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**AN EVALUATION OF THERMAL REMOTE SENSING
AS A LOW-COST REGIONAL GEOTHERMAL
EXPLORATION TECHNIQUE IN NEW MEXICO**

Principal Investigator:
Jack Whittier

Authors:
Michael Inglis
Thomas K. Budge

March 1985

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New Mexico Energy Research and Development Institute

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Final Report

Principal Investigator:

Jack Whittier
New Mexico State University Energy Institute
Las Cruces, New Mexico 88003

4616000

Authors:

Michael Inglis
Thomas K. Budge
University of New Mexico
Technology Application Center

9501237

March 1985

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7. ABSTRACT Airborne and satellite borne thermal infrared scanner data were analyzed for application in the exploration of geothermal resources in New Mexico. The location for this study was the East Mesa Geothermal Field near Las Cruces, New Mexico. Primary sensor was the Thermal Infrared Multispectral Scanner (TIMS) which obtained data at 10-meter resolution. Additional data for comparison came from the Heat Capacity Mapping Mission (HCMM) satellite which provided data at 600-meter resolution. These data were compared to the soils, vegetation, and geology of the area, as well as borehole temperature data in an attempt to explain temperature patterns and anomalies. Thermal infrared scanner data were found to be too sensitive to solar-induced temperature anomalies to directly reflect the presence of subsurface geothermal anomalies but may provide valuable supporting information for a geothermal exploration program.		
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AN EVALUATION OF THERMAL REMOTE SENSING AS A LOW-COST REGIONAL GEOTHERMAL EXPLORATION TECHNIQUE IN NEW MEXICO

1.0 INTRODUCTION

1.1 Problem Definition

Considerable attention has been focused on the potential of the known geothermal resources in New Mexico to serve as a spur for economic development initiatives. In some areas, notably Hidalgo County, Sierra County, and Dona Ana County, private development of the geothermal resources has already begun. However, other resource areas of New Mexico are not experiencing the same attention due, in part, to the absence of reliable data that characterize the resource. Currently, it is expensive and time consuming to explore large areas in an effort to identify the most promising sites for more intensive exploration efforts.

The single most important aspect of geothermal energy exploration is the acquisition of temperature data. No matter how many geophysical surveys are completed, how much literature is reviewed, or how many geological maps are prepared, geothermal anomalies remain unknown until temperature data are collected. One of the most common and proven techniques for delineating geothermal energy anomalies is the drilling and logging of shallow temperature gradient holes. Although this exploration procedure is relatively inexpensive, the costs rise substantially as the area to be delineated increases or as the grid size is reduced in an area of fixed size. A reliable and low-cost method of collecting temperature data over large areas would permit much more thorough assessment of potential geothermal energy resource areas prior to undertaking expensive detailed site-specific surveys.

1.2 Project Objective

The objective of this project was to evaluate the technical and economic feasibility of using aerial and satellite acquired thermal data to detect geothermal energy resource areas in New Mexico. Desirably, these data could identify directly the subsurface temperature anomalies or identify an indicator which could then be used in conjunction with existing data for delineation of a geothermal anomaly.

Two quite different thermal data acquisition systems were available for this study and each offered a different potential for geothermal exploration. The Heat Capacity Mapper Mission (HCMM) is a satellite-based, broad-spectrum thermal scanner of low ground resolution (i.e., 0.6 kilometers) (NASA, 1980). The second, a National Aeronautics and Space Administration (NASA) thermal infrared multispectral scanner (TIMS), was aircraft borne and could be flown at varying altitudes and, therefore, varying ground resolutions. For this study, the TIMS provided 10-meter ground resolution. A literature search was performed prior to this research and, to our knowledge, no previous study had evaluated the TIMS or HCMM data effectively in the application to geothermal resource exploration. Engineering design studies conducted by NASA had shown the scanners to be accurate in the measurement of specific temperature differences (NASA, undated).

