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Attitude Determination Studies for the Earth Observation System AM1 (EOS-AM1) Mission

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The application of Kalman filter-based attitude determination, with simultaneous gyro bias estimation, to the Earth Observation System (EOS) AM1 mission with stellar measurements is analyzed. The study examines the predictive capability of covariance analysis as compared with Monte Carlo analysis, showing that thrice the square root of the Kalman filter covariance matrix diagonal is a reasonable prediction for the 99.7% Monte Carlo results, but not of worst-case performance. The study also establishes further insight into the sensitivity of EOS-AM1 attitude determination performance to simulated stellar-lunar geometries by comparing Monte Carlo performance predictions using a statistically generated star field (including statistical lunar blockage gaps) with those using a physical model (real star field and lunar and solar ephemerides). This study further demonstrates that, with EOS-AM1 parameters, the performance is driven by the sensor noise rather than the gaps in the star field and confirms these conclusions by Monte Carlo assessments of the orbits with short and long star gaps.

Introduction

THE Earth Observation System (EOS) AM1 mission will deliver precision attitude information to support geolocation of diverse Earth surface imaging and cloud observing scientific payloads. The overall attitude knowledge requirements determine the allocation (Table 1) of the attitude update filter contribution to the overall pointing error budget.[1]

EOS-AM1 will use a gyro-star tracker inertial reference system to deliver the required attitude knowledge and stability. This spacecraft uses Kearfott SKIRU-DII gyros and Ball CT-601 solid state star trackers, designated ST1 and ST2. Since the star tracker measurements are used approximately once each 10 s (subsequent to this study, the update interval has been changed to 8.192 s), the shorter period stability requirements (1.8 and 9 s) rely on the gyro performance and the magnitude of the attitude updates produced by the star tracker driven attitude update filter (AUF).[2] The long-period (420 s) stability is driven by the absolute attitude determination error of the AUF as it periodically corrects the gyro-propagated attitude. Additionally, since there are occasional large gaps in the star field (with no ability to correct the gyro-propagated attitude), the knowledge of the gyro bias becomes important.

Accordingly, it is shown later that the EOS AUF simultaneously estimates both the gyro bias and the attitude error. Typical single-orbit results are shown, as are summaries of the performance statistics observed over a series of Monte Carlo runs. The performance is contrasted between a statistical star field (with statistically generated lunar blockage) and a physically correct star field with accurate lunar and solar ephemerides. The attitude error performance is assessed for both nominal (two tracker) operations and failure conditions (single tracker). Conclusions, based on comparisons of these runs, are also presented. Also, since EOS-AM1 was baselined to use a single star measurement per tracker, the total number of stars in the tracker field of view was not investigated.

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Theoretical Background

The AUF planned for EOS-AM1 is a Kalman filter that estimates both attitude error and gyro bias. The filter is based on an attitude uncertainty model,[2] in rotating body coordinates, discretized at the attitude update time interval (approximately 10 s). Since the EOS-AM1 spacecraft tracks nadir, and since the nominal nadir pitches at a constant orbital rate, many of the gyro error sources can be viewed as equivalent bias drifts. In other words, the effects of misalignment, scale factor error, and bias drifts can be lumped together as an equivalent bias drift. For example, pitch axis scale factor error cannot be distinguished from pitch axis bias drift. Similarly, roll and yaw axis gyro misalignments (causing the pitch rate to be projected into the yaw or roll axes) cannot be distinguished from bias drifts in those axes. In light of this lack of observability of many gyro parameters, the EOS-AM1 AUF estimates the net equivalent bias drift for each orthogonal gyro axis. This Kalman filter only predicts the ability of the system to reject random noise in the measurements and in the state variables; it does not predict the ability to reject systematic errors such as thermally induced alignment errors. The performance of this filter in the context of orbital variations in alignment and an evaluation of the explicit effects of scale factor errors and other modeling uncertainties are the subjects of follow-on studies.

Statistical Star Field Results

Based on previously developed star gap and lunar blockage statistics,[3,4] a random star map was defined, and the lunar blockage was then placed randomly over this star field. The star pattern statistical modeling was based on artificially populating a ±4-deg strip around the boresight orbital track of one of the star trackers, ST1 [field of view (FOV): 8 × 8 deg], with 72 stars[3,4] available for measurement per orbit. This random geometry was generated for every simulated seven-orbit Monte Carlo run. To define steady-state performance levels, performance statistics were collected over the

Table 1 Update filter allocation for EOS-AM1

	Update filter allocation (99.7% value), arcsec
Roll	12.4
Pitch	12.1
Yaw	6.9

final three orbits of each run, thus ignoring the transient performance of the first three orbits. (The EOS-AM1 orbital period is 5934 s.)

