AIRBORNE MULTISPECTRAL REMOTE SENSING IMAGING FOR DETECTING IRRIGATION CANAL LEAKS IN THE LOWER RIO GRANDE VALLEY

Yanbo Huang and Guy Fipps
Biological and Agricultural Engineering Department
Texas A&M University
College Station, TX 77843-2117
yanbo@tamu.edu
g-fipps@tamu.edu

Stephan Maas
Department of Plant and Soil Science
Texas Tech University
Lubbock, TX 79415
stephen.maas@ttu.edu

Reginald Fletcher
USDA ARS Kika de la Garza, Subtropical Agricultural Research Service
Integrated Farming and Natural Resources Research Unit
Weslaco, TX 78596
rfletcher@weslaco.ars.usda.gov

ABSTRACT

Techniques and methods are available to detect water leaks, but traditional field survey methods for detection of water leaks in irrigation systems are costly and time consuming. Airborne thermal remote sensing has been proposed, studied, used, and shown great promise as a quick and cost-effective remote sensing method of determining the location of leaks in irrigation canals. This research presents a new research of airborne multispectral remote sensing for leak detection and potential seepage identification in irrigation canal networks conducted in the Lower Rio Grande Valley, Texas. A multispectral imager which combines Red, NIR, and Thermal sensors has been used to collect image data over the 24 selected canal segments over 8 irrigation districts. The image triples have been processed with regular and batch operations using ERDAS Imagine. The result of field reconnaissance verified image analysis well overall. This research has established an airborne multispectral remote sensing method to rapidly provide high-resolution imaging data and detect leaks, and determine potential seepage of irrigation canals. This technology would have widespread application.

INTRODUCTION

Irrigation water distribution networks are used extensively for agricultural and municipal water supply. In the Lower Rio Grande Valley (LRGV) of the Texas-Mexico border region, irrigation districts deliver raw water to municipal treatment plants through the same canals and underground pipelines used to deliver water to farms. In 2000, the total water supply for this region was 1,278,090 ac-ft (TWDB, 2002) and the most recent estimate of average conveyance efficiency of the districts in the Rio Grande Water Planning Region (Region M) was 70.8% (Fipps, 2000). With this loss rate, 373,202 ac-ft of water were lost in the conveyance process from the 3000 miles of canals, pipelines, and former channels (resacas) of the Rio Grande in the LRGV, and losses in the future are expected to continue to be of this magnitude unless action is taken to reduce the loss.

This problem is experienced nationwide. Irrigation remains the largest use of freshwater in the United States and totaled 153,000 thousand ac-ft in 2000 (Hutson *et al.*, 2000). California, Nebraska, Texas, Arkansas, and Idaho accounted for 53 percent of total irrigated acreage (32,670 thousand acres). It is difficult to obtain reliable estimates for conveyance loss. USGS has used 19% as the conveyance loss rate (Solley *et al.*, 1998), which would yield a freshwater loss in the U.S. for the year 2000 of approximately 29 million ac-ft.

The problem is generally thought to extend internationally, although even rough estimates of conveyance loss are not available. Irrigation of cropland has become widely a used practice throughout the world and has greatly increased the productivity of farmland. It has made it possible to farm in regions that would not be farmable without irrigation. But, with nearly 70% of the total water use throughout the world coming from irrigation for cropland, the need for newer and more efficient practices is clearly important (Disrude, 2004).

In order to reduce the water loss, it is necessary to identify the sources and locations of the loss. Water loss in irrigation distribution networks can occur through several mechanisms, including excess seepage over an area, point leaks from breaks or fissures in the canals or pipelines, and evaporation. Leaks and seepage are generally considered to represent a large majority of the loss. Conventionally, a variety of methods are available for detection of leaks and seepage in water systems, including measurement of pressure or flow rate change (Tucciarelli *et al.*, 1999; Paquin *et al.*, 2000), acoustic signal analysis of running water (Hunaidi and Chu, 1999), and radar detection of soil moisture content (Hunaidi and Giamou, 1998). However, these methods are expensive, time-consuming, labor-intensive, especially considering the large areas in most irrigation districts, and often do not precisely locate leaks. Therefore, a quick and cost-effective method is needed.

