SENSOR LETTERS
Vol. 10, 1–7, 2012

In-Situ Calibration of Relative Reflectance for Visible/Near-Infrared Imaging Spectrometer

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(Received: 30 June 2011. Accepted: 20 September 2011)

Nowadays, the field calibration of the ground-based imaging spectrometer mainly relies on the standard reference panel (white or gray panel). It does not meet specific test requirements when the imaging spectrometer is used for multi-angle and multi-scale trails in the field. To solve this problem, the current study attempts to seek a rapid and stable calibration method of relative reflectance. The visible/near-infrared imaging spectrometer (VNIS) is employed to probe the calibration method. The VNIS is composed of a Hamamatsu C8484-05G camera, a V10E spectrograph, a 1.9/35 mm C-mount zoom lens, and a mirror scanner. The V10E spectrograph has a slit size of 30 μm by 14.3 mm and can collect hyperspectral imagery in the wavelength range of 400–1000 nm with a spectral resolution of 2.8 nm. When VNIS was used to collect digital number values of reference objects (blue cloth, green cloth, gray cloth, black cloth, and gray reference panel) under natural sunlight, the ASD FieldSpec®3portable spectrometer (ASD) was also synchronously utilized. A linear relationship was established through the gathered data of reference objects from VNIS and ASD, and the calculation formula of relative reflectance was proposed according to the reflectance inversion formula after applying the transformative radiation correction formulas. A new field calibration method was presented based on the digital number values. The method can meet the requirements of reflectance inversion of hyperspectral imaging data by comparing the reflectance curves that came from VNIS and ASD.

Keywords:

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1. INTRODUCTION

With the intensive research on quantitative remote sensing in recent years, centimeter or even millimeter spatial resolution hyperspectral imaging data have been urgently needed to solve the mixed pixel problem due to different objects, and provide reliable ground data support for research on aerospace or aviation scale. At the same time, to explore the best observation method for utilizing multi-angle remote sensing to investigate the hot spot effect of ground objects, the development and application of ground-based imaging spectrometer have emerged and also obtained many research results.[1–4]

In the quantitative study of hyperspectral imaging data, the relationship of the electromagnetic signals received by the imaging spectrometer and non-imaging spectrometer and the physical characteristics of ground objects were required for analysis and application; hence, the calibration of imaging spectrometer is indispensable. The calibration consists of laboratory calibration and field calibration. The former is conducted under ideal laboratory conditions. Laboratory calibration mainly solves the calibration of wavelength position, radiation accuracy, and spatial positioning of the hyperspectral imaging spectrometer. Field calibration aims to draw the exact physical parameters of different objects from hyperspectral images. The field calibration of reflectance inversion must be done to the hyperspectral imaging spectrometer. Field calibration is the calibration of relative reflectance, which needs to select the radiometric calibration sites or reference objects, and is realized through the simultaneous measurement of ground targets when the hyperspectral imaging spectrometer oper-

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 1546-198X/2012/10/001/007 doi:10.1166/sl.2012.1845

ates under normal conditions. The commonly used field calibration methods of relative reflectance can be divided into two categories: (1) Field calibration for aerial spectrometer. John Schott[5] placed cloths of different colors on the ground and performed field correction of reflectance inversion on the Airborne Visible Infrared Imaging Spectrometer. Wan et al.[6] chose the pool and cement ground as reference objects, and performed the field calibration of reflectance inversion on the Operational Modular Imaging Spectrometer. These methods artificially placed reference objects or selected different ground objects as the standard. (2) Field calibration based on near-ground hyperspectral imaging spectrometer. Monteiro et al.,[7] Ye et al.,[8] and Tong et al.[9] Synchronously acquired the data of the standard white panel using the Imaging Spectrometer and ASD FieldSpec®3portable spectrometer, and completed the reflectance inversion of target objects through the radiometric calibration formula. This method used the standard reference panel (white or gray panel) as the calibration object. In this paper, visible/near-infrared imaging spectrometer (VNIS) was used to collect the plant information on the ground; thus, the effect of light in the atmospheric radiation transfer was not considered. Referring to the method of reflectance inversion in (2), when VNIS was used to observe ground objects from the vertical direction, the standard reference panel can be placed in the field of view. When observing from a multi-angle, the reference panel cannot be placed within the view field because the limitation of view field for VNIS. Therefore, a more efficient and effective field calibration method is required to solve reflectance inversion for VNIS. This work referred to aviation and ground-based calibration methods, and attempted to establish the linear relationship between digital numbers of imaging and non-imaging spectrometer (under the natural sunlight), and then converted reflectance of hyperspectral imaging data according to a new calibration formula. That aims to provide meaningful exploration for field calibration of ground-based visible/near-infrared imaging spectrometer.

