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Moderate Resolution Imaging Camera (MoRIC) of China's First Mars Mission Tianwen-1

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Abstract: China's first Mars exploration mission will carry out comprehensive global surveys of the planet from data collected by instruments carried in orbit and roving on the planet itself. Goals of the mission include detailed inspections and surveys of key areas on the surface of Mars. One of the main scientific payloads installed on the orbiter is the moderate resolution camera. Its mission is to image the surface of Mars sufficiently to produce a global remote sensing image map of the planet, and to explore and record changes to the topography of Mars, including major geological structures, and to advance research on topography and geomorphology in general. The moderate resolution camera uses a lightweight and compact integrated design; its primary components are an optical module, a focal plane module, a camera control module, a power and interface module, a camera support module, a thermal control module, and a reference module. Radiometric calibration, color calibration, and geometric calibration have been carried out to ensure that the camera can acquire sufficient accurate data to complete mission goals. This paper introduces the camera's detection mission, its system composition, and its working principle; it also describes the camera's ground calibration tests and their results, and provides a reference for processing the camera's scientific data and for future applications.

Keywords: Mars exploration; moderate resolution camera; system composition; working principle; calibration test

1. Introduction

China's first Mars exploration mission will achieve three project objectives of "orbiting, landing, and roving" in order to carry out comprehensive global surveys of the entire planet, and detailed inspections of key areas on the Mars surface. China's first Mars exploration mission consists of an orbiting probe (hereinafter referred to as the "orbiter") and a landing and roving probe (hereinafter referred to as the "landing rover"). The mission's scientific goals are: (1) to map the characteristics and changes of the topography and geological structures of Mars; (2) to determine the soil characteristics and water ice distribution on the surface of Mars; (3) to study the material composition of the surface of Mars; (4) to collect data regarding the Martian atmospheric ionosphere and surface climate and environmental characteristics; (5) to study the gravitational field and internal structure of Mars (Geng Y, et al., 2018). The main scientific missions of the orbiter are: (1) to analyze the atmospheric ionosphere and interplanetary environment of Mars; (2) to explore the surface and groundwater ice on Mars; (3) to determine the Marian soil type distribution and explore major structures on Mars; (4) to detect significant Martian topographic and geomorphologic features and monitor their changes; (5) to investigate and analyze the material composition of the surface of Mars (Li CL, et al., 2018).

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The moderate resolution camera is one of the main scientific payloads installed on the orbiter. In order to meet the camera's volume, weight, power consumption, and other design criteria and to ensure the accuracy of its geometric calibration, the design of the moderate resolution camera was based on a step-staring frame imaging scheme along the orbit direction by an area array color imaging sensor with small distortion and easy exposure time control. The moderate resolution camera has the following imaging advantages: (1) the color imaging sensor is combined with the signal processing circuit, and it is set on the focal plane of the optical system. The electronic scanning mechanism replaces the traditional optical-mechanical scanning mechanism, thereby significantly improving system response characteristics, simplifying system structure, reducing the instrument's volume and mass, making the structure compact, improving the system's reliability, and raising the level of system design to a higher level; (2) it has high imaging efficiency and small distortion because the entire full-swath image is acquired almost at the same time; (3) staring imaging can provide longer integration time, which is beneficial to improve the signal-to-noise ratio; (4) the time interval between each frame image is limited only by the integration time, data acquisition rate, and data transmission capacity, so it can achieve a high time resolution.

The camera module is integrated with other orbiter payloads to optimize the scientific mission of exploring Martian topographic and geomorphologic features and their changes. The main missions of the moderate resolution camera are: (1) to image the surface of Mars and draw a global remote sensing image map of Mars, and (2) to explore the topography and changes of Mars, enabling research into Martian geological structure, topography, and geomorphology. In order to maximize the scientific range of this exploration mission, the moderate resolution camera can be used to conduct imaging of the Earth, the Moon, the Earth–Moon system, Mars, and other celestial bodies in the Earth–Mars transfer orbit, as well as possible small celestial bodies; it can be instructed to conduct (3D) imaging of the near Mars point and the pre-selected landing zone in the Mars parking orbit, and to detect and study suitable landing points; it can conduct (3D) imaging of the actual landing point in the relay orbital section, which will provide support for scientific planning of the rover and comprehensive study of the landing zone. In the Mars orbiting section, the moderate resolution camera uses a shooting strategy in which the shooting interval varies with the orbital altitude and speed of the substellar point, which can ensure that the image overlap rate of two adjacent images along the Mars probe's flight direction reaches 60%, and the overlap rate of images between adjacent orbits reaches 15%, so that the global remote sensing images of Mars can be fully detailed.