In this study we used an airborne multi-spectral remote sensing system to develop an advanced, cost effective approach for rapid leak detection of the canals in the irrigation distribution networks. The advantage of this newly developed approach is that it has the capability to evaluate the surrounding conditions of canals related to leaks and seepage at the same time in the region. The success of this approach will produce better information regarding leaks supplied to the irrigation districts, which will lead to increased water availability and better management of water use and allocation.

LITERATURE REVIEW

Remote sensing has been used in a few reported cases to detect leaks in aqueducts, either directly through changes to soil and surface water content or indirectly through effects on the vigor and health of overlying vegetation. Airborne remotely sensed thermal imagery has been used in detection of canal leaks. In what is arguably the most complete description of the use of remotely sensed imagery to detect canal leaks, a thermal IR over-flight of the North Unit Irrigation District of central Oregon was done to locate canal leakage during the 1979 irrigation season (Nells, 1982). An HRB Singer AN/AAS 14 optical-electronic scanning system mounted on a Mohawk OV-1 aircraft was used. The IR wavelength used in the sensor system for the study was from 8 to 18 μm. A critical assumption for interpretation of the image data was that leakage adjacent or nearly adjacent to the canal system would create higher soil moisture than non-leakage sites. Soil moisture and conductivity were significant factors influencing thermal characteristics of the soil, and thus the thermal infrared imagery. Oscillations of temperature in a moist soil are less than in a dry soil area, since sites high in moisture cool slower after sunset and warm slower during the daytime (Myer's, 1975). Thus, moist sites (canal leakage areas) emitted more radiation during the evening hours and less radiation during periods of peak incoming solar radiation than sites with lower soil moisture. Of 39 sites identified as possible leakage areas, twelve (12) were verified through field analysis as actual leakage sites for a 31% detection accuracy. No additional leakage sites were discovered beyond the 12 labeled on the imagery; in other words, while there were false positives identified in the images, there were no false negatives detected. Despite the low detection accuracy, time saved by only checking the positive sites on the image rather than the entire canal system for leakage could result in significant labor savings and improved management. This work did find that misinterpretation of the image could occur from dense natural vegetation, farm canals, or drainage ditches adjacent to the main canal, small holding ponds, and low depression areas of natural drainage. But, the interpretation could be significantly improved by simultaneously collecting and interpreting color photography to supplement the thermal infrared imagery.

Pickerill and Malthus (1998) applied airborne multispectral remote sensing to leak detection from rural aqueducts. Daedalus AADS 1268 Airborne Thematic Mapper (ATM) multispectral scanner remotely sensed data were obtained over Vyrnwy Aqueduct, North West England. Additional, true color aerial photographs were taken to aid image interpretation. Analysis of the spectral profiles of two known leaks in a wheat field and in a recently harvested cereal crop suggested that different indices and single bands were required in order to identify each leak. The spectral profile of the first leak responded best to a ratio of NIR to red reflectance. Conversely, the NIR to red reflectance ratio was less useful in differentiating the second leak from its surroundings. Thermal image data were also examined for their ability to distinguish the leaks from their surroundings, but there were no significant temperature differences between the leaks and their surroundings.

An airborne thermal image scanner was used to measure irradiance in wavelength range from 8- to 14-μm over an experimental site in the LRGV for measurement of surface temperature and to delineate water-stressed and well-watered fields in large irrigated areas (Bartholic et al., 1972). Image resolution was about 0.6 m square per pixel and the ground width of each scan was approximately 900 m. The image data was recorded on analog magnetic tape and on 70-mm film, making it possible to digitize the analog record for computer analysis. A relation between film density by a microdensitometer, gray scale step voltage, and blackbody temperature was established. Based on this relationship, different temperatures were obtained for various test plots. Through comparison with ground truth data, they concluded that thermal imagery offered potential for delineating water-stressed and non-stressed fields, evaluating uniformity of irrigation, and evaluating surface soil water conditions.

