A. Batch Star Identification

The batch SID identifies three reference stars by comparing the data to a star catalog. A nominal set containing about 200 stars which are within the detecting capability of the scanner should provide enough candidates for tracking at any attitude. Three major operations are performed by this algorithm, namely, star pair selection, spin rate determination, and star matching.

Star Pair Selection

Star data containing magnitudes and transit times information for both clock and cone slits are recorded sequentially in a stack register according to their time order of detections. A procedure based on magnitudes and elevation angles is commenced for pairing two star pulses corresponding to the clock and cone slit transits. To determine if two consecutive pulses $(i, i+1)$ are recorded from the same star, a relative intensity check is executed which is defined by the following inequalities:

$$(I_i + I_{i+1})\alpha/2 \leq I_i, I_{i+1} \leq (I_i + I_{i+1})/2\alpha \tag{1}$$

where I denotes the pulse intensity and $\alpha < 1$ is the relative intensity measurement accuracy. If both intensities are within bounds, an elevation angle test is performed. From the transit time difference between pulses, the star elevation angle E_i relative to the rotor can be evaluated as

$$E_i = \tan^{-1}\{k_1 \sin[\omega(t_{i+1} - t_i)] - k_2 \cos[\omega(t_{i+1} - t_i)]\} \tag{2}$$

where k_1, k_2 are constants determined from the scanner mounting configuration (Ref. 7), ω is the spin rate, and t_i, t_{i+1} are pulse transit times. The angle computed should be within the scanner cone FOV. However, when there is a large initial spin rate uncertainty, the FOV criterion is increased accordingly to avoid deleting any valid star pair. If both tests are satisfied, the two pulses are assumed to be a valid star pair. However, ambiguous situations can occur when more than two pulses of equivalent magnitudes are grouped together, thereby, satisfying both tests. In such a situation, two consecutive pulses with the least magnitude difference will be considered as a valid star pair.

Spin Rate Determination

Spin rate is determined from the periodic pattern of the stars in terms of magnitudes and elevation angles. Magnitudes recorded for the same star over two revolutions should be within the relative intensity measurement accuracy of the scanner. In addition, the elevation angles computed should be within the limit of residual nutation and wobble. Subsequently, each star pair is checked against all other pairs following it in the data stream according to the two criteria. When both tests are satisfied, the difference in clock slit transits is computed. Spin rate is then determined by averaging the clock slit transit differences. With the improved spin rate, the star pair selection procedure is repeated for one revolution of data.

Star Matching

From one revolution of data, four pulse pairs are chosen as matching candidates. The criteria are large magnitudes, no ambiguity, and well within the scanner cone FOV. Matching is then performed based on the absolute magnitude and angular separation test.

For each candidate, a magnitude compatible star set is defined from the star catalog with its elements satisfying the constraint

$$rI_{im} \leq I_{kc} \leq (1/r)I_{im} \tag{3}$$

where I_{im} is the measured magnitude of the ith pair, I_{kc} is the cataloged magnitude of the kth star, and $r < 1$ is the absolute measurement accuracy of the scanner.

The angular separation between any two candidate (i,j) is computed by taking the dot product of the spacecraft-body-referenced star vectors evaluated from the clock and cone angle measurements. Similarly, the angular separation between any two star vectors expressed in EME50 from the corresponding compatible set is evaluated. The difference between these two angles is then checked to ascertain if it is less than the criterion Δ defined as

$$\Delta = 2\eta \sin(2\zeta/3) + 2\phi \sin(\zeta/2) + \nu \tag{4}$$

where ζ is the clock angle separation between candidates i and j, η is the nutation angle, ϕ is the wobble angle, and ν is the measurement uncertainty introduced by the scanner. All possible combinations of the element in the four sets are tested for angle compatibility. The matching combination with the most pair matches and triangle matches are considered to be the correct identification. From the matching combination, three stars which establish a triangle with the lowest distribution index λ for three star vectors S_i, $i = 1,2,3$ are chosen as references. The index is defined as

$$\lambda = |(S_1 S_2)(S_2 S_3)(S_3 S_1)| \leq (0 \leq \lambda < 1) \tag{5}$$

to ensure large angular separations among the stars for improved performance of the Attitude Estimator.

