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# On-orbit calibration using a micro-scaleplate of light for remote sensing cameras

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ABSTRACT

Camera calibration is a prerequisite for image position determination in a space mission of spacecrafts. However, how to realize on-orbit camera calibration without the space and time limitation remains a crucial but unsolved issue. To overcome this problem, we present an efficient solution. We propose to use micro-scaleplate of light that generate two dimensional equally spaced sub-beams. A structured aperture focal plane with a known focal length is placed on the focal-plane of a normal optical system, producing the two dimensional grids with the structured prior position as calibration targets. This is confirmed experimentally. The experimental results show that the use of the micro-scaleplate provides a valuable calibration tool for on-orbit cameras.

## 1. Introduction

High-resolution remote sensing cameras have become essential tools in earth observation applications [1–4]. High-accuracy image position determination constitutes one of the most significant functions of a remote sensing camera in a space mission. Calibrating camera is a prerequisite for the realizing of the image position determination function.

Many approaches to calibrate a camera exist for different applied systems [5–10]. As the working conditions, remote sensing camera calibration includes two stages: 1) on-ground calibration before the launch; and 2) on-orbit calibration after the launch. Both of the two stages are crucial to calibrating a remote sensing camera. On-ground calibration is used to design a space mission before the launch. On-ground calibration approaches are mainly based on laboratory measuring angles [11–13]. An uncalibrated optical camera is placed on a precision turntable to capture the light of single pixel illumination, produced by a collimator. At different rotation angles of the turntable, multiple positions from different field of views (FOVs) can be obtained to realize the calibrating of the camera [14]. Unrestricted to the space and time, on-ground calibration approaches can use multiple cutting-edge techniques, such as active-vision-based self-calibration [15], a set of optimal conditions [16], and crossed-phase diffractive optical elements (DOEs) [17]. On-orbit calibration is used to determinate on-orbit internal parameters of a remote sensing camera or to correct the drifting of calibrated results on ground because of vibration during complicated launches and on-orbit working conditions. On-orbit calibration methods mainly include self-calibrating bundle adjustment (SCBA) [18], ground control point (GCP) [19], 180-degree satellite maneuvers (180-SM) [20]. However, the SCBA suffers from long computation times [21], which is not suitable for the limited on-board computing resource. The GCP and 180-SM both possess common characteristics with the aid of external targets. However, external targets can be only captured when the satellite works at a specific orbit position and a specific imaging time. Therefore, these calibration methods based on the use of external targets are limited by space and time.

Consider the above drawbacks, a micro-electromechanical-system (MEMS) integration method, which is based on point-source focal plane, integrated on the focal-plane of an un-calibrated camera, is used for calibrating a smart camera [22,23]. This method can implement on-orbit calibration and has the high calibration accuracy. However, the focal plane fabrication is very difficult, restricted to the focal plane space. Moreover, the optical system needs also to be modified. Therefore, this method suffers from the development difficulty of a remote sensing camera.

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To overcome this problem, we present an efficient solution using micro-scaleplate of light (mSOL), which is a normal optical system with a known focal length and prior self-luminescence targets. The mSOL can be used as an infinite target, simulating ground objective, to calibrate camera. Because of its micro-structure, it can easily integrate into a remote sensing camera system for on-orbit system, without the increasing of development difficulty. This opens the door to on-orbit calibration without space and time limitation.

## 2. Results

### 2.1. Calibrating a camera with mSOL

High-accuracy image-positioning determination (IPD) is one of the most common space tasks for Earth observation satellites. The positioning determination accuracy directly determines the performance of an Earth observation satellite. The IPD is mainly determined by elements of exterior orientation and intrinsic orientation parameters of a remote sensing camera. The intrinsic orientation parameters are the prerequisite for the IPD. The intrinsic orientation parameters of a remote sensing camera include the principal distance and principal point. The principal point is the intersection point between the camera image plane and the principal optical axis. The principal distance is the distance between the centre of camera optical system and its image plane. In this paper, we use an mSOL to calibrate the intrinsic orientation parameters of remote sensing cameras. Fig. 1 shows the principle of calibrating a remote sensing camera. The mSOL is composed of an area-array light source (LS), a structured aperture focal plane (SAFP), and a normal optical system (OS). The SAFP includes multiple apertures, which are denoted by $S_1$, $S_2$,. . ., $S_N$, and $N$ is the total number of apertures. The $N$ image points, denoted by $P_1$, $P_2$,. . ., $P_N$, are generated on the focal plane of the remote sensing camera. Based on these aperture positions and image-point positions, we calculate the internal parameters of the remote sensing camera.