Jackson (1984) surveyed airplane and satellite remotely sensed images for farm management applications. Flights with multispectral image scanners over agricultural targets clearly showed that emitted thermal infrared radiation was an indicator of the water content of soil and several visible and near-infrared bands could readily distinguish vegetation. Radiometers that measured emitted IR radiation in the 8-14 μm wavelength were used to infer the temperatures of the plants and soils.

PREVIOUS WORK

In August of 2001, we conducted our first experiment with an airborne thermal imager for detecting leaks from irrigation canals. The thermal imaging unit, Inframetrics 600L IR Imaging Radiometer, was produced in 1980s by Inframetrics, Inc. (N. Billerica, MA 01862). For the flights, a GPS receiver and a screen console were incorporated to include geographic coordinates on the video. A second console was connected for the pilot to maintain the flight track. The Inframetrics unit monitor recorded the surface temperature as gray scale values from 0 to 255 on standard VHS tape. Water and wet areas have different temperature signatures from the temperature signatures of surrounding soil, structures and vegetation. The unit recorded a rectangular footprint with an 8 bit radiometric resolution, i.e. 256 gray levels and the size of the image was approximately 240 x 320 pixels. The FOV (field of view) was 15^o in the vertical axis and 20^o in the horizontal axis. By calculation, the swath width for the flight was 107.5m (352.7ft) at a flight altitude of 305m (1,000ft) and 215m (705.3ft) at a flight altitude of 610m (2,000ft). Thus, for a 305m flight altitude, the spatial resolution of the 240 x 320 imagery was 0.335 m per pixel (1.1 ft per pixel), and the total area of each image was 862m^2 (93,112.8ft^2). For a 610m flight altitude, the spatial resolution was 0.67 m per pixel (2.2 ft per pixel) with a total area of each image of 3447.6m^2 (371,090ft^2).

Following data collection, we digitized the video recording, processed the spectral content, evaluated the images, and identified 45 sites as having possible leaks. Each site was then located using the GIS maps of the district. Eleven of the sites were inspected, and ten were found to have leaks for a 91% success rate. Two of the 11 sites were in unlined earth canal segments, which had obvious holes. The other sites were in concrete canals with cracks, which were the likely sources of the leaks. However, not all of the leaks were visually apparent although they did appear on the images. This early experiment allowed us to conclude that thermal imaging was a promising technology for the evaluation of irrigation canal conditions and leak detection (Huang and Fipps, 2002).

CURRENT RESEARCH

For irrigation canal leak detection, remote sensing imagery would need to be acquired with a surface resolution of a few meters at most. Earth-observing satellite systems are limited in the spatial resolution with which they can make such observations. Low-resolution satellite systems such as NOAA-AVHRR and Terra-MODIS are applicable only to regional-scale studies. The spatial resolution of other thermal IR satellite systems, such as Terra-ASTER, Landsat 7 ETM, and CBERS, ranges from 60 to 100 meters. While high-resolution satellite imagery is currently available in the visible and near-IR wavelengths from systems such as IKONOS and QuickBird, there are no civilian high-resolution thermal IR satellite systems currently operating, nor are any planned for the near future. In the absence of space-based systems, aircraft observations will be necessary for studies involving remote sensing. While several airborne remote sensing systems are commercially available, none contain the combination of sensors (visible, NIR, and thermal) necessary to support a wide variety of water resource studies. We are currently developing multispectral (Red, NIR, and thermal) remote sensing techniques for determining the leaks of irrigation canals.

DATA ACQUISITION SYSTEM

The airborne multispectral remote sensing system was developed by integrating commercially available imaging and computer components. The system combined high-performance, high-resolution imaging sensors in the visible, near-IR, and thermal IR wavelengths. It was highly successful in agricultural remote sensing studies in California, where it was used to detect the spatial distribution of environmental factors affecting crop growth, including insect pests, soil salinity, and water deficits (Maas et al., 1999, 2000; Fitzgerald et al., 1999a, 1999b, 1999c, 2000; DeTar et al., 1999).

