JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 17, No. 3, May–June 1994

Solar Motion-Based Method of Attitude Recovery: Application to International Ultraviolet Explorer

Roberto Gilmozzi*
ESA/Space Telescope Science Institute, Baltimore, Maryland 21218
and
Ronald E. Pitts†
Computer Sciences Corporation, Lanham-Seabrook, Maryland 20706

The International Ultraviolet Explorer is a geosynchronous orbiting telescope launched by NASA January 26, 1978, and operated jointly by NASA and the European Space Agency. The spacecraft was built with six gyroscopes to provide an inertial reference system for spacecraft attitude and control and with prime and redundant mechanical panoramic attitude sensors for coarse attitude determination. Following the failure of the fourth gyroscope in 1985, a new attitude control system was uplinked to the spacecraft using a fine sun sensor and the two remaining gyros for three-axis stabilization. By 1985 both panoramic attitude sensors had failed, and an alternate method developed for coarse attitude determination was not applicable to the newly installed control system. We present here a new method of attitude recovery that uses the relative motion of the sun with respect to the inertial reference provided by the remaining two gyros and that has been employed since 1985. This general technique should be of use to other spacecraft where weight is critical or there is a desire to avoid mechanical devices.

I. Introduction

THE International Ultraviolet Explorer (IUE) is a geosynchronous orbiting telescope launched by NASA January 26, 1978. The telescope is operated in a real-time observing mode for 16 hours a day by NASA from the Goddard Space Flight Center in Greenbelt, Maryland, and for eight hours a day by the European Space Agency (ESA) from the Villafranca del Castillo Satellite Tracking Station near Madrid, Spain. The spacecraft was originally built and is now jointly administered by NASA, ESA, and the United Kingdom's Science and Engineering Research Council (SERC). A description of the spacecraft and science instrument is given by Boggess et al.[1,2] A discussion of the science instrument characteristics and the processing of the raw science data is given by Turnrose et al.[3,4] A complete description of the spacecraft's mechanical and electronic systems is found in the System Design Report.[5,6] A general history of the spacecraft has been written by Boggess et al.[7] and a description of observatory operations given by Fälker et al.[8]

During the 15 years that the spacecraft has been on station, four of the original six gyroscopes, designed to provide the inertial reference required for pointing and slewing the telescope, have failed. Since the failure of the fourth gyro in 1985, an attitude control system has been employed that uses a solid state, two-dimensional fine sun sensor (FSS) to provide the third axis of stabilization. The locations of the gyroscope package at the base of the telescope tube and the FSS arrays on the sunward side of the spacecraft are shown in Fig. 1. A discussion of this two-gyro/FSS control system has been given by Femiano.[9] By 1985, both externally mounted mechanical panoramic attitude sensors (not shown), designed for coarse attitude determination (i.e., to within a few degrees), had failed. An alternate method for coarse attitude determination, then in use, was not applicable to the newly installed two-gyro/FSS control system. A new method, which was developed and is presented as follows, has been tested and successfully used for more than seven years.

II. Astronomical and Spacecraft Coordinate Systems

The standard astronomical coordinate system for expressing positions of stars, planets, and other astronomical sources is the celestial equatorial coordinate system of right ascension and declination (α, δ), which can be pictured as the projection of the Earth's system of longitude and latitude onto the celestial sphere of the sky. There is a celestial equator and north and south celestial poles. The zero point of declination is the celestial equator. The zero point of right ascension is the ascending node of the sun's apparent yearly orbit among the stars (i.e., the ecliptic) as it crosses the celestial equator and is called the First Point of Aries (γ). There is also a second, similar astronomical system that uses the ecliptic equator and ecliptic poles with the corresponding coordinates of ecliptic longitude and latitude (λ, β). Since the β symbol has a differ-

