NEAR REAL-TIME METER-RESOLUTION AIRBORNE IMAGERY FOR PRECISION AGRICULTURE: AEROCAM

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ABSTRACT

Precision agriculture often relies on high resolution imagery to delineate the variability within a field. Airborne Environmental Research Observational Camera (AEROCam) was designed to meet the needs of agriculture producers, ranchers, and researchers, who require meter-solution imagery in a near real-time environment for rapid decision support. AEROCam was developed and operated through a unique collaboration between several departments at the University of North Dakota, including the Upper Midwest Aerospace Consortium (UMAC), the School of Engineering & Mines, and flight operations at the John D. Odegard School of Aerospace Sciences. AEROCam consists of a Redlake MS4100 area-scan multi-spectral digital camera that features a 1920 x 1080 CCD array (7.4-micron pixels) with 8-bit quantization. When operated at 6,000 ft above ground level, multispectral images with 4 bands in the visible and near infrared have a ground sample distance of one meter with a horizontal extent of just over one mile. Depending on the applications, flying at different altitudes can adjust the spatial resolution from 0.25 to 2 meter. Equipped with an inertial measurement unit (IMU) system, the images acquired can be geo-referenced automatically and delivered to end users near real-time through our Digital Northern Great Plains system (DNGP). The images are also available to Zone Mapping Application for Precision-farming (ZoneMAP), an online decision support tool for creating management zones from remote sensing imagery and data from other sources. Operating since 2004, AEROCam has flown over 250 sorties and delivered over 150,000 images to the users in the Northern Great Plains region, resulting in numerous applications in precision agriculture and resource management.

Keywords: precision agriculture, AEROCam, remote sensing, near real-time, ZoneMAP, DNGP.

INTRODUCTION

Spatial imagery has been used for crop management since 1929, when aerial photography was used to map soil resources (Seelan et al., 2003). Compared to satellite based sensors, images from aircraft-based sensors have a unique role for monitoring seasonally variable crop/soil conditions and for time-specific and time-critical crop management (Moran et al., 1997). For example, Lamb and Brown (Lamb and Brown, 2001) suggested to use airborne remote sensing for identifying and mapping weeds in crops because of its ability to generate timely and accurate weed maps. Aerial photographing and imaging techniques have been developed (e.g., Ahern et al., 1986; Everitt and Nixon, 1985; Everitt et al., 1986; King, 1995) for a variety of precision agriculture practices, such as monitoring crop condition, growth and yield (e.g., Yang et al., 1999), delineating management zones (e.g., Fleming et al., 2000), and detecting weeds (e.g., Brown et al., 1994).

While typically offering a finer spatial resolution (~ 1-5 m) than satellite observations (15 - 60 m for e.g. SPOT, Landsat or ASTER), airborne remote sensing is also associated with higher costs due to the usage of aircrafts and crew time. Therefore, despite its potential in precision agriculture, airborne imagery is seldom routinely used by agricultural producers or ranchers. To overcome these limitations, the Upper Midwest Aerospace Consortium (UMAC) developed and has been flying the Airborne Environmental Research Observation Camera (AEROCam), providing high resolution images for non-commercial applications in the Northern Great Plains regions of the USA. Images are typically acquired during the growing season of the area (May to October) and provided at no cost to the users in near real-time through the Digital Northern Great Plains system (Zhang et al., 2010a). Users can also access AEROCam images through our other projects, such as Zone Mapping Applications for Precision-farming (ZoneMAP) (Zhang et al., 2010b).

Here we report the development and calibration of AEROCam and provide a few examples of how AEROCam imagers have been used in real applications.

DEVELOPMENT

AEROCam consists of a Redlake MS4100 area-scan multi-spectral digital camera that features a 1920 x 1080 CCD array (7.4-micron pixels) with 8-bit quantization. With four spectral bands at blue, green, red and near-infrared, the camera can record images in either true color or standard false color (near-infrared, red and green) format. The system also includes an inertial measurement unit (IMU), GPS, and specially designed software application for image acquisition planning, processing, and archiving. When operated at 6,000 ft above ground level, images have a ground sample distance of one meter with a horizontal field of just over one statute mile. Ground sample distances within the range of .25 to 2 meters can be accommodated depending on user requirements and mean elevation of the site.

