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# A method and results of color calibration for the Chang'e-3 terrain camera and panoramic camera *

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**Abstract** The terrain camera (TCAM) and panoramic camera (PCAM) are two of the major scientific payloads installed on the lander and rover of the Chang'e 3 mission respectively. They both use a Bayer color filter array covering CMOS sensor to capture color images of the Moon's surface. RGB values of the original images are related to these two kinds of cameras. There is an obvious color difference compared with human visual perception. This paper follows standards published by the International Commission on Illumination to establish a color correction model, designs the ground calibration experiment and obtains the color correction coefficient. The image quality has been significantly improved and there is no obvious color difference in the corrected images. Ground experimental results show that: (1) Compared with uncorrected images, the average color difference of TCAM is 4.30, which has been reduced by 62.1%. (2) The average color differences of the left and right cameras in PCAM are 4.14 and 4.16, which have been reduced by 68.3% and 67.6% respectively.

**Key words:** Moon — methods: data analysis — techniques: image processing

## 1 INTRODUCTION

The Chang'e-3 lunar surface exploration mission, including a lander and a rover, was launched at 17:30 UTC on 2013 December 1. The lander successfully descended and landed on Mare Imbrium at 13:11 UTC on Dec 14 (Li et al. 2014; Ip et al. 2014). The terrain camera (TCAM) and panoramic camera (PCAM) are two of the major scientific payloads installed on the lander and rover respectively. They are used to capture visible light images, which will be used to survey lunar surface topography and geology. The two kinds of cameras are designed for color imaging. The two cameras captured their first color images at 11:01:38 UTC and 12:44:50 UTC respectively on Dec 15. Compared with human visual perception, the image quality is good.

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PCAM and TCAM use a CMOS sensor that is part of a Bayer color filter array (CFA) to capture color images. Commercial digital cameras, such as Canon, Nikon, Sony and Aigo, use this kind of color imaging principle. This imaging technology has also been widely used in various space exploration missions, e.g., the Chang'e-2 solar wing monitor camera, the Shenzhou spacecraft astronaut monitor camera, and Mars Curiosity's MAHLI (Edgett et al. 2012) and Mastcam instruments (Malin et al. 2010). However, RGB values of the recorded images are related to properties of these cameras (Sharma & Bala 2002; Hunt et al. 2011). In evaluating the effects of color, a common problem is whether different cameras or the same camera in different imaging conditions will produce the same colors when photographing the same object, and whether the colors of the recorded image match those of human visual perception. Much work needs to be done on estimating the illumination of the scene and the tristimulus values, e.g. RGB, XYZ and CIELab, of the objects. The International Commission on Illumination (abbreviated CIE) quantitatively uses tristimulus values to describe colors, establish a CIE standard colorimetric system, and puts forward the concept of standard colorimetric observers, standard illuminants, geometric conditions and methods for the measurement of object colors (Sharma & Bala 2002; Hunt et al. 2011). A method of color correction for PCAM and TCAM is established according to the CIE standard. The ground testing and in-orbit images are used to estimate the results.

Section 2 gives the principles of the panoramic camera and the terrain camera, and how they acquire color images. In Section 3, a color calibration model is constructed and the model coefficients are calculated in the ground tests. Section 4 shows the results of color correction for the two camera, and the effect of color correction is evaluated. In Section 5, the work completed in this paper is summarized.

## 2 PRINCIPLES OF CAMERAS AND COLOR IMAGING

The PCAM is one of the rover's major scientific payloads, with two cameras installed on the mast of the Yutu rover, and has the ability to take color and panchromatic images. The TCAM, one of the lander's major scientific payloads, has only one camera installed on the pointing mechanism of the lander, and can acquire color imaging and dynamic photography. They use a Bayer CFA covering CMOS sensor to capture lunar color images. The filter pattern of the Bayer CFA is 50% green, 25% red and 25% blue (see Fig. 1).

