

Mammoth Lakes Thermal Imagery

Technical Data Report



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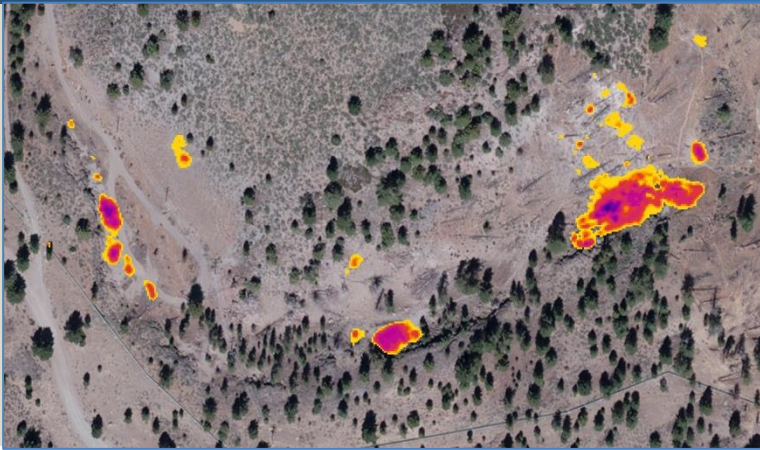
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Cover Photo: Sample image showing heat signature of natural and man-made features near Whitmore Hot Springs in Casa Diablo area, east of US Hwy 395.

INTRODUCTION

Thermal Infrared imagery overlaying base satellite imagery emphasizing heat signature of natural features



In August 2016 Quantum Spatial (QSI) was contracted by the USGS WR Branch of Regional Research to collect thermal infrared (TIR) imagery of the Mammoth Lakes study area located in California. Data collection is part of a monitoring program to detect any adverse impact from developing energy from a new well field in Casa Diablo IV (CD-IV). The TIR imagery is focused on the measurement and mapping of geothermal emissions in the study area and will be complementary to field-based measurements of both surface temperature and CO₂ gas emissions.

This report accompanies the delivered TIR imagery, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset. Imagery acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to USGS WR Branch of Regional Research is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates and acreage collected of the Mammoth Lakes site

Project Area	Contracted Acres	Buffered Acres	Acquisition Dates and times
Mammoth Lakes	11,922	12,661	10/11/2016 11:49pm to 10/12/2016 2:23am

Deliverable Products

Table 2: Products delivered to USGS WR Branch of Regional Research for the Mammoth Lakes site

Mammoth Lakes Products Projection: UTM 10N Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (Geoid12a) Units: meters	
Rasters	0.9 m Thermal Infrared Imagery <ul style="list-style-type: none"> • Mosaic of TIR imagery of the AOI (format 32 bit *.tif; Cell Value = Celsius). • Mosaic of TIR imagery of the AOI (format 16 bit *.tif; Cell Value = Kelvin X 10). • Layer files (color ramps) highlighting hotspot based on temperature ranges (*.lyr).
Vectors	Shapefiles (*.shp) <ul style="list-style-type: none"> • Mammoth Lakes survey boundary (polygon). • Sensor Exterior Orientations (point). • Air Target Thermal Blankets (point) • Identified hotspots containing statistical analysis (polygon).
Imagery files	TIR Imagery Files <ul style="list-style-type: none"> • Radiance calibrated TIR imagery (Kelvin X 10) (3,434 frames).

