Star Scanner Attitude Determination for the OSO-7 Spacecraft

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The inertial orientation of the OSO-7 spacecraft is computed from the times at which known stars or planets transit planes fixed in the spacecraft.[1] Both the reference planes and the timing information are provided by the star scanner instrument aboard the spacecraft, whereas the star identification and the statistical estimation of a set of parameters describing the spacecraft attitude are accomplished in a ground station computer facility. A recursive, least-squares determination is made of a vector of first-order differential corrections to the attitude state vector. This paper presents a discussion of the hardware, software, system, and flight experience aspects, and eleven months of successful flight experience. The scanner used a photomultiplier detector with some onboard processing of the data. The spacecraft-to-computer interface consists of a "very low telemetry data rate." Preliminary analysis indicates the system accuracy to be 3 arcmin (3σ) in each attitude Euler angle. The system accuracy can be improved by modeling the attitude perturbations and operation at slower spin rates.

Nomenclature

$\mathbf{r}^v$ = a vector in the $(X_8 Y_8 Z_8)$ coordinate system
$\mathbf{r}^s$ = a vector in the $(X_9 Y_9 Z_9)$ coordinate system
$\mathbf{R}$ = a vector in the $(X_1 Y_1 Z_1)$ system
$T_i(\ )$ = a rotation matrix, describing a rotation about the ith axis of a coordinate system
ε = the obliquity of the ecliptic
S = the angle, measured in the ecliptic plane, from the first point of Aries to the sun
ϕ = spacecraft roll angle—a rotation about the X_3 axis
η = spacecraft pitch angle—a rotation, in the negative sense, about the Y_4 axis
β = the yaw offset of the star scanner from the body reference axis
β_s = the initial spacecraft yaw angle at the reference time for the altitude solution
B_s = spacecraft yaw angle, $B_s = 2\pi - \beta_s + \beta + \omega_s t$; a rotation about Z_5, or spacecraft spin axis
E_0 = the angle between the spacecraft spin axis Z_5 and the intersection of the scanner slit planes, the X_6 axis; a rotation about the Y_6 axis
γ = rotation of the leading slit plane about the X_7 axis
θ = rotation of the leading slit plane about the X_8 axis into the trailing slit plane
ω_s = wheel spin rate
$\mathbf{r}_{th}$ = a first-order Taylor's series expansion of $\mathbf{r}$ based on the best-known state vector $\mathbf{P}$
$\mathbf{r}_0$ = $\mathbf{r}$ evaluated at the best-known state vector $\mathbf{P}$
$\partial \mathbf{r}_0/\partial \mathbf{P}$ = a $(3 \times M)$ matrix of partial derivatives of the vector $\mathbf{r}_0$ with respect to the vector $\mathbf{P}$, $(M = 4$ or $7)$
$\Delta\mathbf{P}$ = a vector of first-order differential corrections to the vector $\mathbf{P}$
$\mathbf{r}_{,M}$ = $\begin{bmatrix} r_{1,M} \\ r_{2,M} \\ r_{3,M} \end{bmatrix}$ the observed, or measured, value of $\mathbf{r}$ at the time of star transit
r_2 = the second component of the vector $\mathbf{r}$
$r_{2,Th}{}^{i,K}$ = the second component of the vector $\mathbf{r}_{Th}$, evaluated for ith star transit of the Kth slit
$X_i^K = r_{2,M}{}^{i,K}$ = the error between the theoretical and measured values of r_2 for the ith star transit of the Kth slit
A = matrix of the normal equation of the least-squares estimate of the vector $\Delta\mathbf{P}$
t_i = the time of the ith star transit
$[\ \ ]_K$ = indicates vector of the Kth row of the enclosed matrix
$r_2{}^{v,s}$ = a generic term, indicating either $r_2{}^v$ or $r_2{}^s$

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Introduction

THE concept of a multislit star scanner aboard a spinning vehicle for attitude determination has been successfully applied several times in recent years. A wide variety of instruments has been developed, varying in field-of-view, reticle design, effective spin rate range, timing instrumentation, telemetry configuration, and attitude determination software systems. These include systems for Project Scanner, S^3, SAS-A, and the Applications Technology Satellite (ATS-C).[1–4]

The OSO-7 star scanner system differs from previous systems in, among other things, a low data rate, which is enforced by the limited amount of telemetry allocated; relatively noise-free star data, which simplifies the data processing system; and a digital data handling system in the spacecraft, which eliminates the requirement of processing analog signals in the software system.

