Development of a Direct Match Technique for Star Identification on the SWAS Mission

Walter K. Daniel
IthacoTechnical Services
Lanham, Maryland, USA

Thomas E. Correll
Mark O. Anderson
Attitude Control and Stabilization Branch
Special Payloads Division
NASA Goddard Space Flight Center
Greenbelt, Maryland, USA

A direct match technique for star identification was developed for use with the star tracker on the SWAS spacecraft. In this technique, tracker searches are used in a two-step process for an implicit direct match star identification. A simulation of the star acquisition process was created and used in the preparation of guide star selection requirements. Flight software implementing this star acquisition technique has been developed and tested.

INTRODUCTION

The Submillimeter Wave Astronomy Satellite (SWAS) is a three-axis stabilized stellar-pointing spacecraft set for launch in July 1995. This mission is the third to be developed under the Small Explorer (SMEX) program. The scientific instrument is a submillimeter wave detector coupled with a spectrometer. The 3σ pointing requirements for this mission are 57 arcseconds about the X- and Y-axes and 28.5 arcminutes about the Z-axis.

SWAS ACS MODES

The SWAS Attitude Control System (ACS) must progress through other modes before star acquisition can begin. After separation from the Pegasus XL launch vehicle, analog electronics in the SWAS Attitude Control Electronics (ACE) Box will utilize a simple B-dot and precession controller to reduce body rates and point the solar panels at the Sun. After the flight computer has been activated and checked out, the ACS will be commanded to Digital Sun Pointing mode, a software version of the B-dot/precession controller.

The next mode is Inertial Sun Pointing (ISP) in which attitude determination is accomplished using a magnetometer, sun sensor, gyroscopes, and a Kalman filter. During ISP, the spacecraft

Z-axis is pointed at inertial targets near the North and South ecliptic poles. These targets ensure sufficient illumination of the solar panels in addition to satisfying instrument Earth limb avoidance requirements. When the spacecraft is North of the ecliptic plane, the North target is used; when South of the plane, the South target is used.

ISP pointing prepares the ACS for transition into Auto-Stellar Acquisition (ASA), a Stellar Pointing submode. During ASA, the spacecraft z-axis is pointed at the same North and South ecliptic pole targets, but attitude determination is accomplished with the star tracker, gyroscopes, and Kalman filter. ASA serves two purposes: to ease the transition from ISP to Stellar Pointing and to provide an attitude hold function when science targets have been missed.

There are three types of observations available during Stellar Pointing: Fixed, Nodding, and Mapping. Fixed observations require the ACS to maintain pointing of the instrument on a target. Nodding observations require that the ACS slew the spacecraft between on-source and off-source attitudes in order to allow for instrument calibration; the maneuvers can be up to 3.0° and the spacecraft must be settled to within 20 arcseconds in 15 seconds. Nodding and Mapping observations are similar except that maps comprise several points in a two-dimensional pattern. The ACS incorporates an efficient nonlinear slewing controller for timely maneuvering of the spacecraft between observational targets. A scientific timeline of the targets is uploaded to the spacecraft and the slew controller computes the approapriate slew to the next target on board.

SWAS STAR TRACKER

The star tracker on the SWAS spacecraft is a Ball Aerospace CT-601 CCD-based device. This tracker has a field of view of approximately 8.0° by 8.0° and can track up to five stars at once. Stars with instrument magnitudes between 1.0 and 6.0 can be located; the device will track any star brighter than the magnitude specified for a search. The basic CT-601 includes a Full Field search that continuously scans for stars in the field of view and a Directed search that locates stars in small 8.0 arcminute square windows. The SWAS tracker also includes a Reduced Field of View (RFOV) search that functions like the Full Field search but is of selectable size and location.

The star tracker reports positions of stars in terms of two angles α and β from the boresight of the device. The ACS flight software uses star unit vectors, so the tracker angles are converted to vectors and unitized. The equation that relates the angles to a vector is

$$S = -\tan(\beta)\, \mathbf{i} + \tan(\alpha)\, \mathbf{j} + \mathbf{k}$$

where S is the star vector in the tracker frame, α and β are the tracker angles, and **ijk** are the unit vectors for the star tracker axes. Equations for computing tracker angles from a unit vector are

$$\alpha = \arctan(y/z)$$
$$\beta = -\arctan(x/z)$$

where x, y, and z are the components of the unit vector.

Testing of the star tracker and acquisition algorithms required equipment for stimulating the detector as well as simulating the tracker output. The CT-601 includes a small LED bonded in the optics that simulates a star; this device is under the control of the tracker microprocessor and is referred to as the Built-In Test Equipment (BITE) star. Ball also provided an external LED stimulator that fits over the tracker lightshade. Light from each of the five LEDs is focused by lenses to approximate point sources. Brightness of the five LEDs is controlled by an independent GSE computer. When dynamic simulator testing of the ACS is performed, a star tracker simulator is connected to the SWAS 1553 bus while the actual tracker is powered off. The star tracker simulator receives attitude quaternions from the dynamic simulator and star tracker commands from the flight computer, computes which stars are tracked, and sends the simulated star tracker data to the flight computer via the 1553 bus.