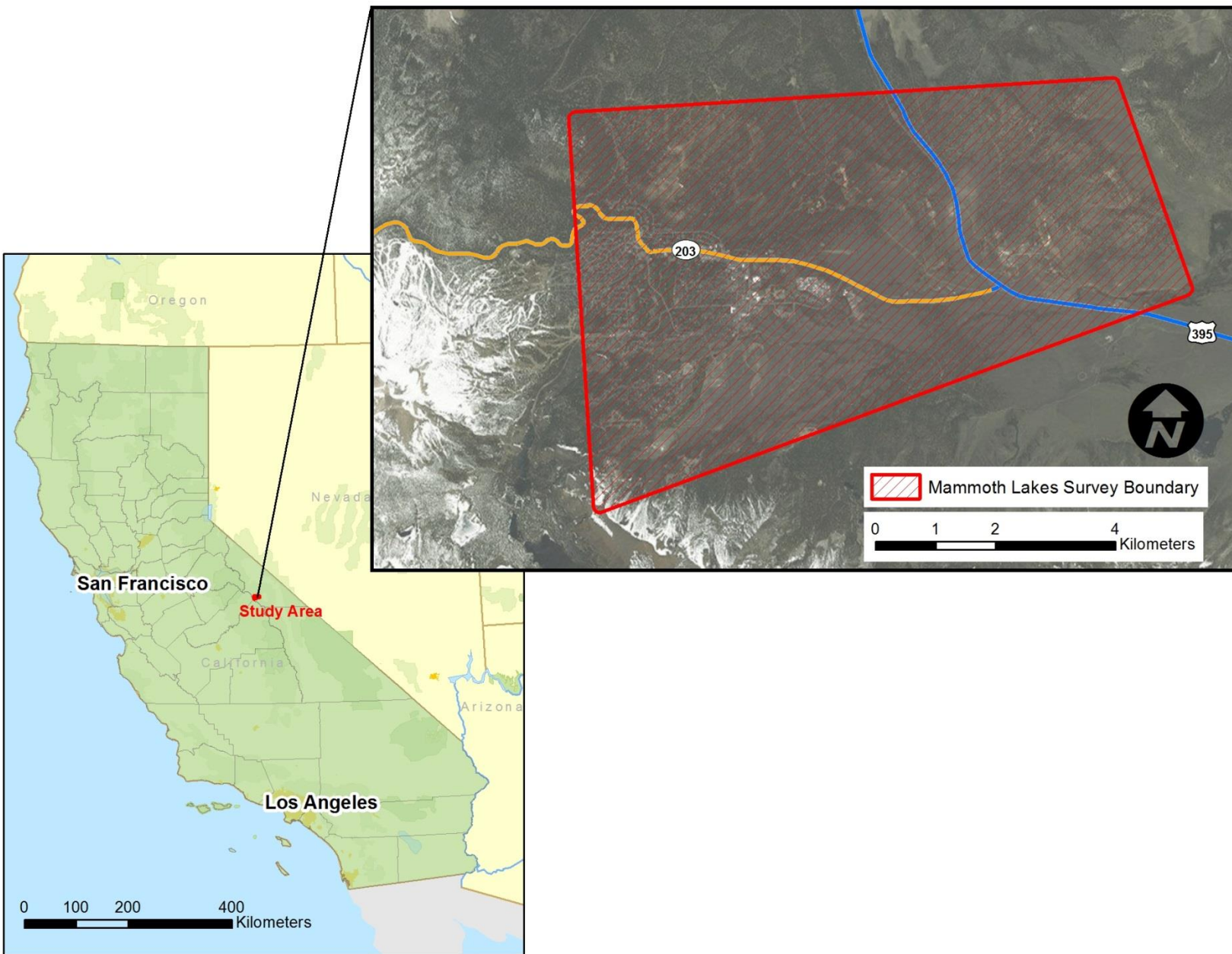


Figure 1: Map of the Mammoth Lakes study area in Central California

QSI's Cessna Caravan was used for the Mammoth Lakes TIR project. A QSI sensor specialist operated the FLIR SC6000 system.



Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Mammoth Lakes TIR study area at the ≤ 1.0 m target ground sampling distance (GSD). The TIR acquisition flight was executed during late night **October 11 to early morning October 12, 2016** (Table 1). A night acquisition was chosen for the Mammoth Lakes project in order to minimize the background heat signature caused by solar radiation observed during the daytime. Flight planning also took atmospheric conditions (clear sky, dry weather, no rain) into consideration to find the ideal flight window. Under these conditions, the thermal contrast between geothermal heat sources and the background heat signature was maximized allowing for the best probability of detecting anomalies.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private and military property access and potential air space restrictions were reviewed.

Airborne Survey

Images were collected with a FLIR system's SC6000 sensor (8 – 9.2 μm) mounted to a Cessna Caravan 604MD aircraft (Figure 2). The SC6000 is a calibrated radiometer with internal non-uniformity correction and drift compensation. Sensor and acquisition specifications of the TIR method for the Mammoth Lakes study are listed in Table 3.

Table 3. Summary of TIR sensor and acquisition specifications

FLIR System SC6000 (LWIR)	
Wavelength:	8 – 9.2 μm
Noise Equivalent Temperature Differences (NETD):	0.035° C
Pixel Array:	640 (H) x 512 (V)
Encoding Level:	14 bit
Horizontal Field-of-View:	35.5°
Acquisition Date(s):	October 11-12, 2016
Flight Above Ground Level (AGL):	1800 m
Speed	150 kts
Pixel Resolution:	≤ 1 m
Total Number of Photos	3,434

