N94- 35618

Spacecraft Attitude Determination Accuracy From Mission Experience*

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Abstract

This paper summarizes a compilation of attitude determination accuracies attained by a number of satellites supported by the Goddard Space Flight Center Flight Dynamics Facility. The compilation is designed to assist future mission planners in choosing and placing attitude hardware and selecting the attitude determination algorithms needed to achieve given accuracy requirements. The major goal of the compilation is to indicate realistic accuracies achievable using a given sensor complement based on mission experience. It is expected that the use of actual spacecraft experience will make the study especially useful for mission design.

A general description of factors influencing spacecraft attitude accuracy is presented. These factors include determination algorithms, inertial reference unit characteristics, and error sources that can affect measurement accuracy. Possible techniques for mitigating errors are also included. Brief mission descriptions are presented with the attitude accuracies attained, grouped by the sensor pairs used in attitude determination. The accuracies for inactive missions represent a compendium of mission report results, and those for active missions represent measurements of attitude residuals. Both three-axis and spin stabilized missions are included. Special emphasis is given to high-accuracy sensor pairs, such as two fixed-head star trackers (FHSTs) and fine Sun sensor plus FHST. Brief descriptions of sensor design and mode of operation are included. Also included are brief mission descriptions and plots summarizing the attitude accuracy attained using various sensor complements.

Introduction

This paper summarizes a report for the National Aeronautics and Space Administration Flight Dynamics Division (FDD) entitled *Attitude Determination Accuracy From Mission Experience* (Ref. 1). The report is a compendium of information about the attitude determination accuracies attained using various sensor complements. It is based on flight data available to the Attitude Section of the FDD at Goddard Space Flight Center. The report is expected to be useful in the early mission planning and design stages for future spacecraft.

The three-axis stabilized missions included in the report are the Upper Atmosphere Research Satellite (UARS); the Heat Capacity Mapping Mission (HCMM); the Gamma Ray Observatory (GRO); the Stratospheric Auroral and Gas Experiment (SAGE); the Ocean Studies Satellite 1 (SEASAT-1); the Solar Maximum Mission (SMM); the Magnetic Field Mapping Satellite (MAGSAT); Dynamics Explorer 2 (DE-2); the Extreme Ultraviolet Explorer (EUVE); the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX); and the Topographic Explorer (TOPEX). The spin stabilized missions included are the Communications Technology Satellite (CTS), Dynamics Explorer 1 (DE-1), the Small Scientific Satellite 1 (SSS-1), the Interplanetary Monitoring Platform 8 (IMP-8), the International Sun-Earth Explorer 3 (ISEE-3), the International Ultraviolet Explorer (IUE), Geostationary Operational

*This work was supported by the National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center (GSFC), Greenbelt, Maryland, under Contract NAS 5-31500.

Environmental Satellites 3 and 5 (GOES-3 and GOES-5), the Atmospheric Explorer 3 (AE-3), the Small Astronomy Satellite 2 (SAS-2), and the Italian Experimental Communications Satellite (SIRIO).

Attitude Sensors

The attitude determination accuracy depends on sensor types, sensor placement, sensor calibration, attitude determination algorithm, data quantity and quality, and mission design. The attitude sensors used on board the three-axis stabilized spacecrafts included in the survey are: the Charge-Coupled Device Star Tracker (CST), the Fixed-Head Star Tracker (FHST), the Fine Sun Sensor (FSS), the Fine-Pointing Sun Sensor (FPSS), the Digital Sun Sensor (DSS), the Horizon Sensor (HS), the Stationary Earth Sensor (SES), and the Three-Axis Magnetometer (TAM). The attitude sensor measurements are propagated using gyro data. CST models CT-601 and CT-401 and the NASA standard star tracker FHSTs are manufactured by Ball Aerospace Systems Group, formerly known as Ball Brothers Research Corp. (Ref. 2). The Sun sensors are manufactured by ADCOLE. The integral horizon scanner/momentum wheel systems are manufactured by Ithaco Corp. Body-mounted horizon scanners and SES systems are manufactured by Barnes Corp. Most spacecraft use fluxgate magnetometers manufactured by Schonstedt Co.

Two types of conventional gyroscopes are used on spacecraft to measure changes in the orientation: rate gyros (RGs) and rate-integrating gyros (RIGs). Usually, several gyros are grouped together in an inertial reference unit (IRU). Most gyros are supplied by Teledyne Systems Company; Bendix Corp.; Honeywell, Inc.; and Northrop Corp. For three-axis stabilized missions, the sensor measurement accuracies ranged from 0.001 to approximately 0.7 degree (1σ). The most accurate sensor is the CST (3 arc sec measurement accuracy, 1σ), followed by the FPSS (5 arc sec, 1σ), the FHST (10 arc sec, 1σ) and the FSS (60 arc sec, 1σ). The DSS has a measurement accuracy of approximately 0.15 degree. Using an Earth infrared emission model, the HS can attain an accuracy of 0.2 to 0.3 degree. The SES can attain an accuracy of approximately 0.1 degree. Due to current Earth magnetic field modeling limitations, TAMs can attain an accuracy of only 0.3 to 0.5 degree (Ref. 2). Further Earth magnetic field modeling refinements may significantly improve accuracy, since the instrument design itself does not impose such a poor accuracy limit.