2. Function and Performance

The main functional indicators of the moderate resolution camera are: (1) able to acquire color images with moderate resolution on the surface of Mars; (2) capable of automatic exposure and remote-control exposure; (3) having measures to reduce stray light; (4) capable of sufficient sampling and windowing; (5) capable of imaging when the solar elevation angle is not less than 10°, and striving to perform imaging when the solar elevation angle is not less than 5°.

The moderate resolution camera is not designed for use during the launch or orbit-capture stages of the Mars probe; it will be functional during the following stages: Earth–Mars transfer orbit, parking orbit, relay orbit, and remote sensing orbit stages of the Mars probe mission. The main performance indicators are shown in Table 1 (Wu J, et al., 2009). The camera's working modes include a standby mode and a shooting mode.

Standby mode: The moderate resolution camera is supported by the primary working power supply; the camera-related thermal control circuit is in the power-on state, and the thermal control module is in the working state.

Shooting mode: The moderate resolution camera is supported by the primary working power supply; the camera's thermal control circuit and imaging circuit are in the working state, and the thermal control module is in the working state.

Table 1. Main technical performance indicators.

	Items	Main parameters and performance
1	Color	Color (standard RGB)
2	Wavelength range	Visible light
3	Ground sampling distance (GSD)	98 m@400 km
4	Imaging swath	401 km@400 km
5	Number of effective pixels	4096×3072
6	Field angle	53.3°×41.2°
7	Quantized value (bit)	12
8	Signal-to-noise ratio S/N (dB)	51.9 (target reflectivity: 0.2, solar elevation angle: 30°)
9	System static MTF	≥0.37 (full FOV)
10	Data compression ratio	No compression, 3 x compression, 4 x compression, 6 x compression (default), 12 x compression
11	Weight (kg)	3.5
12	Power consumption (W)	19.72

3. Working Principles and System Design

3.1 System Composition

The moderate resolution camera uses a lightweight and compact integrated design, suitable for installation on the orbiter. The optical axis of the camera points to the core of Mars, and some optical modules are exposed outside the cabin. The camera's main functional hardware modules are an optical module, a focal plane module, a camera control module, a camera support module, a thermal control module, and a reference module. (1) Optical module: effectively obtains optical signals from the surface of Mars; (2) focal plane module: performs photovoltaic conversion of the optical images to corresponding electrical signals, thus obtaining digital images; (3) camera control module: generates focal plane unit CMOS bias voltage; generates focal plane unit CMOS drive timing signal; communicates with CMOS via the SPI port, and configures and reads parameters; receives image signal output by focal plane unit CMOS and analyzes and caches images; performs automatic exposure calculation based on the image and controls the exposure; outputs the image data stream and engineering parameters in the prescribed format; communicates with the load controller of the orbiter via the RS422 interface, receives control commands and parameters, and returns the instrument to working status; (4) camera support module: fixes the optical module, the focal plane module, and the camera control module, and ensures the mechanical characteristics of the camera; (5) power and interface module: provides the power required for camera operation and thermal control, and achieves docking with the load controller of the orbiter; (6) thermal control module: ensures the working ambient temperature and storage ambient temperature of the camera; (7) reference module: provides the reference for installation of the camera. For software, the moderate resolution camera only has one camera control and image processing FPGA.