The objective of examining remote sensing techniques for geothermal exploration was to assess the applicability of airborne or space borne scanning. Once the important characteristics had been identified, other thermal systems and less expensive systems could be utilized. Airborne thermal scanning systems which scan the terrain and subsequently record that scanline as a line on film could be applied to specific problems

such as geothermal energy exploration. An economic benefit to aerial photography and engineering firms which fly cameras and scanners could result as well as the expansion of exploration tools to be applied to geothermal resource areas in New Mexico. All of the thermal scanner data acquired is digital and, therefore, can be manipulated and managed by computer. The computer-assisted approach offers future potential when integrating selected data sets for an exploration program.

1.3 Project Approach

Two locations were examined with the HCMM data and one location with the TIMS data. The HCMM has large geographic coverage while the TIMS is limited in available coverage. The Las Cruces East Mesa and the Mesilla Valley were chosen for detailed examination because of the excellent subsurface temperature data available from previous studies (Icerman and Lohse, 1983), the relatively undisturbed terrain, rather consistent vegetation cover, and low relief. Figure 1 illustrates three lines of available TIMS coverage, each 4.6 kilometers wide. Flightline number two was selected for the detailed study. The HCMM data were available for all of this area.

The project was structured to compare the existing geothermal, geological, and geophysical data on the Las Cruces East Mesa Geothermal Field with the data obtained from the TIMS and HCCM. This approach would lead to the formulation of a model which could identify areas with enhanced likelihood for the presence of geothermal anomalies. Such a model could then be applied to other suspected resource areas where geothermal baseline data do not exist.

Figure 1. Map of study area with flightlines indicated.

The digital thermal data were enhanced, classified, and plotted using the image processing facility at the Technology Application Center, University of New Mexico (TAC). The plots were overlaid on detailed soil surveys, surface geology structure, vegetative cover, gravity surveys, and 30- and 90-meter temperature contours obtained from temperature gradient hole logging (Kottlowski, 1960; Seager, et al., 1976; Kelley and Matheny, 1983; Gile, 1981; Gile and Grossman, 1979; Icerman and Lohse, 1983).

Several anomalies were found by visual interpretation in both the satellite and aircraft data. One anomaly found in the TIMS data was identified as either moist soil resulting from a recent localized storm or a warm air mass documented by the nighttime flight. The other anomalies correlated to known "hot spots" (e.g., Tortugas Mountain) but do not consistently relate to the known subsurface temperatures. There appear to be strong relationships with the acquired thermal infrared (IR) data and surface drainage, recent faulting within the alluvium, rock type, geomorphic features (e.g., groundwater basins), elevation, and what appears to be subsurface groundwater flow patterns.

There may be too much detail found in the TIMS data. Having a resolution of 10 meters, the thermal IR data detects many microclimate anomalies such as small vegetated drainages, clumps of vegetation, and depressions. These microclimates maintain a different temperature from their surrounding environment due to a controlled air flow or air drainage. Should a resolution element larger than 10 meters be used, many of these anomalies could be averaged into a larger ground area detected by the thermal IR scanner.

2.0 APPLICATION OF THERMAL SCANNING TECHNOLOGY TO GEOTHERMAL RESOURCE EXPLORATION

2.1 Background

Objects emit or radiate energy as a function of their temperature. This emitted radiation is an external expression of the energy state of the object that may be remotely sensed and used to determine the apparent temperature of the object. Current technology does not allow the wavelength of this radiated energy to be recorded directly by photographic means. In the case of thermal energy, electronic detection must be used. The premise of this study is that surface materials, such as soil and rock, which are heated by subsurface geothermal activity will be higher in temperature than surface materials in non-geothermal areas and that these temperature differences should be detectable through the use of electronic scanners.

Although thermal data cannot be recorded directly on photographic film, scanners are able to produce images of thermal radiation by indirect means (Figure 2). A thermal scanner (a) builds a two-dimensional record of radiant temperature data for a swath beneath the aircraft or spacecraft. The scanner contains a rotating mirror assembly (b) that moves the viewing area of a photon detector along scan lines that run perpendicular to the direction of flight. This process allows the scanner to repeatedly measure the emitted energy from one side of the aircraft or spacecraft to the other along successive scan lines. The detection signal (c) along each scan line is related to the emitted energy from objects along the scan line. The forward movement of the sensor causes a new strip of ground to be covered in successive scan lines. Contiguous scan lines result in a series of signal outputs

Figure 2. Schematic diagram of thermal scanner system operation.

covering a swath below the scanner. The signal for each line may be used to modulate the intensity of a single-line cathode ray tube, exposing an image line on black and white film (d).

