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Measuring Heat Loss from Flat-Roof Buildings with Calibrated Thermography

A thermally calibrated reference area can eliminate much of the uncertainty in measuring surface temperature and provide for a measure of heat flux that is bounded by quantifiable errors.

Introduction

The application of thermography and remote sensing in energy conservation holds the potential for a reduction of time and cost in surveying surfaces of large structures, in the implementation of energy policy, and in the performance of energy-related services for the public. This realization has motivated many engineering and public out-reach projects at various levels of technical sophistication over the past several years. In most of these studies, thermography has been a tool for qualitative interpretation of building temperature and identification of areas of excessive heat loss, i.e., "hot spots." Attempts have also been made to evaluate thermographic data for a quantitative measure of surface temperature and heat flux. These efforts have been subject to numerous errors and inaccuracies resulting from imprecise knowledge of local environmental conditions, surface emissivities, and details of the construction of the building envelope.

Abstract: *The objective of this study is to demonstrate calibrated thermography as a means of predicting the heat losses of flat-roof buildings using calibrated digital data from a thermal infrared aerial survey.*

Such a survey conducted at the Ohio State University has provided several results: calibrated thermography is a useful way to measure heat losses; it provides a method for calibrating thermal infrared digital data; and it provides a means for producing a calibrated temperature (2°C-contour interval) map to graphically represent the digital thermal infrared data. The present study demonstrates that a thermally calibrated reference area within a flat-roof surface can eliminate much of the uncertainty in measuring surface temperature and provide for a measure of heat flux that is bounded by quantifiable errors. The major sources of inaccuracy and imprecision are surface material emissivities and local environmental conditions, i.e., wind speed, cloud cover, and sky temperature.

This pilot project, conducted at the Ohio State University, demonstrates the role for calibrated reference areas within a remotely recorded thermogram, and identifies the major sources of inaccuracy. The present paper summarizes the results and procedures of this study, as well as those of other related studies. Overall, present and past work has resulted in a body of data, balanced be-

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tween qualitative and quantitative information, which can provide future researchers and practitioners a basis for designing their studies and interpreting their results.

Prior Studies

In general, the major data product from a thermographic survey is the exterior surface temperature. However, the relation of this temperature to the energy being consumed in the heating of the building is not easily obtained. Paljak (1972) stated that the measurement of building surface by thermal imaging must be confined to locating the defects in the thermal insulation and, perhaps, to defining the type of defect. Grot et al. (1976) stated that thermal imagery can give a practical means of determining the temperature of the building surface, but this temperature does not provide the amount of heat loss. Relative heat losses among various building types were determined from thermal imaging by Hazard (1973). Sampson and Wagner (1976) reported that aerial thermal imagery provides a means of determining building roof insulating characteristics but that emissivity difference, normal radiation variation, and wind effects complicate the interpretation of the image. Burch *et al.* (1978) stated that thermal imagery produced gray tones corresponding to surface temperatures, the practical value of which is that the techniques distinguish between insulated and non-insulated surfaces. The major source of uncertainty is the minimum detectable temperature difference recorded, i.e., the temperature resolution. They indicated that this is minimized under still-air conditions.

In the remainder of this section we review three prior thermographic studies which can serve as case histories on both residential and institutional buildings. Generally, they are of a qualitative nature and have formed the necessary background for designing the present study. The three studies are (1) an airborne thermographic survey of the Ohio State University campus in 1975, (2) a similar thermographic study of the campus at the University of Cincinnati in 1976, and (3) a 1978 airborne survey of residential buildings in Wichita, Kansas.

The Ohio State University Study

In March 1975, Daedalus Enterprises, Inc., Ann Arbor, Michigan conducted an energy-loss survey using a thermal infrared scanner. The primary purpose was to show the distribution of apparent energy losses from campus building roof tops. The energy-loss distribution was displayed on Digicolor thermal infrared (TIR) mosaics and continuous tone TIR imagery. An example of the latter is shown in Figure 1 at 1:4800 scale.

The TIR black-and-white imagery (Figure 1) was produced by the Daedalus DS-1210 infrared scanner, the flight being performed between 0943 and 1045 EDST on 27 March 1975 at two flying heights, one at 300 m and the other at 600 m above the campus. During the flight the sky was overcast, with a ground level ambient air temperature of 2°C. More than 100 buildings were within the survey, ten of which Daedalus indicated had anomalous heat-flow displays, but heat losses were not reported.

Imagery tones and other observed data such as roof surface materials and local weather conditions were used in the interpretation and analysis.

Fig. 1. Thermogram of a portion of The Ohio State University, Daedalus Enterprises, Inc., 27 March 1975.

Briefly, the procedure provided notations on each building image tone or color and its corresponding temperature. Next, insulation was noted; then roof type, surface, shape, and activities within were identified. If the roof surface was warm (light-toned), without insulation, and without wind cooling effects and other factors considered, the building was noted as having an energy loss; Robinson Laboratory was given such a notation. On the other hand, if a roof surface was cold (gray-toned), had insulation, was without wind cooling effects, and was unoccupied, an apparent no-energy loss was observed.