3.2 Working Principles

The moderate resolution camera uses a step-staring frame imaging scheme with low distortion and easy exposure time control. The camera's optical module collects the optical information of the target image in the field of view on the surface of Mars and images it on the CMV12000 color sensor target surface. The CMV12000 sensor converts the optical information into original image data. The resolution of the original image data is 4096 × 3072; the quantized value is 12 bit, and the data size of a single image is 144 Mbit. The CMV12000 sensor transmits the original image data to the external SDRAM at a transmission rate of 125 Mbps. The camera control and image processing FPGA reads the original image data from the external SDRAM, which first conducts full-swath, or windowing or sampling treatment, then encodes the original image data by an 8B/10B coding scheme, and finally reads the exposure starting time, time information, and camera working status of the image, packages them into the image data, and transmits the image data stream to the load controller of the orbiter at a transmission rate of 16 Mbps. The load controller compresses full-swath images, but does not compress windowed or sampled image data. The automatic exposure function module of the camera control and image processing FPGA performs automatic exposure calculations at a frequency of 4 frm/s. The adjustment of exposure time is determined by the difference between the calculated average gray value of the current frame and the target gray value. When the gray deviation is large, a large adjustment of the exposure time is used to increase the convergence rate. When the gray deviation is small, the exposure time is adjusted to make minor improvements. The camera control signals include two circuits of OC remote control command signals of the load controller of the orbiter and RS422 serial communication signals. The camera communicates with the load controller of the orbiter via the RS422 serial port to implement functions such as camera control, data injection, and engineering parameter acquisition. The data packet sent by the orbiter's load controller is received and processed by the camera control and image processing FPGA inside the camera. The FPGA then forwards the data or demands to the relevant circuit module according to the content to realize control of the camera's working mode and injection of parameters. Meanwhile, the camera's working condition is controlled by the camera and collected by the image processing FPGA, forming the data packet and transmitting the data packet to the load controller of the orbiter. The FPGA communicates with the CMV12000 color imaging sensor through an SPI interface and sends commands and parameters related to the CMV12000 color imaging sensor.

3.3 System Design

3.3.1 Probe selection

The analysis was made based on the camera's mission function and performance index requirements, as well as on the Martian light, temperature, and irradiation environment (Ouyang ZY, et al., 2012) and the properties of the camera's CMOSIS's CMV12000 color imaging sensor, whose main performance parameters are: ① spectral response range is 350 nm to 900 nm, ② effective pixel number is 4096 × 3072, ③ pixel size is 5.5 μm × 5.5 μm, ④ sensitivity is 4.64 V/lux·s, ⑤ ADC is 12 bit, ⑥ full trap charge is 13500e, ⑦ PRNU: < 1.27% (RMS), ⑧ dynamic range: 60 dB, ⑨ QE × FF: 50%@550 nm, ⑩ operating temperature is −30°C to 70°C.

3.3.2 Optical system and optical module design

Adaptation to the particular space radiation, extreme cold or hot temperatures, and light environment on Mars is the challenge that the moderate resolution camera must face while acquiring satisfactorily clear and real images. Unless proper measures were taken in its design, the space radiation on Mars would hamper normal operation of the camera, causing, in particular, a sharp decline in the transmittance capability of the optical module. The optical system thus utilized irradiation environment adaptability design technology; all optical materials were chosen to have anti-radiation capability, ensuring that the camera could properly acquire images. Moreover, because temperature variation inside and outside the orbiter will be drastic, advanced designs enable the optical lenses to withstand the extreme temperature shock (ranging from −180°C to +80°C) and to adapt to the particular temperature environment on Mars, ensuring high imaging quality and guaranteeing that the moderate resolution camera could see clearly. The optical module is designed to operate normally in a vacuum thermal environment with temperature range of +5°C to +35°C. How to take "true color" photographs on the Mars has been a challenge for designers. After extensive consideration, calculation, and experiments, a cutoff wavelength range of the optical module was chosen that ensures the camera's ability to acquire realistic images (Yu GB, et al., 2015).

The main technical parameters of the camera's optical system include: ① wavelength range is 430 nm to 690 nm, ② field of view is 53.1° × 41.1°, ③ clear aperture is 4.5 mm, ④ focal length is 22.52 mm, ⑤ F-number is 5, ⑥ modulation transfer function (MTF) is more than 0.45, ⑦ spectral transmittance is more than 70%, ⑧ out-of-band rejection ratio: When the wavelength is shorter than 350 to 410 nm, the average transmittance for the normal incidence of the optical filter τ_1 is ≤ 2%; when the wavelength is longer than 710 to 1000 nm, the average transmittance for the normal incidence of the optical filter τ_2 is ≤ 2%, ⑨ operating temperature is 5°C to ~35°C. The structure diagram of the optical system, modulation transfer function curve, and distortion curve of the optical system, are respectively shown in Figures 1, 2 and 3, and the structural design of the optical module is shown in Figure 4.

