Monitoring Geothermal Activity in Yellowstone National Park Using Airborne Thermal Infrared Remote Sensing

CMU Neale [*a], S. Sivarajan[a], O. Z. Akasheh[b], C. Jaworowski[c], H. Heasler[c]

[a] Biological and Irrigation Engineering Dept., Utah State University, Logan, Utah, USA
[b] CALMIT, University of Nebraska,313 Hardin Hall, Lincoln, NE 68853-0973, USA
[c] Yellowstone Center For Resources, Yellowstone National Park, WY 82190, USA

ABSTRACT

High-resolution multispectral images in the green (0.57 µm), red (0.65 µm), near-infrared (0.80 µm) and thermal infrared (8-12 µm) bands were acquired using the Utah State University airborne multispectral system over several active geothermal areas in Yellowstone National Park as part of an ongoing monitoring program initiated in the Fall of 2005. The imagery was acquired under clear sky conditions at two different times of the day, early afternoon and midnight, with the objective of studying the geothermal properties of the different active thermal areas in the park as well as providing calibrated thermal imagery for long-term monitoring of changes. The paper will describe the image acquisition and processing methodology, as well as surface emissivity and atmospheric corrections conducted to obtain at-surface temperatures. Examples of the products obtained over different areas will be shown and discussed.

Keywords: Thermal infrared remote sensing, geothermal features, airborne remote sensing

1. INTRODUCTION

Remote sensing in the thermal infrared part of the spectrum has been used in the past in many satellite based applications such as the estimation of energy balance terms and evapotranspiration over large agricultural areas[1,2,3,4]. Presently, several satellite sensors such as the LANDSAT Thematic Mapper; the ASTER and MODIS instruments of the Earth Observation System satellites provide thermal infrared imagery. Unfortunately this thermal imagery has medium to low spatial resolution (60 to 1000 meter pixels) and though it covers large areas, it is not adequate for identifying and measuring the temperature of small pools and springs and the surrounding thermal features that occur at much finer spatial scales in Yellowstone Park. In the thermal infrared band using commercially available technology, monitoring at high spatial resolution can only be attained through airborne remote sensing.

Airborne thermal infrared remote sensing is a proven method of obtaining high-spatial resolution thermal imagery. Several applications using thermal imagery can be found in the literature. For example, Torgesen et al, (2001)[5], used airborne thermal remote sensing to assess water temperatures in rivers and streams, related to fisheries habitat. Quattrochi and Luvall (2003)[6] presented several applications using airborne and satellite based thermal infrared applications to retrieve surface parameters and processes.

The Utah State University airborne multispectral digital system contains a precision thermal infrared imager that has been used in numerous applications that require high-resolution data. For example, Chavez et al, (2005)[7] used thermal infrared imagery with 6-meter pixel resolution to map the spatially distributed energy balance terms (net radiation, soil heat flux, sensible heat flux and latent heat flux) and compared with ground measured fluxes using eddy covariance flux towers and footprint functions.

Yellowstone National Park (YNP) receives over 2 million visitors per year. Most of the park is geographically located in the caldera of a volcano and thermal activity manifests itself at the surface through geysers, hot springs, mud pots and fumaroles, all popular tourist attractions. These thermal features are constantly changing as a result of tectonic movements which re-route underground courses of water and steam and need to be monitored continuously for the protection of the public. Due to the sometimes rapid change in the extent and temperature of some of these

[*] christopher.neale@usu.edu ; phone +1 435 7973689; fax +1 435 7971248

springs and surrounding thermal features, a cost effective and accurate method needs to be developed for their continuous long-term monitoring.

In 2005, YNP entered into a cooperative research agreement with Utah State University (USU) for the purpose of using airborne remote sensing technology for monitoring thermal activity in the park. This paper describes the methodology in acquiring and processing the imagery to obtain calibrated thermal mosaics of active geothermal areas as well as details of the monitoring program.

2. METHODOLOGY

2.1 Description of the Airborne Remote Sensing System

The present generation of the USU airborne multispectral digital system is based around three Kodak Megaplus 4.2i Digital Cameras with the imaging sensor producing images with approximately 2000 x 2000 pixels[8]. The spectral bands are obtained with interference filters centered in the green (0.55 µm), red (0.67 µm) and near-infrared (0.8 µm) portions of the electromagnetic spectrum. The cameras are mounted in a high-grade aluminum/carbon composite mount installed through a porthole in the belly of a Cessna TP206 single engine aircraft, dedicated to remote sensing. A FLIR SC640 thermal infrared camera is used to thermal images in the 8 – 12 µm range. This instrument is mounted through a different porthole aligned with the multispectral system cameras. Prior to 2008, an Inframetrics 760 thermal scanner was also used. Both the digital and thermal infrared cameras are controlled by boards and software installed in a fast PC computer with two 500 GB hard drives for storage of the imagery. Details of the multispectral system and thermal infrared camera installed in the Cessna TP206 aircraft can be seen in Figure 1.