SWAS GUIDE STAR CATALOG

The CT-601 star tracker is a new device, so a new star catalog with the appropriate instrumental magnitudes was developed by the SWAS principal investigator's institution [1]. Personnel at the Smithsonian Astrophysical Observatory (SAO) converted the magnitudes in the Bright Star Catalog to CT-601 instrumental magnitudes to form the bulk of the SWAS star catalog. The magnitude conversion was developed by SAO based on test data from Ball. Stars from other catalogs were used to add dimmer visual stars that will appear bright enough to the CT-601 to be tracked. Those stars that were not suitable for use by the CT-601 (e.g., multiples) were flagged as unsuitable for use as guide stars. Locations for all stars were computed for 1996.5, approximately one year into the planned SWAS mission. As of early 1995, the SWAS star catalog contained approximately 4500 entries.

The star catalog is not stored on the SWAS spacecraft. The five stars for the two ASA targets are contained in EEPROM and loaded into memory whenever the flight computer performs a cold start. A unit vector in the J2000 frame and a CT-601 instrumental magnitude for each of the two to five guide stars for a scientific target are inserted into the Fixed, Nodding, or Mapping command for observing that target. If instrument magnitude errors are found during the mission, the errors can be corrected in the SWAS catalog so that future uses of those guide stars will be successful. Early in the mission, the star tracker will be powered on during ISP to gather observations of stars that will be used to validate magnitude conversion before star acquisition is attempted.

TWO-STEP STAR ACQUISITION

There are two types of star acquisitions: Auto-Stellar from ISP and Stellar or Auto-Stellar from a previous target. An accurate attitude solution is available for each type, so a direct match star identification technique [2] was used. The acquisition sequence is completed in two steps.

The first step in the star acquisition sequence is begun when the onboard attitude solution is within 100 arcseconds of the target attitude. The flight software formulates a RFOV search and

sends a command to the tracker via the 1553 bus. This search is designed to find a relatively bright, isolated star that is referred to as the "base" star. Ideally, the base star is located near the center of the FOV and is the brightest guide star for that target. When the tracker begins tracking one or more stars, the flight computer attempts to match the base star by magnitude. The flight software computes the α and β offsets between the predicted and observed positions of the matched base star, essentially the attitude errors about the x and y axes of the tracker. The z attitude error is almost unobservable near the center of the FOV, so it is assumed to be zero. This assumption is made using the nature of the attitude errors and the geometry of the spacecraft; note that this technique is equivalent to improving the attitude estimate by using just one observation.

The second step of the star acquisition sequence takes place after the base star is matched by magnitude. The α and β offsets are added to the predicted positions of the remaining "field" stars for the target. One Directed Search command for all field stars in the FOV is sent to the tracker with the improved position estimates based on the base star observation. The Directed Search windows are rather small (8.0 arcmin square) and only one star can be tracked in each. The finite size of these windows means that star can still be found if the z attitude error is nonzero (but still small). After one or more field stars are acquired and matched by magnitude, Kalman filter updating of the onboard attitude quaternion is begun.

Apart from magnitude matching, no explicit star identification is performed in this sequence. Star identification is implicit based upon the isolation of the base star and the small size of the Directed Search windows (see Figure 1). Magnitude matching is relatively loose because of the unknown nature of the CT-601 performance on orbit as well as the unproven SWAS guide star catalog. Early in the mission, search commands will be sent for stars 1.0 magnitude dimmer than expected and the magnitude matching range will be ± 0.75. With experience on orbit, the matching range may be reduced to make guide star selection easier.

GUIDE STAR SELECTION CRITERIA

For a star acquisition to be successful, the base star must be selected so that no other star within the magnitude matching range may appear in the RFOV window. Of course, the base star itself must be in the window. There are two valid approaches to choosing this window size: finding the largest window that the guide stars will support or setting the window larger than the expected attitude error at the beginning of the star acquisition. In addition to base star requirements, there are separation requirements for the field stars to ensure an accurate attitude solution.

