N94- 35640

Application of Star Identification Using Pattern Matching to Space Ground Systems at GSFC*

D. Fink and D. Shoup
Computer Sciences Corporation (CSC)
Lanham-Seabrook, Maryland

Abstract

This paper reports the application of pattern recognition techniques for star identification based on those proposed by Van Bezooijen to space ground systems for near-real-time attitude determination. A prototype was developed using these algorithms, which was used to assess the suitability of these techniques for support of the X-Ray Timing Explorer (XTE), Submillimeter Wave Astronomy Satellite (SWAS), and the Solar and Heliospheric Observatory (SOHO) missions. Experience with the prototype was used to refine specifications for the operational system. Different geometry tests appropriate to the mission requirements of XTE, SWAS, and SOHO were adopted. The applications of these techniques to upcoming mission support of XTE, SWAS, and SOHO are discussed.

1.0 Introduction

The Van Bezooijen pattern-matching technique is based on a series of tests, as are most star identification algorithms. Each test compares the scalar value of an observable characteristic of the observed stars with the scalar value of the same characteristic of candidate reference stars, with the test being not for strict equality between the two numeric values but for a match within specified tolerances (i.e., using an inexact, or "fuzzy," comparison). Each such characteristic that can be represented as a scalar quantity is termed a pattern dimension. The pattern dimensions that were used in this study to identify a star are the separation angles between it and all other stars in the region viewed by a tracker and within a larger catalog region, the brightness of a star within some wavelength band (e.g., visual or instrument magnitude), and the angle between a star and some reference direction (e.g., the Sun vector). Tests are performed to compare the values of potential candidates in each pattern dimension against the values of the observed stars, and in every such comparison those candidate pairs that can be ruled out with certainty are eliminated. When all such tests have been completed, the candidate stars that remain are voted for by counting up the number of times that each candidate star has survived as a possible match to one of the observed stars. The candidate with the highest vote tally for a given observed star (if any) is declared the winner. We suspected that Van Bezooijen's techniques would be especially well suited to the multiple, simultaneous, high-accuracy star observations possible with the Charge-Coupled Device (CCD) star trackers to be flown on the X-Ray Timing Explorer (XTE), Submillimeter Wave Astronomy Satellite (SWAS), and Solar and Heliospheric Observatory (SOHO) missions.

Clearly, this is a probabilistic method that assumes that the odds of some other candidate star being found which has a score equal to the correct star is small, based on the set of tests and votes used. A principal objective of this analysis was to establish that the odds of identifying the observed stars correctly are sufficiently great to consider this method reliable in an automated, real-time setting, assuming realistic levels of error in the observed data. The other principal objective was to determine whether the algorithm and associated data structures could execute and be regenerated quickly enough to fit into a real-time system with a 4-sec update limit when running on an HP 715/50 workstation supporting XTE/SWAS. The timing requirements for SOHO were less stringent, but identification results within 10 min were desired.

Performing this analysis required a prototype, as the algorithms previously had not been implemented in the Flight Dynamics Facility (FDF). Building the prototype provided an opportunity to observe the performance of the algorithm and to take advantage of the lessons learned from the preliminary analysis to prepare the specifications for the operational system. The prototype was originally built using only the first two of the pattern dimensions (separation and magnitude), with a separation test as described in Van Bezooijen's special algorithm. In the special algorithm separation test, observed stars are compared in separation only pairwise with separations of candidate stars, rather than the more exacting comparison of "match groups" composed of up to all the observed stars considered as one geometric element, as used in Van Bezooijen's general algorithm. Van Bezooijen's special algorithm includes a

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

"field of view (FOV) rotation tolerance" test which was not implemented in this prototype. We omitted that test because initially, one goal was to use spacecraft attitude only to ensure that a tracker boresight would lie within the confines of the zone catalog being used as the source of candidate stars. Two types of zone catalog were required to meet the mission requirements of XTE/SWAS and SOHO: a small circle region (or cap catalog) for XTE/SWAS, and a band centered around either a small or great circle (a band catalog) for SOHO. Analysis of these early results led to a decision to implement additional geometric tests based on partial a priori knowledge of the spacecraft attitude to improve recognition accuracy, as Van Bezooijen had done, although these tests are somewhat different from his: these tests were designed to accommodate the different identification geometries for cap and band catalogs.

2.0 Method

Both the star identification (STARID) prototype itself and the simulator that drives it were written in FORTRAN 77 and were compiled and executed on a 33 MHz, 486 PC, equipped with 16 MB of RAM. Comparison of PC industry literature indicated this machine is several times slower than the target HP 715/50 computer at floating point operations of the sort that make up the bulk of the algorithm's computations. We used the 33 MHz 486 time as a conservative measure of whether we were satisfying our 4-sec update limit, since the operational system on the HP platform must do more than just star identification. For the final timing runs, the compiler performance options were enabled. Input and output files resided remotely on a PC network file server. All position and magnitude variables obtained from the star catalog were stored as REAL*4 variables. All separation values were also maintained in REAL*4 precision, and angular data were processed using trigonometric functions without any particular attempt to minimize memory use and computation time.

The PC version of the operational Multimission Three-Axis Support System (MTASS) Run Catalog (MMS_RCAT) currently in use for ground support of the Upper Atmosphere Research Satellite (UARS) and Extreme Ultraviolet Explorer (EUVE) was used for all XTE/SWAS-type cap catalog runs. The PC version of the SOHO catalog (SOHO_RUN) was used for the SOHO-type band catalog runs. In all the results presented in this paper for XTE/SWAS, all stars down to magnitude 6.5 were used from the MMS_RCAT catalog; for SOHO, all stars down to magnitude 8.0 were used from the SOHO_RUN catalog. These magnitude limits were hardcoded in the XTE/SWAS and SOHO versions of the prototype and were not input parameters.

STARID attempts to determine the SKYMAP numbers (*SKYMAP Star Catalog System Description*, Slater, 1992) of the observed stars by matching them pairwise with the catalog star pairs it generates. STARID returns the SKYMAP number of the catalog star it believes matches the observed star; it returns a flag value for observed stars which ended up matching more than one candidate catalog star equally well; and it returns another flag for observed stars which it determines did not match a catalog star at all. The simulator then tabulates the results.

A summary of the input parameters is provided in Table 1 and parameter descriptions accompany each test. The values used in the table are close to the expected mission tolerances, with a margin in whatever direction would affect the identification process adversely, while still providing a semblance of nominal behavior.

