APPLICATIONS AND LESSONS LEARNED WITH AIRBORNE MULTISPECTRAL IMAGING

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ABSTRACT

Airborne digital frame cameras offer a cost-effective, widely-distributed, and versatile technology that is underutilized by geologic remote sensing. Sensors can include one, four, or more digital cameras simultaneously recording selected wavelength bands of reflected visible and near-IR light. These cameras can be used to provide up-to-date and spectrally-rich images for many geological applications, including infrastructure, natural hazards, nearshore environments, neotectonic zones, and outcrops. New images can be rapidly collected and interpreted with this technology at highly competitive spatial resolutions (1 foot to 2 meters), ranging between film-based photography and space-borne imagery. The imagery can be used for detection or for mapping at planning scales. Low cost, single-engine aircraft are routinely used for the acquisitions. New acquisitions can be ordered through commercial sources. Some of the vendors use airborne differential GPS and Inertial Motion Units (IMU's) mounted on the camera to improve mapping accuracy and turn-around.

The digital images can be processed, mosaicked, and rectified to varying degrees of x,y accuracy using off-the-shelf software for integration into a GIS. There are significant challenges meeting cartographic accuracies required for engineering applications with these sensors. Providers of this technology need to understand the inherent limitations to ensure client expectations are met, especially if the imagery and derived products are integrated with digital orthophotographs, parcel maps and tabular databases using GIS. Human intervention and interpretation ensures a more accurate spectral classification. Draping the enhanced imagery and/or classification over a DEM enables synthetic stereo pairs and anaglyphs to be constructed, improving interpretations and presentations. If appropriately implemented, airborne multispectral imaging can greatly expand business opportunities for the geologic remote sensing community.

1.0 INTRODUCTION

This paper addresses digital frame cameras that collect imagery in the VNIR spectrum (visible light to near-infrared). The technology, its limitations and strengths, the importance of planning, scope of image processing, and costs are key elements to understand in order to appropriately use the cameras for geological applications. Many companies can acquire the imagery, usually using low cost, single-engine aircraft. Users have to decide between the advantages and disadvantages of single and multi-camera (multispectral) systems.

2.0 OVERVIEW OF AIRBORNE CAMERA TECHNOLOGY

Typically, these cameras have arrays that range from 1024 x 1024 to 2000 x 3000 lines and samples. Most cameras record an 8-bit to 12-bit B&W image (256 to 4096 levels of gray). The shutter is either mechanical or electronic. The exposure time and aperture setting (f-stop) is adjusted prior to flying depending on conditions and the brightness of the features of interest. Each frame is "instantaneously" recorded, so unlike hyperspectral line scanners, there is minimal geometric distortion due to aircraft motion during acquisition. The altitude of the aircraft and the focal length of the lens determine the ground sampling distance (gsd). Most imagery is acquired with gsd's between 1 foot and 2 meters. For a typical camera, 1-meter pixels are acquired ~2,000 meters (~7000 feet) above

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ground level (AGL). The area imaged at 1-meter gsd with a 1000 x 1500 array would be 1 km x 1.5 km. The digital image would contain 1,500,000 pixels and would be 1.5 MB in size, given an 8-bit camera. This small file size makes this technology ideal for rapid turn-around and PC-based image processing. Most digital cameras are VNIR systems (capable of recording reflected visible to near-infrared light). A filter is placed over the lens (in some systems the filter is inserted behind the lens in the optical path) that transmits only selected portions of the wavelength spectrum. For a single camera operation, the filter is usually chosen that generates natural color (blue-green-red wavelengths) or color-infrared (green-red-nearIR wavelengths) imagery.

