Infrared Physics & Technology 77 (2016) 51–57

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Regular article

Analysis and modeling of radiometric error caused by imaging blur in optical remote sensing systems

Xufen Xie [a,b], Yuncui Zhang [a], Hongyuan Wang [b,*], Wei Zhang [b]

[a] Research Institute of Photonics, Dalian Polytechnic University, No. 1 Qinggongyuan, Ganjingzi District, Dalian 116034, China
[b] Research Center for Space Optical Engineering, Harbin Institute of Technology, No. 2 Yikuang Street, Nangang District, Harbin 150080, China

HIGHLIGHTS

- We analyze practical implications of radiometric error caused by imaging blur.
- We use an imaging model to analyze the radiometric error caused by imaging blur.
- Error model is used to estimate radiometric error in blurred remote sensing image.
- We determine the optimal parameters of the error model.
- We verify the propose error model by simulations and experiments.

ARTICLE INFO

Article history:
Received 30 November 2015
Revised 10 May 2016
Accepted 10 May 2016
Available online 18 May 2016

Keywords:
Imaging blur
Radiometric error
Stochastic fractal characteristics

ABSTRACT

Imaging blur changes the digital output values of imaging systems. It leads to radiometric errors when the system is used for measurement. In this paper, we focus on the radiometric error due to imaging blur in remote sensing imaging systems. First, in accordance with the radiometric response calibration of imaging systems, we provide a theoretical analysis on the evaluation standard of radiometric errors caused by imaging blur. Then, we build a radiometric error model for imaging blur based on the natural stochastic fractal characteristics of remote sensing images. Finally, we verify the model by simulations and physical defocus experiments. The simulation results show that the modeling estimation result approaches to the simulation computation. The maximum difference of relative MSE (Mean Squared Error) between simulation computation and modeling estimation can achieve 1.6%. The physical experimental results show that the maximum difference of relative MSE between experimental results and modeling estimation is only 1.29% under experimental conditions. Simulations and experiments demonstrate that the proposed model is correct, which can be used to estimate the radiometric error caused by imaging blur in remote sensing images. This research is of great importance for radiometric measurement system evaluation and application.

1. Introduction

For remote sensing data or images, RA (Radiometric Accuracy) of a measurement represents the proximity of the observed signal to the true value, and is therefore, considered to be one of the most important specifications for space-borne instruments [1]. In general, two elementary factors affect the RA: The observed external error and the internal calibration error. The observed external error consists of at least three parts: the measurement noise, the scatter radiation, and the additional incident radiation from adjacent targets caused by the PSF (Point Spread Function) of non-ideal system. And the PSF is regarded as one of the primary uncertainties in the observed signals [2]. The internal calibration error consists of radiometric model error, radiometric calibration experiment error, and the fitting or interpolation algorithm error, etc. Therefore, the internal calibration error is caused by the inexact measurement of the instrument's radiometric response. Conducting radiometric measurements with cameras requires inverting the radiometric calibration equation to solve out the scene radiance. Researchers want to quantify errors of remote sensing imaging instruments by ground calibration. However, the system characteristics are often varying for launching progress and uses. Therefore, calibration cannot reduce these errors, particularly those stemming from imaging blur. As well as the PSF corresponds to imaging blur which

* Corresponding author.
E-mail addresses: xiexf@dlpu.edu.cn (X. Xie), zhang_yc@dlpu.edu.cn (Y. Zhang), fountainhy@hit.edu.cn (H. Wang), wzhang@hit.edu.cn (W. Zhang).

http://dx.doi.org/10.1016/j.infrared.2016.05.010
1350-4495/

is influenced by many factors [3]. Existing researches have suggested that imaging blur is a significant radiometric error factor for imaging systems [4,5]. The radiometric error related to imaging blur has attracted the attention of researchers for a long time. In the 1970s, Steel and Boivin pointed out that diffraction causes radiometric error, and it should be corrected [6–8]. In 2003, Edwards and McCall stated that diffraction produces a higher radiometric error at the long-wave band [9]. In 2005, Parr et al. showed that the diffraction effect substantially influences RA [10]. The aforementioned publications emphasize the analysis of the diffraction effect. In fact, the PSF descripts for the imaging blur, originate from the impact of the platform vibration, atmosphere, optical system, electronics, and so on. Moreover, the imaging blur produced by different factors can be treated as a coupled one. Therefore, it is difficult to analyze imaging blur factors in imaging blur researches. Many researchers have studied on the adjacent effect of PSF in space-borne cameras [2,3]. Du and Voss researched the radiometric error produced by the PSF [11]. The radiometric error resulting from PSF non-uniformity was also observed [12]. At the same time, many types of restoration methods were adopted for spatial resolution and RA [1,2,13]. However, there is still a lack of research on the estimation of radiometric errors caused by imaging blur.

In this paper, we formulate analysis approach for radiometric errors caused by imaging blur. According to the system state analysis on the radiometric errors caused by imaging blur, we propose a standard imaging blur radiometric error estimation technique. A model used in estimating the imaging blur radiometric error based on the stochastic fractal characteristics of remote sensing images was built and we also validated it experimentally. This research is useful for estimating the radiometric error caused by imaging blur in optical remote sensing imaging measurement. It can contribute to the field of radiometric measurement because of its role in enhancing RA and improving system design.