Consider a RFOV window of size 2R by 2R (see Figure 2). If the window is centered on the predicted position of a base star, the attitude solution can be in error by as much as the angle R. To determine the maximum exclusion angle, consider the worst case misidentification (see Figure 3). If the base star is on the edge of the circle towards one corner, the farthest location in the search window from the base star is 2.414R away in the opposite corner. In the worst case, one star could be 0.75 magnitude brighter than predicted while another could be 0.75 dimmer, so the magnitude exclusion amount is 1.5 instrument magnitude. If a star within 1.5 magnitudes is an
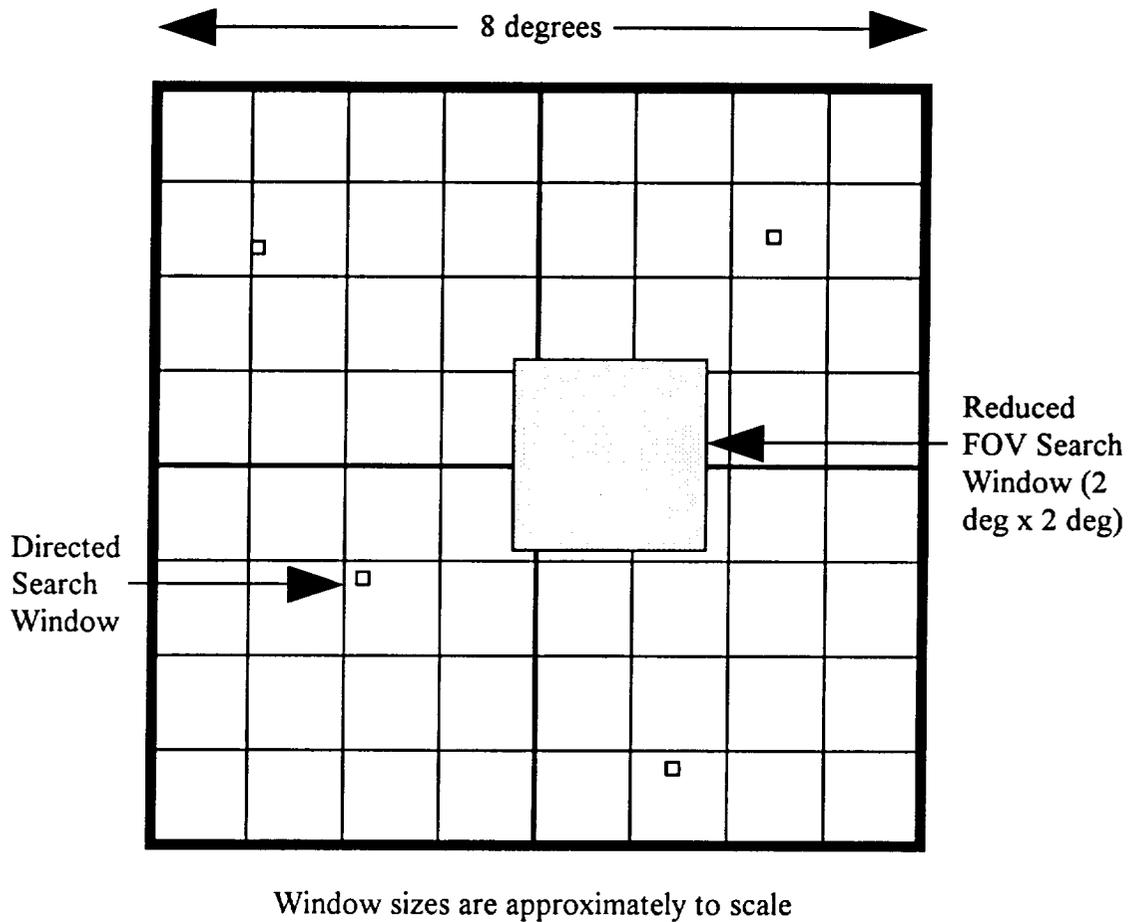
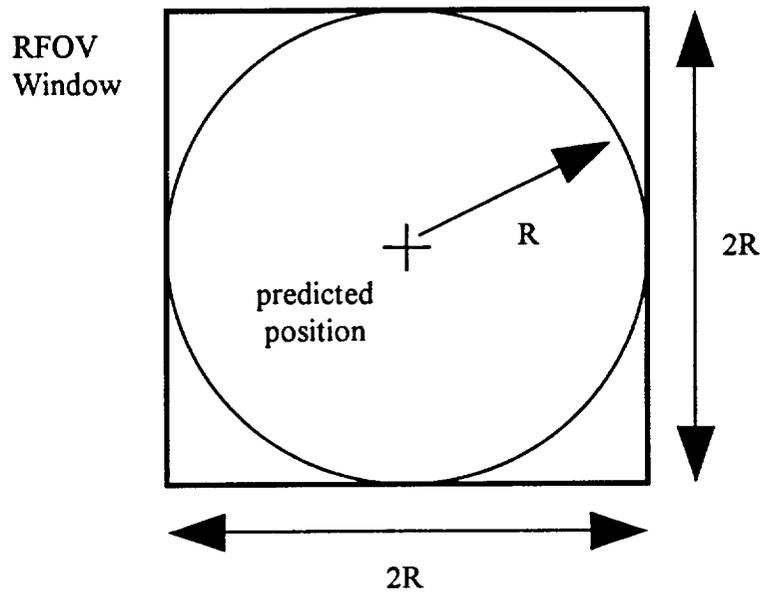Figure 1. SWAS Star Acquisition Search Windows
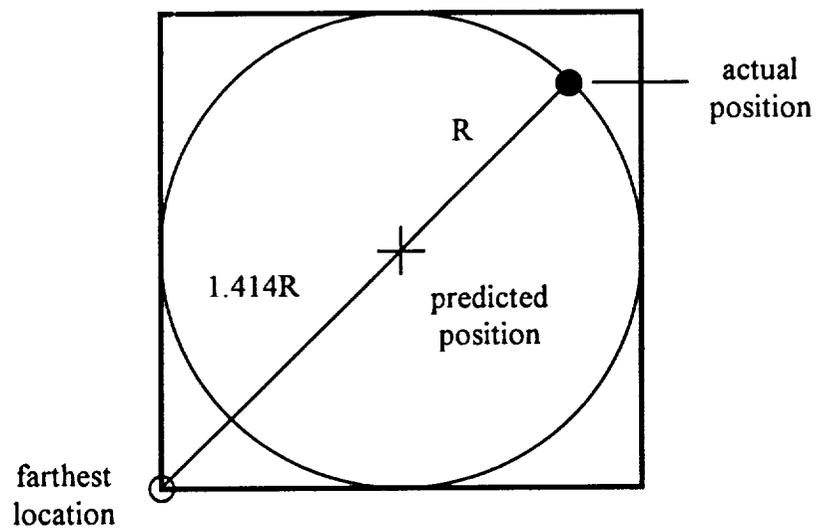
Figure 2. Reduced Field of View Window Size