The camera system was developed and operated through collaboration between UMAC, the School of Engineering & Mines, and the John D. Odegard School of Aerospace Sciences, all at the University of North Dakota.

Requests for image acquisition are announced and selected before the growing season starts. Depending on the total number of requests, flying conditions, and cloud cover, efforts have been made to fulfill as many requests as possible. Even-driven requests, such as damage assessment after a storm event, are also considered. Since operation in 2004, AEROCam has flown over 250 sorties and delivered over 150,000 images to the users in the Northern Great Plains region.

SPECTRAL AND RADIOMETRIC CALIBRATION

AEROCam is intended to be used for both scientific and practical applications in precision agriculture and natural resource management; therefore precise determination of its electronic, optical, spectral and radiometric characteristics is needed. In collaboration with the Airborne Remote Sensing Laboratory at the NASA Ames Research Center, we fully characterized the electro-optical components of the AEROCam, producing these primary measurements sets: (1) bandpass spectral responsivity; (2) raw output in digital number throughout the dynamic range of the camera, corresponding to known radiometric input levels; and (3) digital number output response to a Lambertian illumination at different integration times.

Spectral Responses

Spectral characterization was performed using an Oriel 7345 tunable narrowband monochromator, with associated Quartz Tungsten Halogen light source, changeable reciprocal linear dispersion gratings, off-axis parabolic mirror collimator, and turning mirror with a surface accuracy < $\lambda/4$, where λ is the wavelength. The FWHM for the collimated light is 1.5 nm. A full spectrum scan at a wavelength interval of 20 nm was first performed to determine the

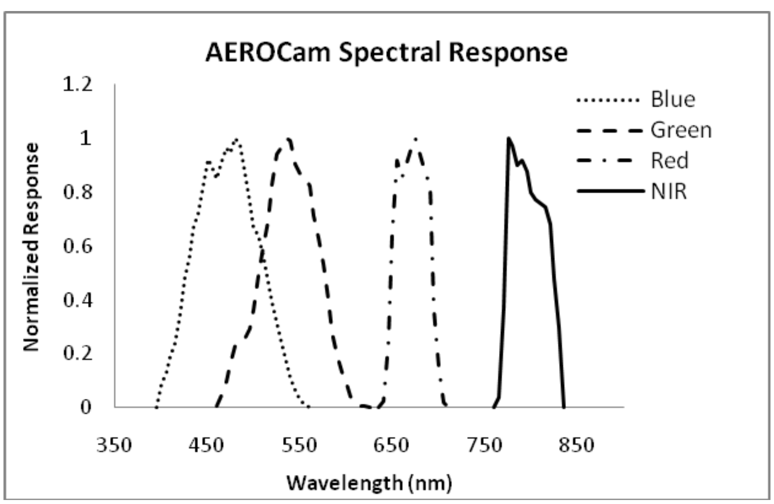

Fig. 1. AEROCam Normalized Spectral Response Curves

approximate spectral response curve and the peak response for each band. Then for each band, the spectral response was determined at a fine wavelength interval of 5 nm. Before and after each spectral response measurement, reference scans were taken using a calibrated silicon photodiode to monitor the stability of the light source. Fig. 1 shows the normalized spectral response curves determined for AEROCam. There is an overlap in the spectral response between the blue and green bands. Because of the overlap, it is recommended to use images recorded in the green, red and near-infrared bands. Table 1 summarizes the central wavelength and the full width at half maximum for each band.

Fig. 1. AEROCam Normalized Spectral Response Curves

Channel	Band	Center Wavelength (nm)	FWHM (nm)
1	Blue	470	430 - 510
2	Green	540	505 - 575
3	Red	665	650 - 690
4	NIR	795	765 - 825

Flat Field

Because no two CCD detectors are the same, it is expected that the quantum efficiency is different for different CCD detectors. Also the artifacts in the optical system will alter the distribution of radiation impinging upon the CCD array. Combination of these two factors leads to differences in photo-electric responsivity. Because of this, even a uniform illumination may not appear as a flat field in the image.

