Multispectral imaging systems for airborne remote sensing to support agricultural production management

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Abstract: This paper investigated three different types of multispectral imaging systems for airborne remote sensing to support management in agricultural application and production. The three systems have been used in agricultural studies. They range from low-cost to relatively high-cost, manually operated to automated, multispectral composite imaging with a single camera and integrated imaging with custom-mounting of separate cameras. Practical issues regarding use of the imaging systems were described and discussed. The low-cost system, due to band saturation, slow imaging speed and poor image quality, is more preferable to slower moving platforms that can fly close to the ground, such as unmanned autonomous helicopters, but not recommended for low or high altitude aerial remote sensing on fixed-wing aircraft. With the restriction on payload unmanned autonomous helicopters are not recommended for high-cost systems because they are typically heavy and difficult to mount. The system with intermediate cost works well for low altitude aerial remote sensing on fixed-wing aircraft with field shapefile-based global positioning triggering. This system also works well for high altitude aerial remote sensing on fixed-wing aircraft with global positioning triggering or manually operated. The custom-built system is recommended for high altitude aerial remote sensing on fixed-wing aircraft with waypoint global positioning triggering or manually operated.

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1 Introduction

Remote sensing has been widely used and shown promise as an effective tool for managing agricultural application and production. Remote sensing can be performed by either space-borne, airborne or ground-based platforms, or a combination of them. Earth-observing satellite systems, such as Landsat systems (NASA-National Aeronautics and Space Administration, Washington, DC), have an advantage for large-scale analysis at regional levels but are limited in spatial resolution. High-resolution satellite systems, such as IKONOS (GeoEye, Dulles, Virginia) and QuickBird (DigitalGlobe, Longmont, Colorado), have been available in recent years, but scheduling these systems for appropriate bands, location of flight, proper altitude, and time of acquisition is difficult. Airborne remote sensing systems offer a flexible, do-it-yourself platform to configure for high quality, high spatial resolution imagery at any desired spectral combination,

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location, altitude, and time. Use of hyperspectral remote sensing on aircraft in agriculture has been steadily increasing during the past decade[1-6]. Compared with hyperspectral systems, multispectral systems are much lower in cost and are less data-intensive. Airborne multispectral techniques are cost-effective and a good source of crop, soil, or ground cover information for agricultural application and production[7-15,10,16].

In practical use of airborne remote sensing, different types of multispectral imaging systems have been adopted based on economic and technical feasibilities. This research investigates three different types of multispectral imaging systems for airborne remote sensing to support management in agricultural application and production. The systems include low-cost ADC (Agricultural Digital Camera), a relatively expensive and high performance multispectral camera, and a high-cost, custom-built multispectral camera. These cameras can be operated manually or can be triggered with GPS (Global Positioning System) waypoints or GIS (Geographic Information System) shapefile polygons. With automatic control to compensate aircraft rotations, stabilized multispectral imaging of the relatively expensive, high performance camera can be accomplished.

The objectives of the research are:

1) To investigate practical issues of the three types of multispectral camera systems;

2) To summarize and compare the advantages and disadvantages of each system in different configurations.

The information provided from this research will benefit further development of practical aerial remote sensing systems. System applications are suitable for fixed-wing aircraft and unmanned autonomous helicopter platforms.

2 Imaging systems

2.1 Low-cost ADC camera

The ADC camera started with the product of Dycam, Inc. (Chatsworth, California) in the early 1990s. The Dycam ADC camera (Figure 1) is a commercially available multispectral digital camera that includes a modification to obtain images specifically in the red and NIR (Near Infrared) spectral wavebands. The camera provides 24 bit color images with 8 bits per band. The image size is 496×365 Pixels. The Dycam ADC host software supports the IPVI (Infrared Percentage Vegetation Index), NDVI (Normalized Difference Vegetation Index) and SAVI (Soil Adjusted Vegetation Index). The 24-bit "color" image from the camera is evaluated by the software as one of the three supported vegetation indexes. The processed "VI (Vegetation Index)" image directly represents the result of the index equation used on a pixel-by-pixel basis. The resulting 8-bit image can be palletized, saved and exported for use with other software. The camera is easy to operate, rugged and compact.

The Tetracam ADC camera (Figure 1) appeared as the advanced replacement for the Dycam. The up-to-date Tetracam ADC camera is equipped with a 3.2 megapixel CMOS (Complementary Metal–Oxide–Semiconductor) sensor (2048×1536 pixels) or a 5.0 megapixel CMOS sensor (2560 × 1920). It has green, red and NIR sensitivity with bands approximately equal to Landsat Thematic Mapper 2, Thematic Mapper 3 and Thematic Mapper 4, which fall in the 520–600 nm, 630–690 nm, and 760–900 nm wavelengths. Band information provides data needed for extraction of NDVI, SAVI, canopy segmentation and NIR/Green ratios. Standard GPS data capture from an external receiver adds position data to the images. The camera weighs 640 grams with 8 AA alkaline batteries. The 3.2 megapixel ADC fitted with an 8.5mm lens is able to achieve a 0.5 meter/pixel ground resolution at 1340 m (4400 ft) AGL (Above Ground Level). The current cost of the Tetracam ADC camera is about $5,000.

Currently a proprietary software package, PixelWrench2, is used to work with the Tetracam ADC camera to manage and process ADC images. Another proprietary software package, SensorLink, provides a GPS waypoint triggering application enabling camera triggering at pre-defined waypoints.