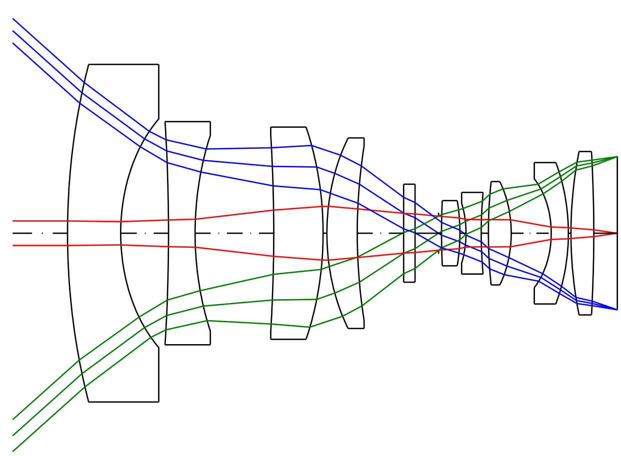

Figure 1. Structure diagram of the optical system.

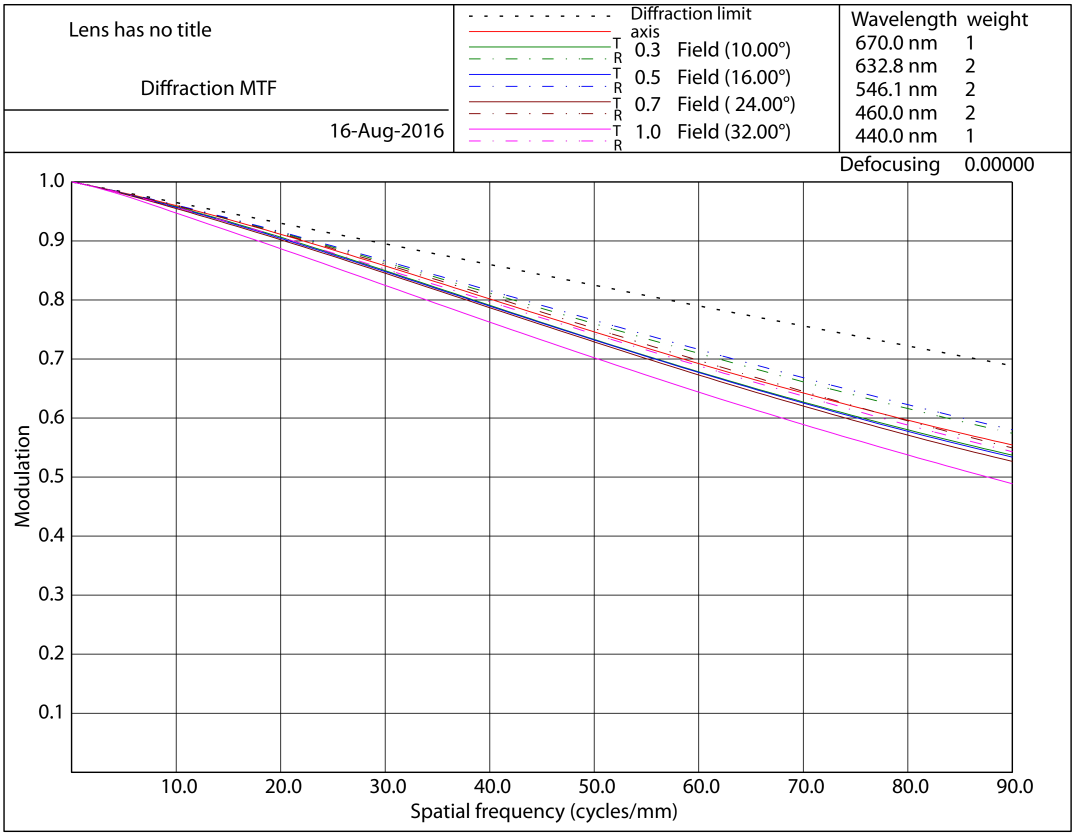

Figure 2. Optical modulation transfer function curve.