The advantages of the CST are its high accuracy and its ability to provide enough information for complete three-axis attitude determination. Its disadvantages are its small FOV; Earth, Sun, and Moon interference; its high computational overhead; and little mission experience. The FHST is advantageous for its high accuracy. Except for mission experience, it has the same disadvantages as the CST. The advantages of the FSS are its moderate accuracy and a moderately wide FOV. The disadvantages of the FSS are that it can track only a single target and that it experiences Earth occulatations and horizon distortions. The DSS has a larger FOV but, in addition to the disadvantages of the DSS, a limited accuracy. The HS and the SES need no target acquisition and can take measurements anywhere in orbit. Their disadvantages are their incomplete compensation for seasonal and latitudinal perturbations in the infrared horizon height, their limited accuracy, and their susceptibility to Sun interference. In addition, these sensors can take measurements only when the attitude and orbit are near the design values. The advantages of the TAM are that attitude measurements can be taken anywhere in orbit and that, when combined with gyro data, the TAM measurements provide complete information for three-axis attitude determination with a small amount of data (over time). The TAM suffers from very limited accuracy and significant biases (up to ± 10 mG) that must be removed correctly.

The attitude sensors used on board spin stabilized spacecrafts included in the survey are the single-axis FSS, the single-axis DSS, the V-slit Sun sensor, the single- and multiple-slit star scanner, the Body-Mounted Horizon Sensor (BHS), and the TAM. The single-axis Sun sensors are manufactured by ADCOLE (Ref. 2). The star scanners are manufactured by Ball Aerospace Systems Group and Honeywell. Their accuracies range from 0.02 to approximately 1 degree. The most accurate sensors are the single-axis FSS (60 arc sec, 1σ) and the multiple-slit star scanner (0.033 degree, 1σ). Like the double-axis DSS, the single-axis DSS can attain a measurement accuracy of approximately 0.15 degree. The BHS is similar in performance to the HS, attaining an accuracy of 0.2 to 0.3 degree. The single-slit star scanner achieves an accuracy of approximately 0.3 degree.

The advantages of the multi-slit star scanner are its accuracy, wide coverage, and ability to acquire both angle and phase measurements. Its disadvantages are that it can track only a few targets and suffers from Earth, Sun, and Moon interference. The single- and double-axis FSSs behave similarly, as do the single- and double-axis DSSs. The BHS behaves like the HS. The advantages of the multi-slit Sun sensor are its wide coverage and its ability to acquire both angle and phase measurements. Its disadvantages are that it can track only a single target and experiences Earth occultation.

A single sensor producing a single observation vector (the Earth vector or the Sun vector, for example) does not provide enough information to determine all three axes; therefore, the sensor complements include at least two attitude sensors. Usually, the sensors for three-axis stabilized missions provide two angular measurements. In general, the sensors for spin stabilized satellites provide only one measurement, either the arc length separation between the spin axis and a known reference vector or a rotation angle around the spin axis between two known vectors. Therefore, spin stabilized missions also use at least two attitude sensors.

When selecting the sensors and their placement, care must be taken to avoid Earth, Sun, and Moon interference. In addition, the TAMs should be placed as far away as possible from instruments that generate magnetic fields. Maximum attitude determination accuracy is attained when the instrument boresights are perpendicular, since the attitude uncertainty depends on the sine of the angle between the observations.

The listed accuracies can be achieved only after calibration and in optimum circumstances. Calibration includes alignment and transfer function correction. The launch shock can produce misalignments of about 0.1 degree. Missions requiring attitude accuracy of this order or better require in-flight alignment. The TAM calibration should take into account the effect of magnetic torquer assemblies (MTAs) and other electrical instruments. The HS, SES, and BHS transfer function should model the effect of the infrared horizon height variations due to latitude and seasonal changes.

The attitude determination accuracy also depends on the attitude determination algorithm and the amount of data used. Single-frame solutions are more rudimentary and provide less accuracy than multiple-frame methods such as the batch least-squares and sequential filter methods. Multiple-frame methods require data propagation; therefore, the gyro errors must be included in the analysis. The use of large amounts of data is always recommended, since the random error is inversely proportional to the square root of the number of measurements. Biases and misalignments are to be removed through proper calibration, and anomalous data should be discarded.

A variety of error sources can degrade accuracy. The most important error sources are measurement noise generated within the sensor, residual misalignments, stray light and bright objects, the South Atlantic Anomaly, measurement time uncertainty, star magnitude, near-neighbor interference, variation in the temperature of the Earth atmosphere, Earth atmospheric refraction, telemetry data precision, the Earth magnetic field, the spacecraft residual magnetic field, and bit flipping. Increasing the number of measurements mitigates the first of these error sources, and in-flight alignment reduces the effect of the second. Additional precautions must be taken to mitigate the other error sources. Stray light can disable an FHST. It can induce errors of up to several arc seconds in single-and double-axis FSS measurements (Ref. 3). The error induced in HS and SES measurements can reach up to 0.4 degree. The South Atlantic Anomaly can induce errors of up to 100 arc sec in the FHST position measurements. For 1-rotation-per-orbit missions, the measurement time uncertainty can produce errors of up to 12 arc sec in the FHST and double-axis FSS position measurements.

For spinning missions, the measurement time uncertainty can produce errors of up to 10 arc sec in single-axis FSS measurements and 0.01 degree in multiple-slit star scanner measurements.

In FHSTs, dim star position measurements can have random errors of up to 15 arc sec using a reduced circular field of view (FOV), or up to 25 arc sec through the entire FOV. The FHST position measurement errors quoted are for stars not dimmer than magnitude 5.7. The FHSTs are not designed to track stars dimmer than magnitude 5.7. If used to track stars dimmer than the design limit, the FHST position measurement random errors can be much larger than the values given above. Even when the stars for the mission catalog are carefully selected, near-neighbor stars induce FHST and CST measurement errors of up to 7 arc sec.

Variation in the temperature of the Earth atmosphere can induce errors of up to 0.1 degree in SES measurements and up to 0.3 degree in HS and BHS measurements. Earth atmospheric refraction can produce errors of up to 0.1 degree in single- and double-axis FSS and DSS measurements and of several arc minutes in both FHST and multiple-slit star scanner measurements. The current telemetry data precision is responsible for errors of up to 8 arc sec in FHST measurements, 0.003 degree in single- and double-axis FSS measurements, 0.13 degree in single- and double-axis DSS measurements, 0.005 degree in BHS measurements, and from 0.05 to 0.2 degree in TAM measurements. The modeling errors produced by an Earth magnetic field model of degree 6 or higher can induce errors of up to 1.0 degree in the TAM measurements. Bit flipping can affect any sensor, and the errors can be very large.

