Integrated Study of Systematic Monitoring and Mapping Thermal Springs and Features in Yellowstone National Park

Final Report For CESU Task Agreements J1580090425 and J1580050608
From 2008 to 2009

By

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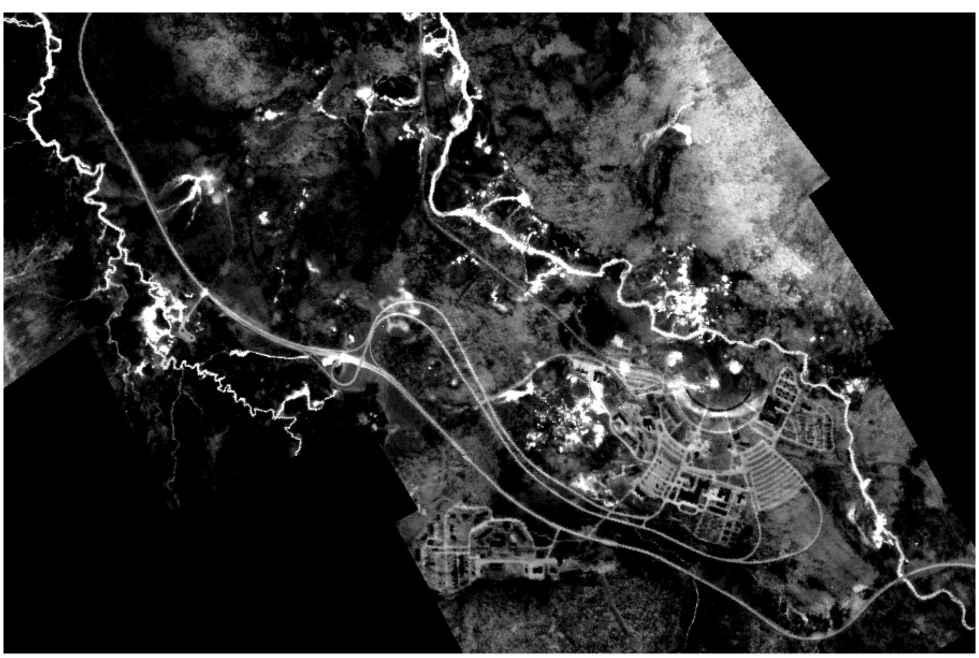


EXECUTIVE SUMMARY

The need for accurate and continuous monitoring of geothermal activity in Yellowstone Park, led to the CESU agreement with Utah State University, to explore the use of high resolution airborne imagery for this purpose. The first three years of this research effort and monitoring program have resulted in interesting improvements in image acquisition, processing and calibration techniques that have led to higher quality products. These improvements are described in the Methods section of the report and sample of the delivered products are shown in the Results and Discussion chapter. The ultimate goal of this effort is to be able to obtain repeatable results from year-to-year so that more sophisticated applications can be made with the imagery, such as heat flow calculations and accurate change detection in the geothermal areas and features.

As a result for the need of more accurate temperature detection, a new FLIR SC640 camera was purchased and used in 2008. In addition, all TIR imagery acquired was at 1-meter pixel resolution.

An energy balance study was initiated during the period of this CESU with the purchase of equipment and the installation in June of 2009 of two energy balance towers in a crater close to The Gap in Norris Geyser basin. This experiment has been ongoing since then, and will provide data to improve the modeling of heat flow and correct for steam generation over hot pools.

INTRODUCTION

The continuous monitoring of thermal features and hydrothermal areas within Yellowstone National Park is important for understanding the changing nature of these systems. Yearly monitoring provides information for protection of visitors and park personnel as well as information required for the placement of infrastructure. In addition the data is used for scientific applications such as monitoring of hydro-geothermal explosions, heat flow calculations and change detection.

Previous monitoring efforts over the last 4 years in Yellowstone NP have shown that airborne remote sensing in the thermal infrared part of the spectrum provides the appropriate spatial resolution and temperatures to identify the small-scale thermal features such as hot spots, pools, vents etc.

In order to support this project, the Utah State University airborne multispectral digital system now includes a precision thermal infrared imager (FLIR SC640) which provides crisp, high-quality digital imagery, used for monitoring thermal features.

This report describes the monitoring program in 2008 and describes the equipment installed for a proposed energy balance study in a crater located close to the gap, Norris Geyser Basin. This was a recommendation resulting from the first CESU agreement.

METHODS

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 digital images with approximately 2000 x 2000 pixels (Cai and Neale, 1999). The camera can be operated in 8 bits or 10 bits, but for most applications images with 8 bits (256 grey scale levels) are sufficient. The shortwave spectral bands are obtained with interference filters centered in the green (0.545-0.560 μm), red (0.665-0.680 μm) and NIR (0.795-0.809 μm) portions of the electro-magnetic 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. 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.

Prior to 2008, the USU research aircraft was a Piper Seneca II Turbo light twin engine aircraft. This aircraft was changed to a single engine Cessna turbo TP206 during the summer of 2008 and used to acquire the imagery described in this report.

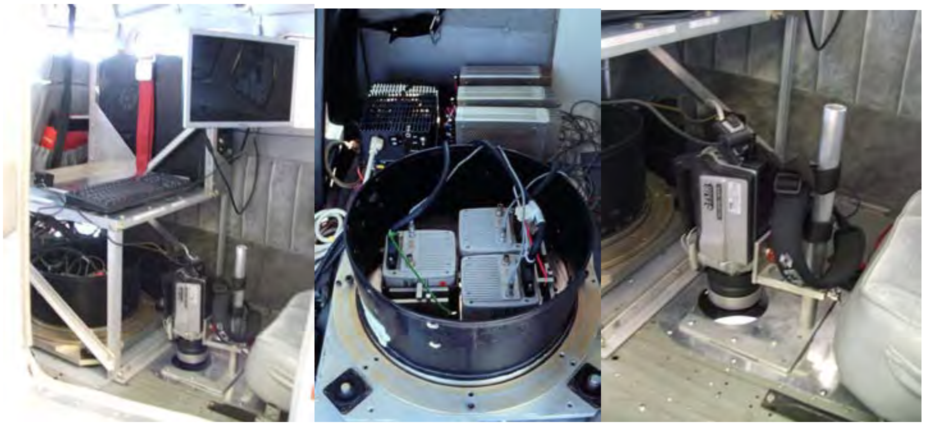


Figure 1. Details of the USU airborne multispectral remote sensing system and FLIR SC640 thermal IR camera installed in the Cessna TP206 remote sensing aircraft.

