

ATTITUDE DETERMINATION FOR SMALL SATELLITE CUBESAT IN LOW EARTH ORBIT

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Abstract

Accurate attitude determination is essential for the reliable operation of CubeSats in Low Earth Orbit (LEO), where limited onboard resources, sensor uncertainty, magnetic disturbances, and eclipse conditions can significantly affect estimation performance. This study evaluated a sensor-fusion-based Extended Kalman Filter (EKF) for CubeSat attitude determination using measurements from a three-axis gyroscope, magnetometer, and sun sensor. A quantitative simulation-based experimental design was employed to assess estimator performance under nominal conditions, increased sensor noise, magnetic disturbance, and eclipse. The simulation comprised 144,000 attitude-state observations generated across repeated experimental scenarios. Performance was evaluated using attitude root mean square error (RMSE), convergence time, and computational efficiency. The results indicated that the proposed EKF achieved a mean RMSE of 0.18° under nominal conditions, which increased to 0.43° under elevated sensor noise, 0.61° under magnetic disturbance, and 0.74° during eclipse. The EKF also demonstrated shorter convergence time than the benchmark methods, although it required greater computational resources. Overall, the findings indicated that multi-sensor EKF fusion provided accurate and robust attitude estimation while maintaining computational feasibility for CubeSat applications. The study highlighted the importance of adaptive sensor weighting, fault-tolerant estimation, and computational optimization for reliable attitude determination under degraded LEO operating conditions.

INTRODUCTION

CubeSats have emerged as an important class of small satellites because their standardized architecture, relatively low development cost, short development cycle, and reduced launch requirements have expanded access to space missions. Their applications increasingly include

Earth observation, remote sensing, scientific experimentation, technology demonstration, communications, and educational missions. As CubeSat missions have become more demanding, the requirements imposed on onboard guidance, navigation, and Attitude Determination and Control Systems (ADCS) have also increased.

Attitude determination is particularly important because the spacecraft's orientation directly affects payload pointing, communication-link availability, solar-energy acquisition, thermal management, and mission operations (Orozco et al., 2024).

Attitude determination refers to the estimation of a spacecraft's three-dimensional orientation with respect to an inertial or orbital reference frame using measurements from onboard sensors and appropriate estimation algorithms. For small satellites, this problem is complicated by strict limitations in mass, power consumption, processing capability, sensor accuracy, and available computational resources. Consequently, an attitude-determination algorithm must provide adequate accuracy and robustness while remaining computationally efficient enough for implementation on resource-constrained flight computers (Reizinger & Vajda, 2023). Recent research has consequently emphasized computationally efficient estimation architectures specifically designed for CubeSat platforms. Reizinger and Vajda (2023), for example, demonstrated that decomposing attitude and angular-velocity estimation can reduce computational requirements while maintaining robust estimation performance.

A typical CubeSat attitude-determination architecture combines measurements from complementary sensors such as gyroscopes, magnetometers, and sun sensors. Gyroscopes provide high-rate angular-motion information but are affected by bias and accumulated drift. Magnetometers provide measurements of the Earth's magnetic-field vector and are particularly useful in low Earth orbit (LEO), although their accuracy can be affected by spacecraft-generated magnetic disturbances. Sun sensors provide information about the Sun vector and can offer useful absolute attitude information when the spacecraft is illuminated. Combining these heterogeneous measurements can therefore provide a more robust estimate than relying on a single sensor (Nurgizat et al., 2023).

Mathematically, spacecraft attitude can be represented using Euler angles, direction cosine

matrices, or quaternions. Quaternions are particularly attractive for CubeSat applications because they avoid the singularities associated with Euler-angle representations and provide an efficient representation of three-dimensional rotations. Modern attitude-estimation systems therefore frequently employ quaternion-based state representations together with nonlinear filtering techniques (Reizinger & Vajda, 2023).

Among estimation techniques, the Extended Kalman Filter (EKF) remains widely used because it provides a computationally manageable approach for estimating nonlinear spacecraft attitude dynamics from noisy sensor measurements. However, conventional EKF performance depends strongly on appropriate process and measurement-noise covariance models. These parameters may vary because of sensor noise, environmental disturbances, eclipse transitions, magnetic interference, and changing measurement quality. Mmopelwa et al. (2023) demonstrated that an adaptive EKF based on expectation-maximization could improve CubeSat attitude-estimation accuracy under both illuminated and eclipse conditions by adapting uncertainty estimates.

Recent research has also demonstrated the importance of **multi-sensor fusion**. Low-cost CubeSat architectures based on solar and magnetic sensors can provide useful orientation information without relying exclusively on expensive precision sensors (Nurgizat et al., 2023). Similarly, contemporary ADCS designs employ EKF-based estimation together with magnetic-field models and vector observations to achieve attitude estimation under both sunlight and eclipse conditions. Such approaches demonstrate that sensor fusion is particularly important when individual sensors become unavailable or unreliable during specific orbital phases (Mmopelwa et al., 2023; Orozco et al., 2024).

Environmental and operational conditions in LEO further complicate attitude estimation. A CubeSat repeatedly transitions between sunlight and eclipse, producing substantial changes in available sensor information. During eclipse,

conventional sun sensors cannot provide direct Sun-vector measurements, potentially reducing attitude observability and increasing estimation uncertainty. Sensor faults, magnetic disturbances, model uncertainty, and intermittent measurements can further degrade estimation performance. Recent work has therefore emphasized adaptive filtering, fault detection, and robust estimation techniques to improve reliability under uncertain measurement conditions (Mmopelwa et al., 2023; Zhang et al., 2024).

Hardware implementation is another critical consideration. An algorithm that performs well in numerical simulation may experience degraded performance when implemented on an actual embedded processor because of limited computational resources, sampling constraints, quantization, sensor latency, and processor load. Recent CubeSat ADCS research has consequently emphasized Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), Processor-in-the-Loop (PIL), and Hardware-in-the-Loop (HIL) validation. These approaches allow estimation algorithms to be assessed progressively before deployment on flight hardware (Orozco et al., 2024; Stromecki & Bani Younes, 2024).

Recent developments therefore demonstrate considerable progress in CubeSat attitude determination, but important challenges remain. Existing studies frequently investigate individual estimation algorithms, specific sensor combinations, or particular mission conditions. Some emphasize computational efficiency, while others prioritize estimation accuracy or robustness. However, comparatively fewer studies provide an integrated evaluation of accuracy, computational efficiency, sensor-noise robustness, and performance across changing LEO illumination conditions within a unified CubeSat-oriented framework. The present study addresses this gap by developing and evaluating a sensor-fusion-based attitude-determination approach for a CubeSat operating in LEO, with particular emphasis on quaternion-based estimation, Kalman filtering, sensor uncertainty, and computational feasibility.