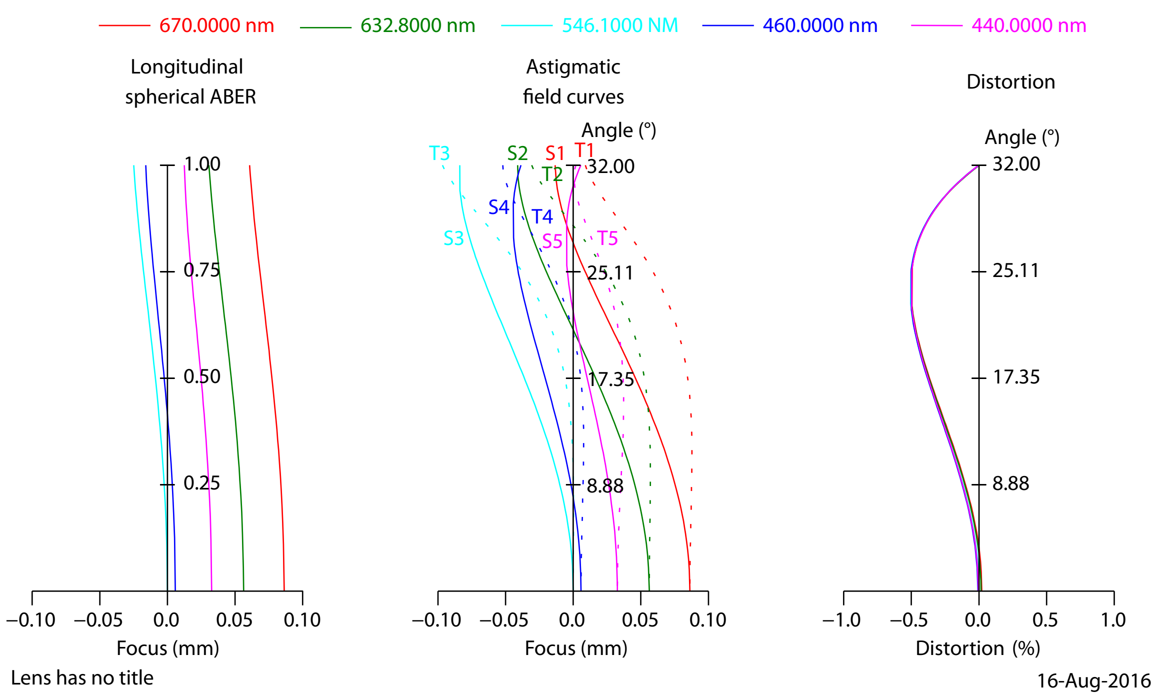

Figure 3. Distortion curve of the optical system.

3.3.3 Structural design of the camera

In terms of the camera's structural design, the following were the main considerations: ① the mechanical environment conditions of launch, transfer, and separation must be met, ② the optical system's imaging quality requirements must be met, ③ the camera modules must not exceed payload maximum weight and size limitations, ④ thermal control conditions of the camera should be met. As previously described, the camera payload consists of an

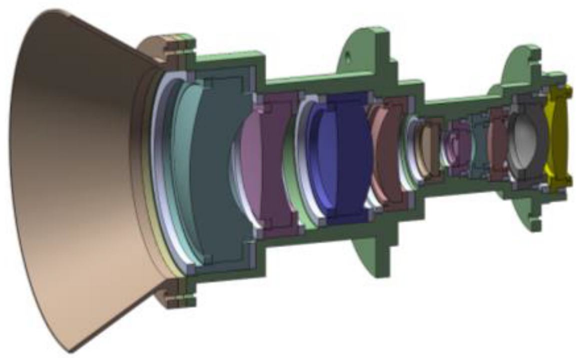

Figure 4. Structural design diagram of optical lenses.

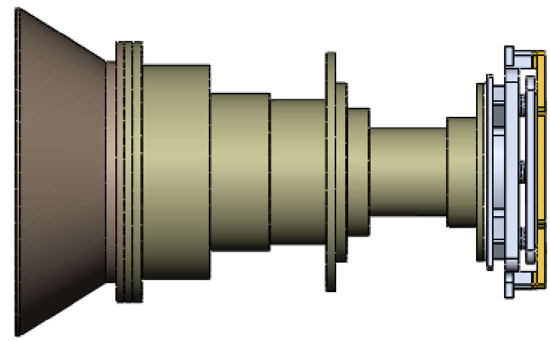

Figure 5. Schematic diagram of CMOS circuit board and optical module modular design.

