Radiometric calibration of large dynamic range low light level camera

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Abstract: The low light level camera (LLLC) can acquire images of Visible/Near Infrared (VIS/NIR) targets in large dynamic range which are from daylight to starlight conditions. Accurate radiometric calibration for the LLLC was a key part of determining the performance of the camera, and it′s very important to the quantitive application of images. The output radiance of the uniform light source which is used to calibrate the LLLC should be in the range from 1×10^{-9} W/(cm^2·sr) to 3×10^{-2} W/(cm^2·sr). For realizing high-precision radiometric calibration, a uniform light source which had constant spectrum in each output level was designed. A three-integrating-sphere transfer design was adopted and the difficulty of constant spectrum for each output level of the light source over multiple orders of magnitude was overcame. The design of the uniform low light level source for radiometric calibration was introduced. Furthermore, the accuracy of spectral radiance measurement for such a large dynamic range light source was also a challenge. The spectral radiance of each output level of the light source was obtained by transfer measuring method. The result of radiometric calibration for large dynamic range LLLC was given. The uncertainty of radiometric calibration for the LLLC achieved 18% (k=2).

Key words: radiometric calibration; low light level; dynamic range; spectral calibration

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大动态范围微光相机的辐射定标

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摘　要： 微光相机可以获取从白天到夜晚星光照明条件下的大动态范围可见光目标的图像，辐射定标是确定微光相机辐射性能的关键环节，对于微光相机获取的遥感图像的定标化应用有十分重要的意义。对微光相机进行辐射定标的均匀辐射定标源的输出辐亮度范围需要覆盖 $1\times10^{-9}\sim3\times10^{-2}$ W/(cm^2·sr)。为了实现在如此大动态范围内对微光相机的高精度辐射定标，设计了在每一个输出辐亮度级次均具有不变光谱分布的均匀辐射定标源。介绍了微光辐射定标光源的设计，采用三积分球级联式的设计方式，解决了在跨越多个数量级的大动态范围情况下，辐射定标源各辐亮度级次仍能保持一致光谱分布的难题。另外，如此大动态范围内保证各个辐亮度级次下光谱辐亮度的测量精度具有很大难

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度，通过传递测量的方法解决了微光各级次下光谱辐亮度测量的问题，给出了大动态范围微光相机的辐射定标结果，微光相机辐射定标的不确定度达到了 18% (k=2)。

关键词： 辐射定标； 微光； 动态范围； 光谱定标

0 Introduction

The low light level camera (LLLC) is used to acquire images of Visible/Near Infrared (VIS/NIR) targets in large dynamic range which are from daylight to starlight conditions for meteorological research. There were some researches on radiometric calibration method for low light level imager in worldwide institutes and universities. University of New Hampshire developed a facility for optical calibration at low light level in 2006. Beijing Institute of Space Mechanics & Electricity (BISME) built a large dynamic range radiometric calibration system in 2013. BISME also applied the relevant patent in 2016, the application No. is CN201611194034.4. The difficulty of radiometric calibration of the LLLC is mainly in design and calibration of the large dynamic range light source with constant color temperature. Eliminating stray light from background and realizing vacuum environment are also challenges for radiometric calibration[1-3].

The LLLC includes two channels which are named as high-light detecting channel and low-light detecting channel. There are 10 gains selectable for each channel. The LLLC is composed of a wide field-of-view (FOV) lens and two detectors mounted on the focal planes of the two channels. Figure 1 shows the optical schematic of the LLLC.

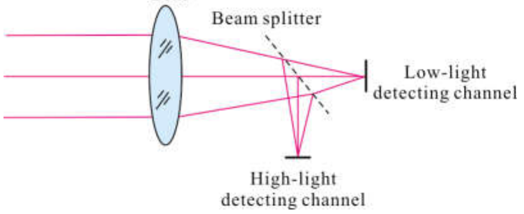


Fig.1 Optical schematic of the LLLC

The focal length of the LLLC is 32 mm, f-number is 3.3 and full FOV is 30°. By dividing the incident beam into two beams with different energy portion, the two channels have same spectral range of 450-1 000 nm.