The following parameters were used[2]: the gyro white noise drift standard deviation was $\sigma_1 = 6 \times 10^{-3}$ arcseconds (arcsec)/$s^{1/2}$, the gyro random walk drift standard deviation was $\sigma_2 = 2.3 \times 10^{-5}$ arcsec/$s^{3/2}$, and the star tracker noise equivalent angle was $\sigma_s = 5.33$ arcsec.

Typical Single-Run Results

Typical single tracker attitude determination results for the last three orbits of a single run of the Monte Carlo study are shown in Fig. 1. It can be seen that the attitude errors generally remain within the 1σ envelope defined by the diagonal elements of the time-varying covariance matrix underlying the AUF. The covariance envelope increases during substantial gaps in the stars, as seen by comparing lunar blockage gaps (low points) in the ST1 star patterns with the 1σ envelope curves (particularly in the pitch and yaw axes). Although the covariance envelope (really the standard deviation or square root of the corresponding covariance matrix diagonal element) correlates with the star gaps, the instantaneous attitude error does not. The instantaneous error is driven by the instantaneous noise rather than the overall statistics.

Typical dual tracker attitude determination results for the last three orbits of a single run of the Monte Carlo study are shown in Fig. 2. As for the single tracker, the covariance envelope peaks generally correlate with gaps in one tracker or the other. However, the relative observability of the different axes can also be seen. Pitch

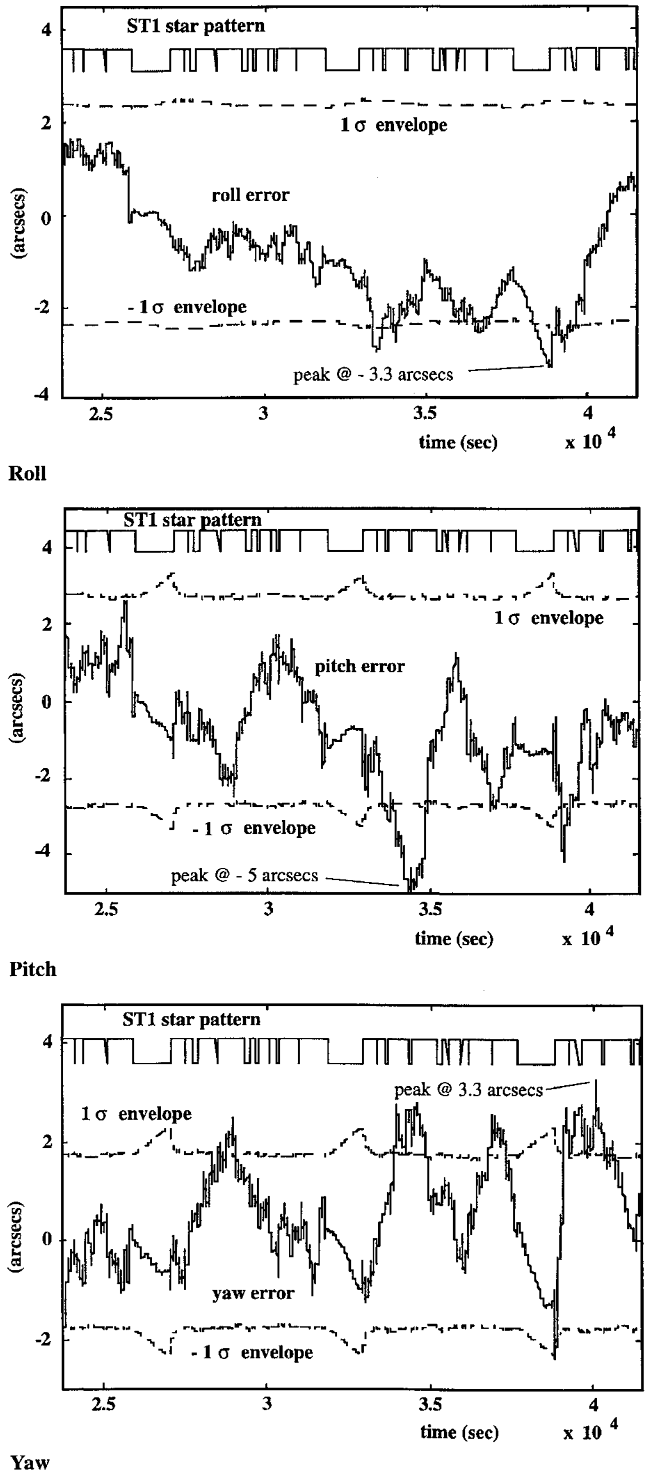

Fig. 1 Attitude determination errors: single star tracker.