The ADC cameras are portable and can be used on the fixed-wing aircraft such as single-engine Cessna 210 (Cessna Aircraft Company, Wichita, Kansas), Air Tractor 402B (Air Tractor, Inc., Olney, Texas), and the UAV

(Unmanned Autonomous Vehicle) helicopter with limited payload such as Rotomotion SR 20 (Rotomotion, LLC, Charleston, South Carolina).

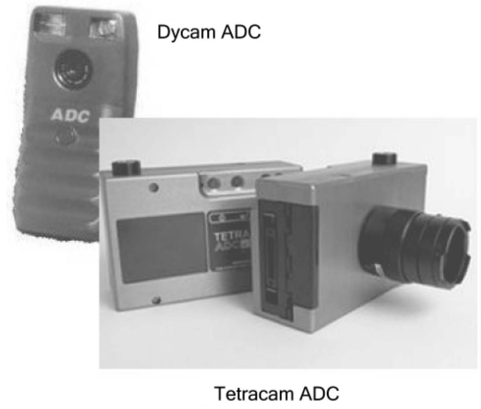


Figure 1 ADC cameras

2.2 Geospatial systems MS 4100 camera

The MS 4100 camera (Geospatial Systems, Inc., West Henrietta, New York) is a multi-spectral 3-CCD (Charge-Coupled Device) color/CIR (Color Infrared) digital camera. This camera is a straight upgrade of the previously available DuncanTech MS 3100 and 2100 cameras. The MS 4100 high-resolution 3-CCD camera provides a digital imaging quality with 1920 (horizontal) ×1080 (vertical) pixel array per sensor and wide field of view of 60 degrees with 14 mm, f/2.8 lens. Color-separating optics works in concert with large-format progressive scan CCD sensors to maximize resolution, dynamic range, and field of view. The MS 4100 camera is available in two spectral configurations: RGB (Red Green Blue) for high quality color imaging and CIR for multispectral applications. The camera images the four spectral bands from 400 to 1000 nm, and acquires separate red (660–40 nm bandwidth), green (540 – 40 nm bandwidth), and blue (460 – 45 nm bandwidth) image planes. The camera provides composite color images and individual color plane images. It is also able to acquire and provide composite and individual plane images from red, green, and NIR (800–65 nm bandwidth) bands that approximate Landsat satellite thematic mapper bands (NASA, Washington, D.C.; USGS, Reston, Va.). The MS 4100 is able to further provide RGB and CIR images concurrently and has the option for other custom spectral configurations. When running the RGB or CIR configuration individually, a base configuration will support any three-tap configuration running at 8 bits per color plane (i.e. 24-bit RGB). Adding a fourth 8 bit tap or outputting 10 bits per color plane requires an additional port with a second cable. The MS 4100 camera configures the digital output of image data with CameraLink standard or parallel digital data in either EIA-644 or RS-422 differential format. The camera works with the NI IMAQ PCI-1424/1428 framegrabber (National Instruments, Austin, Texas). With the software DTControl-FG (Geospatial Systems, Inc) and the CameraLink configuration, the camera system acquires images from the frame-grabber directly from within the DTControl program. The current cost of the MS 4100 camera is about $20,000.

In practical use of the camera on aircraft, operation of the camera would require a technician to control imaging and any ancillary control functions. This is somewhat impractical for small agricultural airplanes as the pilot cannot operate the camera effectively and fly the airplane simultaneously. Control automation is necessary for the multispectral camera in order to reduce labor required and maintain consistency of camera operation. Based on the needs in agricultural research and applications. The TerraHawk camera control system (TerraVerde Technologies, Inc., Stillwater, Oklahoma) is commercially available and is being integrated to automate the operation of the MS 4100 camera with 1) Dragonfly software to control the operation of the camera, especially to trigger the camera based on the field shapefile polygon with GPS receiver; 2) a gimbal controller to stabilize and control the camera for roll, pitch, and yaw aircraft rotations during flight.

2.2.1 MS 4100 standalone

MS 4100 camera can be operated manually by a technician sitting behind the pilot on the Cessna 210 aircraft. However, on Air Tractor 402B agricultural aircraft, the camera must be placed in the chamber underneath the pilot. In manual operation, the pilot can use a wired remote control to trigger the camera, but this is very difficult for the pilot to trigger the camera accurately over the target field especially when flying at

305−457 m (1,000−1,500 ft) AGL. Dragonfly software provides a powerful function to automatically trigger the camera based on the target field shapefile polygon with any submeter-accuracy GPS, such as AirMap 1000 aviation mapping GPS receiver (Lowrance Electronics, Inc., Tulsa, Oklahoma) (Figure 2). Dragonfly configures the camera control based on GPS navigation. As long as the GPS coordinates touch the edge of the target field shapefile polygon, the camera automatically starts acquiring images continuously with a preset overlay such as 50% as default until the aircraft goes through the field polygon with GPS control. The cost of Dragonfly is $3,000.