Hitchcock/Civil-Aeronautical Buildings. These are connected buildings composed of class rooms and offices. The roof is flat, covered with asphalt/gravel composition and insulated. The tone of this composite building indicates a cold surface, giving a no-heat loss observation (see 1, Figure 1).

Denney Hall. The roof surface is built-up asphalt/gravel composition, insulated and with a drop-type ceiling over the office. The only heat loss appeared over the stairwells and the ventilators. Activities are those associated with offices and classrooms. The building was not fully occupied at the time of survey. This building has little or no apparent heat loss (see 2, Figure 1).

Administration Building. The roof is peaked, of wood construction covered with an oxidized copper surface. The top floor has a drop ceiling with an attic air space; there is no insulation. The copper surface, being an excellent conductor, has heated up. The building was fully occupied during the spring break. The roof side facing the Oval (south) is cooler than the other areas, perhaps because of the wind on that surface. This building exhibits a heat loss (see 3, Figure 1).

Robinson Laboratory. This building has saw-tooth construction of series of wooden inclined wedges covered with clay-tile shingles. The building had a great amount of heat loss. There are drop ceilings in the offices, but no insulation above (see 4, Figure 1). Table 1 contains the examples of the observed and recorded rooftop conditions.

THE UNIVERSITY OF CINCINNATI STUDY

Thermal imagery and data from a survey of the University of Cincinnati Campus were studied. The data are semi-quantitative, without the necessary ground truth for temperature calibration. The data products, a general data analysis, and an estimated ground truth are given below:

Flight line directions: North-South over main part of Campus and East-West over Hospital
Flight height: 300 m, scanner black body calibration information at −2°C and 18°C
Ambient air temperature: −2°C
Sky conditions: overcast
Wind: SW 2 m/s
Flight time: 10:34-10:45 EST, 31 January 1976.

The image tone or color is expected to indicate the need for roof insulation. Some rooftops were field checked and photographed to assist the interpretation of the thermal infrared imagery. There tall buildings triangulate the campus, providing a means to photograph the surfaces of the buildings.

Figure 2 provides a view for the reader to observe the data as given in the following paragraphs.

The Library roof was light-toned, indicating heat loss. The southeast corner appeared somewhat cooler, probably because of a wet surface (see 1, Figure 2).

Corbett Pavilion had three temperature conditions. The flared metal surface was hot, the south section adjacent to Gym Road was light-toned, but the eastern curvilinear segment, on Gym Road, was somewhat cooler. A black (cool) rectangular section appeared just north of the flared segment (see 2, Figure 2).

Emery Auditorium had a light-toned roof sur-

TABLE 1. SUMMARY OF FINDINGS ON CAMPUS BUILDINGS

Conditions associated with findings	Insulation	Roof Materials	Shape of Roof Surface	Ceiling	Activity	Open/Closed During Spring Break	Heat Loss
Hitchcock/Civil Aeronautical	yes	gravel, asphalt	flat	drop	offices, classrms	open	no
Denney Hall	yes	gravel, asphalt	flat	drop	offices	open	no
Administration Building	no	copper	hip	drop	offices	open	yes
Robinson Laboratory	no	wood, tile	saw tooth	drop	offices, classrms	lab equip. mach. shop	yes

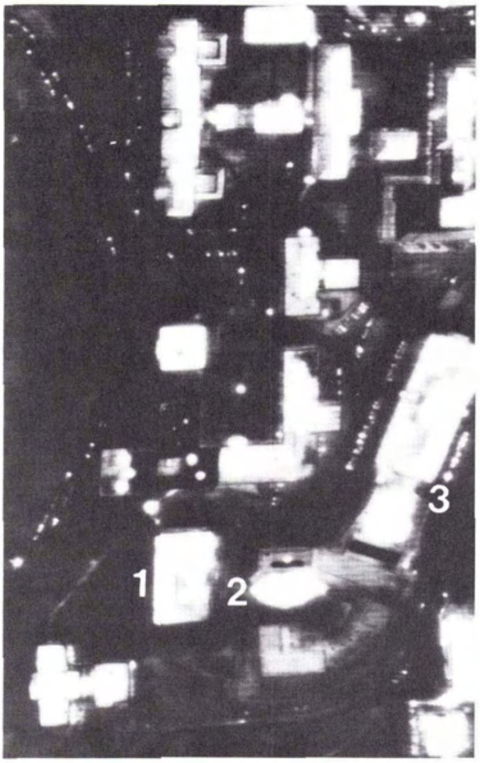

FIG. 2. Thermogram of some University of Cincinnati buildings, Daedalus Enterprises, Inc., 31 January 1976.

face. The open spaces in the center of the roof were cooler. Table 2 gives a means of comparing the building heat losses. (See 3, Figure 2).

THE WICHITA, KANSAS STUDY

Two aerial surveys were conducted over the city of Wichita. The first produced standard thermograms, and the second gave digital data. Ground data for the first mission were as follows:

Lake surface:	3°C
Canal surface:	6°C
Ambient temperature:	−3°C
Cloud cover:	almost none
Wind:	none, still night
Time of day:	10-11 P.M.
Flight lines:	E-W down 21st St. W-E down 1st st. Turned at Canal River, 18th St.