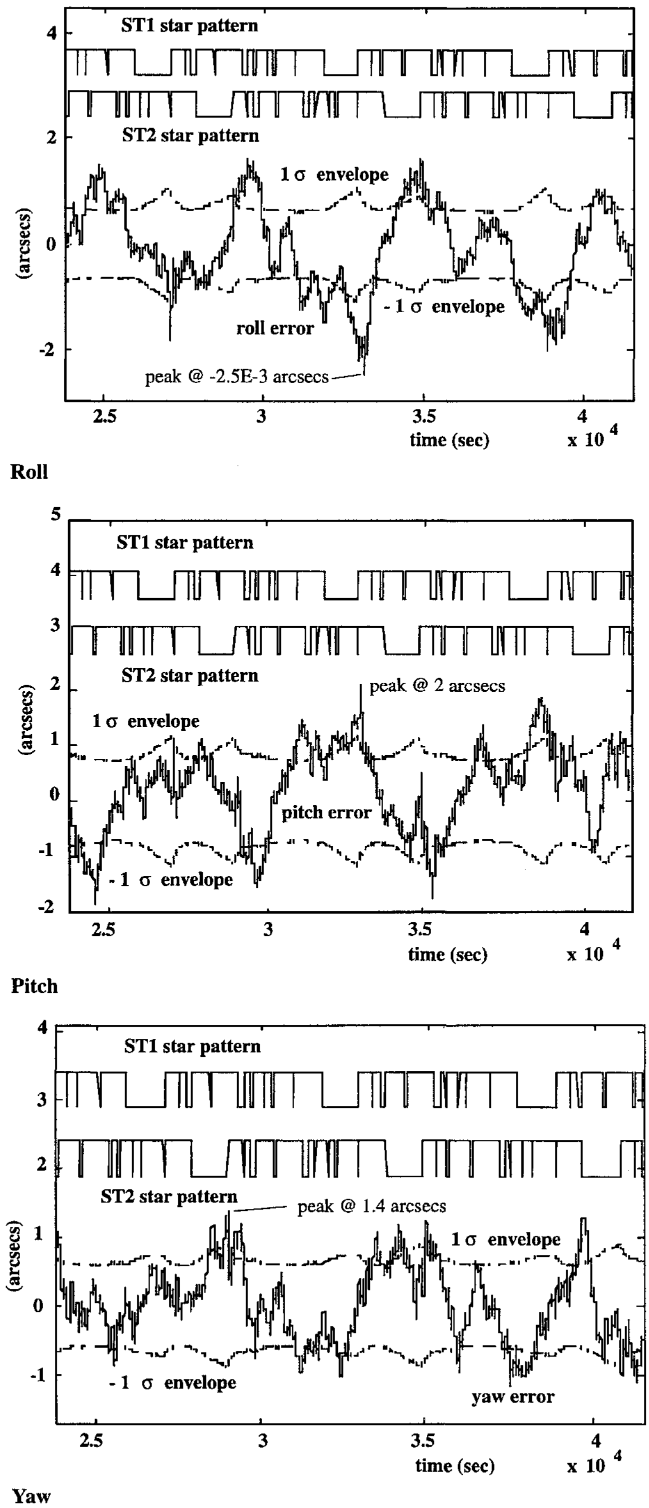

Fig. 2 Attitude determination errors: two star trackers.

axis covariance peaks result whenever a gap in either tracker occurs. Roll axis covariance tends to peak when tracker 1 gaps occur, with less sensitivity to tracker 2 gaps. Conversely, yaw axis covariance peaks result when tracker 2 gaps occur. Comparing the results of Fig. 2 with the results of Fig. 1, one can see that the dual tracker attitude errors are substantially less than single tracker errors.