The principal requirements placed on the star scanner system are to determine the spacecraft attitude to 0.1° during the nighttime period, with a new attitude solution every 15.36 sec (the length of the telemetry block). The star scanner system was turned on shortly after the spacecraft was placed in orbit on Sept. 29, 1971, and provided attitude solutions accurate to better than 0.05°.

The accuracy requirements influence not only the type of measurements required from the electro-optic system, but also the type of mathematical model for the attitude motion. A simple model was chosen for the motion, based on the predicted attitude behavior of the OSO-7 spacecraft—an inertially fixed spin axis provides an attitude solution accurate to 0.01° (1 σ). Addition of the body fixed nutation degree of freedom should permit solutions good to 0.001° (1 σ).

The celestial targets included in the data base for the system include bright stars (visual magnitude of 3.5 or brighter) and the planets Mars, Jupiter, Saturn, Venus. The stars are in a fixed data base of epoch 1970.0, and their positions are corrected for proper motion and regression of the equinoxes.

The data reduction system consists of a series of computer programs which remove spurious data, determine the wheel spin rate by autocorrelation of the slit crossing times, identify the stellar sources of data, and make a recursive, least, squares estimate of a set of first-order differential corrections to the set of spacecraft attitude parameters.[2]

Hardware Discussion

The electro-optical hardware was designed around the spacecraft requirements and constraints. These design requirements and constraints were a) provide 0.1° attitude information each 15.36 sec during orbit night; b) use only 150 bits per second telemetry data; and c) consume less than 1.5 w. The hardware to accomplish the attitude solution was kept as simple as possible while providing relatively noise-free star data. The electro-optical hardware consists of a stray light shield, an optical system (to collect and focus energy from the target stars), an opaque reticle with a pair of precise, narrow transparent slits, a photomultiplier tube, and an electronic signal processor as shown in Fig. 1.

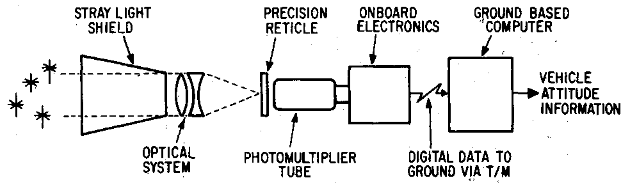

Fig. 1 Star scanner system.

The stray light shield provides light attenuation in the order of 10^{-6} for sources up to 27° to the optical axis. The lens and reticle assembly provides another factor of 10^{-3} for an over-all stray light penetration of 10^{-9} for angles of 27° and greater to the optical axis. This is sufficient for orbit night operation and has provided limited orbit day operation at times during OSO-7 operation.

The optical assembly is a simple camera lens design. The lens consists of a 100-mm, f/2.0 lens stopped down to f/2.8. A 1-cm-thick flat quartz window was added to prevent losses in lens transmission due to the orbital radiation environment. This quartz window has proven sufficient since no loss in system sensitivity has been observed in over 10 months in orbit.

The usable field-of-view of the scanner lens system is 11.6° full angle. Although the lens system is capable of a much larger field-of-view, the intent was to restrict the star intensity variation over the entire field-of-view to less than 0.1 star magnitudes.

The reticle pattern consists of a precisely etched modified "V" slit upon an opaque quartz substrate as shown in Fig. 2. The lens focuses the star image onto the reticle which is at the focal plane. As a star is swept across the reticle by the vehicle rotation, light is transmitted when the star is within the "V" slit. The two slits are used to determine the azimuth and elevation angle of the star transits. The "V" slit when projected through the lens system onto the celestial sphere represents an instantaneous field-of-view (IFOV) area of 0.86 square degrees.