Image Acquisition

High-resolution shortwave (3 bands) and thermal infrared imagery were acquired with the USU airborne digital system over different areas of Yellowstone Park, according to the monitoring plan devised by the YNP technical personnel and USU. The pixel resolution in the shortwave bands (green, red and near-infrared) was 1-meter while in the thermal IR it was also 1-meter for the night-time flights. For a 1-meter pixel resolution using the 20 mm Nikon lens of the shortwave digital cameras, the flight altitude was 7000 feet above ground level (agl). Considering the ground elevations at Yellowstone over the thermal feature sites varied between 6000 and 7500 feet, the flight altitude usually varied between 13000 and 14500 feet. This required the use of oxygen masks by the pilot and co-pilot during the image acquisition. For safety reasons, the nighttime flights with the FLIR SC640 camera were conducted with a zoom lens so that the aircraft could operate well above the terrain.

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 and a flight altitude to capture the appropriate resolution at an average ground altitude along the flight line.

The night-time image acquisition over-flights in 2008 were conducted on September 12th, under clear sky conditions, between 11:52 pm and 2:00 am. Cold air and surface temperatures are usually rapidly attained at those altitudes and time of the year, due to irradiative cooling of the surface.

Additional flights were conducted on September 17 during the daytime between 1:45 and 3:00 pm local time under clear skies, usually the hottest time of the day, in order to acquire multispectral shortwave imagery and additional thermal imagery over new areas previously not flown. The thermal imagery from the daytime flight can be used along with the nighttime imagery usually acquired approximately 12 hours apart, to study the thermal inertia of the surface materials around the thermal features with the intent of eventually developing a technique to remove the solar surface heating from the nighttime temperatures. The shortwave band imagery was acquired at 1-meter spatial resolution and used to correct the temperatures obtained from the night-time and daytime thermal imagery for surface emissivity. This process will be described in the next section.

Image Processing

The individual spectral band images from the shortwave band 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 (Neale and Crowther, 1994) and for lens radial distortions (Sundararaman and Neale, 1999) 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 Information Advisory Committee. A 3rd order polynomial transformation was used. The root mean square (rms) error for the individual image rectification was kept to less than one meter. The rectified images were then stitched 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). The incoming irradiance from the sun and sky was measured every minute using an Exotech radiometer with similar spectral bands placed overlooking (from nadir) a standard reflectance panel with known bi-directional properties setup in a central location in the Park (Figure 2). Once the image strips were calibrated, they were stitched together forming a mosaic covering the entire study area.

The calibrated and rectified 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. In addition, it was important that thermal images match the 3-band mosaic as the latter would be used in the correction of the thermal image for surface emissivity.

Thermal images from the FLIR SC640 were extracted from the digital movies providing individual frames at 60% overlap. Each thermal image was rectified using common control points with the 3-band mosaic and then stitched together along the flight lines to form image strips. These were then calibrated using the camera calibration files to obtain at-aircraft temperatures. Several calibrated strips are then stitched together to form a mosaic covering the study area.

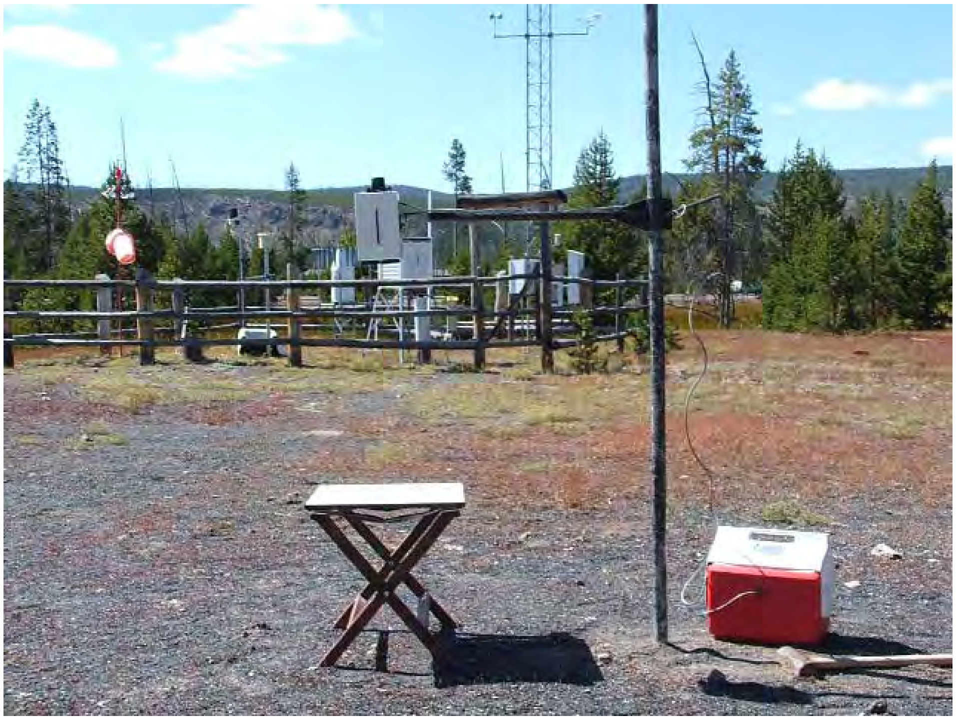


Figure 2. Standard reflectance panel and Exotech 4-band radiometer measuring incoming irradiance from the sun setup in the Upper Geyser basin area during one of the daytime flights in Yellowstone Park.

The at-aircraft temperature image was corrected for atmospheric effects at the time of the over flight using the MODTRAN radiative transfer model (Berk et al, 1989). For such, radiosonde data from a nearby weather station (Riverton, WY) 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 profile was adjusted to compensate for the differences in ground surface altitudes. The correction for surface emissivity was based on the technique by Brunsell and Gillies (2002) described below:

The Normalized Difference Vegetation Index (NDVI) was applied to the calibrated 3-band image mosaic obtaining an image layer:

$$NDVI = (NIR - Red) / (NIR + Red) \quad (1)$$

The NDVI was then scaled to obtain the N* parameter in raster form:

$$N^* = (NDVI - NDVI_0)/(NDVI_{max} - NDVI_0) \quad (2)$$

Where $NDVI_0$ is the bare soil NDVI value of the scene and $NDVI_{max}$ is the maximum NDVI of the scene corresponding to full cover dense vegetation.
The fraction of vegetation cover (Fr) becomes:

$$Fr = N^{*2} \quad (3)$$

The surface emissivity layer is obtained by linearly scaling the emissivity between bare soil (ε_{soil} = 0.92) and full dense vegetation cover (ε_{veg} = 0.98) using the Fr image layer:

$$\varepsilon_{surf} = Fr\ (\varepsilon_{veg}) + (1 - Fr)\ \varepsilon_{soil} \quad (4)$$

Standing water was taken into account separately. A classification of the 3-band image was conducted to extract a water body mask layer and used in a model within ERDAS Imagine to assign an emissivity of 0.985 to clear water surfaces present in the scene, mostly lakes and hot pools. Finally, the emissivity layer and the at-aircraft temperature image corrected using the MODTRAN model results are used in an ERDAS Imagine model to obtain the at-surface temperature image, corrected for atmospheric effects and surface emissivity. In general, these corrections increased the values of the at-aircraft temperatures by several degrees.