Thermal data are usually recorded in flight on magnetic tape. In aerial scanning, these tapes are later processed on the ground to produce black and white images. In spacecraft scanners, the thermal data are either transmitted directly or recorded on magnetic tape onboard the satellite for later transmission to ground receiving stations for processing.

The two thermal sensors used for this project were fundamentally different both in their basic nature and in their operation. The primary sensor was the Thermal Infrared Multispectral Scanner (TIMS) carried on an aircraft, and the secondary sensor was carried by a satellite known as the Heat Capacity Mapping Mission (HCMM).

2.2 Thermal Infrared Multispectral Scanner Data

The TIMS is a conventional electro-optical scanning device which produces six discrete data bands over the 8 to 14 micrometer (μm) thermal infrared portion of the electromagnetic spectrum. The system was designed and developed by the NASA Earth Resources Laboratory as a definition tool for future space borne, geology-oriented sensors.

The operation of a multispectral scanner is illustrated in Figure 3. Radiation from the ground is received at the rotating mirror. In the TIMS, the incoming energy is separated into several spectral wavebands that are sensed independently. A dichroic grating is used to separate the wavelengths in the incoming radiation. By placing an array of detectors at the proper geometric positions behind the grating, the

incoming beam is essentially separated into multiple narrow channels, each of which is measured independently.

As shown in Figure 3, the signals generated by each of the detectors of the TIMS are amplified by the system electronics and recorded by a multi-channel magnetic tape recorder. If the TIMS data analysis procedure is to be visually oriented, the scanner output is normally recorded on an analog recorder and converted to images after the flight using a ground-based film recorder. If the analysis procedure is to be digitally oriented, it is preferable to electronically convert the analog scanner output signal to a digital format prior to recording in flight. The digitization process ensures that data collected in several spectral bands are precisely synchronized. These data are initially recorded on high-density digital tape on board the aircraft. On the ground, the tape is converted to computer tape for subsequent processing.

The TIMS data flown over Las Cruces were obtained from an altitude of 4,000 meters from a Lear Jet aircraft on June 27, 1983, at 2:00 in the morning. The resolution, or ground area covered by one data point, was 10 meters by 10 meters and the width of the flightline was 4.6 kilometers. The nominal spectral bands covered are shown in Table 1. The sensitivity of the scanner is in a range of 0.1 to 0.3°C. The TIMS data were acquired at night to remove the majority of sun-induced thermal responses. The following day aerial photography was acquired over the same flightline. The aerial photos were used for field reconnaissance, construction of a vegetation map, and for selection of control points in the image correction processs.

Figure 3. Multispectral scanner operation.

Table 1. Spectral bands for the TIMS.

Channel	Spectral Coverage
1	8.2 to 8.6 μm
2	8.6 to 9.0 μm
3	9.0 to 9.4 μm
4	9.4 to 10.2 μm
5	10.2 to 11.2 μm
6	11.2 to 12.2 μm

After the data had been preprocessed by NASA, each flightline was displayed on a TV monitor and examined. The shades of gray displayed by the data represented differences in temperature, darker grays being cooler and lighter grays being warmer. Since the TIMS intensity values are linear with temperature, the temperature of any ground surface target can be calculated using the following equation:

$$T_T = \left(\frac{BB_H - BB_L}{C_2 - C_1} \right) (C_T - C_1) + BB_L, \quad (\text{eq. 2.1})$$

where T_T = temperature of target,

BB_H = high blackbody temperature,

BB_L = low blackbody temperature,

C_2 = high blackbody radiometric value,

C_1 = low blackbody radiometric value, and

C_T = count value of target.