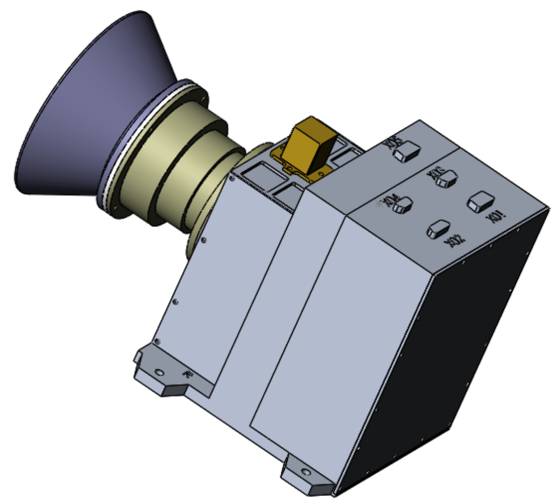

Figure 6. Three-dimensional diagram of camera structural design.

optical module, a focal plane module, a camera control module, a power and interface module, a camera support module, a thermal control module, and a reference module. Based on the relationship between the focal plane module and the optical module, they are perpendicular to each other; the control module and power and interface module are parallel to the circuit box. The back of CMOS color imaging sensor utilizes a special copper strip thermal conduction device which allows heat generated during CMOS to flow to the mechanical structure of the camera; this resolves the difficulty of dissipating heat from the CMOS's high-power-consumption and creates a temperature difference between the CMOS and the camera's mechanical structure of 5°C, which enables the camera to function in the extremely wide temperature range of its work environment (−180°C to +80°C).

The structural design of the camera has the following characteristics: ① CMOS circuit board and optical module modular design to ensure that the relative position between CMOS color imaging sensor and the optical module is fixed; ② modular design and assembly technology of CMOS circuit board and optical module to ensure that the error of perpendicularity between the optical axis of the optical system and CMOS color imaging sensor is not more than 0.01 mm; ③ modular design and assembly technology to ensure that the error between the optical axis and the benchmark mirror is not more than 1'; ④ modular design and assembly technology to ensure that the error of parallelism (perpendicularity) between the probe pixel and the installation surface was not more than 2 pixels. A structural design diagram of the camera is shown in Figures 5, 6.

4. Ground Calibration Test and Results

4.1 Radiometric Calibration Test and Results

The aim of the radiometric calibration was to eliminate pixel response inconsistencies caused by camera imperfections, to avoid occurrence of unequal output gray values when pixels of incident were homogeneous and consistent, and to build the functional relationship between camera output signal and input radiation quantity to insure actual physical significance. The radiometric calibrations were both relative and absolute.

During the relative radiometric calibration test, six exposure times (5 ms, 10 ms, 15 ms, 20 ms, 30 ms and 40 ms) were utilized to acquire camera images at 10 temperatures (−20°C, −10°C, 0°C, 5°C, 10°C, 15°C, 20°C, 30°C, 40°C and 50°C) for dark current calibration; six exposure times (5 ms, 10 ms, 15 ms, 20 ms, 30 ms and 40 ms) were utilized to acquire camera images at 5 homogeneous illumination levels (729.65 μw/cm^2, 321.50 μw/cm^2, 1260.23 μw/cm^2, 1937.00 μw/cm^2 and 196.93 μw/cm^2) for inhomogeneous response calibration. After the relative radiometric calibration, maximum inhomogeneous value of images of the camera's RGB channels were: R, G, B = [1.79%, 1.78%, 2.09%].

During the absolute radiometric calibration test, four levels of saturation (80%, 60%, 40% and 20%) were utilized to acquire images at 5 homogeneous light intensities (729.65 μw/cm^2, 321.50 μw/cm^2, 1260.23 μw/cm^2, 1937.00 μw/cm^2 and 196.93 μw/cm^2) for absolute radiometric calibration. The maximum error after calibration was 2.92%.

4.2 Color Calibration Test and Results

The color spectral response of the camera's CMV12000 color imaging sensor was known to be inconsistent with the color matching function of the CIE standard observer. An additional challenge was presented by the light conditions on the Mars surface. These factors could be expected to cause the camera's images to exhibit a color cast. Accordingly, a two-step color correction method that combines color calibration with white balance was designed (Ren X, et al., 2014; Zhao RJ, et al., 2016). First, under a D65 standard light source, the inconsistency between the response of CMV12000's color imaging sensor and the CIE standard color matching function was measured and used to determine the camera's RGB color correction matrix (as shown in Table 2) which was obtained utilizing the least squares adjustment of the 24-color code. Second, again using a D65 standard light source, the least squares adjustment of the three-order neutral color codes was adopted to obtain the camera's white balance correction matrix (as shown in Table 2), which improved the generalization ability of the traditional single-color code white balance correction coefficient and effectively reduced the impact of the Martian surface's light conditions on the color balance of the camera's images.

