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# A Performance Evaluation Approach for Satellite Attitude Control System in Tracking Mode

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**Abstract:** The study of satellite performance evaluation can reveal the ability of satellite systems to fulfil corresponding tasks in the space environment, and provide information support for the resource allocation and mission scheduling of in-orbit satellites. In this paper, we took the satellite attitude control system in attitude tracking mode as the research object. In accordance with the system's mission requirements, the control performance evaluation indicator set, characterized by a generalized grey number, is constructed to tackle the uncertainty and inadequacy of information contained in flight status data resulting from the complex space operating environment and sensor measurement noise. An improved principal component analysis method based on generalized grey number is proposed to solve the weight amplification caused by the correlation between performance indicators and realize the weight allocation of the indicators. Finally, the grey-target decision model is established to determine the weights of the performance indicators, and the performance evaluation model is established under the tracking mode. The feasibility of the grey-target decision-evaluation model based on the improved principal component is confirmed through comparative experiments.

**Keywords:** performance evaluation; grey-target decision; tracking mode; satellite attitude control system

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## 1. Introduction

In recent years, with the development of space technology both domestically and internationally, satellite technology has matured significantly. Its application fields have been expanding, playing an increasingly important role in national defense security [1], space exploration [2], and socio-economic fields [3]. With the development of the space industry and the complexity of satellite missions, there is an increasingly urgent need to accurately assess and monitor the health status of satellite components in real time [4,5]. The study of satellite system effectiveness assessment can understand the satellite operation status in real time, and provide information support for the reasonable allocation of spaceborne resources and space-mission planning, which is also the basis for improving satellite work efficiency and optimizing mission design.

The comprehensive performance evaluation of satellite systems has been of wide concern at home and abroad. Early research mainly focused on the entire satellite platform and established different performance evaluation models through various methods. A et al. combined fuzzy theory with the analytic hierarchy process in order to establish an evaluation criteria framework for satellite performance and implemented this assessment method [6]. Bolkunov et al. derived performance indicators from the perspectives of primary functional performance, regulatory system performance and cost performance, and proposed a comprehensive methodology for assessing navigation satellite effectiveness [7]. Li Chang et al. achieved the performance evaluation of geostationary orbit remote sensing satellites by establishing a solar illumination model that integrated with the ADC performance evaluation model and satellite system characteristics [8]. Yu Yeluo et al. proposed an enhanced fuzzy reasoning performance evaluation method, which was based on the original single-factor evaluation index fuzzy reasoning. The method incorporated multi-factor comparison and analytic hierarchy process, achieving the performance evaluation of navigation satellites [9]. Zhou Xiahe et al. developed a communication satellite performance evaluation model based on the GA-BP (genetic algorithm–back propagation) neural network method [10].

With the deepening of research work, in recent years, the performance evaluation research carried out by scholars has gradually focused on satellite structure, power supply, attitude control and other subsystems. Kazakeviciute et al. examined the effectiveness of remote sensing image segmentation for remote sensing satellites, and evaluated the performance of remote sensing satellite images by determining the correlation between the subjective and objective segmentation quality indexes [11]. Based on fuzzy mathematics and hierarchical analysis, Yang Jun established an index system for evaluating the performance of satellite navigation systems and illustrated the evaluation process and methodology with examples [12]. Shao et al. used grey system theory to construct a multi-state system performance evaluation model for the inaccurate and insufficient data of the communication satellite system [13]. Liu et al. used the hierarchical analysis method to calculate the weights of the indicators, established the ADC model and simulated the indicator values, and finally completed the comprehensive performance evaluation of the satellite system [14]. At the present stage, most of the performance evaluation methods of satellite systems are subjective, such as hierarchical analysis and ADC model, while the uncertainty of sensor measurement and the multi-source disturbance of the space environment are ignored.

In order to solve the above problems, this paper takes the attitude control system of an earth observation satellite as an example., Firstly, it establishes the performance evaluation indicator set under the attitude tracking mode and characterizes the uncertainty of the performance index through the generalized grey number. Secondly, it uses the improved principal component analysis method based on the generalized grey number to determine the weight of the index, so as to overcome the problem of too strong subjectivity in the process of indicator weighting. The performance evaluation of the attitude control system is realized by using the grey-target model.

## 2. Problem Description

### 2.1. Satellite Attitude Control System Tracking Model

In the tracking mode, the satellite attitude control system continuously collects and analyzes the positional and directional information of target objects. Based on the information, it guides the satellite direction and attitude adjustments to ensure the stable operation of satellites in an ever-changing environment, which can enable satellites to achieve high-precision positioning and orientation control. This mode is applicable across various satellite domains, including communication, navigation, meteorology, military, and scientific research.

Attitude tracking keeps the satellite attitude in a given orientation and maintains attitude stabilization such as orientation to the sun and orientation to the earth. Typically, the satellite will enter the attitude tracking mode after performing attitude maneuvers to complete the corresponding space observation tasks. This mode operates over an extended period, often lasting several hours or even days. Taking the sun-pointing mode under the tracking mode of the satellite attitude control system as an example, in the sun- pointing mode, in order to enhance the efficiency of the solar panels and maintain the best angle of solar illumination, the satellite attitude control system needs to realize the accurate pointing control of the sun. The schematic diagram of the sun-pointing mode is shown in Figure 1.

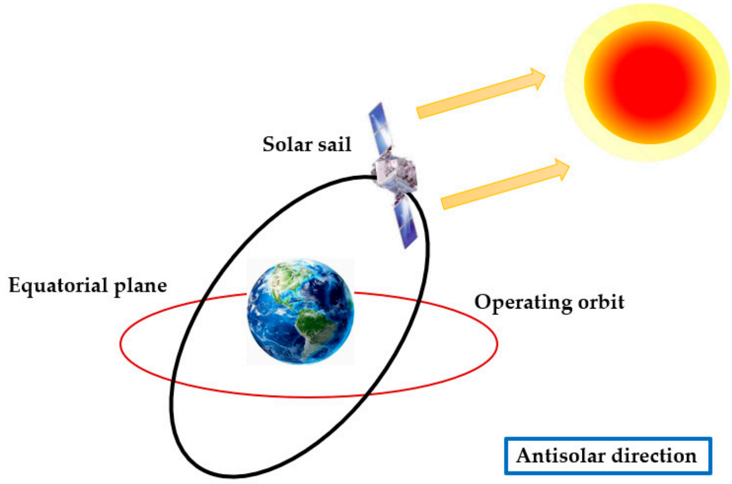



**Figure 1.** Schematic diagram of satellite operation in orbit in sun-pointing mode.

Oriented to the mission requirements of the tracking mode, the control performance indicators of the satellite attitude control system tracking mode should be able to meet the characteristics of speed, accuracy and stability. Specifically, the following aspects can be considered:

(1) Rapid control response: In the process of a satellite tracking targets, the control system needs to exhibit a swift response rate to promptly adjust the attitude to the target state, thus ensuring the tracking accuracy and stability of the satellite. Therefore, the attitude control response time can be selected as a performance evaluation indicator.