Using the available computer-compatible tapes that provided thermal infrared digital data for an area near Wichita State University, three types of products were generated. The first step in this generation was to locate a sample area. This was accomplished by examination of the numeric printout. A dwelling with its surroundings was chosen as the sample area. The maximum width that can be processed by the computer is 64 pixels. One pixel is approximately 0.25 m^2. The sample area is (96) (0.5 m) (64) (0.5 m) = 1536 m^2. The total swath of each scan line is approximately 300 m, depending on the flying height and scan angle.

The digital product, Figure 3, provided thermal data with numerical intervals or units. These units were assumed to be radiation values. A 0 to 12 range of pixel values was observed. With zero representing the coolest temperature, it was assigned a blank symbol. As temperature values increased, numbers were assigned up to 12. This numeric product is quite easy to read. Because calibration data were not available, absolute temperatures were not represented by the numeric symbols. From the digital map, a numeric printout of contour lines was plotted for constant temperatures as shown in Figure 4. In the sample area the house, roof, chimney, porch, various plants and trees around the house, and cars parked in the yard and on the street can be observed. The roof surface of the house is void of numbers because it was the cooler surface.

Minimal ground data were available for the second flight in that the wind and cloud conditions were not as favorable as in the first flight. Ambient air temperature, wind velocity and direction, cloud cover, moisture conditions, relative humidity, flight line direction, and flying height would have provided a means to convert apparent temperatures to absolute temperatures.

From these earlier surveys it was learned that to estimate the heat losses using the thermograms one needs aerial photographs of building roof surfaces to estimate the surface materials and their

TABLE 2. UNIVERSITY OF CINCINNATI CAMPUS SURVEY

Building	Use	Type Roof	Tone	Heat Loss
Library	Library	Builtup, Flat	Light, Except SE Corner	yes
Corbett Pavilion	Theater	Copper, Builtup	Light on Flared Section, Dark on Pavilion	yes no
Emery Auditorium	Conference Meetings	Builtup, Flat top	Light, Except Flat top, Stage	yes no

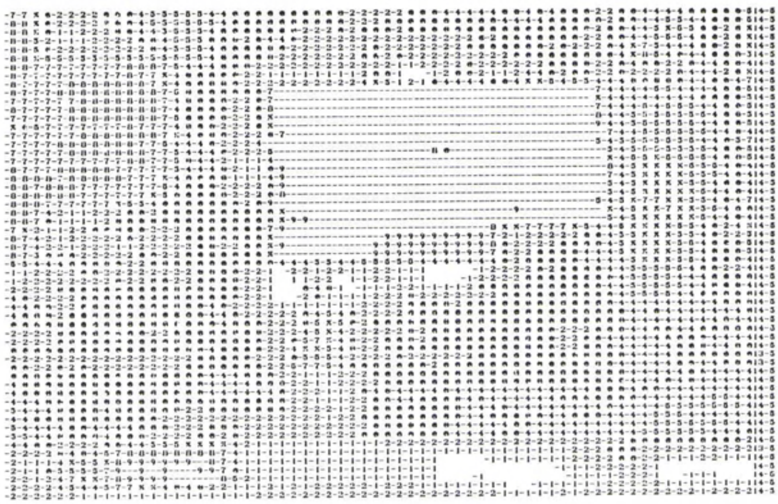

FIG. 3. Digital map of selected residence, Wichita, Kansas (data courtesy Elmer Hoyer, Wichita State University, 1978. Prepared by R. D. LaRue, The Ohio State University, 1979).

emissivities. It was observed that the following calibration data were needed: First, a width locator is required. Second, corrections for geometry and radiation variance of non-vertical sections of the width must be acquired to produce "true" radiation values. These values can be converted to apparent temperatures. Finally, a ground-based calibration reference is needed to convert apparent temperatures to absolute temperatures. Additional information such as the type of insulation, inside building temperatures, and gas or heating fuel consumption would have been useful.

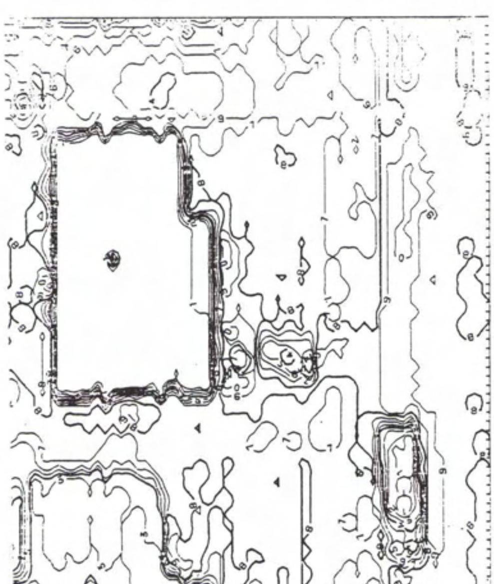

FIG. 4. Thermal contour map of temperatures from data supplied by Elmer Hoyer, Wichita State University, 1978.