The variable C_T , or gray value of a ground object, was obtained from the display monitor using a movable cursor. The high and low blackbody temperatures and radiometric values were either provided by NASA or obtained from the data tape. To obtain the temperatures for a single channel, several gray values were selected from the monitor covering the entire temperature range of the data. Equation 2.1 was then applied to the gray values and a temperature for each gray value obtained. Since the temperatures and gray values are linear, the temperature of any gray value can be found by finding the gray/temperature value location on the graph.

Figure 4 shows the temperature graph for all six channels of flightline #2. The immediate feature of the graph is that all six lines have essentially the same slope and are not much different regarding the gray values and equivalent temperatures. This situation was also evident in viewing the data on the monitor where each channel looked very similar. Four of the six channels were used for further study. Channels 1, 2, and 3 were selected because they were somewhat separated on the graph. Channels 4, 5, and 6 show essentially the same data so channel 4 was selected to be representative of this group. Channel 6 also had a large amount of noise and, consequently, was excluded from further consideration.

2.3 Heat Capacity Mapping Mission Data

The HCMM unmanned satellite was launched on April 26, 1978, and was the first NASA research effort directed mainly toward observations of the thermal state of the Earth's land surface. The HCMM operated from April 1978 to September 1980 and sensed data during the day in both the reflective and thermal infrared and at night in the thermal infrared only. Due to the designed orbit of the satellite, the HCMM was able to image the day and night thermal infrared response of a given area within a 36-hour period, thus enabling studies concerning the thermal inertias of soils and rocks.

Compared to the TIMS, the HCMM had an extremely crude resolution of 600 meters. For this reason and the fact that the HCMM images selected for this project were collected during October 1978, the HCMM data were used only in a secondary mode as qualitative support of the TIMS findings. One of the objectives of using the HCMM data, however, was to

Figure 4. Temperature/gray value conversion graph for the TIMS data. The numbers on the lines identify the specific sensor channel (see Table 1).

examine its potential use over very large areas since one HCMM image covers 700 x 700 square kilometers. The HCMM bandwidths were 0.5 to 1.1 μm for the reflective infrared and 10.5 to 12.5 μm for the thermal. Sensitivity of the thermal sensor was 0.4°K (NASA, 1980).

Table 2 shows the gray value/temperature conversion of the HCMM. There have been discussions among scientists concerning whether or not the HCMM temperatures are actually 5°K too cold (de Paratesi, 1983). Because of this question, the coarse resolution, and the fact that the TIMS and HCMM data come from different seasons and different years, the HCMM data were used mainly as a qualitative comparison on this project. The data sets were compared for basic temperature trends from one time period to another, hopefully to identify any anomalies caused by atmospheric or meteorological phenomena. The actual temperature values obtained from the two data sets were not compared.

3.0 PROJECT METHODOLOGY

3.1 Image Processing

The first step in the computer analysis of the data was to remove all channels from an entire flightline from the digital tape, place the data on a disk, and visually examine the data. The next step in the analysis was to correct the geographic orientation of the data and any distortions caused by scanner malfunction or aircraft flightline deviations. Figure 1 shows that the flightline was oriented in roughly a northwest-southeast direction. However, as Figure 5 shows, when first displayed on the TV monitor, the data have no direction or spatial orientation (Figure 5a), instead the data are simply an arrangement of horizontal lines and vertical columns of data points forming an image.

Table 2. Temperature/gray value conversion chart for the HCMM data.

Gray Value	Temp. (°K)	Gray Value	Temp. (°K)	Gray Value	Temp. (°K)
0	260.0	17	267.4	34	274.3
1	260.5	18	267.8	35	274.7
2	260.9	19	268.2	36	275.1
3	261.3	20	268.6	37	275.4
4	261.8	21	269.1	38	275.8
5	262.2	22	269.5	39	276.2
6	262.7	23	269.9	40	276.6
7	263.1	24	270.3	41	277.0
8	263.6	25	270.7	42	277.4
9	264.0	26	271.1	43	277.7
10	264.4	27	271.5	44	278.1
11	264.9	28	271.9	45	278.5
12	265.3	29	272.3	46	278.9
13	265.7	30	272.7	47	279.2
14	266.1	31	273.1	-	-
15	266.6	32	273.5	-	-
16	267.0	33	273.9	255	340.0

a. Actual data display

b. Corrected data display

Figure 5. Geographic correction of aerial scanner data.

