A system-level analysis model for lunar calibration of multispectral payload on remote sensing satellites

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Abstract. Remote sensing satellites are playing an increasingly important role in earth resource exploration, and the radiometric calibration on orbit of satellite has an important impact for retrieving information of earth resources from remote sensing images of a satellite. This paper presents an system-level analysis model for lunar calibration suitable for multispectral payload of remote sensing satellites. Through simulation and calculation analysis, the results show that this method can obtain the payload imaging parameters which are required for lunar calibration missions, ensure the quality of remote sensing images and the accuracy of radiation calibration, and provide reliable data for retrieving information of earth resources.

1. Introduction
In order to obtain high-precision satellite remote sensing data required for earth resource exploration, remote sensing satellites need to perform radiation calibration on orbit. Celestial object calibration has attracted more and more attention due to its advantages of less environmental factors and short-period. In celestial calibration, the moon is the near-Earth object with the largest viewing angle outside the sun. The moon observation data has the advantages of not being affected by the earth’s atmosphere, and the moon’s spectrum can cover all visible-near-infrared spectral bands. Suitable as a reference radiation reference source for satellite solar reflection channels. The reflection characteristics of the moon are very stable, which is suitable for the stability tracking of the radiation response of the sensor, and can be used for the absolute radiation calibration of remote sensing satellites [1].

A method of attitude compensation for lunar calibration by optical remote sensing satellite is proposed by Gao Han, Bai Zhaoguang et al. [2]. This method is based on a certain integration time of a camera to calculate the attitude control parameters required for satellite attitude maneuver, thereby solving the problem of mismatch between integration time and push-broom speed during imaging the moon. However, this method does not actually analyze the imaging parameters such as the camera's gain and integral number required in the lunar calibration mission, and cannot fully meet the system-level satellite parameter setting requirements for the lunar calibration mission.

Based on the characteristics of the passive optical load of remote sensing satellites, this paper proposes a system-level analysis model for lunar calibration, and performs simulation verification and calculation analysis.
2. System-level analysis model for lunar calibration

The analysis model mainly includes modules for designing the lunar calibration work mode, simulation parameter determination, STK-based simulation of typical operating conditions, the limitation of saturation voltage on imaging parameters, and the demand analysis for integral number caused by SNR. The specific models are shown in Figure 1.

Figure 1. System-level analysis model for lunar calibration.

3. Lunar calibration work mode design

The mode covers five phases from the angular momentum adjustment and stabilization phase, the inertial orientation phase, the lunar imaging phase, recovery to ground imaging attitude phase, and the nominal angular momentum restoration phase, as shown in Figure 2. Among them, T0 is the beginning of lunar imaging time, and T1 is the ending time. t1 to t4 are the length of time for attitude maneuver at each stage. If the timing of lunar calibration is selected, the value are also different.

Figure 2. Process of lunar calibration.
4. Simulation of typical working conditions for lunar calibration

4.1. Calculation of the integration time of the camera for imaging the moon

The relative position relationship of Earth, Moon and Star is shown in Figure 3:

![Figure 3. Sketch map for distance to the moon.](image)

In the figure, \( R_1 \) is the radius of the earth, \( H \) is the height of the satellite orbit, \( f \) is the focal length of the optical payload, \( L_1 \) is the average distance between the earth and the moon, \( d \) is the size of the pixel, and LSSD is the lunar surface sampling distance.