(2) High control accuracy: The control accuracy under tracking mode requires the satellite attitude control system to have a certain degree of robustness and anti-interference ability to cope with the influence of external environmental changes and interference. The system should be able to effectively recognize and mitigate interference to maintain good control accuracy. Therefore, the attitude pointing accuracy can be selected as a performance evaluation indicator.

(3) Control stability: Under the tracking mode, the satellite attitude control system should have good stability and be able to maintain the stability and accuracy of the satellite attitude during long-time operation, so as to fulfill the demands of tracking targets. Therefore, the pointing stability can be selected as a performance evaluation indicator.

(4) Low energy consumption: The satellite attitude control system should adopt energy consumption optimization strategies under tracking mode to minimize energy consumption and improve the energy efficiency of the system, and energy-saving strategies can be adopted, such as reducing the power output of the controller and optimizing the controller's working mode, in order to prolong the satellite's lifespan. Therefore, the attitude control energy consumption can be selected as a performance evaluation indicator.

### *2.2. Challenges in System Performance Evaluation under Tracking Mode*

In order to achieve a reasonable performance evaluation of the satellite attitude control system under the influence of multi-source uncertainties, the research faces the following difficulties:

(1) Dynamic environment influence: The satellite attitude control system typically operates in a dynamic environment under tracking mode, where factors such as environmental noise, atmospheric resistance, magnetic interference, and solar radiation may influence data, leading to fluctuations that cannot accurately reflect the tracking control performance. Addressing the formidable challenge at hand involves devising methodologies to mitigate the impact of uncertainties, extracting operational status information from attitude control systems, and thereby achieving precise assessments of system efficiency.

(2) Multi-indicator assessment and trade-off: The performance evaluation under the tracking mode of the satellite attitude control system often involves multiple indicators,

such as pointing accuracy, control energy consumption, and control response speed. However, the baselines of these indicators are not the same, and the coupling between the indicators is strong. How to establish a reasonable evaluation model for multiple performance indicators is a very challenging problem.

To solve the above problems, firstly, this paper measures the uncertainty in the calculated indicators by evaluating the grey number standardization method; secondly, in this paper, the principal component analysis method is improved under the operation rules of grey number, so that each index can be objectively and reasonably weighted according to its own characteristics.

## 3. Satellite Attitude Control System Evaluation Indicator Set Construction

### *3.1. Performance Evaluation Indicator Set*

According to the efficiency analysis of the satellite attitude control system in tracking mode in Section 2.1, the control performance indicator set of the satellite attitude control system in tracking mode is constructed, as shown in Figure 2, including six performance indicators such as attitude pointing accuracy, pointing stability and maneuvering average angular velocity.

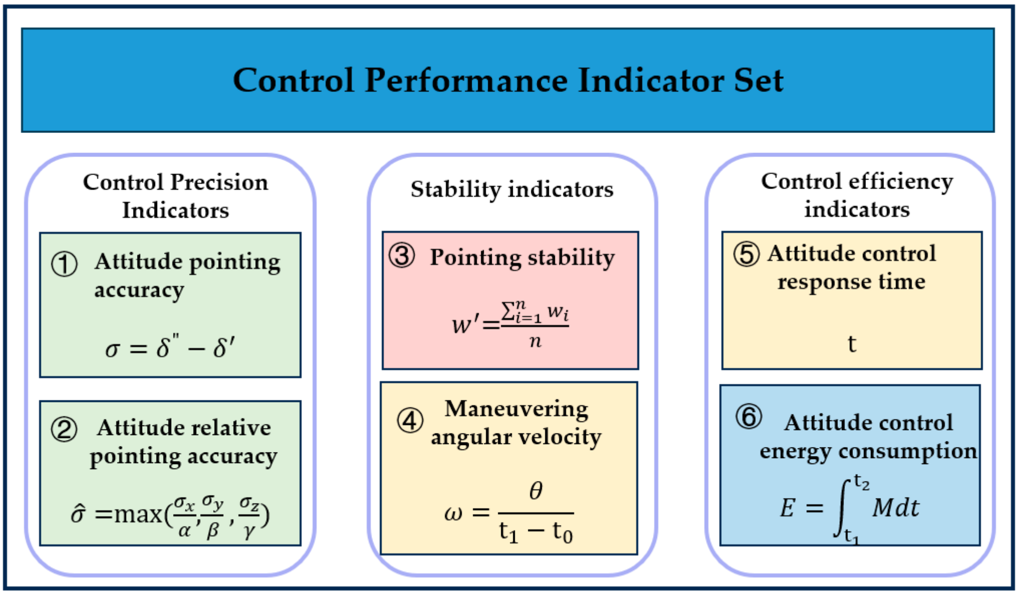



**Figure 2.** Attitude tracking mode performance evaluation indicator set.

According to the operating principles and control model of the attitude control system of the earth observation satellite, the definition and calculation methods of the performance indicators were studied, and the calculation methods for each indicator in the performance evaluation indicator system are as follows:

(1) Attitude pointing accuracy.

Satellite attitude pointing accuracy refers to the deviation between the expected and actual pointing directions after the satellite undergoes three-axis rotation. Assuming that the initial unit vector $\delta$, after rotating the initial unit vector $\delta$ by an angle of $\theta = (\alpha, \beta, \gamma)$ in Eulerian angle order, it is turned to a predetermined position to become the vector $\delta'$. In fact, various errors are generated during the rotation in tracking mode, and the initial unit vector $\delta$ cannot be turned to a predetermined position to become vector $\delta'$, but rather to vector $\delta''$. Then we have [15,16]:

$$\delta'' = \rho(\theta, T) \cdot \delta \tag{1}$$

$$\rho(\theta, T) = Rot(x, \alpha + \Delta\alpha) Rot(y, \beta + \Delta\beta) Rot(z, \gamma + \Delta\gamma) \tag{2}$$

In Equation (2), $T$ represents the error generated by the rotation process, $\rho(\theta, T)$ represents the total rotation matrix, $\Delta\alpha$, $\Delta\beta$, $\Delta\gamma$ represent the three-axis error caused by the error, which can be described as:

$$\sigma = \delta'' - \delta' = [\rho(\theta, T) - \rho(\theta)] \cdot \delta \tag{3}$$

In Equation (3), $\rho(\theta)$ represents the ideal rotation matrix, the pointing error $\sigma = [\sigma_x, \sigma_y, \sigma_z]$ is obtained and the attitude pointing accuracy is $\sigma_0 = \max(\sigma)$.