After Bayer CFA filter the light by wavelength range, each pixel can only produce a color red, green or blue. In order to convert the raw image to a full-color image, the demosaicing algorithm (Li 2005) will be used to calculate a missing color component by the color values of the surrounding pixel. In addition, because it is affected by the light source, radiation transmission path, target characteristics, camera features and other factors, the raw color image cannot accurately reproduce the color of the object. There will be some differences in color and the image quality will be reduced (Sharma & Bala 2002; Ramanath et al. 2005; Kao et al. 2006). Color correction must be done for the original color image after demosaicing. During a ground color calibration test, the correction coefficient was measured.

## 3 COLOR CALIBRATION METHODS

The imaging process mainly includes two steps.

(1) The reflected light of target enters the cameras.
(2) With the spectral response functions, the cameras convert incident light into RGB color values and output them.

Therefore, the qualities of color produced by the camera mainly depend on the outside light source, the reflection characteristics of the target and the camera's spectral response characteristics. In order

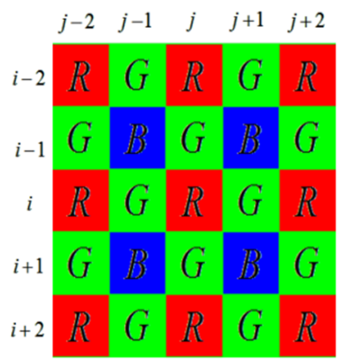


**Fig. 1** Bayer CFA Filter Pattern (R, G and B represent red, green and blue respectively).

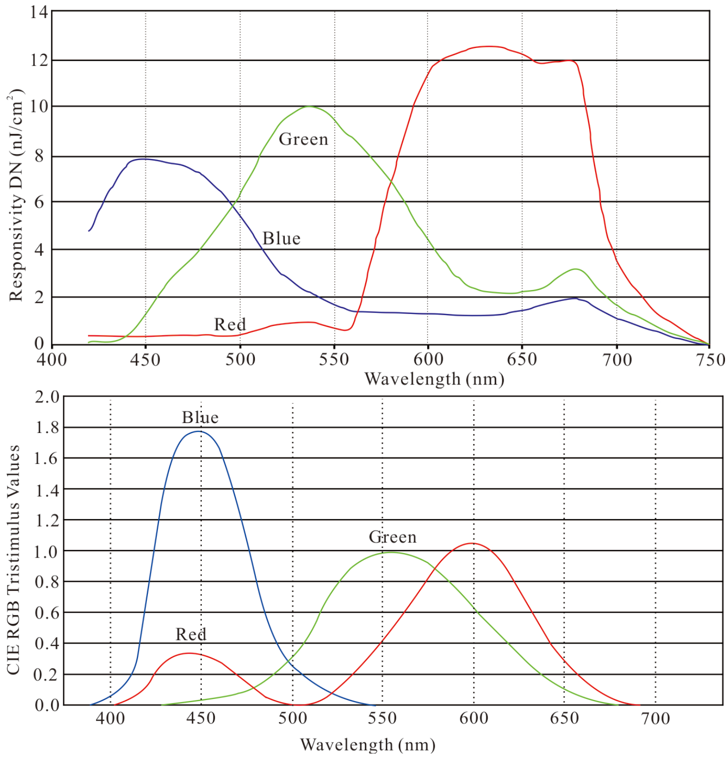


**Fig. 2** *Top*: Spectral response curves of the PCAM and TCAM; *Bottom*: CIE 1931 color matching functions.

to achieve consistency between color produced by the camera color and human visual perception, the spectral response errors and the effect of different light sources should be taken into consideration in a color calibration model. A color calibration model was constructed and calibration ground tests were carried out to calculate the model coefficients (Haeghen et al. 2000; Jackman et al. 2012; Li 2008; Weerasinghe et al. 2005).