Calibration of Thermal Surveys

In this section, the determination of the building heat losses is addressed with calibration data, where one is using thermograms and known environmental conditions and building roof surface parameters. Over the past few years considerable effort has been expended to define building heat loss using aerial thermal imagery. The results of such studies have established that aerial thermograms can readily give approximate temperature distributions, but not roof surface temperatures. Additionally, to our knowledge no thermographic survey has yet provided measurements of roof temperatures relating the temperature to the heat flux at the surface. The inclusion of a known thermal reference in the thermogram would alleviate uncertainty to a great degree and provide a means to quantitatively evaluate the thermogram, as well as give a means to extrapolate data from one part of the thermogram to another.

When one considers the prior quantitative studies, it appears that the inclusion of a thermal reference in the thermogram will reduce the uncertainties in the measured surface temperature and will provide a means by which heat transfer rates can be estimated. For the latter, good accuracy can be obtained when accompanied with measurements of local wind speed, ambient temperature, and sky temperature. These additional data will considerably reduce the uncertainty in the convection heat loss calculation at the surface and allow a correction to be applied to the apparent surface temperatures determined by the TIR scanner.

If a thermal reference is placed on a flat roof that is higher than surrounding buildings and trees, as reported in the present study, there is no energy received from these surroundings. When clouds are present, the effective sky temperature will be higher than the deep sky temperature.

The thermal reference for the reported overflight was constructed using the following guidelines:

- The area of the thermal reference should be large enough to be resolved by the TIR scanner and provide more than one elementary area element in the thermogram.
- The total power input to the thermal reference should be known as accurately as possible.
- The conductive and convective heat losses from the edges and back of the reference should be held to a minimum and quantified if possible.
- The emissivity of the surface coating of the reference should be known to within a specified accuracy in the wavelength band of the scanner.
- The wind speed over the reference should be measured during the scan.
- The surface of the reference should be of a uniform thermal conductance to provide a nearly consistent surface temperature.

Based on these guidelines and on theoretical considerations provided by Kulacki *et al.* (1981), a schematic of the thermal reference was designed as depicted in Figure 5.

The thermal reference is an electrical heating pad backed by a nearly adiabatic surface so that almost all the heat generated in the heater is transferred to the ambient through the exposed surface. The exposed surface of the heater is covered by a thin sheet of aluminum which maintains a uniform surface temperature because of its high conductivity and the structural and environmental integrity of the apparatus. A paint coating of high emissivity is applied to the aluminum sheet. The temperature of the reference surface is monitored with thermocouples attached to the underside of the aluminum sheet. During overflights, temperature data at the reference surface were recorded with these thermocouples as well as with a portable radiometer. The latter also provided temperature measurements at selected stations. Measurements of applied voltage and current to the reference surface determined the heat flux on that station.

Acquisition of Data

The experimental phase of the present study comprised, in part, airborne quantitative, thermally calibrated TIR scans of the roof of the Hitchcock/Civil Aeronautical-Astronautical Engineering Building on the Ohio State University campus. This building has a flat roof with the

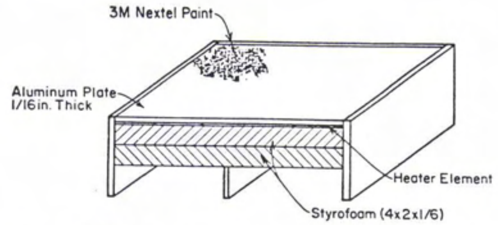

Fig. 5. Schematic of thermal reference (Kulacki *et al.*, 1981).

usual ventilation equipment housings and elevator shaft. Overflights were made at an altitude of 450 m using a TIR scanner operating in the 8 to14 micrometre spectral range. The instantaneous field of view is one mrad, representing a patch of ground of 0.5 m by 0.5 m.

Ground-Based Data Collections

In addition to the electrical data, other data were collected at the roof surface and, concurrently, wind velocities, ambient temperatures, and surface conditions were recorded.

Data were collected from stations 1 to 16, the locations of which are identified in Figure 6 and Table 3. Targets 1, 2, and 14 were the heat flux-pad calibration sources. The heat flux pads were operated such that the surfaces were at greater temperatures than the roof surface temperatures. Target 11 was 4 ft by 6 ft (1.31 m by 1.97 m) surfaced with smooth aluminum foil. Targets 8, 9, and 10 were circular tubs or buckets of water of 1.3, 1, and 0.3-m diameter, respectively. Targets 3, 4, 5, 6, 7, 12, 13, 15, and 16 were primarily roof surfaces, stations on the asphalt-pebble mix composition.