For multiple camera operation, filters that transmit narrower bands of light are chosen. For instance, a four-camera system may be configured so that each camera's filter passes one of the following bands of light (center value followed by +/- range):

Blue:	450 +/- 80 nanometers
Green:	550 +/- 80 nanometers
Red:	650 +/- 80 nanometers
NIR:	850 +/- 200 nanometers

Each camera will record an individual B&W image that represents either reflected blue, green, red, and near-infrared light. Aperture settings (f-stops) are typically different for the visible light and the near-IR cameras. The four-camera system can be configured so that it acquires imagery that is very similar to the 4-band, Landsat 1,2,3 MSS sensor. A common digital camera is the Kodak 420 and 460 series. These cameras use Kodak's proprietary RADC (Run Adaptive Differential Coding) image compression. The images are downloaded to hard disk card or flash memory card immediately after acquisition. The camera has an ISO range of 200 to 800 for the black-and-white model. A vignetting algorithm can be applied to each frame of imagery to minimize radial drop-off in reflected light energy due to the curvature of the lens.

2.1 GEOMETRIC CALIBRATION

The geometric quality of each frame of imagery is determined by the quality of the array and also by the quality of the lens. Lens quality has been improving as customers are demanding more geometrically accurate images. Photogrammetric film-based cameras have calibrated lenses. Digital camera lenses are beginning to undergo some level of calibration to improve generating maps from the imagery. Ground control points (GCP's) and a digital orthophotograph can be effectively used to georeference or rectify each frame to map space. If a DEM is available, "orthorectification" can be achieved, but the x,y accuracy of each pixel is dependent upon the quality of the DEM. Photogrammetric techniques are being used with stereo, digital-camera imagery to derive an up-to-date DEM to support orthorectification and a more accurate x,y location for each pixel. Newer digital camera systems have an inertial motion unit (IMU) attached that provides camera attitude. Combined with aircraft differential GPS, these IMU's can locate each frame to within 3-15 pixels of true x,y location (depends on the quality of the IMU and other factors during acquisition; Mostafa and others, 1998). Accurate x,y locations for each pixel can be achieved by integrating GPS, IMU, GCP's, and DEM's.

2.2 BAND-TO-BAND REGISTRATION

With multi-camera systems, a band-to-band registration algorithm must be implemented. Some band-to-band registrations use an automated, image edge-matching technique to align the individual B&W images from each of the cameras. The algorithm generates image-to-image control point files that can be re-created for each image as they are processed, or the control points derived from the first frame at the beginning of a flight line can be applied to all the frames along that flight line. The alignment of the cameras (the direction each camera points) needs to be excellent so that there is minimal pixel offset between the frames. Poor camera alignment degrades the effectiveness of the IMU and tends to degrade the band-to-band registration. Using matched lenses of superior quality improves band-to-band registration, as does a good algorithm. If the bands are poorly registered, the multispectral imagery will be blurry, interpretations will be degraded, and classifications will be less accurate.

2.3 RADIOMETRIC CALIBRATION

Several digital camera models were not designed for airborne operation. They are *not* radiometrically calibrated nor is there much effort made to ensure the camera's radiometric performance in the field. There is no compensation for variability between detectors on the CCD array, system noise, or correlation of radiance with each f-stop or shutter speed. Images collected by these systems cannot be used with sophisticated and/or automated classification algorithms. Nevertheless, there is significant spectral information within each band. Excellent color images can be generated and decent land-use classification can be done if they are supported by significant operator intervention. Frame cameras that are designed for airborne operation and that are radiometrically calibrated enable the user to accomplish sophisticated, automated, and time-sequential classifications. However, there can be significant overhead to characterize and radiometrically calibrate a sensor in the lab and to monitor the calibration in the field.

Camera and system limitations, along with changes in sun angle and atmospherics during the acquisition program, vary the amount of reflectance recorded by digital cameras and can result in subtle (and occasionally not-so-subtle) variations in color between some frames and some flight lines. These variations can be disconcerting to the client. Color balancing programs are more effective with one-camera systems compared with multiple-camera systems. For a given feature, variations in color between frames needs to be taken into account by the analyst during any classification or interpretation process.