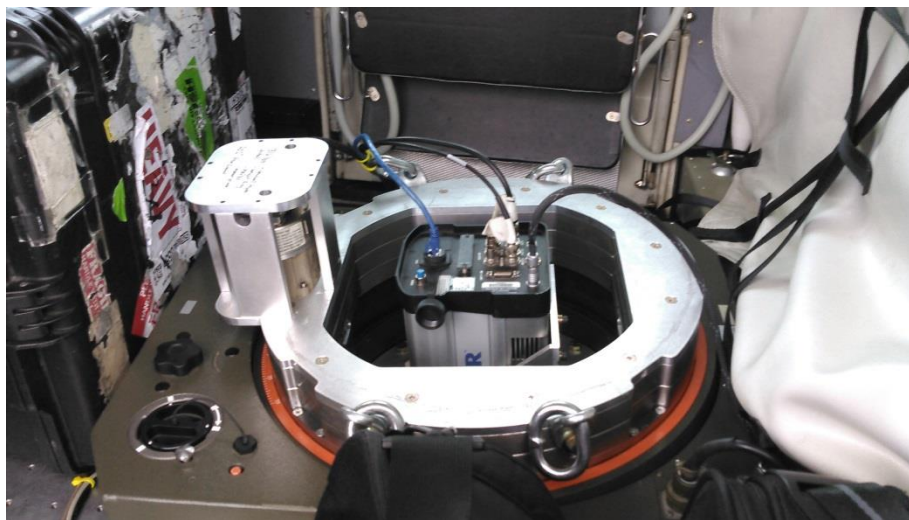


Figure 2: FLIR SC6000 system installed on the aircraft for the Mammoth Lakes project.

The FLIR SC6000 sensor uses a focal plane array of detectors to sample incoming radiation. A challenge when using this technology is to achieve uniformity across the detector array. The sensor has a correction scheme which reduces non-uniformity across the image frame; however, differences in temperature (typically $<0.5^{\circ}\text{C}$) can be observed near the edge of the image frame. To minimize the effects of non-uniformity sufficient overlap between images was designed in the flightplan so as not to use image frame edges in the final mosaic.

The study area was surveyed with an opposing flight line side lap of $\geq 30\%$ and $\geq 60\%$ forward lap. To accurately solve for position (geographic coordinates x, y, z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the data collection missions. Position and altitude of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS data logger. Also pitch, roll, and yaw (heading) were measured 200 times per second (200 Hz) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft/sensor position and attitude data are indexed by accurate GPS time. Flight altitudes were selected to optimize flight time while achieving the target resolution ($\leq 1\text{ m GSD}$) for the project (Table 3).

Thermal infrared images were recorded directly from the sensor to an on-board computer as raw counts which were then converted to radiant temperatures. The individual images were referenced with time, position, and heading information provided by a global positioning system (GPS) (Figure 3).