Although the absolute attitude determination errors described earlier are important for long-term (420 s) attitude determination performance, individual updates influence short-term (1.8 and 9 s) attitude determination stability. Typical single tracker attitude update performance is illustrated in Fig. 3. For the particular run illustrated, peak attitude updates of 1.04 and 0.86 arcsec were observed for pitch and yaw, respectively. These are the worst case sizes of individual updates at 10-s intervals. In reviewing the data of Figs. 1 and 3, some correlation of update size and lunar blockage gap was observed. If the attitude updates exhibited a substantial shift in one direction for several update cycles after a gap, then substantial controller response might be expected. As seen in Fig. 4, no such trend was observed.

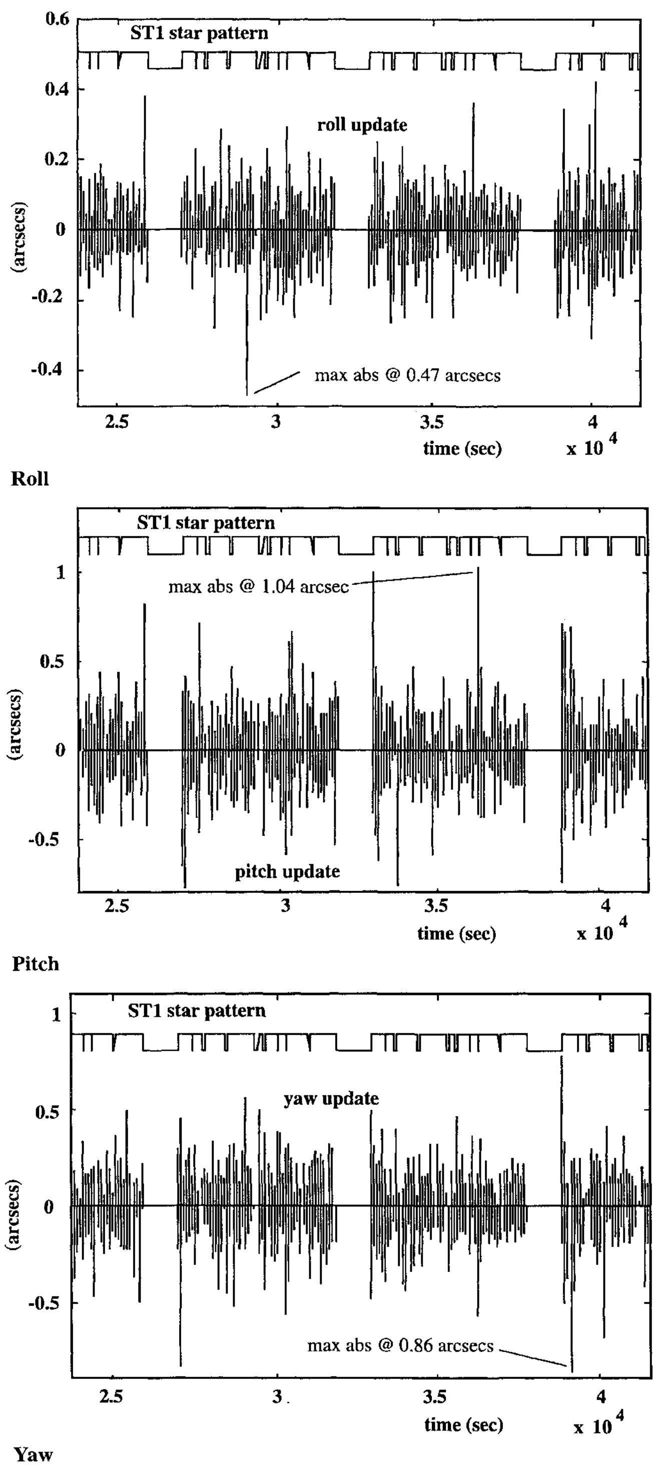

Fig. 3 Attitude updates: single star tracker.

Comparison of Monte Carlo Attitude Determination Results

The preceding data represent typical results for a single run of the Monte Carlo study. For the complete Monte Carlo study, 380 runs were accomplished. For each single run a random star field and a lunar blockage gap were generated. Each single run consisted of seven orbits, with the first three orbits allowing transient performance to settle to steady-state values. Both dual and single tracker cases were considered. For each case, the maximum covariance matrix prediction and the peak attitude errors over the last three orbits of each run were retained, along with a statistical characterization (mean and standard deviation) of the final three orbits.