B. Sequential Star Identification

The sequential SID algorithm is designed to operate in real time when the spacecraft is in a steady-state condition. It can only search for the three reference stars as defined. The basic idea is to predict a time range within which a particular star can be observed. Coincidence pulses within the predicted range are checked for magnitude and elevation angle compatibility with the defined values. When the star is confirmed, the transit time information is routed to the AE for attitude updating. If confirmation cannot be achieved, the next star will be considered. Two stages of operation are involved: search phase and output phase.

Search Phase

The main objective of this phase is to establish timing synchronization between the algorithm search time and the actual star transit. It is initiated by trying to locate the first reference star. All pulses will be checked until two consecutive pulses which satisfy the absolute magnitude criterion are detected. The relative magnitude and elevation angle check will then be executed. When the "first" star is confirmed, the time range of occurrence of the next star is predicted from the relative clock angle and spin rate.

For all pulses within range, absolute/relative magnitude and elevation angle checks are performed. When all three reference stars are confirmed within one revolution, the search phase is considered to be successfully completed. Otherwise, the search phase will be repeated until a set time limit expires, indicating a fault condition.

Output Phase

This phase is initiated after the completion of the search phase, and a similar procedure of prediction and confirmation is executed. The elevation angle and the relative clock angle for each confirmed star are updated for the next prediction. This enables the algorithm to tolerate a gradual drift in the $\boldsymbol{H}$ vector. At the end of each revolution, spin rate is updated by averaging the transit time difference between revolutions for all the confirmed stars.

IV. Attitude Estimator

The attitude estimator (AE) is designed to sequentially process the star scanner measurements and determine the spacecraft's attitude and angular momentum vector in EME50 coordinates with a 3σ error of less than 0.5 mrad. The AE formulation uses the least-squares method to determine the attitude which satisfies the necessary condition of star and slit normal orthogonality. Nutation and wobble are initially considered in the dynamical modeling. However, they are assumed negligible during steady-state operations owing to the presence of a passive nutation damper in the magnetometer boom and an onboard wobble control algorithm. Consequently, a pure-spin dynamics model is assumed as a step towards simplifying the onboard implementation.

A. Formulation of the Dynamics Model

A spacecraft inertial coordinate frame A established by three orthogonal vectors

$$A=[\boldsymbol{a}_1,\boldsymbol{a}_2,\boldsymbol{a}_3]$$

is first defined, with $\boldsymbol{a}_3$ aligned with the estimated angular momentum vector $\boldsymbol{H}$, and $\boldsymbol{a}_1$ lying in the plane defined by $\boldsymbol{H}$ and the line-of-sight (LOS) vector of the "first" reference star. A is also called the attitude matrix of the spacecraft.

The basic concept in the model formulation is that when a star falls in the scanner slit FOV, the star vector $\boldsymbol{S}$ is orthogonal to a vector $\boldsymbol{n}$ normal to the scanner slit. The star vector is defined in EME coordinates, and the slit normal is defined in rotor coordinates (R).

To determine the coordinate frame A, it is necessary that both $\boldsymbol{S}$ and $\boldsymbol{n}$ are expressed in this coordinate frame, i.e.,

$$\boldsymbol{S}=A^T\boldsymbol{S}_E \tag{6}$$

and

$$\boldsymbol{n}=[I+\boldsymbol{e}_\eta\times][I+\boldsymbol{e}_\phi\times]\begin{cases}[\omega(t_1-t_0)]_3^T\boldsymbol{n}_{1R} & \text{clock slit crossing}\\ [\omega(t_2-t_0-\xi)]_3^T\boldsymbol{n}_{2R} & \text{cone slit crossing}\end{cases} \tag{7}$$