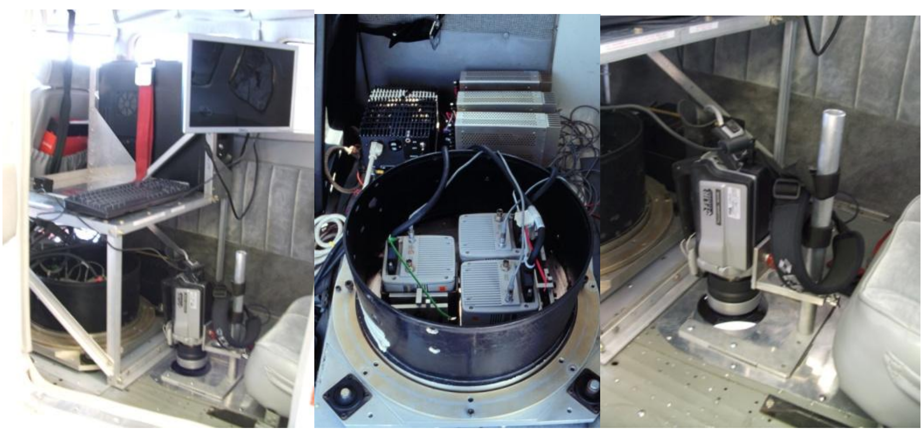


Figure 1 Details of the USU airborne multispectral remote sensing system and FLIR SC640 thermal IR camera installed in the Cessna TP206 remote sensing aircraft.

2.2 Image Acquisition and Processing

High-resolution shortwave (3 bands) and thermal infrared imagery were acquired with the USU airborne digital system over different areas of the park, according to the monitoring program devised by the YNP technical personnel and USU. The pixel resolution in the shortwave bands was 1-meter while in the thermal IR it varied between 1 to 3.5 meters depending on the study area and objectives. Flight lines were planned to ensure 30% overlap between images in parallel flight lines and 80% overlap along the flight lines to guarantee complete coverage over the study areas.

The image acquisition over-flights were planned to occur in early September, during night time hours, under clear sky conditions, when usually the colder air temperatures are attained due to radiative cooling of the surface. A typical nighttime image acquisition campaign ranged from 11:30 pm to 3:00 am. The study areas are usually over flown a couple of times at the beginning of the mission in order to set the initial temperature range of the thermal IR camera or scanner and make sure it is in focus. The Inframetrics 760 scanner used in 2005 and 2006 required the range of temperatures to be carefully set to avoid saturation of the image over really hot spots which can reach up to

90 ºC.   Contrast sometimes was lacking on the imagery due to the wide range of possible temperatures from freezing or below zero on exposed soil in non-thermally active areas to really hot spots within the thermally active areas.   These images were stored on S-VHS tapes and later frame-grabbed at a 60% overlap for processing. The new SC640 camera has a different sensor technology and is fully digital and non-interlaced resulting in crisper images. The camera is set to always acquire imagery with the range of -40 and 120 ºC, so saturation of the pixels is always avoided in this case. The images are stored on a computer disk in a digital movie format and later extracted using software at the appropriate overlap and contrast.

Additional flights were conducted during the daytime around 1:00 to 2:00 pm local time under clear skies, usually the hottest time of the day in order to acquire multispectral shortwave imagery and additional thermal imagery. The thermal imagery from the daytime flight can be used along with the nighttime imagery usually acquired approximately 12 hours prior, to study the thermal inertia of the surface materials around the thermal features.   The shortwave band imagery was acquired at 1-meter spatial resolution.