Imaging in the terrestrial thermal IR is accomplished using a 12-bit digital camera such as the Indigo Systems Merlin. 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. 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 are fitted with astronomy-grade interference filters to allow them to image targets in the red (0.66 micron) and near-IR (0.8 micron) wavelengths with extreme sharpness. The image data from all three cameras is captured using a PCI-bus computer with two Bitflow Roadrunner digitizing boards (each board can handle up to two cameras). The computer also runs the software to control image acquisition by the cameras. Data and commands for all three cameras are displayed on a touch-sensitive, flat-screen monitor. Acquired imagery is saved to a hard disk drive within the computer and later written to CD-ROM for distribution and analysis.

A small camcorder is used to provide a real-time, true-color display of the general area being imaged by the system. Experience has shown that this type of display makes it easier for the operator of the system to recognize landmarks during an imaging mission (as opposed to recognizing them in the multispectral displays on the computer monitor) and give directions to the aircraft pilot regarding adjustments to the flight track.

Experience with the system has shown that, when flown aboard a light aircraft such as a Cessna at an altitude of approximately 5000 feet AGL, such a remote sensing system should produce imagery in the visible, near-IR, and thermal IR with a surface resolution of 1 to 2 meters. This, coupled with the 12-bit character of the cameras, should allow detailed imaging of surfaces, particularly at the scales of urban and agricultural landscapes. Imaging of larger areas, such as natural landscapes, can be accomplished by flying at higher altitudes.

WORKING PROCEDURE

In general, leak detection of irrigation canals using remote sensing should go through the following procedure:

- Canal survey to determine the segments needed to evaluate
- Generate a GIS map to show geographic locations of the selected canal segments for pilot and imager operator
- Flyover to acquire imagery of the canal segments
- Processing of the imaging data
- Image analysis to identify suspicious leak points and potential seepage areas
- Field reconnaissance to verify image analysis

IMAGE PROCESSING METHODS

In the process of data acquisition three cameras, Red, NIR and Thermal, take pictures synchronously. This generates an image triple at each scene. After the airplane flies over a canal segment, a series of such image triples are obtained. The image data come with the files in the format of RAW (.raw). The name for each file contains the camera name, the acquisition time (hours, minutes, seconds), and the latitude and longitude. The "HEADER INFO" of the image data files comes up as:

Samples: 1024 (for Dalsas), 320 (for Merlin)
Lines: 1024 (for Dalsas), 240 (for Merlin)
Bands: 1
No Offset
Data Type: Integer
Byte Order: Host(Intel)
Interleave: BSQ

The procedure for image processing is as follows:

- Image format conversion
  After flyover, the image data are typically provided as in RAW format. When importing into a remote sensing software, the RAW image data will be converted to a format the software can manipulate.
- Image registration
  Registration is a process to transform the Red, NIR, and Thermal images from the scene into one coordinate system. Registration is necessary in order to be able to compare or integrate the data obtained from different measurements
- Image stack
  This function is to stack the three registered Red, NIR, and Thermal images into a composite image.
- Image geo-reference
  This process is to establish the relationship between page coordinates (i.e. x,y) of a planar map of image with known real-world coordinates (i.e. longitude/latitude, UTM, etc). Typically, ground control points (GCPs) can be collected with GPS technique. The collected GCPs can be used to geo-reference the images. A digital orthophoto quadrangle (DOQ) is a computer-generated image of an aerial photograph in which image displacement caused by terrain relief and camera tilts has been removed. It combines the image characteristics of a photograph with the geometric qualities of a map. All DOQ's are referenced to the North American Datum of 1983 (NAD83) and cast on the Universal Transverse Mercator (UTM) projection. Primary (NAD83) and secondary (NAD27) datum coordinates for the upper left pixel are included in the header to allow users to spatially reference other digital data with the DOQ. So, Digital Ortho Quarter Quads (DOQQ's) can be also used to geo-reference the images.
- Image AOI generation
  This function is to clip the images into the area of interest (AOI).
- NDVI image generation
  Based on the AOI composite image, the image of normalized difference vegetation index (NDVI) can be generated as:

  $$NDVI=(NIR- Red)/(NIR+Red)$$

  NDVI has been widely used for remote sensing of vegetation for many years for different sensors (Jensen, 1996).