3.0 PLANNING

Flight planning is essential for good imagery. New images can be rapidly collected and interpreted with this technology at highly competitive ground sampling distances (gsd's - 1 foot to 2 meters) that range between film-based photography and space-borne imagery. Depending on the application, most imagery should be flown +/- 2.5 hrs of local noon. The imagery is usually flown with a sidelap of 30% and a forward lap of 30% to ensure no gaps and to ensure that the optimum central portion of each frame is available for a digital mosaic. If the frames are rectangular with the larger dimension perpendicular to the axis of the aircraft, then the flight lines should be flown North-South to minimize sun glint.

For aerial acquisition, a concern is the time it takes to move the newly acquired image from the array to some storage device. This recycling time determines how often an image can be acquired as the aircraft progresses along the flight path. For the larger arrays our experience with one system has been 20 seconds. This imaging limitation becomes critical with decreased altitude (smaller gsd) and increased forward lap (e.g. 60% for stereo coverage). For one high-spatial resolution, stereo-overlap program, our aircraft acquired every other frame on one pass along the flight line followed by another pass where they acquired the missing frames, creating stereo coverage along the entire flight line. Teaming with local aerial photogrammetrists to design flight programs and to improve understanding of critical x,y issues that impact client satisfaction is recommended.

4.0 IMAGE PROCESSING

Vignetting, color balancing, and band-to-band registration (for multi-camera sensors) are routinely applied to each frame. Each B&W image can be sharpened with edge-enhancement filters. The frames can be worked individually or combined into a digital mosaic. If there is sufficient overlap, stereo pairs can be developed and either printed or loaded onto a stereoscopic computer system for heads-up interpretation. If a four-camera sensor is employed, different color composites can be created (see Figure 1). Principal components and ratio algorithms can be applied to the multi-camera data. Draping the enhanced imagery and/or classification over a DEM enables synthetic stereo pairs and anaglyphs to be constructed, improving interpretations and presentations.

The digital images can be processed, mosaicked, and rectified to varying degrees of x,y accuracy using off-the-shelf software for integration into a GIS (Figure 2). Typically the digital frames are georeferenced or rectified to a digital orthophotograph (e.g. USGS DOQQ) to closely position each pixel to their true ground location. With manual systems, approximately 5-25 control points can be selected between each digital camera frame and the orthophotograph. An image-to-image rectification program can then applied to digitally warp each frame to the orthophotograph. After each frame is tied to the orthophotograph, a mosaicking program is applied that selects the optimum area of each frame and digitally feathers seams (while minimizing misalignments) between overlapping frames. Color balancing of multi-camera systems is difficult, so often the digital mosaics have areas with excessive color variation between frames.

Features recorded with three or more cameras are typically classified based on their spectral characteristics. Uncalibrated multi-camera systems have limitations that necessitate an experienced image processor evaluating the spectral classification and upgrading it with human-determined spatial information (size, location, texture, context, etc.). We have found that with these systems the same ground feature may have a digital number (DN) or range of digital numbers recorded that is *not* consistent across a number of frames. The classifier must look at the entire area prior to beginning work to determine the range of color variation that can be ascribed to radiometric limitations. Once this comprehensive manual overview is completed, the impact of the color variation for any given feature can be minimized. Human intervention and interpretation ensures a more accurate classification. Digital classification of features, based on spectral characteristics, is superior with multispectral digital camera imagery as compared with scanned color and color IR film.

5.0 APPLICATIONS

Digital imagery collected by single and multi-camera systems are excellent planning tools. The imagery can be used for detection or mapping. Regional mapping can be done using large digital mosaics (Figures 2 and 3), District-wide mapping with smaller mosaics (Figure 4), and local mapping with single frames (Figure 5). The spectral richness of color or color-IR imagery collected with single digital camera is comparable to film photography, while multi-camera imagery (multispectral) is spectrally superior to film photography. Often the digital imagery is used to update features seen on older USGS DOQ's (Figure 6). USGS DOQ's are effective basemaps for georeferencing or rectifying each digital camera frame. After georeferencing, individual frames of features of interest can be integrated with other maps within a GIS (Figure 7). This is a very effective presentation tool to focus the client on the value of the imagery and/or classifications derived from the imagery.

