Research on Effects of Satellite Attitude on Modulation Transfer Function of High-resolution Space Optical Remote Sensor

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Abstract. In this paper, the necessity of analysing the satellite platform attitude maneuver performance impact on imaging quality is pointed out, basing on a review of high-resolution space optical remote sensor development. Using some mission requirements and the satellite performance indicators as simulation input conditions, with Monte Carlo method, the analysing of attitude maneuver range that meets the modulation transfer function of image motion velocity compensation larger than 0.95 was taken. The simulation results were showed in three-dimensional surface graphs intuitively, which indicated the attitude stability and attitude measurement accuracy specifications of the satellite platform meet the imaging requirements in the range of elevation angle within±5° and rolling angle within ±45°.

1. Introduction
Foreign research hotspots in the field of space-to-ground observation have gradually shifted from military high-scoring reconnaissance satellites to agile commercial satellites with high resolution and high maneuverability. In September 1999, the American Space Imaging Corporation successfully launched the first commercial high-resolution remote sensing satellite, IKONOS-2, with a full-color spatial resolution of 0.8 meters, the first time in the commercial field to break through meters. In October 2001, American Digital Global successfully launched the QuickBird-2 commercial high-resolution remote sensing satellite. The spatial resolution reaches 0.61 meters. In October 2009, Digital Global successfully launched the WorldView-2 satellite, achieving an optimal ground pixel resolution of 0.46m at an altitude of 770km, and a single over-the-top can achieve a complete imaging of the 112km × 138km area. It can achieve stereo imaging of 112km × 63km. Subsequently, the WorldView-3 and WorldView-4 satellites are launched in 2014 and 2016 respectively, achieving an optimal ground pixel resolution of 0.31m at an altitude of 617km. The main advantage of this type of satellite is that it can be imaged during satellite maneuver.

In the past 20 years, with the support of major national projects such as high-scoring projects, China's space-to-ground observation transmission cameras have developed rapidly. In 2015, the “Jilin No. 1” star group developed by Changguang Satellite Company was successfully launched, which can realize high-definition dynamic video imaging, and have the ability to track sensitive large targets. The satellite has a large field of view angle, and can be realized by maneuvering sideways large-scale ground and sea observations. At present, the number of “Jilin No. 1” constellations has reached 14 and...
can provide timely remote sensing information in various fields such as agriculture and forestry production, environmental monitoring, and geographic mapping.

In the development of agile imaging satellites, the range of attitude maneuvers that satellite imaging can adapt to is an important technical indicator. Studying the impact of satellite platform attitude maneuvers on imaging quality can not only demonstrate whether the satellite platform attitude-related performance meets the imaging requirements of visible light loads, but also provide imaging performance estimates for Optical satellites in orbit applications. The TDICCD image motion matching error under different platform maneuvers is an important factor that causes image quality degradation. To this end, many researchers have performed simulation analysis on this. Yongchang Li et al. [4] aimed at the large field of view imaging of off-axis cameras. In this condition, the image motion velocity model and compensation strategy of the remote sensing camera are analysed. Jiangtao Xu et al. [5] analysed the degradation model of the sensor under the effect of image motion for TDI-CMOS simulation, and based on this, derived the MTF model of the linear abnormal image shift of the sensor along the orbit and cross-orbit directions. Haiqiu Liu et al. [6] analysed the change law of space camera image movement caused by spacecraft vibration with time, and the experiment proved the correctness of the image movement model caused by spacecraft vibration. This article mainly focused on the mission requirements of classical agile imaging satellite, and analysed the impact of the platform attitude performance index on the image modulation transfer function when the satellite platform is maneuvering at a large angle. Based on a brief description of the development trend of agile imaging satellites, first, the impact of platform attitude performance on imaging quality is analysed; then, simulation calculation methods are explained; finally, simulation results are detailed and analysis conclusions are given.

2. Impact of platform attitude performance on imaging quality
There are four main objective indicators of image quality: MTF, signal-to-noise ratio, dynamic range, and positioning accuracy. When the camera is in orbit, all the elements in the imaging link will affect the above four indicators: the internal factors mainly include the optical system, electronics, the camera's orbital mechanical and thermal environment; the external factors include the lighting conditions and the atmospheric environment, Satellite platform attitude, etc. Among them, the attitude performance of the satellite platform, as the main interface performance between the satellite and the optical load, directly affects the MTF index of the image. Various elements in the imaging link constitute various levels of influencing factors for on-orbit MTFs. In this paper, the MTFs mentioned below are all influencing factors caused by TDICCD image shift matching errors.