The SAFP is located on the focal plane of the OS. The focal length is expressed by $f_{SOL}$, which is a priori known parameter. The mSOL is located in the front of a remote sensing camera, and the unit vector of their optical axis is parallel, but has opposite signs. Let the coordinate of $i^{-}$th structured aperture of the mSOL be denoted by $(L_{sx}, L_{sy})$. Let the coordinate of the corresponding image point be denoted by $(L_{px}, L_{py})$ when optical system is an ideal system. The imaging relationship of the ideal system is expressed as:

$$\left(\frac{L_{px}}{f_{camera}}, \frac{L_{py}}{f_{camera}}\right) = \left(\frac{L_{sx}}{f_{SOL}}, \frac{L_{sy}}{f_{SOL}}\right). \tag{1}$$

In actual system, the origin of the image coordinate system is not located on the optical axis of the optical system, which means the principal point is not (0,0). Let $(u_0, v_0)$ be the principal point of the remote sensing camera. In an actual system, the imaging relationship can be expressed as:

$$\begin{aligned}[\hat{L}_{px} \quad \hat{L}_{py} \quad 1]^T &= \begin{bmatrix} L_{px} \\ L_{py} \\ 1 \end{bmatrix} + \begin{bmatrix} u_0 \\ v_0 \\ 1 \end{bmatrix} \\ &= \begin{bmatrix} f_{camera} & 0 & u_0 \\ 0 & f_{camera} & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{L_{sx}}{f_{SOL}} & \frac{L_{sy}}{f_{SOL}} & 1 \end{bmatrix}^T,\end{aligned} \tag{2}$$

where $f_{camera}$ is the focal length of the optical system of the remote sensing camera, $f_{SOL}$is the focal length of the optical system of the mSOL. When considering optical system distortion of the camera and the mSOL, the above equation becomes

$$\begin{aligned}[\hat{L}_{px} \quad \hat{L}_{px} \quad 1]^T &= \begin{bmatrix} L_{px} \\ L_{py} \\ 1 \end{bmatrix} + \begin{bmatrix} u_0 \\ v_0 \\ 1 \end{bmatrix} \\ +\Delta(x, y) &= \begin{bmatrix} f_{camera} & 0 & u_0 \\ 0 & f_{camera} & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{L_{sx}}{f_{SOL}} \\ \frac{L_{sy}}{f_{SOL}} \\ 1 \end{bmatrix} + \Delta(x, y)\end{aligned} \tag{3}$$

where $\Delta(x,y)$ is the deviation of the position due to the camera distortion. Let $(x,y)$ be undistorted position and in normalized image coordinates. Normalized image coordinates are calculated from image coordinates dividing by the focal length. The deviation position using a radial distortion is expressed as

$$\Delta(x, y) = \begin{bmatrix} \Delta L_{px} \\ \Delta L_{py} \\ 0 \end{bmatrix} = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} K = \begin{bmatrix} \frac{L_{px}}{f_{camera}} \\ \frac{L_{px}}{f_{camera}} \\ 0 \end{bmatrix} K = \begin{bmatrix} \frac{L_{sx}}{f_{SOL}} \\ \frac{L_{sy}}{f_{SOL}} \\ 0 \end{bmatrix} K, \tag{4}$$

with

$$K = k_1 r^2 + k_2 r^4 + k_3 r^6, \tag{5}$$

where $r$ is calculated by the normalized image coordinates as:

$$\begin{aligned} r^2 = x^2 + y^2 &= \left({}^{L_{px}}\!/\!{}_{f_{camera}}\right)^2 + \left({}^{L_{py}}\!/\!{}_{f_{camera}}\right)^2 \\ &= \left({}^{L_{sx}}\!/\!{}_{f_{SOL}}\right)^2 + \left({}^{L_{sy}}\!/\!{}_{f_{SOL}}\right)^2, \end{aligned} \tag{6}$$

where $k_1$,$k_2$, and $k_3$ are the coefficients describing (radial) distortion of the optical system of the remote sensing camera. The principal distance and principal point can be calculated by solving the following equation:

$$\min_m \left\| \begin{bmatrix} \hat{L}_{px} - u_0 \\ \hat{L}_{py} - v_0 \end{bmatrix} - f_{camera} \begin{bmatrix} \frac{L_{sx}}{f_{SOL}} \\ \frac{L_{sy}}{f_{SOL}} \end{bmatrix} \left(1 + k_1 r^2 + k_2 r^4 + k_3 r^6\right) \right\|^2. \tag{7}$$

in Eq. (7), the $(\hat{L}_{px}, \hat{L}_{px})$ is obtained using the extraction calculation from the captured image of the remote sensing camera. The mSOL provides $L_{sx}$, $L_{sy}$, and $f_{SOL}$. $r$ is obtained using Eq. (6). Based on Eq. (7), the intrinsic orientation parameters $(f_{camera}, u_0, v_0)$ of the remote sensing camera are calculated.

In order to achieve the on-orbit calibration, the mSOL is integrated into a remote sensing camera. Based on Eq. (7), the mSOL utilizes the self-parameters, such as focal length, structured aperture, in combination with the image points captured by a remote sensing camera, to calculate the internal parameters of the remote sensing camera. Fig. 2 shows the mSOL integrated in the optical system of a remote sensing camera; the mSOL is installed on the truss of the remote sensing camera. Co-axis remote sensing cameras usually include view-off-axis-type three mirror anastigmatic (TMA) [24,25] optical systems and view-coaxis-type TMA optical systems. The view-off-axis-type TMA with asymmetric FOV could avoid the blocking of incoming light and be used in remote sensing cameras. When a remote sensing view-off-axis-type optical system is considered, the optical axis of the mSOL is consistent with off-axis field of view (FOV).