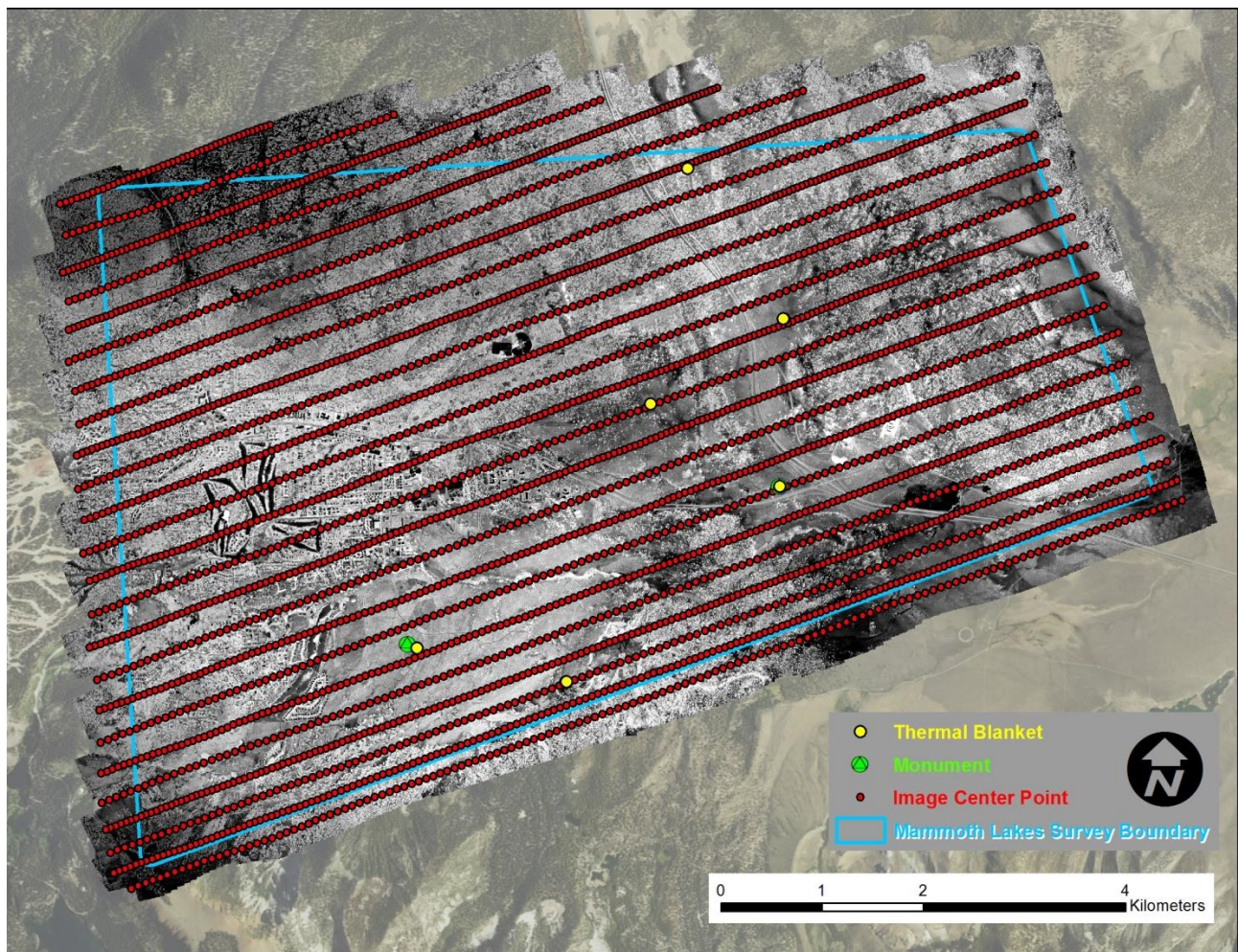


Figure 3. Each point on the map represents a thermal image location.

Ground Control

Ground control surveys, including monumentation and thermal targets were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final thermal imagery products.

Monumentation

The spatial configuration of ground survey monuments provided redundant control for the TIR flight. Monuments were also used for collection of thermal air targets (TAT) using fast-static (FS) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for TAT coverage. QSI created two new monuments for the Mammoth Lakes TIR project (Table 4).

Table 4: Monuments established for the Mammoth Lakes acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
MAM_01	37° 37' 42.70061"	-118° 57' 51.26434"	2368.255
MAM_02	37° 38' 27.90781"	-118° 55' 18.89731"	2220.598

To correct the continuously recorded onboard measurements of the aircraft position, QSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1Hz recording frequency) over each monument. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS¹) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine positional accuracy.

Thermal Aerial Targets (TAT)

TATs were collected using fast-static (FS) survey techniques. A Trimble R7 base unit was positioned at a nearby monument concurrently with a roving Trimble R8 receiver. FS surveys record observations for up to fifteen minutes on each TAT in order to support long baselines for post-processing. Relative errors for any TAT position must be less than 6 cm horizontal and 8 cm vertical in order to be accepted (See Table 5 for Trimble unit specifications).

¹ OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. <http://www.ngs.noaa.gov/OPUS>.

Table 5: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7	Zephyr Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R8 Model 2	Integrated	TRMR8_GNSS	Rover

Aerial targets were placed throughout the project area prior to imagery acquisition in order to correct airborne GPS data the spatial accuracy of the thermal imagery mosaics (**Figure 4**). Located within FS range of the ground survey monuments, the targets were secured with surveyor’s nails and routinely checked for disturbance

The air targets used for the Mammoth Lakes project were thermal blankets approximately 2 x 1m in size. The blankets create high temperature contrast in the thermal imagery and are easily identified.



Figure 4. Thermal blanket used to geospatially correct the TIR imagery

TIR Imagery Calibration

Response characteristics of the TIR sensor are measured in a laboratory environment. Response curves relate the raw digital numbers recorded by the sensor to emitted radiance from a black body. Following the survey, the raw collected TIR images (initially containing digital numbers) are converted to radiance temperatures based on the factory calibration. The calculated radiant temperatures are adjusted based on atmospheric conditions and ground verification data. For the Mammoth Lakes project, the adjustment was based on atmospheric conditions data extracted from the local meteorological station Bigwood in Mammoth Lakes (#KCAMAMMO17) and the ground verification was based on the kinetic water temperatures measured in water bodies at six (6) sites (Figure 5). This adjustment is performed to correct for path length attenuation between the ground surface and the sensor and the emissivity of water (0.96).