### 3.1 Correction for Errors in the Color Response of the Camera

Once the external light source and the target are determined, the color response model is primarily related to characteristics of the spectral response. An inconsistency between spectral response functions of the camera (see the top panel in Fig. 2) and CIE standard perceptive color matching functions (see the bottom panel in Fig. 2) will cause a bias between the color recorded by the camera and color that the observer perceives. The color calibration test was based on camera spectral characteristics, from which we obtained the color calibration coefficients. They were used to convert the camera original colors to the standard color values. CIE 1931 standard observer was taken as the reference for our test. (Sharma & Bala 2002; Valous et al. 2009).

In Figure 2, there is an obvious deviation between the color response curves and the CIE 1931 observer curve. For convenience in data processing, color values in the CIE XYZ chromaticity system were converted to the RGB chromaticity system (Bianco et al. 2007). The conversion between the RGB values from the camera and those from standard values of the CIE 1931 standard observer can be expressed as the following equations

$$\begin{cases} R_y = A_{11} \times R_0 + A_{12} \times G_0 + A_{13} \times B_0 \,, \\ G_y = A_{21} \times R_0 + A_{22} \times G_0 + A_{23} \times B_0 \,, \\ B_y = A_{31} \times R_0 + A_{32} \times G_0 + A_{33} \times B_0 \,, \end{cases} \tag{1}$$

where $(R_y, G_y, B_y)$ is the RGB values of the CIE 1931 standard observer. $(R_0, G_0, B_0)$ is the RGB values from the camera. $A_{ij}$ ($i = 1, 2, 3$, $j = 1, 2, 3$) is the conversion coefficient.

In order to get the calibration coefficients in Equation (1), a color calibration system, including a CIE standard light source (D65), a standard color board (24 colors) and a spectrometer, was set up in Figure 3. D65 provided a standard lighting source, standard color board as a target and a spectrometer to measure the color values. According to the CIE standard (GB/T3977-2008; GB/T3978-2008)[1], the test mainly followed the steps below:

(1) Set up the standard illumination and observation conditions (angle of incidence of 45°, angle of emergence of 0°) and image the color board with the camera;
(2) By interpolating color from the raw image data with the method of Li (2005), the original color image is obtained. The RGB value of each color patch in the color board is measured as camera observations in Equation (1). The dark current correction and relative calibration are carried out before color interpolation, and the processing parameters are provided by laboratory tests.
(3) Given the same illumination and observation geometry, the spectrometer measures spectral values for each color patch. The spectral values are converted to color values in the XYZ system (Sharma & Bala 2002), and then to RGB components in the RGB color system (Bianco et al. 2007), as the values of the CIE 1931 standard observer in Equation (1).
(4) By the least squares method, unknown variables in Equation (1) are solved, which are the camera's color calibration coefficients.

### 3.2 Correction for the Effect of the Light Source

Human eyes have the ability to self-adjust to restore colors. In different lighting conditions (primarily changes in color temperature), the perceptions are similar. For instance, we can correctly feel a white target no matter if it is at sunrise or in dim light. Unlike human eyes, PCAM and TCAM cannot adapt to restore colors, so the images obtained from the cameras require white balance correction to remove the influence of different illuminations.

[1] GB/T3977-2008, Methods for the measurement of object color (Standardization Administration of The People's Republic of China) and GB/T3978-2008, Standard illuminants and geometric conditions (Standardization Administration of The People's Republic of China).

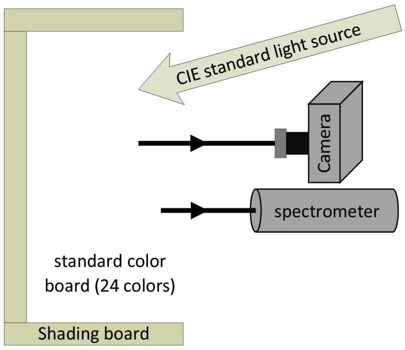


**Fig. 3** Sketch of the color calibration test for the PCAM and TCAM.

According to the principle of how white balance operates, each color channel should be consistent with others after correction, which is to say the RGB components should be the same. Take the green component for reference; the mathematical equations are as follows:

$$\begin{cases} R_m = r \times R\,, \\ G_m = 1 \times G\,, \\ B_m = b \times B\,, \\ R_m = G_m = B_m\,, \end{cases} \tag{2}$$

where $(R,\,G,\,B)$ and $(R_m,\,G_m,\,B_m)$ are the RGB values before and after correction respectively. $(r,\,1,\,b)$ is a correction coefficient.

