QUANTITATIVE EVALUATION OF AIRBORNE VIDEO TIR SURVEY IMAGERY

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SUMMARY - An airborne video thermal infrared survey was conducted over the Taupo Industrial Area and Pony Club geothermal areas, east Taupo, on the night of **3** March 1999. Ground truth measurements obtained from both water features and ground surface and near-surface were used to calibrate and interpret the imagery. The temperature calibrated imagery agreed well with the ground surface measurements, and anomalous geothermal features >~2°C above ambient were detected. A relationship between surface temperature and surface heat flow was derived and a heat flow map produced from a calibrated TIR image of the site. The heat flow from the anomalous geothermal areas at the site was found to be **~2.5MW$_{th}$**.

1. INTRODUCTION

The airborne video thermal infrared (TIR) scanner technique has been successfully used for mapping and monitoring changes in surface geothermal activity for over 10 years, and at more than a dozen New Zealand fields (Mongillo, 1988, 1992, 1998; Mongillo and Bromley, 1992). The method was developed to overcome the practical problems associated with ground-based procedures (e.g. their incomplete, often time consuming and expensive nature) and provides economic, comprehensive, high spatial resolution (~1-2 m) maps of geothermal surface activity.

The TIR method is based on the principle that all objects having kinetic temperatures (T) above absolute zero (0°K) emit thermal infrared radiation with a total energy content directly dependent on the temperature (T^4). This radiation is detected from areas of interest by a scanner and converted to brightness levels that are recorded on standard videotape as analogue, grey-level imagery. The imagery brightness variations represent the thermal intensity distribution in the scene and, in general, the higher the surface feature temperature, the brighter (whiter) it appears. Analysis of the imagery is conducted by digitizing the video imagery and applying computer image processing techniques *(ibid.)*.

Qualitative analysis of airborne TIR imagery has provided very useful mapping and monitoring (e.g. change detection) results in New Zealand studies *(ibid.)*. However, quantitative analysis makes it possible to map surface temperature distributions and identify smaller temperature differences and changes (~1-1.5°C) with greater confidence, and may also provide the opportunity to estimate surface heat flows.

The basic quantitative analysis of video TIR imagery has been "demonstrated" in several New Zealand studies (e.g. Mongillo and Bromley, 1992), however, it has not been investigated in detail. Practically, there are still many uncertainties and complications associated with quantitative analysis and interpretation which relate to: the relationship of TIR imagery temperatures to "true" ground temperatures; the effects of surface cover variation (e.g. water features, bare ground, vegetation); the survey time of day; the reproducibility of results, which bears upon their precision and levels of difference and change discrimination; the effects of altitude differences; the accuracy with which video imagery can be geometrically corrected (e.g. registered to a base map); and the capability for estimating surface heat flow and the associated constraints (e.g. surface cover variations, time of survey, types of ground measurements required).

Consequently, it was decided to conduct a video TIR survey to investigate, in detail, the quantitative capabilities of the video TIR technique. The initial results are presented here.

2. THE SURVEY

2.1 Survey Area

The survey area chosen for this study is approximately 2.8 km north-south by 1.2 km east-west in size, and is located along the eastern edge of Taupo town (Figure 1). It includes both the Pony Club and Taupo Industrial Area thermal zones and provides several sites which have the range of ambient to very active thermal ground confined to areas ~100 m in size.

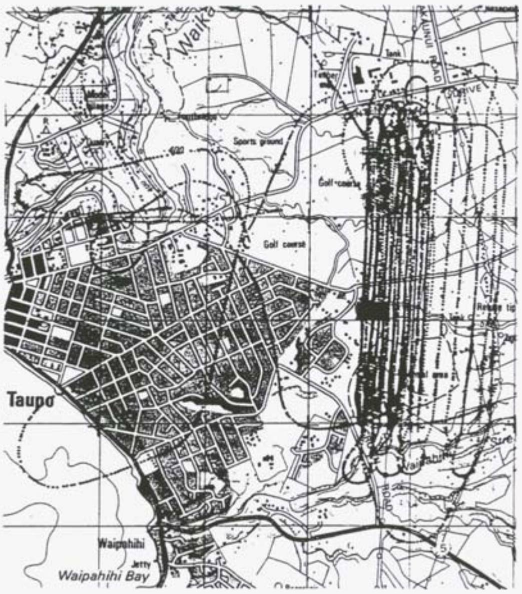

Figure 1. Sketch showing the survey area, the flight lines (dotted) and image study site (black rectangle) (Basemap: LINZ, 1987).