2. INSTRUMENTS AND METHODS

2.1. Instrument Introduction

The visible/near-infrared imaging spectrometer (VNIS) consists of a Hamamatsu C8484-05G camera, a V10E spectrograph, a 1.9/35 mm C-mount zoom lens, and a mirror scanner (Fig. 1). The Hamamatsu C8484-05G is a high spectral resolution digital camera. The V10E spectrograph has a slit size of 30 μm by 14.3 mm, and can collect hyperspectral imagery in the wavelength range of 400–1000 nm with a spectral resolution of 2.8 nm. Together with the mirror scanner, the Hamamatsu C8484-05G collects the images in a push-broom manner and generates hyperspectral image cubes with effective pixels of 1344 (spatial axis) by 1024 (spectral axis). The angular field view of the

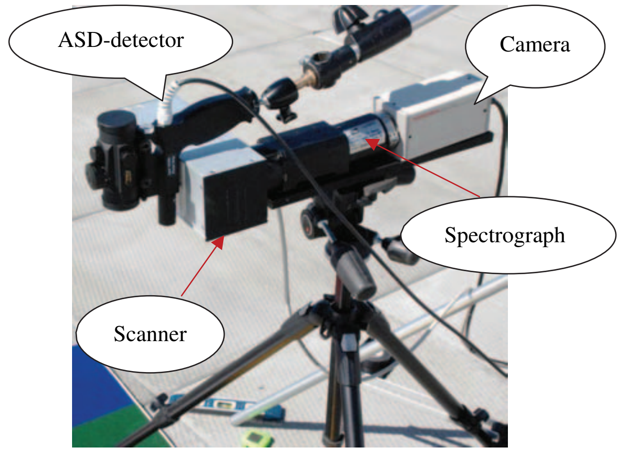

Fig. 1. The components of visible/near-infrared imaging spectrometer.

imaging spectrometer is 14° (horizontal) by 11° (vertical) by 18° (diagonal). The performance parameters are listed in Table I.

The ASD FieldSpec®3portable spectrometer (Analytical Spectral Devices Inc., Boulder, Colorado, USA) was employed to calculate and calibrate the apparent reflectance of the imaging spectrometer. For ASD, its wavelength region is 350–2500 nm and with 25° field of view. Its spectral resolution is 3 nm from 350 nm to 1000 nm and the spectrum sampling interval is 1.4 nm, but its spectral resolution is 10 nm and spectrum sampling interval is 2 nm from 1000 nm to 2500 nm. In the present paper, the ASD wavelength was interpolated to the sampling interval of the imaging spectrometer.

2.2. Common Field Calibration Methods

Reflectance spectra measured under solar illumination are strongly modified by the absorbing molecules in the atmosphere.[10] To identify the division of the target signal as the reference, all multiplicative parameters are radioed out. Nevertheless, diffuse illumination, scattered light of the instrument, the measurement equipment, and the persons doing the measurement may significantly influence the total measured signal (Goetz et al., 1997). Reflectance measurements of homogenous ground targets, at the scale of imaging sensors, can be used to model at sensor radiances for vicarious calibration experiments. In addition,

Table I. Key performance parameters of Spectrometer.