(2) Relative attitude pointing accuracy.

Relative attitude pointing accuracy refers to the ratio between the attitude pointing accuracy of a satellite's attitude maneuver process and the maneuver angle when the satellite undergoes an attitude maneuver. In the paper, the maximum error of the three axes is selected as the relative attitude pointing accuracy $\hat{\sigma}$:

$$\hat{\sigma} = \max\left(\frac{\sigma_x}{\alpha}, \frac{\sigma_y}{\beta}, \frac{\sigma_z}{\gamma}\right) \tag{4}$$

(3) Pointing stability.

The pointing stability is the rate at which the attitude angle changes with time due to disturbances during the time the satellite remains attitude stabilized. The three-axis attitude stability is during the time period that the satellite remains attitude stabilized [15]:

$$\omega' = \frac{\sum_{i=1}^{n} \omega_i}{n} = [\omega_x{}', \omega_y{}', \omega_z{}'] \tag{5}$$

In Equation (5), $\omega'$ represents the attitude stabilization of the three axes, $\omega_i$ represents the instantaneous angular velocity within steady-state time, n represents the time n seconds after the end of the maneuvering process. During steady-state time, the attitude stabilization is $\Delta\omega = \max(\omega')$.

(4) Maneuvering angular velocity.

Maneuver angular velocity refers to the rate of change of attitude angles during the time period when a satellite is undergoing an attitude maneuver. As shown in Figure 3, the 3D vector can be regarded as the unit vector $\delta$ rotated to obtain, then the attitude angle change of the satellite after the maneuver can be regarded as finding the angle $\theta$ between two 3D vectors.

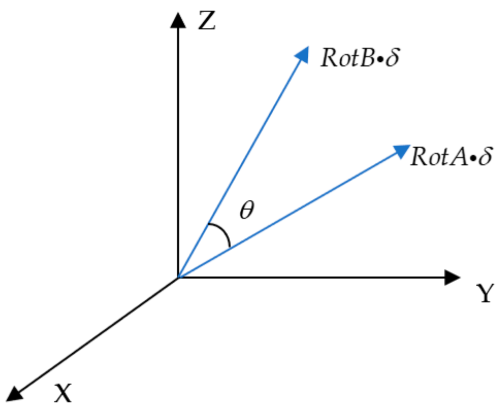



**Figure 3.** Schematic diagram of composite attitude angles.

The attitude angles of the satellite before and after the attitude maneuver are $RotA \cdot \delta$ and $RotB \cdot \delta$, respectively. According to the spatial geometry relationship, the combined attitude angle of the satellite maneuvering process can be calculated from the rotation matrix:

$$\theta = ar\cos\left(\frac{trace\left(RotARotB^T\right) - 1}{2}\right) \tag{6}$$

In Equation (6), *trace* represents the trace of the solving matrix. If $t_0$ is the start time of the maneuver and $t_1$ is the end time of the maneuver, then the angular velocity of the maneuver $\omega$ is:

$$\omega = \frac{\theta}{t_1 - t_0} \tag{7}$$

(5) Attitude control response time.

Attitude control response time $t$ refers to the time required for the satellite to start performing the corresponding attitude adjustment after receiving the attitude control command, in which the attitude and target attitude errors need to be satisfied within the pointing accuracy range (±5%).

(6) Attitude control response time.

Attitude control energy consumption refers to the energy consumed by the satellite attitude control system, according to the principle of dynamics, the control torque of the flywheel can be calculated as [15]:

$$M = J\alpha = J\frac{d\omega}{dt} \tag{8}$$

In Equation (8), $M$ represents the control torque, $J$ represents the rotational inertia of the flywheel, which is a constant value. $\alpha$ represents the angular acceleration of the flywheel, which can be calculated from the flywheel rotational speed. Setting the satellite for attitude control during the time period $[t_1, t_2]$, the energy consumed by the flywheel is:

$$E = \int_{t_1}^{t_2} Mdt \tag{9}$$

The moments calculated for each of the four flywheels are integrated and summed to give the attitude control energy consumption as:

$$E_0 = E_1 + E_2 + E_3 + E_4 \tag{10}$$

In Equation (10), $E_1, E_2, E_3, E_4$ represent the attitude control energy consumption of the four flywheels, respectively.

### *3.2. Standardization of Performance Indicators*

Satellite data often exhibit inconsistencies in units and types. In order to rationalize the assessment results, it is essential to standardize the metrics before conducting evaluations. Based on the trend of metric values, these metrics can be categorized into benefit-based indicators, cost-based indicators, and range-based indicators [17]. For the satellite attitude control system, attitude pointing accuracy, relative attitude pointing accuracy, pointing stability, attitude control energy consumption, attitude control response time are cost-based indicators, and maneuvering angular velocity is a benefit-based indicator. For benefit-based indicators, larger values are preferable, while for cost-based indicators, smaller values are better. Therefore, they can be standardized according to Equations (11) and (12), respectively [18]:

$$I_x = \begin{cases} 0 & , \quad I_{x0} < I_{x\min} \\ \frac{I_{x0} - I_{x\min}}{I_{x\max} - I_{x\min}} & , \quad I_{x\min} \le I_{x0} \le I_{x\max} \\ 1 & , \quad I_{x0} > I_{x\max} \end{cases} \tag{11}$$

$$I_c = \begin{cases} 0 & , \quad I_{c0} > I_{c\max} \\ \frac{I_{c\max} - I_{c0}}{I_{c\max} - I_{c\min}} & , \quad I_{c\min} \le I_{c0} \le I_{c\max} \\ 1 & , \quad I_{c0} < I_{c\min} \end{cases} \tag{12}$$

In this paper, the efficiency indicators are uniformly transformed into the [0, 1] interval, and the standardized value of 1 represents that the indicator reaches the theoretical optimal value, and 0 represents that the indicator does not reach the target value range.

### 3.3. Grey Numerical Transformation of Indicators

In the process of performance indicator computation, different performance indicators originate from distinct sources. Due to the dynamic environmental noise, atmospheric resistance, magnetic field interference, solar radiation and other factors, the operational data obtained from this system exhibit characteristics of uncertainty such as greyness and randomness. In this paper, before determining the weights of the indicators, we carried out grey numerical transformation on the performance indicator values, and adopted the generalized standard grey number to characterize the indicator values unanimously, so as to eliminate the influence of systematic errors, and carry out the subsequent performance evaluation work on this basis.