The site used for this study (Figures 1 and 2) is located about 350 m south of Broadlands Road and 200 m east of Miro Street. It is about 350 m by 185 m in size, relatively flat, though slightly inclined; with surface conditions which range from ambient to bare, weakly steaming ground surrounded by stunted kanuka. The majority of the site is covered by relatively short (5-10 cm high) grass, with an irregular distribution of stressed and dead patches about 0.5-3 m in size

2.2 Ground Control Measurements

Ground control temperature data used for quantitative calibration and interpretation of the TIR imagery were obtained from both water bodies and ground surface and shallow sub-surface using hand-held probes (±0.5°C). Prior to the TIR survey (on 10 and 23 February and 1 March 1999), a series of ground temperature measurements (surface; 5, 10, 15 and 100 cm depths) were made at two off-site ambient locations (Wairakei, Radio Station Hill); at distributed locations on the study site (A2-A5); and along a 110 m long transect (Al, T1-T37) positioned at the southern edge of the site (Figures 2a and 3b).

On the night of the TIR survey surface temperatures were measured on the Waikato River at Cherry Island (21.6°C at 21:30 NZDT) and at the three largest pools at AC Baths (30.0, 36.3 and 38.3°C, during the period 22:00-22:33 NZDT). Ground measurements were also obtained at the Ngauruhoe Domain (off-site ambient; 18:30; 3/03/99 and 01:30; 4/03/99) as well as along 47 m of the western end of the 110 m transect (23:01; 3/03/99 - 00:47; 4/03/99 NZDT) (Figure 3c); at four locations (A6, X2, X4 and A7) along a parallel transect positioned about 40 m further north (19:10-21:15 NZDT) and at an ambient local site (A5).

2.3 The TIR Survey

The TIR survey was conducted on the night of 3 March 1999, during the period 21:38-22:45 NZDT. A FLIR 2000 video TIR scanner, mounted on a Squirrel helicopter was used to acquire the imagery, which was recorded on a standard Sony SLV-X825MN video cassette recorder powered through an inverter. Survey flight was controlled using GPS navigation.

The weather had been generally very hot and dry for several weeks prior to the survey, though a light rain had fallen the week before. The sky was clear and ground conditions were dry on the night of the survey. A strong southerly wind was present during most of the survey, with some periods during which low altitude pumice dust clouds were present.

The area was surveyed from two altitudes. First, the entire 2.8 km x 1.2 km area was covered by 13 flight lines, from 700 m above ground level (agl), at a spatial resolution of 1.1 m and flight line separations of 75-150 m. Then, the western 75% of the area was covered by 14 flight lines, from 350 m agl, at a resolution of 0.6 m, with line separations of 50 m.

2.4 Ground Temperature and Image Analyses

The calibration temperature data, obtained on the night of the TIR survey, were corrected for probe errors (correction ≤0.4°C) using calibrated mercury thermometers.

Image processing and analysis were performed using two systems. Image digitizing from videotape and pre-processing were conducted using the PC-EPIC software operating on a 486/33 PC with a MATROX MVP-AT processor. Pre-processing consisted of de-striping the images to remove periodic brightness banding (Mongillo, 1988; 1992) and re-sampling to produce images with square-shaped pixels and approximate geometric correction. The resulting images were then transferred to a Silicon Graphics workstation, where they were filtered with a 3x3 low pass spatial filter to reduce noise, temperature calibrated and analyzed using ERDAS/IMAGINE 8.3.

A time-dependent temperature-brightness function was required to calibrate the imagery. Linear (least-squares-fit) equations relating image

Figure 2a. Temperature calibrated video TIR image [T(°C) = 0.243*DN+13.35] obtained from 700 m agl. The image covers an area of 350 m x 185 m and has a spatial resolution of about 1 m. The temperature transect is located by the black line. South is towards the top.