When shooting with a space-borne camera, the image motion velocity caused by factors such as the orbital motion of the aircraft, the rotation of the earth, and changes in the attitude of the aircraft is $V_r$ [1]. It will be projected on the $P_1$ axis and $P_2$ axis of the image plane coordinate system. After that, the forward image motion velocity $V_{p1}$ of the TDI CCD push-broom direction and the lateral image motion velocity $V_{p2}$ perpendicular to the TDI CCD push sweep direction are obtained. $V_{p1}$ and the TDI CCD push sweep direction form an angle $\beta$, which is called the deflection angle, as shown in Figure 1.

The image motion velocity $V_r$ is related to the aircraft velocity, the aircraft geocentric distance, the subject geocentric distance, the latitude and longitude of the satellite subastral point, the attitude angle of the aircraft and its attitude angular rate, the radius of the earth, the rate of rotation of the earth, and the camera focal length.

The deflection angle $\beta$ is calculated by,

$$\beta = \arctan(V_{p2} / V_{p1})$$  \hspace{1cm} (1)

The accuracy of the drift angle adjustment directly affects the imaging quality of the space camera. The deviation of the deflection angle adjustment will cause residuals of image motion matching of TDICCD, and the effect of image motion matching residuals on the imaging system is determined by the following formula [2].
MTF = sinc(\(\frac{\pi \cdot f_c}{2 \cdot f_N} \cdot \Delta d\)) \tag{2}

in the formula,

\(f_c\) —— Characteristic frequency, equal to Nyquist frequency \(f_N\);

\(\Delta d\) —— Image motion matching residuals in pixels.

Figure 1. Diagram of image motion velocity and deflection angle.

When adjusting the deflection angle, the error \(\Delta \beta\) in the adjustment of the drift angle is caused by the estimation error of the image motion velocity direction, the control error of the satellite yaw attitude angle, the installation adjustment error of the camera image plane coordinate system and the camera coordinate system in the yaw direction, the installation adjustment error of the camera coordinate system and the satellite body coordinates in the yaw direction, etc.. The error \(\Delta \beta\) should meet,

\[
\Delta \beta \leq \arcsin \left( \frac{\Delta V_p}{V_p} \right) = \arcsin \left( \frac{\Delta d \cdot a / t}{N \cdot a / t} \right) = \arcsin \left( \frac{\Delta d}{N} \right) \tag{3}
\]

in the formula,

\(a\) —— pixel size;

\(t\) —— integration time;

\(N\) —— integration level of TDICCD.

According to the formulas (2) and (3), and considering the task requirement that the MTF impact factor is less than 0.95, the image motion matching residual should be less than 1/3 pixel. For the integration level that can be set in the CCD, allowable image motion matching residuals are shown in Table 1,

| Integral level | Relative error of allowable image motion velocity matching(‰) | Allowable Error of deflection angle(′) |
|----------------|---------------------------------------------------------------|---------------------------------------|
| 8              | 41.6                                                          | 143.16                                |
| 16             | 20.8                                                          | 71.609                                |
| 32             | 10.4                                                          | 35.806                                |
| 48             | 6.9                                                           | 23.873                                |
| 64             | 5.2                                                           | 17.905                                |

Input parameters required for simulation calculations are as followed,

- Orbit type: Sun Synchronous Circular Orbit
- Orbit height: 600km
- Optical axis pointing ability: pitch, roll ± 45°
- Attitude determination accuracy: better than 0.02° (3 axes, 3 σ)
• Attitude stability: better than $2 \times 10^{-3} \, \text{o} / \text{s}$ (3 axes, $3 \sigma$)

According to the performance requirement that the average signal-to-noise ratio in orbit is better than 39dB, the typical integration level of TDICCD can be determined to be 48 levels. In summary, the simulation calculation task is transformed into: under the above platform index conditions, determine whether the image motion matching residual meets the requirements of the image motion velocity matching error less than 6.9 ‰ and the deviation angle correction error less than 23.8'.