As an illustration, the results for the roll attitude error observed in the 380 runs are summarized in Fig. 5 (for the single tracker case), where the magnitudes of the peak attitude errors observed in the final three orbits of each run are plotted (the bold curves) in an ascending order. The significant variation between the best and worst runs highlight the peril of using statistics from any single run to predict worst case performance. Additionally, for comparison, the means and means plus thrice the standard deviations over the same final three orbits are plotted for each run. For any single run, the mean plus 3σ characterization of the attitude errors generally (but not always) bounds the actual peak observed. Since the diagonals of the Kalman covariance matrices represent the variances (σ^2) of the states, taking thrice the square roots of the diagonals of the covariance matrices represents a 3σ prediction. These covariance matrix predictions $[3\sqrt{(P_{ii})}]$ are relatively invariant across the runs and generally bound the attitude errors.

The peak attitude determination errors are summarized in Table 2 and quantify the significant run-to-run variations observed in

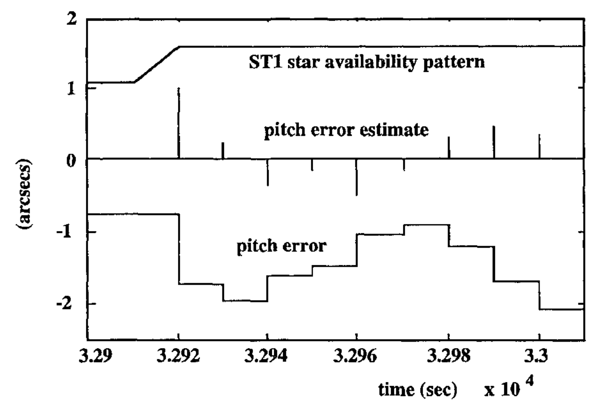

Fig. 4 Pitch attitude updates after lunar blockage: single star tracker.

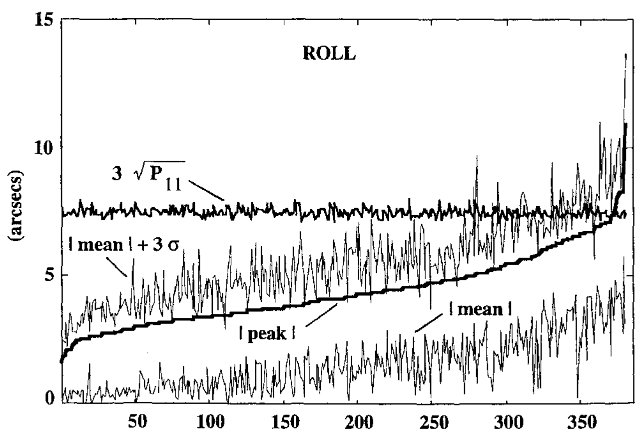

Fig. 5 Monte Carlo Roll attitude error: single star tracker, statistical star field.

Table 2 Monte Carlo peak error: statistical star field

		Peak attitude det. error, arcsec		
ST		Roll	Pitch	Yaw
ST1	Max.	10.96	12.57	9.02
	Min.	1.57	2.69	2.29
	99.7%	8.83	12.18	7.42
ST1 and ST2	Max.	5.11	4.01	3.41
	Min.	1.22	1.49	1.23
	99.7%	3.92	3.96	3.12

Table 3 Monte Carlo peak covariance prediction: statistical star field

		Peak attitude det. error, arcsec		
ST		Roll	Pitch	Yaw
ST1	Max.	8.05	11.47	7.73
	Min.	7.13	8.96	6.54
	99.7%	8.02	11.28	7.68
ST1 and ST2	Max.	3.94	4.13	3.49
	Min.	3.01	3.22	2.58
	99.7%	3.93	4.10	3.43

Table 4 Monte Carlo peak update: statistical star field

		Peak attitude det. error, arcsec		
ST		Roll	Pitch	Yaw
ST1	Max.	1.00	2.62	2.31
	Min.	0.31	0.72	0.62
	99.7%	0.76	2.58	2.14
ST1 and ST2	Max.	1.13	1.27	0.78
	Min.	0.34	0.38	0.29
	99.7%	0.99	1.05	0.77

Fig. 5. For example, the minimum peak attitude determination error observed for single tracker (ST1 only) roll axis error was 1.57 arcsec, whereas the maximum peak observed was 10.96 arcsec. In other words, for one seven-orbit run, the peak attitude determination error observed (during the final three orbits) was 1.57 arcsec, whereas in another run, the peak error seen in the last three orbits was 10.96 arcsec. Generally, the range of variations seen in Table 2 imply a factor of 4 to 5 between the minimum peak and the maximum peak. Clearly the attitude error performance of any single run is not predictive of expected performance, even though three complete orbits worth of data were included for each run. Identical conclusions result for the dual tracker case and for single and dual tracker gyro bias determination. Given the 3σ nature of the EOS-AM1 requirements, the statistical 99.7% peak performance values from Table 1 are the significant performance measures for later comparisons.