Three sets of radiometric measurements for the 16 targets were recorded, each one at a different time during the overflight. The radiometric temperature measurements were made with the Raytech model R-380-RVC hand-held radiometer. These measurements are given in Table 3. This

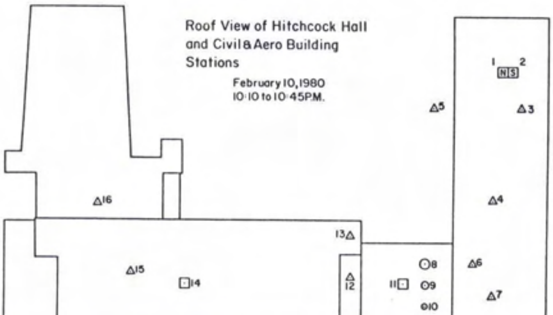

Fig. 6. Data collection stations, roof surface, Civil and Aeronautical Engineering and Hitchcock Hall buildings. (Mintzer *et al.*, 1980)

TABLE 3. RADIOMETER READINGS VS. TEMPERATURE NUMBERS

CAE & Hitchcock Buildings				10 February 1980
Station No.	Radiometer[1] Reading (°C)	Temperature[2] Number	Δ	Description
1	+13	+12	+1	North CAE heat pad
2	+13	+11	+2	South CAE heat pad
3	−5	−8	+3	Spot
4	−5	−7	+2	Spot
5	−5	−4	−1	Roof CAE 1st floor
6	−3	−4	+1	Spot
7	−6	−8	+2	Spot
8	0	−2	+2	Large pool
9	0	−2	+2	Small pool
10	+10	−4	+14	Bucket
11	−28	—	—	Aluminum
12	−5	−7	+2	Spot
13	−5	−7	+2	Spot
14	+5	+5	0	Heat pad Hitchcock
15	−5	−7	+2	Spot
16	−5	−7	+2	Roof Hitchcock Auditorium

[1] Recorded from 10:35 to 10:45 P.M., $\sigma = \pm 1°C$
[2] Digital Data recorded at 10:42 P.M., $\sigma \simeq \pm 1$ unit

instrument has a spectral range from 8 μm to 14 μm (Table 3), a resolution of ±1°C, and a field of view of 15:1 (distance to target diameter). At the time of measuring each station, the radiometer was calibrated using a reading on a completely mixed ice-water bath and observing a laboratory mercury thermometer temperature. Before calibration, the instrument was allowed to come to steady-state (ambient) temperature; thermal mittens were used to insulate the instrument while hand-held. Radiometer measurements of targets 1 to 4 and 6 to 15 were made at a 1-m distance and 60° to 70° angle from the horizontal. Measurements of targets 5 and 16 were made at distances of 10 m and 6 m, respectively, at a 40°-view angle from horizontal.

During this study the flight ambient temperature was −6°C and the inside building temperature was 24°C, providing a good indoor/outdoor temperature contrast. The dew point spread during the flight verged on the acceptable. Wind velocity recorded for the time of the flight was never more than 2 m/s. Surface wind conditions are considered critical if the velocity is greater than 4 m/s. Although the sky was not entirely clear during the flight, the cloud cover was observed as scattered and less than 20 percent.

For the airborne data acquisition, the flight plan included the time of airborne data collection between five hours after sunset and 4:00 A.M. The primary weather conditions that affect the data collection are temperature, clouds, temperature/dew point spread, and wind velocity (Schmer and Dick, 1978). To determine the weather conditions that could be expected in the vicinity of Columbus, a study was made of a ten-year set of data obtained from the National Oceanic and Atmospheric Administration. The condition of the rooftops was not a limiting factor in the data collection. There was no snow cover, and no heavy frost- or water-covered areas on the rooftops that would change the radiation characteristics. The above limitations on cloud cover, wind velocity, and possible periods of good weather conditions went into the planning of the operation.

During the airborne survey, the wind speed at roof level varied between 0 and 1 m/s in gusts from 0.5 to 2 m/s lasting approximately 1 to 3 minutes. Gusts generally occurred every 1 to 3 minutes with low level fluctuations in speed on the order of 0.5 m/s. These data were recorded using a simple anemometer/generator set with a graphical analog output. The accuracy of these velocity measurements was on the order of 0.2 m/s.

The instantaneous field of view (IFOV) for the Texas Instruments' equipment used was less than or equal to 0.5 m by 0.5 m at ±45° nadir for the imagery, and ±28° nadir for the digital data record. The delivered data products were film negatives and positives, made in continuous tone black-and-white 70-mm imagery at a scale of 1 in. to 200 ft, and computer compatible tape data for digital representation of the thermograms.

RESULTS

COMPUTER PROCESSING

The processing of thermal infrared digital data (Figure 7) acquired in this TIR survey required the use of the computer. The raw data product, in tape format, was recorded with a resolution of ±2°C and was used to produce both digital and uncalibrated contour maps (Figures 7 and 8). A thermogram of the CAE and Hitchcock Hall Buildings is shown in Figure 9.

The SURFACE II Graphics System (Sampson *et al.*, 1976) provided the commands for preparing the uncalibrated temperature contour map. This software package is available at The Ohio State University Instruction and Research Computer Center. Because the digital data were in a relative form, they were scaled to set the minimum level at −9 and maximum level at +14, as shown in Figure 7.

MATHEMATICAL MODELS FOR TEMPERATURE ESTIMATES

One important result of the data analysis was the estimation of the roof surface temperatures, based on the airborne digital data, roof surface measurements on the Civil and Aeronautical Engineering Building and a model as shown in Figure 10. Once a contour map is obtained, the temperature of each ground data station is established. The temperature number is defined as the number read from the digital map for a given location. A temperature number was recorded for each of the ground stations. A ground data set that was recorded close to the time of overflight was used in the data analysis.