where $[\theta]_i$ represents a right-handed rotation of angle θ about the ith coordinate axis; t_1 and t_2 are the clock and cone transit times, respectively; t_0 is the clock slit transit time of the "first" referenced star; and $\xi \triangleq \Delta\gamma/l$ (Fig. 5), $\boldsymbol{n}_{jR}$ $j=1,2$ are the clock and cone slit normals which are constant unit vectors for known slit mounting orientations in R after in-flight misalignment calibration. For the slit misalignment errors in clock and twist (rotation about slit boresight), defined respectively by $\epsilon_1,\epsilon_\delta$ and $\epsilon_2,\epsilon_\alpha$ for the clock and cone slits, and where β is the slanted angle defined in Fig. 5, the slit normals are then given by

$$\boldsymbol{n}_R=\begin{cases}\{[\epsilon_1]_3[\epsilon_\delta]_1\}^T\boldsymbol{n}_L & \text{clock slit}\\ \{[\epsilon_2]_3[\epsilon_\alpha+\beta]_1\}^T\boldsymbol{n}_L & \text{cone slit}\end{cases} \tag{8}$$

where $\boldsymbol{n}_L$ is the vector $[0\ 1\ 0]^T$. Furthermore,

$$\boldsymbol{e}_\eta=[\delta t]_3\begin{bmatrix}\eta_x\\ \eta_y\\ 0\end{bmatrix} \qquad \boldsymbol{e}_\phi=[\omega t]_3\begin{bmatrix}\phi_x\\ \phi_y\\ 0\end{bmatrix} \tag{9}$$

where δ is the precession rate, and the x, y components of the nutation angle η_x, η_y and the wobble angle ϕ_x, ϕ_y are assumed small. The notation $[\boldsymbol{e}\times]$ is a matrix cross-product operator defined as

$$\boldsymbol{e}\times=\begin{bmatrix}0 & -e_3 & e_2\\ e_3 & 0 & -e_1\\ -e_2 & e_1 & 0\end{bmatrix} \qquad \text{for } \boldsymbol{e}=\begin{bmatrix}e_1\\ e_2\\ e_3\end{bmatrix}$$

For some special modes of spacecraft maneuver (e.g., all-spin mode) when wobble and nutation become significant, the vector $[\eta_x,\eta_y,\phi_x,\phi_y]$ can be simultaneously estimated together with the attitude error by utilizing Eqs. (6) and (7). However, with the presence of a passive nutation damper and an onboard wobble control algorithm, nutation and wobble are insignificant during steady-state operations. In fact, nutation, if ignored, will be averaged out over time, while wobble usually will not since it is synchronized with the star transits. In the sequel, we will consider a pure-spin dynamics model for the AE formulation because onboard memory size and execution time margins are of major concerns in the design of control algorithms. The slit normal is expressed in a coordinate frame which differs slightly from A owing to the effect of nutation and wobble. We now have

$$\boldsymbol{n}=\begin{cases}[\omega(t_1-t_0)]_3^T\boldsymbol{n}_{1R} & \text{clock}\\ [\omega(t_2-t_0)]_3^T\boldsymbol{n}_{2R} & \text{cone}\end{cases} \tag{10}$$

B. Attitude Estimator Algorithm

At each star crossing time k, our objective is to determine $A(k)$ from the previous estimate $A(k-1)$ from the star vector $\boldsymbol{S}(k)$, and the transit times $t_1(k)$ and $t_2(k)$ provided by the sequential SID. Let γ be the desired angular rotation (attitude error) about the axes of $A(k-1)$ to assume a new $A(k)$. By small angle approximation, we formulate the following equation:

$$([I-\gamma\times]\boldsymbol{S}(k))\cdot\boldsymbol{n}_i(k)=v_i(k) \qquad (i=1,2) \tag{11}$$

where $\boldsymbol{S}(k)$ and $\boldsymbol{n}_i(k)$ are expressed in the $A(k-1)$ coordinates, and $v_i(k)$ is the associated measurement noise. Rearranging Eq. (11), one can obtain

$$\epsilon_i(k)=(\boldsymbol{S}(k)\times\boldsymbol{n}_i(k))\cdot\boldsymbol{\gamma}(k)+v_i(k) \qquad (i=1,2) \tag{12}$$

where $\epsilon_i(k)=\boldsymbol{S}(k)\cdot\boldsymbol{n}_i(k)$.