During the same set of Monte Carlo runs, the peak values of the time-varying covariance matrices were also determined. Such covariance results are shown in Table 3. In contrast to the peak attitude determination errors of Table 2, the covariance predictions of Table 3 show relative run-to-run invariance. Further, the covariance results of Table 3 are reasonably predictive of the 99.7% values of Table 2. These results indicate that covariance analysis represents a solid prediction of 99.7% behavior of the performance of this AUF but that actual worst-case performance can exceed the covariance predictions.

While Tables 2 and 3 predict the overall attitude determination performance over long time intervals, the short-term behavior is defined by the sizes of the attitude updates. These updates represent step changes in the estimated attitude and occur approximately every 10 s. The spacecraft controller has a substantially longer time constant (nearly 100 s) and so will not respond significantly to the updates. These updates represent changes in the attitudes used to interpret the instrument data; however, the way these data are used, the effects of a single update will be averaged over the entire 10-s interval, resulting in an effective drift of the update size divided by the update interval. Table 4 summarizes the attitude update magnitudes observed through the Monte Carlo study (with the statistical star field). The run-to-run variation is substantial, with a factor of 3 to 4 between the minimum peak update and the maximum peak update across the runs. Because of the 3σ nature of the EOS-AM1 requirements, 99.7% results are retained as the predictions of attitude update magnitude.

Physical Star Field Results

In addition to the random star field described earlier, a complete physical star catalog was developed[5] and augmented with solar and lunar ephemerides. In addition, the changing geometry of the EOS-AM1 orbit with respect to the field of stars was modeled. Since the EOS-AM1 spacecraft is in a sun-synchronous orbit, its orbit plane precesses at approximately 1 deg per day. This causes the trajectory of the star tracker FOV to change throughout the course of the year. Studies with the physical catalog acknowledge the realistic, time-varying geometry of the star tracker trajectory, as well as the actual physical location of the moon against the field of stars, as viewed from the spacecraft position in orbit about the Earth. In contrast, the statistical studies assumed the orbit was fixed against the random star field and randomly located the lunar blockage gap.

The physical star field study was accomplished for a 29-day period in 1998 (the expected first year of EOS-AM1 operations). The choice of the initiation of the simulation periods was based on an estimate of the cumulative maximum star gap per orbit over a 29-day window in 1998, based on one orbit simulation per day for the year 1998. The worst maximum star gap starting point was determined to be June 26, 1998. Note that, in view of the simplicity of the estimation process, this date does not necessarily represent the absolute overall worst-case scenario over the entire 29-day period but indicates the general daily trend. Each simulation consists of a single run covering 430 orbits of which the results of the first five orbits are rejected to avoid transient effects. Thus the simulation essentially consists of a run of 425 consecutive orbits spanning a period of 29 days thereby covering a full lunar cycle. Each simulation thus contains a mix of periods with lunar blockage of the trackers as well as periods without lunar blockage gaps. These results should thus represent a more accurate prediction of the time-weighted performance than perpetual gaps as considered in the statistical study.

As in the statistical case, peak errors and covariance matrix predictions were collected for this physical star field case. Figure 6 shows the results for the roll attitude error observed in the 425 orbits. Consistent with Fig. 5, the covariance matrix predictions and the final orbit mean plus 3σ values tend to bound the actual peaks in any single run. In contrast with Fig. 5, substantial variations in the covariance matrix predictions result for realistic geometries. Since the data of Fig. 6 are sorted by peak attitude error magnitude, the time correlation is not apparent; however, the larger covariance matrix predictions tend to correlate with the lunar blockage intervals.