Table 3 presents the difference (Δ) between the temperature number and the radiometric temperature. The data were used to calibrate temperatures. The data from stations 10 and 11 are excluded. Station 10 was a bucket of water which provided too small a surface area for consistently accurate temperature measurements. Station 11 was a 4 ft by 6 ft (1.31 m by 1.97 m) sheet of aluminum foil which reflected the sky temperature and, thus, produced variable surface temperature data during intermittent cloud cover.

The straight-line equation (Figure 10) giving the radiometric temperatures for a given temperature number was devised after trying several mathematical models. Some factors are not included in these models such as material emissivity, effect of wind, cloud coverage, and image distortion. The

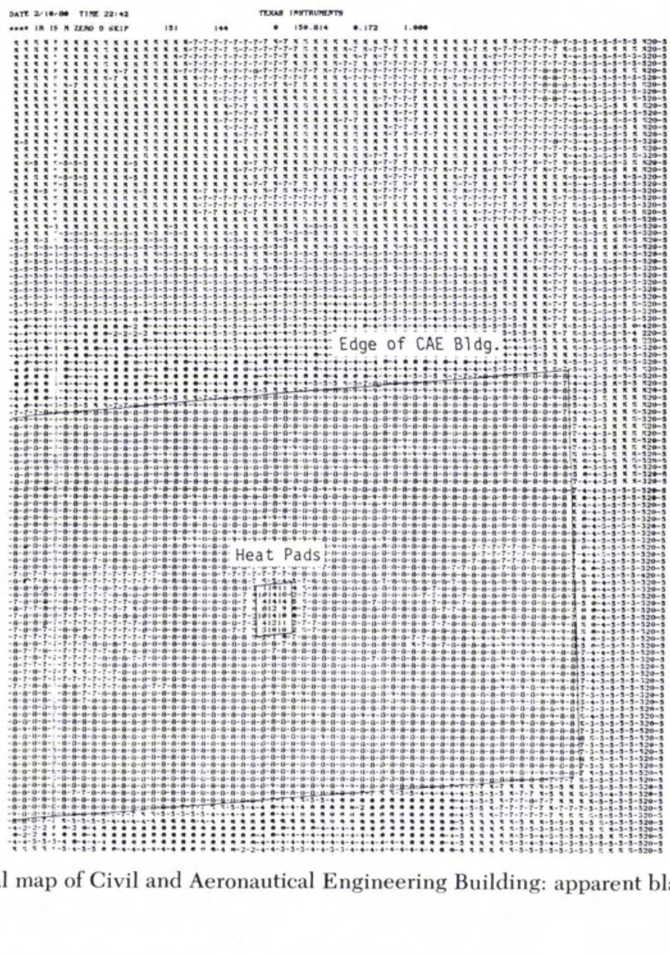

FIG. 7. Portion of digital map of Civil and Aeronautical Engineering Building: apparent black body temperatures. (Mintzer *et al.*, 1980.)

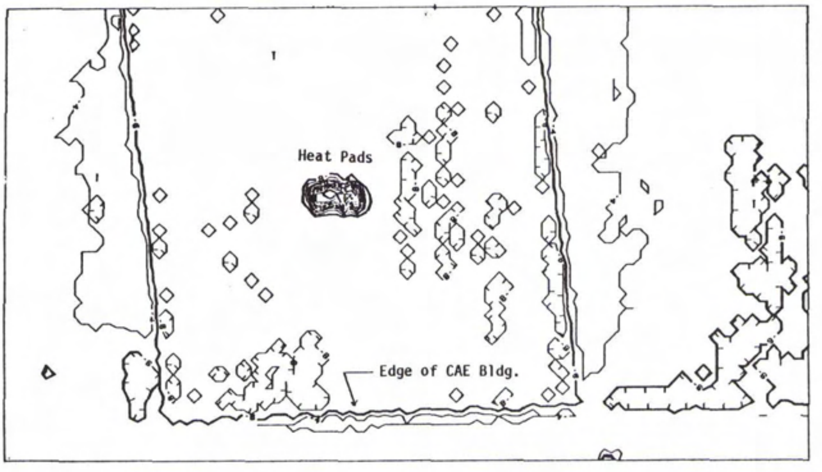

FIG. 8. Uncalibrated temperature contour map: Contour interval, 2.0°C. (Mintzer *et al.*, 1980.)

two models attempted were straight-line and second-order polynomials. The straight-line mathematical model is of the form $Y = bX + c$. In this investigation we used X as the temperature number of a ground station and Y to represent the radiometric temperature. The values of b and c were computed using the standard condition equation and a least-squares adjustment of the linear model. The variables X and Y were treated as observations with unit weights. The number of conditions provided by the system of equations was 14; thus, the degrees of freedom for this case were 12 for two parameters.

The following values were obtained through the adjustment: $b = 0.96 \pm 0.04$ and $c = 1.5 \pm 0.3$. Thus, the straight-line model is $Y = 0.96X + 1.5$, shown as plotted in Figure 10. Note that it follows the general trend of the observed data points.

