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RADIOMETRIC CALIBRATION FOR EARH OBSERVATION SATELLITE OPTICAL INSTRUMENT

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Abstract. *On-board optical instrument perform the conversion from incoming radiance to digital image. During the life-time, the instruments may suffer from changing calibration parameters causing degraded image. Radiometric calibration is a key process to ensure the reliable radiance data derived from satellite image. The process aims to compensate for the offsets caused by the dark current and minimize the radiometric non-uniformity of individual pixel of the on-board detector. This paper describes the radiometric calibration for optical instrument on earth observation satellite and demonstrated for VNREDSat-1 data.*

Keywords: optical instrument; optical payload; radiometric calibration; VNREDSat-1.

Classification numbers: 06.20.fb; 07.60.-j; 42.79.-e.

I. INTRODUCTION

Earth observation small satellites are becoming more and more widely used in many important applications. Performing one mission from the “National strategy for Space Technology research and application – 2020”, as well as in the progress of master the technology for manufacture, operation and exploitation of small satellite system, the Vietnam Academy of Science and Technology (VAST) has successfully completed the project: “Vietnam natural resources, environment and disaster monitoring small satellite project” (VNREDSat-1). VNREDSat-1 satellite was successfully launched in 07/05/2013 and equipped with optical payload of 2.5 and 10 meter ground spatial resolutions in panchromatic and multi-spectral bands respectively. The satellite has been functioning reliably and providing a useful source of information for various remote sensing applications such as agriculture, forestry, urban area management, natural resources, environment and disaster monitoring [1]. In order to ensure the image quality of the image products, VNREDSat-1 raw data shall be calibrated to correct and minimize two radiometric parameters: non-uniform gain and offset occurred by the nature of the optical payload, used in VNREDSat-1 satellite. The calibration procedure composes of two main steps: radiometric calibration and geometric calibration. Within this article frame, the structure and operation principle of the optical payload and the radiometric calibration shall be presented.

II. DESCRIPTIONS OF VNREDSAT-1 OPTICAL INSTRUMENT

The optical instrument, embarked on VNREDSat-1 is based on “New Astrosat Observation Modular Instrument” (NAOMI) product line of earth observation optical payload. VNREDSat-1 instrument provides data in four spectral bands consisting of one Panchromatic (PAN) and three multi spectral (MS) with ground sampling distance of 2.5m and 10m resolutions respectively. The optical instrument is based on a push-broom concept with about 1.5° optical Field of View. It is

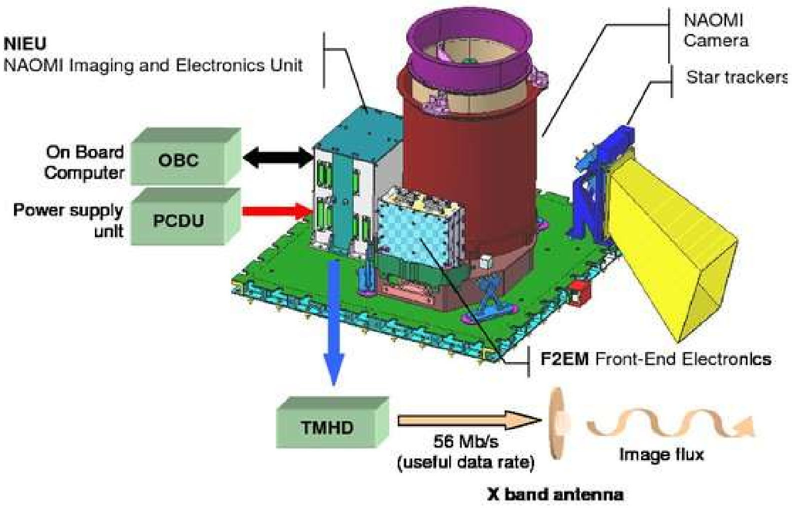


Fig. 1. Overall of NAOMI instrument [2].