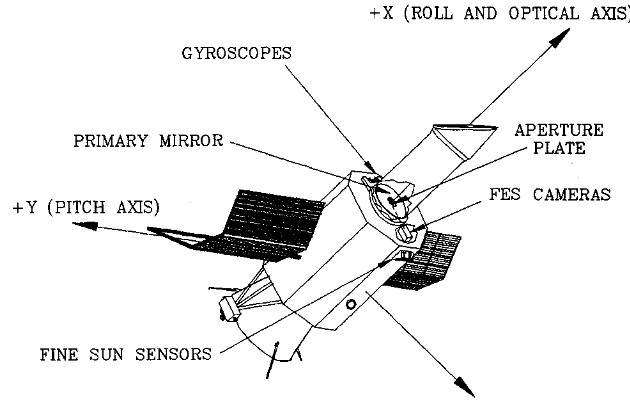

Fig. 1 Control axes of the International Ultraviolet Explorer and its main attitude control sensors. The control system holds the sun in the *X-Z* plane at all times.

Received Aug. 27, 1990; revision received March 9, 1993; accepted for publication March 23, 1993.

*Resident Astronomer, IUE Observatory/ESA; currently Chief, Science Observatory Branch, Science Program Division, 3700 San Martin Drive; affiliated with Astrophysics Division, Space Sciences Department, ESA.

†Resident Astronomer, IUE Observatory/NASA, Astronomy Programs, 10000A Aerospace Road.

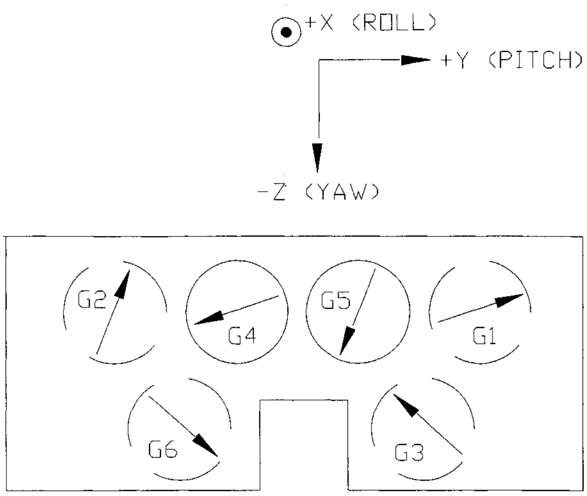

Fig. 2a Relation between the gyro input axes (i.e., direction of maximum sensitivity) and the spacecraft control axes. All gyros are tilted 20 deg with respect to the *Y-Z* plane to allow moderate sensitivity to roll motion of the spacecraft. Gyros 4 and 5 are still operational.

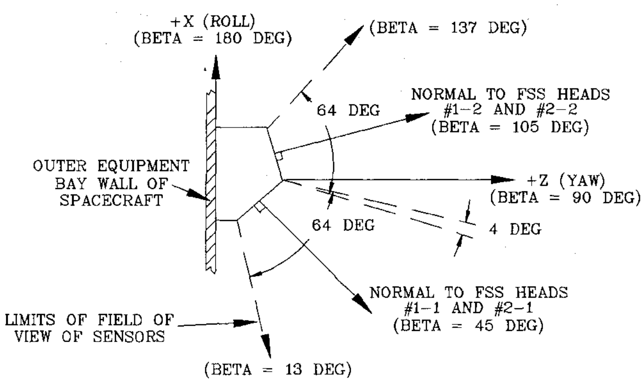

Fig. 2b Relation between the fine sun sensors and the spacecraft control axes. There are four sensor arrays. Each two-dimensional solid state sensor array can sense the solar direction within a square field of view 64 deg on a side centered on the solar normal direction in the *Y-Z* plane. The directions of the centers of fields of view in the *X-Z* plane are shown.