In each simulation the simulator selects random directions to generate main cap or band catalogs, and sensor FOV catalogs (which are cap catalogs in these simulations) within those main catalogs. The set of stars available in each FOV catalog, if any, is sampled at random for up to five simulated observed stars, to whose position and magnitude noise is added. For the results presented in this paper, Gaussian white noise was used. Note that measurement noise and sensor FOV calibration error were not modeled separately but were treated as a single Gaussian white noise process. The position errors are uniformly and randomly distributed in direction, in addition to being Gaussian-distributed in magnitude. These simulated observed star positions and magnitudes are then passed anonymously from the simulator to STARID, along with the cap or band catalog within which they and their view catalog all lie. All observations used for each identification attempt can be considered to be from a single time, made from a single inertially-fixed circular tracker FOV.

The random direction of the star tracker FOV can be controlled by reading an input base direction and a bound from that desired direction, within which the catalog generation vector must lie. An option is also provided to misalign the spacecraft-centered inertial reference frame from the true geocentric inertial (GCI) frame, to produce the sort of large, systematic observed star position error one sees in flight data when the spacecraft-body-to-GCI transformation has large errors.

Following the identification of candidate pairs based on separation tests, either star in the observed pair could be either star in any of the identified candidate pairs. The following section summarizes the magnitude and geometry tests used to determine which of the candidates should be given a vote of confidence as being each observed star, which will subsequently be counted and compared to the tallies for competing candidates for the same observed star. Note that a given pair of candidates may fail these tests entirely, in which case there will be no votes cast for either candidate in the pair. Depending on the geometry and the setting of the tolerances, a given pair may also obtain ambiguous results from the geometry tests, in which case a vote is cast for each of the candidates as being each of the observed stars in the pair, in the expectation that other pairings provide votes to resolve the ambiguity, or the user may need to resolve the ambiguity through changing test tolerances.

Table 1. Basic Input Parameters

Input Parameter Definition	Variable Name	Cap Catalog Baseline Value	Band Catalog Baseline Value
For cap catalog runs, the angle, in degrees, within which to restrict the uniformly and randomly distributed catalog a priori boresight. For band catalog runs, the angle, in degrees, within which to restrict the uniformly and randomly distributed pole axis of the band catalog.	*RCCAT*	180.00°	180.00°
For cap catalog runs, the angle, in degrees, within which to restrict the uniformly and randomly distributed sensor boresight vector, measured from the catalog a priori boresight. For band catalog runs, the angle, in degrees, within which to restrict the uniformly and randomly distributed sensor boresight vector, measured from the center of the band catalog.	*RCVIEW*	6.66°	0.10°
Simulated observation position noise, 1 σ	*SIGOBS*	0.00083° (3")	0.00083° (3")
Simulated observation magnitude noise, 1 σ	*SIGMAG*	0.10	0.10
+ - Bound on error in simulated observed magnitudes	*RCMAG*	0.6	0.6
Cap catalog radius (only applies to cap catalog case)	*CCAP*	10.66°	N/A
Half width of band catalog (only applies to band catalog)	*WBAND*	N/A	2.1°
Coelevation of sensor boresight for band catalog generation	*COEL*	N/A	90.0°
Half width of tracker boresight	*FOVMAX*	4.0°	2.0°
Maximum-range-of-separation hashing function used to select catalog star pairs, e.g., 2**FOVMAX* (deg)	*HMAX*	8.0°	4.0°
Separation tolerance to use in building hashing tables, and in final separation tolerance test (deg)	*SEPTOL*	0.0066°	0.0066°
Magnitude tolerance for rejection of a candidate star by the magnitude check	*XMTOL*	0.6	0.6
Magnitude tolerance to use in determining which star in a pair of observed stars is brighter	*TMAGMX*	0.6	0.6
Angular threshold at which two cross-product vectors are considered parallel in cap catalog cross-product tests	*CAPMAX*	90.0°	N/A
Angular threshold at which the difference in star vector-to-catalog generation vector angles are considered large enough for the closeness-to-pole test, and considered too large for the cross-product test to be applied (deg)	*BANTOL1*	N/A	0.13°
Angular threshold used in the closeness to pole test, at which star vector-to-catalog generation vector angles of the closer stars or further stars are considered more different than they should be, considering the error in the position of the pole of the band catalog (deg)	*BANTOL2*	N/A	7.2°
Angular threshold at which two cross-product vectors are considered parallel in band catalog cross-product test (deg)	*BANMAX*	N/A	90.0°
Flag to perform a 3-2-1 rotation on observed vectors, with respect to body coordinate axes (logical)	*LIBROT*	T	T
For *LIBROT* = *T*, the first rotation angle	*PHI*	0.0116667°	0.1000000°
For *LIBROT* = *T*, the second rotation angle	*THETA*	0.0116667°	0.1000000°
For *LIBROT* = *T*, the third rotation angle	*PSI*	0.0166667°	180.0000000°

In the following summary we use the input variable names as defined in Table 1 for brevity and clarity. In this discussion we refer to the candidate pairs as indexed by *J*, and the observed pairs as being indexed by *I*. We refer to a candidate acceptability flag *IFLAG(J,I)*, initialized to −1, and a relative order flag *LORD(J,I)*, initialized to 0.

2.1 Magnitude Tests

STEP 1: On option, attempt to determine the matching order using relative magnitude. If the magnitude test is not selected, then set *LMAGT* to *FALSE*, for the benefit of the logic used below in the geometry tests, to indicate that none of the candidates has been prescreened by a magnitude test. If the magnitude of a pair of observed stars differs by less than *TMAGMX* then set *LMAGT* to *FALSE*, skip this test, and proceed to the geometry tests below.

STEP 2: If the magnitude difference between this pair of observed stars is *TMAGMX* or greater, then set *LMAGT* to *TRUE*, and test each of the candidate pairs for that observed pair as follows: Compare the brighter of the observed stars to the first star in the candidate pair (candidate pairs were created with the brighter star first). If the difference in magnitude is greater than *XMTOL*, set the acceptability flag for this candidate for this pair to the "no" value, *IFLAG(J,I)* = 0, and go on to the next candidate pair. If the difference in magnitude is acceptable, compare the dimmer star of the observed pair with the dimmer candidate.

STEP 3: If the difference in magnitude between the dimmer observed star and the dimmer candidate star is greater than *XMTOL*, reject the *J*th candidate by setting *IFLAG(J,I)* = 0, and go on to the next candidate pair. If the difference is acceptable, set an order flag *LORD(J,I)* = +1 if the matching order was found to be that the first observed star matches the first candidate and the second observed star matches the second candidate, or set the *LORD(J,I)* = −1 if the reverse order was found. When all candidates have been checked, proceed on to the next candidate pair, then proceed to the geometry tests.