2.3 Image Processing

The individual spectral band images from the digital cameras of the USU system are 2012 x 2014 pixels in size, thus at 1-meter pixel resolution, each image covered and area of approximately 2 x 2 Km. The single band images were first corrected for lens vignetting effects[9] and for lens radial distortions[10] and registered into 3-band images ready for geo-rectification. This was accomplished using common control points obtained from a digital color-IR orthophotoquad produced by the Wyoming Geographic Advisory Committee. A 3rd order polynomial transformation was used. The rms error for the individual image rectification was less than one meter. The rectified images were then mosaicked along the flight lines forming image strips. These strips were calibrated to a reflectance standard using the system calibration obtained through a similar procedure as that described by Neale and Crowther (1994)[9] along with the incoming irradiance from the sun and sky measured every minute using an Exotech radiometer with similar bands placed overlooking (from nadir) a standard reflectance panel with known bi-directional properties.   The panel setup was positioned in a central location in the Park. Once the image strips were calibrated, they were stitched together forming a mosaic covering the entire study area.

The calibrated 3-band mosaic was then used as the base map for rectification of the thermal imagery as it was acquired on the same date and better represented the surface conditions at the time. Each thermal image was rectified using common control points and then stitched together along the flight lines to form image strips. These were then calibrated using the camera calibration to obtain at-aircraft temperatures. Several calibrated strips would be stitched together to form a mosaic covering the study area.

The at-aircraft temperature image was corrected for atmospheric effects using the MODTRAN radiative transfer model[11].   Radiosonde data from a nearby weather station was used to obtain the profile of air temperature, dew point temperature and pressure between the surface and the aircraft altitude, required by the model. The correction for surface emissivity was based on the technique by Brunsell and Gillies (2002)[12], where the scaled Normalized Difference Vegetation Index (NDVI) obtained from the calibrated 3-band image mosaic was used to obtain a fraction of vegetation cover layer and linearly scale the emissivity of the surface between bare soil (0.92) and full dense vegetation cover (0.98).   Water was treated separately. A quick classification of the 3-band image was conducted to extract a water body mask and used in a model within ERDAS Imagine to assign an emissivity of 0.985 to clear water surfaces present in the scene. Finally the emissivity layer and the at-aircraft temperature image corrected using the MODTRAN results are used in a model to obtain the at-surface temperature image.

3. RESULTS AND DISCUSSION

One of the main monitoring areas is the Upper, Midway and Lower Geyser Basin, approximately 22 Km in length and 12 Km in width and is shown on the left side of Figure 2 mapped using the high resolution 3-band mosaic product generated from imagery acquired during the 2005 image acquisition campaign. Over 300 individual 3band images at 1-meter pixel resolution were used to produce this product with the appropriate overlap between images and among the flight lines. The yellow box shows this area enlarged at full resolution on the right-hand side of the figure. Portions of the corresponding thermal IR mosaics are shown in Figure 3 for daytime and nighttime flights obtained during the 2005 campaign using the Inframetrics 760 scanner. Details of the Old Faithful geyser and the hot springs in the surrounding area can be seen in Figure 4, where 1-meter pixel resolution imagery is displayed acquired using the FLIR SC640 camera.

Additional high resolution imagery from the Upper Geyser basin acquired with the FLIR SC640 can be seen in Figure 5. The high pixel resolution allows for the detection of the temperatures of the pools and geysers, which include the Oval Spring and Grand Geyser in the southwest corner of the image, Calida Springs, Comet and Daisy Geysers in the northwest corner of the image.