Energy Balance Study

One of the recommendations from the first CESU between YNP and USU was to conduct a complete energy balance study on the ground level, to acquire data required for studying heat flow in thermal areas, the relationship between heat flux and surface temperatures in dry and wet areas such as pools. The generation of steam over hot pools was perceived as masking the ability to retrieve true surface temperatures from the airborne remote sensing. This present research effort also covered the purchase and installation of the energy balance equipment. The experiment was devised and the equipment was purchased in late winter and early spring 2009. The NPS geologists identified a crater resulting from a hydrothermal explosion in the Norris Geyser Basin, in an area called The Gap for the experimental setup. This area was off-limits to the general public and relatively hidden. The equipment purchased for this experiment is listed in Table 1 below.

Table 1 List of equipment purchased for the energy balance study implemented during the period.

Equipment Description	Unit
1 CR1000 Dataloggers	1
CR1000 accessories	1
CR3000 datalogger	1
Software Upgrade of Loggernet from previous version	1
6 Apogee Infrared radiometers IRR-P	6
IRR mounting kits	8
Apogee Extra cabling	1
1 Hukseflux NR01 Net Radiometer	1
1 NR-Lite-L Net Radiometer with 50 ft lead	1
1 NR-Lite Mounting Kit	1
5 Rebs soil heat flux plates	4
1 Rebs platinum soil temperature probe	1
4 108-L50 Water/soil temperature probes	4
2 TCAV-L soil temperature probes	2
2 Hydra Probes	2
3 Vaisala HMP45C Relative Humidity and temperature probes	3
3 Gill Radiation Shields	3
1 RM Young Wind Monitor for wind speed and direction	1
1 Tipping bucket rain gauge	1
2 14"x16" enclosures	2
CM310-PL mounting Poles	2
2 Solar Panels	2
Masts and guide wires	6
Materials and Tools	1

The installation of the two towers was carried out in June 2009. Figure 3a shows tower #1 installed on the upwind side of the crater lagoon in a hot sintered area. The tower contained a 4-way net radiometer, a rain gauge, temperature and relative humidity sensor, soil heat flux plates and corresponding soil temperature thermocouples on 3 different areas: one very hot and two medium temperatures. In addition thermal infrared radiometers (TIR) were pointed at the surface where the heat flux plates and temperature sensors (Figure 3b) were located as well as to the area in the lagoon where the water temperature sensor was located at the tip of a log (Figure 3c and 3d). This tower was controlled by a CR3000 datalogger from Campbell Scientific powered by a 12 volt battery maintained with a solar panel. Tower #2 shown in Figure 4a was installed downwind on the other side of the lagoon from Tower #1. Its approximate location can be seen in Figure 5b where the cursor is positioned on the image. The instrumentation installed consisted of a net radiometer (NR-Lite), temperature and relative humidity sensor, soil heat flux plates and soil temperatures sensors at two locations with corresponding TIR's pointing to the surface (Figure 4b). A water temperature sensor and corresponding TIR sensor can be seen in Figure 4d and 4c. Figure 5a shows an areal TIR image of the crater and lagoon taken with the FLIR SC640 camera. Tower #1 was located on the hot sintered mound south of the lagoon while tower #2 was placed north of the lagoon, its location approximately marked in Figure 5b.