After corrections are applied, the desired image should look like Figure 5b where the image has a true north direction and the re-created flightline is oriented in the same northwest-southeast direction of the actual flightline.

To begin the correction process, 7½' topographic quadrangles covering the flightline were obtained and attached to a digitizing tablet. Three known Universal Transverse Mercator (UTM) grid intersections were then digitized and the grid coordinates entered for each. With these three known points, the computer is able to triangulate and calculate the UTM coordinates of any points on the map.

In the next step of the process, identifiable features were located on both the base map and on the raw data display. These features, called control points, usually consist of sharp bends in roads, road intersections, small dams and stock ponds, and bends in drainage patterns. Once a feature has been selected on the map, the location is digitized and the UTM coordinates recorded. The same point is then located on the raw data and the line and column coordinates are recorded. The end result of this procedure was a list of 28 points, each point having a pair of UTM and TIMS coordinates. Table 3 is an example of a portion of the control point list.

The UTM and TIMS coordinate pairs were entered into the computer and a set of equations were formulated to reorient the TIMS data to the UTM grid. The computer rejected four of the points because neither set of coordinates would allow those points to be properly located onto the grid. Each pixel or data point in the four-channel TIMS file was then run through the equations and relocated in a new file which was oriented

Table 3. Partial listing of control points.

Point #	<u>UTM Coordinate (Meters)</u>		<u>TIMS Coordinate</u>	
	Easting	Northing	Scanline	Column
1	334689	3585613	1599	351
2	332634	3586010	1469	181
3	337347	3583678	1892	473
4	340107	3582501	2126	623
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
28	326427	3594920	362	165

in the direction of the actual flightline with true north to the top of the display screen.

The HCMM data were corrected in the same manner as the TIMS data. Since the HCMM data covered a much larger area than the TIMS data, the excess HCMM data were removed by drawing a polygon around the TIMS flightline using the display screen. Since both the TIMS and HCMM data had been corrected to the same UTM grid, the polygon could be transferred to the HCMM data display and all data outside of the polygon blackened. The result was a HCMM raw data file corresponding only to the data in the reoriented TIMS flightline.

3.2 Image Classification

After image correction, the next step was to classify the image into spectral (i.e., temperature) groups. Unsupervised classifications involve algorithms that examine a large number of unknown pixels and divide them into classes based on natural groupings present in the image values. The basic premise is that values within a single ground feature should be close together in the measurement space, whereas data from different features should be comparatively well separated.

The unsupervised method can be illustrated with a two-channel data set. Natural groupings in the data can be usually identified by plotting a scatter diagram. For example, in Figure 6, pixel values acquired over an agricultural area from a hypothetical non-thermal multispectral scanner have been plotted. Three groupings are apparent in the scatter diagram. After comparing the classified image data to ground reference data, one cluster could be found to correspond to wheat, one to barley, and one to soybeans (indicated by W, B, and S).

Figure 6. Example of a two-channel plot. The letters refer to arbitrary data clusters.

For image data of more than two channels, plotting image values to visually identify natural spectral groupings is difficult. Statistical techniques (e.g., cluster analysis) are available that may be used to automatically group an n-dimensional set of observations into natural spectral classes. The result of applying a cluster analysis is simply the identification of spectrally distinct classes in the image data. After the data are clustered, reference data, such as maps and images, are used to associate the spectral classes with the cover types of interest.

In order to classify the raw data, the computer searches the four-channel file for spectrally homogeneous blocks of data. The search program begins by examining 3 x 3 blocks of pixels looking for spectrally homogeneous blocks. As these blocks are found, a series of statistical measures are computed such as their mean, standard deviation, and coefficients of variation. When the entire data file has been searched and the statistics compiled, a clustering algorithm is applied, which clusters together those class statistics that are the most similar.