2.2 Geometry Tests: Perform the following tests as indicated, depending on whether a cap or band catalog is being used.

Cap Catalog:

STEP 4: Form the unit cross product of the two observed star vectors and the unit cross product of the two candidate star vectors. Compute the angular difference *CRSSEP* between these two unit cross-product vectors, and its supplement *CRSSEN* = 180.0 deg− *CRSSEP*. If *LMAGT* is *FALSE*, the order of multiplication that gives the cross products within a user-specified angular tolerance *CAPMAX* determines the proper pairing of the observed and candidate vectors. If *CRSSEP* ≤ *CAPMAX*, set *LORD(J,I)* = 1 to record that the first observed star matches the first candidate and the second observed star matches the second candidate, or if *CRSSEN* ≤ *CAPMAX*, set *LORD(J,I)* = −1 to record that the order is the reverse. If neither order of multiplication satisfies the angular tolerance, set *IFLAG(J,I)* = 0, and go on to the next candidate pair.

STEP 5: If *LMAGT* is *TRUE*, check the order flag *LORD(J,I)*; if it is zero as it was earlier initialized, proceed with the test as above in STEP 4. However, if *LORD(J,I)* is 1 or −1, just check that order of the cross-product multiplication to confirm or refute it. If the cross products are not within the user specified angle *CAPMAX*, set *IFLAG(J,I)* = 0, and go on to the next candidate pair. If the angle is within *CAPMAX*, the order is confirmed to be that given by the magnitude test. Continue on with the next candidate pair.

Band Catalog:

STEP 6: First determine whether the observed and candidate stars can be distinguished based on their angular distance from the one axis which is known with some certainty, the pole of the band catalog. Find the angle between each observed star vector and the catalog generation vector, and the angle between each reference star vector and the catalog generation vector. Compute the angles *GTO1* and *GTO2* from each member of the pair of observed stars to the catalog generation vector. Compute *GTODIF*, the absolute value of the difference between *GTO1* and *GTO2*. Compute the angles *GTR1* and *GTR2* from each member of the pair of candidate stars to the catalog generation vector. Compute *GTRDIF*, the absolute value of the difference between *GTR1* and *GTR2*. If both *GTODIF* and *GTRDIF* are greater than *BANTOL*1, proceed with the test at STEP 7 below. If either *GTODIF* or *GTRDIF* is less than or equal to *BANTOL1*, check the absolute difference between *GTODIF* and *GTRDIF*; if it is greater than *BANTOL1*, set *IFLAG(J,I)* = 0, and go on to the next candidate pair. If the absolute difference between *GTODIF* and *GTRDIF* is less than or equal to *BANTOL1* proceed instead to the cross-product test below at STEP 10.

STEP 7: If both *GTODIF* and *GTRDIF* are greater than *BANTOL1*, compute the absolute difference between *GTODIF* and *GTRDIF*; if it is greater than *BANTOL1*, set *IFLAG(J,I)* = 0, and go on to the next candidate pair. If the absolute difference between *GTODIF* and *GTRDIF* is less than or equal to *BANTOL1*, then determine the greater of *GTO1* and *GTO2* and the greater of *GTR1* and *GTR2*. Compare the greater angles with one another. If the absolute difference is not within *BANTOL2*, set *IFLAG(J,I)* = 0, and go on to the next candidate pair. Compare the lesser angles to one another; if the absolute difference is not within *BANTOL2*, set *IFLAG(J,I)* = 0, and go on to the next candidate pair. If, however, both the greater and the lesser angles were within *BANTOL2* of one another, then this geometry test has established a probable matching order of each observed star in the pair to a single candidate: the observed star with the greater angle to the pole going with the candidate with the greater angle to the pole and the observed star with the lesser angle to the pole going with the candidate with the lesser angle to the pole.

STEP 8: If *LMAGT* is *FALSE*, the probable matching order determined above is judged valid, we have paired the observed star that is closer to the catalog generation vector with the reference star that is closer to the catalog generation vector, and the further with the further, with *BANTOL2* used to confirm that the angles were in fact in the expected range. Proceed with the next candidate pair.

STEP 9: If *LMAGT* is *TRUE*, compare the probable matching order based on the closeness to the catalog generation vector to the order determined by the magnitude test. If they do not agree, set *IFLAG(J,I)* = 0, and go on to the next candidate. If the order is confirmed, proceed to the next step.

STEP 10: If the difference between the observed and reference angles is less than *BANTOL1*, check the cross product of the two observation vectors and the cross product of the two reference vectors as is done for cap catalogs.

3.0 Full Sky Tests and Results

For the first series of cap catalog tests there were 10 randomly selected large cap catalogs, 10 randomly selected viewing attitudes within each large cap catalog, and up to 5 observed stars per view, for a total of 498 observed stars. The same random number seed was used to begin each test, so the same sequence of attitudes and stars is represented in these cap catalog tests.

For the first series of band catalog tests there were 10 randomly selected directions for the pole of the band catalog, with 10 randomly selected viewing attitudes within each band catalog, and up to 5 observed stars per view, for a total of 495 observed stars. The same random number seed was used to begin each test, so the same sequence of attitudes and stars is represented in these band catalog tests.

3.1 Effect of Increasing Attitude Error

Simulating Attitude Error and Tracker Off-Pointing

The effects of attitude error and tracker off-pointing were also examined in this study because they constitute systematic error sources differing from the random errors in star position and magnitude.

Attitude Error

Attitude error is simulated by generating a nominal GCI-to-body transformation, obtaining the observed star positions in that body frame, and then perturbing those observations by rotating them by the angles given in the indicated 3-2-1 rotation sequence $(\Delta\phi, \Delta\theta, \Delta\psi)$. The observations are converted back to GCI using the inverse transformation of the unperturbed GCI-to-body transformation. The error that is simulated by introducing this rotation is similar to what happens when the transformation matrix used to convert from spacecraft body coordinates to GCI is in error by the respective rotation angles used (i.e., an error in the knowledge of the spacecraft attitude).