Figure 3. Basis for Exclusion Angle

angle E separated from the intended base star, the maximum allowable attitude error R is E/2.414 and the maximum RFOV window size is 2R (E/1.207).

The star Altais in the constellation Draco (see Figure 4) was chosen as the base star for the North ASA field. Altais has a predicted instrument magnitude of 2.86 is approximately 7.1° from the ecliptic pole [3]. Altais is the brightest star within 10° of the ecliptic pole. The nearest star of similar brightness is Epsilon Draconis with 3.69 instrument magnitude. The separation between the stars is 4.12°, so the maximum allowable error is 4.12°/2.414 or 1.7°. The largest allowable RFOV window is 3.4° square.

The South ASA field is based on Alpha Pictoris (see Figure 5), a relatively isolated star that is 6.9° from the ecliptic pole [3]. This star has a predicted instrument magnitude of 3.49 and is the brightest catalog star within 12° of the ecliptic pole. A nearby star with magnitude 4.67 is 4.82° from Alpha Pictoris, so the maximum allowable error is 4.82°/2.414 or 2.0°. The RFOV window for this target can be no larger than 4.0° by 4.0°.

When the spacecraft slews between science targets, the attitude is propagated using the gyroscopes only. The gyroscopes have been tested, so approximate performance parameters (drift rate, scale factor error, bias error) are known. These parameters were used in the high-fidelity SWAS Integrated Simulation to predict attitude determination error at the end of slews. Several runs were made for each slew angle to find the largest attitude error R for that slew. The results (Table 1) were tabulated for mission planning purposes [4]. As before, the RFOV window is 2R by 2R, but the star catalog must now be checked to verify that no other stars will appear in the window and be misidentified.

Table 1. Predicted Attitude Error as a Function of Slew Angle

Slew Angle (deg)	Attitude Error (deg)
5	0.023
10	0.030
20	0.050
30	0.072
40	0.093
60	0.140
90	0.210
120	0.280
150	0.340
180	0.410