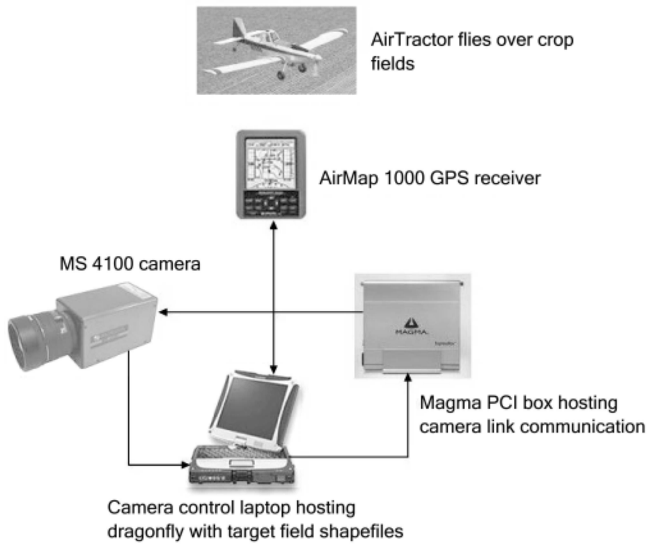


Figure 2 GPS trigging of MS 4100

2.2.2 TerraHawk integration

For stabilization control of the MS 4100 camera, the TerraHawk system was integrated for MS 4100 aerial imaging with the control computer, Dragonfly software, and the gimbal system. In the camera control system, a gimbal is provided for camera mounting for autonomous compensation of roll, pitch, and yaw. The gimbal maintains camera position at or near vertical nadir view and corrects for aircraft yaw by aligning the camera with the GPS heading. The camera is mounted in the gimbal by use of a secure, adjustable height lock. Vertical positioning allows optimal placement of the camera within the fuselage port, even placing the camera several inches below the gimbal if needed. The gimbal axis is located near the base to minimize side to side displacement of the camera due to the gimbal operation when the camera is placed in the camera control system. After use, the camera can be detached from the gimbal for protected storage.

As Figure 3 shows, the MS 4100 camera, the gimbal, a control computer, and a touch pad are integrated into a case containing a GPS unit. This case has been placed over a 38 cm diameter opening in the rear cargo area of the Cessna 210 aircraft for aerial imaging. However, this case could not fit the lower chamber of Air Tractor 402B.

Figure 3 TerraHawk integration case

Using this system, the imaging mission can be set up prior to flight so that the pilot can concentrate on safe operation of the airplane. In operating the camera control system, the Dragonfly software displays a moving map that gives the current aircraft location relative to the fields that need to be imaged. It automates image acquisition by automatically triggering the camera to start imaging at a preset interval once the plane crosses the field boundary. The field boundaries are defined by ESRI (Redlands, California) shape files, which are selected during the flight setup. A GPS track can also be displayed and saved showing the flight path for future reference. During flight, the auto camera control feature optimizes camera exposure settings as well. The TerraHawk system adds an additional $20,000 to the camera system.

2.3 Custom-built TTAMRSS system

TTAMRSS (Texas Tech Airborne Multispectral Remote Sensing System) is a custom-built multispectral remote sensing system based on three high-performance, high-resolution digital cameras to cover the visible, NIR, and thermal IR wavelengths (Figure 4). This system was developed by Dr. Stephan Maas at Texas Tech University. Imaging in the terrestrial thermal IR with TTAMRSS is accomplished using a 12-bit digital camera such as the Indigo Systems Merlin (Niceville, Florida). This camera is capable of resolving the temperature range of the target into 4096 discrete levels, allowing an extremely sensitive analysis of surface temperature variations. Imaging in the visible and near-IR wavelengths is accomplished using two 12-bit digital cameras such as the Dalsa 1M30 (Waterloo, Ontario, Canada). These cameras are capable of resolving the surface reflectance of the target into 4096 discrete brightness levels, allowing subtle differences in vegetation density to be detected. These two digital cameras can be fitted with astronomy-grade interference filters to allow them to image targets in the red (660 nm) and NIR (800 nm) wavelengths with extreme sharpness. The image data from all three cameras is captured with a PCI-bus computer with two Bitflow Roadrunner digitizing boards.

Before TTAMRSS, a similar SAMRSS (Shafter Airborne Multispectral Remote Sensing System) was developed and used at the USDA-ARS laboratory at Shafter, California and OKSI, Inc. (Torrance, California).

The TTAMRSS and SAMRSS systems were highly successful in agricultural remote sensing studies. They have been used to determine the spatial distribution of environmental factors affecting crop growth[17-23] and to detect irrigation canal leakage[24].

The cost to construct a complete TTAMRSS or SAMRSS was approximately \$70,000−\$80,000, which is much more expensive than ADC cameras or the MS 4100 camera, although they are more capable systems.