For a sequence of indicators $X = \{x_1, x_2, \cdots, x_n\}$, if the type of attribute value of each indicator both contain grey number, probability number, fuzzy number and interval fuzzy number, and the value domain is $D[0,1]$, then the value of the indicator attribute of this sequence can be uniformly characterized by generalized grey number [19,20]:

$$G(\otimes_A(x)) \in \left\{\delta_A(x) \cup \mu_A(x) \cup M_A(x) \cup g_A^{\pm}(x)\right\} \in \bigcup_{i=1}^{n} [a_i, b_i] \in D[0,1]^{\pm} \tag{13}$$

In Equation (13), $i = 1, 2, \cdots n$ represents the $i$ indicator, $\delta_A(x)$ represents the set of probability numbers, $\mu_A(x)$ represents the fuzzy set, $M_A(x)$ represents the interval-valued fuzzy set, $g_A^{\pm}(x)$ represents the set of grey numbers, $D[0,1]^{\pm}$ represents the set of all generalized grey numbers in the interval [0, 1].

In order to facilitate the operation, scholars proposed the generalized standard grey number, any generalized grey number can be converted to the generalized standard grey number. For any generalized grey number $G(\otimes_i) = [a_i, b_i](a_i < b_i, i = 1, 2, \cdots, n)$, they can be converted using Equation (14) [21]:

$$G(\otimes_i) = a_i + c_i \times \gamma_i(\gamma_i \in [0,1]) \tag{14}$$

In Equation (14), $a_i$ represents the white part of the grey number, $c_i \times \gamma_i$ represents the grey part of the grey number, $\gamma_i$ represents the unit grey factor.

In the attitude tracking mode, it can be considered that the further each indicator of the satellite attitude control system is from the expected value, the greater the impact of uncertainty caused by factors such as environment and measurement. Let all the values of an indicator after standardization be $I_i = (i = 1, 2, \cdots, m)$, which can be greyed out according to Equation (15):

$$G(\otimes_i) = I_i + |I_i - \mu| \left(\gamma_i - \frac{1}{2}\right) \tag{15}$$

In Equation (15), $i = 1, 2, \cdots, m$, $\mu$ and $I$ are the statistical mean and standard deviation, respectively. The probability distribution of the unit grey coefficient is determined by the source and nature of the uncertainty of the indicator. In the absence of sufficient information, it is generally assumed $\gamma_i \sim N\left(0.5, \frac{1}{36}\right)$.

This section describes accurately and comprehensively the control performance of the satellite attitude control system in tracking mode by selecting the indicators in four aspects: fast control, high control accuracy, stable control and low energy consumption. It also solves the problem of discrepancies in the scale of satellite indicator data through the standardization of the indicators, and finally eliminates the effects of data uncertainty and error caused by the space-orbit environment and sensor measurements through the grey-numbering processing of the indicators.

## 4. Establishment of Performance Indicator Evaluation Model

The determination of performance indicator weights is based on the system's operational principles and task execution. These weights reflect the significance and prioritization of performance indicators within the comprehensive evaluation framework. As a result, during the performance evaluation process, adopting an appropriate method to establish indicator weights is of utmost importance.

According to the classification of the influence of human factors in the weighting process, indicator weighting methods can be divided into subjective weighting methods and objective weighting methods [22]. The subjective weighting methods rely on the subjective judgment of the decision maker, while the indicator weights usually assigned by the objective weighting method change dynamically with the change of the data set. In this paper, based on the satellite telemetry data to assess the effectiveness of the satellite attitude control system, the determination of the weights depends entirely on the characteristics of the actual data, and it is more appropriate to use the objective weighting method.

Principal component analysis (PCA) is a commonly used objective weighting method, which is more suitable for solving the weights of indicators in tracking mode. However, PCA can be affected by the correlation of the indicators, which will make the obtained indicator weights inaccurate. Compared with the traditional principal component analysis method, the improved principal component analysis method based on generalized grey number is proposed in this section. The method offers greater adaptability and flexibility, and has advantages in dealing with uncertain data, adapting to different data types, and retaining more information.

### *4.1. Improved Principal Component Weight Determination Method Based on Generalized Grey Numbers*

When evaluating the satellite attitude control system, the indicator weights are only related to the characteristics of the telemetry data itself, so it is more appropriate to use the objective weighting method to deal with the attitude control system work data. Principal component analysis (PCA) is a commonly used objective weighting method. Its fundamental concept involves transposing the initial indicator matrix, calculating several principal components along with their eigenvalues, and ultimately determining indicator weights by the product of variance contribution rates and principal components [23].

Let the set of evaluation indicators of the performance indicator system be $X = \{x_1, \cdots, x_i, \cdots, x_j, \cdots, x_n\}(i, j = 1, 2, \cdots, n)$, and the weights $W = \{\omega_1, \cdots, \omega_i, \cdots, \omega_j, \cdots, \omega_n\}$ are calculated by the principal component analysis method. The weight of $j$ indicator can be expressed as follows [24]:

$$\omega_j = \frac{\sum\limits_{i=1}^{n} \lambda_i g_{ji}}{\sum\limits_{i=1}^{n} \lambda_i} \tag{16}$$

In Equation (16), $\lambda_i$ represents the eigenvalue of the indicator covariance matrix, g represents the eigenvector of the covariance matrix and its corresponding eigenvector is $\xi_i = [g_{1i}, g_{2i}, \cdots, g_{ni}]^T_{n\times 1}$, which can be obtained from the properties of eigenvalues and eigenvectors:

$$\begin{bmatrix} Cov(1,1)g_{1i} + Cov(1,2)g_{2i} + \cdots + Cov(1,n)g_{ni} \\ Cov(2,1)g_{1i} + Cov(2,2)g_{2i} + \cdots + Cov(2,n)g_{ni} \\ \cdots \\ Cov(n,1)g_{1i} + Cov(n,2)g_{2i} + \cdots + Cov(n,n)g_{ni} \end{bmatrix} = \begin{bmatrix} \lambda_i g_{1i} \\ \lambda_i g_{2i} \\ \cdots \\ \lambda_i g_{ni} \end{bmatrix} \tag{17}$$

In Equation (17), $Cov(i,j)$ is the covariance between the indicators. The covariance is calculated as [24]:

$$\begin{aligned} & Cov(x_i, x_j) = E(x_i, x_j) - E(x_i) \cdot E(x_j) \\ & = \left[E(a_i, a_j) - E(a_i) \cdot E(a_j)\right] + \left[E(a_i, c_j) - E(a_i) \cdot E(c_j)\right] \cdot \gamma_j \\ & + \left[E(a_i, c_i) - E(a_i) \cdot E(c_i)\right] \cdot \gamma_i + \left[E(c_i, c_j) - E(c_i) \cdot E(c_j)\right] \cdot \gamma_i \gamma_j \end{aligned} \tag{18}$$

Therefore, the covariance matrix and eigenvectors based on generalized grey numbers can be calculated. Based on the correspondence of the matrices can be obtained:

$$\lambda_i g_{ji} = Cov(j,1)g_{1i} + Cov(j,2)g_{2i} + \cdots + Cov(j,n)g_{ni} \tag{19}$$

The expression for the indicator weights obtained from the principal component analysis can be converted into [24]:

$$\omega_j = \frac{Cov(j,1)\sum\limits_{i=1}^{n} g_{1i} + Cov(j,2)\sum\limits_{i=1}^{n} g_{2i} + \cdots + Cov(j,n)\sum\limits_{i=1}^{n} g_{ni}}{\sum\limits_{i=1}^{n} \lambda_i} \tag{20}$$

In Equation (20), $Cov(j,i)(i \neq j)$ represents the moderator variable for the weight of the remaining indicators $x_j$.