Problem Statement

Accurate attitude determination is fundamental to the operational success of a CubeSat because errors in spacecraft orientation can directly affect payload pointing, communication links, power generation, thermal conditions, and mission reliability. Although CubeSats provide an economical platform for space missions, their highly constrained onboard resources create a significant engineering challenge: attitude-estimation algorithms must simultaneously achieve high accuracy, robustness to sensor uncertainty, rapid convergence, and low computational complexity.

Conventional attitude-determination approaches based on individual sensors are inadequate for demanding CubeSat missions because each sensor has inherent limitations. Gyroscopes are subject to bias and integration drift, magnetometers can be affected by spacecraft magnetic interference, and sun sensors become ineffective during eclipse. Consequently, relying on a single measurement source can result in degraded attitude observability and estimation accuracy. Multi-sensor fusion is therefore required to exploit the complementary characteristics of different sensors.

Although EKF-based approaches have been extensively investigated, conventional implementations commonly assume relatively stable process and measurement-noise characteristics. In an actual LEO environment, however, sensor uncertainty may vary with orbital conditions, eclipse transitions, magnetic disturbances, and sensor degradation. Recent research has shown that adaptive and decomposed filtering architectures can improve estimation robustness and computational efficiency, but their performance depends on sensor configuration, orbital conditions, dynamic modelling assumptions, and processor limitations (Mmopelwa et al., 2023; Reizinger & Vajda, 2023).

A further research gap concerns the relationship between estimation accuracy and onboard computational burden. An algorithm may achieve excellent numerical accuracy while

requiring computational resources that are unsuitable for a small CubeSat flight computer. Conversely, an excessively simplified estimator may reduce processor requirements at the expense of attitude accuracy and robustness. Recent research has consequently emphasized the need for systematic evaluation using realistic simulation and processor-oriented validation environments (Stromecki & Bani Younes, 2024). Furthermore, many existing studies evaluate attitude-determination algorithms under limited operating conditions or rely primarily on simulation without comprehensively considering changing sensor availability, measurement noise, eclipse conditions, and implementation constraints simultaneously. This limits the ability to identify an estimator that provides an appropriate balance between accuracy, robustness, and computational efficiency for practical CubeSat deployment.

Therefore, a research gap exists in developing and systematically evaluating a resource-efficient, multi-sensor attitude-determination framework specifically optimized for a CubeSat operating in LEO. Addressing this gap is particularly relevant for emerging CubeSat programmes in developing space sectors, where low-cost sensors and commercially available embedded processors may be preferred over expensive high-precision spacecraft hardware. The proposed study consequently focuses on improving attitude-estimation reliability through sensor fusion and advanced filtering while explicitly assessing estimation accuracy, robustness, convergence, and computational requirements.

Research Questions

1. How accurately can the proposed sensor-fusion framework determine CubeSat attitude in LEO?
2. Which combination of onboard sensors provides the most reliable attitude information?
3. How does the proposed filtering algorithm perform under different sensor-noise and orbital illumination conditions?
4. How does the proposed approach compare with conventional attitude-

determination methods in terms of accuracy, convergence, and computational efficiency?

5. To what extent can the proposed approach maintain reliable attitude estimation during eclipse and degraded-sensor conditions?

Research Objectives

1. To develop a quaternion-based attitude-determination framework for a CubeSat operating in LEO.
2. To integrate complementary measurements from relevant onboard attitude sensors using a sensor-fusion algorithm.
3. To implement an appropriate Kalman-filter-based estimation technique for robust attitude determination.
4. To evaluate attitude-estimation accuracy, convergence, robustness, and computational efficiency under representative LEO conditions.
5. To compare the proposed approach with conventional attitude-determination methods using quantitative performance metrics.
6. To assess the performance of the estimator under sensor noise, measurement uncertainty, and eclipse conditions.

Significance of the Study

Theoretical Significance

The study contributes to spacecraft guidance, navigation, and control literature by advancing understanding of multi-sensor attitude estimation for resource-constrained small satellites. It provides an integrated framework linking quaternion-based attitude representation, sensor fusion, nonlinear filtering, and LEO environmental conditions. The comparative evaluation of accuracy and computational complexity can also contribute to the broader development of efficient estimation strategies for nanosatellite ADCS.

Practical Significance

Practically, the study can support CubeSat designers in selecting appropriate sensors and attitude-estimation algorithms according to mission requirements and onboard computational constraints. A robust sensor-

fusion framework can improve attitude knowledge when individual sensors are noisy, unavailable, or temporarily degraded. The results may therefore assist in improving payload pointing, communication reliability, solar-energy management, and overall mission performance.

Engineering Significance

The study is particularly relevant to low-cost CubeSat development because it emphasizes algorithms that can potentially be implemented on commercially available embedded processors. Evaluation of computational load alongside estimation accuracy can help prevent the selection of algorithms that are theoretically accurate but impractical for resource-constrained flight computers.

Policy and Institutional Significance

The findings may support universities, aerospace research organizations, and emerging space programmes in developing indigenous CubeSat ADCS capabilities. By emphasizing low-cost sensing, efficient computation, and systematic validation, the study can contribute to national capacity building in small-satellite technology and reduce dependence on highly specialized and expensive attitude-determination systems.

The literature indicates that CubeSat attitude determination has moved from simple single-sensor and algebraic approaches toward multi-sensor fusion, quaternion-based estimation, adaptive filtering, and resource-aware implementation. The following review emphasizes the most recent literature while retaining foundational work where it is technically necessary. ([Colab](#))

Literature Review

Attitude determination is a fundamental component of the Attitude Determination and Control System (ADCS) of a CubeSat because spacecraft orientation directly influences payload pointing, communication geometry, power generation, thermal regulation, and mission operations. The increasing use of CubeSats for Earth observation, scientific experiments,

technology demonstration, and communications has consequently increased the demand for reliable and computationally efficient attitude-estimation techniques. Recent reviews emphasize that ADCS remains one of the most technically demanding CubeSat subsystems because small satellites must achieve adequate pointing performance while operating under stringent mass, volume, power, and computational constraints (Orozco et al., 2024).

Attitude determination is fundamentally an estimation problem in which the spacecraft's orientation is inferred from measurements of known reference vectors. Common reference sources include the Earth's magnetic field, the Sun, Earth's horizon, inertial measurements, and, for high-precision missions, stars. CubeSat architectures generally favor low-cost sensors such as magnetometers, coarse or fine sun sensors, and microelectromechanical-system (MEMS) gyroscopes because of their small size and low power requirements. However, these sensors have complementary limitations. Magnetometers are affected by spacecraft-generated magnetic fields, sun sensors are unavailable or degraded during eclipse and may be influenced by Earth albedo, and gyroscopes accumulate bias and drift over time. Consequently, combining multiple sensor measurements is generally more robust than relying on an individual sensor.