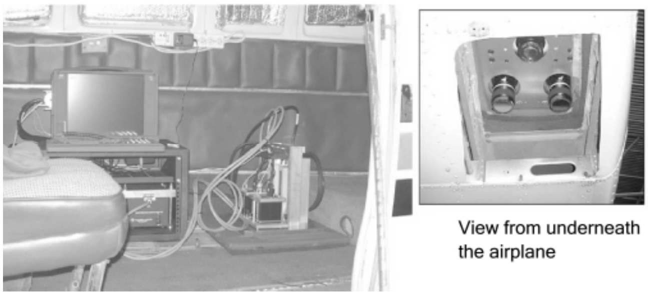


Figure 4 TTAMRSS system

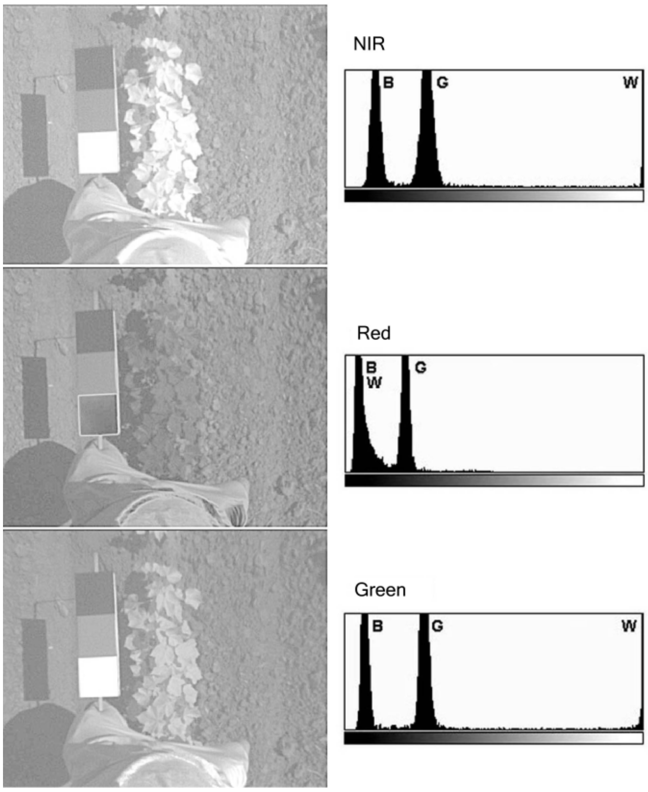
3 Issues for practical applications

3.1 ADC camera

As described in the previous section, the ADC cameras are low-cost, effective imaging devices for agricultural remote sensing. However, in practice the cameras have two major disadvantages:

1) Dynamic range problem

The Dycam ADC and early version of Tetracam ADC are 8-bit systems. Their dynamic ranges are too narrow to adequately image the targets with a wide range of brightness levels. To study this, a simple ground test was conducted using an 8-bit Tetracam ADC. The images in Figure 5 show a row of cotton plants and bare soil, along with a calibration panel with black, white, and gray square sections. The histogram of the NIR image shows the digital count values for the white calibration panel and some of the cotton leaves to be at about 255. This means that the real values exceed the dynamic range of the sensor. The 8-bit system cannot obtain the entire range of brightness values in the dynamic range of the sensor. A more troublesome situation occurs for the red image. Here, the digital count values for the white



Note: B – black panel; W – white panel; G – gray panel

Figure 5 Dynamic range test of 8-bit ADC camera calibration panel are less than the values for the gray panel. This is an artifact of the automatic exposure mode of the ADC camera. The ADC camera can be setto run in manual exposure mode, but the range of brightness will still exceed the dynamic range of the sensor.

To alleviate the problem, more bits are need. The current version of Tetracam ADC camera is using a 10-bit system. However, the single CCD sensor must be shared by three bands. Therefore, the image quality is typically not high.

2) Poor GPS triggering in low altitude on fixed-wing aircraft

During imaging fly-overs, the cameras can be triggered manually or automatically based on data from GPS receivers. For GPS-based triggering, Tetracam, Inc. (Chatsworth, California) provides a software named SensorLink to interface with the camera. SensorLink captures positioning data from a GPS receiver connected to the host computer's serial port. It compares the GPS data to a group of preset waypoints in latitude and longitude, and displays the direction to the waypoints.

In July and August of 2008, a Tetracam ADC camera was mounted on Air Tractor 402B connected with a host laptop and the AirMap 1000 GPS receiver. With the configuration, tests were conducted to evaluate GPS triggering of the camera through SensorLink in three experimental fields labeled 11, 13 and 14. In SensorLink the order of triggering was set as field 14, 11, and 13. The results of the testing indicated issues requiring further study.

Table 1 illustrates results of the test on July 31, 2008. Five runs were flown with different settings of allowable positioning tolerance. The GPS triggering points were close to preset waypoints (Figure 6). However, the triggering function was not reliable. In the five runs only the fourth run triggered all three fields.

Table 2 illustrates results of the August 6, 2008 test. Two runs with larger positioning tolerances were flown. The GPS triggering points still were close to preset waypoints (Figure 7). However, the triggering function was still not reliable. In the two runs only the second run triggered all three fields.

Table 1 Results of testing on July 31, 2008

Run	Triggered	Tolerance zone/m	Field	Speed (Knots)	Heading	AGL(ft)
1	Only field 14 (missedfield 11 and 13)	60	14	123.4	91.3	850
			11			
			13			
2	Only field 14 (missed field 11 and 13)	60	14	123.6	90	1200
			11			
			13			
3	None (missed all)	50	14			
			11			
			13			
4	Field 14, 11, and 13	70	14	124.6	89.9	1000
			11	122.5	89.3	1000
			13	127.2	89.7	1100
5	Field 14 and 11 (missed field 13)	70	14	114	90.1	1100
			11	125.4	88.7	1075
			13			

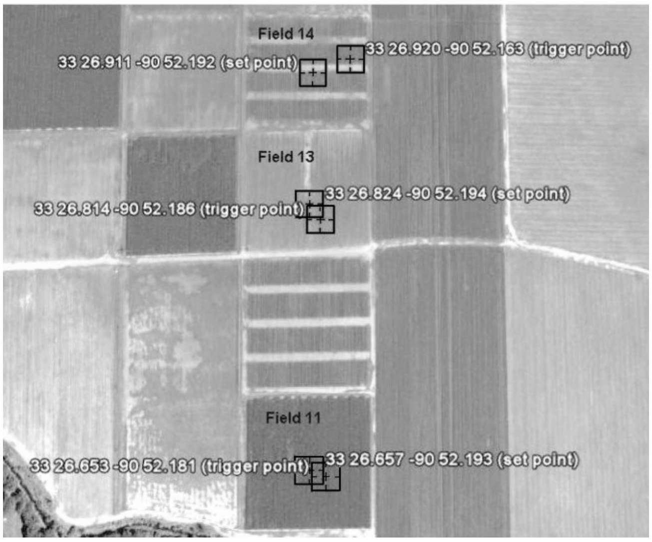


Figure 6 Google map showing camera triggering at run 4 on July 31, 2008

Table 2 Results of testing on August 6, 2008

Run	Triggered	Trigger condition	Field	Speedd (Knots)	Heading	AGL (ft)
1	Only field 14 (missed field 11 and 13)	1 msec exposure time and 110 metertolerance zone	14	115.3	920.7	1000
			11			
			13			
2	Field 14, 11, and 13	1 msec exposure time and 120 metertolerance zone	14	114.5	91.4	1000
			11	125.9	89.4	1000
			13	126.1	89.4	1000