The detector system is a photomultiplier tube. The photocathode surface is the E-type (S-20) tube with 14 dynodes. The detector surface is located 0.3 in. behind the focal plane of the lens

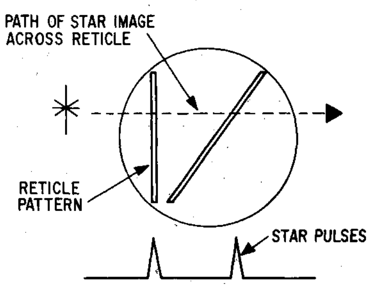

Fig. 2 Reticle geometry

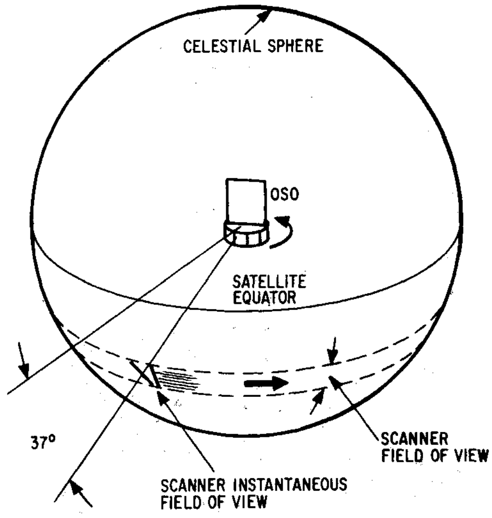

Fig. 3 Scanner field-of-view.

system. The star transits of the "V" slits are converted to electrical signals to be enclosed by the signal processor.

The signal processor filters the star transits, encodes the transit data into digital words, and transfers the stored data upon command from the spacecraft telemetry system. The signal processor detects each star crossing above a ground selectable threshold (8 discrete steps between +1.75 and +3.5 magnitudes). The signal is then filtered as to pulse width (moon discrimination) and crossing with a maximum slit crossing time (slit separation angle). If the data passes both of these tests it is encoded into three 8-bit words containing 14-bits first crossing time, 9 bits second crossing time difference, and 1 flag bit. This data is then stored and shifted out on the next "read-command" from the spacecraft which occurs at the rate of one each 160 msec. The flag data bit is used to indicate when more than one star has transited the IFOV in the time equivalent to the maximum slit separation angle.

System Considerations

The star scanner was designed to provide relatively noise-free data on at least 3 stars per spacecraft revolution. These data were to be obtained in any inertial orientation of the spacecraft as long as the Earth did not block more than half the scanned field-of-view shown in Fig. 3. The major design considerations

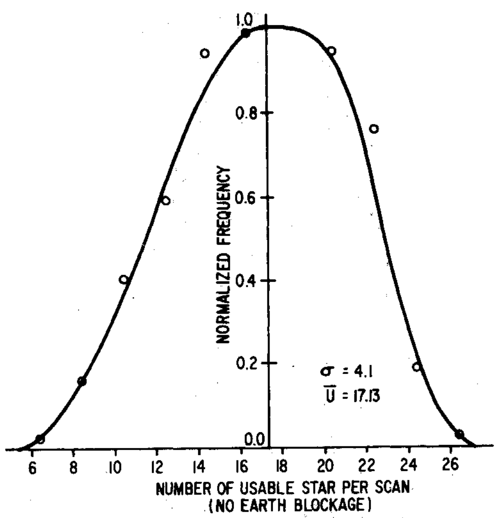

Fig. 4 Star distribution.

were the sensitivity, tilt of the scanner, and the instantaneous field-of-view.

The limiting magnitude was then selected to be +3.5 (S-20 magnitude) based on statistical samples of the possible spacecraft inertial attitudes. It was found that a 10°-wide band at 53° to the spin axis would contain 6 stars per revolution 99.7% of the time as shown in Fig. 4. This analysis did not consider the planets and was, therefore, a conservative design.

The second design consideration was to select the "tilt" of the elevation slit. This tilt angle was selected based on the number of usable stars that could transit both slits before a second star entered the field-of-view (setting the flag bit high). Even though the number of stars continues to increase as the threshold magnitude is made dimmer, the number of usable stars reduces depending on the slit separation angle. This is due to the fact that the star density has reached the point where more than one star transits the IFOV within the maximum separation angle. This would then result in confusion when associating transit times to star azimuth or elevation. The scanner separation angle was set at 5° to allow operation at star densities equivalent to +3.5 magnitude stars.