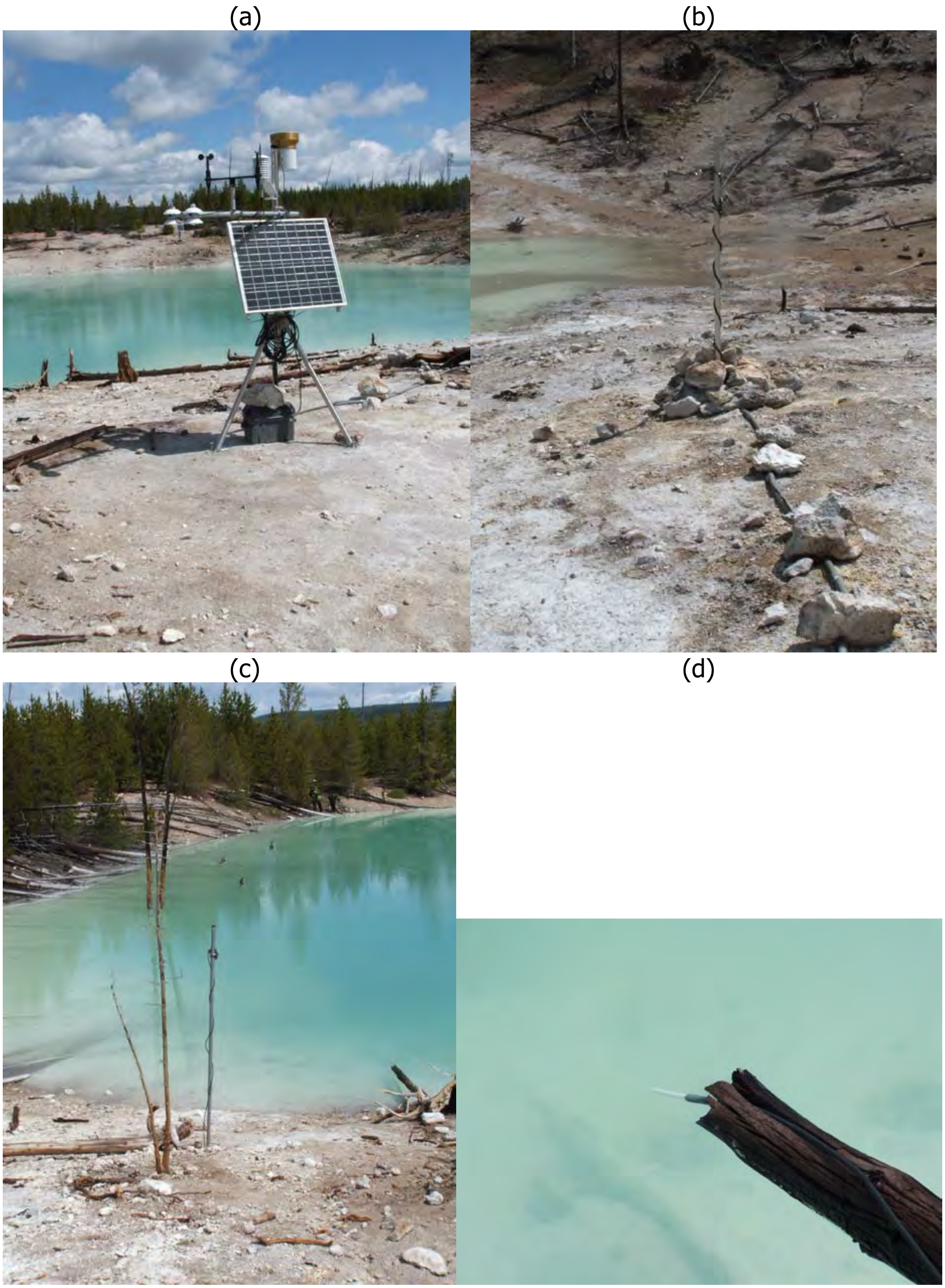


Figure 3. Energy balance tower #1 installed on the upwind side of the crater lagoon, The Gap, Norris Geyser basin.

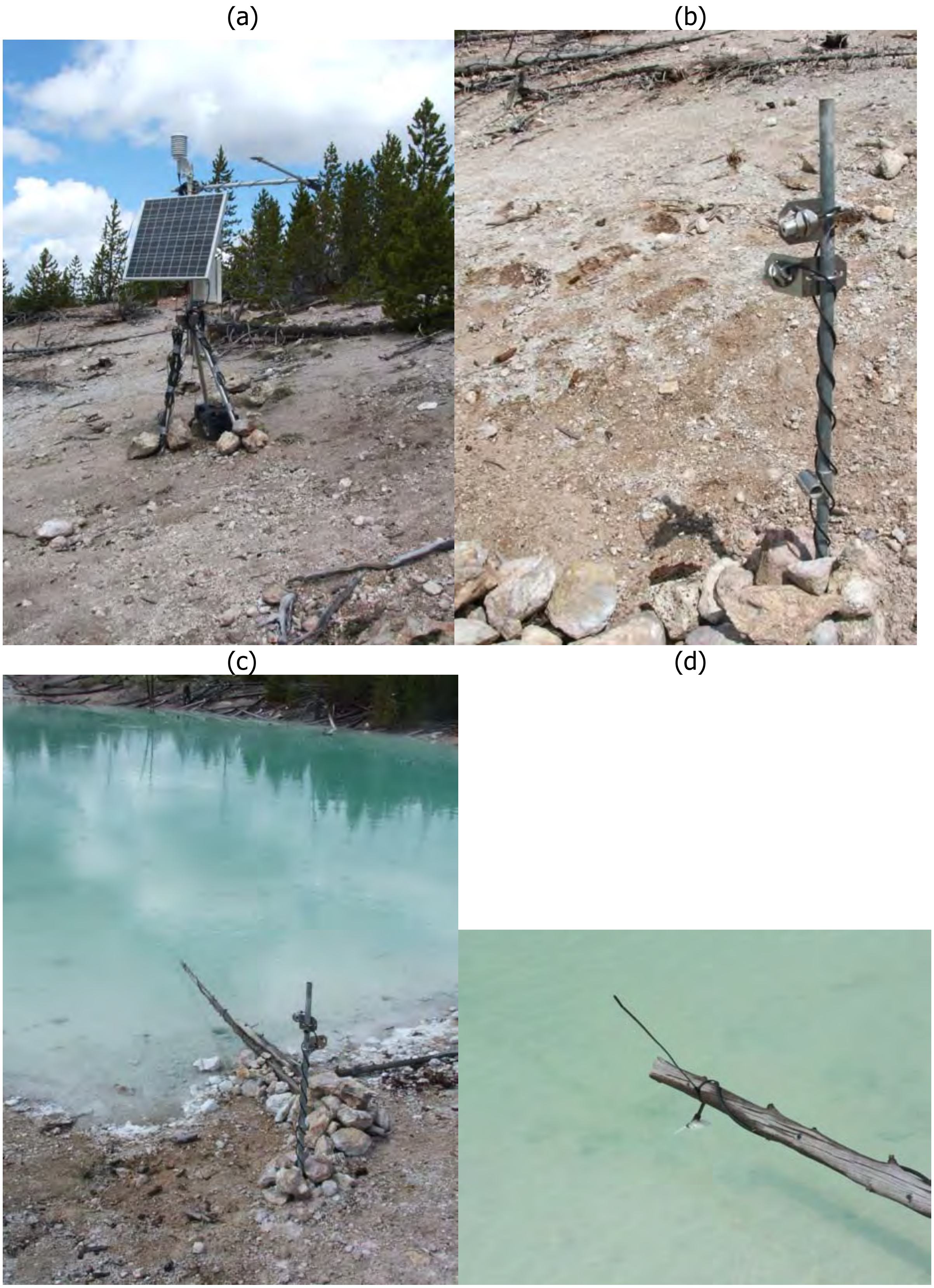
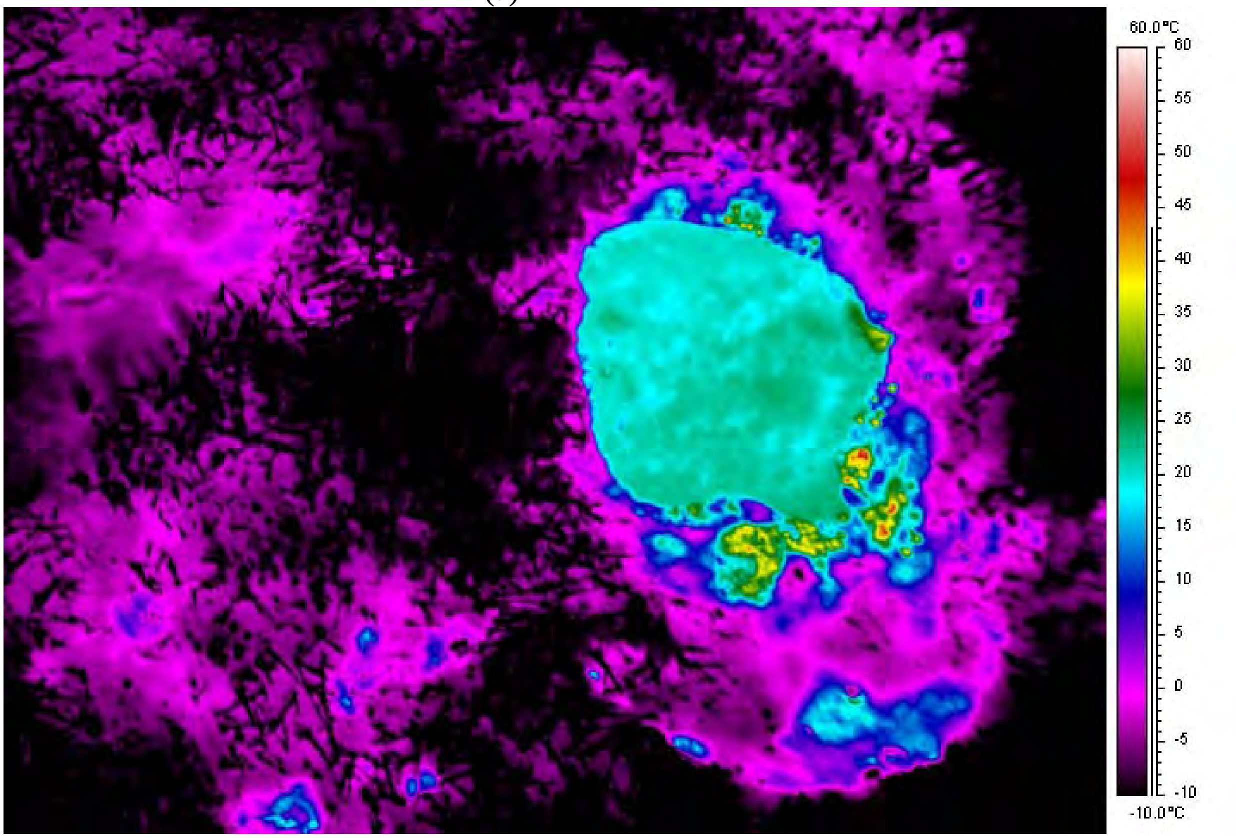