Change-detection is effectively accomplished with digital camera imagery. Figure 8 shows changes captured with a four-camera airborne system compared with a color digital orthophotograph that is 2-3 years older. However, *parcel-level* interpretations, classification, land-use statistics, taxation, and litigation are <u>not</u> appropriate applications due to inherent mapping limitations of current airborne digital camera technology. There are significant challenges meeting cartographic accuracies required for engineering applications with these sensors. Providers of this technology need to understand the inherent limitations to ensure client expectations are met, especially if the imagery and derived products are integrated with digital orthophotographs, parcel maps and tabular databases using GIS. Under the <u>best</u> of conditions (*including* flat terrain), we have found that features on digital mosaics will be within ~3 pixels of their true x,y location. Across open, sparsely populated terrain with topographic relief and where little ground control is available, the absolute location error can increase to ~5-10+ pixels.

6.0 COSTS

Commercial, single-camera systems are often for rent at aerial photography companies. The cost of flight planning, contracting an aircraft (with pilot and camera operator) for a 2-hour local mission, and acquiring ~10 overlapping frames with a 2000 x 3000 array at 1 meter gsd may approach $2500. The geographical area imaged would exceed ~10 x 30 km in color or colorIR. Processing (including georeferencing and digital mosaicking) could add another $1500, depending on the airborne system's technology. Multi-camera systems represent more significant investments. A basic acquisition may cost from $5000-$9000 while processing (including band-to-band registration) may add another $2000 for ~300 sq. km. coverage of multispectral imagery. Several companies build or provide multi-camera services.

7.0 ACKNOWLEDGMENTS

The aircraft crews, photogrammetrists, and orthorectifying specialists at HJW have been very helpful upgrading our understanding and use of digital frame cameras. In particular, Neil King, Supervisor of HJW's Ortho Department, has been very supportive helping us implement software solutions and explaining geometric and radiometric issues.

8.0 REFERENCES

Mostafa, M.M.R., K-P Schwarz, and P. Gong, "GPS/INS Integrated Navigation System in Support of Digital Image Georeferencing," *The Institute of Navigation 54th Annual Technical Meeting*, Denver, CO, 9 p., 1-3 June 1998.

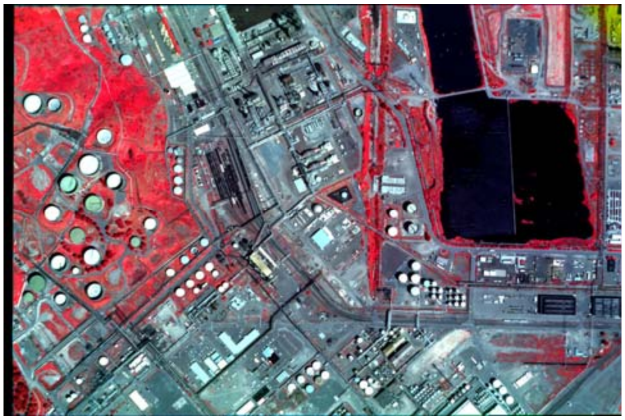

Figure 1. Single frame (1000 x 1500) of multi-camera digital image rendered in color IR of a refinery.

Figure 2. Digital mosaic of ~75 frames of single-camera imagery. Dark area in center is burned forest. GSD = 2 meters. USGS DOQ was the base for georeferencing. Turn-around time <5 days. Imagery acquired with colorIR filter.