The correlation coefficients and calculation results between the evaluation indicators of the satellite attitude control system for the daily pointing mode are shown in Table 1. The indicators of attitude control response time and average angular velocity during maneuvers exhibit relatively high correlation coefficients with the other indicators.

**Table 1.** Sum of correlation coefficients for evaluation indicators.

| Indicators | Pointing Accuracy | Relative Accuracy | Stability | Response Time | Angular Velocity | Energy Consumption |
|---|---|---|---|---|---|---|
| Sum of correlation coefficients | 1.8834 | 1.8378 | 1.9274 | 1.9425 | 2.1987 | 1.5909 |

In response to the issue of excessively large inter-indicator correlation coefficients in traditional principal component analysis (PCA) methods, this paper proposes an improved principal component weight calculation method based on the generalized grey number. The calculation expression of the improved principal component weights is as follows:

$$\omega_j^0 = |Cov(j,j)|\sum_{i=1}^{n}|g_{ji}| + F(j,1)\sum_{i=1}^{n}|g_{1i}| + \cdots + F(j,n)\sum_{i=1}^{n}|g_{ni}| \tag{21}$$

$$F(j,i) = \begin{cases} (\max|Cov(j)| - |Cov(j,i)|/|Cov(j,i)|) \\ 1 \end{cases} \tag{22}$$

In Equation (21), $\omega_j^0$ represents the weight of the $j$ indicator. In Equation (22), $\max|Cov(j)|$ represents the maximum value of the first row of the covariance matrix. The improved method uses $F(j,i)$ instead of the correlation coefficient $Cov(j,i)$ used in the traditional principal component method; according to the definition of $F(j,i)$, when the correlation coefficient $Cov(j,i)$ is larger, the value of $F(j,i)$ will be smaller, so the improvement in principal components to a certain extent eliminates the influence of the correlation of the indicators on the weights of the indicators. In order to ensure that the sum of the indicator weights is 1, the weights should be processed according to Equation (23):

$$\omega_j^{\otimes} = \frac{\omega_j^0}{\sum\limits_{i=1}^{n} \omega_j^0} \tag{23}$$

The traditional principal component analysis and the improved principal component method proposed in this paper were used to calculate the weights of the assessment indicators under the day-to-day pointing mode, respectively, and the results of the weight determination are accurate to four decimal places, as shown in Table 2:

**Table 2.** Comparison of weight determination results.

| Methods | Pointing Accuracy | Relative Accuracy | Stability | Response Time | Angular Velocity | Energy Consumption |
|---|---|---|---|---|---|---|
| Principal component | 0.0529 | 0.0063 | 0.0216 | 0.5072 | 0.3382 | 0.0737 |
| Improved principal component | 0.1198 | 0.2147 | 0.1292 | 0.1837 | 0.1249 | 0.2277 |

In the weighting results of the principal component analysis method, the weights of the two indicators of attitude control response time and maneuvering angular speed are 0.5072 and 0.3382, respectively, while the weights of other indicators are not more than 0.1. As shown in Table 2, the correlation coefficients between these two indicators and other indicators are the largest. Based on the analysis in the previous section, it can be seen that larger correlation coefficients will amplify the results of the calculation of the weights of these two indicators, while in the calculation results of the improved principal component method proposed in this paper, the weights of attitude control response time and maneuvering angular velocity are 0.1837 and 0.1249, respectively, and the weight values are reduced, effectively weakening the influence of the indicator correlation on the weights of the indicators. Compared with the traditional principal component analysis method, the weight determination method proposed in this paper is more reasonable.

### *4.2. Implementation Steps of Grey-Target Decision Assessment Model*

In the process of performance evaluation for satellite attitude control systems, the sources of performance indicators vary and exhibit characteristics of uncertainty in the form of grey system data. Traditional methods of performance evaluation would lead to inaccurate results. The fundamental idea behind a grey-target decision is to compare the proximity of each indicator sequence to an ideal sequence, often referred to as the target center. This method is commonly used to address multi-objective decision-making or assessment problems [25–28]. Therefore, the grey-target bull's-eye distance of the work process indicator sequences can be calculated, and the bull's-eye distance can be used to characterize the comprehensive evaluation value. This approach facilitates the ranking of the performance of different working processes.

Based on grey-target decision theory, this paper adopts the improved principal component method based on the generalized grey number to determine the weights, and establishes the grey-target evaluation model to evaluate the performance of the satellite attitude control system tracking mode. The specific methodological steps are as follows:

(1) Process the satellite telemetry data, extract the data of the day-to-day pointing mode, and solve the performance indicator of each work process according to the definition of the indicator, and pay attention to the problem of the reference coordinate system when calculating.

(2) Normalize the solved index data to obtain the standardized index matrix $A_{m\times n} = (a_{ij})$, where $a_{ij}$ is the $j$ processed efficiency index of the $i$ group of attitude control processes.

(3) The standardized data are greyed out and expressed by the generalized standard grey number.

(4) Calculate the weights of the indicators according to the improved principal component weight model based on the generalized grey number, and the weights are calculated as $W = \{\omega_1^{\otimes}, \omega_2^{\otimes}, \cdots, \omega_n^{\otimes}\}$.