Figure 4. Energy balance tower #2, located downwind of the lagoon.

(a)



(b)

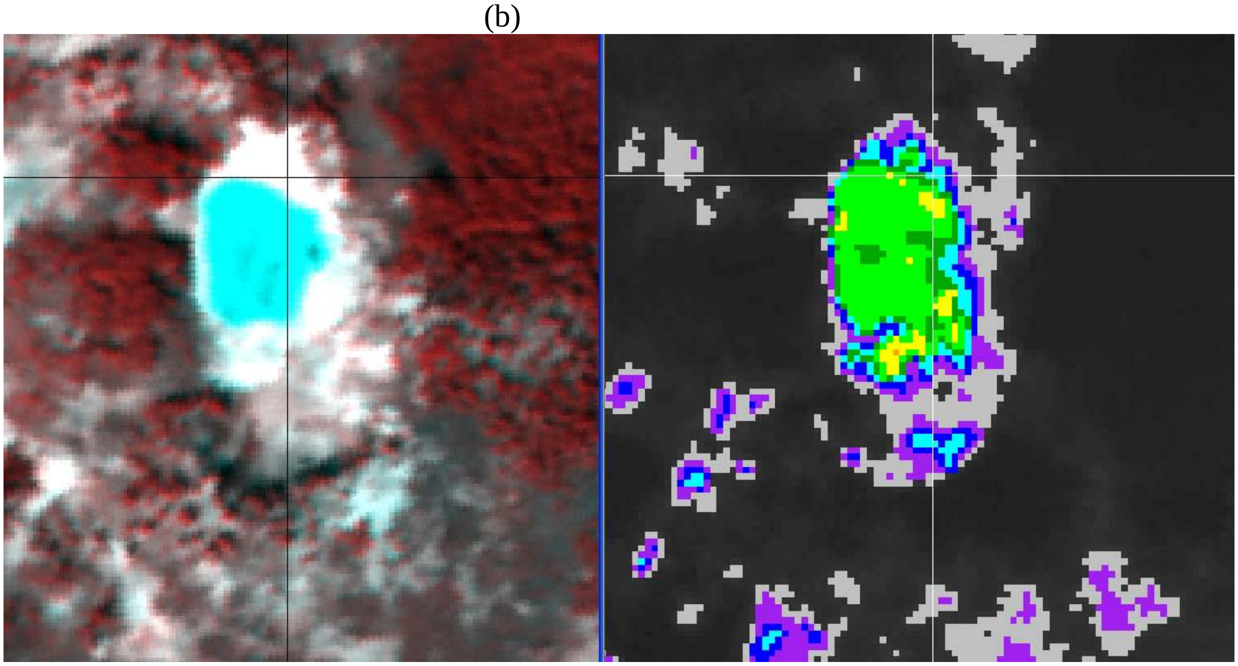


Figure 5. Oblique, daytime thermal infrared image with a NPS contract helicopter (a) visible image (b) and nighttime thermal infrared image (c) of the crater and lagoon.

IMAGE ACQUISITION DATES

Table 1 below summarizes the image acquisition flights for 2008. The new areas flown were the Mushpots, Canyon, NSF Earthscope borehole strainmeter locations, Norris Geyser Basin (NGB) and Mammoth Hot Springs (MHS), while the repeat areas were Upper Geyser Basin (UGB) and Hot Spring Basin (HSB).