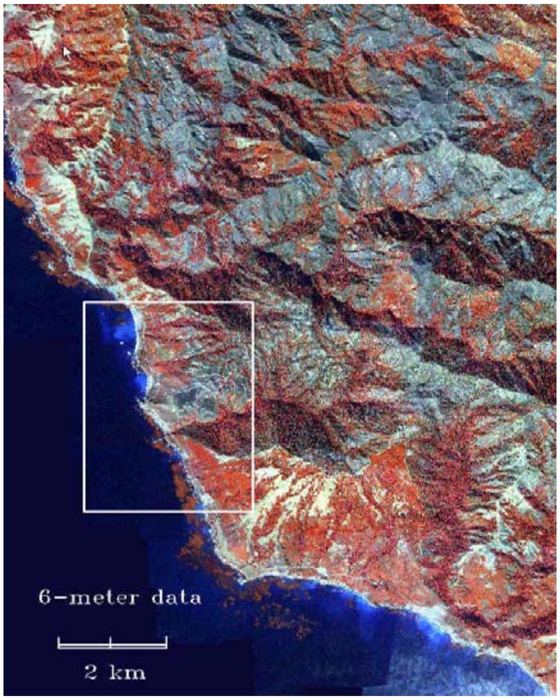

Figure 3. ColorIR mosaic of ~20 single camera frames of mountainous coastal area for regional mapping. Pixels resampled to 6 meters for 1:24,000 scale plotting. Area in white outlined box in Figure 4.

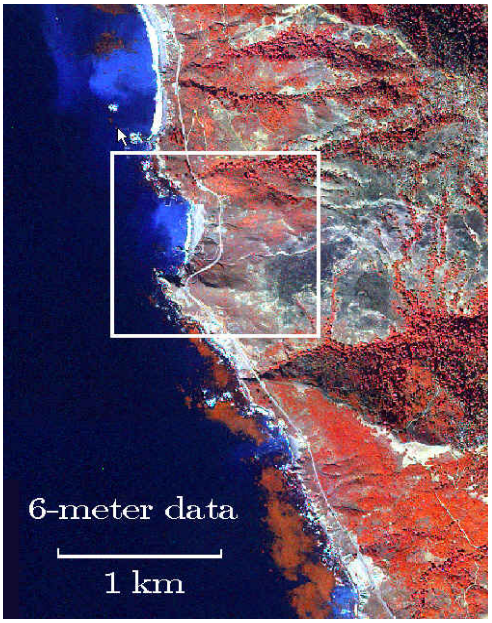

Figure 4. ColorIR mosaic containing ~6 single-camera frames. Pixels resampled from 2 to 6 meters for plotting. Kelp beds are seen offshore.

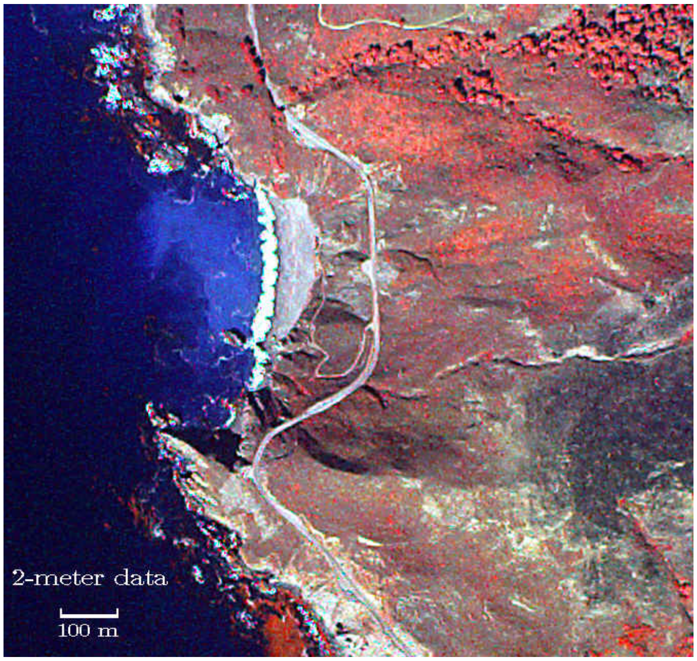

Figure 5. Zoom-in of color IR mosaic (see Figures 3 and 4) from single-frame camera for local mapping. Roads, outcrops, surf, beach, and vegetation are clearly depicted. Georeferenced to 1:24,000 base.