For the second model, the average standard deviation of adjusted observations was computed separately for the digital map temperature numbers (X) and radiometric readings (Y). These values are $\bar{\sigma}_x = 0.52$°C and $\bar{\sigma}_y = 0.50$°C.

The second-order polynomial was also used to model the data; the general form is $Y = aX^2 + bX + c$. The observations X and Y were defined above. Also, the values of the parameters were computed by a least-squares adjustment. The degrees of freedom became 11 for three parameters. The curve obtained from the adjustment was plotted for $Y = 0.012X^2 + 0.92X + 0.8$, providing a similar result to the straight-line model.

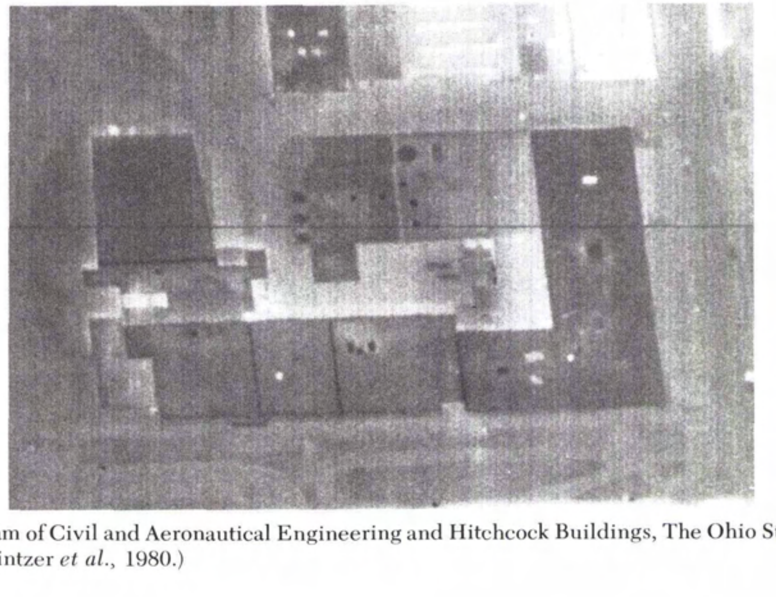

FIG. 9. Thermogram of Civil and Aeronautical Engineering and Hitchcock Buildings, The Ohio State University, 10 February 1980. (Mintzer *et al.*, 1980.)

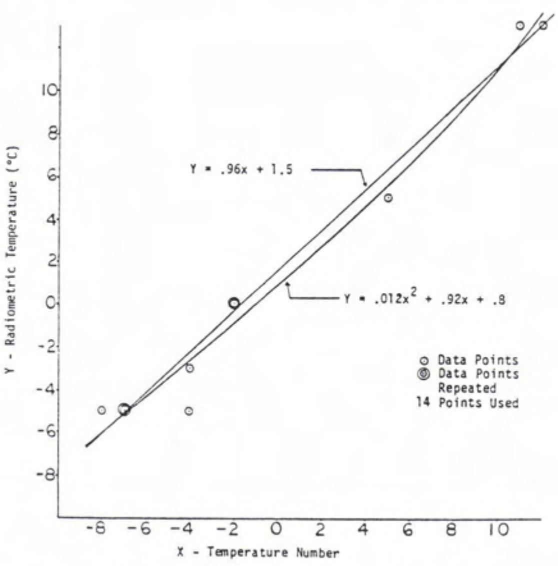

FIG. 10. Radiometric versus temperature number. (Perez Rodriguez, 1980.)

The calibration of the measuring system was achieved by investigating the relation between the temperature numbers and the radiometric readings. The relation is expressed by the equation $Y = 0.96X + 1.5$, where X is the temperature number and Y is the radiometric reading. The straight-line model suggested that the surface temperature of the roof could be estimated with a precision of ±0.5°C.

Using the calibrated roof temperatures a calibrated temperature contour map was compiled (see Figure 11.). One might also show roof surface temperatures with a three-dimensional diagram (Figure 12). This type of display provides an idea of the hottest areas of the roof surface from observing the location of the "spikes."

HEAT LOSS ESTIMATION

The digital data obtained in this study were used to estimate the heat loss from the roof of the CAE Building, the calculations being made from the airborne and ground data obtained on 10 February 1980. Estimates of the convective and radiative components of the heat loss were included in the calculations. For details on this procedure the reader is referred to the report by Mintzer *et al.* (1980).