(5) Compare the size of each indicator of different control processes to obtain the optimal vector, the bull's eye $G(\otimes_0)$. The comparison of the size of the grey number is realized by comparing the size of the mathematical expectation, for the grey numbers $G(\otimes_1)$ and $G(\otimes_2)$, the size relationship is:

$$\begin{cases} G(\otimes_1)>G(\otimes_2) & E(G(\otimes_1))>E(G(\otimes_2)) \\ G(\otimes_1)<G(\otimes_2) & E(G(\otimes_1))<E(G(\otimes_2)) \\ G(\otimes_1)=G(\otimes_2) & E(G(\otimes_1))=E(G(\otimes_2)) \end{cases} \tag{24}$$

According to Equation (23), the center of the target can be compared to obtain the center of the target as:

$$G(\otimes_0) = \{\max(G(\otimes_{i1})), \max(G(\otimes_{i2})), \cdots, \max(G(\otimes_{in}))\} \tag{25}$$

(6) Calculate the off-target distance for each attitude control process data $d(G(\otimes_i), G(\otimes_0))$, and the center-of-target distance can be calculated according to Equation (25):

$$d(G(\otimes_i), G(\otimes_0)) = \sqrt{\omega_1^{\otimes}(G(\otimes_{i1}) - G(\otimes_{01}))^2 + \cdots + \omega_n^{\otimes}(G(\otimes_{in}) - G(\otimes_{0n}))^2} \tag{26}$$

In Equation (26), $G(\otimes_i)$ represents the index sequence of a control process. Finally, the performance of each operational process is ranked based on the calculated results according to the target distance. A smaller target distance indicates better performance.

### *4.3. Performance Indicators of the Performance Evaluation*

In order to judge the accuracy of the results of the performance evaluation model, this paper focuses on the reliability of the assessment method from the perspectives of compatibility degree and deviation. A higher degree of compatibility indicates that the results of the evaluation method are more closely aligned with those of other methods, rendering them more representative and leading to more accurate assessment outcomes. Assuming that $n$ motorized processes are assessed by $m$ methods, the degree of compatibility is defined as [29]:

$$r(i) = \frac{1}{m-1}\sum_{i\neq j}^{m} r(i,j) \tag{27}$$

$$r(i,j) = 1 - \frac{6}{n(n^2-1)}\sum_{k=1}^{n}(d_i(k) - d_j(k))^2 \tag{28}$$

In Equations (27) and (28), $r(i)$ represents the compatibility degree of the $i$ method, $r(i,j)$ represents the rank correlation coefficient of the $i$ and the $j$ methods. $d_i(k)$ and $d_j(k)$ represent the ranking numbers of the results of the $k$ maneuvering process in the $i$ and the second methods, respectively.

Deviation refers to the extent to which the assessed value of the performance of a method differs from the assessed value of the results of other methods. The smaller the value of the deviation, the more reliable the assessment is as the method does not deviate significantly from the results of other methods. The outlier can be defined as the square of the difference and the mean value, which can be calculated:

$$D(i) = \frac{1}{n(m-1)} \sum_{k=1}^{n} \sum_{j \neq i}^{m} \left(e_i(k) - e_j(k)\right)^2 \tag{29}$$

In Equation (29), $e_i(k)$ and $e_j(k)$ represent the evaluated values of the performance of the $k$ maneuver in the $i$ and $j$ methods.

In this section, an improved principal component weight determination method based on generalized grey numbers is proposed. This method has better adaptability and flexibility compared with the traditional principal component analysis method, and can deal with the data uncertainty problem caused by complex factors such as space orbit environment. Based on this, a grey-target decision evaluation model is established by using the grey-target decision theory, which enables performance evaluation of the satellite attitude control system to be achieved in tracking mode.

## 5. Evaluation Experiment and Analysis

The satellite data utilized in this study originated from the telemetry data from a certain Earth observation satellite over the period August 2021 to October 2021. Prior to the assessment, data preprocessing was conducted based on operational modes. A total of 44 sets of complete operational data were extracted from sun-pointing modes under attitude tracking patterns. These data were used as a basis for conducting the evaluation experiments.

### *5.1. Evaluation Results for Sun-Pointing Mode*

According to the indicator solution method described in the previous section, the values of the indicators for the sun-pointing mode are computed. After normalizing the efficiency indicators, a comprehensive efficiency assessment is conducted using an improved principal component-based grey-target model. The results of the comprehensive evaluation are sorted based on the size of the efficiency value, and the smaller the distance to the bull's-eye, the better the efficiency. The control process indicator values for the top 10 positions in the sun-pointing mode are presented in Table 3, while the indicator values for the bottom 10 positions are shown in Table 4.

**Table 3.** Top 10 evaluation results for sun-pointing mode.

| Process | Pointing Accuracy | Relative Accuracy | Stability | Response Time | Angular Velocity | Energy Consumption | Off-Target Distance |
|---|---|---|---|---|---|---|---|
| S14 | 0.6427 | 0.9669 | 0.6936 | 0.6000 | 0.7892 | 1.0000 | 0.2502 |
| S13 | 0.8078 | 0.8404 | 0.9622 | 0.5143 | 0.7315 | 0.8212 | 0.2640 |
| S35 | 0.6052 | 0.7269 | 0.9534 | 0.6000 | 0.7653 | 0.8798 | 0.2730 |
| S26 | 0.7855 | 0.9822 | 0.7028 | 0.4571 | 1.0000 | 0.7725 | 0.2880 |
| S37 | 0.8942 | 0.9881 | 0.5508 | 0.6571 | 0.9712 | 0.5709 | 0.3018 |
| S17 | 0.7047 | 0.9213 | 0.8955 | 0.5143 | 0.7542 | 0.6443 | 0.3048 |
| S19 | 0.8667 | 0.9250 | 1.0000 | 0.3143 | 0.6799 | 0.9409 | 0.3214 |
| S27 | 0.9206 | 0.9145 | 0.8621 | 0.3429 | 0.6720 | 0.7978 | 0.3269 |
| S39 | 0.7822 | 0.9677 | 0.8772 | 0.8571 | 0.1213 | 0.8600 | 0.3354 |
| S13 | 0.7263 | 0.9760 | 0.6363 | 0.6286 | 0.9749 | 0.4826 | 0.3355 |

**Table 4.** Bottom 10 evaluation results for sun-pointing mode.

| Process | Pointing Accuracy | Relative Accuracy | Stability | Response Time | Angular Velocity | Energy Consumption | Off-Target Distance |
|---|---|---|---|---|---|---|---|
| S24 | 0.8474 | 0.0808 | 0.8004 | 0.5143 | 0.7058 | 0.0000 | 0.6864 |
| S23 | 0.7855 | 0.1962 | 0.8114 | 0.4000 | 0.6649 | 0.0000 | 0.6758 |
| S25 | 0.7313 | 0.0393 | 0.0000 | 0.5429 | 0.7161 | 0.8880 | 0.6223 |
| S21 | 0.7364 | 0.9800 | 0.7925 | 0.8000 | 0.0000 | 0.0000 | 0.6115 |
| S33 | 0.5773 | 0.8597 | 0.7982 | 0.0000 | 0.5759 | 0.3190 | 0.5854 |
| S30 | 0.0000 | 0.7595 | 0.7795 | 0.3714 | 0.6589 | 0.2882 | 0.5838 |
| S43 | 0.7760 | 0.0000 | 0.7962 | 0.4571 | 0.6824 | 0.5500 | 0.5821 |
| S41 | 0.8397 | 0.0100 | 0.9065 | 0.4286 | 0.6727 | 0.5828 | 0.5724 |
| S10 | 0.4414 | 0.9074 | 0.1045 | 0.1429 | 0.8045 | 0.6519 | 0.5569 |
| S6 | 0.2314 | 0.8781 | 0.0000 | 0.7714 | 0.2527 | 0.7054 | 0.5498 |

As shown in Figure 4, it can be seen that the S14 and S38 processes have the smallest center-of-target distance and the best overall effectiveness of the attitude control system; the S24 and S23 processes have the largest center-of-target distance and the worst overall effectiveness.