2. Radiometric error analysis for optical imaging system

Radiometric measurement with an imaging system involves a retrieval process through the use of a radiometric calibration model [14]. The radiometric calibration of an image system is also an imaging process. And the imaging target is a radiometric standard source. The imaging process can be described as in Eq. (1):

$$Y_{ij} = Ge_{ij} T_{int} \tau_{eff} \int_{\lambda_1}^{\lambda_2} Le_{\lambda}(x,y) R_{ij}(\lambda) d\lambda \otimes h(x,y) \cdot A_{ij} \left[\frac{\pi \cos^4 \theta_{ij}}{4F^2+1}\right] + Y_{N_{ij}} + Y_{D_{ij}} + N_{ij} \quad (1)$$

where (i,j) is the element number of the detector; (x,y) is scene coordinate corresponding to (i,j), Le is the system entrance radiance; $h(x,y)$ is a PSF of the system; N is the system random noise; Y_N is the digital value of the response to stray radiation; Y_D is the digital value of the system DC response; $R(\lambda)$ is the detecting element responsivity, which expresses the detector response to energy at a unit interval, unit area, and at the wavelength of λ; A is element area of the detector; F is the F number of the optics system; θ is the off axis angle of the detection unit; T_{int} is the integral time; τ_{eff} is the transmittance of the optics system; Ge is the transfer coefficient.

Owing to the characteristics of radiometric calibration, Eq. (1) can be condensed when it describes the system radiometric response. Because of the uniformity and stability characteristics of the radiometric standard source, the radiation source is nearly constant. The energy surrounded by the PSF is considered to be unity in physics. Therefore, the convolution of this constant and the PSF is a constant. The random noise is embodied in the zero exposure level and gain of the system in radiometric calibration. The statistical nature random noise cannot be expressed by the radiometric calibration equation. Furthermore, the difference among individual pixel responses is also eliminated by nonuniformity correction. The response of multi-element detectors in the imaging system is also calibrated assuming uniformity. Therefore, the system imaging model can be condensed to Eq. (2) when it describes system radiometric response:

$$Yc = Ge \cdot A \cdot \frac{\pi \cos^4 \theta}{4F^2+1} \cdot T_{int} \cdot \tau_{eff} \cdot \frac{\int_{\lambda_1}^{\lambda_2} Le(\lambda,T) R(\lambda) d\lambda}{L_0} \cdot L_0 + Y_N + Y_D \quad (2)$$

The last two elements of the equation (i.e., Y_N and Y_D) can be combined and named as Bc to represent the bias of the system. All the rest of the equation can be written as $Gc \cdot L_0$, and Gc represents the gain of the system. Therefore, the system radiometric calibration equation can be described as Eq. (3):

$$Yc = Gc \cdot L_0 + Bc \quad (3)$$

This equation is the linear radiometric calibration model. The response linearity of the system to varying light inputs in the cameras is usually measured during ground calibrations.

The Eq. (3) describes system response characteristics as the Eq. (2), however it weakens the imaging chain factors. Therefore, the parameter Gc and Bc can fluctuate and lead to radiometric error.

The radiometric standard source possesses the characteristics of uniformity and stabilization. The radiometric calibration model just describes the response properties of the imaging system, which is essentially different from the imaging model. This leads to differences between the calibration equation and the actual imaging state and induces systematic errors. The reasons are listed as follows: (i) the system response non-uniformity and random noise cannot be displayed in the radiometric calibration model; and (ii) the radiometric calibration model of the system cannot describe imaging blur because of the uniformity of the radiometric standard source. This means that the radiometric calibration coefficient cannot express the system attenuation to high frequency information, thereby causing the direct radiometric errors of the imaging system. Therefore, the estimating standard of the error should be in accordance with the radiometric calibrated system state. Assuming that the system calibrated state can reflect the actual scene, which produces an ideal image. Thus the hypothetical image of the system calibrated state should be seen as the standard image for error analysis. This standard image has the following characteristics: (i) there is no system response nonuniformity; (ii) there is no imaging blur which can lead to image digital value attenuation at high frequencies; (iii) there is no random noise; and (iv) the standard image is only scaled to the scene and transformed for radiation. It is important to understand that system response nonuniformity, imaging blur, and random noise always exist in multi-element imaging systems and the standard image is an ideal image.

According to the standard image concept, the radiometric error can be estimated by Eq. (4):

$$e_{ij} = Y_{ij} - Ys_{ij} \quad (4)$$

where e_{ij} is radiometric error of the (i,j) pixel, Y_{ij} is the actual system response digital value, Ys_{ij} is the standard image digital value. When Y_{ij} and Ys_{ij} is expanded, the radiometric error can be described as Eq. (5):

$$e_{ij} = G_{ij} \cdot Le(x,y) \otimes h(x,y) + B_{ij} + N_{ij} - Gc \cdot Le(x,y) - Bc \quad (5)$$

where G_{ij} represents gain and B_{ij} is the bias of the (i,j) pixel of the actual system. The Eq. (5) can be further written as Eqs. (6) and (7),

$$\begin{aligned} e_{ij} &= (Gc + \Delta G_{ij}) \cdot Le(x,y) \otimes h(x,y) - Gc \cdot Le(x,y) + (B_{ij} - Bc) + N_{ij} \\ &= [\Delta G_{ij} \cdot Le(x,y) \otimes h(x,y) + \Delta B_{ij}] \\ &\quad + [Gc \cdot Le(x,y) \otimes h(x,y) - Gc \cdot Le(x,y)] + N_{ij} \end{aligned} \quad (6)$$