capable of capturing square images of 17.5 km × 17.5 km by one 7000 pixel PAN and four 1750 pixel MS detectors from 680 km altitude, which is the orbital height of the satellite above the Earth surface. The row scanning is obtained by the sampling of Time-Delayed-Integration (TDI) linear detector and the column scanning is obtained by the satellite velocity on its orbit. The lightweight and compact optical payload is composed of the camera and its electronics. The camera, core of the instrument, is composed of a telescope, a focal plane embedding the TDI detector together with the optical filters and the video front-end electronics and a main structure interfacing with the satellite and the telescope via iso-static mounting devices. The payload electronics module is composed of analogue video and digital electronics. This electronics acquires the 12 video outputs (8 for PAN channel and 4 for MS channel) from the video front-end electronics module (F2EM) [2].

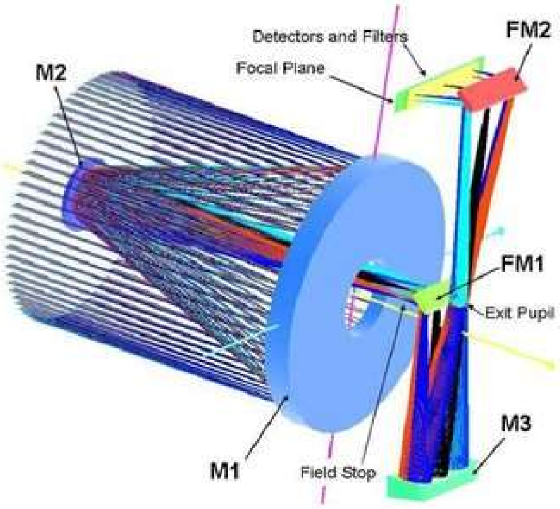


Fig. 2. Optical design of NAOMI Instrument [2].

The optical assembly of NAOMI instrument is based on a Korsch-type telescope including three aspheric mirrors (M1, M2 and M3) and two folding mirrors (FM1 and FM2). The focal plane of the optical instrument presents several key advantages compared to classical CCD based focal plane: use of TDI technology for enhancement of Signal to Noise ratio performances without slewing, availability of 4 MS channels registered with respect to PAN channel thanks to the monolithic structure of the detector, improved and secure radiometric performances through the ability to adjust the effective integration time by modifying the number of active TDI lines, compactness and low power dissipation [2].

The 200 mm pupil aperture, leading to an F-number of F/16, is located on the primary mirror. The optical filtering is ensured by highly integrated filters, including masks to minimize spectral cross-talk. The spectral response of the optical filters is illustrated in the Figure 3.

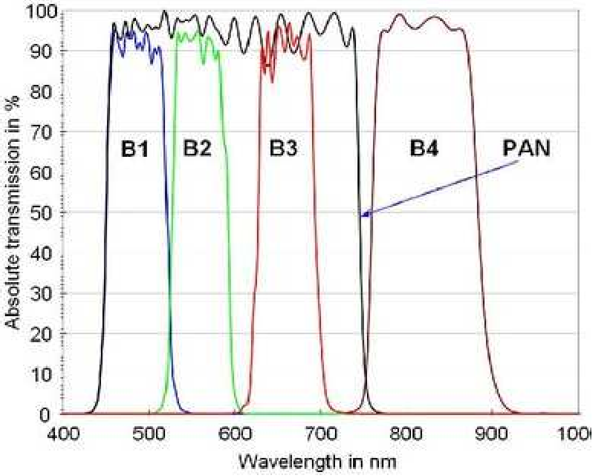


Fig. 3. Spectral response of the NAOMI optical filters [2].

III. RADIOMETRIC FORWARD MODEL

The radiometric model (or forward model) describes the optical and electronic transformation of the signal between detector input and digital number which is stored in the data storage media. Optical aberrations are excluded and treated separately on normalized image. Therefore the radiometric model of the optical payload deals with the transfer from at-sensor radiance level to quantized digital number.