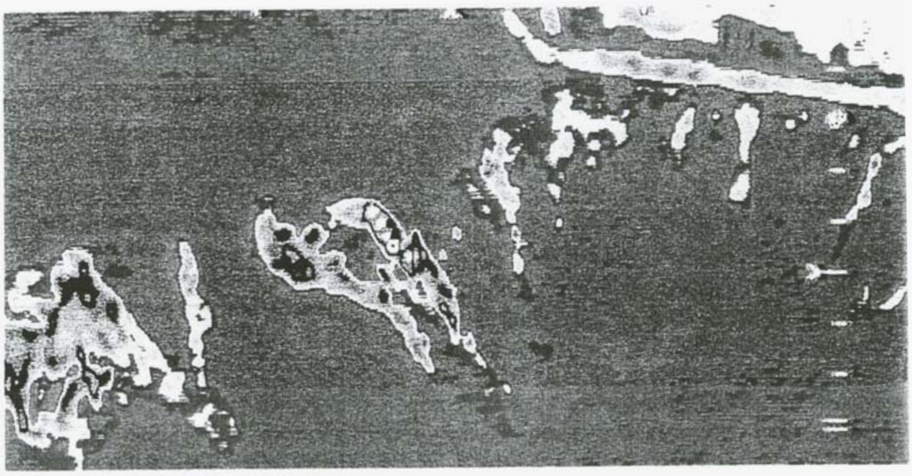

Figure 2b. Temperature calibrated video TIR image [T(°C) = 0.239*DN+15.35] acquired at 350 m agl, covering the central area of that in Figure 4a. The image covers an area of 175 m x 93 m with a spatial resolution of about 0.6 m. South is towards the top. See Figure 2a for the temperature wedge.

Figure 2c. Conductive heat flow map corresponding to Figure 2a. The image colours relate to conductive heat flows (in W/m^2) as follows: black: < 40; purple: **45;** cyan: 75; green: 150; yellow: 250; red: 350; pink: 450 and white: > 500.

brightness levels of the calibration water features and the time they were acquired were derived. The time an image was obtained then allowed the corresponding calibration feature brightnesses to be calculated. The linear (least-squares-fit) equation that related these calculated brightnesses to the calibration temperatures then became the calibration function for that image. Application of this linear equation to the image converted its brightness levels to temperatures.

The possibility of using TIR imagery to estimate heat flow was also examined. It requires ground sub-surface temperatures at the time of survey to correlate directly with the surface temperatures and shallow temperature gradients (Allis et *al.*, 1999). If this relationship holds, the heat flow (Q) versus surface temperature (T) equation: $Q = B*(T-T_0)$, where B depends directly on the thermal conductivity and T_0 is the ambient surface temperature, can be derived and used to convert a temperature calibrated TIR image to a heat flow map. A thermal conductivity of 0.6 W/mK (±50 %) was assumed on the basis that the shallow ground material and conditions are similar to those at Craters of the Moon ***(ibid.)***.

3. RESULTS AND DISCUSSION

3.1 TIR Imagery

The TIR imagery was found to suffer from two serious unexpected problems: (1) severe banding, characterized by a repeating series of 2-brighter/2-darker lines, with typical differences of ~30-40 %; and (2) a time-dependent temperature calibration function, caused by an unexplained decrease in image brightness during the survey. Correction methods for the first problem typically reduced the banding differences to about 5-10 %. The 3x3 spatial filtering further reduced these differences, often to an indistinguishable level. Remnant banding is observable as short, thin horizontal lines (Figures 2a and 2b).

Calibration analysis showed that a linear temperature (T) versus image brightness (DN) relationship was a good approximation, with the slopes of the functions approximately constant (0.24 1°C/DN) and the T-intercept increasing with time, from about 12.9 to 16.2°C, during the period of the survey. The error in the absolute temperatures is estimated to be about ± 1.5-2°C.

Temperature calibrated, pseudo-coloured images, of the study site, acquired from 700 m agl (at 21:50 NZDT) and 350 m agl (at 22:26 NZDT), are presented in Figures 2a and 2b, respectively. The temperature-colour relationship is the same for both images, covering the 517 (dark-blue) to 240°C (white) range (Figure 2a). In both images, which are similarly oriented, with south towards the top, the yellow area at the upper right is a flat, pumice surface timber yard (22°C) and the yellow linear feature is a pumice road. The most obvious geothermal areas occur in a band across the centre of the images and are green (19°C), yellow (22°C), orange (25°C), red (28-30°C) and white (240°C) in colour. Features having temperatures greater than 23-24°C (light-orange) are generally bare, thermal ground, with white crust sometimes present when temperatures are greater than about 28-30°C.