Some common techniques used to mitigate the error sources affecting the FHST and CST are providing sunshades; avoiding pointing the instrument near the Sun, Earth, or Moon; limiting the star reference catalog to brighter stars; removing any catalog star with bright neighbors; and correcting sample time for spacecraft rotation. In addition, measurements should be discarded if taken when the target star is near a planet, when the instrument is occulted by the Earth, when the spacecraft is in the South Atlantic Anomaly, or when the target star image is near the Earth limb. To mitigate the error sources affecting the FSS and single-axis FSS, the analyst should discard anomalous data and data acquired when the Sun is near the Earth limb, correct the sample time to reduce the measurement time uncertainty, and consider a large number of observations. To moderate the effect of the error sources affecting the HS and the BHS, the analyst should discard anomalous data, use an Earth radiance model or atmospheric temperature measurements, and select the correct Earth oblateness model.

In addition, attitude determination accuracy can be improved for the SES by changing the operation mode in order to avoid measuring in the quadrant containing the error sources. DSS measurements taken near the Earth limb should not be used. TAMs should not be used in the South Atlantic Anomaly, and the most accurate available Earth magnetic field model should be used for their calibration. TAM calibration should include coupling with magnetic torquers, and the magnetometers should be placed as far away as possible from instruments that generate magnetic fields. Star scanner measurements taken near the Sun, Moon, and Earth limb should not be used. Time corrections and a large number of observations can reduce the effect of the measurement time uncertainty. All anomalous sensor data should be discarded.

The mission design factors affecting the data quality include planned attitude motion and rates, desired pointing directions, planned attitude maneuvers, data rates used for attitude sensors and for the IRUs, spacecraft orbit, launch time, Sun position with respect to the spacecraft, and communication constraints.

Attitude Determination Accuracies From Flight Data

The important attitude results from flight data are presented in Figs. 1–12. Each of these graphs displays the attitude uncertainties corresponding to rotations about the roll, pitch, and yaw attitude axes (Refs. 4–30).

The results presented are generally determined differently for active and inactive missions. For inactive missions, the only information available is contained in reports of mission attitude performance. The best estimate determined from mission reference documents is given. Often, attitude accuracies must be inferred from reports on sensor performance (since sensor performance may be attitude accuracy dependent). Data from inactive missions, especially ones that have been inactive for a considerable period of time, may be less reliable than results for active missions because of inconsistency in the reference sources consulted and methods used for attitude accuracy estimation.

For active missions, information from mission reports can often be supplemented or even replaced by direct measurements of the spacecraft data and the attitudes determined from these data. The most accurate pair of sensors is considered a reference pair. Attitude uncertainty for the reference pair is determined by statistically combining the measured uncertainty of the attitude at epoch (from the Attitude Determination System (ADS)) with known uncertainties that are not included in the ADS attitude uncertainties. The ADS uncertainties chiefly reflect the effects of measurement noise and must be combined with terms reflecting the effects of postcalibration alignment uncertainties, FOV variances, and other parameter uncertainties to provide a more accurate estimate for attitude determination accuracy.