A coordinate system, L, is defined with the star vector aligned with L_1, and L_2 aligned with the clock slit normal at transit. This enables simple expressions of the sensitive axes' ($\boldsymbol{S}\times\boldsymbol{n}_i$, $i=1,2$) orientations to be defined in the L_2-L_3 plane (Fig. 6). As the change in the actual attitude between the two transits $t_1(k)$ and $t_2(k)$ is small, the attitude update can be performed immediately after the cone slit transit, using both clock and cone transit information. With $\boldsymbol{\gamma}(k)$ expressed in

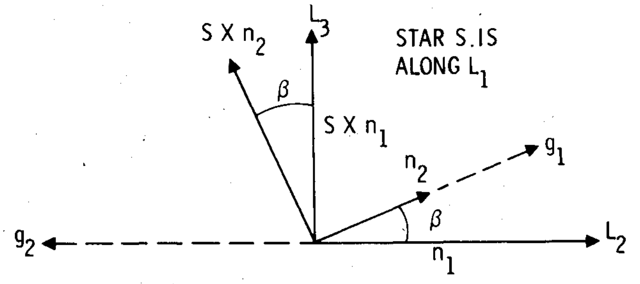

Fig. 6 Star-normal coordinate frame *(L)*.

L_2-L_3 coordinates, Eq. (12) can be written as

$$\epsilon(k) = \begin{bmatrix} 0 & 1 \\ -\sin\beta & \cos\beta \end{bmatrix} \gamma(k) + V(k) \qquad (13)$$

where $\beta \neq 0$,

$$\epsilon = [\epsilon_1, \epsilon_2]^T \qquad V = [v_1, v_2]^T$$

With the assumption that the error γ is much larger than the noise V, Eq. (13) is solved to give

$$\gamma(k) \triangleq \begin{bmatrix} \cot\beta & -\dfrac{1}{\sin\beta} \\ 1 & 0 \end{bmatrix} \epsilon(k) \qquad (14)$$

in the L_2-L_3 plane. Then, with n_1, n_2 defined in $A(k-1)$, $\gamma(k)$ can be transformed back to the $A(k-1)$ frame by

$$\gamma(k) = (\epsilon_1(k) n_2(k) - \epsilon_2(k) n_1(k)) / \sin\beta \qquad (15)$$

C. The Estimator Gain

Although we have derived a desired rotation about the coordinates of $A(k-1)$ to assume a new $A(k)$, it is desirable, for better noise tolerance, that the actual attitude update be controlled by different estimator gains $K(k)$ depending on whether the spacecraft is in the transient or steady state. Hence the actual rotational angle is

$$\rho(k) = K(k)\gamma(k) \qquad (16)$$

At transient state, fast reduction in the attitude error is desirable and hence full gain on star information is used. Such a gain, however, weighs equally on the true attitude error as much as on the effect of noise. At steady state, the gain is reduced to a minimum magnitude (e.g., comparable to the size of jittering), so that sporadic, high frequency noise can be adequately filtered out.

The estimator gain $K(k)$ can be set at

$$K(k) = \begin{cases} 1 & (k \leq k_0) \quad \text{transient state} \\ K_{\min} + k_0/2k & (k > k_0) \quad \text{steady state} \end{cases} \qquad (17)$$