The high-light detecting channel can cover a radiance range from 1×10^{-5} W/(cm^2·sr) to 3×10^{-2} W/(cm^2·sr) and the low-light detecting channel can cover a radiance range from 1×10^{-9} W/(cm^2·sr) to 1×10^{-4} W/(cm^2·sr). By combining the dynamic range of the two detecting channels, the camera can obtain the images of scenes with large dynamic range of radiance.

For realizing high-precision absolute radiometric calibration and relative radiometric calibration for the LLLC in laboratory, it's necessary to design a uniform light source with constant spectrum in each output radiance level. The uniform light source should have continuous and smooth spectrum in spectral range of 450-1 000 nm[4-7].

The accurate spectral radiance measurement of the uniform light source has been considered in design of the source. A three-integrating-sphere transfer model is adopted in design of light source. A spectroradiometer is used to calibrate the spectral radiance of the light source. Spectral radiance can be measured by the transfer relationship among the integrating spheres.

The LLLC is set up in a thermal vacuum chamber (TVC) when acquiring the calibration data on count of the detector of low-light detecting channel has to work at the temperature -20 ℃ which is as same as the operating temperature on orbit.

1 Calibration principles

Absolute radiometric calibration coefficient A for one of the gains of the camera can be calculated as follows.

$$DN(i)=L_e(i)\cdot A+B \tag{1}$$

Where, $DN(i)$ is digital number output of the camera, B is the dark current output of camera, $L_e(i)$ is the equivalent radiance at output level i of the light source. $L_e(i)$ can be calculated according to Eq.(2):

$$L_e(i)=\int L(i,\lambda)R(\lambda)\mathrm{d}\lambda \tag{2}$$

Where, $L(i,\lambda)$ is the spectral radiance at output level i of the light source, $R(\lambda)$ is the relative spectral response of the camera.

2 Experiment setup

The equipment layout of radiometric calibration for the LLLC is shown in Fig.2. Absolute radiometric calibration of the LLLC is operated in a dark laboratory in Test and Evaluation Center for Space Optical Remote Sensors of BISME. The ceiling and walls of the dark laboratory are painted with black coating, the reflectance of the black coating is less than 0.03. The dark laboratory can realize the primary dark environment for radiometric calibration. The uniform low light level source is set up in the dark laboratory. The exit port of the light source is on the wall of the calibration darkroom. The LLLC is set up in the TVC which can achieve a vacuum degree less than 1×10^{-3} Pa. On-ground support equipment including image acquiring device are put outside of the calibration darkroom. The darkroom is also painted with black coating and designed well for removing the stray light from outside. There is no light source producing stray light in the calibration darkroom besides the low light level source. Figure 3 shows the equipment in the calibration darkroom.

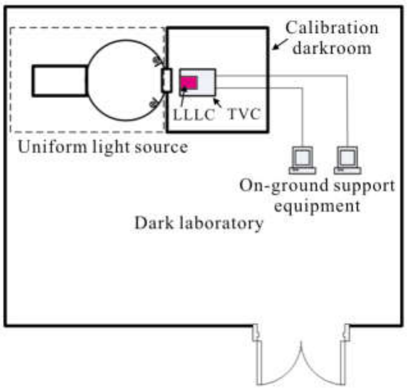


Fig.2 Layout of radiometric calibration equipment in lab

The uniform light source is designed to three-integrating-sphere transfer model. The relationship of output between adjacent integrating spheres can be calibrated with two spectroradiometers. The two spectroradiometers are calibrated by a small integrating sphere which is traceable to National Institute of Metrology, China (NIM). The output radiances of the light source cover a radiance range from 1×10^{-9} W/(cm$^2\cdot$sr) to 3×10^{-2} W/(cm$^2\cdot$sr). The colour temperatures are near 2 850 K. The colour temperatures of all output levels are almost the same, which means that the spectral distributions of each output level are almost the same. The uniform light source can provide constant source spectrum over more than 7 orders of magnitude. There are 6 radiance levels in almost each order of magnitude of light source, so the response linearity of the LLLC can be obtained in different low light levels.