In the 700 m image (Figure 2a), the dark (≤17°C) and light (18°C) blue areas in the lower portion of the 700 m image are grass covered paddock, while those at the upper left are two flat, bare pumice surfaces. The ambient surface temperature areas in this image are dark blue (≤17°C). The less intense thermal anomalies are identified by the lighter-green colours (19-20°C). Anomalies as small as ~1 m in size are easily recognized and the locations and relative intensities of the features agree well with the field measurements (see discussion below).

The 350 m image (Figure 2b) covers the central portion of the 700 m one, and was obtained about 36 minutes later. It has twice the spatial resolution (0.6 m) as the 700 m image and, as expected, shows much greater detail. There is very good quantitative agreement between the images for temperatures 221"C (dark-green). At lower temperatures, however, the 350 m image is generally about 1°C higher. It is very unlikely that the temperature of the area increased 0.5 hr after the 700 m image was acquired, and this difference is ascribed to calibration inaccuracies. A 350 m image created with temperatures reduced by 1°C did produce much better agreement at the lower temperature levels.

3.2 Ground Temperatures

Temperatures obtained from the 700 m calibrated TIR image along the southern transect (Figure 2a) are presented in Figure 3a. The ground temperature measurements made along the transect for both the pre-TIR survey and TIR survey periods are also presented in Figures 3b and 3c, respectively. There is very good correlation between the pre-survey 5, 10 and 15 cm depth temperature trends (solar heating effects on the surface temperatures cause poor agreement); the calibration ground temperatures obtained on the night of the survey, and the TIR image temperatures. These results clearly demonstrate the capability of the TIR method to detect thermal anomalies in areas covered by 5-10 cm tall grass.

Quantitatively, there is very good agreement (≤8 % difference) between the image and measured ground surface temperatures (Figures 2(a), 2(c); Table 1) for ambient and less intense geothermal activity areas (image temperatures ≤21°C), where grass is present. Much larger differences occur for areas with image temperatures ≥22°C, though the results still clearly indicate the presence of significant surface activity. The generally small widths and sizes of the more intense geothermal areas compared to the more diffuse, less intense ones, in combination with a slight misalignment of the image and ground transects and the spatial filtering effects are probably responsible for a significant portion of these differences.

Table 1. Comparison of image and measured ground temperatures fiom Figures 3a and 3c.

Site	Cover	Position	Temperature (°C)	
		(m/pixel)	Image	Surface
A1#	grass	0/50	19	20.0
T1	grass	1/52	19	18.9
T3	patchy	5/60	21	-
T5	patchy grass	9/70	19	
T9	patchy grass	17/80	21	20.3
T11	dry grass	21/100	18	-
T15	bare	28/107	22	24.1
T19	unhealthy	33/120	20	21.6
T23	bare, crusty	41/140	39	26.1
T25	grass	47/165	20	19.1
A5	grass	-	17	16.1

This site is located at the western end of the southern transect and is the origin of measurement for the other site positions.

3.3 Conductive Heat Flow Estimates

The ground calibration data obtained on the night of the TIR survey allowed conductive heat flows to be estimated (Table 2). They were calculated using the data uncorrected for diurnal effects, which introduces error, but should still provide reasonable estimates useful for this demonstration. Data for the ambient site (A5) were not used, since the near surface temperatures are controlled by diurnal effects. The relationship between the conductive heat flow (Q, in W/m^2) and surface temperature (T_s, in “C), using the data in Table 2, is well approximated ($R^2 = 0.92$) by a linear least-squares-fit function:

$$Q(W/m^2) = 27.5*(T_s-16.3)$$

The results indicate an “ambient” temperature of 16.3°C which is in good agreement with that measured at A5 (16.1°C), the “ambient” location on the survey site. Dawson (1964) measured a surface heat flow of 300-400 W/m^2 from ground with a 15-cm depth temperature of 90°C. A linear extrapolation, using the two highest 15-cm depth temperatures measured in the present study (78.9

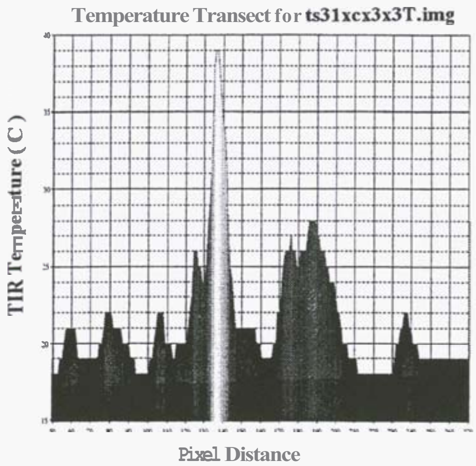

Figure 3a. Surface temperatures (°C) along the southern boundary transect obtained from the TIR image presented in Figure 2a. A pixel is about 0.4 m in length.