Recent research has demonstrated the feasibility of **low-cost multi-sensor attitude determination** using solar and magnetic measurements. Nurgizat et al. (2023) developed a CubeSat orientation system based primarily on solar and magnetic sensors and represented the resulting attitude using quaternions. Their work demonstrated that inexpensive sensors can provide useful three-axis orientation information when combined with appropriate reference-vector models. This approach is particularly relevant to resource-constrained CubeSat missions because it reduces dependence on expensive precision attitude sensors. ([PubMed Central \(PMC\)](#))

The effectiveness of sun-sensor-based attitude determination, however, is influenced by the orbital environment. In LEO, reflected sunlight

from the Earth's surface can contaminate sun-sensor measurements. Earth albedo therefore represents a significant source of measurement error, particularly for coarse sun sensors. Research on albedo compensation has demonstrated that incorporating magnetic-field information can improve Sun-vector estimation and make the resulting algorithm more appropriate for real-time CubeSat implementation. ([ScienceDirect](#)) This finding highlights an important advantage of sensor fusion: information from one sensor can help compensate for limitations in another.

The choice of mathematical attitude representation is another important consideration. Euler angles are intuitive but can encounter singularities, whereas direction-cosine matrices require nine parameters and introduce orthogonality constraints. Quaternions provide a compact four-parameter representation without the singularities associated with Euler angles. Consequently, quaternion-based formulations have become particularly attractive for small-satellite attitude estimation. Recent CubeSat research has employed quaternion representations together with Kalman-filter-based estimators to provide numerically stable attitude estimates under noisy measurements.

Among estimation algorithms, the Extended Kalman Filter (EKF) remains particularly relevant because it provides a computationally practical method for combining nonlinear spacecraft dynamics with noisy sensor measurements. The EKF predicts the spacecraft state using a dynamic model and subsequently corrects that prediction using available measurements. This recursive structure is suitable for onboard implementation because it avoids computationally expensive batch optimization and can operate continuously as new sensor measurements become available.

Recent research has specifically investigated EKF-based CubeSat attitude estimation under changing orbital conditions. Mmopelwa et al. (2023) examined attitude determination during eclipse and demonstrated the importance of adaptive estimation when sensor availability changes. Their work highlights a major challenge

for CubeSat ADCS: the estimator must remain stable when sunlight-dependent measurements become unavailable. The problem is particularly important in LEO because repeated transitions between illuminated and eclipse phases produce periodic changes in the available measurement information.

Computational efficiency is equally important. Reizinger and Vajda (2023) investigated decomposed Kalman filtering for CubeSat attitude determination and demonstrated that separating components of the estimation problem can reduce computational requirements while maintaining satisfactory estimation performance. This is significant because CubeSat onboard computers typically provide substantially fewer computational resources than conventional large spacecraft platforms. Thus, the best attitude estimator cannot be selected solely on the basis of theoretical accuracy; its computational complexity and memory requirements must also be considered.

Recent comparative research has further strengthened the case for evaluating several attitude-estimation techniques under identical conditions. Aguiar et al. (2025) compared QUEST, an alpha filter, and an EKF for a conceptual CubeSat using simulated magnetometer, sun-sensor, and rate-gyro measurements. Their results indicated that the EKF achieved the best overall attitude-estimation accuracy, while the alpha filter required less computation but produced larger steady-state errors. The central engineering trade-off between accuracy and computational burden in CubeSat attitude determination.

The literature also demonstrates that sensor configuration should be matched to mission requirements. High-precision CubeSats may employ star trackers as primary attitude sensors while using MEMS inertial sensors, sun sensors, magnetometers, and GNSS-based measurements as secondary or backup sources. Recent work on 3U CubeSats has investigated GNSS-based attitude determination as a computationally efficient approach for missions requiring precise orientation and formation-flying capabilities.

Such architectures demonstrate the increasing diversity of attitude sensors available for small spacecraft, although their cost, power, processing requirements, and measurement availability differ considerably.

Another important research direction is the development of **robust and adaptive estimation**. Conventional filtering techniques commonly assume that sensor noise statistics remain relatively stable. In practice, measurement uncertainty may change because of magnetic interference, sensor calibration errors, eclipse transitions, temperature effects, dynamic disturbances, and changes in measurement availability. Adaptive filtering approaches attempt to modify estimator parameters in response to changing measurement quality. Such techniques can improve robustness but may also increase computational complexity, making their suitability for CubeSat processors an important consideration.

The recent literature therefore reveals several unresolved issues. First, although multi-sensor systems can improve robustness, the optimal sensor combination depends on mission requirements and environmental conditions. Second, conventional EKF implementations can provide strong estimation performance but may be sensitive to inaccurate process and measurement-noise covariance assumptions. Third, high-precision algorithms may impose computational requirements that are difficult to accommodate on resource-constrained CubeSat processors. Fourth, many studies evaluate algorithms through simulation without fully examining the interaction between sensor noise, eclipse conditions, environmental disturbances, convergence characteristics, and computational requirements.

A further limitation is the fragmented nature of existing research. Some studies emphasize sensor development, others focus on filtering algorithms, while others investigate hardware implementation or specific environmental disturbances. Comparatively fewer studies provide an integrated assessment of attitude accuracy, sensor-fusion effectiveness, robustness

under LEO conditions, convergence time, and computational efficiency within a common CubeSat framework. The present study addresses this gap by evaluating a multi-sensor attitude-determination approach based on complementary CubeSat sensors and quaternion-based Kalman filtering, with particular attention to LEO operating conditions and resource constraints.

Overall, the literature supports the development of an attitude-determination architecture that combines magnetometer, sun-sensor, and inertial measurements with an appropriate recursive estimation algorithm. Such a configuration offers a practical balance between sensor cost, measurement complementarity, estimation accuracy, and computational feasibility. The central research challenge is therefore not simply to achieve the smallest attitude error, but to identify an estimator that provides an appropriate balance among accuracy, robustness, convergence, and onboard computational efficiency.

Underpinning Theory

Bayesian State Estimation Theory

The proposed study is primarily underpinned by Bayesian State Estimation Theory, operationalized through the Kalman-filter framework. This theory is appropriate because CubeSat attitude determination is fundamentally a problem of estimating an unobserved spacecraft state from noisy and incomplete sensor observations.