The third consideration was the choosing of the IFOV area. The detection of a star in the presence of a relatively large background can present many problems to the data encoding as well as the ground identification of the stars. Reference 5 was used to determine the maximum and minimum sky brightness from Zodiacal and Galactic sources. The scanner must still reliably detect a +3.5 magnitude star in the presence of 200–1035 tenth magnitude background stars per square degrees. Figure 5 shows the equivalent star magnitude of the background as a function of the IFOV in square degrees.

The conclusion based on background only is that the smallest IFOV is desired. However, the signal-to-noise ratio and the noise equivalent angle are also effected by the slit width. The electronic bandwidth is determined by the slit width and the spin rate. The net effect on the scanner system is that the noise equivalent angle, which is related to both the width of the slit and the magnitude of the system background noise, improves as the slit width is reduced to nearly the optics resolution. The OSO-7 scanner was then designed to have a minimum IFOV consistent with the lens system.

The major limitation was the physical limitations of the slit manufacturer. Several companies could make very narrow slits but could not hold the tolerance over the long length required (about 0.8 in.). The result was a compromise at 0.86 square degrees. This then set the equivalent magnitude of the background between +2.6 and +4.2 magnitude. Although a small IFOV was desired adequate performance could be expected since in regions of high background density the brighter targets are found. This then allowed the scanner to operate with a brighter

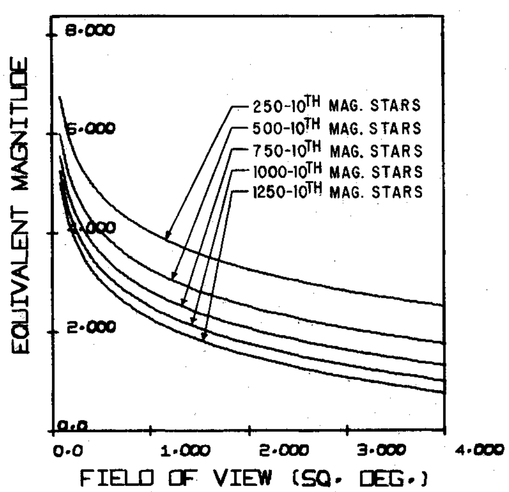

Fig. 5 Equivalent background magnitude.

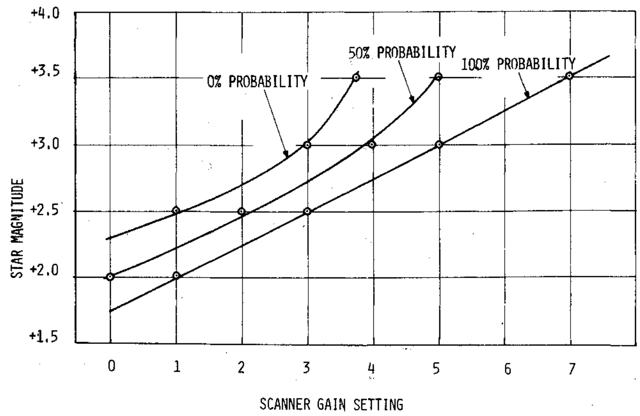

Fig. 6 Probability of detection (no background).

star threshold in high-density attitudes reducing the effect of background noise.

System Performance

The performance of the star scanner was based on the probability of detecting a star in the presence of a simulated background condition. The calibration of both the star and the background was accomplished using a procedure similar to that used on OAO.[6] The flight scanner system was then presented with stars of different magnitude in simulated background conditions. The detection probability was then determined based on the number of proper detections compared to the number of stars presented to the scanner. Figure 6 shows the results of these ground tests for different scanner gain settings and the no-background condition. Figure 7 demonstrates the effect of exposing the scanner to a background equivalent to +3.5 magnitude.

The flight data from OSO-7 indicates that star calibration is within 0.1 magnitude but the background is either not as bad as predicted or there was an error in the simulation of the background. Operational performance of the scanner in orbit is roughly midway between the 50% and the 100% probability curves of Fig. 6 which indicates a background magnitude of +4.0 or less (by ground simulation standards).