Other data pertinent to the heat loss estimate:

Cloud cover:	20 percent broken with 17-km visibility and becoming more dense at time of survey
Scanner filter:	8.5-13.2 μm
Wind:	1 ± 0.5 m/s with gusts to 2 m/s
Heat Flux Pad Temp:	13°C, radiometric (55.4°F)
Roof Temperature:	−5°C, radiometric (23°F)
Sky Temperature:	−28°C, radiometric (−18.4°F)
Ambient Temperature:	−4.4°C, thermometer (24°F)
Heat Flux Pad Power:	710.4W (239 W/m² @ 4.0 A)
Area of CAE Roof:	390 m²

With these data, the heat loss from the roof was estimated as shown in the following calculations. First, the radiative component for the heat flux reference pad and the roof are calculated; i.e.,

$$q_{\text{rad, roof}} = \sigma\epsilon(T^4_{\text{roof}} - T^4_{\text{sky}})$$
$$= 24.1 \text{ Btu/h} - \text{ft}^2 = 76 \text{ W/m}^2$$
$$q_{\text{rad, ref}} = 158 \text{ W/m}^2$$

The convective loss from both the roof and the heat flux reference pad are estimated from the data contained in the report; is,

$$34 \leq q_{\text{conv, ref}} \leq 138 \text{ W/m}^2 \text{ and}$$
$$4 \leq q_{\text{conv, roof}} \leq 32 \text{ W/m}^2.$$

This range of values is presented to reflect the variability in the wind speed. Also, these values

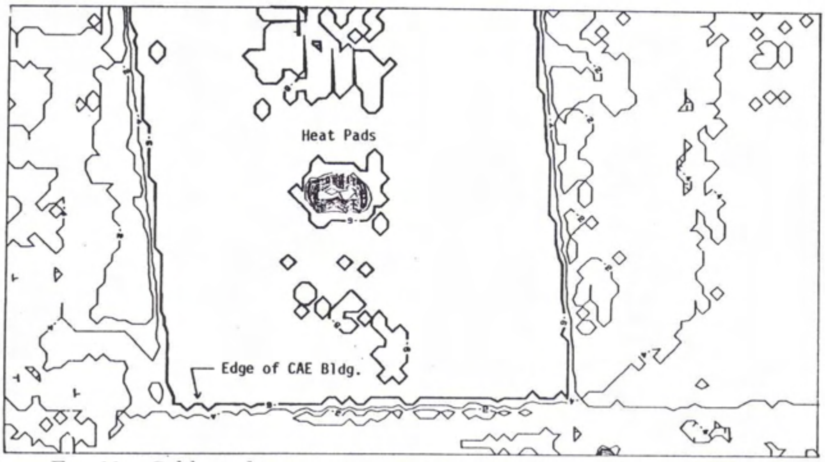

FIG. 11. Calibrated temperature contour map: Contour interval, 2°C. (Mintzer *et al.*, 1980.)

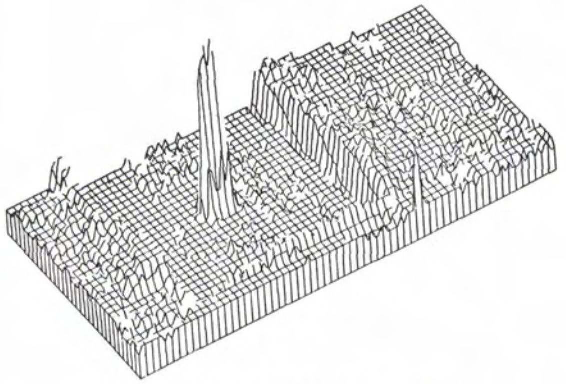

FIG. 12. Three-dimensional diagram. (LaRue, 1980.)

assume that the convective heat transfer coefficient on the pad is approximately the same for the roof surface.

Summing the convective and radiative components of the heat loss, one has

$$80 \leqslant q_{\text{roof}} \leqslant 112 \text{ W/m}^2$$
$$190 \leqslant q_{\text{ref}} \leqslant 296 \text{ W/m}^2$$

Note that q_{ref} includes the values obtained from the direct electrical power input. Because calibrated digital data for temperature predicts radiometric temperature in good agreement with measured pad temperature, the heat flux value for the roof is considered as the correct order of magnitude. The uncertainty in the values for both q_{roof} and q_{ref} is ± 10 to 20 percent.

For the area surveyed, the heat loss from the roof is calculated as less than 2300 W (7222 Btu/h). This is equivalent to approximately 0.25 m^3/hr of natural gas, based on a nominal heating value of 35.4 GJ/m^3 (9800 W-hr/m^3).

The primary factors affecting low level flight data are digital image distortion and wind effects. Image distortion can be treated effectively by either appropriate computer software for producing the temperature contour map from the digital data or knowledge of the actual area surveyed. Wind effects are rather difficult to treat because they represent a generally uncontrolled element in the heat loss from the heat flux reference pad. This element of uncertainty in the data will be reflected in the reference pad temperature and the estimated heat loss calculated above.

With the calibrated data, a final temperature contour map was prepared from the linear regression of radiometric temperature on temperature number. The contour levels represent the surface temperatures of the roof. The process used demonstrated what can be done with digital data, calibrated with known heat flux pad temperatures and computer processing of data.

CONCLUSIONS

- Thermal infrared digital data can be used to produce roof surface temperature maps.
- A method for calibrating thermal infrared digital data has been presented.
- Computer programs (available from Texas Instruments) were satisfactory for analyzing the acquired thermal infrared digital data.
- A temperature contour map of the surface temperatures on the Civil and Aeronautical Engineering Building (CAE) was prepared from the digital data.
- A mathematical model was devised for estimating calibrated roof temperatures (heat losses) from the acquired thermal infrared scanner data using a calibrated reference heat pad and temperature measurements.

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