The final step in the spectral data collection process is the generation of a two-channel plot. The two-channel plot displays the means of all classes in the statistics file for any two TIMS channels. Figure 7 shows the TIMS plot developed for this project. Each letter on the plot represents the spectral mean of one of the classes and the double column on the left is used to correlate the class symbol with the class number. The abscissa represents the responses from the TIMS channel 4, progressing from black at the origin (cool) to white at the far right (warm). The ordinate represents the responses from the TIMS

Figure 7. Two-channel plot for a TIMS classification.
The letters represent distinct temperature
classes.

channel 2, with black (cool) at the origin and white (warm) at the top. This plot shows the progression of classes up the temperature scale from the coolest (class T) to the warmest (class S).

Upon completion of this training data process, the raw data file was classified using a maximum likelihood unsupervised classifier. An unsupervised classification simply means that the computer has compiled training statistics without help from an operator. The term "maximum likelihood" means that the computer compares the spectral values of each pixel in the raw data file to each of the statistically defined classes in the statistics file. The computer then calculates the probability that a pixel belongs to each class in the statistics file and assigns the pixel to the class with the highest probability. This calculation was performed for every pixel in the raw data file. When the classification was completed, the data were displayed on the television screen and analyzed. A color table was then loaded onto the classification. This color table was created by the computer whereby each class is assigned a color based on the class location on the two-channel plot. An operator can then highlight each class in a distinctive color to view the precise spatial distribution and location.

4.0 ANALYSIS AND CONCLUSIONS

4.1 Image Classification

The image processing methodology applied to the TIMS and HCMM data was selected to best utilize the thermal data during analysis. This image processing methodology was applied to the six narrow spectral bands of the TIMS data to evaluate the need for either a narrow-band or broad-band scanner. Multiple narrow spectral bands provide information

within a very restricted range but may provide a spectral identification normally lost in a wider spectral band. Single-channel, broad-band scanners are less complex and, therefore, less expensive to operate. Should a broad-band scanner provide all of the same data as found in a multiple narrow-band scanner, cost savings in the collection of data would result.

Processed HCMM and TIMS data were overlaid onto known data or interpreted data in search of correlations to plotted TIMS and HCMM temperature values. Any relationships between the TIMS and/or the HCMM data and the surface or subsurface data could then be applied to other geographic areas for identifying target areas for temperature gradient hole drilling.

The most critical factor in analyzing thermal IR data is knowing the physical and temporal conditions under which the surface is heated. Heat from the earth's interior tends to flow through the surface at a nearly constant rate making a small contribution of the total surface radiation as compared with the thermal input from the sun. Materials at or immediately below the surface are heated by incoming solar radiation during the day. At night, temperatures drop by radiative cooling, convection, and conduction. During a single diurnal cycle, the unconsolidated surface layers experience heating and cooling to depths between 50 and 100 centimeters (Short and Stuart, 1982). Over an annual cycle, small shifts in mean temperature can occur in some materials to depths of 10 to 15 meters. Before dawn, the surface zone (i.e., the top 50 cm) shows the least influence of solar radiation on ground temperature for anytime during the diurnal cycle.

Interpretation of the image data began with the analysis of the TIMS classification. Examination of the two-channel plot for this classification clearly showed the relative temperature positions of all twenty-four classes. A class-by-class examination showed that the cooler classes closely corresponded to vegetation and cool, moist soils along drainages. This observation is shown in Figure 8b, a printout of the cooler classes around Tortugas Mountain. The mid-range temperature classes showed a relatively close correlation to soils classes and differences in vegetation density (Figure 8c). The warmer classes clearly delineated the higher landforms which exposed a large proportion of bare rock (Figure 8d). These features possessed higher temperatures as an effect of solar heating rather than from a geothermal source. By collecting predawn thermal IR data, the solar induced thermal accumulations of the previous day were diminished allowing geothermal temperature flow from within the earth to have its greatest impact on surface temperature for a given diurnal cycle.