ERDAS Imagine (Leica Geosystems, Atlanta, GA) will be used to process the image triples obtained in the flyover. With ERDAS Imagine, the major steps in image processing, such as image format conversion, image stacking and NDVI image generation can be implemented in batch, which help automate the processes. Other steps, such as image registration, image geo-reference and AOI image generation, are less difficult to run regularly than in batch specifically for the airborne image data over irrigation canals.

RESULTS AND DISCUSSION

On February 28, 2005, the airborne multispectral remote sensing system flew over pre-selected 24 canal segments over 8 irrigation districts in the Lower Rio Grande Valley, Texas (Figure 1 and Table 1). This flyover generated 439 image triples.

To process the image triples for each canal segment, the imaging points were overlaid on the GIS layers. Figure 1 shows a GIS map indicating a canal segment in Delta Lake and the imaging points on the DOQQ photograph.

The GIS map shows find that some of the imaging points may be out of the area of interest. Figure 2 indicates that among the thirteen imaging points, three of them are out of the area. Then, through quality checking, it was found that there seems to have an occasional glitch with the system, as sometimes the image from the Dalsa1 and/or 2 cameras were not correctly recorded. So, these out-of-area images and glitched images are excluded in image processing. The rest of the images are considered effective. Figure 3 shows the sequence and the condition of the imaging points over the Delta Lake canal segment. It indicates that besides three out of area imaging triples, there are three defect imaging triples. Seven imaging triples are effective and left for processing.

With ERDAS Imagine, image processing is conducted step by step through regular or batch operation:

- Image format conversion from RAW to IMAG band by band with batch operation
- Image registration between Red, NIR, and Thermal images with regular operation. In this process, image resampling could be run in batch. However, because GCPs are different in each of the image scenes and ERDAS Imagine does not generate the resampling data files before the batch operation starts, this results in that the batch operation for resampling is much more difficultly implemented than the regular operation.
- Image stack to generate a composite image containing individual band image, Red, NIR, and Thermal, with batch operation

Image georeferencing to DOQQ with regular operation with RMS errors all within 0.4 m

- For the same reason as in image registration, in this process, it is much more difficult to run image resampling in batch than in regular
- Image AOI generation to focus on the irrigation canal segments and adjacent areas with regular operation
- NDVI image generation to show the degree of vegetation along the canal segments and adjacent areas with batch operation

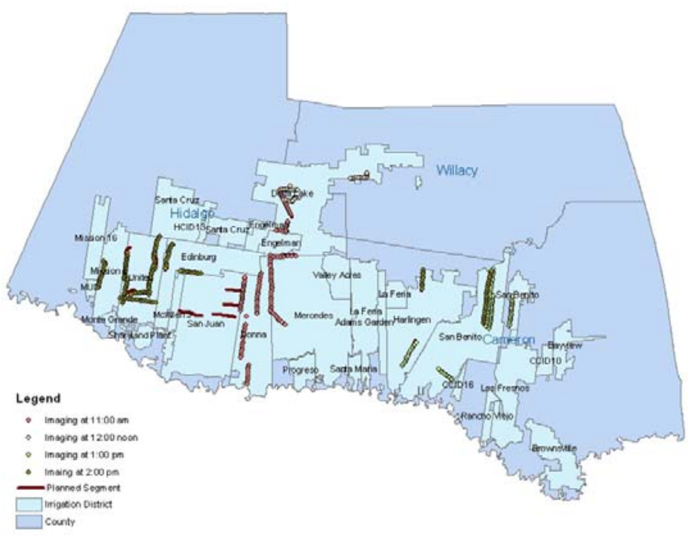

Figure 1. GIS map showing the imaging points over the canal segment in the valley.