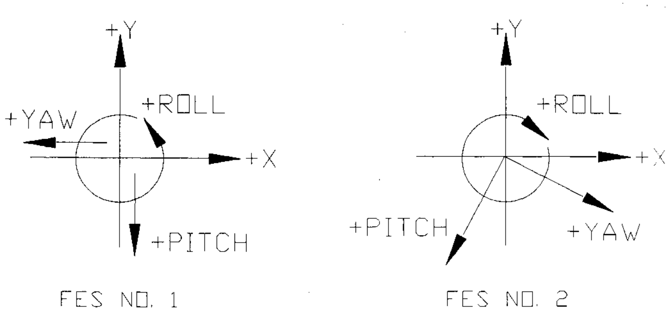

Fig. 2c Relation of the fine error sensors' (FES) fields of view and the directions of stellar motion as the result of motions about the spacecraft control axes. The optical axis of the telescope coincides with the + *X* control axis. The sensors are designed to simultaneously detect small motions about either the *Y* or *Z* spacecraft control axes.

ent meaning in the IUE coordinate system, the symbol b is used for ecliptic latitude throughout this paper.

The IUE spacecraft can move about any one of three independent axes of pitch, yaw, and roll. The system is local and defined in terms of the structure of the spacecraft (see Fig. 1). However, zero points of the IUE system are defined in terms of the position of the sun and the north celestial pole (NCP). Pitch is measured in terms of the beta angle (β), which is 0 deg at antisolar point and 180 deg when pointing at the sun. Roll is measured eastward from the projection of the NCP onto the roll plane of the spacecraft to the positive yaw axis, which always lies in the roll plane and points in the sunward direction. The zero point in yaw is the current pointing of the spacecraft with the sign of the yaw determined by the righthand rule about the positive yaw axis. The orientation of the six gyros with respect to these axes is shown in Fig. 2a. Gyros G4 and G5 are still operational. All gyros are mounted at an angle of 20 deg with respect to the normal of the *Y-Z* plane to allow moderate sensitivity to motion about the roll axis of the spacecraft. The orientation of the FSS arrays is shown in Fig. 2b. There are a total of four arrays, two prime and two backup. The FSS registers nominal sun presence in the β range of 13–137 deg. The current operational range is 28–135 deg. The arrays are two dimensional. At a β of 90 deg, the sensors can detect sun presence ± 32 deg from the *X-Z* plane.

III. Maneuvering the Spacecraft

Standard transformations may be made between the spacecraft and astronomical coordinate systems using Euler angles. These transformations along with the input of a solar emphemeris (i.e., required due to apparent solar motion as IUE orbits the sun) provide the basis for the IUE ground system computer to convert the difference in right ascension and declinations of the current and desired telescope targets into appropriate differences of pitch, yaw, and roll, which are then uplinked to the spacecraft. Because of the slow motion of Earth's axis of rotation (i.e., and thus the NCP), the particular equator and epoch of the equatorial coordinates used in the calculations must be specified. The IUE uses epoch 1950.0 coordinates. For a thorough discussion of spacecraft attitude control and determination see Wertz.[10]

Until recently, earth-based telescopes were built with one axis of the telescope aligned with Earth's axis of rotation. Such telescopes can be moved in the declination axis and set to the particular value of the target. Motion about the polar axis then allows for setting the right ascension and tracking the target star as the Earth rotates underneath the telescope. Since the implementation of the IUE two-gyro/FSS control system, which requires that the FSS face the sunward direction at all times to allow for attitude control, IUE maneuvers from target to target have been made in an analogous manner.

The calculated β of the next target (i.e., a measurement of the pitch angle) is determined and the telescope maneuvered in pitch until the FSS heads read the appropriate value. The telescope is then rotated simultaneously in the yaw and roll axis for the second "leg" of the maneuver such that the β remains constant until the target is reached. The axis of rotation for this "sunline" slew lies about a line from the spacecraft to the sun. The pitch and sunline legs of slews may be done in either order. These maneuvers are generally accurate to within several minutes of arc. Thus the fine error sensor (FES), which in camera mode produces a 15.8 arc minute square image, is all that is needed to confirm final spacecraft attitude and select the actual target by comparing the FES image with a standard star chart of the area.

The FES cameras are located below and to the side of the aperture plate of the telescope, which in turn is located just below the primary mirror (see Fig. 1). FES No. 2 is the prime camera, and FES No. 1 is the redundant camera. Light from the aperture plate reaches the cameras via a passive beam splitter. In camera mode the FES functions as an image disector with a resolution of $\simeq 8$ arcsec. In tracking mode, used during final target acquisition and as an offset guider, the FES has a resolution of 0.25 arcsec. Motion about the control axes of the telescope as seen by the FES cameras is shown in Fig. 2c. The different axes orientations are due to the beam splitter and differing camera alignments with the optical axis of the telescope.

