Multi-Band Spectrum Camera (MBSC) for Automatic Fixed-Point Reflectance Image Collection in a Crop Field

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Abstract: Here we describe the configuration and operation of a field-use digital imaging system (multi-band spectrum camera, MBSC) that captures images in two spectral bands in the visible and near infrared wavelength ranges, and automatically converts and stores data as reflectance factor (RF) images. The instrument consists of a weatherproof camera unit, a skylight sensor and a PC and hard disc for a control unit. The camera unit has two industrial use digital camera boards attached with interference band-pass filters and objective lenses. The skylight sensor has light detectors equipped with band-pass filters identical to those used in the camera unit. The system is designed to collect images in each band and convert data into RF using the skylight intensity at prescheduled times. The MBSC has potential to automatically monitor agronomic variables in fields up to several hundred square meters.

Key words: Digital image, Multiband, Reflectance factor, Rice paddy.

Digital cameras have been widely used for assessments of crop nutrition and/or stress status, biomass and growth stages (e.g., Adamsen et al., 1999; Purcell, 2000; Matsuda et al., 2003; Jia et al., 2004; Ku et al., 2004; Casadessus et al., 2007; Takemine et al., 2007; Crimmins and Crimmins, 2008). Although most applications have been restricted to the periodic collection of color images with ordinary hand-held digital cameras, several authors have used digital cameras equipped with near infrared band-pass filters (e.g., Omine, 2007; Okada and Ikeba, 2008; Sakamoto et al., 2010). Technological developments, such as improved sensitivity and camera calibration with solar illumination, allow the continuous collection of narrow-band spectral reflectance data. We developed a dual-band digital image collection system (PDC: portable dual-band digital camera, Kimura Oyo Kogei, Inc., Saitama, Japan) that measures the daily-averaged reflectance factor (DARF) in the visible red (RED) and near infrared (NIR) bands (Shibayama et al., 2009). The system acquires radiometric data for models of nitrogen uptake and leaf area index in paddy rice fields (Shibayama et al., 2009; 2011). The PDC used a standard camera board with a restricted image size (640 × 480 pixels) and fixed programmable camera sensitivities (exposures). In use, images taken under various solar light intensities were calibrated by turning off automatic exposure control (AEC) built-in on the camera board and recording several images at several programmed exposures for each observation. Reflectance factor (RF) was calculated at the end of the observation period. The method required additional data storage for extra shots and processing was time-consuming. Based on this experience, we designed and built a new image collection system: multi-band spectrum camera (MBSC).

The MBSC was developed to meet the requirements of non-destructive collection of quantitative agronomic data. The MBSC captures a 1208 × 1024 pixel image, four times larger than that of the PDC, for finer spatial resolution. The camera boards are industrial grade and should be more stable and long-lasting than standard boards. The system is designed to collect images from each band,
Correct them for peripheral brightness extinction and automatically convert digital number into RF using measured skylight intensity at prescheduled times of day. No post-processing, image selection or conversion is needed. Other features include a user-installable parallax correction between band-images, and integral data processing for band-to-band calculations.

The instrument may enable the automatic, continuous collection of quantitative variables of plant growth such as leaf area, above-ground biomass, plant or weed cover, leaf color and nutrient or stress conditions for several experimental plots in the field of view (Shibayama et al., 2009; 2011). Periodic surveys for those parameters are indispensable for most field crop research but are time- and labor-intensive. Installation of the MBSCs at multiple sites over a period of years will provide an effective database to investigate the growing characteristics of crop varieties with different cultivation methods at different locations over several years.

The objective of this paper is to describe the instrument.