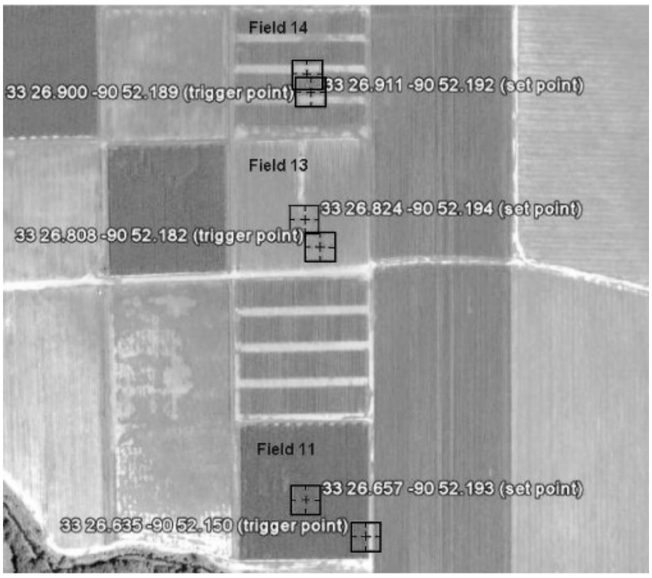


Figure 7 Google map showing camera triggering at run 2 on August 6, 2008

Time and distance function of a trigger constraint feature, which triggers the camera when the aircraft is within a distance from the selected waypoint, was tested on August 5, 2008. In total runs, no camera trigger was missed but the triggering errors were large and the triggering points were a considerable distance from the set points. The exact reason for this is under investigation.

In summary, the Tetracam ADC camera has the following problems with SensorLink GPS triggering:

1) Inaccurate enough GPS triggering

Although GPS triggering could be close to preset waypoints, it was not accurate enough for the camera to obtain an image in one pass to cover the target field.

2) Missing preset waypoints in triggering

This may have been caused by the mismatch of the data updating between the GPS receiver and the triggering software. AirMap 1000 GPS receiver has a 1 s updating interval and the SensorLink (running at 4800 baud) can only process GPS sentences at a 2 s interval. In the test on August 6, 2008, the aircraft flew at about 120 knots (61 m/s). In the two runs, the first run was set at a 110 meter tolerance zone and the second 120 meters. Therefore, the first run missed two triggers with the two second GPS updating rate of the SensorLink and the second run triggered all points (61 m/s).

3) Sequential triggering problem

SensorLink was designed to trigger the preset waypoints in sequence. This meant that if a point was missed or could not be triggered for some reasons, the points after it would never be triggered even though the aircraft flew over the target fields.

4) Low camera imaging speed

The time required for the Tetracam ADC camera to obtain an image is between 3 s and 10 s. With a rapid flash exposure time of 1 ms, most of the time is spent writing the image to the compact flash card. At a ground speed of 120 knots (62 m/s) speed, the aircraft will fly 186 m in three seconds. This means that at least the camera will take images one after another in span of 186 m, which may miss the correct moment to obtain images.

3.2 MS 4100 camera

Compared with the ADC camera, the Geospatial Systems MS 4100 camera is embedded with three CCDs to produce and align images from different bands with a built-in prism. Therefore, this camera provides high quality images. The camera is also equipped with more advanced technologies through the Dragonfly navigation software and the TerraHawk camera automation system. DragonFly provides the capability to trigger the camera based on GPS receiver positioning data over the shapefile polygon of the target field instead of preset waypoints. The polygon shapefile of the target field is generated in ArcGIS (ESRI, Redlands, California) software based on GPS boundary data of the field. The shapefile is then loaded up into Dragonfly. As long as Dragonfly detects the boundary of the field polygon based on a GPS reading, it will trigger the camera to image the target field continuously until it detects that the aircraft is away from the polygon.

In June and July of 2009, MS 4100 camera with Dragonfly (Figure 2) was configured on Air Tractor 402B to fly over the same fields 11, 13 and 14 as the Tetracam ADC camera did in 2008. Figure 8 shows the CIR image series over the fields on July 9, 2009 with irrigated and non-irrigated soybean canopy. Results indicated that this configuration performed well in imaging the target fields with automatic, accurate GPS triggering.

With the acquired imagery each field was covered (Figure 8).

Weight of the MS 4100 is 1.8 kg. Adding to this the weight of the laptop and the Magma PCI box with CameraLink, it would be impossible to safely fly this system on a small UAV such as the Rotomotion SR20. Even if this configuration could be mounted on the UAV SR100 and 200 (maximum payload of 22.7 kg), the design needs to be deliberate because the structure of this type of robotic UAV helicopter is fragile. MS 4100 equipped with the TerraHawk system does not fit UAV platforms nor an Air Tractor agricultural aircraft. An aircraft with larger internal space such as the Cessna 210 is recommended for this configuration.