The focal plane of the camera is composed of 9 CCDs (see Figure 2). It has two imaging modes: same velocity and different velocity. In the same velocity imaging mode, the same integration time is set for the entire image plane, and the reference point is calculated. Focal plane center point is used as calculation reference point; In the different velocity imaging mode, each CCD adopts a separate integration time setting, and the center point of the full-color photosensitive area of each CCD is used as a feature point to calculate the image motion velocity and deflection angle, respectively.

![Figure 2. Focal plane stitching diagram.](image)

3. Simulation calculation

The calculation methods and formulas of the process of obtaining the image motion velocity and deflection angle are detailed in [3]. To analysing the complex influence of multiple factors on image motion matching errors, the Monte Carlo method is more suitable. This is a numerical method for solving approximate solutions of mathematical physics and engineering technology problems through statistical experiments and random simulation of random variables.

We simulated and calculated the MTF influencing factors of the image plane edge points of the camera at the same-velocity and different-velocity imaging modes under different platform maneuvering angles. The platform maneuvering range is within the range of $\pm 45 ^\circ$ pitch and $\pm 45 ^\circ$ roll, calculated at 5 ° intervals. The calculation results are given by a three-dimensional surface graph. Figure 3 is the calculation result of the MTF influence factor of the edge points of the image plane in the same-velocity imaging mode. Figure 4 is the MTF impact factor generated by image velocity matching residual in the push-broom direction in different-velocity imaging mode. Figure 5 shows the MTF impact factor of the horizontal pixels of the image plane edge points in different-velocity imaging mode.

![Figure 3. The MTF impact factor of the push-scan image velocity matching at the edge of the image surface in same-velocity imaging mode.](image)
In the same-velocity imaging modes, the integration time is set by using the image motion velocity calculation value of the image center point. In the different-velocity imaging modes, the integration time is set by using the image movement velocity calculation value of the center point of each CCD. In the full image plane or single-chip CCD, the image velocity matching error of the image surface edge point or CCD edge point is the largest. Therefore, the MTF of the edge point of the image plane or the edge point of the single-chip CCD meets the requirements, which can be used as a necessary and sufficient condition for the full-image surface or the entire CCD to meet the index requirements.

Analysis of the calculation results of the MTF impact factor can be obtained:

- When imaging at the same velocity and different velocity, if the MTF impact factor during satellite subastral point imaging is greater than 0.998, the platform's attitude stability and attitude measurement accuracy can meet the imaging requirements.
- When imaging at the same velocity (Figure 3), the MTF index is only met within a small range of platform attitudes, while at the different velocity imaging (Figure 4), the maximum attitude range of the platform that meets the requirement of an MTF impact factor greater than 0.95 is extended to $\pm 45^\circ$ roll, $\pm 35^\circ$ pitch.
- The mainstream optical load corrects the drift angle through the platform maneuver, so it can only be corrected according to the image center point. Due to the large differences in the calculated values of drift angles at various points on the image plane when the platform is maneuvering, the image distortion caused by the edge of the image plane cannot be corrected by image motion compensation, which causes a large drop in MTF push-scan perpendicular to the push-scan direction.

The full image plane influence MTF lateral factor can be guaranteed to be greater than 0.95 only when the satellite's pitching maneuvering angle is within the range of roll maneuvering angle.
• When maneuvering at a large angle, the image plane $MTF_{lateral} \leq MTF_{push-scan}$. At this time, the MTF impact factor index should be based on the $MTF_{lateral}$ impact factor.

4. Conclusion

According to the mission requirements of classical agile imaging satellite, the performance index of the emulational satellite platform is used as the simulation calculation input, and the Monte Carlo simulation method is used to analyse the satellite attitude maneuvering range that satisfies the MTF influence factor greater than 0.95 when the mechanical stitching scheme is used at the focal plane. The simulation results show that under typical integration level conditions, the platform's attitude stability and attitude measurement accuracy can meet the requirements of imaging quality assurance; using the different velocity imaging mode, the platform can guarantee the range of pitch maneuvering angle and roll maneuvering angle. The full-surface MTF performance index meets the requirements.

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