Software Description

The process of reducing the data involves removal of noise pulses from the data set, identification of the stellar source of each data point, and statistical estimation of the elements of the attitude state vector from the identical star transits.

The attitude state vector used in the attitude solution may be chosen either as

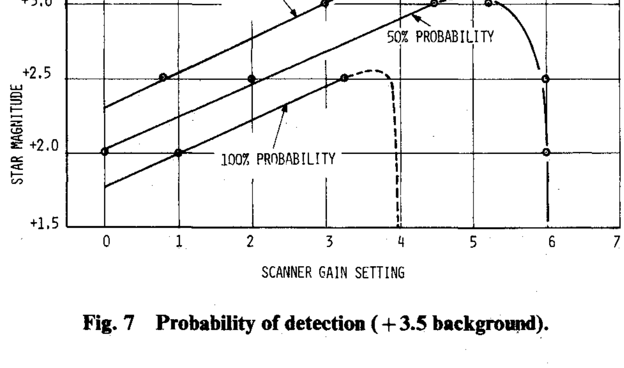

Fig. 7 Probability of detection (+3.5 background).

$$\mathbf{P} = \begin{bmatrix} \phi \\ \eta \\ \beta_s \\ \omega_s \end{bmatrix}, \text{ or as } \mathbf{P} = \begin{bmatrix} \phi \\ \eta \\ \beta_s \\ \omega_s \\ E_0 \\ \gamma \\ \theta \end{bmatrix} \tag{1}$$

The first equation is normally used to solve for the observatory aspect; however, if the spin axis moves relative to the body spin axes, or if it fails to coincide with the body axes, then the second relationship should be used periodically to solve for the slit parameters E_0, γ, and θ.

The transformations between reference coordinate systems are written in terms of direction cosine matrices whose arguments are the Euler angles rotating a vector from the geocentric, inertial system (X_1, Y_1, Z_1) to the slit plane coordinates (X_8, Y_8, Z_8) and (X_9, Y_9, Z_9). T_1 is a rotation about an X axis, T_2 a rotation about a Y axis, and T_3 a rotation about a Z axis.

$$T_1(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix}, \quad T_2(\theta) = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix}$$
$$T_3(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

The problem of solving for the inertial attitude of the spinning spacecraft is, then, the problem of determining the arguments of the Euler angle transformations of Eqs. (3–8). The spacecraft is assumed to spin about an axis that is inertially fixed, defined by the pitch and roll parameters, η and ϕ. The position of spacecraft about that axis is given by the parameters which define the yaw angle B_s—which are β_s, the initial yaw position; β, the yaw offset of the scanner; and $\omega_s t$. E_0, γ, θ then determine the location of the slit planes of the scanner relative to the spacecraft body.

Several coordinate systems are useful in the description of the OSO-7 attitude; (X_0, Y_0, Z_0) is a right-handed, geocentric inertial system with X_0 coincident with the First Point of Aries, Z_0 in the direction of the Earth's rotational pole, both of the epoch of the star catalog. (X_1, Y_1, Z_1) is (X_0, Y_0, Z_0) corrected for the regression of the equinoxes to the epoch of the observation. (X_3, Y_3, Z_3) is a solar oriented system with X_3 in the solar direction, and Z_3 along the pole of the ecliptic

$$\begin{bmatrix} X_3 \\ Y_3 \\ Z_3 \end{bmatrix} = T_3(S)T_1(\varepsilon) \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \tag{3}$$

(X_6, Y_6, Z_6) is a system whose Z axis is fixed along the intended spin axis of the spacecraft, with the X and Y axes in the wheel plane

$$\begin{bmatrix} X_6 \\ Y_6 \\ Z_6 \end{bmatrix} = T_3(B_s)T_2(-\eta)T_1(\phi) \begin{bmatrix} X_3 \\ Y_3 \\ -Z_3 \end{bmatrix} \tag{4}$$