Guide stars for each science target are chosen by the planning scientist for the mission. Personnel at SAO developed planning software for this task [5]. The planning software checks for other mission constraints such as solar panel illumination and instrument Earth avoidance, then searches the SWAS catalog for an appropriate base star. The slew angle from the previous target is used
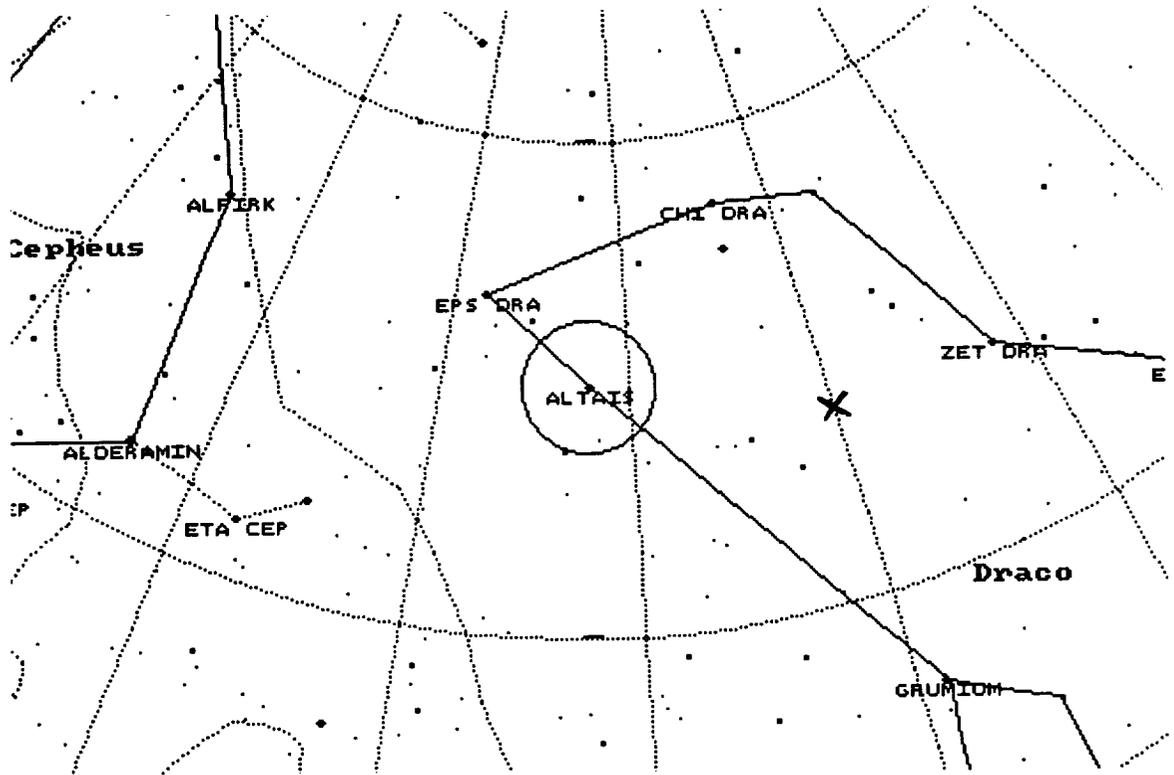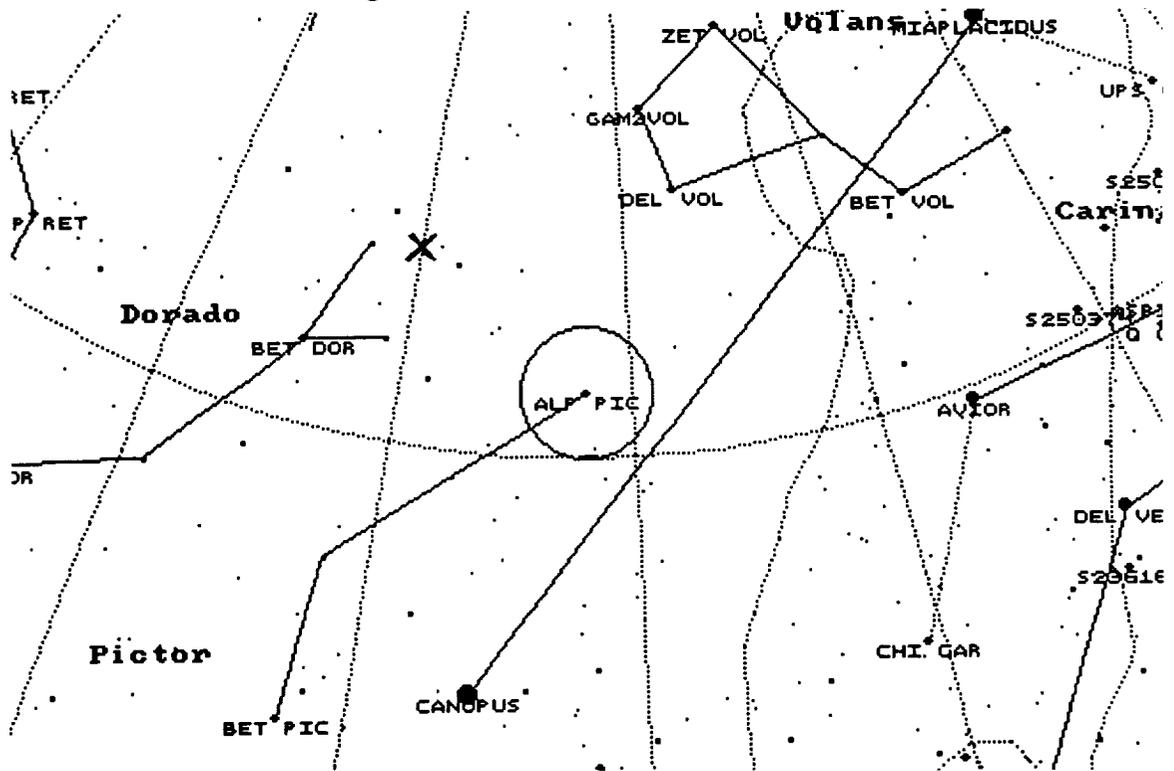
Figure 4. North Ecliptic Pole Region

Figure 5. South Ecliptic Pole Region

to find the attitude error and RFOV window size for that target. Once a suitable base star has been found, the catalog is examined for suitable field stars. Most SWAS targets will be in the galactic plane, so five guide stars (one base plus four field stars) should be in the FOV. SWAS Integrated Simulation results indicated that if only two stars are in the FOV, those two stars must be separated by at least 3.0° for the attitude solution to be sufficiently accurate. The planning software checks field star separation so that this condition is met for two or more stars.

STAR ACQUISITION SIMULATION

A MATLAB simulation of the star acquisition process was developed to test the concept before the start of ACS flight software development. In this script, guide star unit vectors are rotated into the star tracker frame, tracker angles are computed, and RFOV and Directed searches are simulated. The script was used to test the process and evaluate numerous candidate star fields.