Other than the FSS and several other emergency sensors, the IUE spacecraft has no star trackers or other direct means of measuring absolute position. Infrequently, due to errors in either the onboard or ground computers, spacecraft attitude is lost and an attitude recovery is required. In such cases, although the β of any target may be calculated, the target's position on the sunline circle is unknown. Without a means of determining the coarse attitude pointing to within a few degrees, it would take several days of performing small sunline slews at the current β of a target and taking FES images until the target could be unambiguously located and attitude confirmed.

IV. Methods of Attitude Recovery

The original PAS used the positions of the sun and Earth for coarse attitude recovery and required up to 24 h to perform. It was first replaced with a method that relied on the relationship between the spacecraft axes of pitch, yaw, and roll as well as the celestial equatorial coordinate system of (α, δ). No bibliography exists for this method, developed by Albert Holm and Francis Shiffer, since at the time it was never written down but simply "taught" during the training of new resident astronomers. The method involved pointing the spacecraft to the antisolar position. This position in (α, δ) can be calculated from a solar ephemeris. The β is zero, as is the yaw. All uncertainty is confined to the roll angle (i.e., the direction of the NCP). By matching an FES image of the area to a standard star chart, the roll angle can be estimated. Next a small slew of a degree or two is made to another target, an FES image and star chart are used to locate the target and refine the estimated roll angle of the spacecraft. Finally a slew is made to a third target at a β of 15–20 deg to confirm attitude recovery. The method required several hours to execute, and since attitude was recovered by pointing to the antisolar position, it was named the Betazero method. With the introduction of the two-gyro/FSS control system, the spacecraft could no longer be pointed toward the antisolar point due to lack of sun presence on the FSS heads.

Therefore a second method was developed that also relied on a relationship between the spacecraft axes and the astronomical coordinate systems, but that could be performed at any pointing direction. Since this new method measures the rate of change of β of target stars due to solar motion, it was named the Betadot method. The method typically requires an hour for coarse attitude determination followed by a few more hours of performing small sunline slews and taking FES images until the FES image can be matched to a standard star chart and exact pointing confirmed. The only general requirements are an ability to track the sun, an inertial reference (i.e., at least one good gyro sensitive to pitch), and an imaging camera to identify star fields. All computations are performed by the ground computer, and the final attitude is uplinked to the spacecraft at the end of the recovery.

The method may be of use in spacecraft where weight is critical or there is a wish to avoid mechanical devices for determination of coarse attitude pointing.

V. General Solution for the Betadot Attitude Recovery Method

The general solution involves the measurement of the solar motion as seen by the spacecraft with the solar position and relative motion expressed both in the ecliptic coordinate system (λ, b) and in the spacecraft's coordinate system of pitch, yaw, and roll. A subsequent standard transformation converts the resultant attitude determination from (λ, b) into equatorial coordinates (α, δ) used in star charts and the IUE ground system computer.

The initial problem of solar motion and position in the ecliptic and spacecraft coordinate systems is similar to that of the rate of change of zenith distance and azimuth of a star as

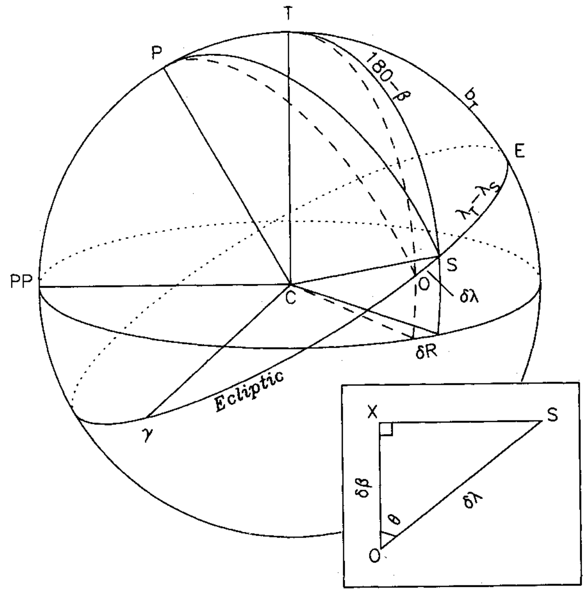

Fig. 3 Ecliptic and spacecraft coordinate systems.