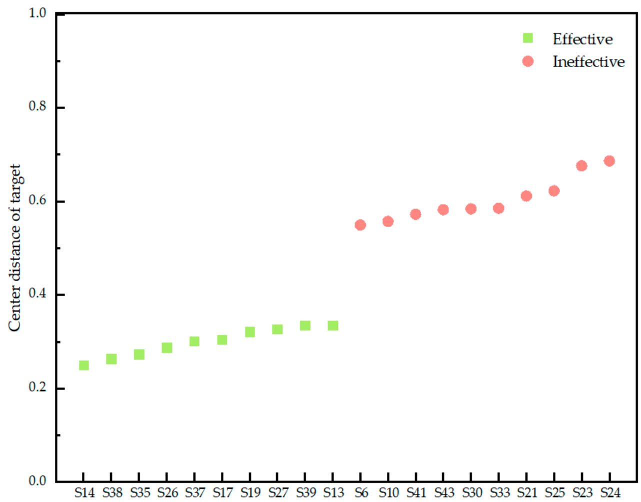
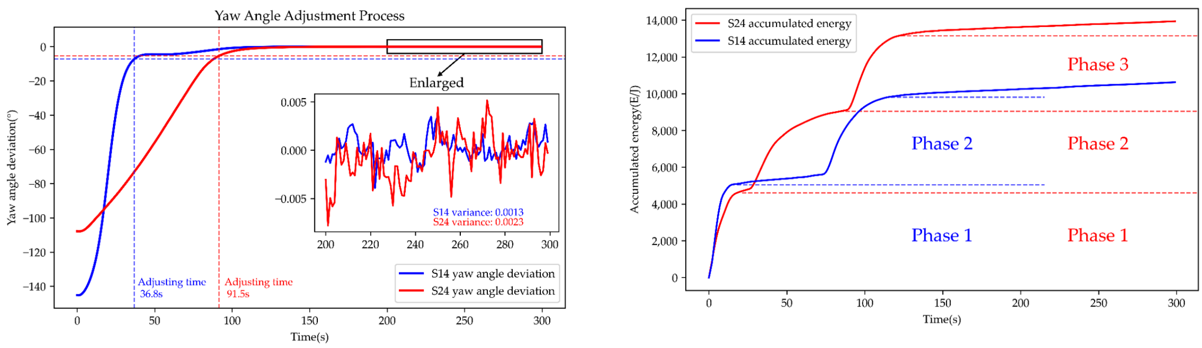



**Figure 4.** Performance evaluation results.

Figure 5a,b, respectively, show the yaw angle adjustment process of S14 and S24 and the accumulated energy consumption during the adjustment process. It can be seen from Figure 5a that the adjustment of the attitude angle of S14 is obviously better than that of S24, and the stability after the adjustment is better. It can be seen from Figure 5b that the adjustment process of S14 goes through two stages, and that of S24 goes through three stages, and the cumulative energy consumption of S14 is significantly less than that of S24. The above indicators, which have great differences in the advantages and disadvantages of the two adjustment processes, together lead to the great difference in the evaluation results of the two.




(**a**) (**b**)

**Figure 5.** Comparison of high and low performance processes of (**a**) attitude angle and (**b**) cumulative energy consumption.

According to Tables 3 and 4, all indicators of the S14 process perform well, and the attitude control energy consumption reaches the optimal level. The S38 control process is relatively stable, with four indicator values above 0.8, so the comprehensive evaluation results of these two control processes are the best. The S24 process is the worst in attitude control energy consumption, close to the worst in relative attitude pointing accuracy, and there is no excellent index value, so the evaluation result of this process is at the bottom. The S23 process is similar to the S24 process, but the relative attitude pointing accuracy is slightly better than S24, and the off-target distance is slightly smaller than S24. Therefore, to improve the performance of these two control processes, the aspects of relative attitude pointing accuracy and attitude control energy consumption need to be considered.

### *5.2. Parameter Sensitivity Analysis*

In this section, a parameter sensitivity assessment of the grey-target assessment model based on improved principal components is carried out, using the operating data of the satellite in the sun-pointing mode, and the inputs of the assessment model are the values of the six indicators in the attitude tracking mode performance evaluation indicator system, and the output of the model is the off-target distance. The main effect coefficients and full effect coefficients of each performance indicator are calculated by the Sobel indicator method based on the Monte Carlo algorithm; the results are shown in Table 5.

**Table 5.** Calculation of sensitivity indices for evaluation indicators.

| Indicators | Main Effect Coefficients | Sort | Full Effect Coefficients | Sort |
|---|---|---|---|---|
| Attitude pointing accuracy | 0.3753 | 1 | 0.3618 | 1 |
| Relative attitude pointing accuracy | 0.1334 | 4 | 0.1337 | 4 |
| Pointing stability | 0.0313 | 5 | 0.0636 | 5 |
| Attitude control response time | 0.3291 | 2 | 0.3066 | 2 |
| Maneuvering angular velocity | 0.0295 | 6 | 0.0069 | 6 |
| Attitude control energy consumption | 0.1654 | 3 | 0.1651 | 3 |

Based on the results of the Sobel sensitivity indicator calculations, the following conclusions can be drawn:

(1) In the grey-target evaluation model based on improved principal components, the results of the main effect coefficient and the full effect coefficient ranking of each performance indicator are identical. The two performance indicators with the highest sensitivity are attitude pointing accuracy and attitude control response time, and the sensitivity indexes of these two performance indicators are obviously larger than other

indicators, with a greater impact on the comprehensive performance of the satellite attitude control system in tracking mode; these two aspects should be given priority in order to improve the performance of the system in attitude tracking mode.

(2) In the grey-target assessment model based on improved principal components, the two performance indicators with the lowest sensitivity are maneuvering angular velocity and pointing stability, and the main effect coefficients and full effect coefficients of these two performance indicators are obviously smaller than those of other indicators, with a relatively small impact on the comprehensive performance of the satellite attitude control system in tracking mode. The priority of these two indicators can be appropriately lowered in the design of satellite platforms or in the research of performance evaluation.