(X_8, Y_8, Z_8) is situated such that X_8, Z_8 lie in the leading slit plane of the star scanner, X_9, Z_9 lie in the trailing slit plane

$$\begin{bmatrix} X_8 \\ Y_8 \\ Z_8 \end{bmatrix} = T_1(\gamma)T_2(E_0 - \pi/2) \begin{bmatrix} X_6 \\ Y_6 \\ Z_6 \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} X_9 \\ Y_9 \\ Z_9 \end{bmatrix} = T_1(\theta) \begin{bmatrix} X_8 \\ Y_8 \\ Z_8 \end{bmatrix} \tag{6}$$

These transformations contain all of the parameters necessary to characterize the attitude of the spacecraft, assuming 1) the wheel spins at a constant rate and 2) the spin axis is inertially fixed. Both of these assumptions are reasonable, for the star scanner is used only during the nighttime period of each orbit when no control gas is expended by the attitude control system and when the servo driving the pointed experiment package is turned off. The transformation to the leading slit plane is then

$$\begin{bmatrix} X_8 \\ Y_8 \\ Z_8 \end{bmatrix} = T_1(\gamma)T_2(E_0 - \pi/2)T_3(B_s)T_2(-\eta)T_1(\phi)T_3(s)T_1(\varepsilon) \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \tag{7}$$

and the transformation to the trailing slit plane is

$$\begin{bmatrix} X_9 \\ Y_9 \\ Z_9 \end{bmatrix} = T_1(\theta) \begin{bmatrix} X_8 \\ Y_8 \\ Z_8 \end{bmatrix} \tag{8}$$

The parameters to be determined in order to solve for the inertial orientation of the body axes (X_6, Y_6, Z_6) are ϕ, η, β_s, ω_s. The parameters E_0, γ, θ may be considered well-known and constants of the problem or may be included in the attitude solution.

Attitude Solution (Parameter Identification)

For each of the slit planes of the star scanner, one may make a first-order Taylor's series expansion about the best-known set of attitude parameters.

Some simplification may be had immediately by noting that at the time of star transit, the star lies in the slit plane, and the vector **r** becomes

$$\mathbf{r}_{,M} = \begin{bmatrix} r_1 \\ 0 \\ r_3 \end{bmatrix} \tag{9}$$

($\mathbf{r}_{,M}$ = observed value at transit time). Then

$$r_{2,\,\mathrm{th}} \simeq r_{2,\,0} + (\partial r_{2,\,0}/\partial \mathbf{P})\,\Delta\mathbf{P} \tag{10}$$

The error for the ith observation is

$$X_i^K = r_{2,\,0}{}^{i,K} + (\partial r_{2,\,0}/\partial \mathbf{P})\,\Delta\mathbf{P} \tag{11}$$

where $K = 1,2$ for the leading and trailing slits, respectively, of the star scanner. The quantity to be minimized, then, is

$$\sum_{K=1}^{2} \sum_{i=1}^{n} (X_i^K)^2 \tag{12}$$

where minimization with respect to the error in the observation leads to the following set of normal equations.[7]

$$A\Delta\mathbf{P} = \mathbf{b} \tag{13}$$

The solution for the vector of differential correction $\Delta\mathbf{P}$ is then

$$\Delta\mathbf{P} = A^{-1}\mathbf{b} \tag{14}$$

After each solution of the normal equations, the attitude vector is corrected where $\mathbf{P}^j$ is the j^{th} estimate of **P**, and $\Delta\mathbf{P}^j$ the j^{th} calculated correction to **P**. The process continues until each of the computed corrections falls below a set level, $\Delta P_i^j \leqslant$ tolerance. After the first few iterations, stars whose residuals exceed 2.5 times the rms value of the residuals are removed from the computation, and the process continues.

Star Identification

Star identification may be done either of two ways in the data reduction computer programs—by comparing the angular separation of pairs of observed stars with the separation of pairs of catalog stars, or by comparing the slit crossing times of data stars with the predicted times for the field-of-view stars. In the former case, more computation must be done, but the technique is somewhat independent of uncertainty in spacecraft attitude.

In the latter case, the star identification is strongly dependent upon knowledge of the direction of the spacecraft spin vector—initial values of pitch and roll attitude angles must be known to about 3°. However, no prior knowledge is required of the yaw angle.