The conversion of radiance at sensor R to digital numbers C is calculated by the radiometric forward equation (1) [3].

$$C(b,p,R(b)) = A(b,p) * R(b) + C(b,p,0) + N(b,p,R(b)) \tag{1}$$

where:

- b: Spectral band (0 for PAN band, 1 to 4 for MS bands),
- p: Image pixel,
- $P(b)$: Number of pixels per band,
- $R(b)$: Mean radiance level of the scene in the b spectral band (in W/(m^2.sr.μm)) ,
- *C(b,p,R(b))*: Output digital number (10 bit quantization level for VNREDSat-1),
- $C(b,p,0)$: Dark current or dark signal equivalent to the digital number output when observing a dark scene,
- $A(b,p)$: Overall radiometric response factor from the input radiance to the output signal,
- *N(b,p,R(b))*: Detector noise,

Assuming the noise is constant for each pixel during image frame transfer, the radiance level at sensor can be estimated:

$$\hat{R}(b) = \frac{C(b,p,R(b)) - C(b,p,0)}{A(b,p)} \tag{2}$$

The dark current $C(b,p,0)$ and radiometric response factor $A(b,p)$ are calculated as follows;

- $C(b,p,0)$: Dark current is considered as an offset of the digital number output and it is defined as output of the payload when observing a dark scene ($R(b)=0$) without the noise term. For satellite optical instrument, $C(b,p,0)$ is obtained by averaging the digital number over a large number of lines recorded in darkness (typically 500 consecutive lines).
- $A(b,p)$: The overall response factor from the input radiance to the output can be considered as two parts: response factor for the specific band ($K(b)$) and relative response factor for each pixel ($\rho(b,p)$). The second part $\rho(b,p)$ is also considered as pixel non-uniformity.

Then the overall response factor $A(b,p)$ is calculated as:

$$A(b,p) = \rho(b,p) * K(b). \tag{3}$$

The radiometric forward equation (1) becomes:

$$\begin{aligned} C(b,p,R(b)) =& \rho(b,p) * K(b) * R(b) + C(b,p,0) + N(b,p,R(b)), \\ \hat{R}(b) =& \frac{C(b,p,R(b)) - C(b,p,0)}{\rho(b,p) * K(b)}. \end{aligned} \tag{4}$$

Based on this radiometric model, the instrument is firstly calibrated on-ground before launch of the satellite to obtain the ground calibration data (initial calibration parameters). On-ground calibration procedure shall be done with nearly perfect dark scene (radiance of 0 W/(m^2.sr.μm)) and nearly perfect uniform radiance scene.

IV. RADIOMETRIC CALIBRATION FOR SATELLITE OPTICAL INSTRUMENT

The objective of the radiometric calibration is to recover the actual radiance ($R(b)$ in Eq. (1)) coming to the detector from the raw data (digital number output of the detector).

According to Eq. (4), in order to estimate the incoming radiance, the following dark current and non-uniformity of the image must be calculated. This creates two steps for radiometric calibration procedure: dark current calibration and pixel non-uniformity calibration. For push-broom instrument, the calibration is performed over a specific numbers of image lines which is captured by linear detector.

IV.1. Dark current calibration

When the satellite is operating in-orbit and calibration is required, dark current image $C(b,p,0)$ is calculated by observing the payload over a very low-radiance areas. These areas can be selected as sea by night.

Assuming that at-sensor radiance, $R \approx 0$ W/sr/μm/m^2, the radiometric model equation becomes:

$$C(b,p(i,j),0) = round(DC(j)), \tag{5}$$

where $p(i,j)$ denote the image pixel i,j denotes the image line and column numbers and *DC(j)* is the dark current or the j^{th} column.

The data captured by the linear detector may suffer from bad quality due to shining objects or spots on the ground which is disregarded during calibration. The bad-pixel is assessed by mean *DC* of the image column:

$$DC_{mean}(b,j) = \frac{1}{nL}\frac{i=1}{nL}C(b,p(i,j)), \tag{6}$$

where nL is the number of lines in image C.