This error corresponds to the situation if one were given an a priori spacecraft attitude for the initial attitude acquisition: this attitude would be loaded into mission support software and would be used for the transformation from body to GCI. When the actual spacecraft inertial attitude differs from that expected, the observations made in sensor coordinates are converted to body coordinates using a presumably good transformation, then converted to GCI coordinates using the faulty transformation. The final GCI components of the observations will differ from those in the reference catalog because of this attitude error, even if all other position-related errors are zero. This effect matters because the geometry tests in the STARID algorithm are not fully coordinate-frame independent. Therefore, we needed to ensure that the expected range of attitude errors is tolerated by the STARID algorithm and does not cause the geometry tests to produce erroneous results. In the XTE/SWAS cap catalog case, we expect the initial attitude to differ from the a priori by no more than several degrees about each body axis. For the SOHO band catalog case, we expect any possible rotation about the *X*-axis but expect no more than 0.1 deg of off-pointing of the *X*-axis from the Sun.

Tracker Off-Pointing

Another effect studied is that due to the tracker pointing in an unexpected direction, observing other than the expected stars. The STARID algorithm is intended to operate autonomously, so it is desirable that a considerable degree of off-pointing be accommodated without human intervention. The STARID algorithm accommodates off-pointing by maintaining an indexed zone catalog larger than the sensor FOV, which is chosen to contain the actual FOV as a subset. The zone catalog should be large enough to encompass the actual sensor FOV, but it should not be any larger than necessary because the odds of a coincidental match between an observed star pair and some random, incorrect candidate star pair increases as the size of the zone catalog increases. In addition, a larger zone catalog requires greater memory and processing overhead. We can simulate this effect simply by choosing the sensor boresight randomly within a specified bound. We can choose the bound to keep the sensor FOV safely within the zone catalog, given expected errors. For example, the XTE/SWAS-type cap catalog simulations use a simulated tracker FOV with a radius of 4 deg, and a nominal tracker off-pointing value of 6.66 deg, so the corresponding cap catalog must be at least 10.66 deg in radius.

Attitude Error Versus Tracker Off-Pointing

In practice, both of these effects will be present. To accommodate them, the STARID geometry test parameters must be set according to the expected magnitude of the attitude error and the expected magnitude of the tracker off-pointing error. The size of the zone catalog also needs to be selected according to the expected tracker off-pointing error. The first series of tests attempted to uncover the effect of attitude error, in the presence of a nominal amount of tracker off-pointing. The nominal values chosen are given in Table 1. In the cap catalog runs, a random error is introduced of up to 6.66 deg in the body *X*-axis position from the nominal boresight of the cap catalog. In the band catalog runs, a random error is introduced of up to 0.1 deg in the *X*-axis position from the nominal pole of the band catalog, with the *Z*-axis selected randomly about the *X*-axis.

3.1.1 Cap Catalog Case

In the cap catalog case, the view direction was confined to within 6.66 deg of the catalog center. To simulate the effect of an error in the conversion from spacecraft body frame to GCI, the *LIBROT* option to perform 3-2-1 ($\Delta\phi,\Delta\theta,\Delta\psi$) rotations was used to introduce increasing attitude errors in the body frame prior to the nominal body-frame-to-GCI transformation being applied to the observed star positions. Attitude errors significantly larger than the diameter of the cap catalog were tested. The results are given in Table 2. In the cap catalog case, the body *X*-axis direction is defined to be the tracker boresight direction. Note that misidentifications did not occur until the rotation angles began to equal the tolerance *CAPMAX*, and the assumptions required for STEP 4 of the geometry test described earlier broke down. Consider the results in Table 2, Run 6. There, we see that an error in the knowledge of the rotation of the tracker about its boresight of 100 deg led to catastrophic failure. If one simply turned off the geometry tests in that case, the result would instead be 1 ambiguous star, 497 stars identified correctly, and no misidentifications.

3.1.2 Band Catalog Case

If, as for SOHO attitude acquisition, only the position of the body axis assumed to lie along the pole of the band catalog is known with any certainty (the pole is nominally Sun-pointing), the ability of the algorithm to tolerate the presence of an error in the body-to-GCI transformation is especially important. Therefore, the band catalog geometry tests need to be effective through the entire range of rotation about the pole. Note in the band catalog case, the body *X*-axis nominally lies along the direction of the pole of the band catalog, and the body *Z*-axis is defined to be the tracker boresight direction. The results are given in Table 3. The results show good tolerance for rotation about the pole of the band catalog, as was desired. Significant tilting of the attitude away from the pole is also accommodated, but more than a few degrees begins to produce a significant number of misidentifications. Taking Run 16 from Table 3, and turning the geometry tests off for this band catalog case, the results are not improved: 159 ambiguous stars, only 259 correctly identified stars, and 77 misidentifications resulted. This trial run shows that the separation and magnitude tests alone are not sufficient for the band catalog cases with the levels of position and magnitude noise used as nominal in this analysis.

Table 2. Increasing Simulated Attitude Error and Nominal Tracker Off-Pointing, Cap Catalog Case (1 of 2)

Run #	$\Delta\phi$	$\Delta\theta$	$\Delta\psi$	# Ambiguous Stars	# Stars Identified Correctly (uniquely)	# Stars Misidentified
1	40°	40°	60°	0 (0.00%)	498 (100.00%)	0 (0.00%)
2	40°	40°	10°	0 (0.00%)	498 (100.00%)	0 (0.00%)
3	40°	40°	30°	0 (0.00%)	498 (100.00%)	0 (0.00%)
4	40°	40°	85°	0 (0.00%)	498 (100.00%)	0 (0.00%)
5	40°	40°	90°	22 (4.42%)	474 (95.18%)	2 (0.40%)
6	40°	40°	100°	379 (76.10%)	2 (0.40%)	117 (23.49%)
7	10°	40°	60°	0 (0.00%)	498 (100%)	0 (0.010%)
8	30°	40°	60°	0 (0.00%)	498 (100.00%)	0 (0.00%)
9	90°	40°	60°	0 (0.00%)	498 (100.00%)	0 (0.00%)
10	100°	40°	60°	55 (11.04%)	438 (87.95%)	5 (1.00%)

Table 2. Increasing Simulated Attitude Error and Nominal Tracker Off-Pointing, Cap Catalog Case (2 of 2)

Run #	Δϕ	Δθ	Δψ	# Ambiguous Stars	# Stars Identified Correctly (uniquely)	# Stars Misidentified
11	110°	40°	60°	71 (14.26%)	410 (82.33%)	17 (3.41%)
12	40°	10°	60°	0 (0.00%)	498 (100.00%)	0 (0.00%)
13	40°	30°	60°	0 (0.00%)	498 (100.00%)	0 (0.00%)
14	40°	90°	60°	0 (0.00%)	498 (100.00%)	0 (0.00%)
15	40°	100°	60°	31 (6.22%)	463 (92.97%)	4 (0.80%)
16	40°	110°	60°	73 (14.66%)	412 (82.73%)	13 (2.61%)