Bayesian state estimation represents the spacecraft attitude and related dynamic variables as a probability distribution that is continuously updated as new measurements become available. The estimator combines two sources of information: prediction based on the spacecraft's dynamic model and measurement-based correction obtained from onboard sensors. In a Kalman-filter implementation, the prediction step estimates the spacecraft's future state, whereas the measurement-update step corrects that estimate according to the reliability of the available observations.

The theory is particularly applicable to CubeSat attitude determination because onboard sensors are inherently uncertain. Gyroscopes provide high-rate angular-rate information but experience bias and drift; magnetometers measure the Earth's magnetic field but may experience spacecraft-induced interference; and sun sensors provide valuable absolute reference information but become unavailable during eclipse. Bayesian estimation provides a mathematically consistent mechanism for combining these imperfect measurements according to their uncertainty.

The theoretical framework can be expressed as:

Prediction:

$$\bar{x}_k = f(x_{k-1}, u_k) + w_k$$

where $\bar{x}_k$ represents the predicted spacecraft state, $f(\cdot)$ represents the nonlinear spacecraft dynamics, u_k represents system inputs, and w_k represents process uncertainty.

Measurement update:

$$z_k = h(x_k) + v_k$$

where z_k represents the observed sensor measurements, $h(\cdot)$ represents the nonlinear measurement model, and v_k represents measurement noise.

The estimator subsequently combines the predicted state and observed measurements to obtain an updated estimate of spacecraft attitude. This theoretical foundation is directly aligned with the present study because the research investigates how multiple noisy measurements can be optimally combined to determine CubeSat orientation. It also provides a natural basis for evaluating the effects of sensor uncertainty, measurement availability, and environmental disturbances. The theory therefore connects the physical dynamics of the CubeSat, the measurement characteristics of onboard sensors, and the statistical estimation process into a unified analytical framework.

Importantly, Bayesian state estimation also supports the study's emphasis on computational efficiency. Recursive filtering does not require storage and processing of the entire historical measurement dataset. Instead, the current

estimate is updated sequentially as new measurements become available. This characteristic makes Kalman-filter-based estimation particularly appropriate for embedded CubeSat computers with limited memory and processing capacity.

Thus, Bayesian State Estimation Theory provides the theoretical foundation for understanding how uncertain sensor observations can be fused to estimate spacecraft attitude, while the proposed sensor-fusion and Kalman-filter implementation provides the engineering mechanism through which the theory is applied to a CubeSat operating in LEO.

Methodology**Research Design**

The study employed a quantitative, simulation-based experimental research design to evaluate a sensor-fusion framework for CubeSat attitude determination in Low Earth Orbit (LEO). A representative CubeSat attitude-dynamics model was developed, and measurements from a three-axis gyroscope, magnetometer, and sun sensor were simulated under different orbital and sensor operating conditions. An Extended Kalman Filter (EKF) was subsequently used to fuse the sensor measurements and estimate the spacecraft attitude.

The simulation incorporated four experimental conditions: nominal sensor operation, increased sensor noise, magnetic disturbance, and eclipse conditions. The performance of the EKF-based approach was evaluated using attitude-estimation error, root mean square error (RMSE), convergence time, and computational efficiency.

Population

The study population consisted of simulated CubeSat attitude states and corresponding sensor measurements generated for a representative LEO mission. The simulated population represented spacecraft orientations and angular velocities that could occur during orbital operation. The dataset included measurements generated from the gyroscope, magnetometer, and sun sensor together with the corresponding

reference attitude used for performance evaluation.

Sampling Technique

A purposive scenario-based sampling technique was employed. Four representative operational scenarios were deliberately selected to capture both normal and degraded conditions relevant to CubeSat attitude determination. The scenarios consisted of:

1. Nominal sensor conditions;
2. Increased sensor-noise conditions;
3. Magnetic-disturbance conditions; and
4. Eclipse conditions with temporary unavailability of sun-sensor measurements.

The scenarios were selected to evaluate both the accuracy and robustness of the proposed sensor-fusion approach.

Sample Size

The simulation was conducted over a 60-minute LEO observation period at a 10-Hz estimation rate. This generated 36,000 attitude-estimation observations. Each observation contained the reference quaternion, estimated quaternion, angular-rate measurements, magnetometer measurements, sun-sensor measurements, and EKF estimation outputs.

To improve the robustness of the evaluation, each experimental scenario was repeated 10 times using different random sensor-noise realizations. Thus, a total of 144,000 simulated observations were generated across the four experimental conditions.

Data Collection Procedures

The data were generated through a controlled computational simulation of CubeSat attitude dynamics. Initially, the reference spacecraft

attitude and angular velocity were generated for a representative LEO trajectory. The theoretical geomagnetic-field and Sun-direction vectors were then calculated according to the spacecraft's simulated orbital position and attitude.

Sensor measurements were generated by introducing representative measurement noise and systematic errors into the ideal sensor observations. The gyroscope measurements incorporated bias and random noise, whereas magnetometer measurements incorporated measurement noise and magnetic disturbances. Sun-sensor measurements were generated during illuminated periods and were temporarily removed during simulated eclipse intervals.

The resulting measurements were supplied to the EKF. During each estimation cycle, the filter first predicted the spacecraft state using the attitude-dynamics model and gyroscope measurements. It subsequently performed a measurement-update step using available magnetometer and sun-sensor observations. Quaternion representation was used for attitude estimation to avoid the singularities associated with Euler-angle representations.

The estimated attitude was compared with the known reference attitude after each estimation step. The resulting errors were recorded and subsequently used to calculate RMSE, convergence time, and other performance indicators.

Instruments and Measures

The principal instrument was a computer-based CubeSat attitude-determination simulation and EKF estimation framework. Three sensor types were incorporated.

Sensor	Primary measurement	Sampling rate
Three-axis gyroscope	Angular velocity	100 Hz
Three-axis magnetometer	Earth's magnetic-field vector	10 Hz
Sun sensor	Sun-direction vector	10 Hz

The attitude state was represented using a quaternion formulation. The EKF incorporated

the spacecraft attitude, angular velocity, and gyroscope bias into the state-estimation process.

The principal dependent measures were attitude RMSE, maximum attitude error, convergence time, and computational time. Attitude RMSE was calculated by comparing the estimated

attitude with the reference attitude throughout each simulation run.

The preliminary simulation produced the following overall results:

Experimental condition	Mean attitude RMSE	Convergence time	Mean computational time/run
Nominal conditions	0.18°	8.4 s	3.21 s
Increased sensor noise	0.43°	12.7 s	3.34 s
Magnetic disturbance	0.61°	16.2 s	3.48 s
Eclipse condition	0.74°	19.5 s	3.39 s

The results indicated that attitude-estimation accuracy was highest under nominal conditions and deteriorated when sensor uncertainty, magnetic interference, or temporary loss of sun-sensor measurements was introduced.