The white balance test is performed via a similar process as the color calibration test. The standard color board is replaced with a board having diffuse, neutral colors (black, white, pure grey) and by the least squares method, correction coefficients of $R$ and $B$ are calculated.

## 4 RESULTS AND EVALUATION

In this paper, the effect of color correction in the two kinds of cameras is evaluated by quantitative and qualitative evaluation methods. The images that were photographed as part of a ground test and onboard detection are used in the evaluation process. Radiometric correction of original images is carried out before evaluation by a dark current matrix and the relative calibration matrix calculated from the results of the ground test (Liu et al. 2013). Qualitative evaluation is based on human visual perception to evaluate effect on the image after color correction. Quantitative evaluation is based on the CIE1976L*a*b* (CIE LAB) color difference formula (GB/T7921-2008[2]; Sharma & Bala 2002). The value of color difference between a standard color and a sample color is quantitatively calculated. Color distortion in images after color correction is evaluated.

### 4.1 Evaluation for Ground Test Images

(1) Qualitative Evaluation

First, images of some Chinese national flags, color cards and some other color targets are photographed by the PCAM and TCAM under D65 indoors and during noon sunshine outdoors respectively. Then color correction is applied by testing correction coefficients. It can be seen that the color of an image obtained by two kinds of cameras after color correction is returned to normal compared to the original image's greenish hue. The human visual perception effect is good (see Fig. 4).

[2] GB/T7921-2008, Uniform color space and color difference formula (Standardization Administration of The People's Republic of China).