For low-orbit remote sensing satellites, the orbit height is about several hundred kilometers, and the average distance between the Earth and the moon is 384,000 kilometers. Therefore, it can be assumed that the distance between the satellite and the moon is approximately equal to the distance between the Earth and the moon. Therefore:

\[
LSSD \approx d \times \frac{L_1}{f}
\]

When the satellite photographs the moon, the moon can be regarded as a circular plane. When the satellite does not perform inertial imaging with maneuver, the projection speed of the satellite's flying speed along the orbital direction on the moon is similar to the satellite's velocity component in the direction of the equatorial plane normal, which is:

\[
v_{\text{moon}} = v_{\text{sat}} \cdot \cos(\varphi)
\]

In the above formula: \( \varphi \) is the latitude of the satellite to the ground, and the TDICCD integration time is the time when the satellite swept one pixel on the moon, that is,

\[
t_{\text{moon}} = \frac{\text{LSSD}}{v_{\text{moon}}}
\]

When there is no attitude maneuver, the imaging integral time of the satellite to the moon at different latitudes of the earth is shown in Table 1:

| latitude (°) | Satellite - Moon relative speed (km/s) | P-band interval integration time (s) |
|-------------|--------------------------------------|-------------------------------------|
| 80          | 1.2222                               | 0.3984                              |
| 60          | 3.5217                               | 0.1382                              |
| 40          | 5.4016                               | 0.0901                              |
| 20          | 6.6327                               | 0.0734                              |
| 0           | 7.0611                               | 0.0689                              |

As can be seen from the above table, the shortest integration time required for the P band to image the moon is 68ms and the design integration time range of the load camera is 0.08 ~ 0.12ms. It can be known that the design integration time of the camera for normal ground imaging is far shorter than the...
theoretical integration time required for imaging the moon. The attitude maneuver of the satellite around the Y axis needs to be used when imaging the moon to reduce the distortion of the moon image. Combined with the maneuverability of low-orbit large remote sensing satellites, the rotation speed of the satellite around the Y axis is designed to be 0.06°/s ~ 0.12°/s.

4.2. Analysis based on STK

In consideration of minimizing the time spent in the abnormal attitude to the earth in the solar illumination area during the attitude establishment phase, the orbital position of the lunar scanning imaging is selected to be at the end of the earth shadow area, and the satellite will stay in the shadow of the earth during the lunar imaging phase.

Based on the above orbit arc, a typical case of rotation speed of 0.1°/s around the + Y-axis was selected for simulation:

| Project Parameter | Rotation speed of the satellite around +Y axis (°/s) | Imaging time (s) |
|-------------------|-----------------------------------------------|-----------------|
|                   | 0.1                                           | 310             |

After receiving the inertial directional injection command, the satellite attitude simulation curve is as follows:

![Simulation curve](image)

**Figure 4. Planning and measuring angular velocities of satellite.**

It can be seen from the above simulation results that under this condition, the satellite can complete the attitude maneuver of lunar calibration and return to the normal imaging attitude of earth after the mission of lunar calibration.

5. Limitation of saturation voltage on imaging parameters

When the camera takes an image of the moon, integration number setting range must not cause voltage saturation. Based on the attitude maneuver scheme based on Section 4, and combining the mobile ability of large-scale remote sensing satellite, can calculate the integral time of certain rotation speed around Y-axis of satellite. Then calculate the TDICCD voltage under the condition of integral time, and see if it is exceeding the maximum limit capabilities of the device, so as to set up the right camera parameters.

For a TDICCD camera, the signal voltage of TDICCD is:

\[ V_s = \frac{100 \cdot \pi \cdot L(\lambda)}{4F^2} \cdot \frac{R(\lambda) \cdot M}{N} \cdot t \cdot \tau \cdot \Delta \lambda \]  \hspace{1cm} (4)

(1) In formula 4, L(\lambda) refers to the apparent radiance.
(2) $R(\lambda)$ is the responsiveness of TDICCD at the full level;
(3) $M$ is the actual used integral number;
(4) $t$ is the integral time of TDICCD;
(5) $\Delta \lambda$ is band width;
(6) $\tau$ is the optical transmittance of the camera;

Let's calculate the rotation speed around the Y-axis, the integration time, and the requirements for using the TDI series in orbit. The simulation is divided into 6 working conditions, as shown in Table 3:

| Condition | 1 | 2 | 3 | 4 | 5 | 6 |
|-----------|---|---|---|---|---|---|
| Gain      | Level 1 | Level 1 | Level 1 | Level 1 | Level 1 | Level 1 |
| Integral number | Level 1 | Level 2 | Level 3 | Level 1 | Level 2 | Level 3 |
| Apparent radiance | High condition | | | | | | Low condition |