seen by a terrestrial observer given by Smart.[11] Using this as a guide to the IUE problem, we have the following:

Let the position of the sun on the celestial sphere as seen by the spacecraft at point C be point O (see Fig. 3). The motion of the sun is assumed to be eastward along the ecliptic (i.e., counterclockwise as seen from the north ecliptic pole, point P). In time t, the sun moves a small distance along the ecliptic to position S. The spacecraft is pointing at a star at point T. In ecliptic coordinates, the sun's position at S is (λ_S, b_S), where λ_S is the ecliptic longitude in the range of 0 to 360 deg measured eastward from the First Point of Aries (γ) and b_S is the ecliptic latitude in the range of ± 90 deg. Since the sun moves along the ecliptic, $b_S = 0$. The original solar position at point O is ($\lambda_S - \delta\lambda$, 0), where $\delta\lambda$ is small. The target star of the spacecraft, point T, has ecliptic coordinates of (λ_T, b_T).

In the spacecraft coordinate system, the star at point T with the sun at point O has a beta angle of $\beta - \delta\beta$ where $\delta\beta$ is small. The projection of the NCP onto the roll plane is point PP. Measured counterclockwise to the positive yaw axis, which always lies in the sunward direction, the roll angle is $R - \delta R$ where δR is small. At time t later when the sun is at S, the corresponding values are β and R. Yaw is held constant over the time interval t and need not be considered.

Let T be the pole of a spherical coordinate system with the roll circle serving as the fundamental circle and point PP as the zero point of the system. Arc TS lies within the telescope pitch plane and is therefore equal to $(180 - \beta)$. The height of point S above the roll circle can then be expressed as $(\beta - 90)$, and its distance along the fundamental circle is R. The corresponding coordinates at point O are $(\beta - \delta\beta - 90)$ and $(R - \delta R)$.

Because the change in position of the sun from point O to point S is small, triangle OXS can be considered a right 180-deg triangle with sides of $\delta\beta$, $\delta\lambda$, and small circle arc XS. Let θ be the angle TSE. This is then also the angle XOS. With these relationships, let us express the unknown ecliptic telescope coordinates (λ_T, b_T) in terms of β and its derivative $\dot{\beta}$.

The length of small circle arc XS is given by

$$XS = \delta R \cos(\beta - 90) \tag{1}$$

and can also be expressed for small triangle OXS as

$$XS = \delta\lambda \sin(\theta) \tag{2}$$

Combining Eqs. (1) and (2) we have

$$\delta R \cos(\beta - 90) = \delta\lambda \sin(\theta) \quad (3)$$

Also noting that for small triangle *OXS*

$$\delta\beta = \delta\lambda \cos(\theta) \quad (4)$$

and that

$$\sin(180 - \beta) = \sin(\beta) \quad (5)$$

and applying the sine formula to spherical triangle *TSE*, then

$$\sin(\theta) = \sin(b_T)/\sin(\beta) \quad (6)$$

Taking the derivative of Eq. (3) with respect to time, using Eq. (6), and noting that

$$\cos(\beta - 90) = \sin(\beta) \quad (7)$$

we obtain for $\dot{R}$

$$\dot{R} = \dot{\lambda}_S \sin(b_T)/\sin^2(\beta) \quad (8)$$

Next, using the cosine formula for spherical triangle *TSE* we have

$$\cos(180 - \beta) = \cos(b_T) \cos(\lambda_T - \lambda_S) \quad (9)$$

Taking the derivative with respect to time and again applying Eq. (5) yields

$$\dot{\beta} = \dot{\lambda}_S \cos(b_T) \sin(\lambda_T - \lambda_S)/\sin(\beta) \quad (10)$$