	The key parameters
Spectrum range	400∼1000 nm
Spectrum resolution	2.8 nm
Spatial resolution	≥ mm
Sampling interval	2.4 nm
Pixel dimension	6.45 μm × 6.45 μm
FOV	14° (horizontal) × 11° (vertical) × 18° (diagonal)
Image resolution	1344 (spatial) × 1024 (spectrum)

they can be used to compile spectral libraries of known endmembers for spectral unmixing applications, and reference objects for further comparison.[12] Field calibration of imaging spectrometer is used to build a quantitative relationship between the output signal of each detector unit of spectrometer and the actual ground objects radiation corresponding to each unit. It is the key to quantifying remote sensing information.[13]

The commonly used field calibration methods of relative reflectance are expressed as Eqs. (1) and (2).

$$\mathrm{Ref}_{\mathrm{target}} = \frac{\mathrm{DN}_{\mathrm{target}}}{\mathrm{DN}_{\mathrm{panel}}} * \mathrm{Ref}_{\mathrm{panel}} \quad (1)$$

$$\mathrm{Ref}_{\mathrm{target}} = \frac{\mathrm{Rad}_{\mathrm{target}}}{\mathrm{Rad}_{\mathrm{panel}}} * \mathrm{Ref}_{\mathrm{panel}} \quad (2)$$

where $\mathrm{Ref}_{\mathrm{target}}$ and $\mathrm{Ref}_{\mathrm{panel}}$ represent the reflectance of target objects and standard reference panel, respectively; $\mathrm{DN}_{\mathrm{target}}$ and $\mathrm{DN}_{\mathrm{panel}}$ pertain to the digital number of target objects and standard reference panel, respectively; and $\mathrm{Rad}_{\mathrm{target}}$ and $\mathrm{Rad}_{\mathrm{panel}}$ indicate the radiance of target objects and standard reference panel, respectively. In the current study, reflectance values are multiplied by 100, and expressed as Ref(%).

$$\mathrm{Rad} = a * \mathrm{DN} + b \quad (3)$$

$$\mathrm{Rad} = \frac{(\mathrm{DN} - \mathrm{Noise})}{\mathrm{Gain}} \quad (4)$$

In Eqs. (3) and (4), Rad represents the radiance of each spectral band of imaging spectrometer; DN indicates the digital number outputted when imaging spectrometer scanned ground reference objects; coefficient a shows the gains of the spectrometer under fixed integration time; intercept b means the offset of the spectrometer; Noise represents the dark current of the spectrometer itself; and Rad is short for Radiance. Its unit is $\mathrm{W} \cdot \mathrm{cm}^{-2} \cdot \mathrm{sr}^{-1} \cdot \mathrm{nm}^{-1}$.

3. PRESENTATION AND APPLICATION OF REFERENCE OBJECT-BASED FIELD CALIBRATION

3.1. Experimental Design

Two experiments were designed to calibrate relative reflectance of VNIS. Experiment 1 was carried out on April 19, 2011 in the State Precision Agriculture Research and Demonstration Base of Xiaotangshan town of Changping district in Beijing (40.18°N, 116.27°E). The research on VNIS field calibration was conducted using ASD. Selected blue cloth, green cloth, gray cloth, black cloth, standard white panel, and standard gray panel were used as calibration reference objects, and one data collection was completed every 1 h. The imaging spectrometer was placed on the 5, 10, 15, and 20 meter aerial platform, and hyperspectral images of wheat were acquired at the jointing stage under different scales. The aim was to verify the feasibility of field re-calibration using gray and black cloth. During the experiment, the weather was cloudless and breezy. The calibration time was from 10:00 am to 4:00 pm.

Experiment 2 was performed on May 1, 2011 at the Beijing Academy of Agriculture and Forestry (39.93°N, 116.27°E). The photosynthetic characteristics of different C3 and C4 plants were determined from 9:00 am to 5:00 pm using the hyperspectral imaging spectrometer and fluorescent spectrometer. Data were collected at 1 h intervals.