The bad-pixels removal (or filtering of bad pixels) is done by keeping the image lines within absolute deviation threshold. The pixels are selected if the condition (9) is met.

$$\max\left|C(b,p(i,j)) - DC_{\text{mean}}(b,j)\right| \leq a. \tag{7}$$

Dark current is computed for on “good” pixel set $\blacksquare_{DC}$

$$\tilde{C}(b,j) = \frac{1}{nL_{\Omega}} \sum_{i \in \Omega_{DS}} C(b,p(i,j)), \tag{8}$$

where nL_{Ω} is the number of good pixel lines

In reality, the satellite images are of large area with huge amount of pixels, therefore block-by-block is recommended for computation and processing. Additionally, several images over the same area with similar imaging conditions can be used for dark current calibration, and the results are obtained by weighted mean.

IV.2. Pixel response non-uniformity (PRNU) calibration

PRNU calibration is done to compensate for non-uniformity of individual detector pixel. This is due to the different radiometric response factors on detector elements. Therefore, the instrument shall image over a high-radiant homogeneous area such as dessert or pack ice.

Assuming homogeneous area with constant radiance: $R(b) = R$

The radiometric model equation is derived as:

$$C(b,p(i,j),R) = round(K(b) \times PRNU(j) \times R + DC(j)) \approx K(b) \times PRNU(j) \times R + DC(j). \tag{9}$$

Firstly, the mean line is computed:

$$C_{mean}(b,jR) = \frac{1}{nL}\sum_{i=1}^{nL} C(b,p(i,j),R) - \tilde{D}C(j), \tag{10}$$

where nL is the number of lines in image S.

On the other hands, C_{mean} for j^{th} column is derived from (11):

$$C_{mean}(b,j,R) \approx K(b) \times R \times PRNU(b,j) \tag{11}$$

Thanks to homogeneous imaging, the expression ($K(b) \times R$) contains only low frequency and measured on ground and does not evolve during lifetime. Whereas, $PRNU(b,j)$ contains both low frequency (LF) and high frequency (HF) elements.

$$PRNU(b,j) = PRNU_{HF}(b,j) \times PRNU_{LF}(b,j) \tag{12}$$

In order to filter the low frequency parts, high-pass Gaussian filter is used:

$$Gauss(j) = \frac{1}{2\pi\sqrt{\sigma}} \exp?\left(-j^2/(2\sigma^2)\right), \tag{13}$$

where σ represents the width of the filter and the cut-off frequency is $(1/3\sigma)$.

The low frequency term is obtained by convolution with the Gaussian filter:

$$LF(j) = C_{mean}(b, j, R) * Gauss(j). \tag{14}$$

The high frequency part of PRNU is then:

$$PRNU_{HF}(b, j) = \frac{C_{mean}(b, j, R))}{LF(j)} \tag{15}$$

The LF part of PRNU from the PRNU is calculated using the same Gaussian filter:

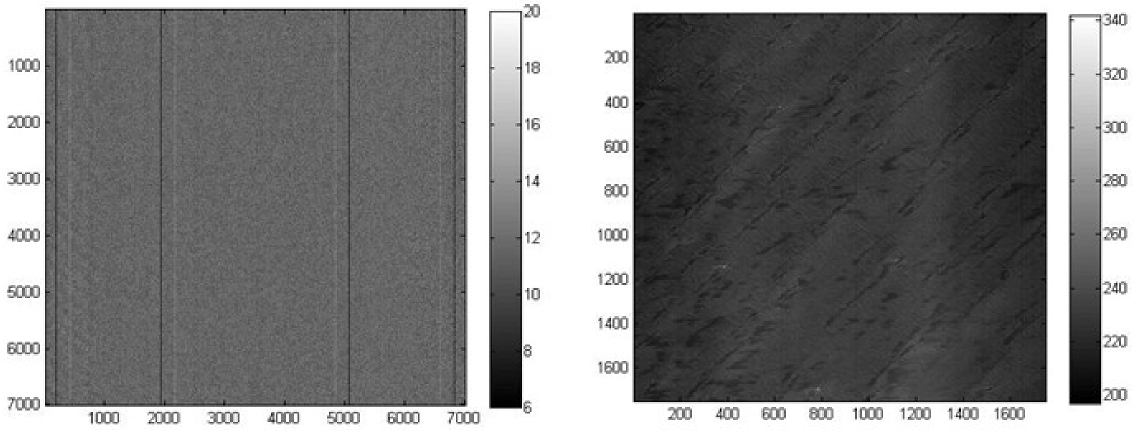
$$PRNU_{LF}(b, j) = PRNU_{ground}(b, j) * Gauss(j) \tag{16}$$

where the $PRNU_{ground}$ is the on-ground instrument calibration data and provided by the instrument vendor.