In the SWAS star acquisition process, guide star unit vectors in the inertial frame are rotated into the tracker frame using direction cosine matrices. In the MATLAB simulation, this rotation was accomplished with the matrix equation

$$S_t = A_{err} * A_{bt} * A_{ib} * S_i$$

where S_i is the star unit vector in the inertial frame and S_t is the vector in the tracker frame. A_{ib} is the direction cosine matrix that transforms the vector from the inertial to the SWAS body frame; this matrix is extracted from the current attitude quaternion. The constant A_{bt} is the body-to-tracker transformation matrix made necessary by the mounting of the star tracker -83° about the z axis from the body frame. A_{err} is an error matrix that allows deliberate introduction of small attitude errors about the X, Y, and Z axes for testing purposes.

Once the guide stars have been rotated into the tracker frame, the unit vectors are converted into tracker angles α and β for use in CT-601 search commands. The RFOV search for the base star is simulated by searching through the guide star list for that target. Once the base star is located, α and β offsets are computed and simulated Directed searches are performed. If no stars are found in the RFOV window, the star acquisition is aborted. If no stars are found in the Directed search windows, the star acquisition is aborted. If at least one field star is located, the acquisition is complete.

Numerous star fields and attitude error situations were examined with the completed star acquisition simulation. An important parameter is the amount of Z attitude error that will cause field stars to appear outside the Directed search windows. Runs with several different star fields showed that the Z error must be greater than 1.5° in order to cause difficulties; the expected Z error is typically 0.5°, so the assumption of zero Z attitude error inherent in the star acquisition process is valid for this mission.

Plots of the star tracker view are made by the MATLAB script. Figure 6 is a plot from a simulation of the North ASA field. The circles represent the predicted star locations while the target vector is the "+" symbol. The base star is shown by an asterisk while the field stars are shown by "x" symbols. Attitude errors of 0.25° about the X axis, 0.5° about the Y axis, and 0.25° about the Z axis were included in the simulation run portrayed by this plot. The use of the α and β offsets of the base to correct the locations of the Directed search windows for the field stars is rather clear in this plot. A plot from simulation run with the same errors for the South ASA field is shown in Figure 7.

FLIGHT SOFTWARE IMPLEMENTATION

After the star acquisition process was tested in simulation, the process was molded into an algorithm suited for coding in a real-time system [6]. The overall structure is that of a state machine in which different actions are performed in the different states. Up to five stars numbered 0 (primary base star), 1 (backup base star), 2, 3, and 4 are taken from the observation command. Failure checking was implemented in a separate module to catch star acquisition problems.

When the ACS software indicates that the spacecraft has neared the target and switched to the fine pointing controller, the first state "InitBaseStarAcq" is entered. In one 100 millisecond control cycle, the software formulates and sends the RFOV search for the base star. The next state is "AcsBaseStarSearch" in which the software examines the star tracker output in order to match the base star by magnitude. If the base star is not matched within a set time, the state switches the base index from 0 to 1 and restarts the star acquisition process. If the base star is matched by magnitude, the state computes the α and β offsets, predicts the positions of the field stars, and sends one Directed search command to the star tracker.

During "AcsStarFieldSearch," the software waits for the results of the Directed search command. Field stars are matched by magnitude and a separation index is calculated. This index is simply the sum of the squares of the separation angles between the field stars and the base star. When the index reaches a sufficiently high value, enough separated stars are available for an accurate attitude solution and the process continues. Early in the mission, the index must be greater than 16 square degrees, requiring a separation of 4° if there are just two guide stars for the target. After the index has exceeded the required value, updating of the Kalman filter attitude solution with star information can begin.

The "AcsStarFieldSearchUpdate" state serves two purposes. For most star acquisitions, the beginning of Kalman filter updates means that the spacecraft will slew to settle accurately on the target. Once the state detects settling, it checks for any missing guide stars and sends Directed search commands to reacquire them. This state also allows for multiple chances at recovering stars during Nodding and Mapping Observations. Once settling on the target takes place, the "AcsTrackField" state remains in force until a new Nodding/Mapping point is commanded or a new target comes in the scientific timeline. If the slew is to a new target, all tracker searches are discontinued and the star acquisition process starts again with the new guide stars.