$$(k = 1, 2, 3, \ldots)$$

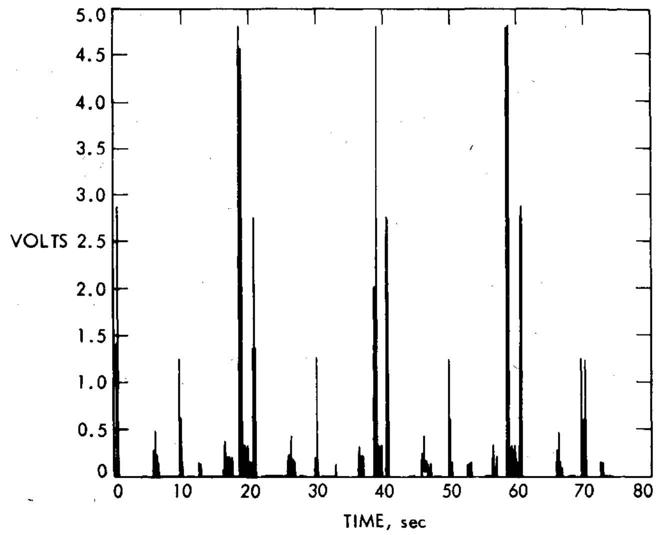

Fig. 7 Star-scanner pulse sequence.

where k is a star crossing counter (three per revolution), and is set to zero whenever an external torque is applied to the spacecraft (e.g., thruster firings). k_0 can be chosen based on the distribution of the three identified stars S_i, $i = 1,2,3$ in the inertial space. If any two stars are orthogonal to each other, theoretically, the attitude error can be taken out in one revolution under noise-free condition. In a deterministic sense, the estimation error $e(k)$ can be reduced to $e(k) = \lambda e(k-3)$ per revolution in the transient state, where λ, defined in Eq. (5), is a star distribution index indicating the degree of orthogonality in the referenced stars' distribution. Assuming the spacecraft attitude is initialized by the batch SID with an error around 17 mrad, λ vs k_0 can be determined by Table 1, where $k_0 = 3n$, and n is the number of revolutions required to reduce the error from 17 to 0.3 mrad. From the above relation, k_0 can be assigned a value onboard each time λ is computed from a set of identified stars.

V. Simulation Results

To evaluate the performance of the AD algorithms, a program was developed to simulate the star-scanner data on the UNIVAC 1108. The dynamics of a dual-spin spacecraft were simulated, using a three-body model (rotor, stator, and scan platform). A star catalog containing 200 stars was used, and the star field observed was defined by the input attitude of the spacecraft and nutation angle. The data are generated for 60 revolutions at 20 inertial pointing directions along a nominal Galileo trajectory. A sample of such data for four revolutions is shown in Fig. 7. Successful identifications were achieved in all cases by the batch SID, and the sequential SID successfully tracked the three reference stars during subsequent revolutions. The processing time is approximately 30 s for the batch with a 1σ uncertainty of 0.074 mrad/s in spin rate determination. The processing time of the sequential SID for each prediction and confirmation is small, and no problem is envisioned for execution time margin.

The AE was simulated and tested with various orientations of the $\boldsymbol{H}$ vector in EME50. Figure 8 compares the convergence of the $\boldsymbol{H}$ vector for two different star distributions, $\lambda = 0.08$, 0.76 under noise-free situation. Table 2 shows the corresponding star distribution index, the initial and final errors, and the number of star crossings prior to attitude convergence for each test case. Transit time noise up to $\sigma = 1.3$ ms and nutation angles between 0.1 and 2 mrad were tested. The results of one of the test cases from Table 2 with $\boldsymbol{H} = [100]^T$ are depicted in Figs. 9a and 9b, and show the attitude update parameter of the error and the estimation error in $\boldsymbol{H}$ vs star observations (3 per rev).

Table 1 Star distribution index vs transient period

λ	0.014	0.12	0.24	0.34	0.49	0.59	0.63	0.65	0.75	0.8
k_0	3	6	9	12	18	24	27	30	45	54

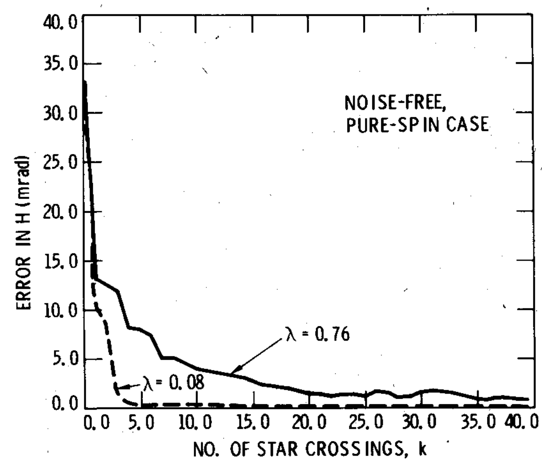

Fig. 8 Angular momentum (*H*) attitude error.