3.2. The Application of Common Field Calibration Methods

3.2.1. Panel-Based Field Calibration

The relative reflectance calibration of the ground-based imaging spectrometer requires a white panel as the reference standard. It is similar to the field calibration of non-imaging spectrometer ASD,[14, 15] in placing the standard white or gray panel within the view field of the imaging spectrometer, adjusting the exposure time of the spectrometer, and completing the image acquisition of target objects and standard reference panel (Fig. 2).

According to Formula (1), if the $\mathrm{Ref}_{\mathrm{panel}}$ and $\mathrm{DN}_{\mathrm{panel}}$ of standard gray panel and the $\mathrm{DN}_{\mathrm{target}}$ of target objects were measured by ASD, then the $\mathrm{Ref}_{\mathrm{target}}$ of target objects can be calculated. The same results were also obtained by Formula (2). For Formulas (1) and (2), $\mathrm{Rad}_{\mathrm{panel}}$ and $\mathrm{Rad}_{\mathrm{target}}$ only denote radiance of targets, and $\mathrm{DN}_{\mathrm{panel}}$ and $\mathrm{DN}_{\mathrm{target}}$ pertain to the digital number of targets. The results are shown in Figure 3.

3.2.2. Based-Radiance Field Calibration

Field calibration is indispensable for imaging spectrometer. Otherwise, it is difficult to ensure the accuracy of

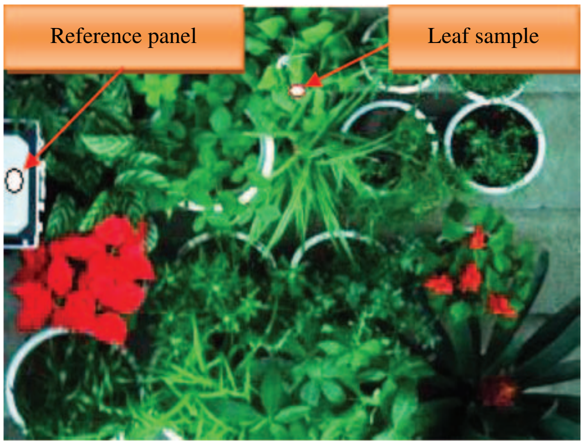

Fig. 2. Panel-based field calibration procedure.

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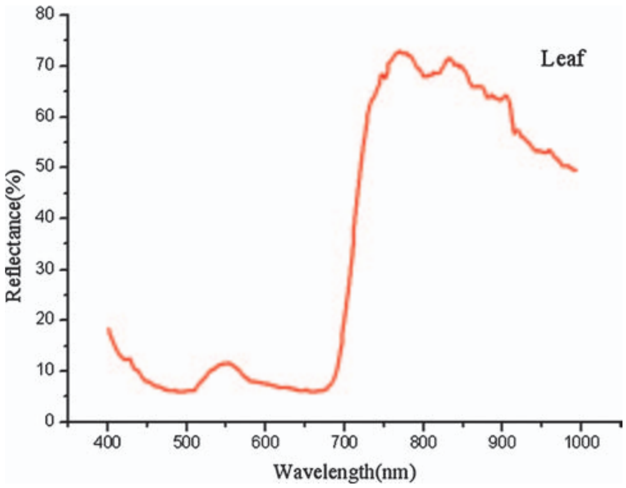

Fig. 3. Panel-based reflectance calibration.

imaging data and satisfy the needs of quantitative analysis. Radiation calibration was used in the current study to perform reflectance inversion by acquiring the radiance of the standard gray panel using ASD when the solar radiation energy was the strongest and the weakest (10:00 am and 5:00 pm, respectively) in the same day. The DN values of the standard gray panel were earned by VNIS twice. Figure 4 represents the initial DN_{panel} of the standard gray panel at 10:00 am and 5:00 pm, respectively. According to Formula (3), if the Rad_{panel} and DN_{panel} of the standard gray panel are known, the corresponding coefficient a and intercept b can be calculated. The Ref_{leaf} of target leaf also can be obtained by combining it with Formula (2). If the DN_{panel} and Rad_{panel} of the standard gray panel and the Dark Noise of the spectrometer are known, the gains can be obtained at different times according to Eq. (4). The Rad_{leaf} of target leaf can be calculated combining with Formula (2). Figure 5 shows the results of Formulas (3) and (4) after correction.