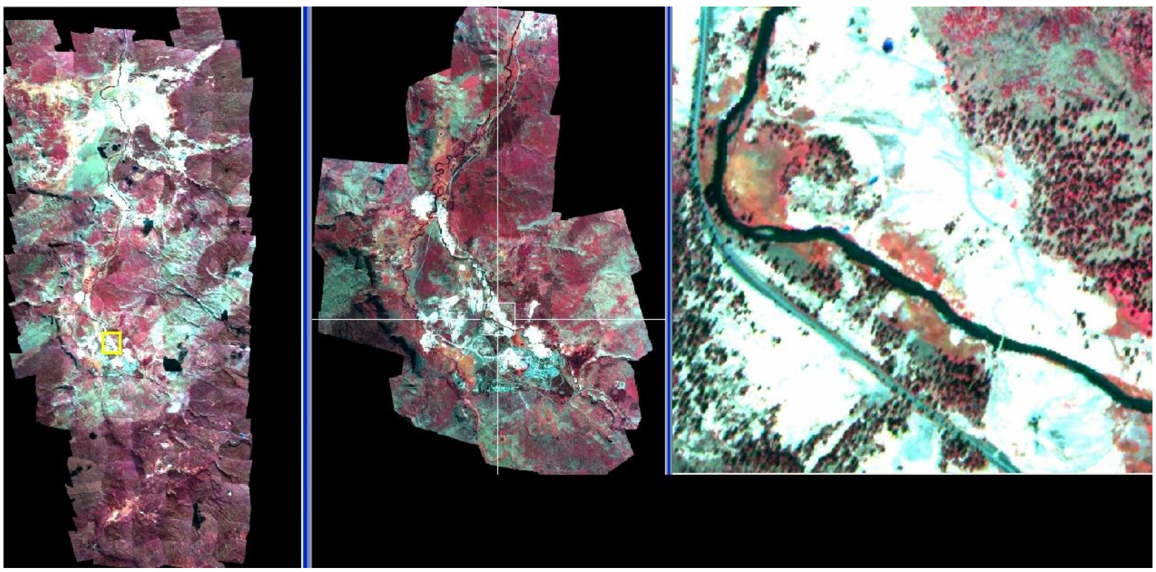
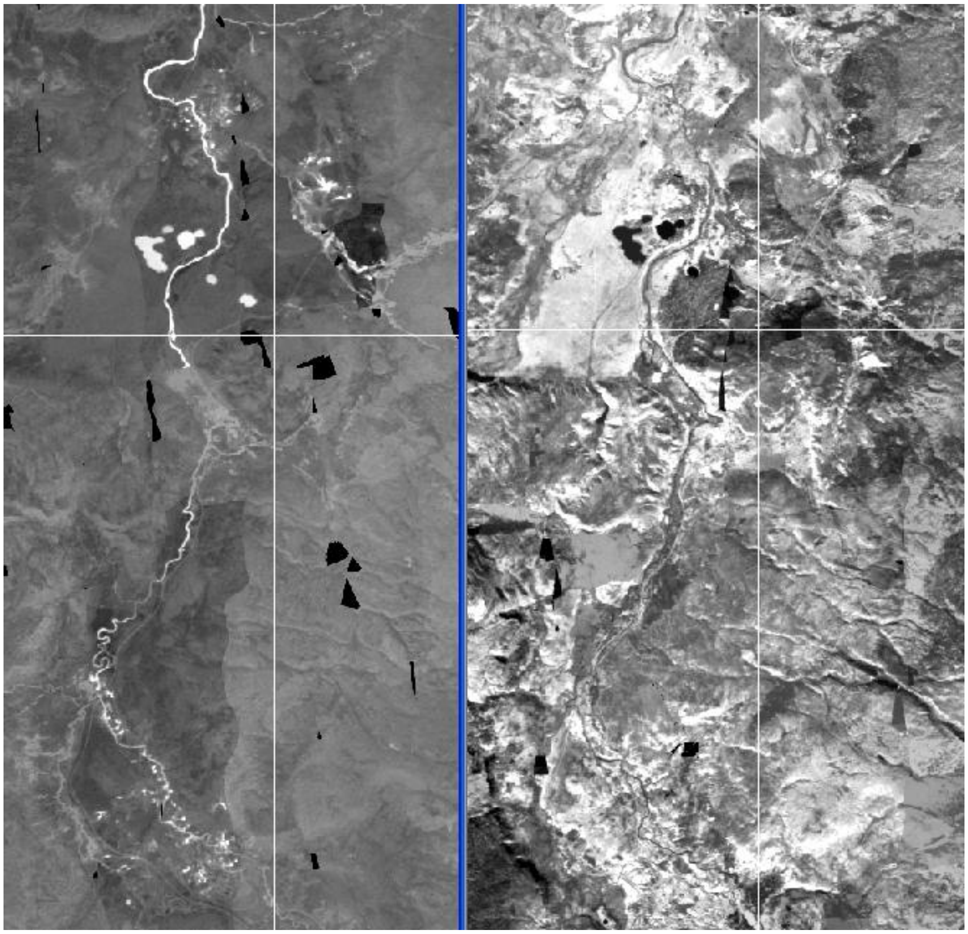


Figure 2 A 3-band mosaic of the Upper, Midway and Lower Geyser Basin Study Area.