Imagery was obtained from a flat-field uniform source, which uses diffuse glass emission plate with multiple reflective internal baffles between the output plate and an adjustable stable light source. The exiting light field is within 1% Lambertian for angles up to 30 degrees. Placement of the camera within a few centimeters of the output diffuser further improved quality of the exiting light field, as near-field de-focus effects averaged any residual source variations from dust or other minor source defects. The light intensity was fixed during the experiment and the camera was set with f-stop 8, gain 12, and integration time of 4, 5, and 1.2 ms for the red, near-infrared, and green/blue bands, respectively. The

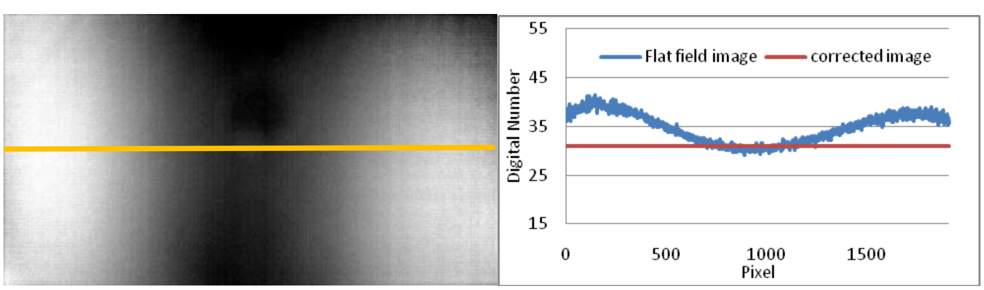

Fig. 2. A red band AEROCam image over a flat field (left) and variation of the pixel values along the yellow line (right). The image was linearly stretched to highlight the non-uniformity in photo-electronic responsivity. The flat field correction is to reproduce a uniform response shown as the red line.

red band imageis shown in Fig. 2 and as is apparent, the photo-electronic responsivities are not uniform across the CCD array. Contrary to the vignette effect that is typically associated with a lens system where the illumination and hence the response would drop as a ray moving from center to the edges of a CCD array (Jia and Tang, 2005), the camera used in AEROCam shows an elevated response towards the edges. The similar patterns were observed for the other bands too. The AEROCam camera has a CCD array of 1920 × 1080 detectors, the flat field correction is determined for CCD detector.. From Fig. 2, a ratio is formed for each CCD detector of its value to the value of the center CCD (an example is shown as blue curve); the ratios were then applied to re-produce a uniform response (red line). Note the parameters derived for the flat field correction differ for different CCD lines.

Radiometric Calibration

Radiometric characterization was performed using a 30 inch Archi 12-bulb integrating sphere calibrated to an FEL lamp traceable to the U.S. National Institute of Standards and Technology (NIST) standard of spectral irradiance. The opening aperture of the integrating sphere is 25 cm in diameter and the camera was placed 9 cm from the aperture. The field of view angle of AEROCam is 114°, 9 cm is the maximum distance away from the aperture to ensure the integrating sphere covering the entire field of view of the camera. The purpose of radiometric calibration is to determine the values of gain (G) and offset (O) such that the radiance (L, W/m^2 sr μm) of the incident light can be calculated from the digital number (DN) recorded by the camera:

$$L = DN \cdot G + O \qquad (1)$$

During the calibration, the light levels were adjusted from 12 lamps down to 9, 6 and 3. At each level, multiple images were taken corresponding to different combinations of f-stop, gain settings, and integration time. The results showed that the camera responses to different light levels linearly with an offset (O) effectively zero under all possible camera settings. Therefore only the values for *G* in Eq. (1) need to be determined. Table 2 lists the gain values determined for f-stop = 8 and camera gain = 12. The gain values for other settings were also determined.