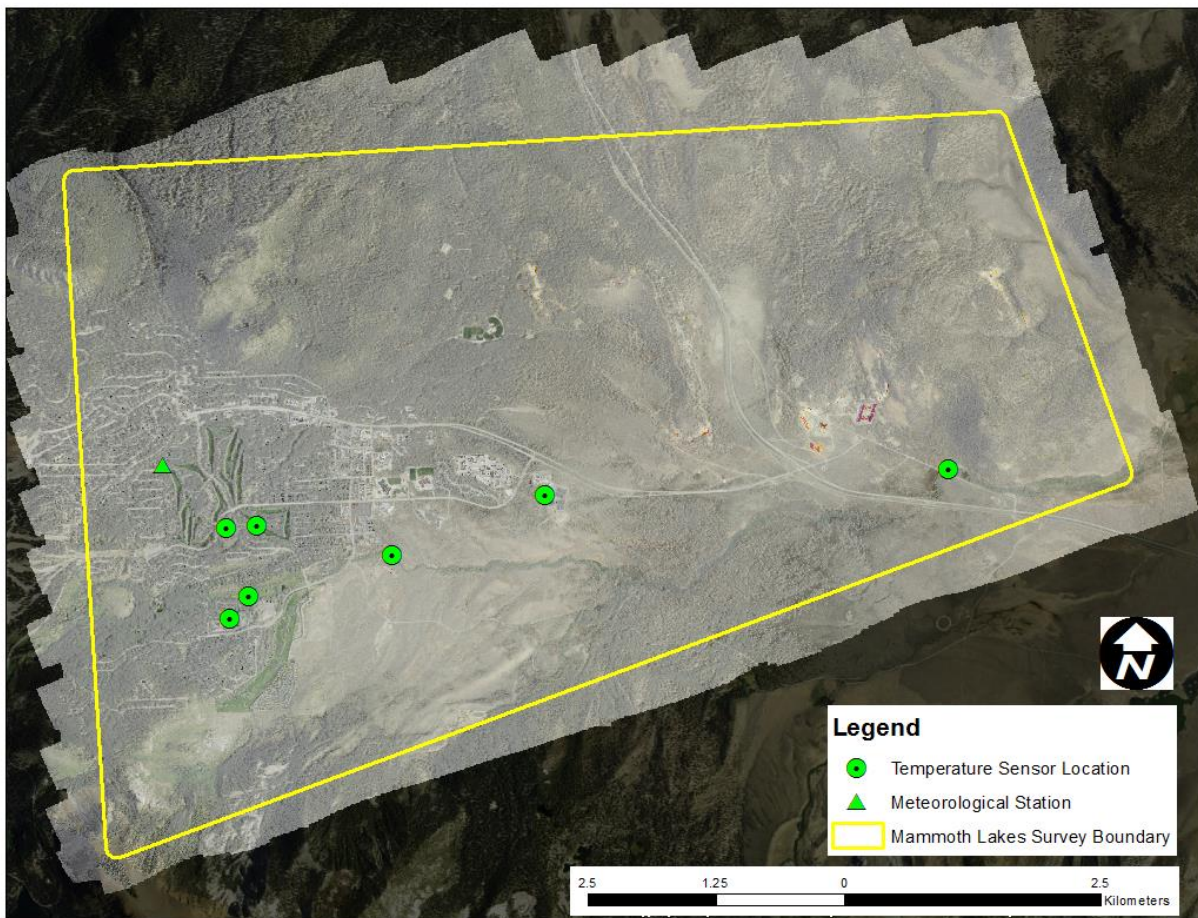


Figure 5: Map of the meteorological station and the six (6) locations of water temperature used for the TIR radiance calibration.

Temperature identification and Color Ramps

The TIR images collected during this survey consisted of a single band representing longwave infrared (LWIR). As a result, visual representation of the imagery is enhanced by the application of a customized color ramp. The selection of a color ramp aims to highlight features most relevant to the analysis (i.e., spatial variability of ground temperatures). The color ramps for the TIR mosaics were developed to maximize the temperature contrast across the study area. The color ramp can be modified by the end user to highlight features or temperature ranges of interest (Figure 6). The color ramp can also be modified and laid over natural color imagery to aid object identification (Figure 7). It is important to note that defining and modifying the color ramps does not change the temperature value recorded in the TIR imagery.