The retrieved temperatures from the airborne imagery were compared with measured pool temperatures by the Park Service technical personnel using thermocouples and loggers. Discrepancies of a few degrees between the retrieved and observed temperatures were found. Several factors could be causing these differences: (1) steam generated above the hot pools could mask the true surface temperature of the water, (2) the position of the water temperature sensors could be a few centimeters below the surface and thus measuring warmer temperatures than the surface skin temperature which could be cooler if no turbulence were present to provide mixing of the water, (3) differences in time between the logged temperatures and the image acquisition flight, (4) errors in calibration of the imagery. These issues need to be sorted out by conducting a ground-based field experiment over a thermal feature to examine the cyclical nature of the daily and seasonal surface temperatures and energy balance. In addition, the effect of steam on thermal infrared measurements of water temperature and surrounding surfaces needs to be examined.



(a) (b)

Figure 3 Surface temperature images of the Upper, Midway and Lower Geyser basin obtained from calibrated airborne thermal IR imagery for nighttime (a) and daytime (b) image acquisition flights on September 15, 2005.

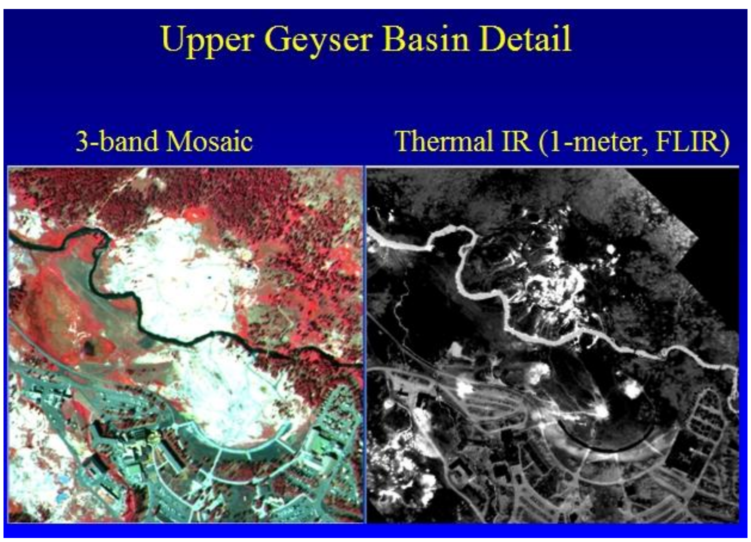


Figure 4 Detail of the 3-band multispectral and thermal infrared imagery of the Old Faithful Geyser and surrounding areas acquired with the USU airborne system.

4. CONCLUSIONS

Airborne thermal infrared remote sensing has the flexibility to provide imagery with the appropriate spatial resolution and optimal timing for monitoring small-scale thermal features in Yellowstone National Park. Future research should study how solar thermal heating and cooling at different times of the year affects the retrieval of accurate and reproducible surface temperature of thermal features, according to the timing of image acquisition. In addition, the effects of steam generated by hot pools and vents on the retrieval of true surface temperature under different conditions of air temperature and humidity needs to be examined.

Reproducible results from year-to-year are the goal of this research with the ultimate objective of estimating the heat flow from the different active thermal areas in Yellowstone Park and detecting changes in these thermal areas.