106
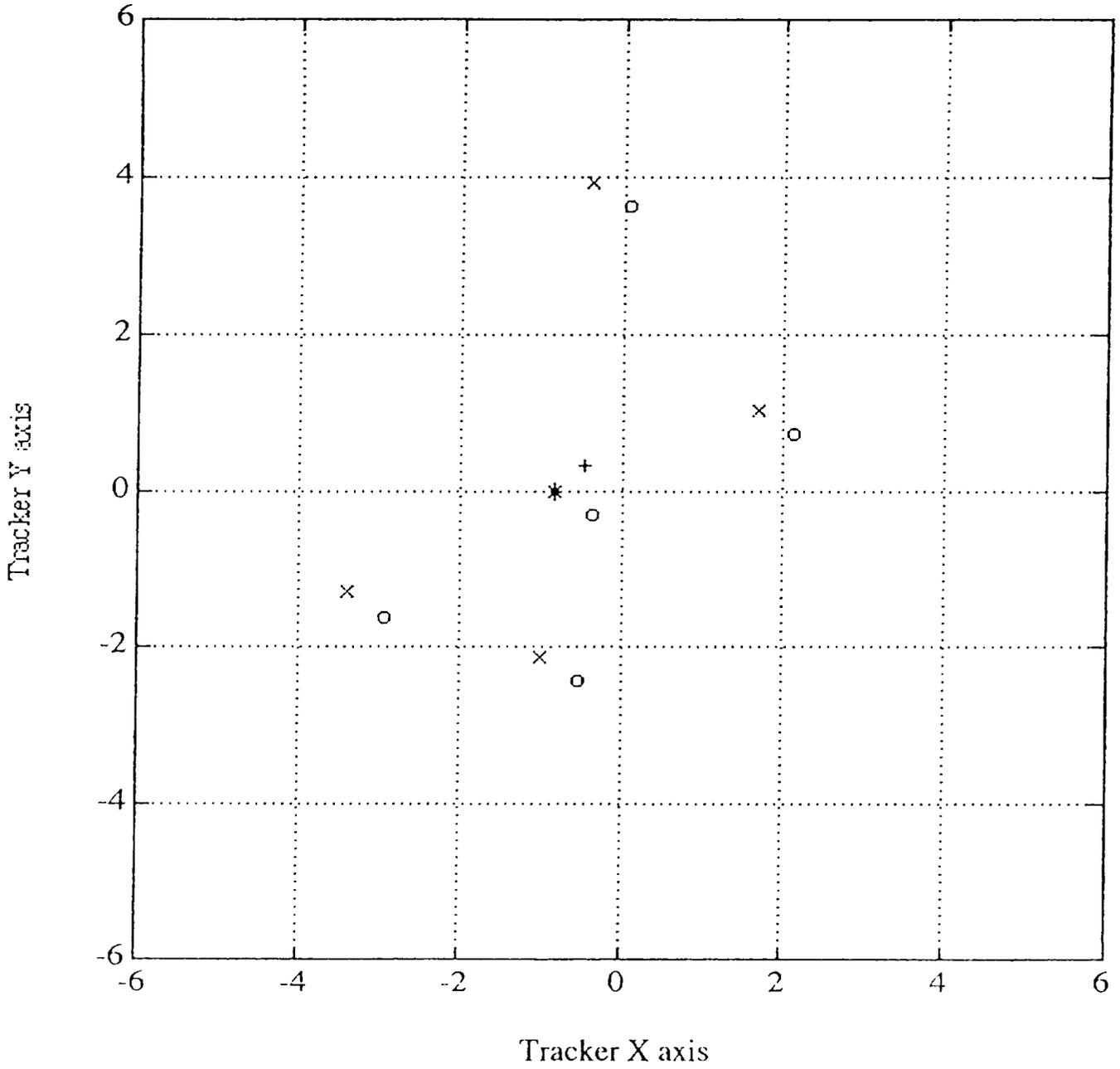
N Altais field, 0.25/0.5/0.25 deg errors

Figure 6. Simulation Plot of North Ecliptic Pole Star Field

107

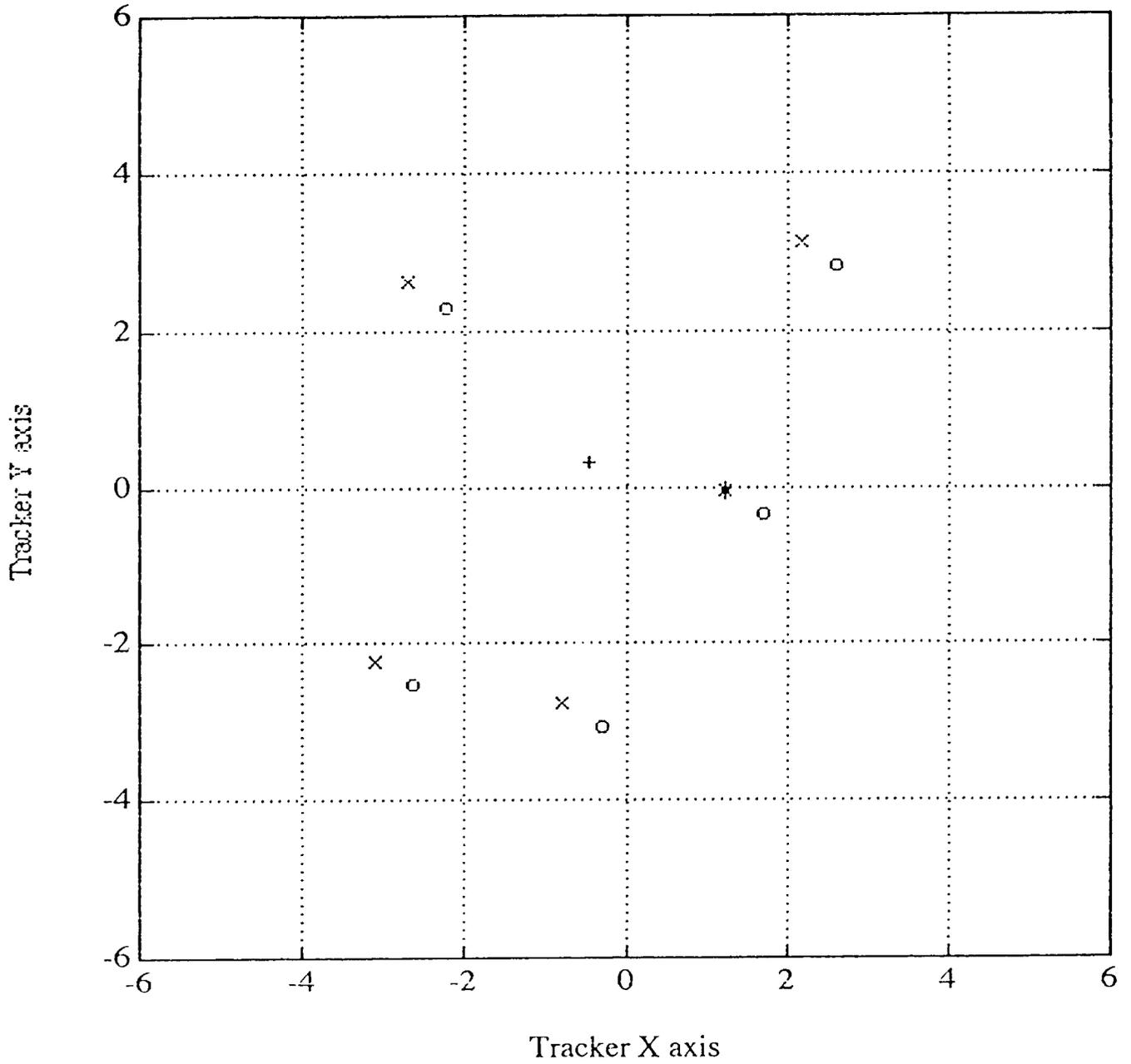## S Alp Pic field, 0.25/0.5/0.25 deg errors