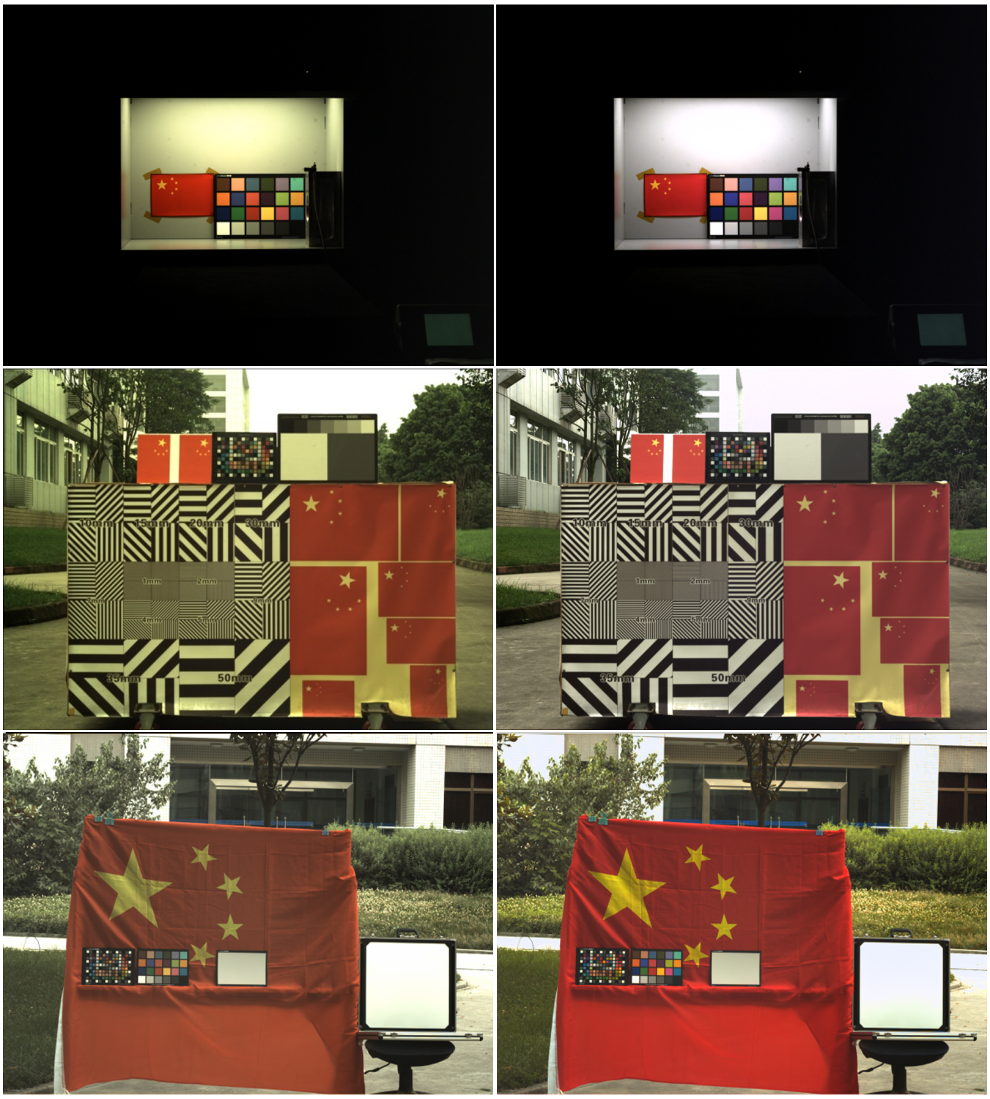

**Fig. 4** *Top:* Picture showing the same kind of Chinese national flag that is carried by the TCAM under D65 light indoors; *Middle:* Picture showing the same kind of Chinese national flag that is carried by the TCAM under natural outdoor light; *Bottom:* Picture showing the same kind of national flag that is carried by the PCAM under outdoor light. Left panels are before color correction while right panels are after.

(2) Quantitative Evaluation

The formula CIE1976L*a*b* (CIE LAB) for color difference is used in this paper (GB/T7921-2008). The value of color difference in images before and after color correction is calculated. The color transformation between CIE XYZ color value and RGB color value is the same as in (Bianco et al. 2007). The RGB color value of 24 colored cards is measured after color correction when they are photographed under the conditions of illumination and observation geometry described in Section 3.1. Then the CIE1976L*a*b* color value is obtained by the color transformation mentioned

**Table 1** Color Difference Analysis Before and After Color Correction

| Camera | Before color correction | After color correction | Color difference reduction |
|---|---|---|---|
| TCAM | 11.35 | 4.3 | 62.10% |
| LPCAM | 13.03 | 4.14 | 68.30% |
| RPCAM | 12.85 | 4.16 | 67.60% |

above to be used as a sample color. As a comparison, the CIE1976L*a*b* color value measured under GB/T7921-2008 is set as the standard color by the National Institute of Measurement and Testing Technology's color calibration test. The average value of the color difference in the PCAM and TCAM after color correction is calculated with the above color difference formula, which is the average value of color difference of 24 samples. On the other hand, the average value of color difference before color correction is also calculated in the same way to analyze the improvement in color compared to the original images. The results are listed in Table 1, where TCAM is the terrain camera. LPCAM is the left panoramic camera. RPCAM is the right panoramic camera.

As can be seen from Table 1, the average value of color difference in the left panoramic camera is 13.03 before color correction, which is obvious, and it is 4.14 after color correction, which is not obvious. The average color difference decreases by 68.3%. Likewise, the average value of color difference for the right panoramic camera is 12.85 before color correction, which is obvious, and is 4.16 after color correction, which is not obvious. The average value of color difference decreases by 67.6%. The average value of color difference for the TCAM is 11.35 before color correction, which is obvious, and is 4.3 after color correction, which is not obvious. The average color difference decreases by 62.1%.