Ground color correction after the color calibration and white balance is shown in Figure 7. Under D65 standard light, camera module output accurately matched the reference color code, and more consistent with the color visible to the human eye.

4.3 Geometric Calibration Test and Results

Geometric calibration of the camera included mainly: the focal length of the camera, the position of the principal point of the image, and the camera's distortion correction coefficient. The grid image method was adopted so that, in its camera calibration range, the camera could photograph the same standard correction target in two or more orientations. The mathematically constrained relationship between the identification point of the standard correction target and the data measured by the total station electronic tacheometer was utilized to work out the camera's principal point, focal length, and distortion correction coefficients (as shown in Table 3, below). The distortion correction coefficient was utilized to employ distortion correction for images photographed by the camera. After correction, the residual error in the direction of X was 0.167 pixel and the residual error in the direction of Y was 0.175 pixel.

Table 3. Results of geometric calibration.

Principal point X_0/wath (pixel size)	2054.4509/4096
Principal point Y_0/wath (pixel size)	1575.7622/3072
Focal length f (pixel size)	4097.3579
Radial distortion coefficient K_1	3.055997990E-9
Radial distortion coefficient K_2	−4.744987862E-16
Eccentric distortion coefficient P_1	2.385176550E-8
Eccentric distortion coefficient P_2	3.285174808E-9
Non-square proportionality coefficient α	2.417221439E-5
Non-orthogonal distortion coefficient β	1.125511817E-4

5. Conclusions

The moderate resolution camera is the main payload of China's first Mars exploration mission orbiter. Its design accomplishes mission objectives, including imaging the surface of the Mars and drawing a global remote sensing image map of Mars as well as exploring the topography and changes of Mars, including surface imaging of the planet, identification of its geological structures, and research on topography and geomorphology. To ensure that the moderate resolution camera could obtain real and accurate exploration data on its mission to Mars, ground testing, environmental simulation tests, and ground calibration tests were conducted during its research and development, to provide reference data for the processing of scientific data obtained in space, and for the benefit of future applications.

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Table 2. Color correction matrix and white balance correction matrix.

Color correction matrix	White balance correction matrix
1.2600 0.1925 –0.5524 –0.2958 1.3606 –0.2652 0.0358 –0.5531 1.8177	1.0482 0.9398 1.0189

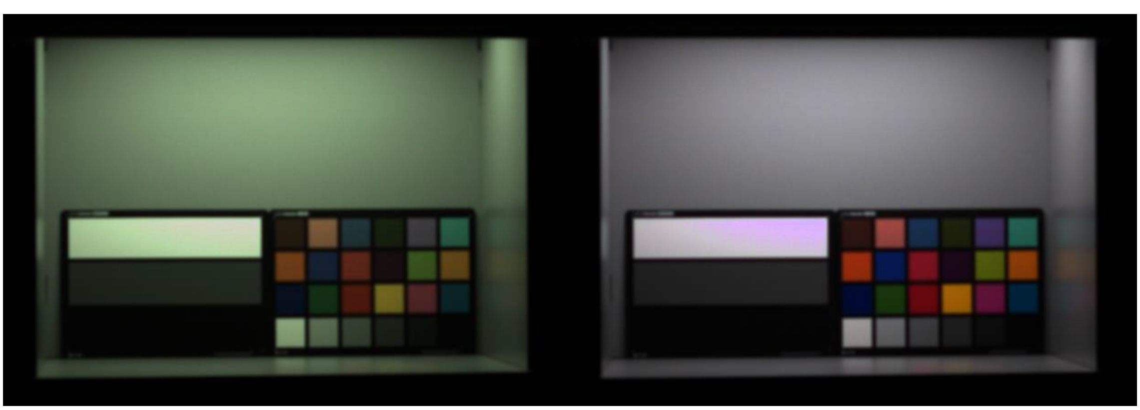

Figure 7. Contrast between image effects of photographing three-order neutral color codes and 24-color codes before and after color calibration under the D65 standard light source in a darkroom. The chromatic aberrations before and after color calibration were respectively 31.3 and 8.1. The left is the image before the color calibration and the right is the image after color calibration.

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