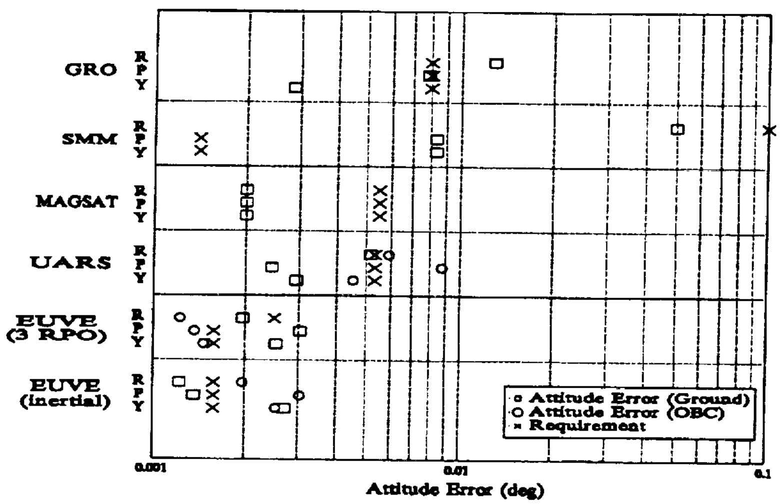

Figure 1. Attitude Accuracies (1σ) Using Two FHSTs

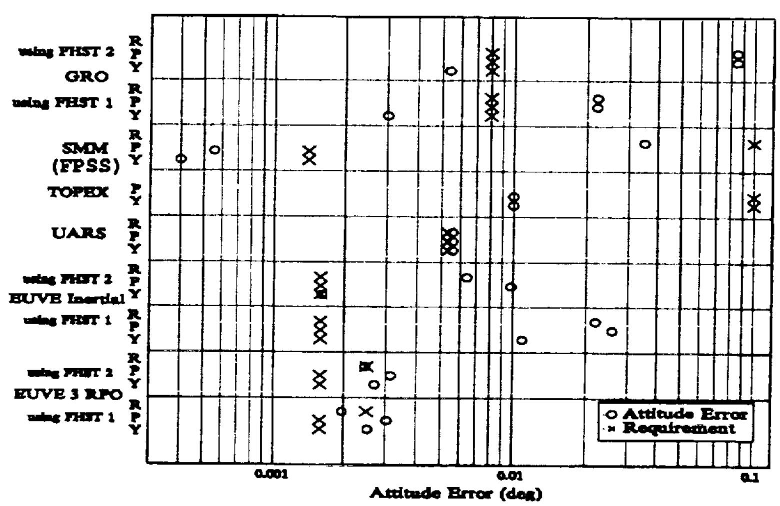

Figure 2. Attitude Accuracies (1σ) Using an FHST and an FSS

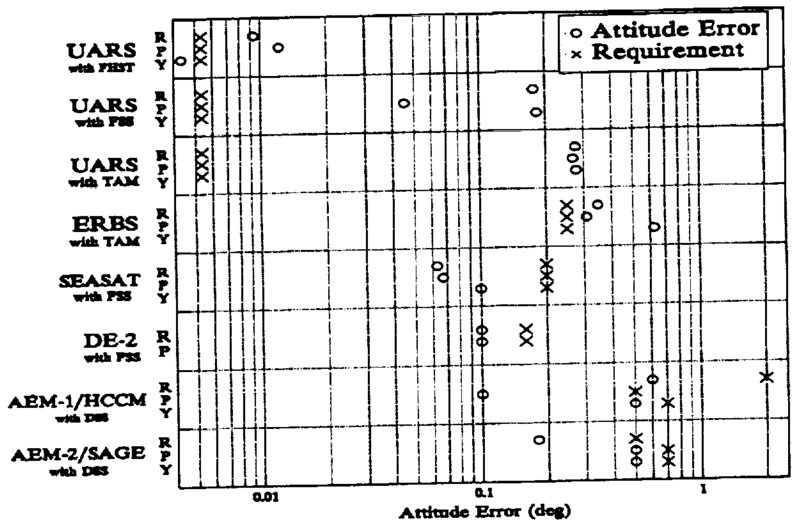

Figure 3. Attitude Accuracies (1σ) Using an HS and Another Sensor (FHST, FSS, DSS, or TAM)

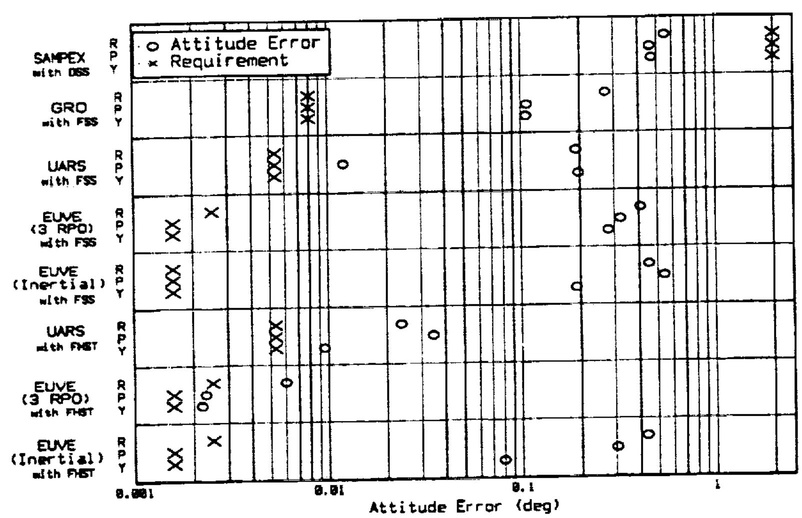

Figure 4. Attitude Accuracies (1σ) Using a TAM and Another Sensor (FHST, FSS, or DSS)

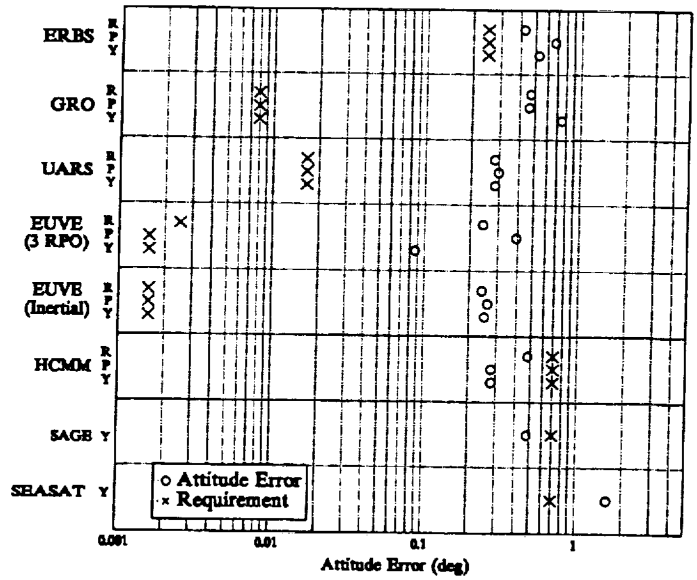

Figure 5. Attitude Accuracies (1σ) Using a TAM and Another Sensor (FHST, FSS, or DSS)

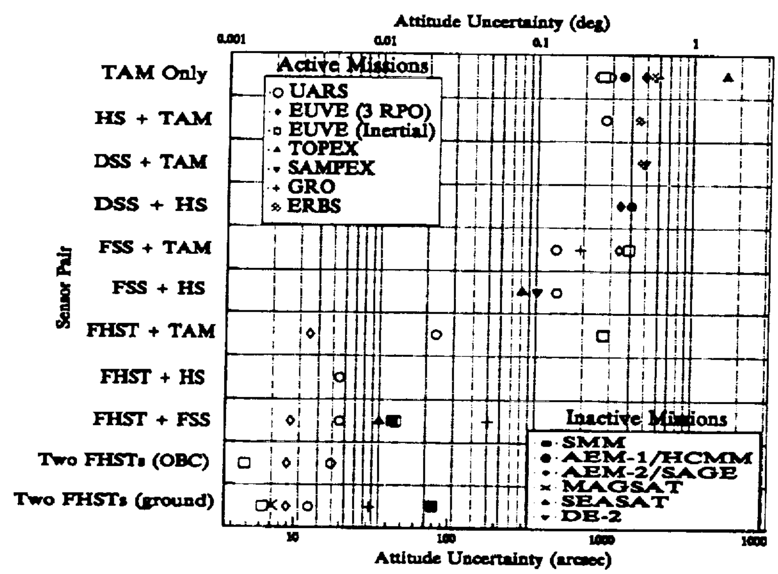

Figure 6. Summary of Three-Axis Stabilized Attitude Accuracies (1σ)