Figure 6. B&W USGS DOQ photograph for comparison to digital frame camera image (Figure 5). The USGS DOQ served as the 1:24,000 base for rectification of new digital color IR imagery.

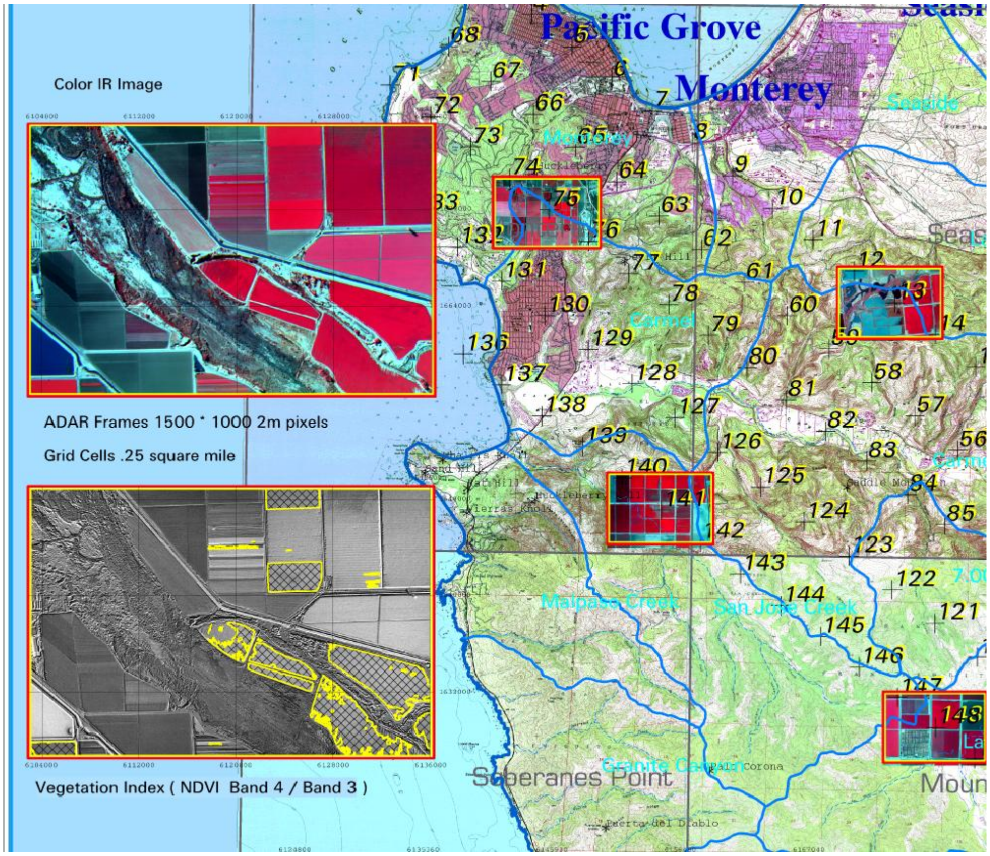

Figure 7. Example of georeferenced frames being superimposed on basemap. HJW creates flight line maps showing centerpoints of imagery. Multi-camera imagery is depicted that has been processed for a vegetation index.

Figure 8. Left image is from a low-cost digital mosaic of airborne multi-camera frames. Right image is 2-3 years older and from a highly accurate and costly color orthophotograph. Note changes in land use.