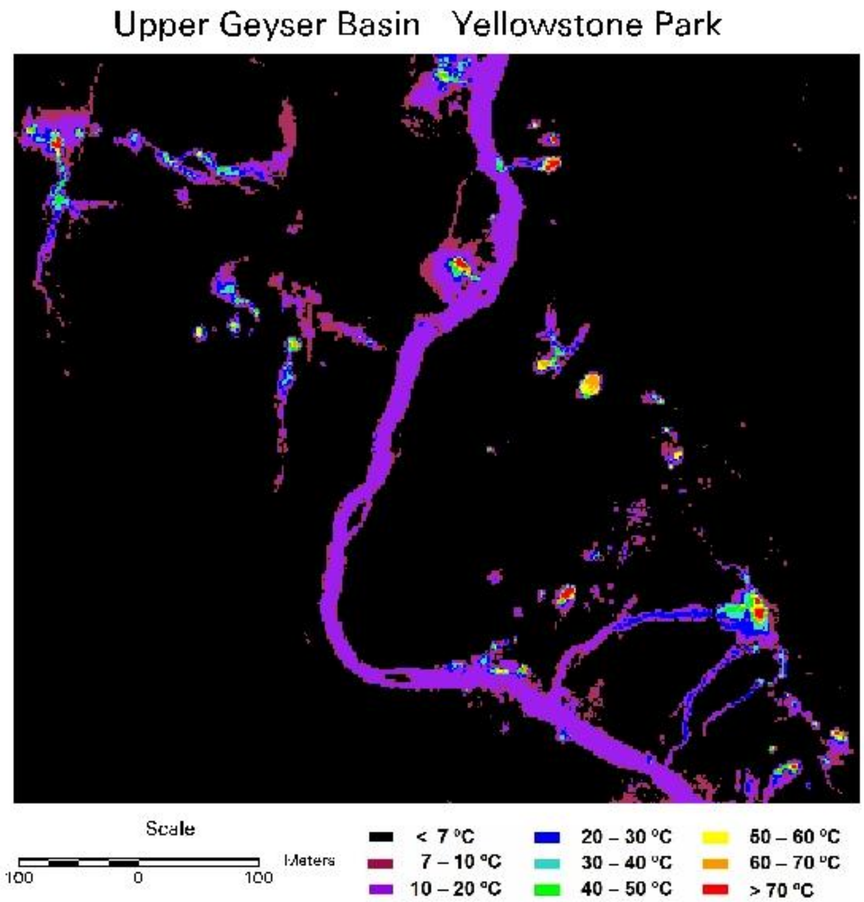


Figure 5 Surface temperature image of a portion of the Upper Geyser Basin in Yellowstone Park, acquired during a nighttime flight.

Acknowledgements

This research was funded by the National Park Service through the Rocky Mountains Cooperative Ecosystem Studies Unit (RM-CESU) RM-CESU Cooperative Agreement Number: H1200040001. Support was also provided by the Remote Sensing Services Laboratory, Dept. of Biological and Irrigation Engineering at Utah State University and the Utah Agricultural Experiment Station.

REFERENCES

[1] Norman, J.M., Kustas, W.P. and Humes, K.S., "A two-source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature." Agric. For. Meteor. 77, 263-293 (1995).

[2] Kustas, W.P. and Norman, J.M., "Evaluation of soil and vegetation heat flux predictions using a simple two-source model with radiometric temperatures for partial canopy cover." Agric. For. Meteor. 94, 13-29 (1999).

[3] Li, F., Kustas, Prueger, J. H., Kustas, W. P., Neale, C. M. U., & Jackson, J. T. "Utility of Remote Sensing Based Two-Source Energy Balance Model Under Low and High Vegetation Cover Conditions." J. Hydromet. 6, 878-891 (2005).

[4] Allen, R. G, Tasumi, M. and Trezza, R., "Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration „METRIC...-Model." Journal of Irrigation and Drainage Engineering. Vol. 133, No. 4, 380-394 (2007).

[5] Torgersen, C.E., Faux, R.N., Mcintosh, B.A., Poage, N.J., and D.J. Norton. "Airborne thermal remote sensing for water temperature assessment in rivers and streams." Remote Sensing of Environment. Vol. 76, 386-398 (2001).

[6] Quattrochi, D.A and J.C. Luvall, [Thermal Remote Sensing in Land Surface Processes], CRC Press, Boca Raton, Florida (2003).

[7] Chávez, J. L., Neale, C. M. U., Hipps, Prueger, J. H. and Kustas, W. P., "Comparing aircraft-based remotely sensed energy balance fluxes with eddy covariance tower data using heat flux source area functions." Journal of Hydrometeorology. Vol. 6, No. 6, 923-940 (2005).

[8] Cai, B. and Neale, C. M. U., "A Method for Constructing 3-Dimensional Models from Airborne Imagery" In: Color Photography and Videography for Resource Assessment. Proceedings of the 17th Biennial Workshop. American Society for Photogrammetry and Remote Sensing, Bethesda, MD (1999).

[9] Neale, C.M.U, and Crowther, B., "An airborne multispectral video/radiometer remote sensing system: development and calibration.", Remote Sens. Environ. Vol.49 (3), pp.187-194 (1994)

[10] Sundararaman, S. and Neale, C. M. U. , "Geometric Calibration of the USU Videography System", In: Videography and Color Photography for Resource Assessment. Proceedings of the 16th Biennial Workshop. American Society for Photogrammetry and Remote Sensing, Bethesda, MD. (1997)

[11] Berk, A., Bernstein, L.S., and Robertson, D.C. "MODTRAN: a moderate resolution model for LOWTRAN 7", Report GL-TR-89-0122. Geophysics Laboratory, Bedford, Maryland, USA. (1989)

[12] Brunsell, N.A., and Gillies, R. "Incorporating Surface Emissivity into a Thermal Atmospheric Correction." Photogrammetric Engineering & Remote Sensing. Vol. 68 (12), pp. 1263-1269 (2002)