Finally, $PRNU$ is then computed by Eq. (12).

V. SIMULATION

The calibration method mentioned in Section IV has been simulated by utilizing VNREDSat-1 satellite data. The aims of the simulation are to calculate the dark current and PRNU from captured image. The data chosen for dark current calibration are VNREDSat-1 image over Atlantic and Pacific Ocean during night time to ensure the very low incoming radiance at the payload (dark images). On the other hands, in order to ensure the uniform surface, satellite images over Lybia and Algeria desert are selected for PRNU calibration. All of these images are captured by VNREDSat-1 satellite in 2017 during clear weather (almost no cloud).



(a) (b)

Fig. 4. Sample VNREDSat-1 images used for radiometric calibrations:(a) Atlantic ocean image for dark current calibration; (b) Lybia desert image for PRNU calibration.

MATLAB tool has been developed and consists of two modules to compute the dark current and PRNU for VNREDSat-1 images utilizing the radiometric model and calibration method described in section III and IV . The inputs composes of panchromatic and multi-spectral images.

The output are the detector relative gain (calculated from PRNU) and dark current values for every single pixel on each band of the on-board detector. These are stored in calibration parameter file (CPF) which will be used for futher image processings.

Some simulation results

Dark current (calculated from image over atlantic ocean)

The DC of the VNREDSat-1 image has been calculated by the MATLAB tool and the outcome for each column are generated.

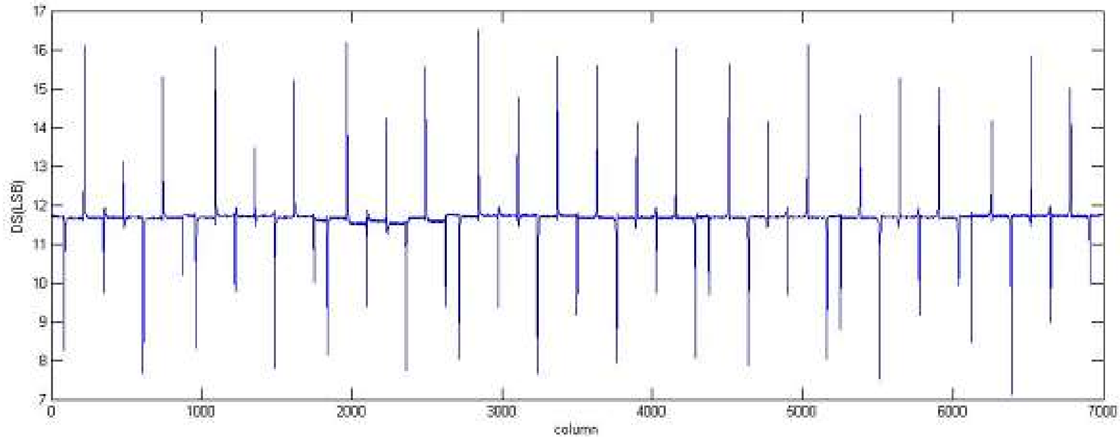


Fig. 5. VNREDSat-1 Dark current (the plot has been scaled up for easy visualization).

The spikes appear in the plot is due to the TDI coupling effect of the detector.

Pixel response non-uniformity (calculated from Lybia image)

PRNU is performed for Panchromatic band using image over Lybia desert to guarantee the uniformity of the observation. High-pass Gaussian filter is used to remove the low frequency parts. Image over Lybia desert reveals some dune of sand, therefore σ=100 is chosen empirically to fit with the actual surface of the scene.