Table 1. Description of image data acquired in flyover

Canal	Type	Irrigation District	Number of Image Triples
Mercedes	Lined	HCCWCID9	49
Donna	Lined	Donna ID	20
Donna	Lined	Donna ID	18
Donna	Lined	Donna ID	8
Donna	Unlined	Donna ID	8
Donna	Unlined	Donna ID	9
Delta Lake	Lined	Delta Lake ID	13
Delta Lake	Lined	Delta Lake ID	16
Delta Lake	Lined	Delta Lake ID	9
Delta Lake	Lined	Delta Lake ID	12
Delta Lake	Lined	Delta Lake ID	14
Harlingen	Unlined	Harlingen ID #1	15
San Benito	Unlined	CCID #2	10
San Benito	Lined	CCID #2	17
San Benito	Unlined	CCID #2	19
San Benito	Unlined	CCID #2	28
San Benito	Unlined	CCID #2	29
Harlingen	Lined	Harlingen ID #1	10
Mission	Lined	HCID6	14
United	Lined	United ID	31
United	Lined	United ID	45
Edinburg	Unlined	HCID1	19
Edinburg	Unlined	HCID1	14
Edinburg	Unlined	HCID1	12
24 canal segments	*14 lined and 10 unlined*	*8 irrigation districts*	*439 image triples*

Figure 2. GIS map showing the imaging points over the canal segment in Delta Lake.

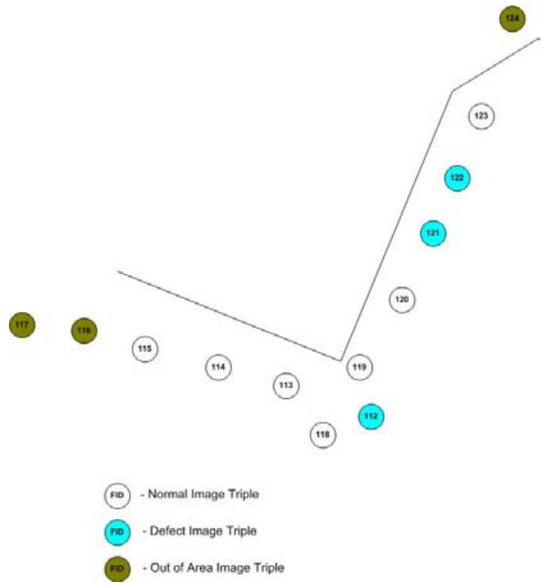

Figure 3. Flying sequence and condition of the imaging points over the Delta Lake canal segment.

Figure 4 shows the AOI imaging triple and the corresponding NDVI image at imaging point FID 113. The AOI images indicate that along the canal there is a wider drainage ditch. The canal section looked in fairly good condition but notice that on the levees there seemed to be a significant amount of vegetation. The NDVI image indicates that the levees of the canal section and the drainage ditch were full of vegetation (bright part on the image). The images were acquired in February. The NDVI image indicates that then, in the fields, there were no crops but bare soil. The levees presented strong vegetation.