Year 2008	Date	Start Time	End Time	Location flown	Processing Status	Observations
3 band						
	9/17/2008	1:45 PM	1:56 PM	Mushpots	Completed & Delivered	
	9/17/2008	1:58 PM	2:12 PM	Canyon	Completed & Delivered	
Day	9/17/2008	2:15 PM	2:26 PM	GS	Completed & Delivered	
	9/17/2008	2:30 PM	2:55 PM	NGB	Completed & Delivered	
	9/17/2008	3.00 PM	3:15 PM	MHS	Completed & Delivered	
Thermal					FLIR SC640 Cameras	
	9/12/2008	11.52 PM	12:13 AM	HSB	Completed & Delivered	
	9/12/2008	12:16 AM	12:25 AM	Mushpots	Completed & Delivered	
Night	9/12/2008	12:39 AM	12:48 AM	Canyon	Completed & Delivered	
	9/12/2008	12:55 AM	12:59 AM	GS	Completed & Delivered	
	9/12/2008	1:04 AM	1:21 AM	UGB	Completed & Delivered	
	9/12/2008	1:31 AM	1:53 AM	NGB	Completed & Delivered	
	9/12/2008	2:00 AM	2:12 AM	MHS	Completed & Delivered	

RESULTS AND DISCUSSION

Samples of the delivered products for the 2008 campaign

Samples of the delivered imagery from the 2008 campaign will be presented in this section, processed as described in the Methods section. Figure 6 shows the 3band and thermal infrared image for Mammoth Hot Springs. Figure 7 presents the Mushpots area in the Sour Creek Dome region. Figure 8 shows a portion of the Grand Canyon of the Yellowstone with an extension on the west side over the strain gauge located in the area. Figure 9 shows the 3band and thermal IR mosaic for Norris Geyser Basin, also flown for the first time in the fall of 2008. Figure 10 shows thermal infrared mosaics for the Upper Geyser Basin and Hot Spring Basin, both repeat areas.

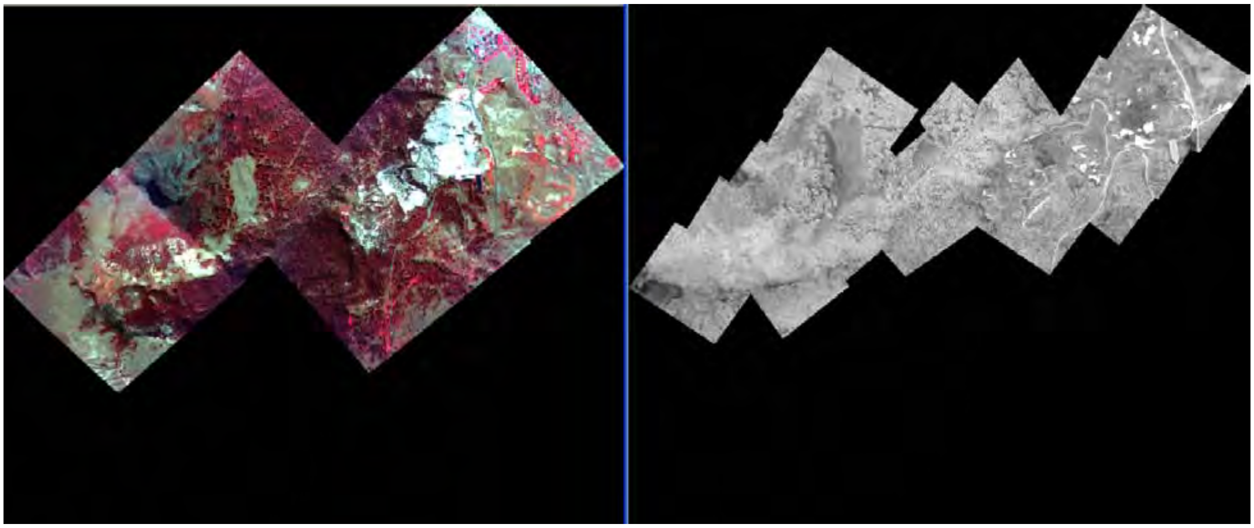


Figure 6. Three band multispectral mosaic (left) and corresponding thermal infrared mosaic (right) of the Mammoth Hot Springs area

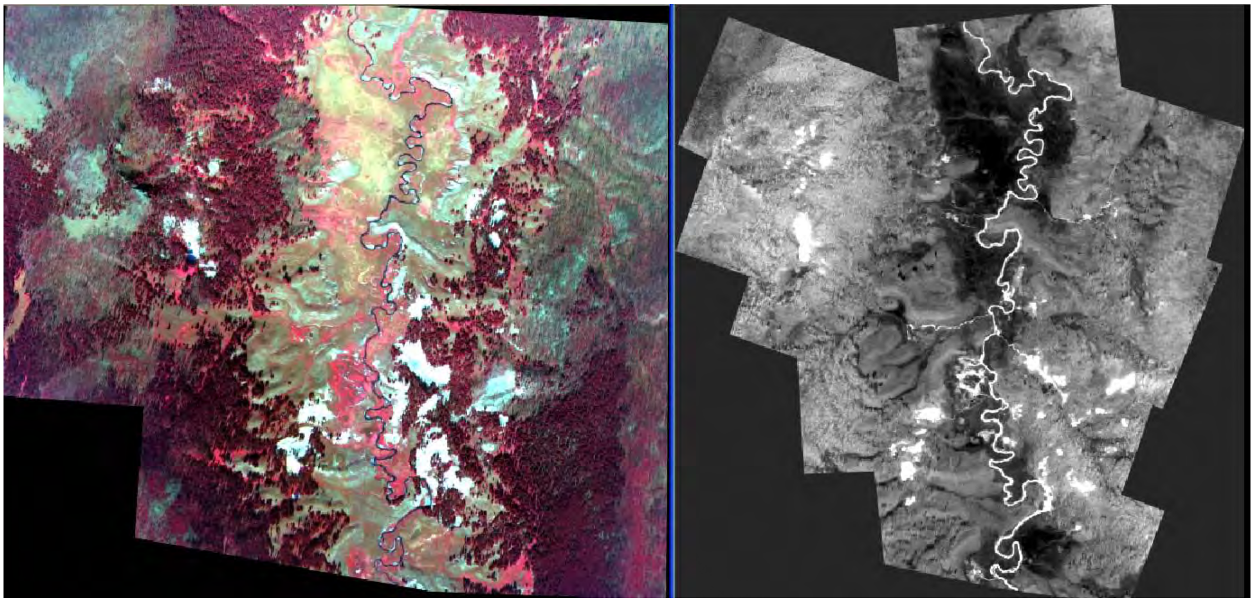


Figure 7. Three band multispectral mosaic (left) and corresponding thermal infrared mosaic (right) of the Mushpots area in the Sour Creek Dome region.