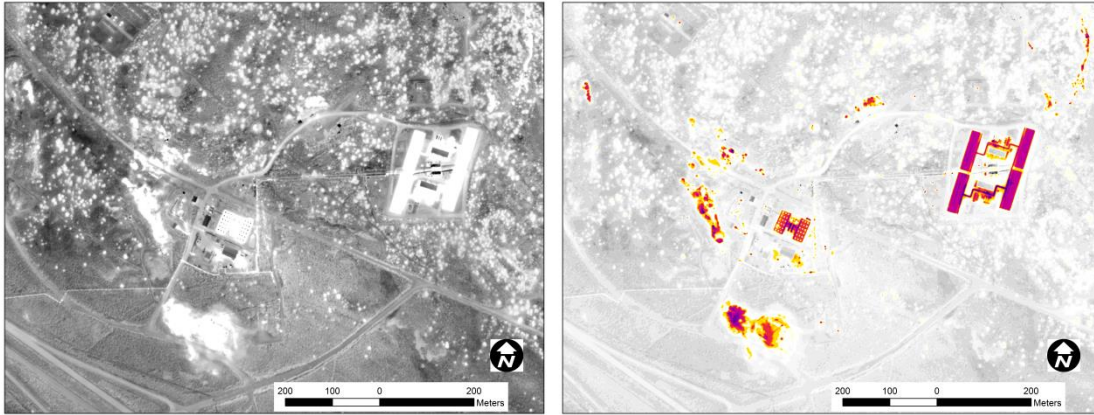


Figure 6: An example of thermal infrared mosaic with a grayscale (histogram stretch applied), left, and customized color ramp.

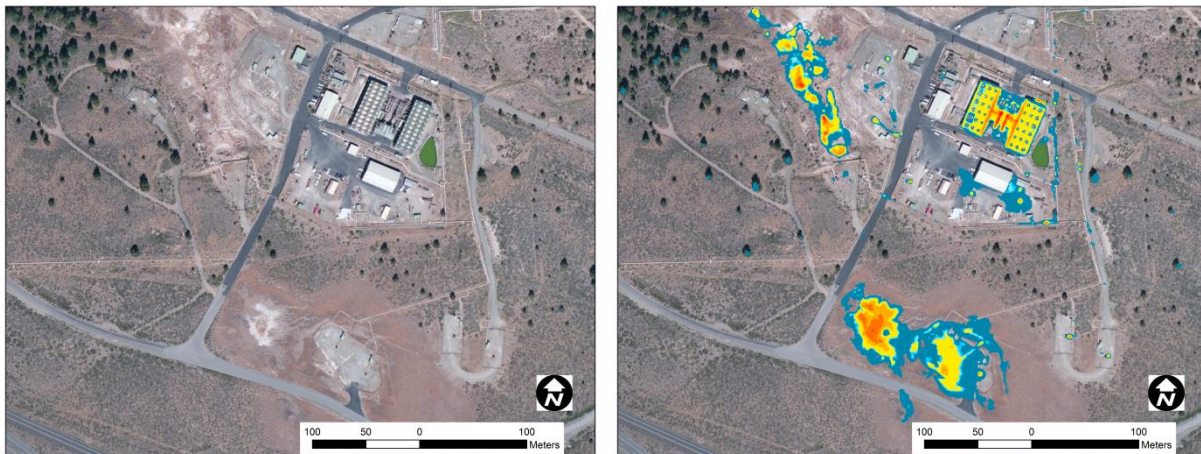


Figure 7: Aerial natural color imagery only, left, vs thermal infrared imagery overlaid the natural colors, right.

Imagery Mosaic

During Airborne GPS (AGPS) post processing static GPS data from monuments established by QSI were used to compute a set of corrections for the aircraft position and attitude throughout the flight. The resulting Smoothed Best Estimate of Trajectory (SBET) is then paired with the camera's time indexed,

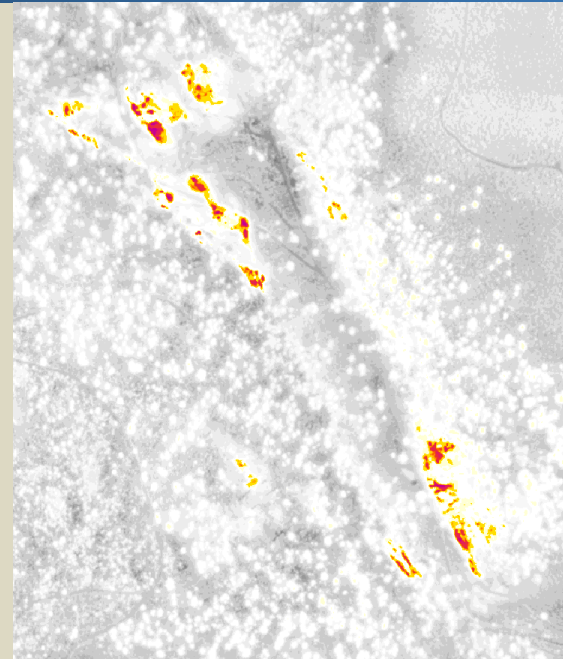
image event file in order to create initial Exterior Orientation parameters on the client specified datum for further use in photogrammetry software.