The peak attitude determination errors are summarized in Table 5. Similar to the statistical case, a substantial run-to-run variation was observed in the peak values; however, the ratios between the minimum peak and maximum peaks nearly double (to six to eight times for the single tracker case). The covariance predictions show substantially better numerical invariance than the actual peaks. Further,

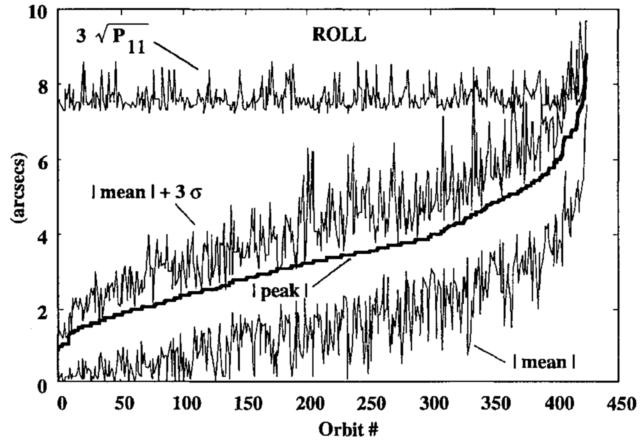

Fig. 6 Roll attitude error with single star tracker: realistic star field. These data are ordered by peak error magnitudes and not by sequential occurrence in the simulation.

Table 5 Peak attitude error: realistic star field

		Peak attitude det. error, arcsec		
ST		Roll	Pitch	Yaw
ST1	Max.	8.77	10.82	7.41
	Min.	0.91	1.65	1.41
	99.7%	8.52	10.54	7.29
ST1 and ST2	Max.	3.79	3.66	3.31
	Min.	0.84	0.84	0.83
	99.7%	3.20	3.24	3.06

Table 6 Peak covariance prediction: realistic star field

		Peak attitude det. error, arcsec		
ST		Roll	Pitch	Yaw
ST1	Max.	8.57	11.28	7.82
	Min.	7.20	8.29	5.62
	99.7%	8.56	11.24	7.82
ST1 and ST2	Max.	3.85	4.07	3.34
	Min.	2.28	2.60	2.19
	99.7%	3.85	4.06	3.33

the 99.7% covariance predictions of Table 6 are a reasonable bound on the expected peak attitude errors of Table 5.

Long and Short Gap Results

To assess the role of the star gaps on the performance for the preceding realistic scenario, artificial cases, representative of long and short gaps, were developed. Based on simulating every orbit over the year 1998, and including lunar blockage, the representative short (150 s) and long (1420 s) star gaps were determined.[5] The simulation was modified to repeat each of these orbits 430 times (using the final 425 orbits, as in the preceding cases). This kept the geometries fixed while allowing noise in the states and measurements. For these extremes, only single tracker performance was assessed.

The results are presented in Fig. 7, where the cumulative probability density functions for these two runs are compared. It is seen that the order of magnitude change in gap (from 150 to 1420 s, 9.5 times) has only a slight (<14%) effect on the 99.7% attitude error. These data confirm the conclusion of previous one degree-of-freedom sensitivity studies[2] that star gaps have little impact on the attitude determination performance for EOS-AM1 and that the performance is primarily noise driven.

These results differ substantially from the intuitive expectation that both gap size and gyro noise would be predictive of achievable attitude determination performance. In fact, further attempts to find a correlation between the attitude determination errors and the gyro bias estimate errors and maximum gap sizes proved to be of no avail, further corroborating the lack of significance of the gap size for EOS-AM1 attitude determination performance. Note, however, that a drastic reduction in the star catalog size to less than 400 stars (as compared with the 1223 stars used here) has a significant impact on the attitude determination performance.

Summary of Results

Focusing on the single tracker attitude determination predictions of the preceding sections, the 99.7% attitude performance results are summarized in Table 7. In general, covariance predictions are reasonable estimates of the performance to be expected. However, in some cases, the peak errors exceed the covariance predictions. This implies that covariance analysis, while a good predictor, cannot be relied on to give the final answer. A reasonable number of Monte Carlo simulations with actual updates must be accomplished to infer 99.7% performance. The results show little difference between statistical star fields and physical star fields and little sensitivity to the differences in the lunar gap (between the short and long gap cases with the physical star field).

Single tracker attitude update results are summarized in Table 8. Consistent with previous studies,[1,3,4] the effect of attitude updates, as attenuated by the low-bandwidth spacecraft attitude controller, is insignificant.