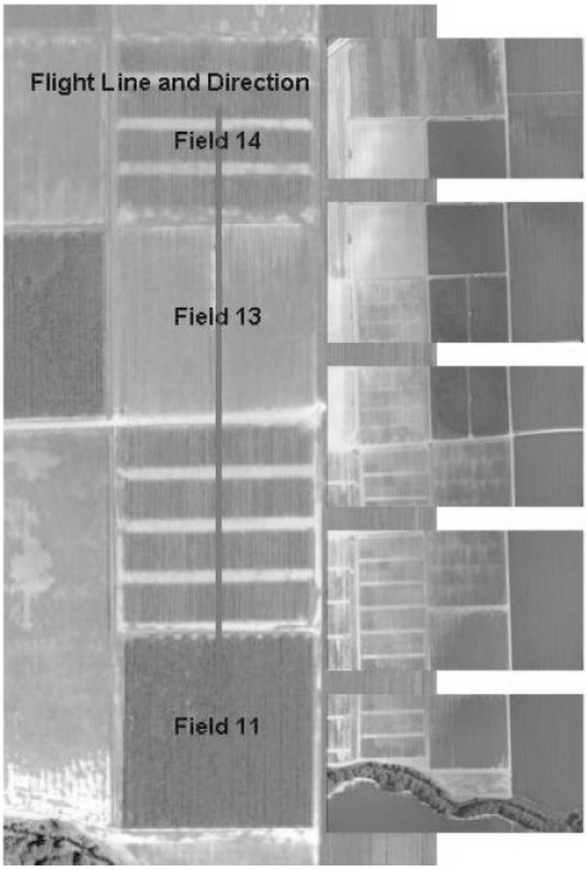


Figure 8 MS 4100 CIR imagery over the target fields on July 9, 2009

3.3 TTAMRSS

TTAMRSS is a high-performance, high-resolution, multispectral imaging system to cover wavelengths from visible, NIR, to thermal IR with 12-bit image pixel representation, which provides a much wider dynamic range than 8-bit systems. This system consists of three separate cameras, two Dalsas and one Merlin thermal, which can be triggered by preset waypoints through Tracker software which was originally developed for Tetracam ADC camera and then modified for TTAMRSS cameras. Use of separate cameras requires more post-processing of the acquired images. One important post-processing task is to co-register the images from three different bands such as red, NIR and thermal. Registration is necessary in order to be able to compare or integrate the separate images obtained from different cameras. For each scene three separate images from different bands are registered pixel to pixel and lined up. Then, the registered images can be stacked up for further processing, such as image enhancement, segmentation and classification.

Registration work is trivial if only a few scenes are imaged. However, if a series of images are needed, this work would be laborious. On February 28, 2005, we conducted a flyover with the TTAMRSS system and acquired multispectral images of twenty-four canal sections located within eleven irrigation districts in the Lower Rio Grande Valley of Texas[24]. In the fly-over, four hundred and thirty-nine image triplets (439 red, 439 NIR, and 439 thermal images) were obtained during the mission. By visual inspection of the original images, one hundred forty of the four hundred thirty-nine imaged canal sites were identified as having possible canal leakage problems. The image triplets from the one hundred forty sites were registered for further analysis. It took a student worker three months to process the imagery.

4 Comparison

Table 3 indicates specifications of Tetracam ADC camera, Geospatial Systems MS 4100 camera, and SAMRSS for practical applications. From the specifications, the three imaging systems can be compared.

The Tetracam ADC camera has certain advantages:

- Inexpensive
- Light weight
- Spectral coverage
- Achievable spatial resolution with the image size

- Contrast resolution with 10 bit digital count

However, because only a single CMOS sensor available, the performance of the camera was limited in practice:

- Slow imaging speed
- Band saturation
- Low image quality
- Limited GPS triggering capability

Thus, use of this camera required a trade-off between flight altitude and image quality on fixed-wing aircraft and in general would be good for LAARS (Low Altitude Airborne Remote Sensing) from UAV helicopters.

Geospatial Systems MS 4100 camera is built with three CCD sensors with advantages in:

- Good spectral coverage
- High image resolution
- Good contrast resolution even with 8 bit digital count
- Fast imaging speed
- Accurate GPS trigger capability
- Automation capability (with TerraHawk support)

However, the camera’s disadvantages are:

- Fairly expensive
- Heavy weight

Therefore, this camera is good for both HAARS (High Altitude Airborne Remote Sensing) and LAARS on fixed-wing aircraft.

Compared with the other two camera systems, TTAMRSS has advantages in:

- Customer-built flexibility
- Wider spectral coverage to the thermal band
- High imaging quality
- High contrast resolution with 12 bit digital count
- Fast imaging speed

However, TTAMRSS is:

- Expensive
- Large mount required for two or three separate cameras
- Requires more image post-processing such as co-registration

Therefore, TTAMRSS is good for HAARS and may be good for LAARS on fixed-wing aircraft.