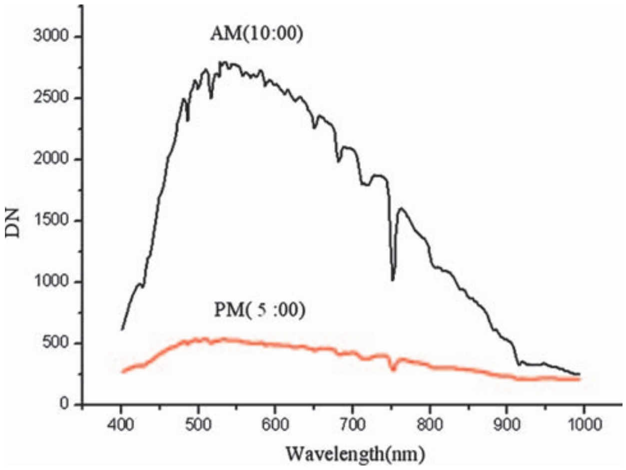

Fig. 4. DNs of panel at different times.

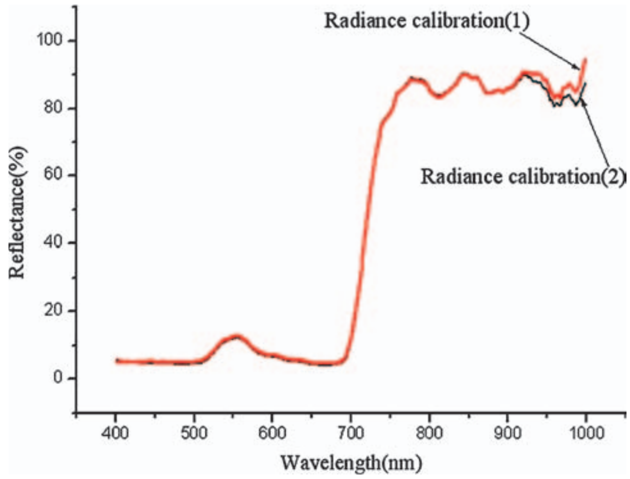

Fig. 5. Results of different radiance calibration methods.

3.3. Reference Object-Based Field Calibration

3.3.1. Choosing Reference Objects

The field calibration of the ground-based VNIS was required in the study. The purpose was to convert multi-angle crop DN information to relative reflectance with physical meaning and to apply it in the quantitative analysis of physiological and biochemical parameters. Referring to the field calibration methods of the relative reflectance and spectrum response characteristics of crops, which have been investigated locally and overseas, the standard white panel was selected as relative white body, and black cloth was selected as relative black body. The green cloth, blue cloth, and gray cloth were also regarded as calibration reference objects to highlight the crop characteristics with the blue peak at 450 nm, the green peak at 550 nm, and the red edge locating 680–750 nm (Fig. 6). A wide range of saturated pixels appeared in the imaging data when using standard white panel to adjust the spectrometer integration time. If the inputted light of the spectrometer was turned down, the acquired lower crop spectral information was too weak. It cannot satisfy the real-time detection of the middle and lower growth information of the crops; hence, the standard white panel was unsuitable for adjusting VNIS integration time. Thus, when using standard gray panel to adjust the spectrometer integration time, it not only guaranteed the better middle and lower spectral information of the crops but also failed to saturate the pixels. This met the purpose of the experiments maximally. Green cloth, green cloth, gray cloth, black cloth, and gray panel were used as calibration reference objects.