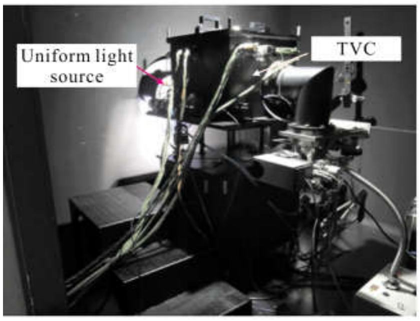


Fig.3 Equipment in the calibration darkroom

3 Calibration results

3.1 Spectral calibration

The relative spectral response of the LLLC is measured by Remote Sensor Calibration Group (RSCG) in BISME. The measuring facility is composed of a halogen light source, double grating monochromator, an off-axis collimator and a reference detector. The reference detector is a silicon detector. The spectral response of the reference detector is traceable to NIM[8].

The relative spectral response of the LLLC is shown in Fig.4. The relative spectral response of the high-light detecting channel is similar with that of low-light detecting channel.

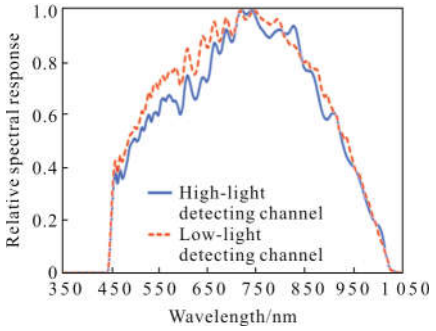
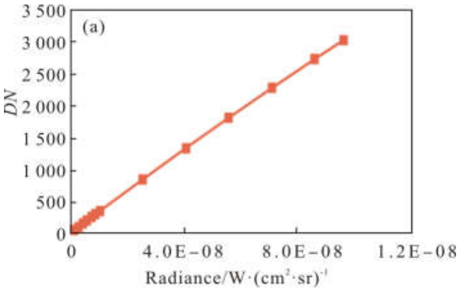


Fig.4 Relative spectral response of the LLLC

3.2 Radiometric calibration

The detector temperature of low-light detecting channel is set at −20℃ in flight for getting good signal to noise ratio (SNR). For avoiding difference between on-ground calibration and on-orbit application, the LLLC is set up in a TVC. The lens of LLLC is used to isolate the ambient environment and the vacuum environment. It's better than taking an optical window on the wall of the TVC as isolation, because an optical window will cause unexpected stray light in calibration.

Figure 5 shows the result of response linearity measurement of the low-light detecting channel at one of the gains of the camera. The output digital number (DN) of camera has removed the dark current output of camera acquired by dark pixel. Then, the absolute radiometric calibration coefficients can be calculated according to Eq.(1).



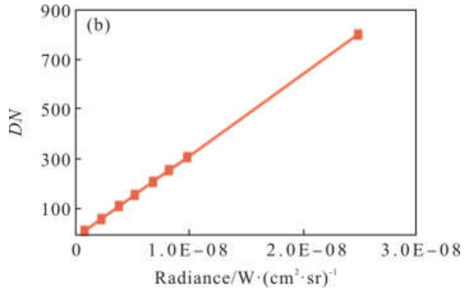


Fig.5 Response linearity of the LLLC

The result of relative radiometric calibration which aims at correcting the differences between responses of pixels is shown in Fig.6.

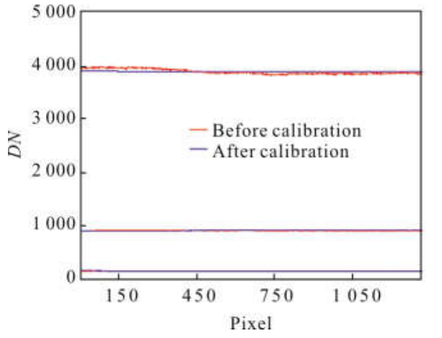


Fig.6 Relative radiometric correction for the LLLC

4 Conclusion

The uncertainty of spectral radiance measurement, reproducibility of the low light level light source output, and stray light are the main errors in radiometric calibration of large dynamic range low light level camera. Uncertainty of spectral radiance is better than 12% by precisely calibrating the transfer relationship between adjacent integrating spheres. The reproducibility of radiometric output of light source is better than 2% by precisely controlling the light energy transferring between adjacent integrating spheres. The stray light in radiometric calibration can be controlled fairly well. The repeatability of relative spectral response measurement is better than 1%. The uncertainty of radiometric calibration for the LLLC achieves 18%(k=2).

The calibration data has been verified in flight. The calibration method for the LLLC is also useful for measuring radiometric performances of general sensor or detector in weak illumination conditions.

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