Table 3. Increasing Simulated Attitude Error and Nominal Tracker Off-Pointing, Band Catalog Case

Run #	Δϕ	Δθ	Δψ	# Ambiguous Stars	# Stars Identified Correctly (uniquely)	# Stars Misidentified
1	0.1°	0.1°	0.1°	3 (0.61%)	492 (99.39%)	0 (0.00%)
2	0.1°	0.1°	90°	3 (0.61%)	492 (99.39%)	0 (0.00%)
3	0.1°	0.1°	180°	4 (0.81%)	491 (99.19%)	0 (0.00%)
4	0.1°	0.1°	270°	3 (0.61%)	492 (99.39%)	0 (0.00%)
5	3°	3°	3°	14 (2.83%)	479 (96.77%)	2 (0.40%)
6	3°	3°	90°	14 (2.83%)	480 (96.97%)	1 (0.20%)
7	3°	3°	180°	19 (3.84%)	476 (96.16%)	0 (0.00%)
8	3°	3°	270°	18 (3.64%)	476 (96.16%)	1 (0.20%)
9	4°	4°	4°	72 (14.54%)	414 (83.64%)	9 (1.82%)
10	4°	4°	90°	78 (15.76%)	409 (82.63%)	8 (1.62%)
11	4°	4°	180°	75 (15.15%)	415 (83.84%)	5 (1.01%)
12	4°	4°	270°	77 (15.56%)	412 (83.23%)	6 (1.21%)
13	5°	5°	5°	115 (23.23%)	361 (72.93%)	19 (3.84%)
14	5°	5°	90°	121 (24.44%)	356 (71.92%)	18 (3.64%)
15	5°	5°	180°	121 (24.44%)	356 (71.92%)	18 (3.64%)
16	5°	5°	270°	122 (24.65%)	356 (71.92%)	17 (3.43%)

3.2 Effect of Increasing Star Magnitude Error

The STARID algorithm input parameters must be consistent with the expected error in the observed magnitudes for the magnitude information to be used effectively as a pattern dimension. The next series of runs was performed with the tolerance *XMTOL*, the maximum difference between the magnitude of an observed star and the magnitude of any of its candidates, above which a candidate star is eliminated from consideration, fixed at 0.6. This value is a reasonable bound for the match between the predicted and actual instrumental magnitude for the majority of cataloged stars. The tolerance *TMAGMX*, the minimum magnitude difference indicating which is the brighter of the two observed stars, was also fixed at 0.6. The upper limit on simulated magnitude error was set to 6, to ensure that the distribution of the magnitude errors was not cut off for the higher values of *SIGMAG* (the simulated observed star magnitude noise standard deviation, 1 σ) that were tested. The results are shown in Table 4 for the cap catalog case and in Table 5 for the band catalog case. The first few runs in each table have a simulated magnitude error within the range for which the fixed

Table 4. Increasing Simulated Magnitude Error, Cap Catalog Case

Run #	*SIGMAG* (simulated magnitude noise, 1 σ)	# Ambiguous Stars	# Stars Identify Correctly (uniquely)	# Stars Misidentified
1	0.10	0 (0.00%)	498 (100.00%)	0 (0.00%)
2	0.15	0 (0.00%)	498 (100.00%)	0 (0.00%)
3	0.20	1 (0.20%)	497 (99.80%)	0 (0.00%)
4	0.25	2 (0.40%)	496 (99.60%)	0 (0.00%)
5	0.30	7 (1.41%)	490 (98.39%)	1 (0.20%)
6	0.35	23 (4.65%)	473 (94.98%)	2 (0.40%)
7	0.40	35 (7.03%)	458 (91.97%)	5 (1.00%)
8	0.45	48 (9.64%)	445 (89.36%)	5 (1.00%)
9	0.50	63 (12.65%)	431 (86.55%)	4 (0.80%)
10	1.00	208 (41.77%)	275 (55.22%)	15 (3.01%)

Table 5. Increasing Simulated Magnitude Error, Band Catalog Case

Run #	*SIGMAG* (simulated magnitude noise, 1 σ)	# Ambiguous Stars	# Stars Identified Correctly (uniquely)	# Stars Misidentified
1	0.10	4 (0.81%)	491 (99.19%)	0 (0.00%)
2	0.15	4 (0.81%)	491 (99.19%)	0 (0.00%)
3	0.20	4 (0.81%)	491 (99.19%)	0 (0.00%)
4	0.25	5 (1.01%)	490 (98.99%)	0 (0.00%)
5	0.30	13 (2.63%)	479 (96.77%)	3 (0.61%)
6	0.35	21 (4.24%)	470 (94.95%)	4 (0.81%)
7	0.40	35 (7.07%)	451 (91.11%)	9 (1.82%)
8	0.45	64 (12.93%)	419 (84.65%)	12 (2.42%)
9	0.50	83 (16.77%)	390 (78.79%)	22 (4.44%)
10	1.00	273 (55.15%)	170 (34.34%)	52 (10.50%)

reasonable tolerances are valid, or nearly so. The later runs show the effect of the magnitude error rising past the point where the fixed tolerances become invalid, showing what might happen if predicted instrumental magnitude and actual were not in as good an agreement as expected. These results also show a general feature of the pattern-matching algorithm: the smooth degradation of identification results as error increases. This feature should be helpful in monitoring during operations, since the number of ambiguous identifications can be watched, and a high number can alert the user that tolerances may need to be adjusted.

3.3 Effect of Increasing Simulated Observed Star Position Error

In this series of runs, the amount of simulated observed star position error was increased while the related STARID input parameters remained fixed at the nominal values given in Table 1. The results are given in Table 6 for the cap catalog case and in Table 7 for the band catalog case.