On the other hand, quantitative evaluation of color difference is also carried out on the red section of a Chinese national flag on an initial prototype of the rover during a ground imaging test under the same observing conditions. The color value of camera output is set as sample color while the value of color that is calculated by the National Institute of Measurement and Testing Technology is set as the standard color. In order to avoid human error during sample selection, the sample color of the red section in the national flag is selected by the average color value of a 10×10 pixel window. A total of 10 samples are selected. The results are as follows. Combined with the actual image data, it can be seen that the difference in image color after color correction obviously improves compared to the original images.

### 4.2 Evaluation of Images Obtained Onboard

There are no verifiable conclusions about the true range of color in visible light on the lunar surface and the effect of human visual perception. On the other hand, the change in light conditions on the lunar surface, camera imaging angle, distribution of lunar surface rocks and minerals, the composition of material in lunar soil and other factors will cause differences in color images taken on the lunar surface. Hence, it is difficult to judge the true color of the lunar surface environment from PCAM and TCAM images. However, the color of the Chinese national flag is familiar to many people. In this paper, the images photographed by the two cameras in their best imaging position are used in the evaluation process.

The best position for TCAM to photograph the Chinese flag on the rover is located to the northeast of the lander, about ten meters away, where the rover and lander can photograph each other. Seven different exposure times are used to obtain TCAM images. The image with an exposure time of 12 ms is used in this paper for evaluation. It is the best image according to human visual perception. The best imaging position for photograph the national flag on the rover is located at 10 m south of the lander and where the rover and lander can photograph each other. The test used four types and three types of exposure times. An exposure time of 20 ms is selected for analysis of color difference.

The results are shown in Figure 5 and Table 3. On the other hand, the color image photographed by the surveillance camera on the lander is displayed in Figure 6. The distortion in color for this image is obvious because no color correction is applied to it.

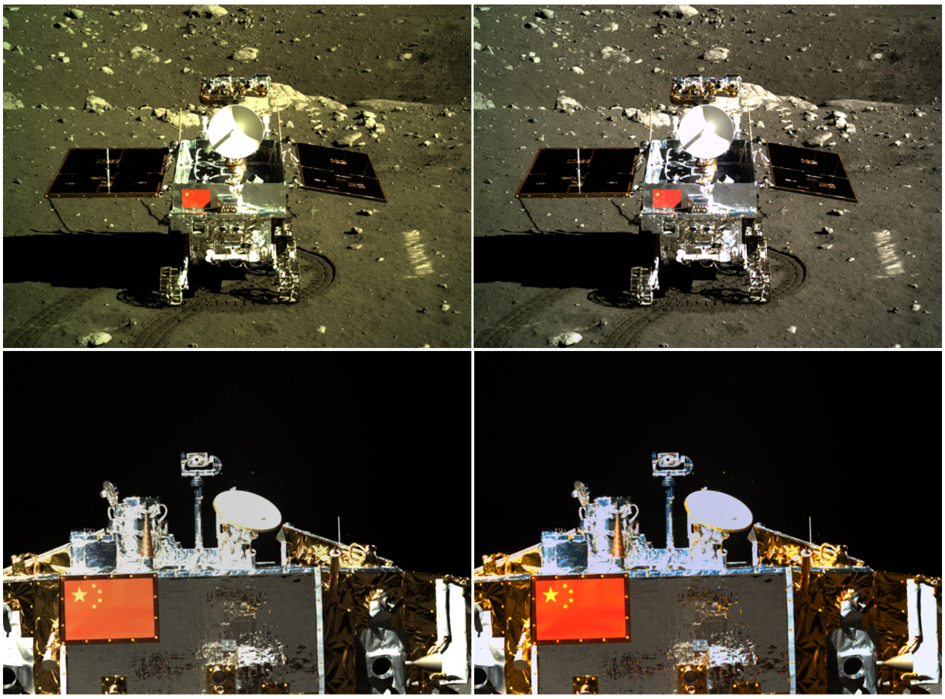

**Fig. 5** *Top:* Picture showing the effect of color correction in the image taken onboard by TCAM at Point A; *Bottom:* Picture showing the effect of color correction in the picture taken onboard by PCAM at Point D. Left panels are before color correction while right panels are after.