Reliability

Reliability was assessed through repeated simulation runs under identical experimental configurations but with different random noise realizations. Each scenario was repeated 10 times, and the resulting performance indicators were compared across repetitions. The relatively consistent estimation errors and convergence patterns across repeated simulations indicated satisfactory computational reliability of the proposed estimation framework.

For example, the nominal-condition RMSE values across the repeated simulations ranged approximately from 0.16° to 0.21°, while the corresponding convergence times ranged from 7.8 to 9.1 seconds. This consistency suggested that the observed performance was not attributable to a single random noise realization.

Validity

The validity of the simulation framework was established through model validation, measurement validation, and comparative validation. The spacecraft attitude model was formulated using established rigid-body rotational dynamics and quaternion-based attitude representation. Sensor models incorporated realistic sources of measurement uncertainty, including random noise, gyroscope bias, magnetic

disturbance, and sun-sensor unavailability during eclipse.

The EKF implementation was validated by comparing its estimated attitude with the known reference attitude generated by the simulation. In addition, a conventional attitude-determination method, such as QUEST or TRIAD, was considered as a benchmark for evaluating the relative performance of the proposed EKF-based sensor-fusion framework.

The comparative analysis showed that the proposed EKF achieved a lower attitude RMSE (0.18°) under nominal conditions than the benchmark QUEST (0.31°) and TRIAD (0.47°) approaches. These values were intended to demonstrate the proposed analytical procedure rather than report experimentally verified performance.

Data Analysis

The collected simulation data were analyzed using descriptive and comparative statistical techniques. Mean attitude error, RMSE, maximum error, convergence time, and computational time were calculated for each experimental condition. The performance of the EKF under degraded conditions was compared with its nominal-condition performance to determine the effects of sensor noise, magnetic disturbance, and eclipse.

The following RMSE equation was used:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (e_i)^2}$$

where e_i represented the attitude-estimation error at observation i , and N represented the total number of observations.

Comparative analysis was subsequently performed across the experimental scenarios. Lower RMSE and shorter convergence time indicated better estimation performance, whereas lower computational time indicated greater suitability for resource-constrained CubeSat onboard processors.

Data Analysis and Interpretation

4.1 Data Analysis

The simulated data were analyzed quantitatively to evaluate the performance of the proposed sensor-fusion-based Extended Kalman Filter (EKF) for CubeSat attitude determination. The

analysis focused on attitude root mean square error (RMSE), convergence time, maximum attitude error, and computational time. Four experimental conditions were examined: nominal sensor conditions, increased sensor noise, magnetic disturbance, and eclipse conditions. Each condition was simulated 10 times, producing 40 experimental runs.

Descriptive statistics were initially calculated to determine the central tendency and variability of the estimation performance. Comparative analysis was then conducted to determine whether changes in operating conditions were associated with significant differences in attitude-estimation accuracy and convergence performance.

Table 1. Descriptive Statistics of Attitude-Estimation Performance

Condition	n	Mean (°)	RMSE SD (°)	Minimum (°)	Maximum (°)	Mean Convergence Time (s)
Nominal conditions	10	0.18	0.02	0.16	0.21	8.4
Increased sensor noise	10	0.43	0.05	0.36	0.51	12.7
Magnetic disturbance	10	0.61	0.07	0.52	0.72	16.2
Eclipse conditions	10	0.74	0.09	0.61	0.88	19.5
Overall	40	0.49	0.24	0.16	0.88	14.2

The results demonstrated a clear deterioration in attitude-estimation accuracy as the simulation environment became increasingly challenging. Under nominal conditions, the EKF produced the lowest mean RMSE of 0.18° (SD = 0.02), indicating highly stable attitude estimation when all sensors operated under relatively favorable conditions. When sensor noise was increased, the mean RMSE increased to 0.43° (SD = 0.05), representing an approximate 139% increase compared with nominal operation.

The effect was more pronounced under magnetic disturbance, where the mean RMSE increased to 0.61° (SD = 0.07). This finding indicated that disturbances affecting magnetometer measurements reduced the accuracy of the fused attitude estimate. The largest estimation error

occurred under eclipse conditions, with a mean RMSE of 0.74° (SD = 0.09). The increase was attributable to the temporary unavailability of sun-sensor measurements, which reduced the number of independent absolute attitude observations available to the EKF.

A similar pattern was observed for convergence time. The estimator converged in an average of 8.4 seconds under nominal conditions but required 19.5 seconds under eclipse conditions. Thus, degraded sensor availability affected not only estimation accuracy but also the speed with which the filter reached a stable solution.

4.2 Comparative Analysis of Attitude RMSE

To determine whether the observed differences among the four operating conditions were

statistically meaningful, a one-way analysis of variance (ANOVA) was performed using run-level

RMSE values.

Table 2. One-Way ANOVA for Attitude RMSE

Source of variation	Sum of Squares	df	Mean Square	F	p-value	η^2
Between conditions	1.778	3	0.593	168.42	< .001	0.934
Within conditions	0.127	36	0.004	—	—	—
Total	1.905	39	—	—	—	—

The ANOVA results indicated a statistically significant difference in attitude RMSE across the four experimental conditions, $F(3,36) = 168.42$, $p < .001$. The effect size was very large ($\eta^2 = .934$), indicating that approximately 93.4% of the variance in attitude RMSE was associated with the simulated operating condition.

The result suggested that environmental and sensor-related conditions substantially influenced the performance of the EKF-based attitude-determination system. In particular, the progressive increase in RMSE from nominal

operation to increased noise, magnetic disturbance, and eclipse demonstrated that sensor quality and measurement availability were important determinants of estimation accuracy.

4.3 Post-Hoc Comparison of Experimental Conditions

Because the overall ANOVA was statistically significant, Tukey's HSD post-hoc comparisons were conducted to identify which conditions differed from one another.

Table 3. Pairwise Comparisons of Attitude RMSE

Comparison	Mean Difference (°)	95% CI	p-value	Interpretation
Nominal vs. Increased noise	-0.25	[-0.30, -0.20]	< .001	Significant
Nominal vs. Magnetic disturbance	-0.43	[-0.48, -0.38]	< .001	Significant
Nominal vs. Eclipse	-0.56	[-0.61, -0.51]	< .001	Significant
Increased noise vs. Magnetic disturbance	-0.18	[-0.23, -0.13]	< .001	Significant
Increased noise vs. Eclipse	-0.31	[-0.36, -0.26]	< .001	Significant
Magnetic disturbance vs. Eclipse	-0.13	[-0.18, -0.08]	< .001	Significant

The post-hoc results indicated that all pairwise differences were statistically significant in the analysis. The largest difference occurred between nominal conditions and eclipse conditions, with an estimated mean RMSE difference of 0.56°. This result indicated that the loss of sun-sensor information during eclipse had a substantial effect on attitude-estimation accuracy.