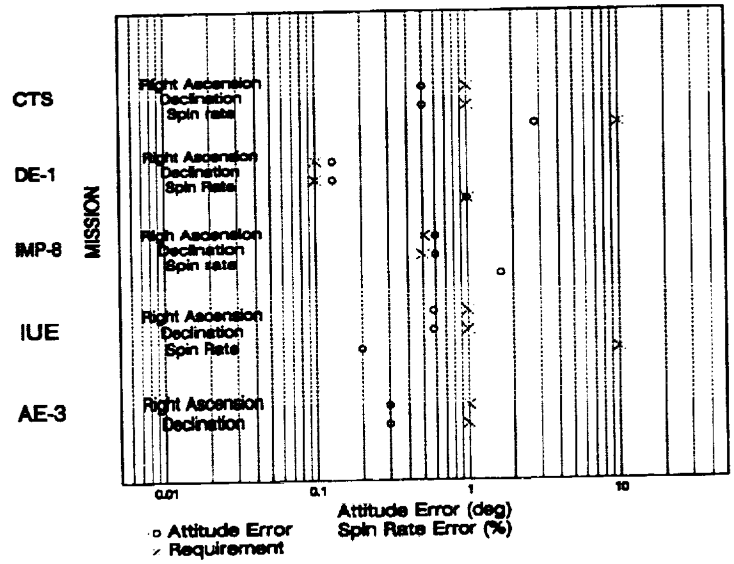

Figure 7. Attitude Accuracies (1σ) of Spin Stabilized Satellites Using a DSS and an HS

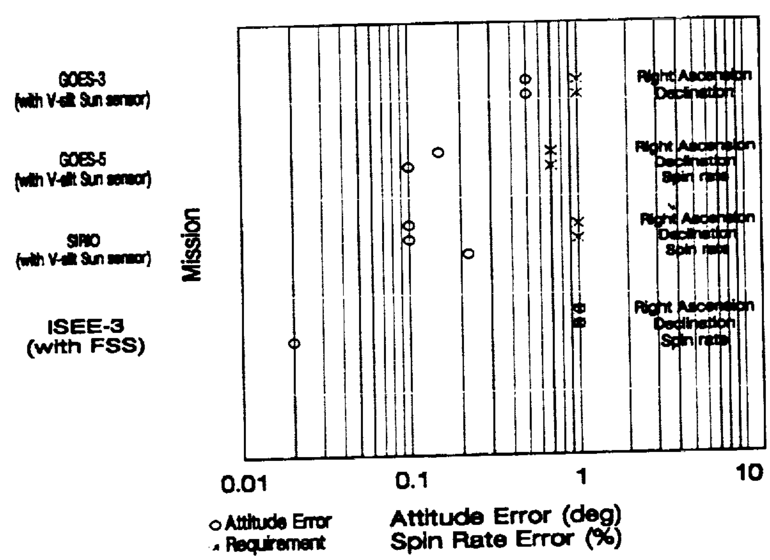

Figure 8. Attitude Accuracies (1σ) of Spin Stabilized Satellites Using an HS and Another Sensor

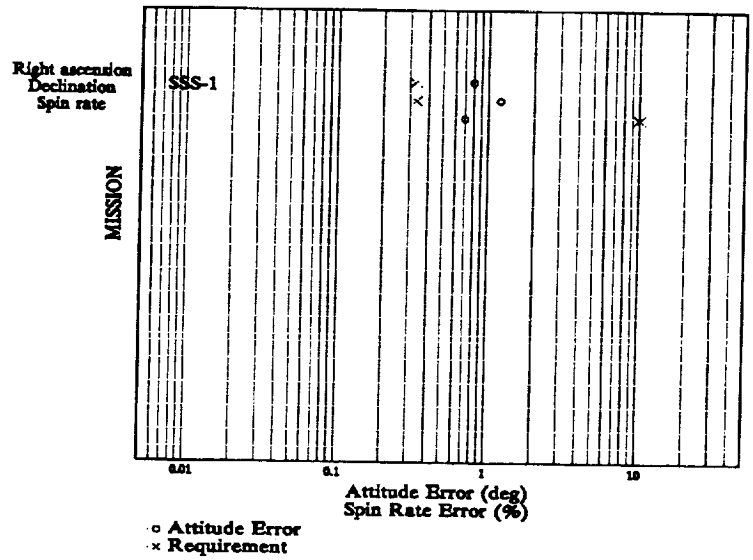

Figure 9. Attitude Accuracies (1σ) of Spin Stabilized Satellites Using a Single-Slit Star Scanner and a Single-Axis DSS

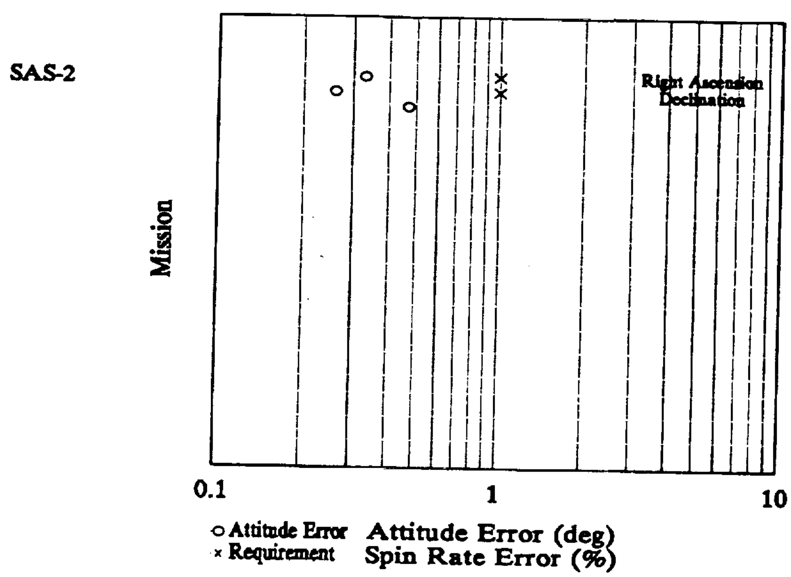

Figure 10. Attitude Accuracies (1σ) of Spin Stabilized Satellites Using a Multiple-Slit Star Scanner and a Single-Axis DSS