3.3.2. Presentation of Reference Object-Based Field Calibration

According to Formula (4), if the DN_{VNIS}, Rad_{panel} of the standard gray panel, and Dark Noise from VNIS are known, the gains can be obtained at different times. When

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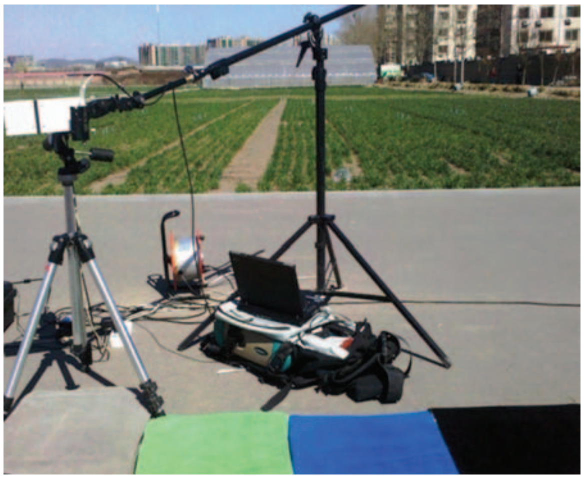

Fig. 6. Reference objects of field calibration.

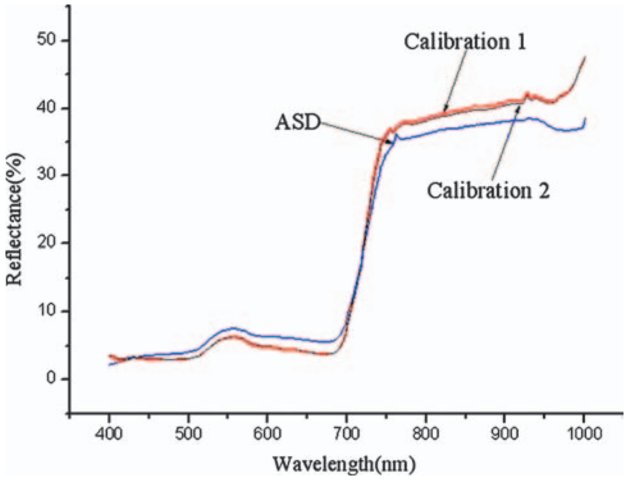

Fig. 7. Calibration results of reference objects.

data are synchronously acquired by ASD and VNIS, the solar irradiance can be regarded as constant, and the Ref_{target} of target objects is calculated using Formula (2). Formula (5) was derived from Formulas (2) and (4), and it was a transformative formula for calculating the reflectance of target objects. For Formula (5), DN_{target}, Dark Noise, and Ref_{panel} are known; hence, the DN values of the standard white panel need to be measured to calculate the reflectance of target. The DN values need to establish a linear relationship between them for calculating the reflectance of target objects if DN values are acquired synchronously by ASD and VNIS as described in Formula (6). A linear relationship between DN values of ASD and VNIS was established, and the target reflectance was calculated. Figure 7 shows the results of the wheat group reflectance spectra. Calibration 1 represented the results generated by the gray panel and four reference cloths. Calibration 2 indicated the calculation results of gray cloth and black cloth. The difference between them was not obvious from the curves. The DN_{wheat} of wheat groups within the VNIS view was determined synchronously using ASD. According to Formula (1), the results after reflectance calculation were shown as the ASD curve in Figure 7.