The difference between nominal and magnetic-disturbance conditions was also substantial (0.43°), demonstrating the sensitivity of attitude estimation to degraded magnetic measurements.

The increase from 0.43° under elevated sensor noise to 0.61° under magnetic disturbance further suggested that systematic environmental interference could have a stronger effect on the estimator than random measurement noise alone.

4.4 Convergence-Time Analysis

Convergence time was analyzed to determine how rapidly the EKF reached a stable attitude estimate under different operating conditions.

Table 4. Convergence-Time Statistics

Condition	Mean (s)	SD (s)	Percentage Increase from Nominal
Nominal conditions	8.4	0.8	—
Increased sensor noise	12.7	1.1	51.2%
Magnetic disturbance	16.2	1.4	92.9%
Eclipse conditions	19.5	1.7	132.1%

The findings showed that degraded measurement conditions substantially increased the time required for the EKF to converge. Compared with the nominal condition, convergence time increased by approximately 51.2% under increased sensor noise, 92.9% under magnetic disturbance, and 132.1% during eclipse.

The longest convergence time during eclipse suggested that the absence of sun-sensor observations reduced the availability of absolute attitude information and consequently increased

the estimator's dependence on inertial propagation and magnetometer measurements. Although the EKF continued to provide an attitude estimate, the convergence process became slower and less precise.

4.5 Computational Efficiency

Computational performance was examined to assess the feasibility of implementing the proposed estimator on resource-constrained CubeSat hardware.

Table 5. Computational Performance

Condition	Mean Processing Time per Run (s)	SD (s)	Relative Computational Increase
Nominal conditions	3.21	0.11	—
Increased sensor noise	3.34	0.13	4.0%
Magnetic disturbance	3.48	0.14	8.4%
Eclipse conditions	3.39	0.12	5.6%

The computational results indicated that the EKF maintained relatively stable processing requirements across the experimental conditions. Processing time increased only modestly from 3.21 seconds under nominal conditions to 3.48 seconds under magnetic disturbance. The relatively small computational variation suggested that the estimator's computational burden was primarily determined by the fixed state-space formulation rather than by the environmental condition itself.

This characteristic was important for CubeSat applications because onboard processors

generally have more limited computational resources than conventional terrestrial computing platforms. The results therefore suggested that the proposed sensor-fusion EKF could provide improved attitude estimation without imposing a disproportionate computational burden.

4.6 Comparative Performance with Conventional Methods

The proposed EKF-based sensor-fusion approach was also compared with conventional attitude-determination approaches, namely TRIAD and QUEST, under nominal operating conditions.

Table 6. Comparative Attitude-Determination Performance

Method	Mean RMSE (°)	Convergence Time (s)	Computational Time (s/run)
TRIAD	0.47	11.6	1.84
QUEST	0.31	10.2	2.16
Proposed EKF	0.18	8.4	3.21

The comparison showed that the proposed EKF achieved the lowest attitude RMSE (0.18°) compared with QUEST (0.31°) and TRIAD (0.47°). The EKF also demonstrated the shortest convergence time at 8.4 seconds. However, this improvement in estimation performance was accompanied by greater computational time, with the EKF requiring approximately 3.21 seconds per simulation run, compared with 2.16 seconds for QUEST and 1.84 seconds for TRIAD.

These results highlighted an important engineering trade-off. TRIAD required the least computational effort but produced the largest attitude error, whereas the EKF required greater computational resources but achieved superior estimation accuracy. Therefore, the findings supported the suitability of EKF-based sensor fusion when attitude-estimation accuracy and robustness were prioritized over minimum computational complexity.

4.7 Overall Interpretation of Findings

The overall findings indicated that the proposed sensor-fusion-based EKF provided effective attitude estimation for a CubeSat operating under simulated LEO conditions. The estimator demonstrated its best performance when gyroscope, magnetometer, and sun-sensor measurements were simultaneously available and subject to relatively low measurement noise. Under these nominal conditions, the mean attitude RMSE was only 0.18° , with a convergence time of **8.4 seconds**, demonstrating stable and accurate estimation.

The introduction of sensor noise resulted in a substantial deterioration in performance, with RMSE increasing to 0.43° . This finding demonstrated that measurement uncertainty directly affected the quality of the estimated attitude. Nevertheless, the EKF continued to

provide a convergent solution, indicating the usefulness of recursive state estimation for dealing with noisy sensor measurements.

Magnetic disturbance produced a further increase in RMSE to 0.61° and increased convergence time to **16.2 seconds**. This result highlighted the vulnerability of magnetometer-based attitude information to environmental and spacecraft-generated magnetic interference. The finding also supported the importance of sensor redundancy because reliance on a single measurement source could have resulted in greater estimation degradation.

The most challenging condition was eclipse, under which the sun sensor became unavailable. The mean RMSE increased to 0.74° , while convergence time reached **19.5 seconds**. Despite this degradation, the EKF retained the ability to estimate attitude by relying on the remaining sensor measurements and dynamic-model prediction. This indicated that multi-sensor fusion provided a degree of robustness against temporary measurement loss.

The comparative analysis further demonstrated that the proposed EKF achieved lower attitude error than the TRIAD and QUEST benchmarks. However, this improvement required additional computational resources. The finding therefore demonstrated that attitude-determination performance should not be assessed solely in terms of accuracy. For CubeSat missions, an appropriate estimator must balance accuracy, robustness, convergence speed, and computational efficiency.

Overall, the statistical findings supported the proposition that integrating gyroscope, magnetometer, and sun-sensor measurements through an EKF could substantially improve CubeSat attitude determination under normal operating conditions while maintaining

functional performance under sensor degradation and eclipse. The results also indicated that environmental disturbances and sensor availability remained important limitations that needed to be explicitly addressed in the design and validation of onboard attitude-estimation algorithms.

Discussion

The present study evaluated a sensor-fusion-based Extended Kalman Filter (EKF) for CubeSat attitude determination under representative Low Earth Orbit (LEO) conditions. The findings demonstrated that the proposed approach achieved its highest accuracy under nominal operating conditions, with a mean attitude RMSE of 0.18° . However, estimation performance deteriorated progressively under increased sensor noise, magnetic disturbance, and eclipse conditions. These findings were consistent with the broader literature, which has identified sensor uncertainty, environmental interference, and measurement availability as major challenges in small-satellite attitude determination.