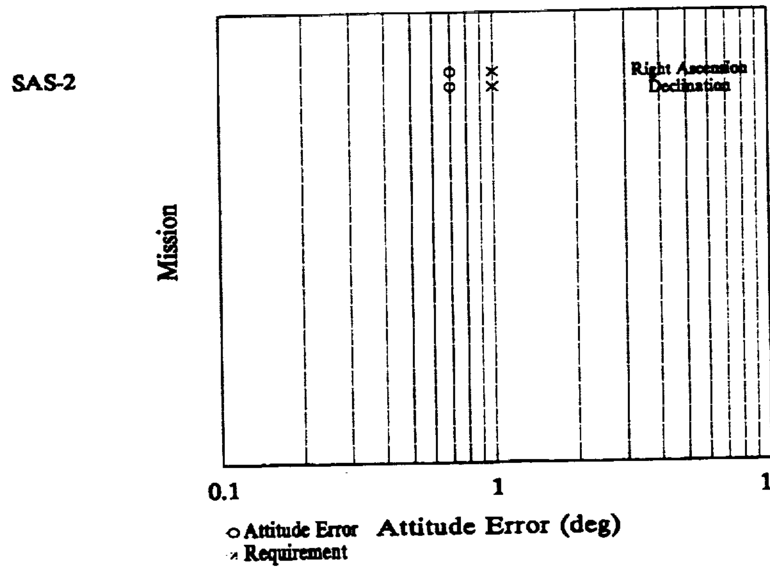

Figure 11. Attitude Accuracies (1σ) of Spin Stabilized Satellites Using TAMs Only

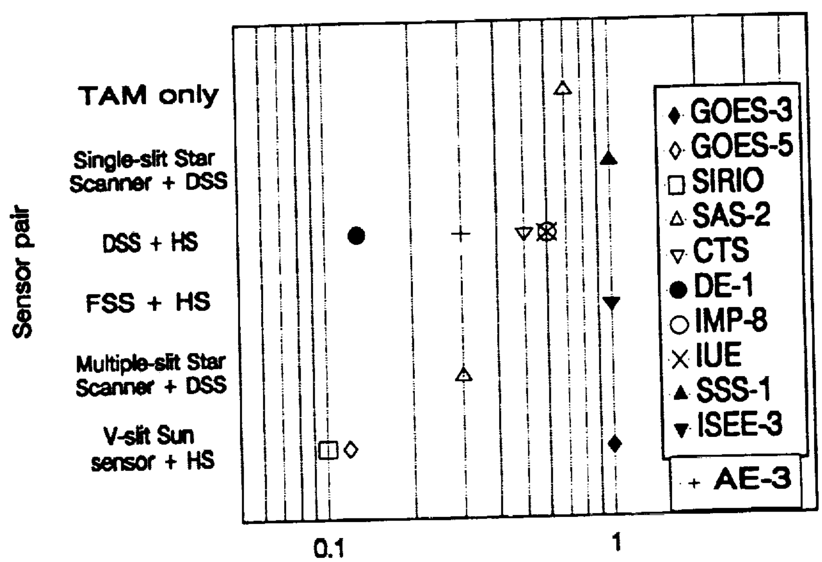

Figure 12. Summary of Spin Stabilized Attitude Accuracies (1σ)

Once reference attitudes have been determined using the most accurate sensor pair, they can be used to estimate the error of less accurate attitudes computed using a less accurate sensor pair. The attitude uncertainty of the less accurate case is determined by statistically combining the root mean square (RMS) attitude residual (between the reference and less accurate attitudes) with the uncertainty in the reference attitude. Attitude accuracies of this type are presented below. In some cases, the reference attitude is not significantly more accurate than the attitude calculated using a different pair. In these cases, because comparison with the reference attitude does not give accurate estimates of attitude error, the attitude accuracy is estimated using the same method as that used for the reference pair.

For the three-axis stabilized missions, the sensor complements analyzed are two FHSTs, one FHST and one FPSS, one FHST and one FSS, one FHST and one HS, one FHST and one TAM, one HS and one FSS, one HS and one DSS, one TAM and one HS, one FSS and one TAM, one DSS and one TAM, and TAMs only. The sensor measurements were propagated using gyro data whenever these data were available. The attitude determination accuracies attained using these sensor complements are shown in Figs. 1-5. Fig. 6 presents a summary of attitude determination accuracies attained by the three-axis stabilized missions surveyed. This plot shows the RMS of the attitude determination accuracies observed per axis. For spinning missions surveyed, the sensor complements analyzed are one single-axis DSS and one BHS, one single-axis FSS and one BHS, one single-axis DSS and one single-slit star scanner, one BHS and one V-slit star scanner, one single-axis DSS and one multiple-slit star scanner, and TAMs only. The attitude determination accuracies attained using these sensor complements are show in Figs. 7-11. The attitude determination accuracies attained in spin-axis stabilized missions are summarized in Fig. 12. RMS values for three-axis stabilized mission attitude determination accuracies ranged between 2 arc sec and 2 degrees (1σ). EUVE and SMM achieved the most accurate attitude determinations: 4 arc sec per axis for EUVE using two FHSTs and 2 arc sec for SMM using an FHST and an FPSS. The spinning missions achieved spin-axis attitude determination accuracies in the 0.1-1.0 degree range (1σ). Among spinning spacecrafts, the best attitude determination accuracies belong to SIRIO and GOES-5 (approximately 0.1 degree) using a V-slit Sun sensor and an Earth sensor.