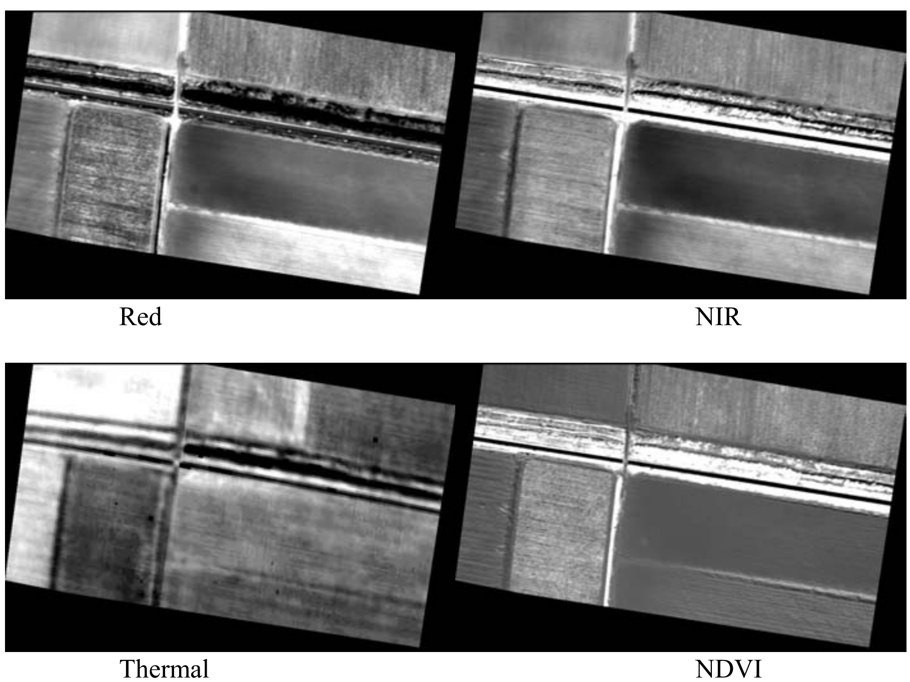

Figure 4. AOI imaging triple and the corresponding NDVI image at imaging point FID 113.

On June 28, 2005, field reconnaissance was performed on four concrete canal segments in Delta Lake, Mission, United and Mercedes. Figure 5 is the picture of the canal segment under the imaging point FID 113. The drainage ditch is on the right side of the canal under the thick bushes. The canal section seemed to be in fairly good condition in general. The grass on the levees presents the potential seepage from canal and/or ditch side. On the right side of the canal, the grass came out around the structure and from the cracks of concrete, which are the points of leaks. The thermal image presents signatures on that also.

Figure 5. Picture of canal segment under the imaging point FID 113.

Figure 6 shows the AOI imaging triple and the corresponding NDVI image at imaging point FID 114. The AOI images also indicate that along the canal there is a wider drainage ditch. The canal section looked in fairly good condition also. The levees presented strong vegetation. It is noticed that the circled area in the thermal AOI presented a much cooler signature than adjacent area.

Figure 7 shows the canal segment under the imaging point FID 114. The drainage ditch is on the right side of the canal under the thick bushes. The canal section did look in fairly good condition in general. The grass on the levees presents the potential seepage from canal and/or ditch side. At the beginning on the left side of the canal there is a big hole on concrete, which should be a significant point of leak. The thermal image presents a cooler signature in that area.

Figure 8 shows the AOI imaging triple and the corresponding NDVI image at imaging point FID 115. The AOI images indicate that the drainage ditch ends at the road. The canal section looked to be in fairly good condition in general. The levees presented strong vegetation. The circled area in the Red and NIR presents strong vegetation, and the corresponding NDVI image reveals that there was a big tree there, and between the tree and the canal was a shadow. The Thermal image indicates that the area around the tree was cool, and the south side of the canal is cooler than the north side.

Figure 9 shows the canal segment under the imaging point FID 115. The canal section did look to be in fairly good condition in general. The south side of the canal had more grass than the north side, which implies the south side had more seepage or leaks. The picture also shows the tree and the shadow between the tree and the canal, which can not relate to the seepage or leak.

The AOI image triples and the corresponding NDVI image at rest of the imaging points for this and other canal segments were similarly used for leak point determination, seepage area identification and field verification. So far, the images of four concrete canal segments in Delta Lake, Mission, United, and Mercedes irrigation districts were processed, and the field reconnaissance on these four segments were performed. Overall, the analysis of the images was verified well by field inspection.