Figure 7. Simulation Plot of South Ecliptic Pole Star Field

Overall star acquisition failure is checked in an independent Failure Detection and Handling module. When the spacecraft first begins a star acquisition at a new target, the FDH module starts a star acquisition timer. If the acquisition has not been completed with a set period of time (300 seconds at the beginning of the mission), the module clears the tracker searches, sends a Full Field search command, waits for 45 seconds so that some stars can be found for later analysis on the ground, then aborts that target. If the spacecraft aborts from a science target, the ACS will command a slew to either the North or South ecliptic pole star field and begin an Auto-Stellar Acquisition. If the spacecraft aborts from ASA, the ACS drops to ISP and the remainder of the scientific timeline for that day is lost.

FLIGHT SOFTWARE TESTING

A significant amount of testing was done on the tracker, simulators, and flight software to verify the proper functioning of the star acquisition process.

The flight star tracker was shipped to Goddard about one year before final integration. Numerous tests were run on the tracker to characterize it for analysis, flight software, and star tracker simulator reasons. The internal BITE star, the GSE LEDs, and a collimated light source were used to stimulate the tracker and investigate the search limits. The flight tracker was also connected to the 1553 bus of the breadboard flight computer to test the interfaces between the tracker and the flight software. A test procedure was created to simulate a star acquisition with the flight tracker and GSE LEDs. The α and β angles for the simulated stars were measured, converted to unit vectors S_t, then rotated back into the simulated inertial frame (i.e., S_i) using the current attitude quaternion from the dynamic simulator setup. A target upload with these unit vectors and measure magnitudes was created and sent to the flight computer. Simulated acquisition were successful and typically faster than two seconds.

The flight tracker was also used to verify the accuracy of the star tracker simulator. Once the flight tracker was returned to Ball for integration in the SWAS instrument, star acquisition testing focused on the flight computer/dynamic simulator environment. Extensive testing of the routines including failure checking was conducted.

Once the instrument was delivered to Goddard and final integration completed, testing shifted to the flight environment. Hardware tests on the star tracker such as aliveness and phasing procedures were developed and performed. Flight software testing continued with the star tracker simulator used in conjunction with the dynamic simulator. While no major problems have been identified, some minor ones were found largely as a result of unexpected combinations of commands from the scientific timeline.

EARLY ORBIT OPERATIONS

The Flight Dynamics Facility will execute star tracker checkout procedures while the ACS is in ISP. FDF has a Real Time Attitude Determination System (RTADS) that allows for star pattern matching using the SKYMAP star catalog. The pattern matching technique used is by

van Bezooijen [7]. For example, the tracker telemetry can be processed to determine if the ISP attitude is accurate enough for an ASA to be successful.

CONCLUSIONS

The implict direct matching star identification technique used by the SWAS ACS with the Ball CT-601 star tracker has been proven effective in prelaunch tests. While the technique is not highly flexible, it has proven to be quite fast. The method of embedding the guide star information in target command uploads preserved a great deal of onboard storage for this modest Small Explorer mission. The SWAS guide star catalog can be updated based on flight experience to increase accuracy.

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