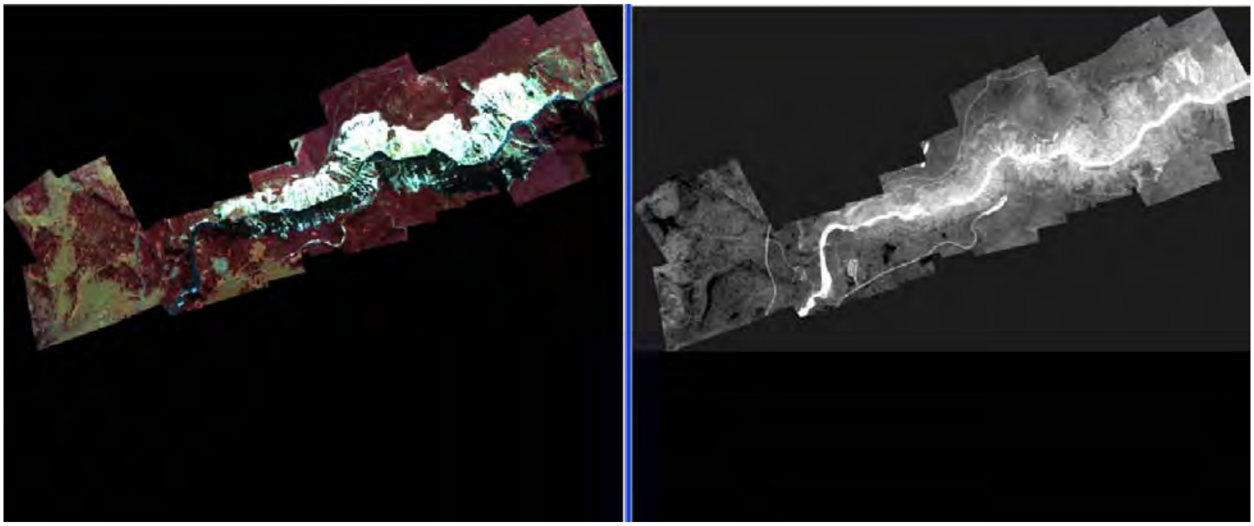


Figure 8. Three band multispectral mosaic (left) and corresponding thermal infrared mosaic (right) of a portion of the Grand Canyon of the Yellowstone River and corresponding borehole strainmeter area on the western side.

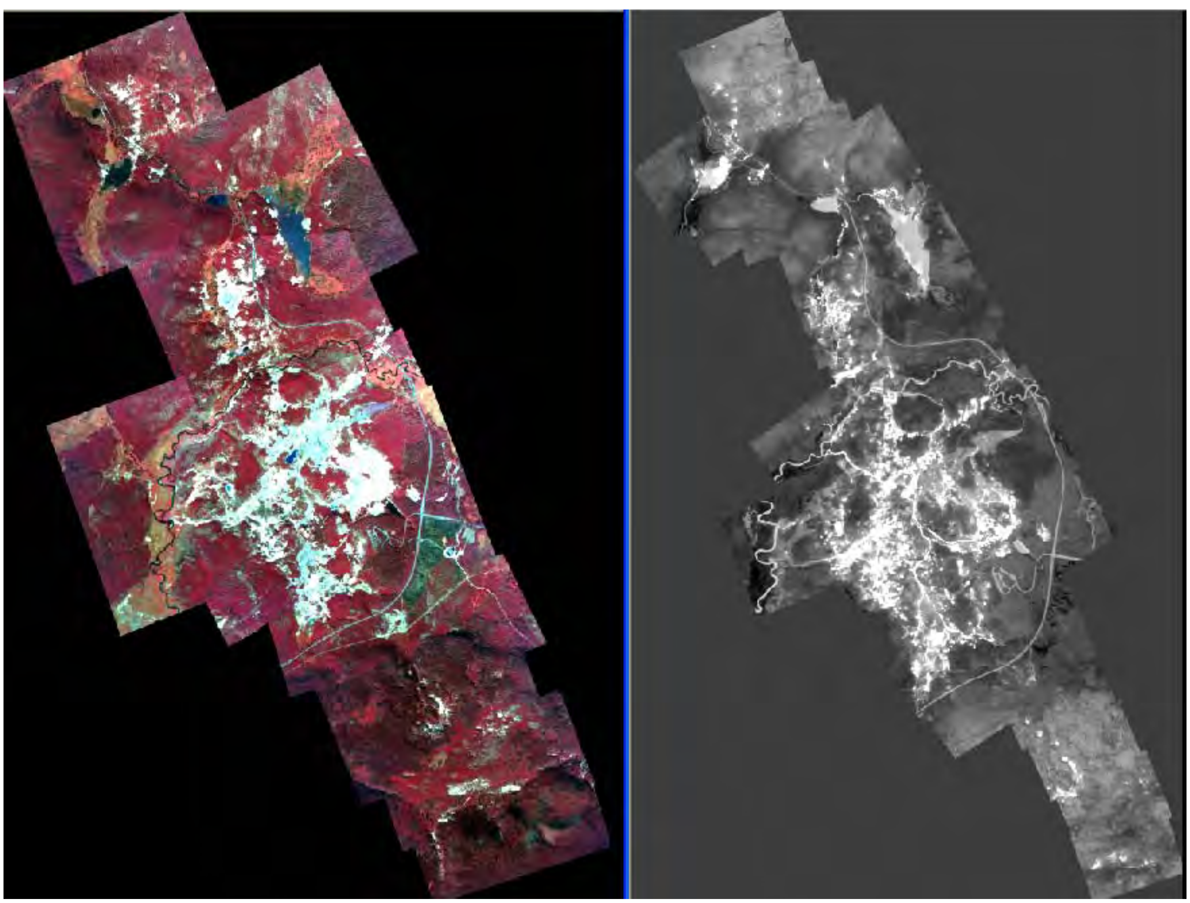


Figure 9. Three band multispectral mosaic (left) and corresponding thermal infrared mosaic (right) of Norris Geyser Basin