Missions using two FHSTs attained accuracies in the 4–180 arc sec range. Spacecraft using an FHST and an FPSS attained accuracies between 2 and 120 arc sec. Missions using an FHST and FSS attained accuracies in the 6–300 arc sec range. Missions using an FHST and an HS achieved accuracies ranging from 12 to 40 arc sec. Those using an FHST and a TAM achieved accuracies ranging from 0.002 to 0.65 degree. Spacecraft using an FSS and an HS achieved accuracies between 0.045 and 0.2 degree. Missions using an FSS and a TAM achieved accuracies between 0.1 and 0.6 degree. The DSS plus HS sensor complement produced accuracies in the 0.1–0.6 degree range. The single mission equipped with a DSS and a TAM included in the survey attained an attitude determination accuracy of approximately 0.5 degree. The spacecraft using an HS and a TAM attained accuracies between 0.3 and 0.6 degree. The TAM-only accuracies ranged from 0.09 to 1.1 degree.

Spinning missions using a DSS and an HS achieved attitude determination accuracies in the 0.1–0.6 degree range. The single spinning mission using a single-axis FSS and an HS achieved an accuracy of about 1.0 degree. Those missions using a multiple-slit Sun sensor and an HS attained attitude determination accuracies in the 0.1–0.5 degree range. The single mission using a single-slit star scanner and a single-axis DSS achieved an accuracy between 0.7 and 1.1 degree. The only mission equipped with a multiple-slit star scanner and a single-axis DSS attained accuracies ranging from 0.25 to 0.5 degree. The single spinning mission surveyed that used TAMs only achieved an attitude determination accuracy of 0.7 degree.

Conclusions and Recommendations

The attitude determination accuracy survey included 10 spin stabilized and 11 three-axis stabilized missions. The sensors used by the three-axis stabilized missions include FHST, FSS, the digital Sun sensor, the Earth sensor, and magnetometers. Most of the recent three-axis stabilized missions use gyros to propagate measurement data. The attitude sensors used by the spin stabilized missions surveyed include the single and multi-slit star scanner, single-axis DSS, single-axis FSS, BHS, and TAM.

The overall accuracy of the attitude sensors used on spin-stabilized satellites ranges from 0.02 to about 1 degree (1σ). For the three-axis stabilized missions, the sensor accuracy ranges from about 0.001 to about 1 degree (1σ). The most accurate sensors used on board the three-axis stabilized missions are the FHST, the related CST, and the FPSS. These instruments achieve high accuracy but at high cost.

Because sensors commonly used on three-axis stabilized missions are more accurate than those used on spin stabilized missions, the three-axis stabilized missions achieved the best attitude determination accuracies. For spinning missions, the attitude determination accuracy ranged from 0.1 to 1 degree (1σ). For three-axis stabilized missions, the attitude determination accuracy ranged from 0.001 to 3 degrees (1σ).

The following recommendations are offered based on the above analysis and experience. These recommendations cannot be considered absolute rules because of the mission design factors mentioned above, which may or may not be negotiable (spacecraft altitude and inclination, for example). However, these recommendations may still serve as useful general guidelines for mission planning. To reduce cost, 1-revolution-per-orbit missions that require an attitude determination accuracy of less than 0.2 degree (1σ) could use digital Sun sensors and horizon sensors. To attain the same accuracy, inertial missions could use digital Sun sensors and magnetometers.

For attitude determination accuracies of less than 0.1 degree, FHSTs or CSTs are required. If an attitude determination accuracy of less than 5 arc sec is required, CSTs and fine-pointing Sun sensors are recommended. Spin stabilized missions that require an accuracy no better than 0.2 degree could use horizon sensors and digital Sun sensors. If a spin-axis determination accuracy of better than 0.2 degree is required, a multi-slit star sensor and a single-axis fine Sun sensor could be used. Missions requiring an attitude determination accuracy no better than 0.4 degree could use magnetometers only.

Multi-frame algorithms are recommended for missions requiring attitude determination accuracies of 0.1 degree or better. Large amounts of data (at least several hundred measurements) should be used. Error source mitigation techniques should be used routinely. IRU errors should be taken into account. In-flight alignment (Refs. 31–33) and transfer function calibration is recommended for missions requiring an attitude determination accuracy of 0.1 degree or better.

References

1. Goddard Space Flight Center, Flight Dynamics Division, 553-FDD-93/098R0UD0, *Sensor Studies Task Spacecraft Attitude Determination Accuracy From Mission Experience*, D. Brasoveanu (CSC), J. Hashmall (CSC), and D. Baker (GSFC), prepared by Computer Sciences Corporation, January 1994

2. J. R. Wertz, ed., *Spacecraft Attitude Determination and Control*, Dordrecht: D. Reidel Publishing Company, 1985

3. Computer Sciences Corporation, CSC/TM-77/6264, *SIRIO Attitude Analysis Postlaunch Report*, L. C. Chen and J. J. McEnnan, October 1977

4. ———, CSC/SD-77/6017UD1, *Applications Explorer Mission-A/Heat Capacity Mapping Mission (AEM-A/HCMM) Attitude System Functional Specifications and Requirements*, R. Byrne, J. S. Legg, J. W. Wood, et al., January 1977

5. ———, CSC/TM-78/6221, *Applications Explorer Missions-A/Heat Capacity Mapping Mission (AEM-A/HCMM) Postlaunch Report*, D. Niebur, F. Baginski, and R. Byrne, September 1978