Table 3 Specifications of three multispectral imaging systems

	Tetracam ADC Camera	Geospatial Systems MS 4100	TTAMRSS
Sensor	A single 3.2 megapixel CMOS sensor/a single 5.0 megapixel CMOS sensor	Three CCD sensors	Two Dalsa 1M30 cameras and one Indigo Systems Merlin thermal camera
Exposure	Auto/Manual	Auto/Manual	Manual
Band Cover	Green: 520 – 600 nm Red: 630 – 690 nm NIR: 760 – 900 nm	Blue: 460 nm with 45 nm bandwidth Green: 540 nm with 40 nm bandwidth Red: 660 nm with 40 nm bandwidth NIR: 800 nm with 65 nm bandwidth	Red: 655-665 nm NIR: 830-870 nm Thermal: 8-14 μm
Image Size	2048×1536 pixels for 3.2 megapixel CMOS sensor/2560×1920 for 5.0 megapixel CMOS sensor for three band	1920 × 1080 pixels for each band	Each Dalsa: 1024×1024 pixels Merlin: 320×256
Image Digital Count	8 bit/10 bit	8 bit	12 bit
Imaging Speed (including writing to storage)	one image/3-10s	one image/2 s	one image /s
Weight	640 g	1.8 kg	26 kg
GPS Trigger	Sequential waypoint trigger through SensorLink ($495)	Shapefile polygon trigger through Dragonfly ($3,000)	Waypoint trigger through Tracker
Cost	$5,000	$20,000 (TerraHawk plus $20,000)	$80,000

Exposure is an important function for each imaging system. The default mode for the Tetracam ADC camera is automatic exposure. It can be set for manual exposure, but with the 8 bits, it is next to impossible to manually set the exposure to include a large range of scene brightness levels. MS 4100 has the option for either auto or manual exposure. TTAMRSS uses manual exposure (called manual gain control in the system). A problem with automatic exposure is that the radiometric characteristics of each image obtained from the system can be different. This could greatly complicate doing radiometric correction to compare images or to convert the digital count values to reflectance, especially if each image doesn't contain calibration information (like the calibration panel in Figure 5). Therefore, whenever possible, remote sensing systems should be run using manual exposure mode.

5 Applications

5.1 ADC Camera for site-specific crop health sensing

So far, the most successful applications of the Tetracam ADC camera were performed using UAV helicopters for LAARS over agricultural fields. With the Tetracam ADC camera an UAV-based LAARS system was developed on Rotomotion SR100 UAV helicopter as an agricultural field monitoring system[25,26]. This system allowed greatly improved spatial resolution, temporal resolution, and reliability when compared with conventional remote sensing platforms. A X-Cell Fury .91 UAV helicopter (Miniature Aircraft USA, Sorrento, Florida) was adapted with the Tetracam ADC camera for LAARS to estimate yield and total biomass of a rice crop[27]. Fifteen rice field plots with five nitrogen-treatments (0, 33, 66, 99 and 132 kg/ha) with three replications on each treatment were arranged for estimating yield and biomass as a function of applied nitrogen. Images were obtained by the multispectral camera mounted on the UAV helicopter operated at the altitude of 20 m over the experimental rice fields. The rice yield and total biomass for five nitrogen-treatments were found to be significantly different at the 0.05 and 0.1 levels of significance, respectively and NDVI values at panicle initiation stage were highly correlated with yield and total biomass with regression coefficient, R^2 of 0.728 and 0.760, respectively. The study also indicated the suitability of using the images from UAV for estimating leaf chlorophyll content in terms of NDVI values with $R^2 = 0.897$.

There are ongoing research activities in USDA - ARS (United States Department of Agriculture - Agricultural Research Service) at College Station, Texas and Stoneville, Mississippi in use of the Tetracam ADC camera on UAV helicopters for LAARS in site-specific crop health sensing and control.

5.2 MS4100 imaging for variable rate application prescription

A 115 ha (285 acres) crop field is located in the eastern part of Burleson County, Texas. The field rotates planting of corn and cotton each year. In 2007, cotton was planted and was ready for harvest in September. Before harvesting, defoliant was required to facilitate the harvesting process.

Due to the variability of soil type, nutrition, and crop vigor in the field, variable rate application of the defoliant is necessary in order to reduce the cost and protect the environment. For variable rate application, a prescription map is needed to direct the application.

For generating the prescription map, many options exist. Ground-measured spatially variable data is one option. Early the year before planting, soil electrical conductivity (EC) was measured at shallow (0−0.3 m) and deep (0−0.9 m) depths using a Veris 3150 EC system (Veris Technologies, Inc., Salina, Kansas). When the cotton canopy was enclosed, the crop vigor was measured using a GreenSeeker handheld data collection and mapping unit (model 505) (NTech Industries, Inc., Ukiah, California), which output NDVI values over the field. The soil EC data and NDVI data can be useful for generating the prescription map.

Another option is airborne remote sensing. A week before harvesting, on September 20, 2007, a Cessna 210 single-engine aircraft carrying a MS 4100 multispectral camera integrated with the TerraHawk camera automation system flew over the field. After the fly-over, the original CIR image was converted to reflectance and georeferenced. Then the post-processed image was transformed into the NDVI image (Figure 9). This NDVI image provided data input for generating the prescription map. With the prescription map, variable-rate defoliant was applied over the cotton field two days after imaging. Then, on September 27, 2007, the cotton in the field was harvested[16].