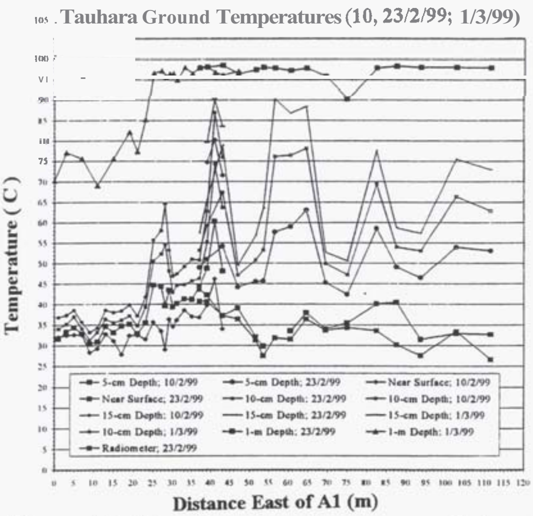

Figure 3b. Ground temperatures measured along a transect corresponding to that in Figure 3a during daylight hours on 10, 23 February 1999 and 1 March 1999.

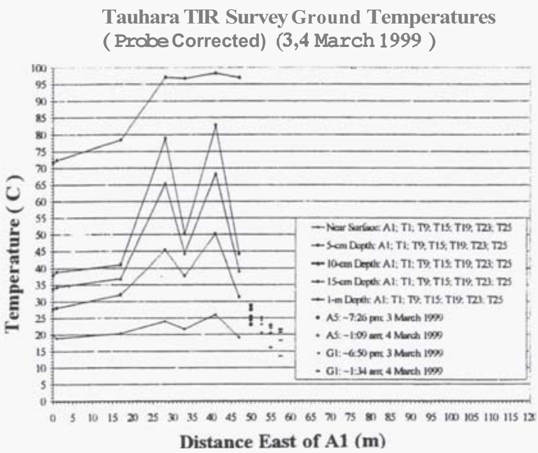

Figure 3c. Grouna temperatures measured along a portion of the transect shown in 3b on the night of the TIR survey.

and 82.7°C), provided a corresponding surface temperature of 30 °C. The resulting heat flow obtained was 380 W/m^2, in very good agreement with Dawson *(ibid).*

Since the TIR imagery temperatures are in generally good agreement with measured surface temperatures, the above equation can be applied to the temperature calibrated TIR image to generate a heat flow map (Figure 2c). The areas of equal heat flow on the image (i.e. areas of the same colour) can be integrated to obtain an estimate of the anomalous heat flow for the site. Geothermal features with image temperatures ≥ 19°C were found to have a total heat flow of **~2.5MW_{th}**. This is believed to be a reasonable estimate, considering the uncertainties associated with the choice of ambient temperature, temperature gradients, image calibration and thermal conductivity used.

Table 2. Ground temperatures, gradients (10cm-surface) and conductive heat flows for the study site (thermal conductivity = 0.6 W/mK).

Site	Temperature ("C)		Temperature Gradient	Heat Flow
	Surface	10-cm	(C/m)	(W/m^2)
A5	16.1	22.0	59	-
A1	20.0	33.9	139	83
T1	18.9	34.4	155	93
T9	20.3	36.9	166	100
T19	21.6	44.4	228	137
T15	24.1	65.4	413	248
T23	26.1	68.5	424	254

4. CONCLUSIONS

Video TIR imagery was obtained to investigate its quantitative application in the New Zealand situation. Serious banding and time dependent calibration problems were solved, producing absolute temperatures with an estimated error of ± 1.5-2°C. The images clearly detected geothermal anomalies with temperatures >~2°C above ambient. A heat flow-surface temperature relationship was derived and used to produce a heat flow map of the study site. The total anomalous geothermal heat flow was found to be ~2.5 MW_{th}.

5. ACKNOWLEDGMENTS

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