**Materials and Methods**

1. **Instruments**

The MBSC was made by Kimura OyoKogeI Inc. (Saitama, Japan) to meet our design. The system comprises a camera unit, a skylight sensor, a control unit and a personal computer (PC) that controls the cameras, captures images and stores data (Fig. 1). The camera unit is fitted with up to three industrial use digital camera boards equipped with interference band-pass filters and objective lenses. The system has a 48.4° short-side field of view in each band and is able to capture 1280 pixel×1024 line spectroscopic images of reflected light at 8-bit resolution. The MBSC is equipped to capture data in two wavelength bands: 645–655 nm (RED) and 850-860 nm (NIR). These bands have proved useful in trials to estimate paddy rice nitrogen uptake using a digital camera system (Shibayama et al., 2009). RED and NIR or adjacent wavelengths are widely used in remote sensing to derive vegetation indices such as normalized difference vegetation index (NDVI, Rouse et al., 1974). A third band could also be measured by installing an additional board and lens in the capped aperture on the case of camera unit (Fig. 1). The camera unit is housed in a weatherproof case, mounted on a tripod or telescopic pole up to 15 m high. The skylight sensor has light detectors equipped with band-pass filters to the same specification as the camera unit and near cosine receptors using silica diffusers. These sensors provide accurate absolute intensity of light insulating from various directions; the sensor is placed horizontally and connected to the control unit with a 3-m cable. The control unit and PC are housed in a weatherproof container and connected to the camera unit by 15 m of USB cable. The control unit uses a 100 V 0.1A AC power source.

2. **Operation**

The MBSC is operated by the ‘MBSC_CTRL’ software (Windows XP Professional, LabVIEW Vision runtime module, National Instruments Japan Co., Tokyo, Japan). MBSC_CTRL provides 10 control routines: (1) automated intermittent observation, (2) operational condition/observation schedule configuration, (3) manual observation, (4) viewer for automated observation image files, (5) viewer for manual observation image files, (6) skylight sensor calibration, (7) peripheral brightness correction, (8) two-band image registration, (9) camera sensitivity calibration, and (10) adjusting calibration parameters.

For an automated intermittent observation (routine (1)), the data conversion mode is selected from: 1) spectral radiance (μW cm−2 sr−1 nm−1) or 2) RF (dimensionless) in each band, 3) raw digital number and 4) band-to-band calculation (default installed is NDVI, which is calculated from difference in two-band intensities divided by the sum of both). Converted optical variables are scaled into 0–255 range integer numbers and saved as image data in bitmap, JPEG or TIFF file format. Irrespective of selected mode, the system preserves the raw image data (in AVI format), skylight sensor readings and camera exposures employed in each shot as a text file. Although it is possible to set the camera to take shots over a fixed exposure range at a fixed exposure interval, MBSC_CTRL is able to automatically select the appropriate camera exposure via a routine that references the skylight sensor readings (routine (1)); as a result, the volume of stored images is greatly reduced.

![Fig. 1. Major components of the multi-band spectrum camera (MBSC) system.](image-url)
In practice, light reflected from green vegetation is low in visible (0−0.1 RF) but varies more widely (0.15−0.8 RF) in NIR wavelength ranges. In addition, the dynamic range of camera sensors relative to the fluctuation range of insolating and/or reflected light intensity may be restricted. Therefore, in RF observation mode, the system allows an operator to select a restricted RF range (0.0−0.25, 0.0−0.5 and 0.0−1.0) in each band from a pull-down menu in routine (2). The restriction utilizes the camera’s dynamic range and quantization bit rate efficiently, but if the observed RF exceeds the preset maximum value (0.25, 0.5 or 1.0), the stored RF value saturates and the original value is irrecoverable.

The observations in any 24-hour period day are programmable at 1-min intervals. The observation options available from the routine (2) include file format and time schedule. A two-band image registration using routine (8) is required to make on-site band-to-band calculation, though MBSC_CTRL simply shifts the visible band image onto the NIR image using one matched-pair of control points in both images that are manually designated by the operator. Finer image-to-image registration, if necessary, is left to users.

3. Conversion algorithm for reflectance factor

We calibrated the skylight sensor in the laboratory using a certified standard electric bulb to obtain coefficients for converting the output voltages into the incident spectral irradiance (μW cm⁻² nm⁻¹) in each band. We took images of a white reference board illuminated with sunlight with the MBSC. The spectral reflectance of the board (measured in the laboratory) and the spectral irradiance measured with the calibrated skylight sensor were used to derive the spectral radiance (μW cm⁻² sr⁻¹ nm⁻¹) of the targeted reference board. To control the light intensity received by the MBSC in a stepwise fashion, we placed one or two- ply neutral density filters in front of the camera lens, and recorded the digital number output. A non-linear calibration equation, for each band, was developed from these parameters to convert the measured digital number into the spectral radiance at each exposure. The exposure value employed at a given spectral irradiance was experimentally selected such that image was unsaturated at RF 1.0. The calibration procedure is described in detail by Shibayama et al. (2009). The RF value is obtained on a pixel-by-pixel basis using the equation:

\[ \text{RF} = \frac{\pi L_b}{E_b} \]  

where \( L_b \) denotes the target’s spectral radiance estimated from observed digital number and the exposure value in the band b, and \( E_b \) denotes the incident spectral irradiance measured by the skylight sensor at the time of image shooting.

4. Field test

The test site was located on the campus of the National Agricultural Research Center for Tohoku Region, Morioka, Iwate, Japan (39°45’ N, 141°08’ E). Paddy rice plots (variety ‘Hitomebore’) were established in a 6×18 m concrete-framed field. Seedlings were transplanted at a 17-cm inter-hill space and a 30-cm row space on 27 May 2010; the panicles emerged on 7 August. The field was irrigated solely from the northern side and drained from the southern side to provide a gradient water temperature. Field investigation at the maximum tiller number stage (26 July) indicated that the southern plots had more stem numbers, leaf areas and aboveground biomass than the

![Fig. 2. Reflectance factor (RF) images of a paddy rice field collected with multi-band spectrum camera (MBSC) taken at 1200 JST on 18 August 2010. The left image is in RED (645−655 nm) and the right is in NIR (850−860 nm). The square labeled ‘C’ indicates the sample area on the concrete frame; square ‘P’ the sample area in the paddy rice canopy; lines ‘a’−’b’ and ‘c’−’d’ show the transects used to examine the RF profiles (see Fig. 3). The eight arrowed points were used to measure the degree of parallax between RED and NIR images in this observation configuration (see text). The RED image has been slightly brightened to show the features clearly in a black and white print.](image-url)
northern plots. The entire field was covered with blue-colored bird-proof net on 16 July; MBSC images were acquired through the net, although the skylight sensor stayed outside.

The camera unit was set on a telescopic pole 6.5 m high; the base of pole was placed 6.5 m from the southern side of the field. The camera looked approximately north, down on the target field with 22º depression angle. The camera unit was 9.2 m from the near side of the field and 25.3 m from the far end of the field. Fully automated image collection in 2-band RF mode began on 26 July, ran from 0700 to 1700 JST each day at 10-min intervals. Ranges for RFs were set 0.0 − 0.5 for RED and 0.0 − 1.0 for NIR.

We evaluated overall performance with RF images obtained at 1200 JST on 18 August. We sampled RF values along transect lines (Fig. 2) in the images to check the performance in correction for peripheral brightness extinction. Eight matched points (Fig 2.) were designated on the RED and NIR images to examine the degree of parallax between the two band images. Variations in RF value response time throughout the day and at different skylight intensity were examined in two sample areas: an area 15 ×15 pixels located on a horizontal surface of a concrete frame (denoted as ‘C’, Fig. 2), and another area 60 ×60 pixels in the rice canopy (denoted as ‘P’, Fig 2) located at near-central position of the image. Frequent observations were made on 18 and 19 August; 18 of August was sunny and clear, 19 August was partly cloudy. On the assumption that optical characteristics of the concrete surface were stable, we measured the spectral reflectance of the concrete surface close to the area ‘C’ on 7 and 8 October using a portable spectroradiometer (wavelength range: 346 −1043 nm and 0.2 nm in steps, Ocean Optic. Inc., Dunedin, FL, USA) equipped with a 12 V DC halogen lamp and a fiberglas light guide. The measured area was a circle 2 cm in diameter covered with a shading top, illuminated from an angle of 45º and observed at the nadir.

We introduced daily-representative RF (DRRF) values; mean values observed at fixed solar irradiance ranges; 20−40 μW cm⁻² nm⁻¹ for RED, and 40−60 μW cm⁻² nm⁻¹ for NIR, regardless of observation time. DRRF values for the sampled area of rice canopy (‘P’) were examined for the seasonal variability of RF values using coefficient of variation (CV = (standard deviation / mean) ×100%) calculated for 10 days in ripening period (21 − 30 August) on the assumption that there was little change in color, biomass and structure of the rice plants during this period.