With Eqs. (8) and (10), we can now solve for the position of the spacecraft in ecliptic coordinates (λ_T, b_T) and obtain

$$b_T = \arcsin[(\dot{R}/\dot{\lambda}_S) \sin^2(\beta)] \quad (11)$$

and

$$\lambda_T = \lambda_S + \arcsin[(\dot{\beta}/\dot{\lambda}_S) \sin(\beta)/\cos(b_T)] \quad (12)$$

One problem remains in that to avoid ambiguity, we need to have $|\lambda_T\text{-}\lambda_S|$ lie in the range of 0 to 180 deg. Thus we need an expression involving the arccosine. Note that the sun always moves eastward along the ecliptic so that the derivative of λ_S will always be positive. Using this and Eq. (12) implies

$$|\lambda_T - \lambda_S|/(\lambda_T - \lambda_S) = |\dot{\beta}|/\dot{\beta} \quad (13)$$

Solving Eq. (9) for λ_T, applying an angle difference relation, and using Eq. (13), we finally obtain

$$\lambda_T = \lambda_S + (|\dot{\beta}|/\dot{\beta}) \arccos[-\cos(\beta)/\cos(b_T)] \quad (14)$$

Equations (11) and (14) represent the general solution to the problem. The solar position in ecliptic coordinates (λ_S, 0) and the solar rate $\dot{\lambda}_S$ can be determined for any date to sufficient accuracy (i.e., 0.01 deg) by using the low-precision formulae for the sun given in the yearly astronomical almanac.[12] Both $\dot{\beta}$ and $\dot{R}$ are directly measured by the spacecraft.

VI. Solution for the IUE Spacecraft

Although fairly accurate measurements of β and $\dot{\beta}$ can be made using the IUE, measurements of $\dot{R}$ yield only its sign due to the coarse resolution of the measurements. Equation (11) must be rewritten in terms of $\dot{\beta}$ and the sign of $\dot{R}$. Again, since $\dot{\lambda}_S$ is always a positive quantity and using Eq. (11), we have that the sign of b_T is given by

$$|b_T|/b_T = |\dot{R}|/\dot{R} \quad (15)$$

Applying an angle difference relation to Eq. (9) and squaring the equation we have

$$\cos^2(\beta) = \cos^2(b_T) \cos^2(\lambda_T - \lambda_S) \quad (16)$$

Solving Eq. (10) for $\sin(\beta)$ and squaring

$$\sin^2(\beta) = (\dot{\lambda}_S/\dot{\beta})^2 \cos^2(b_T) \sin^2(\lambda_T - \lambda_S) \quad (17)$$

Combining Eqs. (16) and (17), noting that

$$\sin^2(\lambda_T - \lambda_S) + \cos^2(\lambda_T - \lambda_S) = 1 \quad (18)$$

and solving for b_T yields

$$b_T = \arccos[\sqrt{(\dot{\beta}/\dot{\lambda}_S)^2 \sin^2(\beta) + \cos^2(\beta)}] \quad (19)$$

The quantity under the square root is always positive. However, we can combine the relation from Eq. (15) with Eq. (19) to remove the sign ambiguity and obtain

$$b_T = (|\dot{R}|/\dot{R}) \arccos[\sqrt{(\dot{\beta}/\dot{\lambda}_S)^2 \sin^2(\beta) + \cos^2(\beta)}] \quad (20)$$

Thus Eqs. (14) and (20) represent the general solution for IUE.

VII. Conversion of Solution into Standard Astronomical Coordinates

Once the ecliptic coordinates (λ_T, b_T) have been obtained, one can apply a standard transformation to obtain equatorial coordinates of (α, δ). The following are taken from Smart[13]:

$$\sin(\delta) = \sin(b_T) \cos(\epsilon) + \cos(b_T) \sin(\epsilon) \sin(\lambda_T) \quad (21)$$

$$\cos(\delta) \cos(\alpha) = \cos(b_T) \cos(\lambda_T) \quad (22)$$

$$\cos(\delta) \sin(\alpha) = -\sin(b_T) \sin(\epsilon) + \cos(b_T) \cos(\epsilon) \sin(\lambda_T) \quad (23)$$

where ϵ is the obliquity of the ecliptic.