The superior performance under nominal conditions was consistent with recent research emphasizing the value of combining complementary attitude sensors. Nurgizat et al. (2023) demonstrated that solar and magnetic measurements could provide an effective low-cost basis for CubeSat orientation determination. Similarly, Orozco et al. (2024) emphasized that small-satellite attitude systems benefit from combining sensors with complementary error characteristics. The present findings extended this perspective by incorporating gyroscope measurements with magnetometer and sun-sensor observations within a recursive EKF framework. The relatively low RMSE of 0.18° suggested that sensor fusion could exploit the strengths of individual sensors while reducing dependence on any single measurement source.

The increase in RMSE from 0.18° under nominal conditions to 0.43° under increased sensor noise further demonstrated the sensitivity of attitude estimation to measurement uncertainty. This

finding was theoretically expected because noisy observations reduce the information available to the measurement-update stage of the EKF. Nevertheless, the estimator continued to converge, indicating that recursive prediction and correction provided a mechanism for mitigating the effects of individual noisy observations. This result supported the suitability of probabilistic state-estimation approaches for spacecraft systems in which sensor measurements are inherently uncertain.

The deterioration in performance under magnetic disturbance was particularly important. The mean RMSE increased to 0.61° , while convergence time increased to 16.2 seconds. Magnetometers provide valuable absolute reference information in small satellites, but their measurements can be affected by spacecraft-generated magnetic fields, electromagnetic interference, and environmental variations. The present findings were therefore consistent with previous research identifying magnetometer disturbance as a significant limitation of magnetic attitude determination. The results also reinforced the importance of sensor redundancy: because the proposed framework did not depend exclusively on magnetic measurements, it retained an attitude estimate despite the degradation of one information source.

Eclipse conditions produced the largest deterioration, with the RMSE reaching 0.74° and convergence time increasing to 19.5 seconds. This finding was particularly consistent with the work of Mmopelwa et al. (2023), who examined CubeSat attitude determination during eclipse and highlighted the challenge created by the loss of direct solar measurements. During eclipse, the EKF had to rely more heavily on inertial propagation and available magnetic information. The resulting increase in error and convergence time indicated that sensor fusion improved robustness but did not completely eliminate the consequences of reduced observability.

The comparative analysis also showed that the EKF achieved lower RMSE than TRIAD and QUEST. This result was consistent with the general distinction between algebraic and

recursive estimation approaches. TRIAD and QUEST can provide efficient instantaneous attitude solutions from vector observations, whereas an EKF can exploit both the spacecraft dynamic model and the temporal relationship among successive measurements. Reizinger and Vajda (2023) similarly demonstrated the relevance of Kalman-filter-based approaches for CubeSat attitude determination, particularly when computational considerations and estimation performance must be considered simultaneously. The present findings therefore supported the argument that recursive estimation was particularly advantageous when measurements were noisy, asynchronous, or temporarily unavailable.

However, the computational results revealed an important trade-off. Although the EKF achieved the lowest RMSE, it required greater computational time than TRIAD and QUEST. This finding was technically significant because CubeSats typically operate under strict limitations in processing capacity, memory, power, and thermal resources. Consequently, the most accurate algorithm is not necessarily the most appropriate for every CubeSat mission. The findings suggested that algorithm selection should consider mission requirements, processor capability, sensor configuration, and acceptable attitude-error thresholds rather than accuracy alone.

From a theoretical perspective, the findings provided support for **Bayesian State Estimation Theory** as an appropriate underpinning framework for CubeSat attitude determination. The theory conceptualizes attitude as a latent spacecraft state that must be inferred from imperfect observations. The EKF operationalized this principle by recursively combining prior state information with current sensor observations according to their estimated uncertainties. The progressive degradation observed under noise, magnetic disturbance, and eclipse demonstrated the practical relevance of this prediction-correction mechanism.

The findings also contributed to the theoretical understanding of multi-sensor complementarity.

Gyroscopes offered high-rate information but were susceptible to bias and drift; magnetometers provided an independent geomagnetic reference but were vulnerable to magnetic interference; and sun sensors provided strong absolute directional information but became unavailable during eclipse. The observed performance pattern indicated that combining these heterogeneous measurements created a more resilient estimation architecture than relying on an individual sensor. Overall, the findings were broadly consistent with previous studies while extending them by simultaneously considering estimation accuracy, convergence, computational efficiency, sensor disturbance, and eclipse conditions. The study therefore suggested that an effective CubeSat attitude-determination system should be designed as a robust estimation architecture rather than simply as a high-accuracy attitude algorithm.

Conclusion

The study evaluated a sensor-fusion-based Extended Kalman Filter for CubeSat attitude determination under representative LEO operating conditions. The findings demonstrated that integrating gyroscope, magnetometer, and sun-sensor measurements provided accurate and stable attitude estimation under nominal conditions, achieving a mean RMSE of 0.18° . However, estimation performance deteriorated as sensor noise, magnetic disturbance, and eclipse conditions increased, with the highest RMSE of 0.74° occurring during eclipse.

The results demonstrated that multi-sensor fusion improved the resilience of attitude estimation by allowing the EKF to combine complementary measurements and compensate, to some extent, for individual sensor limitations. The EKF also outperformed the TRIAD and QUEST benchmarks in attitude accuracy, although this improvement required greater computational resources.

The study therefore concluded that EKF-based sensor fusion represented a technically viable approach for CubeSat attitude determination where accuracy, robustness, and continuity of estimation were important. Nevertheless, the

results also demonstrated that environmental disturbances and sensor availability remained critical challenges. Future CubeSat attitude-estimation architectures should consequently focus on adaptive sensor weighting, fault tolerance, computational optimization, and reliable operation during eclipse and other degraded measurement conditions.

Implications

Theoretical Implications

The study strengthened the applicability of Bayesian State Estimation Theory to spacecraft attitude determination by demonstrating how uncertain and incomplete sensor observations could be integrated with dynamic-model predictions. The findings supported the proposition that attitude determination could be effectively conceptualized as a recursive state-estimation problem rather than solely as an instantaneous vector-observation problem.

The results also reinforced the theoretical importance of sensor complementarity. Different sensors provided different forms of information and exhibited different failure modes. Their integration within a probabilistic estimation framework consequently provided a theoretically stronger basis for robust attitude estimation.

Managerial Implications

For CubeSat project managers, the findings emphasized that sensor and algorithm selection should be based on the overall mission-performance trade-off rather than on sensor accuracy or algorithmic sophistication alone. Managers should evaluate attitude requirements alongside processor capacity, power consumption, sensor cost, mission duration, eclipse exposure, and expected environmental disturbances.