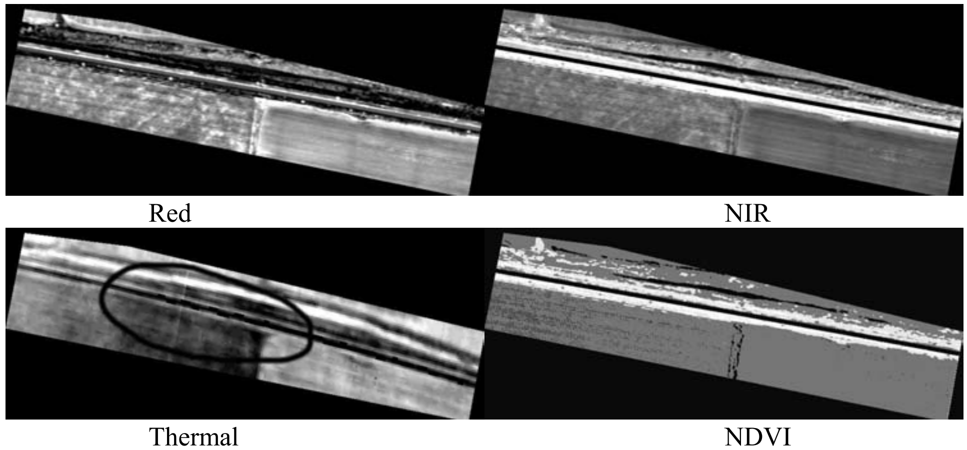

Figure 6. AOI imaging triple and the corresponding NDVI image at imaging point FID 114.

Figure 7. Picture of canal segment under the imaging point FID 114.

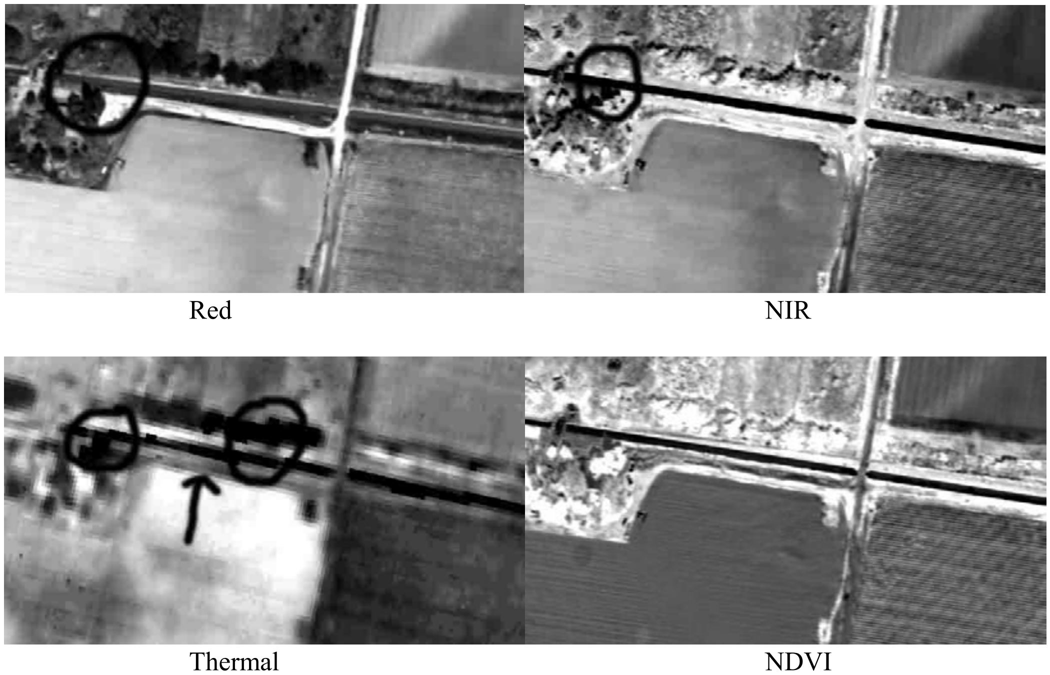

Figure 8. AOI imaging triple and the corresponding NDVI image at imaging point FID 115.

Figure 9. Picture of canal segment under the imaging point FID 115.

CONCLUSIONS

Through this research it can be concluded that airborne multispectral imaging is a promising technique for evaluation of canal conditions and leak detection in irrigation distribution networks. The combination of Red, NIR and Thermal sensors is effective in determining the leak points and identifying the potential of seepage in irrigation canals. The methods and results of this research should provide irrigation districts with a useful tool and information for their management and decision making.

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