Thermal infrared images along with relevant exterior orientation parameters were imported into Photoscan’s Agisoft software. Agisoft uses pixel matches between multiple overlapping images to refine camera interior and exterior orientation parameters in a highly redundant bundle adjustment. A seamless mosaic of all images is created using a surface model mesh built from a sparse point cloud generated by the software. The workflow and softwares used is summarized in Table 6.

Table 6. Imagery processing workflow.

Orthophoto Processing Step	Software Used
Resolve GPS kinematic corrections for the aircraft positional data using kinematic aircraft GPS (collected at 2Hz) and static ground survey data (1 Hz) collected over QSI established monuments.	POSPac MMS v. 7.1
Develop a smooth best estimate trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor heading, position, and attitude are calculated throughout the survey.	POSPac MMS v. 7.1
Create an exterior orientation file (EO) for each photo image with omega, phi, and kappa.	IPAS CO v1.30
Import thermal images and camera calibration parameters to refine camera exterior orientation parameters and generate seamless imagery mosaic	Agisoft v1.2.6
Build custom layer file (*.lyr) for mosaic visualization in ArcMap	ArcMap v10.2

This TIR image highlights a potential geothermal well location identified by the TIR sensor.



Thermal Analysis- Identifying Hotspots

The process of identifying potential hotspot locations across the TIR mosaic is based on recursive automated algorithms and manual steps. Using the calibrated TIR mosaic, the first step is defining the range of background temperature above which temperatures indicate to potential hotspots. The background temperature across the ground surface is correlated to the atmospheric conditions in the survey area around the time of the TIR acquisition, mainly air temperature and cloudiness. Using a QSI proprietary algorithm, temperature anomalies across the TIR mosaic were identified and the warmer-than-background temperatures were classified as a potential hotspot feature (a group of pixels in the TIR imagery mosaic). In the context of the Mammoth Lakes project area, warmer temperature signatures can indicate a potential geothermal well.

Negative values were observed across the survey area's TIR mosaic. However, the 16 bit TIF file format does not contain negative values. Therefore, temperature values were converted from Celsius to Kelvin. Temperatures across the survey area varied between 251.3 °K and 348.2 °K. The analysis of TIR imagery was developed specifically to meet the needs of the Mammoth Lakes project consisting of the following steps (also described in Table 7):

- 1- **Identifying background range of temperatures:** A nearby meteorological stations recorded ambient air temperatures between 8.3 and 11.1 °C during the night of the acquisition and between 8.3 and 8.9 °C during the acquisition window. In turn, the background temperature of the ground surface is expected to be lower than 10 °C.
- 2- **Re-classifying the temperature raster across the survey area:** Temperature intervals were defined to identify heat signatures of features ranging between a specified minimum temperature and the highest temperature of the TIR mosaic. The intervals' minimum temperatures were chosen to be 10 degrees apart starting at 280 °K (280, 290, 300, 310, and 3200 °K).

- 3- **Vectorizing the hotspot features:** The identified features were used to create polygon features in each temperature interval.
- 4- **Calculating statistical information:** For all potential hotspot features, values of maximum, minimum, mean, and standard deviation were calculated.
- 5- **Examining the features:** the final examination involved manual editing of the data in order to remove manmade structures and examine the potential natural hotspots. Examples of the manmade hotspot features are the geothermal facility east of the survey area and heated outdoor pools in the town of Mammoth Lakes. However, all features should be further examined by the end user.

Table 7: Summary of the analysis steps used in the thermal analysis

Analysis Step	Data File	Description	Software used
Color ramp	<i><ProjectName>.lyr</i>	Develop a colorramp that highlights spatial variability of temperatures across the survey area.	ArcMap v. 10.2
Calibrated thermal imagery mosaic	<i><ProjectName >.tif</i>	Convert raw TIR image digital number to radiance temperatures based on the sensor's factory calibration. Adjust radiant temperatures based on the recorded ground control kinetic temperatures.	ExaminIR v. 1.50.3
Potential hotspot identified	<i><Min_Temp>.shp</i>	Feature class shapefile of all potential hotspots with temperature signature above the specified value.	ArcMap v. 10.2 QSI script
Manual examination	<i><Min_Temp>.shp</i>	Visual examination of the features and identifying man-made structures.	ArcMap v.10.2 Google Earth©

Findings

Objects with temperatures above ambient temperature (280°K) were deemed hotspots and potential locations of geothermal activity. As described above these areas were vectorized based on temperature range, however examination of each resulting polygon using available satellite imagery is required in order to remove invalid objects from the dataset including man-made features such as the geothermal

facility and objects inside residential areas (Figure 8). Figure 9 shows the results of this visual inspection, it displays the potential, valid geothermal locations at 3 main zones:

1. At the north-center of the study area, northeast of Mammoth Lakes.
2. In in the vicinity of Casa Diablo geothermal facilities, east of US highway 395.
3. Eastern most zone of the survey area.