Results and Discussion

1. Instantaneous reflectance factor images of rice paddy

The MBSC operated continuously from 26 July to 10 September. Continuous automatic operation over 1.5 months indicated that the MBSC system was robust and reliable.

For this report, the effect of bird-proof nets on RF was neglected. Fig. 2 shows a RF image in the RED and NIR bands of the paddy field taken at 1200 JST on 18 August. At this resolution each plant hill in the nearest part of the field can be discriminated. At this resolution each plant hill in the nearest part of the field can be discriminated. Note that one effect of this configuration is that the change in viewing angle in different parts of the image effectively alters the unit area measured per pixel.

We attribute the cause of the evident depressions in RF values at around 300 and 850 pixels on the ‘a’−’b’ transect lines in both bands (Fig. 3, above) to the shading and reduced plant density at the field boundaries (Fig. 2). We found small but significant trends in the transect lines ‘c’−’d’ where the NIR RF values increased and RED RF values decreased from ‘c’ to ‘d’ (Fig. 3, below). Stem number, leaf area and aboveground biomass were larger in the southern (close to ‘d’ side) than the northern plots, which corresponds with the increase and decrease of RF values. A larger green biomass generally increases RF in NIR and decreases RF in RED.

There was no field survey during the ripening period and the effects of view angles on RF values have not yet been tested. However, we consider that the transect line data (Fig. 3), which are reasonably uniform, indicate that artificial spatial bias or distortion of the RF profiles of both bands was limited. This indicates that the peripheral brightness extinction was corrected accurately.

Generally, images taken with two adjacent cameras do
not match exactly (parallax). Image compositing is required to derive measures, such as NDVI, that require images from both bands. The degree of parallax depends on the distance and viewing angle to the target in the pair of images. Here, we examined actual images to evaluate the parallax at eight matched points (indicated by arrows numbered 1–8, Fig. 2). The horizontal (X) differences between the RED and NIR images varied from 4 to 15 pixels (mean 10.4 pixels). The difference between images in the vertical direction (Y) was −4 to 1 pixels (mean −1.4 pixels). The actual differences in pixels between the two-band images in square ‘P’ (60 × 60 pixels in the paddy field; Fig. 2) were 10 in X and 0 in Y. As a simple linear shift of images reduces the unmatched error to less than 5 pixels, the difference between bands will be negligible or tolerable in most applications.

2. Diurnal changes of reflectance factor

RF was measured at 10-min intervals from 0700 to 1700 JST on 18 and 19 August for area ‘C’ on the concrete frame (Fig. 2) and is plotted against time in Fig. 4. There was little variation in RF from 0900 to 1430 in either band. The larger data variation on 19 August was probably caused by rapid changes in solar irradiance from variations in cloud cover. We attribute relatively stable diurnal variation during the mid-day to the near-isotropic diffusion characteristics of the concrete surface as well as the procedure used to calibrate the MBSC. Observed and averaged RFs in the time period 0900–1430 for area ‘C’ were 0.197 in RED and 0.359 in NIR bands on 18 August, and 0.187 and 0.338 on 19 August. The day-to-day variations were negligible considering that this was a field observation. The reflectance values measured with the portable spectroradiometer at four different points on the concrete surface near square ‘C’ varied from 0.127 to 0.219 at wavelength 650 nm and between 0.225 and 0.302 at 855 nm. The mean RF values in RED of MBSC were just within the measured reflectance range of the spectroradiometer. However, the corresponding values in NIR appear overvalued. The observation geometry of the two methods differs and further tests are required to verify the accuracy of the absolute RF value in NIR measured by the MBSC.