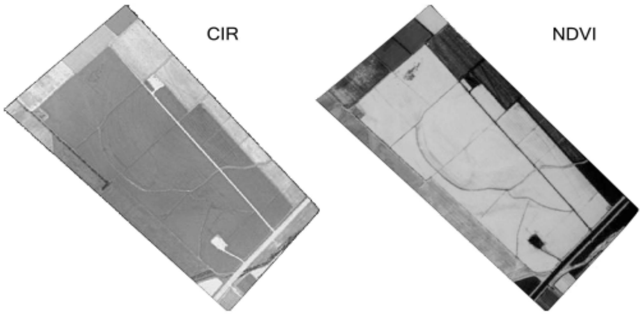


Figure 9 CIR image and NDVI image of the cotton field on September 20, 2007

5.3 TTAMRSS imaging for irrigation engineering and crop field variability characterization

A two-day flight was conducted in August of 2001 over the irrigation canals of two irrigation districts in the Lower Rio Grande Valley of Texas to detect canal leakage. In this fly-over a thermal imager (Inframetrics 600L IR Imaging Radiometer-Inframatrics, Inc., North Billerica, Massachusetts) was used. In order to improve the technology for canal leak detection, the TTAMRSS system which integrated visible, NIR and thermal IR imaging sensors was used in February 2005 to fly over twenty-four canal sections located within eleven irrigation districts in the same region. In the fly-over, more than one thousand multispectral images from red, NIR and thermal IR bands were acquired. After the fly-over, over a hundred imaged canal sites were identified visually as having possible canal leakage problems. The images from different bands for these suspicious sites were registered for leakage analysis.

Figure 10 shows the SAMRSS images obtained from the fly-over for a canal section. With the image analysis, a field site evaluation was conducted to document the type and severity of the leakage at twenty-eight of the suspicious sites. Twenty-six sites were confirmed to have leakages, representing a success rate of 93%[24]. Methods used in this study should have widespread application for detecting leakage and seepage in irrigation canals.

During the summer growing seasons of 2007 and 2008, a study was conducted to determine empirical relationships between remotely sensed vegetation indices and canopy density information, such as leaf area index or ground cover (GC)[17], which are commonly used to derive spatial information in many precision farming operations. In this study, an existing methodology that does not depend on empirical relationships was modified and extended to derive crop GC from high resolution aerial imagery. Using this procedure, GC was calculated for every pixel in the aerial imagery by dividing the perpendicular vegetation index (PVI) of each pixel by the PVI of full canopy. The study involves airborne and ground truth data from 13 agricultural fields in the Southern High Plains of the USA. The airborne data were acquired using the TTAMRSS only contained two Dalsa 1M30 cameras that were sensitive to the light in the red and NIR wavelengths. Results showed that the method described in this study could be used to estimate crop GC from high resolution aerial images with an overall accuracy within 3% of their true values. This application demonstrated the customer-built flexibility of the TTAMRSS.

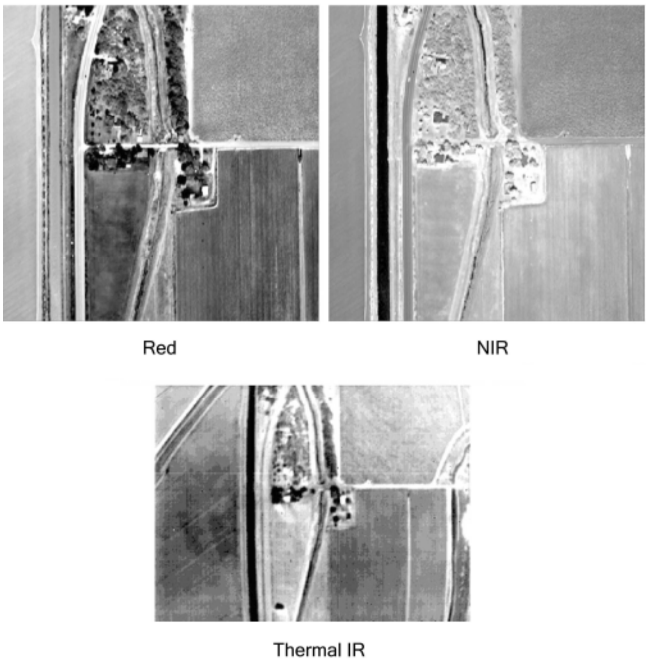

Red
NIR
Thermal IR

Figure 10 TTAMRSS images over a canal section

6 Conclusions

Three representative multispectral imaging systems were investigated for practical application in agricultural production management. Based on the investigation, it can be concluded that:

1) Low-cost systems can also sacrifice performance. Typical problems include band saturation, slow imaging speed and low image quality, such as the 8-bit Tetracam ADC camera with its speed-limited triggering software has demonstrated. This type of system is not recommended for LAARS on fixed-wing aircraft. They are more suitable for slower moving platforms that can fly close to the ground, such as UAV helicopters.

2) High-cost systems such as MS 4100 and TTAMRSS may be more difficult to mount because of their heavier weight and multiple attachments of host

devices. These systems are not recommended on UAV helicopters with limited payload and fragile support structures.

3) Practical applications indicated that field shapefile polygon-based triggering was suitable for imaging from fixed-wing aircraft. Systems such as the MS 4100 with Dragonfly software mounted on Air Tractor 402B agricultural aircraft worked well. However, waypoint-based triggering such as that implemented for the Tetracam ADC camera (and SensorLink) mounted on an Air Tractor 402B did not perform well for LAARS. This type of system did perform well on a UAV-based LAARS[25].

4) Image processing automation is necessary for processing a large number of images, such as in the case of canal leak detection using TTAMRSS. This automation may benefit real time applications also. For variable rate application, rapid image processing methods can be developed in batch mode to perform image processing, prescription map conversion, and prescription map-based application in a near real-time or real-time mode.

5) Whenever possible, manual exposure should be used in imaging instead of automatic exposure. This is necessary to allow different radiometric characteristics of each image to be represented properly.

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