$$\mathrm{Ref}_{target} = \frac{(\mathrm{DN}_{target} - \mathrm{Noise})}{(\mathrm{DN}_{VNIS} - \mathrm{Noise})} * \mathrm{Ref}_{panel} \qquad (5)$$

$$\mathrm{DN}_{VNIS} = \frac{\mathrm{DN}_{ASD} + B}{A} \qquad (6)$$

3.3.3. Application of Reference Object-Based Field Calibration

When VNIS was placed on the ground to investigate the growth change of crops (0.5–3 m), the reflectance calculation can be done using Formulas (1) to (6). Although it was used at aerial platforms (5–50 m), there were many constraints because the standard gray panel was selected as the calibration object. For example, the mechanical damage probability of the standard gray panel increased and the movement was inconvenient. To address this problem, gray cloth and black cloth were chosen as calibration objects because they were not only cheap and easy to move but could also meet the requirements of reflectance calibration. Figure 9 shows the results of reflectance calibration in wheat groups, when the VNIS was placed on a platform with a 15 m height. Analysis of the relative reflectance curve of field calibration indicated that the requirements of the quantitative remote sensing analysis were met fully.

3.4. Comparison and Analysis Between General and New Field Calibration Methods

Whether general standard reference panel or cloth-based methods were used for field calibration of imaging spectrometer, a better reflectance curve was obtained. However, for reflectance curves in the 900–1000 nm region, the reflectance values of near-infrared bands decreased gradually due to the weak spectral response signals in this range. For the radiometric calibration methods (1) and (2) using the standard reference panel, the near-infrared band signals also became weak, but the decrease trend was less obvious than directly placing on the reference panel. The calculation of the correction method (1) was based on the empirical linear method, whereas the correction (2) was calculated after the dark current removal of the spectrometer. The differences between the two methods in the visible bands were not significant, but the differences in the near-infrared bands (900–1000 nm) were obvious. The spectral response signals became weak in the near-infrared bands (900–1000 nm), and this was a common phenomenon for the imaging spectrometer.[16] Comparing different field calibration methods, such as placing the standard reference panel in the view field, radiometric calibration method

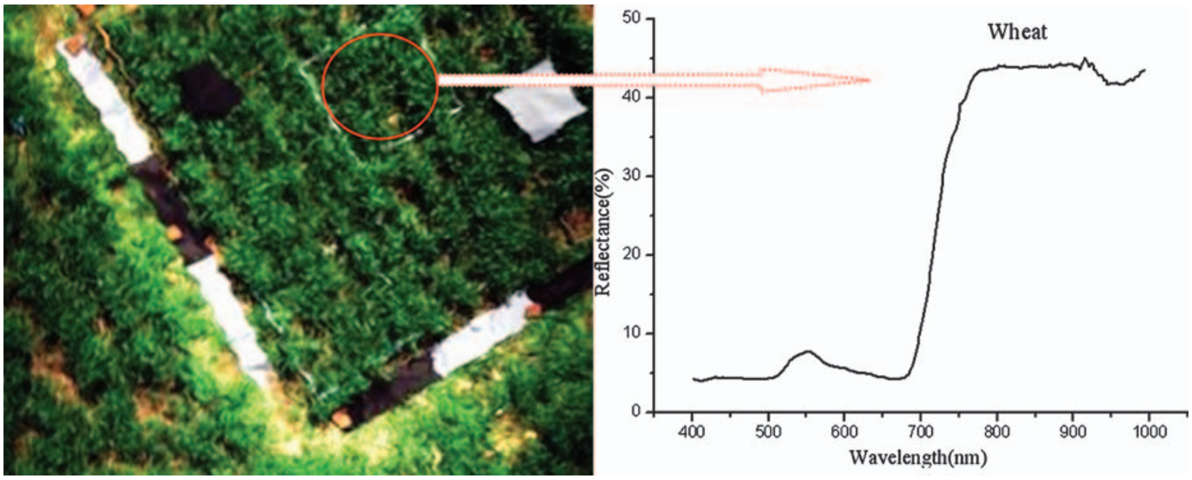

Fig. 8. Field calibration based on gray and black cloth. Results of field calibration based on gray and black cloth.

based on the standard reference panel, and linear correction method based on different reference cloths, the relative reflectance calculated by linear correction method using different reference cloths was observed to contain a better reflectance curve. The result was nearly similar to the reflectance curve of *in-situ* ASD. It demonstrated that this method can meet the requirements of imaging spectrometer field calibration. Analysis of the reflectance calibration results of different reference cloths suggested that the reflectance curve calculated by blue cloth, green cloth, gray cloth, black cloth, and standard gray panel was nearly similar to that of gray cloth and black cloth. There was a difference in the near-infrared bands. It demonstrated that gray cloth and black cloth could also satisfy the requirements of field calibration. Figure 8 shows the calibration results, and proves the feasibility of calibration using gray cloth and black cloth.