The first plot shows the PRNU for PAN channel calculated from the images. The high-pass Gaussian filter is used to separate the low frequency parts of the PRNU, which is the radiance variation due to the sand dunes and depicted in the second plot. The third plot illustrates the PRNU for PAN channel after removing the low frequency parts. However, this filtering also removes several low frequency parts of the PRNU which are not coming from the sand dune radiance variation. Therefore, we need to add the low frequency part of the PRNU measured on ground from the instrument on ground calibration data to acquire the final PRNU.

The process is performed in the same approach for the other multispectral bands.

Practically, the calculated PRNU values shall be compared with the previous calculated PRNU. If the difference is higher than 5%, the PRNU values shall be updated in the calibration files.

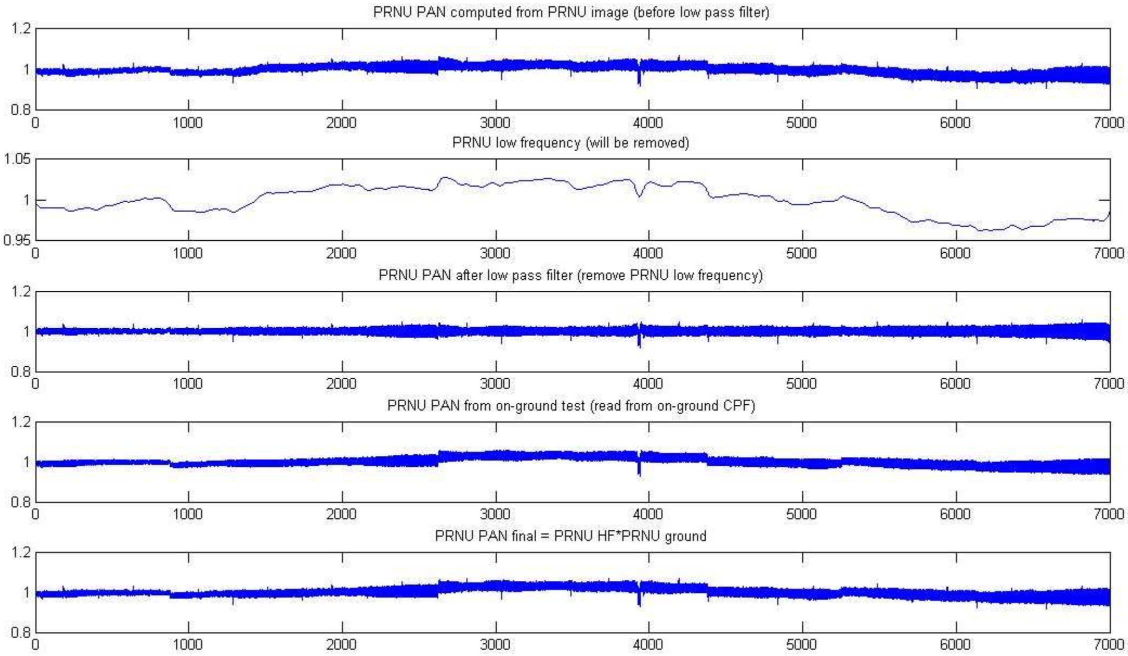


Fig. 6. VNEDSat-1 PRNU calculation for Panchromatic band.

VI. CONCLUSION

The approach of radiometric calibration for optical instrument for earth observation satellite has been presented. It consists of dark current (DC) and pixel response non-uniformity (PRNU) calculation from the satellite images with some specific requirement for the surface darkness and uniformity. The calibration has been applied for VNREDSat-1 satellite data by calculating dark current over Atlantic Ocean and PRNU over Lybia desert. The parameters shall be updated if the outputs are higher than a pre-defined threshold. Other related topics of interest are bad pixel removal in dark current calibration and high-pass Gaussian filter in PRNU calculation. These should be further improved to acquire better accuracy and reliability of the radiance level reaching the optical instrument.

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