Table 2. Gain values from radiometric calibration results.

Integration time (ms)	NIR	RED	Integration time (ms)	GREEN	BLUE
2	2.1480	1.0977	1.1	0.7359	0.834
3	1.3010	0.6473	1.2	0.6429	0.6989
4	0.8718	0.4143	1.3	0.5596	0.6056
5	0.6108	0.2691	1.4	0.4833	0.5246
6	0.4318	0.1704	1.5	0.4213	0.4573
7	0.3060	0.0985	1.7	0.3153	0.3361
8	0.2096	0.0462	2	0.194	0.1888

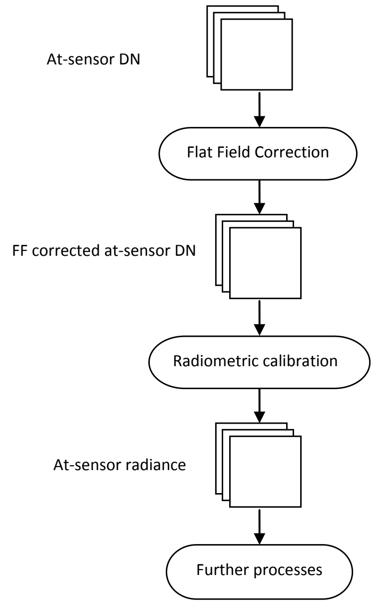

Fig. 3. Schematic diagram of AEROCam calibration

RESULTS AND DISCUSSION

The calibrations allow a precise characterization of the spectral and radiometric performance of the camera. These calibrations, schematically shown in Fig. 3, are applied to all the AEROCam images automatically immediately after

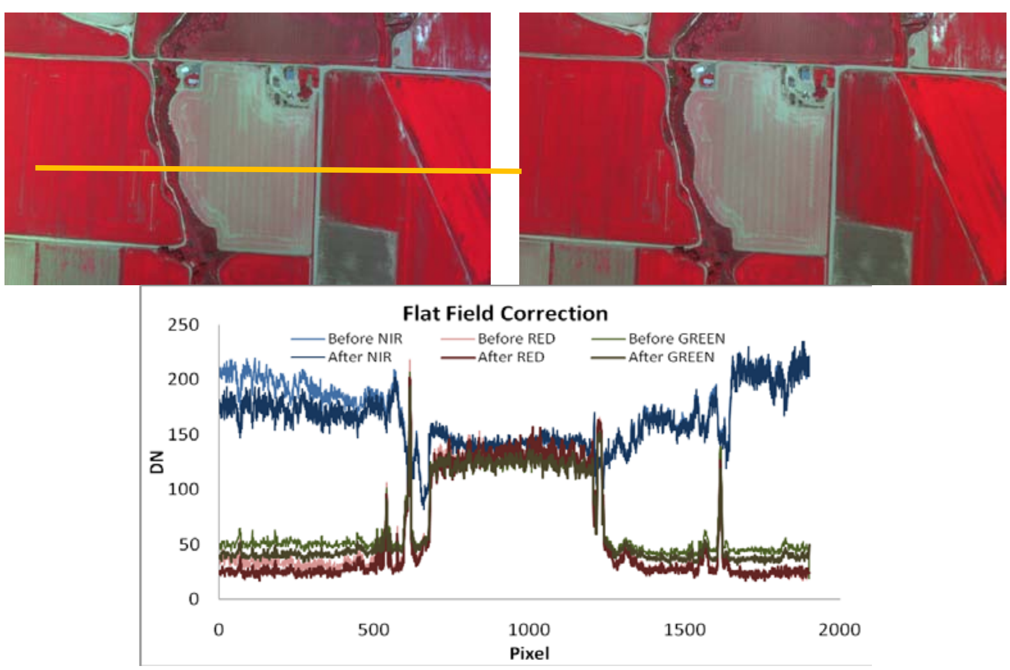

Fig. 5. A false color AEROCam image acquired on June 12, 2009 over a farm field in Worland, Wyoming, and the variations of pixel values along a profile line (yellow) before and after the flat-field correction was applied.

their acquisition. An example of the flat-field correction is shown in Fig. 4, displaying a standard false color image acquired over a farm field. As can be seen from a profiling along a CCD line, the image after the correction appear more uniform in the spectral reflectance, particular towards the sides of the image.