4. DISCUSSION

The purpose of relative reflectance field calibration for the imaging spectrometer is to establish the quantitative relationship between the outputted DN values by each detection element of spectrometer and the corresponding exported radiation. The reliability and the depth and breadth of application largely depend on the accuracy of calibration for remote sensing data. Only after calibration to hyperspectral remote sensing data can the real physical parameters of ground object be extracted from remote sensing images. The hyperspectral remote sensing data of different regions and different times can be compared, and the hyperspectral data from different remote sensors and spectrometers and even the computerized simulation can be compared and analyzed.[17] The field calibration of relative reflectance for imaging spectrometer plays an important role in the application and analysis of the quantitative remote sensing.

Compared with several field calibration methods mentioned in the current paper, the real-time calibration methods based on standard reference panel were found to be easy to operate. With the research requirements of the imaging spectrometer under ground-based, multi-angle and different scales, placing a standard reference panel within the view field had many operational deficiencies. For example, it may cause mechanical damage to the standard reference due to repeated movement and collision. The placing height was also a problem. Operating the field calibration based on reference cloths was relatively complicated. However, the linear relationship between imaging spectrometer and field spectrometer can be established using the DNs determined at different times (when the light was the strongest and the weakest). When imaging data were determined by imaging spectrometer under different scales and angles, ASD can be placed near the test site for the real-time data acquisition of standard white panel. To improve data accuracy, appropriately sized gray and black cloths can be placed within view field for field re-calibration. The field calibration results using cotton cloth with different colors were consistent with the determination results by ASD. The reflectance conversion requirements of the imaging spectrometer were satisfied. The field calibration using gray and black cloths again validated the feasibility of the new method.

The research on field calibration of relative reflectance not only considered the influence of reference objects, such as the selection of standard reference panel and different calibration objects, but also the calibration requirements of different tests. For example, it was not possible to place the reference panel within the view field when the multi-angle experiments were conducted. For a multi-scale study, gray and black cloths can be placed for field re-calibration when the DN of the standard white panel was acquired in real-time by ASD. Differences in solar irradiance at different times were also considered, such as the acquisition of light intensity when light was the strongest and the weakest. All

RESEARCH ARTICLE

these demonstrated the feasibility of the field calibration of relative reflectance based on different reference cloths.

5. CONCLUSION

The field calibration of relative reflectance was researched for VNIS in the paper. It provided meaningful exploration to convert DNs to reflectance data of imaging spectrometer. Comparing the results of different calibration methods, the following conclusions can be drawn:

(1) Inspired by general field calibration for spectrometer, that is, radiation correction methods based on placing standard reference panel within view field and standard reference panel, a new field calibration method based on different reference cloths was proposed. Formulas (5) and (6) were the calibration formulas which can satisfy the requirements of reflectance calibration of imaging spectrometer; the premise was to ensure the same solar irradiance.

(2) Comparing different field calibration methods, such as placing the standard reference panel within the view field and radiometric correction methods based on the standard reference panel and field calibration based on different reference cloths, the relative reflectance calculated by the field calibration based on different reference cloths was found to have a better spectral curve. The calculated reflectance was nearly similar to the reflectance obtained by ASD. The proposed method can therefore meet the field calibration requirements of the imaging spectrometer.

Acknowledgments: This work was subsidized by the China Special Funds for Major State Basic Research (Project Number: 2007CB714406, 2011CB311806), Beijing Natural Science Foundation (Project Number: 4092017).

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