6. ———, CSC/TR-84/6008, *Infrared Horizon Sensor Modeling for Attitude Determination and Control*, T. H. Lee, M. C. Phenneger, S. P. Singhal, and T. Stengle (GSFC), November 1984

7. ———, CSC/TR-79/6008, *SEASAT-1 Postlaunch Attitude Analysis*, S. Bilanow, K. W. Chan, G. F. Manders, and M. C. Phenneger, June 1979

8. ———, CSC/TM-79/6073, *AEM-B/SAGE Attitude Analysis*, C. B. Spence, G. Lerner, D. Niebur, et al., March 1979

9. ———, CSC/TM-79/6223, *Application Explorer Missions-2/Stratospheric Aerosol and Gas Experiment (AEM-2/SAGE) Postlaunch Report*, D. P. Niebur, September 1979

10. ———, CSC/TM-81/6043, *MAGSAT Infrared Horizon Scanner Data Evaluation Report*, S. Bilanow, March 1981

11. ———, CSC/SD-78/6077UD1, *MAPS/MAGSAT Attitude System Functional Specifications and Requirements*, M. B. Baker, R. N. Collier, Y. S. Hoh, et al., September 1978

12. ———, CSC/TM-81/6036, *High Precision Attitude Determination for MAGSAT*, G. Abshire, R. McCutcheon, G. Meyers, et al., April 1981

13. Goddard Space Flight Center, Flight Dynamics Division, FDD/553-90/016, *Solar Maximum Mission (SMM), Summary of Operational Attitude Support*, D. S. Pitone (CSC), prepared by Computer Sciences Corporation, April 1990

14. OAO Corporation, *Dynamics Explorer-A and -B Attitude System Functional Specification and Requirements*, December 1979

15. Computer Sciences Corporation, CSC/TR-85/6703, *Earth Radiation Budget Satellite (ERBS) Attitude Support Postlaunch Report*, E. Burges, R. Pendley, and J. Rowe, August 1985

16. ———, CSC/SD-82/6013, *Earth Radiation Budget Satellite (ERBS) Attitude Ground Support System (AGSS) Functional Specifications and Requirements*, B. Fang, K. Liu, M. Radomski, and S. Smith, September 1982

17. Goddard Space Flight Center, Flight Dynamics Division, 554-FDD-91/114R0UD0, *Gamma Ray Observatory (GRO), Flight Dynamics Analysis Team Support, Postlaunch Report*, L. Kulp (CSC), prepared by Computer Sciences Corporation, February 1992

18. Computer Sciences Corporation, CSC/TR-89/6022, *Gamma Ray Observatory (GRO), Flight Dynamics Support System Specifications: III. Mathematical Specifications, Revision 1*, L. Snyder, March 1989

19. ———, CSC/TM-76/6001, *Communications Technology Satellite (CTS) Attitude Analysis and Support Plan*, M. Joseph, J. Oehlert, G. Page, et al., February 1976

20. ———, CSC/TM-76/6104, *Communications Technology Satellite (CTS) Postlaunch Report*, P. M. Smoth and G. K. Tandon, May 1976

21. ———, CSC/TR-73/6022, *Evaluation of SSS-1 Star Sensor Attitude Determination*, D. F. Alderman, B. M. Beard, H. S. Gotts, and J. E. Kronenfeld, September 1973

22. ———, CSC/TM-79/6061, *ISEE-3 Attitude Postlaunch Report*, P. Batay-Csorba and J. N. Rowe, April 1979

23. ———, CSC/TR-78/6102, *International Sun-Earth Explorer-C (ISEE-C) Attitude Analysis and Support Plan*, J. N. Rowe, P. A. Batay-Csorba, S. K. Hoven, and G. Repass (Goddard Space Flight Center), May 1978

24. ———, CSC/TM-78/6072, *IUE Attitude Analysis Postlaunch Report*, S. Bilanow, W. Boughton, C. Hsieh, and J. McEnnan, March 1978

25. ———, CSC/TM-77/6305, *International Ultraviolet Explorer Attitude Analysis and Support Plan*, D. R. Sood, December 1977

26. ———, CSC/TM-78/6198, *Flight Dynamics Postflight Report for the Geostationary Operational Environmental Satellite-3 (GOES-3)*, W. Boughton and D. Haley, September 1978

27. ———, CSC/TM-81/6149, *Geostationary Operational Environmental Satellite-5 (GOES-5) Attitude Postlaunch Report*, S. Bilanow, H. L. Hallock, R. McCuthcheon, et al., July 1981

28. ———, CSC/TM-75/6004, *Horizon Sensor Behavior of the Atmosphere Explorer-C Spacecraft*, C. F. Gartell, M. E. Plett, and K. S. Liu, May 1975

29. ———, CSC/TM-74/6158, *SAS-2 Attitude Processing Study*, V. Norrod, May 1978

30. Goddard Space Flight Center, Flight Dynamics Division, FDD/544-90/121, *Study of the Earth Albedo Interference on Sun Sensors*, H. Arabshahi (CSC), D. Brasoveanu (CSC), and M. Phennegar (CSC), prepared by Computer Sciences Corporation, September 1990

31. M. D. Shuster, D. S. Pitone, and G. J. Bierman, ''Batch Estimation of Spacecraft Sensor Alignments: I. Relative alignment Estimation,'' *Journal of the Astronautical Sciences*, Vol. 39, No. 4, pp. 519–546, October–December 1991

32. M. D. Shuster and D. S. Pitone, ''Batch Estimation of Spacecraft Sensor Alignments: II. Absolute Alignment Estimation,'' *Journal of the Astronautical Sciences*, Vol. 39, No. 4, pp. 547–571, October–December 1991

33. M. D. Shuster, ''Inflight Estimation of Spacecraft Sensor Alignment,'' *Advances in the Astronautical Sciences*, Vol. 72, pp. 252–274, 1990

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