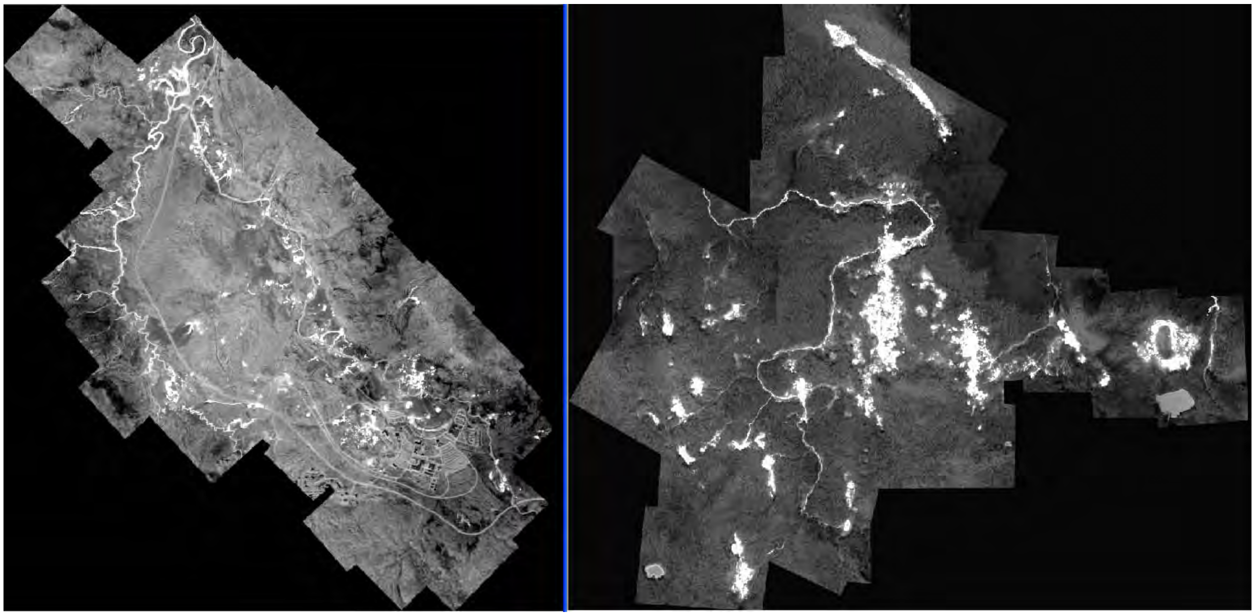


Figure 10. Thermal infrared mosaics of the Upper Geyser Basin (left) and Hot Spring Basin (right), both repeat monitoring areas, flown in previous years.

Interesting features

Figure 11 shows a colorized version of the calibrated thermal infrared mosaic of Norris Geyser Basin. This area was selected for the energy balance study due to its unique thermal features, high heat flow and the fact that it's a closed basin with outflow measurements of water and chloride content.

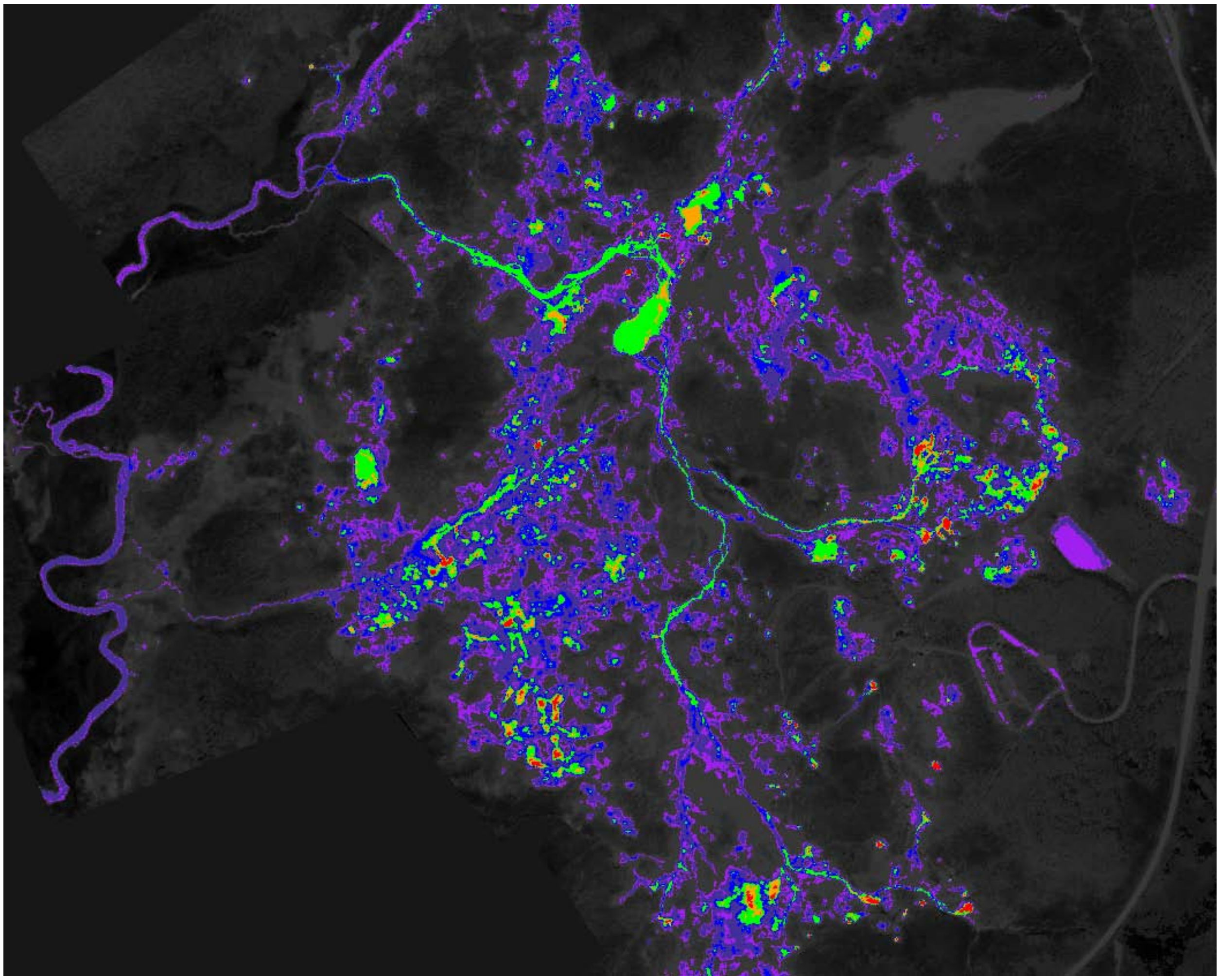


Figure 11. Colorized thermal IR mosaic of a portion of Norris Geyser Basin.

RECOMMENDATIONS FOR FUTURE AIRBORNE TIR ACQUISITIONS

The purchase and use of the FLIR SC640 camera has led to an improvement in the quality and detail of the thermal infrared image products. The energy balance study installed in 2009 should provide the necessary data to understand the heat flow being produced vis-à-vis what is seen at the surface by TIR sensors. The image calibration methodology can be further improved by the correction for steam generated over hot pools, which confound the retrieval of the true surface temperatures of these water bodies.

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