To identify stars by their azimuth position the observatory spin rate is first computed by autocorrelation of the star transit data. The field-of-view annulus is then divided into azimuth bins 0.5° wide and the star transit times reduced modulo the spin period to place each of the star transit data into one of the 720 azimuth bins. The value of β_s which results in a maximum match between the observed star bins and the star catalog bins is then chosen for the initial β_s estimate and each of the transit times is identified with the proper catalog star and star scanner slit. This data is then available to the attitude solution programs. Only stars which are observed in a minimum of three times on at least one slit are retained for use in the attitude solution.

The star transits may also be identified by comparing the total angular separation of pairs of data with the separation of pairs of catalog stars.[2,3] This process has one advantage and two disadvantages compared to the azimuth matching process. First, a larger initial uncertainty in the spin axis orientation may be tolerated, so long as the catalog stars which lie in the scanner field-of-view are included in the search process. However, perhaps ten times the computation is required for this process as is required by the azimuth matching. Further, for a particular star to be identified, at least two transits must be made on each of the slits of the scanner reticle. In regions of the celestial sphere of high star density, this might not occur—a transit time pair (t_1 t_2) is more likely to occur from two stars close in azimuth transiting the first slit successively, than from one star transiting each of the two slits. The azimuth matching technique, however, requires only that a star transit either one of the two slits a minimum of three times during a data block, permitting a greater number of star transits to be identified.

Flight Experience

The star scanner system aboard OSO-H was turned on three days after the spacecraft was launched, on Oct. 2, 1971. Attitude solutions computed for the first data frame (15.36 sec of data) have been computed on a regular basis for the nighttime portion of each orbit since. The original design goal was to compute the pitch, roll, and yaw Euler angles to an accuracy of 6 arcmin (3 σ).

As there is no attitude reference by which the accuracy of the star scanner system may be checked independently, the only accuracy numbers which are available are those generated by the scanner system itself—the computed standard deviations of the solution elements. However, these reflect, besides the noise in the system, the fit of the data to the theoretical model for the spin axis motion. Sample statistics for some data blocks are shown in Table 1.

The computed accuracy of attitude solutions using these data was about one arc minute (one sigma) in each angle. The gain setting of the scanner was 5, permitting observation of stars of magnitude 2.9 or brighter—resulting in 22–27 identified star transits on the leading slit, from 18 to 14 observations on the second slit. There were no improper star identifications in these data.

Table 1 Attitude error (rad)

Date	σ 10^{-3}	σ_η 10^{-3}	$\sigma_{\beta s}$ 10^{-3}	$\sigma_{\omega s}$ 10^{-4}	Stars/ transits
Day 38 15:44:38	0.286	0.407	0.373	0.184	4/31
Day 37 15:45:39	0.173	0.140	0.151	0.145	6/35
Day 37 15:47:42	0.093	0.093	0.085	0.094	5/34
Day 56 6:03:29	0.839	0.359	0.518	0.574	3/21

Fig. 8 Field-of-view stars, mag < 2.9.

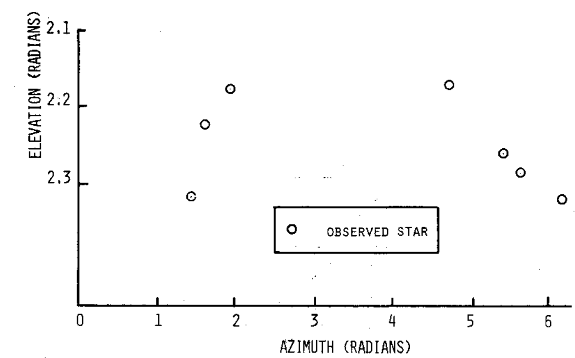

Fig. 9 Field-of-view stars, mag < 2.0.

Figure 8 shows the relative location of stars which lie within the scanner field of view. The open circles indicate observed, identified celestial bodies including three stars and two planets. The dark circles are targets whose data, because of close clustering in azimuth, are flagged by the instrument as suspect targets. Notice that there is a band of azimuth from about 2.0 to 3.7 where there are no targets brighter than 2.9.