Table 7 Attitude error summary[a]

	Roll	Pitch	Yaw
Statistical			
Peak	8.83	12.18	7.42
Covariance	8.02	11.28	7.68
Worst physical			
Peak	8.52	10.54	7.29
Convariance	8.56	11.24	7.82
Best physical			
Peak	8.71	10.75	6.79
Convariance	8.28	11.27	7.45
Long gap physical			
Peak	10.08	11.80	8.46
Convariance	8.48	10.90	7.64
Short gap physical			
Peak	9.21	10.38	7.58
Convariance	7.29	8.25	5.46
Previous prediction[7]	4.8	7.7	2.7
Update filter allocation	12.4	12.1	6.9

[a]All numbers 99.7%, in arcseconds.

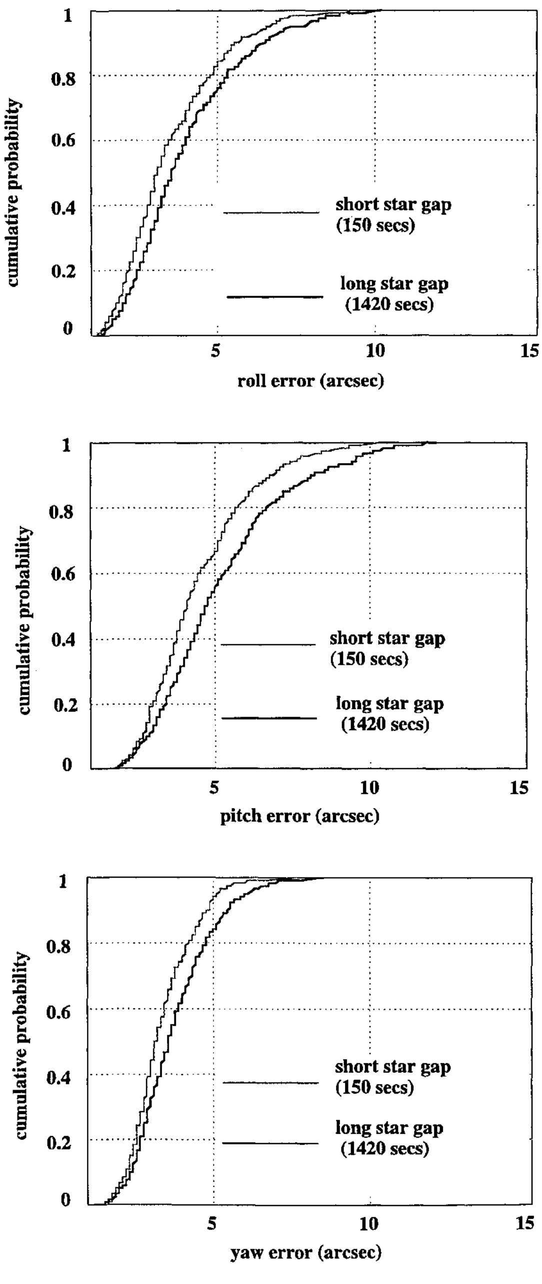

Fig. 7 Attitude error comparison: minimum and maximum star gaps.

Table 8 Attitude update summary[a]

	Roll	Pitch	Yaw
10-s update			
Statistical	0.76	2.58	2.14
Worst physical	0.62	1.92	1.75
10-s controller response			
Statistical	0.0076	0.0258	0.0214
Worst physical	0.0062	0.0192	0.0175
Over 1.8 s			
Requirement	0.2	0.2	0.2
Statistical	0.0014	0.0046	0.0039
Worst physical	0.0011	0.0035	0.0032
Over 9 s			
Requirement	0.8	0.8	0.8
Statistical	0.0068	0.0232	0.0193
Worst physical	0.0056	0.0173	0.0158

[a]All numbers 99.7%, in arcseconds.

Conclusions and Recommendations

The data presented confirm previous conclusions that covariance analysis produces realistic estimates of the statistical performance of a Kalman filter-based attitude and gyro bias determination system, even in the presence of substantial gaps in the star fields. The data demonstrate insensitivity to the star catalog, showing little variation between statistically generated star catalogs (with statistically placed lunar gaps) and a physical star catalog (with realistic lunar ephemeris and realistic orbital precession). Thus, in the early phases of programs, before operational star catalogs are developed, statistical studies can be used to derive reasonable performance predictions. The data further imply that, for the particular parameters associated with the EOS-AM1 hardware, the performance of the system is noise driven, with marked insensitivity to gaps (either natural star gaps or gaps induced by lunar blockage).

Acknowledgments

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