Table 6. Increasing Simulated Observed Star Position Error, Cap Catalog Case

Run #	*SIGOBS* (simulated position noise, 1 σ, sec)	# Ambiguous Stars	# Stars Identified Correctly (uniquely)	# Stars Misidentified
1	0	0 (0.00%)	498 (100.00%)	0 (0.00%)
2	3	0 (0.00%)	498 (100.00%)	0 (0.00%)
3	6	0 (0.00%)	498 (100.00%)	0 (0.00%)
4	9	0 (0.00%)	497 (99.80%)	1 (0.20%)
5	12	3 (0.60%)	493 (99.00%)	2 (0.40%)
6	15	12 (2.41%)	482 (96.79%)	4 (0.80%)
7	18	26 (5.22%)	469 (94.18%)	3 (0.60%)
8	21	48 (9.64%)	446 (89.56%)	4 (0.80%)

Table 7. Increasing Simulated Observed Star Position Error, Band Catalog Case

Run #	*SIGOBS* (simulated position noise, 1 σ, sec)	# Ambiguous Stars	# Stars Identified Correctly (uniquely)	# Stars Misidentified
1	0	4 (0.81%)	491 (99.19%)	0 (0.00%)
2	3	4 (0.81%)	491 (99.19%)	0 (0.00%)
3	6	4 (0.81%)	485 (97.98%)	0 (0.00%)
4	9	5 (1.01%)	485 (97.98%)	0 (0.00%)
5	12	16 (3.23%)	478 (96.57%)	1 (0.20%)
6	15	30 (6.06%)	461 (93.13%)	4 (0.81%)
7	18	61 (12.32%)	424 (85.66%)	10 (2.02%)
8	21	83 (16.77%)	396 (80.00%)	16 (3.23%)

The increasing position errors become apparent both through the effect of the observed separations becoming erroneous, causing invalid indexing into the list of candidates, and from the separation tolerance test for candidates being applied without accounting for the increased error. Note that a value of *SIGOBS*, the simulated observed star position error (1σ), of 3 sec or less is consistent with the expected tracker measurement noise for XTE, SWAS and SOHO missions.

4.0 Band Catalog With Sun-Oriented Pole Tests and Results

This series of tests explores the algorithm performance for a SOHO-type mission where the body *X*-axis is nominally aligned toward the Sun. Since for this mission the Sun-oriented band catalog geometry repeats itself every 6 months, unit vectors toward the Sun were generated from solar-lunar-planetary (SLP) files over the interval of 950701 to 960101 at 1-month intervals. The Sun unit vectors were selected for use as the a priori catalog generation vectors. The body *X*-axis was chosen to lie within a uniform random error of 0.1 deg from the Sun unit vector, and the body *Z*-axis was chosen in a uniformly random direction perpendicular to the *X*-axis. The 3-2-1 rotation of 0.1, 0.1, and 180 deg used previously was applied to simulate the effect of attitude error. Table 8 summarizes the results for this series of runs that used the nominal parameters shown in Table 1, for 4 runs, each with a different seed for the linear congruential generator, to obtain a larger total set of tests. Each individual run generated 6 band catalogs, and used each band catalog for 10 randomly selected views. From these results we see that with nominal errors, the algorithm performed well for the Sun-oriented geometries tested. At the higher levels of error, the results were within a percent or so of the results obtained in the randomly-oriented full sky band catalog tests at the same error level.

Table 8. Sun-Oriented Band Catalog Tests

Test Description	#Stars Total	# Ambiguous Stars	# Stars Identified Correctly (uniquely)	# Stars Misidentified
Nominal Sun-Oriented Band Catalog Series	1192	8 (0.67%)	1184 (99.33%)	0 (0.00%)
Sun-Oriented Band Catalog Series With Serious Attitude Errors: The simulated attitude error rotation was $(\Delta\phi, \Delta\theta, \Delta\psi)$ = (3°, 3°, 3°), the value at which misidentifications began to occur in Section 3.1.	1192	49 (4.11%)	1137 (95.38%)	6 (0.50%)
Sun-Oriented Band Catalog Series With Serious Magnitude Errors: *SIGMAG* was set to 0.3, the value at which misidentifications began to occur in Section 3.2. The upper limit on simulated magnitude error was set to 6.	1192	43 (3.61%)	1138 (95.47%)	11 (0.92%)
Sun-Oriented Band Catalog Series With Serious Simulated Observed Star Position Errors: *SIGOBS* was set to 12 sec, the value at which misidentifications began to occur in Section 3.3.	1192	22 (1.85%)	1167 (97.90%)	3 (0.25%)

5.0 Star Desert and Star Forest Tests

Study of the pattern-matching algorithms suggested that the reliability and execution time of the methods would likely be affected by the varying stellar density encountered from region to region within a given full-sky star catalog. We used the natural variation of stellar density to evaluate the effects of this factor by looking at regions with fewer stars than average ("star deserts") and regions with more stars than average ("star forests").

5.1 Star Desert and Star Forest Tests, Cap Catalog Case

Table 9 summarizes the results of star desert and star forest tests using a cap catalog. The most interesting result is the decrease in ambiguous identifications in the star desert compared to the star forest. Likewise, there was an increase in misidentifications in the serious error cases in the star forest compared to the star desert.

5.2 Star Desert and Star Forest Tests, Band Catalog Case

Table 10 summarizes the results of star desert and star forest tests using a band catalog. Again we see the decrease in ambiguous identifications in the star desert compared to the star forest, and an increase in misidentifications in the serious error cases in the star forest compared to the star desert. The effects are significantly larger, however, than in the cap catalog tests. This is apparently simply due to the larger number of stars in the zone catalog in the band catalog case. The number of candidate pairs is proportional to the number of combinations of *NCAP* items taken 2 at a time, equal to $(NCAP^2 - NCAP)/2$, where *NCAP* is the number of stars in the zone catalog. A given error in the value of an observed star's measurement along a pattern dimension has a much higher probability of leading to misidentification of the observed star pair when using a large zone catalog than when using a small one because of the greatly increased density of candidate pairs with respect to each unit of pattern dimension.

6.0 Performance Considerations

6.1 Execution Time

It is useful to consider the prototype execution times with respect to the values of *NCAP*, the number of stars in the zone catalog, and *NTOT*, the number of candidate pairs from that zone catalog with separation less than the effective FOV width. Recall that in these simulations, all observations used for each identification attempt can be considered to be from a single time, made from a single inertially-fixed circular tracker FOV. Thus, the effective FOV width is just the tracker diameter (8 deg for XTE/SWAS, 4 deg for SOHO). Execution times from a representative set of runs described above are given in Table 11 for cap catalog cases and in Table 12 for band catalog cases. Note that the software wall clock time has a resolution of about 0.055 sec, so "buckets" are noticeable on short times. In the runs we examined, the wall clock time required to reassemble the same zone catalog varies slightly, most likely due to the varying load on the LAN. The first access is almost always the longest, as one would expect, due to overhead in establishing the file connection. The subsequent zone catalog generation times for the same zone catalog were generally more