Figure 8: Identified residential structures, natural color, left, and TIR, right.

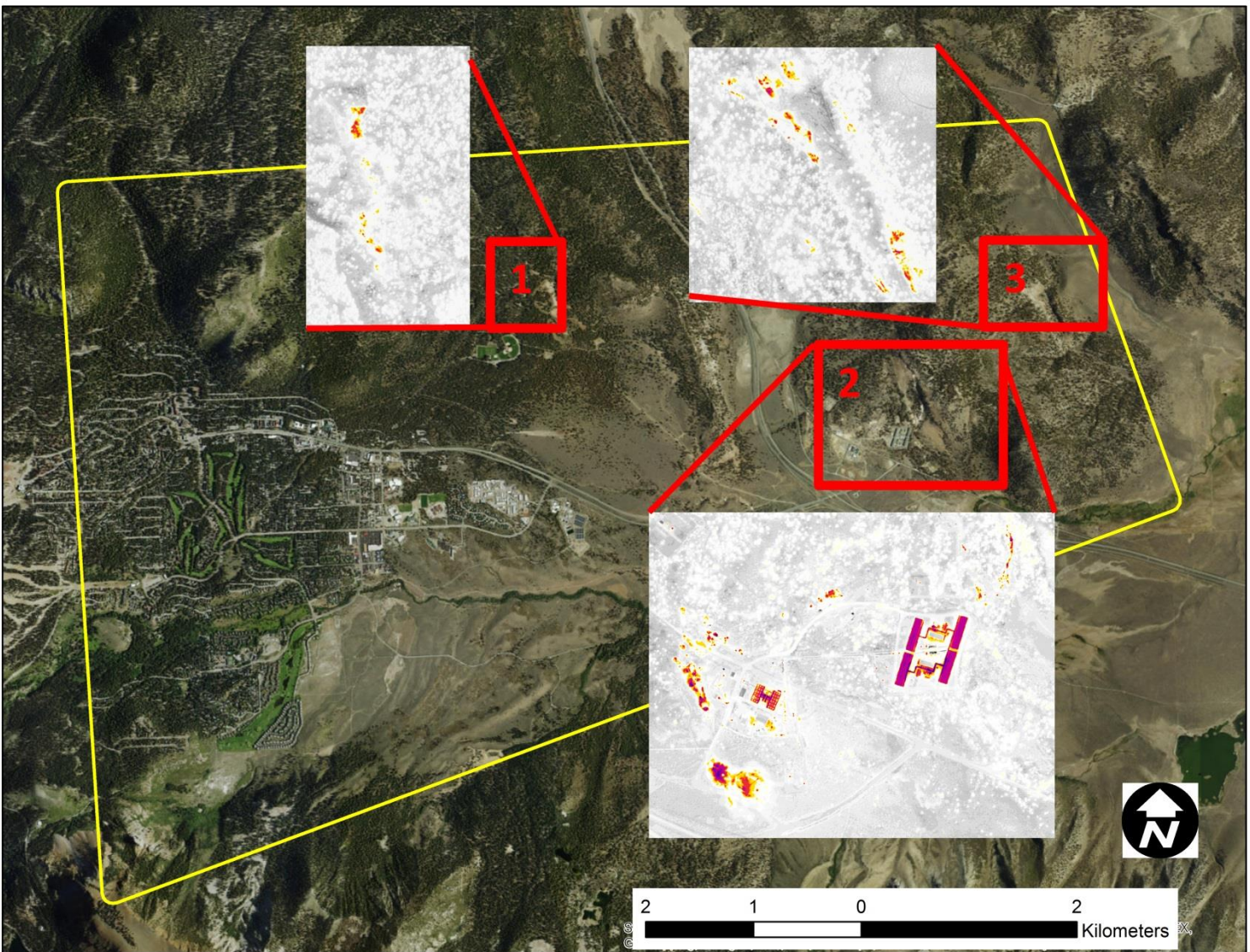


Figure 9: Example of identified hotspot signature for potential geothermal wells.