Diurnal patterns of RFs observed on 18 and 19 August for sample area ‘P’ (Fig. 2) in the rice paddy are shown in Fig. 5. On both dates, the RFs decreased in the morning as the sun rose, reached a minimum at around the solar culmination (sun elevation: 67°), then increased in the afternoon. Measurement accuracy declined in the early and late hours due to low sun elevation and insufficient illumination. The pattern of RF over time in RED and NIR were similar. The range of RF was less than 0.1 in RED and more than 0.6 in NIR. The minimum NIR RF of 0.6–0.7 is one and half times as large as that obtained in other studies from well-developed rice canopies measured from a nadir view direction (e.g., Martin and Heilman, 1986) probably due to the high view zenith angle of the MBSC setting. We note that the MBSC measurements of RFs in both bands varied smoothly in conjunction with the motion of the sun on the clear-sky day. The employed observation geometry, with high view zenith angle and view and illumination directions, should give the minimum RF at the highest sun elevation and show a downward, convex curve for plant canopies with erectophyll leaves (Shibayama and Wiegand, 1985).

It was partly cloudy and occasional cloud cover decreased skylight sensor outputs on 19 August. We expected reflected light intensity to be correlated with the skylight sensor output. However, differences between camera and skylight sensor outputs, from any cause, occasionally increased the calculated RF as shown in Fig. 5. Light diffusion characteristics from rice plants are complex and are theoretically defined by the bidirectional reflectance distribution function (BRDF) (e.g., Kimes, 1983). We speculate that a diffused skylight that could
measure light intensity from all celestial directions might reduce variability in reflected light intensity. Diurnal patterns in RF depend on the sun position, weather condition and the BRDF of the target. The calibration procedure used produced tolerable instantaneous measurements. Further, as the MBSC is an accurate instrument, it is possible to measure a part of the BRDF of a plant canopy and relate this to the leaf orientation and productive structure.

3. Daily-representative reflectance factor

There are few clear days in Japan’s summer cropping season (Akiyama and Kawamura, 2003). Clouds and/or haze, and the diffusing characteristics of plant canopies may all influence estimated RF values. However, agronomic surveys often need to measure not only an instantaneous change in RF but also the central tendency of the day. In previous studies (Shibayama et al., 2009; 2011), we used arithmetic averaging over fixed time periods, such as 0900–1500, to avoid extreme measurements in the early morning and late afternoon. However, an average may not adequately describe the convex diurnal pattern of RF observed in the current study.

To observe consecutively attenuating RFs, we plotted the estimated RF for area ‘P’ (Fig. 2) against the spectral irradiance values measured by the skylight sensor (Fig. 6) and fitted polynomial curves to the data for each band and date. At intermediate skylight intensity, curves of RF on a clear sky day and the next partly cloudy day roughly intersected or were close to each other in the 20–40 μW cm⁻² nm⁻¹ for RED, and 40–60 μW cm⁻² nm⁻¹ for NIR (Fig. 6). These skylight ranges were subjectively selected prior to a preliminary calculation of daily-representative RF (DRRF) values. At higher or lower skylight intensities, values of RF diverged. More accurately, the fitted curves for RED RF intersected at the lower end (≅ 20 μW cm⁻² nm⁻¹) of the selected range. However, there were insufficient data observations at lower skylight intensities (<20 μW cm⁻² nm⁻¹) to provide accurate estimates of DRRF, and consequently, we used the range 20–40 μW cm⁻² nm⁻¹ for RED.

As part of the trial of DRRF values, we used mean values obtained at the fixed solar irradiance ranges defined above, regardless of observation time. The means and CVs of DRRFs for 10 days of ripening period were 0.077 and 4.2% for RED, and 0.823 and 2.9% for NIR with no notable date-dependent trend (Fig. 7). As it is unlikely that the weather conditions of the 10 days were constant, the small CVs indicate the stability and reliability of this system. Further tests in other growth periods with different conditions will be necessary to obtain acceptable DRRF values.
observation configurations are required to draw a firm conclusion for the applicability of this method for measurement of DRRF.

Conclusions

The MBSC successfully collected optically validated, instantaneous RF images in two narrow bands in the visible and near infrared wavelength ranges continuously throughout the latter half of a paddy rice cropping period. In the observation configuration employed, the RF images of the paddy were evidently influenced by the canopy’s BRDF. Further studies are required to develop an appropriate method to estimate daily-representative RF (DRRF) values and validate this method of non-destructive agronomic survey over a range of weather conditions.

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