Table 9. Star Desert and Star Forest Tests, Cap Catalog Case

Test Description	#Stars Total	# Ambiguous Stars	# Stars Identified Correctly (uniquely)	# Stars Misidentified
Star Desert With Nominal Errors: The direction for the cap catalog generation was $(\alpha,\delta)=$ (12.25°, -27.4°), the approximate position of the Southern Galactic Pole (SGP)	1861	19 (1.02%)	1842 (98.98%)	0 (0.00%)
Star Forest With Nominal Errors: The direction for the cap catalog generation was $(\alpha,\delta)=$ (265.6°, – 28.917°), the approximate position of the Galactic Center (GC).	2000	0 (0.00%)	2000 (100.00%)	0 (0.00%)
Star Desert With Serious Attitude Errors: Rotations about each axis were set to values at which misidentifications began to occur in Section 3.1. $(\Delta\phi=40'',\Delta\theta=40'',\Delta\psi=90°)$	1861	118 (6.34%)	1726 (92.74%)	17 (0.91%)
$(\Delta\phi=100°,\Delta\theta=40'',\Delta\psi=60'')$	1861	199 (10.69%)	1643 (88.29%)	19 (1.02%)
$(\Delta\phi=40'',\Delta\theta=100°,\Delta\psi=60'')$	1861	212 (11.39%)	1614 (86.73%)	35 (1.88%)
Star Forest With Serious Attitude Errors: Rotations about each axis were set to values at which misidentifications began to occur in Section 3.1. $(\Delta\phi=40'',\Delta\theta=40'',\Delta\psi=90°)$	2000	106 (5.30%)	1868 (93.40%)	26 (1.30%)
$(\Delta\phi=100°,\Delta\theta=40'',\Delta\psi=60'')$	2000	235 (11.75%)	1726 (86.30%)	39 (1.95%)
$(\Delta\phi=40'',\Delta\theta=100°,\Delta\psi=60'')$	2000	210 (10.50%)	1735 (86.75%)	55 (2.75%)
Star Desert Series With Serious Magnitude Errors: *SIGMAG* was set to 0.3, and the upper limit on simulated magnitude error was set to 6.	1861	51 (2.74%)	1803 (96.88%)	7 (0.38%)
Star Forest Series With Serious Magnitude Errors: *SIGMAG* was set to 0.3, and the upper limit on simulated magnitude error was set to 6.	2000	48 (2.40%)	1945 (97.25%)	7 (0.35%)
Star Desert Series With Serious Simulated Observed Star Position Errors: *SIGOBS* was set to 12 sec	1861	40 (2.15%)	1803 (97.80%)	1 (0.05%)
Star Forest Series With Serious Simulated Observed Star Position Errors: *SIGOBS* was set to 12 sec	2000	21 (1.05%)	1972 (98.60%)	7 (0.35%)

Table 10. Star Desert and Star Forest Tests, Band Catalog Case

Test Description	#Stars Total	# Ambiguous Stars	# Stars Identified Correctly (uniquely)	# Stars Misidentified
Star Desert With Nominal Errors: The direction for the pole of the band catalog was $(\alpha,\delta)=$ (292.3894°, 80.0740°), a position selected because it gave fewer stars (1,292) and fewer candidate pairs with separations up to 4 deg (18,768) than other directions found. This number of stars and candidate pairs is assumed to be near the minimum possible given this input catalog.	1965	11 (0.56%)	1954 (99.44%)	0 (0.00%)
Star Forest With Nominal Errors: The direction for the pole of the band catalog was $(\alpha,\delta)=$ (191.1942°, 27.6408°), a position near the North Galactic Pole (NGP), selected because it gave almost the maximum number of stars (3,124 versus 3,125) and more candidate pairs with separations up to 4° (106,802 vs 106,592 for the 3,125 star case) than other directions found during our random search. This number of stars and candidate pairs is assumed to be near the maximum possible given this input catalog.	2000	40 (2.00%)	1956 (97.80%)	4 (0.20%)
Star Desert With Serious Attitude Errors: Rotations were set to $(\Delta\phi,\Delta\theta,\Delta\psi)$ = (3°, 3°, 3°), the values at which misidentifications began to occur in Section 3.1.	1965	47 (2.39%)	1917 (97.56%)	1 (0.05%)
Star Forest With Serious Attitude Errors: Rotations were set to $(\Delta\phi,\Delta\theta,\Delta\psi)$ = (3°, 3°, 3°), the values at which misidentifications began to occur in Section 3.1.	2000	157 (7.85%)	1813 (90.65%)	30 (1.50%)
Star Desert Series With Serious Magnitude Errors: *SIGMAG* was set to 0.3, and the upper limit on simulated magnitude error was set to 6.	1965	60 (3.05%)	1897 (96.54%)	8 (0.41%)
Star Forest Series With Serious Magnitude Errors: *SIGMAG* was set to 0.3, and the upper limit on simulated magnitude error was set to 6.	2000	108 (5.40%)	1860 (93.00%)	32 (1.60%)
Star Desert Series With Serious Simulated Observed Star Position Errors: *SIGOBS* was set to 12 sec	1965	39 (1.98%)	1923 (97.86%)	3 (0.15%)
Star Forest Series With Serious Simulated Observed Star Position Errors: *SIGOBS* was set to 12 sec	2000	122 (6.10%)	1863 (93.15%)	15 (0.75%)

Table 11. Wall Clock Execution Times for Selected Cap Catalog Cases (Platform: 33 MHz, 486 CPU)

Case Description	Generate Catalog		Create Star Identification Data Structure (SIDS) and Do 1st Star Identification			Subsequent ID Times With Existing SIDS		
	Time	NCAP	Time	NCAP	NTOT	Time	NCAP	NTOT
1st Run from Table 2, Cap Catalog, Random Pointing, Nominal Errors	Min 0.22 s Max 0.49 s	63 67	Min 0.17 s Max 0.22 s	63 84	697 1467	Min 0.10 s Max 0.22 s	63 63	697 697
	Total Time = Sum of all 10 catalogs: (time to generate catalog + time to create SIDS and 1st ID + time for subsequent 9 IDs with existing SIDS) = 18.55 s, 1.9 s average for a new catalog and 10 views/catalog							
1st Run from Table 9, Cap Catalog Case, Star Desert, Nominal Errors	Min 0.17 s Max 0.27 s	49 49	Min 0.16 s Max 0.22 s	49 49	483 483	Min 0.10 s Max 0.22 s	49 49	483 483
	Total Time = Sum of all 10 catalogs: (time to generate catalog + time to create SIDS and 1st ID + time for subsequent 9 IDs with existing SIDS) = 17.86 s, 1.8 s average for a new catalog and 10 views/catalog							
1st Run from Table 9, Cap Catalog Case, Star Forest, Nominal Errors	Min 0.22 s Max 0.38 s	116 116	Min 0.33 s Max 0.39 s	116 116	2701 2701	Min 0.11 s Max 0.33 s	116 116	2701 2701
	Total Time = Sum of all 10 catalogs: (time to generate catalog + time to create SIDS and 1st ID + time for subsequent 9 IDs with existing SIDS) = 20.67 s, 2.1 s average for a new catalog and 10 views/catalog							