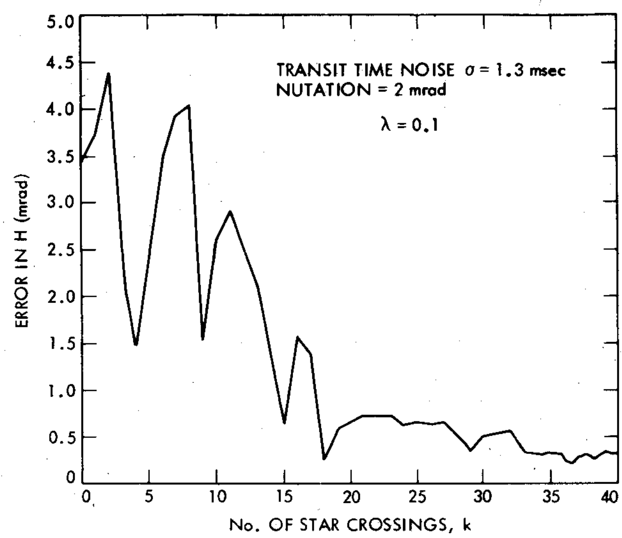

Fig. 9a Angular momentum attitude error.

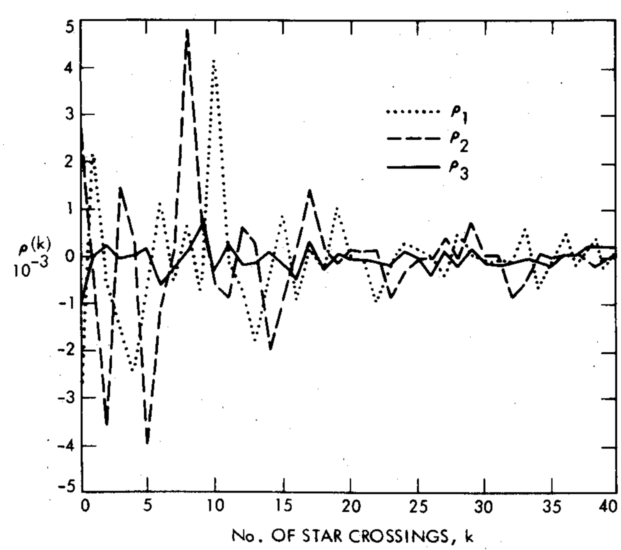

Fig. 9b Attitude update parameter.

Table 2 Attitude matrix (*A*) estimation

H attitude in EME50	Star distribution index λ	Initial/final error per axis, mrad	No. of star crossings prior to convergence
$[100]^T$	0.03	21/0.42	26
$[010]^T$	0.68	15/0.37	60
$[001]^T$	0.02	10/0.35	24
$[0.171, 0.2962, 0.9397]^T$	0.21	17/0.45	38
$[-0.5, -0.5, 0.7071]^T$	0.16	35/0.27	37

VI. Conclusion

An entirely autonomous star-referenced attitude determination system for the dual-spin Galileo spacecraft is presented. Two algorithms pertaining to this system are the star identification and attitude estimator algorithms. The former determines a coarse attitude from the scanner data and defines three reference stars for continuous tracking. The star transmit times are then input to the attitude estimator to establish the spacecraft's attitude. Simulation programs are developed and tested which show that successful star identification was achieved for various spacecraft orientations along a nominal Galileo trajectory, and the spacecraft attitude was estimated to within an accuracy of 0.5 mrad (3σ). These results show that the Galileo mission requirements on attitude determination from star data are met.

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