Assessing Crop Damage Due to the Misapplication of Fertilizer

The high resolution imagery delivered by AEROCam has resulted in numerous positive outcomes in both production agriculture and research applications, one of which is described. Early in the summer of 2009, a farmer in Wyoming hired a company to air spread granulated fertilizer on his sugarbeet fields. The application process was poorly done, producing uneven concentrations of fertilizer between passes across the field. Excessively low and high concentrations of fertilizer, mainly nitrogen, in the soil can greatly affect a crop in terms of decreased production. High concentrations of nitrogen tend to "burn" up the plants and low concentrations would stunt growth. The farmer noticed after his beets had emerged that there were areas of stunted growth compared to the other areas of the field. It appeared that these areas also had straight edges, which would imply that they were not caused by something that would occur naturally. To help identify and map the areas in question, the farmer requested aerial imagery from AEROCam.

On June 12th, July 7th, and July 25th of 2009, imagery was acquired of all of the affected fields in order to see the crop in its various stages of growth (Fig. 5). Questionable areas were identified and then "ground truthed" to confirm what was causing the lower vegetative reflectance values witnessed in the images. Once all the areas were identified and measured, a total of 14 acres were found to be affected. Based on the area calculations, the amount of revenue lost could also be calculated by taking past yield averages for each field and multiplying it by that years beet prices. As a result, the company reimbursed the farmer for an

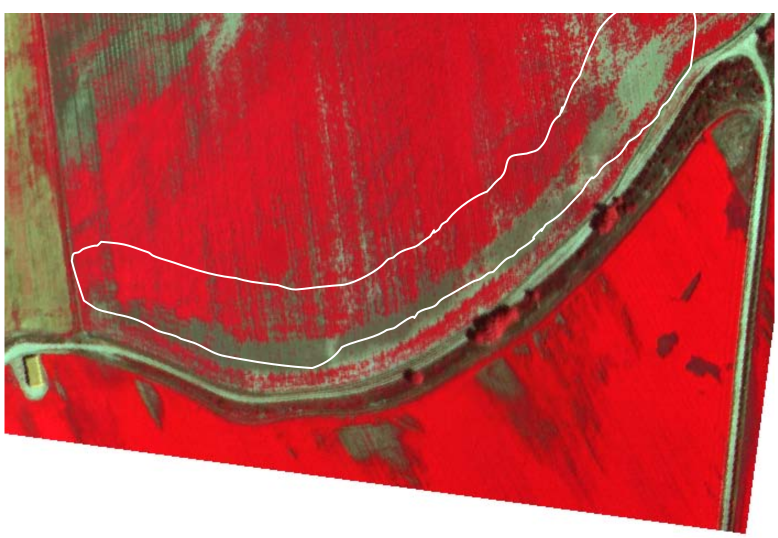

Fig. 6. Half meter resolution AEROCam image showing an area that was affected by the misapplication of fertilizer.

amount of $24,000 due to the damage caused by the misapplication of fertilizer and the subsequent loss in production. Later the farmer commented “They paid the amount that I asked for without argument. I feel that it went smoothly because of the [AEROCam] photos and the ERDAS viewfinder software. Between the two I was able to calculate the damaged acreage and come up with a dollar amount. This is a valuable tool and one that I will find more uses for in the future.” Once the images were acquired, they were used to determine the areas in the sugarbeet fields where fertilizer was spread unevenly producing various gaps and overlaps in coverage.

CONCLUSIONS

Development of AEROCam and delivery of its imagery at no cost to users is one of many projects that UMAC has been conducting in deriving societal benefit from space technology. With the help of AEROCam images, farmers and ranchers benefit economically, students learn practical skills in remote sensing, and researchers are able to develop new applications.

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