Table 12. Wall Clock Execution Times for Selected Band Catalog Cases (Platform: 33 MHz, 486 CPU)

Case Description	Generate Catalog		Create SIDS and Do 1st Star Identification			Subsequent ID Times With Existing SIDS		
	Time	NCAP	Time	NCAP	NTOT	Time	NCAP	NTOT
1st Run from Table 8, Band Catalog Case, Sun-Oriented, Nominal Errors	Min 8.02 s Max 11.48 s	1534 1947	Min 6.97 s Max 11.20 s	1534 2009	28676 42067	Min 0.17 s Max 0.50 s	1534 1747	28676 37616
	Total Time = Sum of all 6 catalogs: (time to generate catalog + time to create SIDS and 1st ID + time for subsequent 9 IDs with existing SIDS) = 135.45 s, 22.6 s average for a new catalog and 10 views/catalog							
1st Run from Table 10 Band Catalog Case, Star Desert, Nominal Errors	Min 4.56 s Max 6.42 s	1292 1292	Min 4.72 s Max 4.89 s	1292 1292	18768 18768	Min 0.11 s Max 0.33 s	1292 1292	18768 18768
	Total Time = Sum of all 10 catalogs: (time to generate catalog + time to create SIDS and 1st ID + time for subsequent 9 IDs with existing SIDS) = 121.19 s, 12.2 s average for a new catalog and 10 views/catalog							
1st Run from Table 10 Band Catalog Case, Star Forest, Nominal Errors	Min 15.32 s Max 22.02 s	3124 3124	Min 28.28 s Max 28.62 s	3124 3124	106802 106802	Min 0.66 s Max 1.10 s	3124 3124	106802 106802
	Total Time = Sum of all 10 catalogs: (time to generate catalog + time to create SIDS and 1st ID + time for subsequent 9 IDs with existing SIDS) = 528.21 s, 52.8 s average for a new catalog and 10 views/catalog							

consistent. The operational systems for support of XTE/SWAS will also have remote access to files, which saves space; but our experience suggests that, to avoid this problem, separate copies of the star catalogs should be kept on each HP 715/50 workstation that may need to run the support software. In the star desert cases, the minimum star identification times were typically those for which the fewest stars were in the simulated sensor FOV, give or take the wall clock resolution.

6.2 Memory Requirements

The largest storage requirements in the prototype are for those arrays that need to be sized larger than the expected number of candidate pairs *NTOT*. *NTOT* is related to *NCAP* by:

$$NTOT = k_g \frac{(NCAP^2 - NCAP)}{2} \tag{1}$$

Pairs of zone catalog stars whose separation exceeds the effective tracker FOV are unobservable, so $k_g \leq 1$.

We have observed that for the range of effective tracker FOV widths and zone catalog sizes used in this study, the constant of proportionality k_g is approximated by

$$k_g \approx 3 \frac{AREA_{TRACKERFOV}}{AREA_{ZONECATALOG}} \tag{2}$$

As stars are not uniformly distributed, the observed values necessarily vary about this or any other approximation. Values of geometric k_g calculated using (2), and apparent k_g calculated using (1) with the *NCAP* and *NTOT* values given in Tables 11 and 12 are given below in Tables 13 and 14, respectively. The approximation gives a conservatively large value of k_g for the range of relative tracker FOV and zone catalog areas we considered.

The relationship between *NCAP* and *NTOT* must be kept in mind to ensure that arrays are dimensioned according to the expected worst-case *NTOT* value. To find the memory requirements of this algorithm for a given catalog if the worst-case stellar density for the catalog is available, multiply that density by the area of the zone-catalog to get an estimate for *NCAP*, and use the approximation for k_g in (1) to calculate a bound for *NTOT*. In practice, a safety margin seems warranted: we used a dimension of 150,000, which was never exceeded in our tests. The *NTOT* = 106802 band catalog case was the largest we found with the SOHO catalog and a 4.2-deg edge-to-edge band.

Table 13. Values of k_g Obtained for Selected Cap Catalog Cases

Geometric k_g	*NCAP*	*NTOT*	Apparent k_g
0.4224	63	697	0.357
0.4224	84	1467	0.421
0.4224	49	483	0.411
0.4224	116	2701	0.405

Table 14. Values of k_g Obtained for Selected Band Catalog Cases

Geometric k_g	*NCAP*	*NTOT*	Apparent k_g
0.0249	1534	28676	0.024
0.0249	2009	42067	0.021
0.0249	1292	18768	0.022
0.0249	3124	106802	0.022

7.0 Conclusions

Based on these results, the prototype algorithm is fast enough for both XTE/SWAS and SOHO mission requirements. Even the periodic updates to the zone catalog and corresponding SIDS initialization for XTE/SWAS-type cases can be accomplished in under 1 sec on the 33 MHz 486, so should not present a problem on the HP 715/50. Initialization does take longer for SOHO-type band catalog cases, but still completed in under 60 sec even for the star forest case.

When operating within XTE/SWAS and SOHO mission parameters, the identification process was almost always successful and was found not to produce incorrect identifications. It was found to degrade smoothly when errors grow above tolerances. However, the degradation was steep for the cap catalog geometry tests once the tolerances were exceeded. With the nominal values of position and magnitude noise, it appears that the separation and magnitude tests alone are often sufficient for good identification results in such a cap catalog case, as we saw with the results in Table 2, Run 6. However, as with the results in Table 3, Run 16, we found that the band catalog geometry tests, even when their tolerances were exceeded, produced significant improvement in identification accuracy over that achieved with separation and magnitude tests alone, with the levels of position and magnitude noise used as nominal in this analysis.

References

Van Bezooijen, R. W. H., "Autonomous Star Referenced Attitude Determination," AAS 89-03, *Guidance and Control*, Proceedings of the Annual Rocky Mountain Guidance and Control Conference, Keystone, CO, 1989

Slater, M. and Hashmall, J. (CSC), *SKYMAP Star Catalog Data Base Generation and Utilization System Description, Revision 3, Update 1*, 554-FDD-89/001R3UD1, Goddard Space Flight Center, Flight Dynamics Division, prepared by Computer Sciences Corporation, August 1992