Figure 9 shows the same field of view with the gain set such that only targets brighter than 2.0 are seen by the scanner. Here all seven targets (five stars and two planets) are so separated in azimuth that good data could be taken from each, demonstrating that having an adequate set of stellar targets is not a matter of having the sensitivity set high, but rather of choosing a proper gain setting for the star scanner instrument to optimize, both in number and in azimuthal distribution, the stellar target array. The most effective way of determining the goodness of fit of a function to a set of data is by examining the fine structure of the residuals of the data—the difference between the theoretical

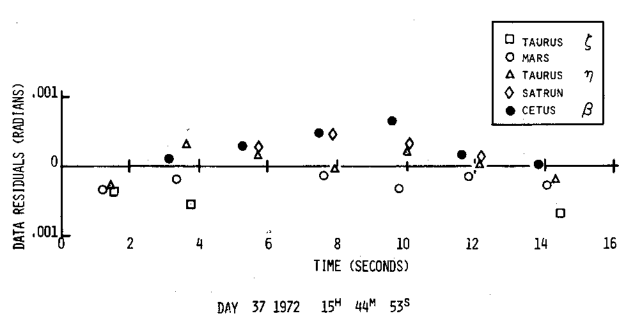

Fig. 10 Data residuals vs time.

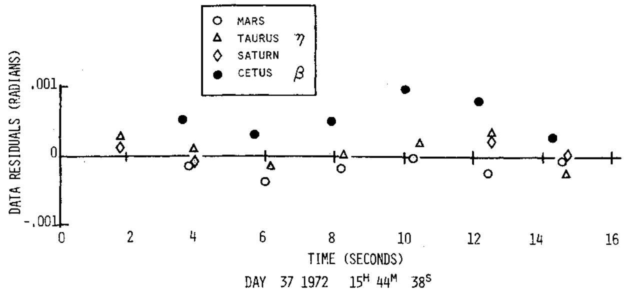

Fig. 11 Data residuals vs time.

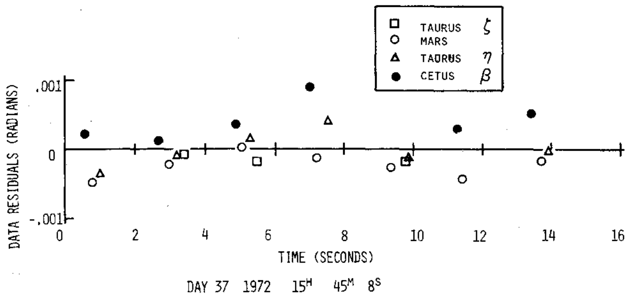

Fig. 12 Data residuals vs time.

value of the fitted function and the measured value. In this case, the function to which the data was fitted was the component of each star vector normal to the slit plane at the time of star transit. If one examines the residual for a particular target, say Mars, over the extent of the data frame, the result is a sinusoid of period approximately 12 sec (Fig. 10).

This is the result of spacecraft nutation. The period is that of the body fixed nutation frequency.[8] The motion is well defined, and could be easily added to the attitude solution. Similarly, the vertical separation of the residual traces for each of the data stars is the result of a small error in the rotational position of the scanner relative to the spin axis (wobble) (Figs. 11 and 12).

If one accounts for the nutation and the wobble of the spacecraft, then the approximate error per data sample is 0.0001 rad, about 22 arcsec. Nutation was not included in the solution for OSO-7 because the predicted nutation amplitude was below the accuracy requirement. However, for accuracies of a fraction of a minute it would be both necessary and easy to include nutation in the solution because the body fixed nutation motion is easily determined from the data.

Conclusions

The OSO-7 Attitude Determination system has demonstrated that with a close-knit hardware design and software data processing the attitude of a spinning spacecraft is easily determined. The very low data rate and the onboard filtering of data has resulted in the nearly real-time attitude solution of the spacecraft attitude. The accuracy of this solution is better than 3 arcmin without modeling such things as nutation and wobble. The accuracy can be significantly better for slower spin rates while at the same time the data telemetry requirements are also reduced. With a telemetry bit rate of less than 150 bits per second, any spinning spacecraft can have this simple attitude determination system.

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