VIII. Effects of Measurement Errors and Some Practical Aspects of Attitude Recovery

At $\beta = 90$ deg, $\theta = b_T$ and the solution for the ecliptic coordinates [i.e., Eqs. (14) and (20)] simplifies to

$$b_T = (|\dot{R}|/\dot{R}) \arccos[\dot{\beta}/\dot{\lambda}_S] \quad (24)$$

and

$$\lambda_T = \lambda_S + (|\dot{\beta}|/\dot{\beta})\pi/2 \quad (25)$$

One can use these formulas to assess the accuracy of the Betadot method. Consider the magnitude of the error on b_T due to the error in the measurement of $\dot{\beta}$ ($\dot{\lambda}_S$ can be calculated to desired accuracy and is not a source of error). Taking the cosine of both sides of Eq. (24) and derivating, one obtains

$$\sigma(b_T) = \sigma(\dot{\beta})/[\dot{\lambda}_S \sin(b_T)] \quad (26)$$

from which it can be seen that the error in the ecliptic latitude determination becomes large for small values of b_T. Figure 4 shows the behavior of $\sigma(b_T)$ for an uncertainty in $\dot{\beta}$ of $\sigma(\dot{\beta}) = 1$ arcsec per hour. This result also suggests a practical attitude recovery strategy. In fact, from Eqs. (24) and (25) it is clear that working at $\beta = 90$ deg offers a clear advantage (i.e., the ecliptic longitude is immediately derived). Moreover, since for small b_T $\dot{\beta}$ will be approaching $\dot{\lambda}_S$ (~ 145 arcsec per hour), a short measurement of $\dot{\beta}$ at the beginning of the recovery will show immediately if $\dot{\beta} \simeq \dot{\lambda}_S$. If this is the case, then $\sigma(b_T)$ will be large. A simple sunline maneuver of ~ 30 deg will take the spacecraft out of the high error zone and also offer an inde-

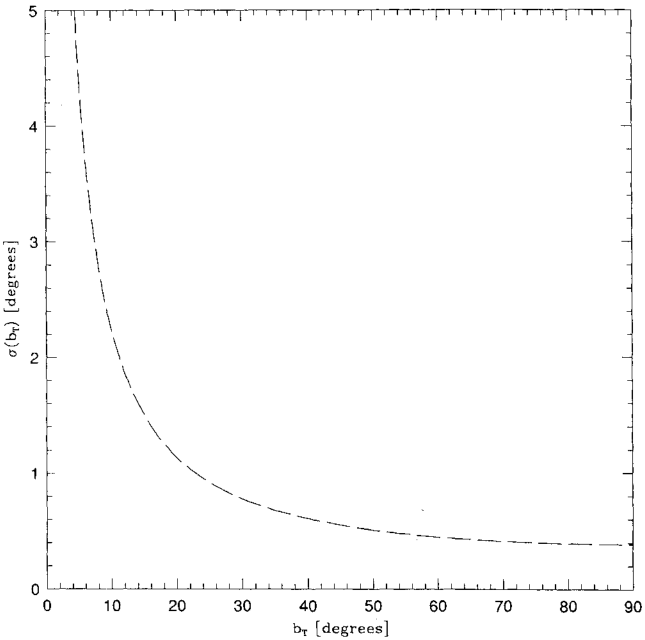

Fig. 4 The behavior of $\sigma(b_T)$ as a function of b_T for an error in the measurement of $\dot{\beta}$ of 1 arcsec per hour.

pendent indication of which ecliptic hemisphere the spacecraft is pointing, thus eliminating the sign ambiguity. Experience over the past seven years has shown that the actual error in b_T, and thus the attitude determination, is typically 1–2 deg, with marginal conditions as large as 3 deg. While the sign of $\dot{R}$ can be measured by tracking a star with the roll axis on gyro control, a much faster method is to cycle the S-band antennas during the intial determination of Betadot. The variation in signal strengths normally allows a quick general determination of how the spacecraft is oriented. Also in practice, successful Betadot recoveries with errors in the range of 1–2 deg have been performed at βs ranging from 60 to 105 deg.