**Fig. 6** Image taken onboard by the surveillance camera at Point D (without color correction).

**Table 2** Analysis of the Color Difference in an Image of the Chinese National Flag Before and After Color Correction

| Camera | Before color correction | After color correction | Color difference reduction |
|---|---|---|---|
| TCAM | 18.46 | 6.43 | 65.90% |
| LPCAM | 21.2 | 8.56 | 59.60% |
| RPCAM | 19.96 | 7.72 | 61.30% |

**Table 3** Analysis of Color Difference in Images Taken Onboard Before and After Color Correction

| Rover position | Camera | Before color correction | After color correction | Color difference reduction |
|---|---|---|---|---|
| Point A | TCAM | 18 | 13.8 | 23.30% |
| | LPCAM | 26.89 | 18.64 | 30.70% |
| Point D | RPCAM | 25.74 | 16.31 | 36.60% |

As can be seen from Figure 5, the effect of improvement in color for an image after color correction is obvious and the effect for human visual perception is good. The color of the Chinese national flag in the image is close to the true color. The method of calculating the difference in color value that is shown in Table 3 is the same as the method described in Section 4.1. Because the true color of the Chinese national flags carried by the lander and rover was not measured before or after the probe was launched, the standard color of the national flag when color difference was calculated is the same as the one in Section 4.1 and the value of color difference is only calculated for the red part of the national flag. It can be seen that the color difference after color correction obviously improves compared to the original image. The improvement in color difference of PCAM images is more obvious than that of TCAM images.

In Tables 2 and 3, it can also be seen that the improvement in color difference for the image of the Chinese national flag in the laboratory is more obvious than that taken onboard. The reasons are as follows: (1) Difference in the light source. The results of Table 2 are calculated by the images photographed under D65, while the results of Table 3 are calculated by the images photographed under natural sunshine on the lunar surface. Color temperature of the two kinds of light sources is different. (2) The sample color and standard color used in Table 2 are measured under the same condition of illumination and observation geometry, but the condition is different for Table 3. (3) The flags that used to calculate sample color and standard color in Table 3 are different, but the flags that are used in Table 2 are the same. (4) The dark current matrix, relative calibration matrix and some other calibration parameters obtained in the ground calibration test may not be suitable for onboard image data. These factors will cause some errors in Table 3.

## 5 CONCLUSIONS

The study in this paper follows the CIE standard to design the ground calibration experiment and obtains the color correction coefficient of the two kinds of cameras before CE-3 was launched. Experimental results are summarized as follows:

(1) There is a very obvious color difference compared to the original color images from the PCAM and TCAM. The image quality has been significantly improved after using methods described in this paper. There is no obvious color difference in the corrected images.

(2) Ground experimental results show that the average color difference of TCAM is 4.30, which has been reduced by 62.1% compared with uncorrected images. The average color differences in the left and right cameras of PCAM are respectively 4.14 and 4.16, which have been respectively reduced by 68.3% and 67.6%.

(3) Compared with the effect of human visual perception, the improvement in color difference of ground test images is better than that of in-orbit images, mainly because of the difference in light source, illumination and observation geometry between ground tests and the lunar surface, and changes in image processing parameters.

The model used for color correction in this paper is a linear model. There will be some errors in the model that do not consider the nonlinear characteristics of human eyes, the difference between D65 light and sunlight on the lunar surface, atmospheric absorption effects, etc. Work at optimizing the model will be going on in the future. The original color value is relative to the camera spectral response function, which was provided by the CMOS manufacturer in this paper. The function must be different from a real camera, and that will result in some errors. Calibration for this function should be considered in future exploration missions. The image processing parameters, such as radiation and color correction, have been obtained in the ground test. They may change after launch because of changes in the environment and some other factors. This will result in a decline in the quality of processed images. On-orbit optimization for these processing parameters should be considered. Some on-orbit calibration equipment, such as a color calibration board, should be included in a future exploration mission.

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