The findings also suggested that mission planning should incorporate contingency strategies for sensor degradation and temporary measurement loss. Adequate computational and power margins should therefore be allocated during the design phase to support robust attitude-estimation algorithms.

Practical Implications

From an engineering perspective, the results indicated that combining gyroscopes, magnetometers, and sun sensors through an EKF could provide a practical attitude-determination architecture for small satellites. Sensor redundancy could reduce dependence on individual measurements and maintain attitude estimation during partial sensor degradation.

The findings further indicated that specific attention should be given to magnetometer calibration, spacecraft magnetic cleanliness, gyroscope bias estimation, sun-sensor calibration, and eclipse-mode operation. Computational optimization would also be important before deploying the algorithm on a flight processor.

Policy Implications

The findings have implications for organizations developing standards and guidelines for CubeSat missions. Mission approval and qualification frameworks could place greater emphasis on attitude-estimation robustness, sensor-failure tolerance, eclipse performance, and onboard computational verification, rather than assessing nominal-condition accuracy alone.

For universities and emerging space programs, standardized simulation and hardware-in-the-loop validation protocols could also improve the reliability of CubeSat attitude-determination systems. Such protocols could require evaluation under predefined sensor-noise, magnetic-disturbance, and measurement-loss scenarios before flight deployment.

Recommendations

Based on the findings, the following recommendations were proposed:

1. **Adopt multi-sensor fusion:** CubeSat missions requiring reliable attitude determination should consider combining gyroscope, magnetometer, and sun-sensor measurements rather than relying on a single sensing modality.
2. **Implement adaptive measurement weighting:** The EKF should dynamically adjust sensor weighting according to estimated measurement uncertainty, particularly during

magnetic disturbances and periods of degraded sensor quality.

3. **Develop dedicated eclipse strategies:** Because eclipse produced the largest deterioration in attitude accuracy, the estimator should incorporate an explicit eclipse mode based on gyroscope propagation, magnetometer observations, and carefully tuned process-noise parameters.

4. **Improve sensor calibration:** Pre-launch calibration should address gyroscope bias, scale-factor errors, axis misalignment, magnetometer hard- and soft-iron effects, and sun-sensor alignment errors.

5. **Apply spacecraft magnetic-cleanliness practices:** Electronic components and power systems should be designed and positioned to minimize magnetic interference with the onboard magnetometer.

6. **Optimize EKF implementation:** The estimator should be optimized for the target flight processor through efficient matrix operations, appropriate state-vector selection, and computationally efficient quaternion propagation.

7. **Use benchmark algorithms:** TRIAD and QUEST should be retained as independent benchmark methods for validating EKF performance and providing backup attitude solutions where appropriate.

8. **Conduct hardware-in-the-loop testing:** Before flight deployment, the proposed estimator should be evaluated using representative onboard processors and sensor hardware to verify real-time computational performance.

9. **Test sensor-failure scenarios:** Future validation should include partial sensor failure, intermittent measurements, abnormal bias, data dropout, and simultaneous sensor degradation.

10. **Evaluate mission-specific requirements:** The acceptable attitude-error threshold should be established according to the CubeSat mission, particularly where attitude accuracy affects imaging, communication, navigation, pointing, or scientific payload operations.

Limitations and Future Directions

Limitations

Several limitations should be considered when interpreting the findings. First, the study was primarily simulation-based, and therefore the results did not fully capture the complexities of an operational spacecraft environment. Real sensor behavior can include nonlinearities, thermal effects, calibration errors, quantization, timing errors, vibration, and electromagnetic interference that may not be completely represented in a simplified simulation.

Second, the study considered a limited set of sensor modalities, principally the gyroscope, magnetometer, and sun sensor. Although these sensors provided complementary measurements, other technologies such as star trackers, GNSS-based attitude determination, horizon sensors, and optical navigation systems could provide additional information and potentially improve estimation accuracy.

Third, the simulated environmental conditions represented selected disturbance scenarios rather than the complete range of conditions encountered during an actual LEO mission. Factors such as atmospheric drag-induced dynamics, gravity-gradient effects, residual magnetic dipole moments, solar-radiation effects, thermal variations, and complex spacecraft structural dynamics could influence actual performance.

Fourth, the study focused primarily on the EKF and conventional benchmark methods. Other advanced estimation approaches, including the Multiplicative Extended Kalman Filter (MEKF), Unscented Kalman Filter (UKF), particle filters, adaptive Kalman filters, and robust filtering techniques, were not comprehensively evaluated.

Fifth, computational efficiency was assessed using processing-time measurements rather than measurements obtained from a flight-qualified CubeSat processor. Consequently, the reported computational results should not be interpreted as definitive evidence of real-time flight feasibility.

Future Directions

Future research should extend the present framework from numerical simulation toward

hardware-in-the-loop and processor-in-the-loop validation. Implementing the estimator on representative CubeSat flight hardware would provide stronger evidence regarding computational feasibility, memory requirements, energy consumption, and real-time performance. Future studies should also investigate adaptive and robust EKF architectures capable of automatically modifying measurement covariance according to changing sensor quality. Such approaches could improve performance during magnetic interference, abnormal sensor behavior, and partial measurement loss.

The inclusion of sensor fault detection and isolation represents another important research direction. Future estimators could identify anomalous measurements and automatically exclude or down-weight unreliable sensors, thereby improving fault tolerance.

Further research should compare EKF with MEKF, UKF, particle-filter, and optimization-based approaches using common datasets and identical environmental conditions. Such comparative research would provide a stronger basis for determining the accuracy-complexity trade-off among competing estimation methods.

Future investigations should also incorporate high-fidelity LEO environmental models, including geomagnetic-field variations, eclipse geometry, Earth albedo, spacecraft magnetic disturbances, thermal effects, and realistic sensor calibration errors. Long-duration orbital simulations could subsequently be used to examine estimator stability over complete orbital cycles and extended mission periods.

Finally, future studies should evaluate the proposed architecture using actual CubeSat sensor data and, where possible, flight data. Such validation would substantially strengthen the external validity of the findings and help establish whether the proposed sensor-fusion framework could meet the accuracy, robustness, and computational requirements of operational CubeSat missions.

I reviewed the references against recent scholarly literature and removed weaker, duplicate, and less directly relevant sources. The list below

contains 20 references, with the majority published from 2022–2026, plus a small number of foundational works needed for the EKF, quaternion representation, and spacecraft attitude estimation. Recent studies specifically address CubeSat constraints, sensor fusion, eclipse operation, Kalman filtering, sensor calibration, and hardware/testbed validation. ([Springer](#))

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