IX. Conclusions

We have developed a new method of attitude recovery for the IUE spacecraft that is based on the measurement of the sun motion as seen by the satellite, and does not depend on any auxiliary hardware. This method can be applied to any spacecraft possessing an inertial frame and the ability to track the sun and to image star fields. The particular formulation for the measurement of solar motion most useful for a particular spacecraft will depend on the hardware configuration of its attitude control system.

Acknowledgments

This work is supported in part by NASA Contract NAS 5-29375. We gratefully acknowledge the significant contributions of the designers, engineers, and software specialists at Goddard Space Flight Center (GSFC), OAO, and Bendix Field Engineering Corporation, who maintain the high productivity of the aging IUE spacecraft, which recently celebrated its 15th anniversary on station. We also wish to thank our colleagues at both the Vilspa and GSFC IUE observatories for useful discussions and for their continuous support. We are particularly indebted to Cathy Imhoff for her significant contribution in the development of the original idea.

References

[1]Boggess, A., Carr, F. A., and Evans, D. C., "The IUE Spacecraft and Instrumentation," *Nature,* Vol. 275, Oct. 1978, pp. 372–377.

[2]Boggess, A., Bohlin, R. C., and Evans, D. C., "In-Flight Performance of the IUE," *Nature,* Vol. 275, Oct. 1978, pp. 377–385.

[3]Turnrose, B. E., Harvel, C. A., and Stone, D. F., "International Ultraviolet Explorer Image Processing Manual Version 1.1," Computer Sciences Corp., CSC/TM-81/6268 under NASA Contract NAS 5-24350, Lanham-Seabrook, MD, Nov. 1981.

[4]Turnrose, B. E., and Thompson, R. W., "International Ultraviolet Explorer Image Processing Manual Version 2.0," Computer Sciences Corp., CSC/TM-84/6058 under NASA Contract NAS 5-27295, Lanham-Seabrook, MD, Dec. 1984.

[5]"System Design Report for the IUE, Vol. I," Goddard Space Flight Center, NASA/GSFC IUE-401-76-099, Greenbelt, MD, Aug. 1976.

[6]"System Design Report for the IUE, Vol. II," Goddard Space Flight Center, NASA/GSFC IUE-401-76-099, Greenbelt, MD, June 1976.

[7]Boggess, A., and Wilson, R., "The History of IUE," *Exploring the Universe with the IUE Satellite,* edited by Y. Kondo, D. Reidel, Dordrecht, The Netherlands, 1987, pp. 3–20.

[8]Fälker, J., Gordon, F., and Sandford, M. C. W., "Operation of a Multi-Year, Multi-Agency Project," *Exploring the Universe with the IUE Satellite,* edited by Y. Kondo, D. Reidel, Dordrecht, The Netherlands, 1987, pp. 21–42.

[9]Femiano, M., "Inflight Redesign of the IUE Attitude Control System," AIAA Space Systems Technology Conference, AIAA Paper 86-1193, 1986, pp. 164–170.

[10]*Spacecraft Attitude Determination and Control,* edited by J. Wertz, D. Reidel, Dordrecht, The Netherlands, 1978.

[11]Smart, W. M., "The Celestial Sphere," *Textbook on Spherical Astronomy,* 5th ed., Cambridge Univ. Press, London, 1971, pp. 48–51.

[12]"Sun, 1988," *The Astronomical Almanac for the Year 1988,* U.S. Government Printing Office, Washington, D.C., ISBN 0 11 886929 9, 1987, p. C24.

[13]Smart, W. M., "The Celestial Sphere," *Text-Book on Spherical Astronomy,* 5th ed., Cambridge Univ. Press, London, 1971, p. 40.