### *5.3. Comparative Analysis of Methods*

In order to verify the feasibility of the proposed method, based on the unified standardized data set in Section 5.1, in this paper, we designed a set of comparative experiments to evaluate the performance of the attitude control system in the attitude tracking mode of Earth observation satellites using the improved principal component grey target and two classical evaluation methods.

The distance between superior and inferior solutions (TOPSIS) method is a method of evaluating system effectiveness by calculating the relative proximity between evaluation metrics and superior and inferior solutions, and the results accurately reflect the gaps between the assessment processes [30]. Fuzzy comprehensive evaluation (FCE) is a method based on fuzzy mathematical theory to make an overall evaluation of things or objects subject to a variety of factors, with clear results and systematic features [31].

The attitude tracking mode performance evaluation study was conducted using both the above methods, and here, the data of the sun-pointing mode is taken as an example, and the comprehensive evaluation results are shown in Tables 6 and 7:

**Table 6.** Top 10 evaluation results for different methods.

| **Improved Principal Component Grey Target** | | **TOPSIS** | | **FCE** | |
|---|---|---|---|---|---|
| S14 | 0.2502 | S14 | 0.7643 | S14 | 0.8107 |
| S38 | 0.3640 | S26 | 0.7560 | S19 | 0.78857 |
| S35 | 0.2730 | S37 | 0.7482 | S39 | 0.78327 |
| S26 | 0.2880 | S38 | 0.7438 | S26 | 0.78066 |
| S37 | 0.3018 | S35 | 0.7393 | S38 | 0.7744 |
| S17 | 0.3048 | S13 | 0.7246 | S37 | 0.7624 |
| S19 | 0.3214 | S17 | 0.7180 | S35 | 0.7579 |
| S27 | 0.3269 | S19 | 0.7088 | S27 | 0.7466 |
| S39 | 0.3354 | S27 | 0.6948 | S17 | 0.7333 |
| S13 | 0.3355 | S4 | 0.6603 | S13 | 0.7259 |

**Table 7.** Bottom 10 evaluation results for different methods.

| **Improved Principal Component Grey Target** | | **TOPSIS** | | **FCE** | |
|---|---|---|---|---|---|
| S24 | 0.6864 | S23 | 0.4678 | S23 | 0.3976 |
| S23 | 0.6758 | S24 | 0.4794 | S24 | 0.4049 |
| S25 | 0.6223 | S3 | 0.4825 | S30 | 0.4799 |
| S21 | 0.6115 | S21 | 0.4882 | S25 | 0.4874 |
| S33 | 0.5854 | S6 | 0.4948 | S43 | 0.4903 |
| S30 | 0.5838 | S25 | 0.5059 | S33 | 0.5014 |
| S43 | 0.5821 | S30 | 0.5124 | S36 | 0.5024 |
| S41 | 0.5724 | S33 | 0.5128 | S41 | 0.5153 |
| S10 | 0.5569 | S43 | 0.5185 | S22 | 0.5352 |
| S6 | 0.5498 | S15 | 0.5190 | S10 | 0.5364 |

According to the definition of performance indicators in Section 4.3 above, the performance evaluation results of the satellite attitude tracking mode were calculated by improving the principal component grey target, the good and bad distance solution method and the fuzzy comprehensive evaluation method. The results are shown in Table 8. In the calculation of deviation, attention should be paid to the trend of off-target distance, which is different from other methods. The smaller the off-target distance, the better the efficiency, while the greater the evaluation value, the better the efficiency. Before calculating the deviation, the off-target distance sorting result is replaced by an equivalent method. If the off-target distance of an attitude tracking process is set, it can be replaced to keep the trend of the evaluation results of the three methods consistent.

**Table 8.** Comparison of evaluation methods of sun-pointing mode.

| | Improved Principal Component Grey Target | TOPSIS | FCE |
|---|---|---|---|
| Maximum–minimum difference | 0.4362 | 0.2965 | 0.4131 |
| Compatibility degree | 0.9238 | 0.9165 | 0.9124 |
| Deviation | 0.0043 | 0.0031 | 0.0055 |

From the evaluation results, the following conclusions can be drawn:

(1) Of the three methods, comprising improved principal component grey target, TOPSIS and FCE, the maneuver process with the highest performance value was S14. The maneuver process with the worst performance of both the TOPSIS and FCE was S23, while the worst process was S24 in the evaluation results of the grey-target model. The differences between the maximum and minimum evaluation results of the three methods were 0.4362, 0.2965, 0.4131, respectively, and the difference found by the improved principal component grey target was the largest, indicating that the evaluation results had a larger span and could more effectively distinguish the advantages and disadvantages of different maneuvers.

(2) The compatibility scores for the three methods were 0.9238, 0.9165 and 0.9124, respectively. The compatibility of the improved principal component grey target was the greatest, while the compatibility of TOPSIS was the least. The greater the compatibility, the closer and more representative the results of this evaluation method are to other methods, and the more accurate the evaluation results are.

(3) Smaller deviation values mean that, compared with other methods, the evaluation results of the improved principal component grey target have less deviation, and the evaluation results are more reliable. The deviation of the four methods was less than 0.01, and the evaluation results are thus reliable. Among them, the deviation of TOPSIS was only 0.0041, the improved principal component grey target in this paper was second; the FCE had the largest deviation.

In summary, the grey-target model based on the improved principal component presented in this paper had better performance under various analysis angles, and the comprehensive performance was the best. Compared with the traditional evaluation methods, the grey-target model based on improved principal component is more suitable for the evaluation of satellite attitude control system tracking mode.

## 6. Conclusions

In this paper, we propose a comprehensive performance evaluation method for a satellite attitude control system in tracking mode. The method is based on grey-target decision theory, and constructs the grey-target assessment model based on im-proved principal components, which solves the problem of the uncertainty and incompleteness of telemetry data information and achieves the performance evaluation of the attitude control system tracking mode. The feasibility and practicability of the evaluation model are verified by comparing the methods. The main advantages of the method proposed in this paper are as follows: (1) The uncertainty problem existing in the flight status data is described by choosing the generalized grey number method; (2) furthermore, the reasonable weight allocation of the performance evaluation indexes is realized by the improvement in the principal component analysis method, so as to establish the performance evaluation model in tracking mode.

This study provides a valuable reference for the operational performance evaluation of satellite attitude control systems and provides guidance for the application of further assessment methods to other operating modes of satellite attitude control systems. Future research will continue to improve on this foundation and expand the application of the performance evaluation method in different space orbit environments and to different types of satellites.

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