Based on the analysis in section 4.1, the simulation was carried out with the boundary condition that the rotation speed of the satellite around the Y-axis was $0.06^\circ/s$ to $0.12^\circ/s$, and the gain and integral number in Table 3 were selected to calculate the signal voltage of TDICCD under the condition of integral time of each band corresponding to a certain Y-axis rotation speed. According to the cut-off voltage of each device, the limitation of imaging parameters was shown as follows:

![Figure 5](image1)

**Figure 5.** Relationship between the voltage of P-band and the rotation speed.

(a) B1 band

(b) B2 band
From the above analysis, it can be concluded that:
(1) For the P-band, when the speed is less than 0.08°/s, imaging parameters other than working conditions 2 and 3 can be selected;
(2) For the P-band, the use of imaging parameters of working condition 3 is not recommended;
(3) For the B4 band, when the speed is less than 0.09°/s, imaging parameters other than working condition 3 can be selected;
(4) For the B1~B3 band, imaging parameters of working conditions 1~ 6 can be used.

6. Demand analysis for integral number caused by SNR

Based on the results analyzed in section 5, common imaging parameters working conditions 2 and 5 were selected as inputs to calculate the SNR for different speeds of the satellite rotating around the Y-axis. The results are shown in the following table:

| Band | Project | Angular speed (°/s) | High apparent radiance SNR(dB) | Low apparent radiance SNR(dB) |
|------|---------|---------------------|-------------------------------|-------------------------------|
| P    |         | 0.06                | 58.48                         | 49.83                         |
|      |         | 0.09                | 54.95                         | 46.31                         |
|      |         | 0.12                | 52.45                         | 43.81                         |
|      |         | 0.06                | 50.01                         | 41.36                         |
|      | B1      | 0.09                | 46.49                         | 37.84                         |
|      |         | 0.12                | 44.00                         | 35.34                         |
|      | B2      | 0.06                | 51.24                         | 42.59                         |
|      |         | 0.09                | 47.72                         | 39.07                         |
|      |         | 0.12                | 45.22                         | 36.57                         |
|      | B3      | 0.06                | 51.81                         | 43.16                         |
|      |         | 0.09                | 48.29                         | 39.64                         |
|      |         | 0.12                | 45.79                         | 37.13                         |
|      | B4      | 0.06                | 51.81                         | 43.16                         |
|      |         | 0.09                | 56.95                         | 48.30                         |
|      |         | 0.12                | 54.19                         | 45.54                         |

**Figure 6.** Relationship between the voltage of B-band and the rotation speed.
If the SNR of high-apparent-radiance required by general image processing needs to higher than 48dB, and the SNR of low-apparent-radiance needs to higher than 23dB, it can be concluded from the data in Table 4:

(2) For B1, B2 and B3: when the rotation speed is greater than 0.09°/s, the integral number should be appropriately increased on the basis of common imaging parameters to obtain better SNR, and the parameters should under the premise of not exceeding the saturation voltage;

(3) For P-band and B4: within the maneuvering capability of the satellite, common imaging parameters can meet the SNR requirements.

7. Conclusion

Based on the analyses of the requirements of passive optical load on imaging parameters for the lunar calibration mission of remote sensing satellites, this paper proposes a system-level analysis method for lunar calibration imaging parameters, constructed the system-level analysis model, and designed the lunar calibration work mode. Through the STK and MATLAB simulation and system level analysis, the payload imaging parameters suitable for lunar calibration are obtained, which proves the validity of the analysis methods mentioned in this paper. This method has strong universality, and can be applied to the lunar calibration task of remote sensing satellites with passive optical load, which can ensure the quality of remote sensing images and radiometric calibration accuracy, and provide reliable data for retrieving information of earth resources form remote sensing images of a satellite.

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