Figures 9a and b are color photographs of the classification of the Goat Mountain and Tortugas Mountain areas, respectively. In both cases, the red classes at A (i.e., the upper 1/3 of the classes) show warmer temperatures, the green classes at B (i.e., the middle 1/3) show intermediate temperatures, and the blue classes at C (i.e., the bottom 1/3) show cooler temperatures. The letter "D" points to an apparent thermal plume feature. Due to the narrow range of the spectral values of the TIMS data, the classification was not able to identify any significant temperature patterns other than those attributable to landforms. A multispectral classification is most successful when surface terrain has differing spectral values from one channel to

a. Topographic map

b. Cool classes

c. Intermediate classes

d. Warm classes

Figure 8. Temperature class printouts of Tortugas Mountain from the TIMS data.

a. Goat Mountain area

b. Tortugas Mountain area

Figure 9. Color-coded TMS classification of Goat Mountain and Tortugas Mountain.

another. The six channels of thermal IR data were nearly identical, greatly reducing the effectiveness of a multispectral classification.

Since the classification did not closely correlate with known geothermal boundaries, the next step in interpretation dealt with the actual temperature values of the TIMS and HCMM data. Using the temperature conversion chart in Figure 4, the TIMS image showing only channel 1 was reconstructed to show known temperatures in 0.5 and 1°C intervals. The 0.5°C image had 38 levels and showed greater thermal detail than the 1°C range. Figure 10 shows an enlarged color photograph of the TIMS 0.5°C image of Goat Mountain with the same color and temperature relationships as displayed in Figure 9. The image shows greater detail than the classification but still shows the same basic cool to warm trends present in the classification. Figures 11b, c, and d show the same area at temperatures of 11 to 12°C, 13 to 15°C, and 15 to 22.5°C, respectively.

The HCMM data were analyzed in the same manner. The temperature interval for each gray level on HCMM was 0.4°K or approximately the same as used for the TIMS data. Figure 12 shows the red-green-blue temperature gradient for the Goat Mountain area. Two differences are immediately noticeable when this HCMM image is compared to the TIMS image of the same area (compare Figures 10 and 12). Due to the large pixel size (i.e., 600 meters) and the resampling method used to geometrically correct the image, the temperature values are shown as contours. The other important difference is that the thermal plume found on the TIMS data is not seen on the HCMM data. This observation lends support to contention that the plume is caused by something other than geothermal activity since temperature signatures resulting from

Figure 10. Color-coded TIRS image of Goat Mountain in 0.5°C intervals.

Figure 11. Temperature group printouts of Goat Mountain from the TIMS data.

Figure 12. Color-coded HCMM image of Goat Mountain in 0.4°K intervals.

geothermal sources do not appear intermittently. The most logical explanation for the plume is a rain shadow, or trace of moist soil, left by a passing rain storm. This shadow would appear warmer than the surrounding soil since the moist soil would retain the solar heat at night longer than dry soil.

The blue (i.e., cool) temperature contours around Goat Mountain may be due to shallow, rapidly moving groundwater. This groundwater may be perched on shallow bedrock, causing steep hydraulic gradients to radiate away from Goat Mountain. If the hydraulic conductivity of the gravelly sediments around the mountain is also high, temperatures around the mountain would be depressed by convective heat transfer.

Figures 13b, c, and d show printouts of the HCMM temperatures as cool, medium, and warm, respectively. When the HCMM images and printouts to similar data from the TIMS are compared, the same general temperature trends are found on both sets of data. The temperature trends are not exactly the same because of the sensor differences and seasonal differences. A five-year difference between image dates always makes comparisons of the data due to changes in soil moisture, vegetation, and weather difficult.

4.2 Comparisons of Remote-Sensed Data with Measured Subsurface Earth Temperatures*

Both the TIMS and the HCMM data were compared directly with measured subsurface temperature data at a depth of 30 meters obtained from prior studies (Icerman and Lohse, 1983). The comparison was

*Jack Whittier and Rudi Schoenmackers are the authors of this section.

a. Topographic map

b. Cool temperatures

c. Intermediate temperatures

d. Warm temperatures

Figure 13. Temperature group printouts of Goat Mountain from the HCMM data.

performed by digitizing the measured and implied geothermal temperature contours at 1°C intervals and superimposing these data over the TIMS and HCCM data. Figure 14 shows the TIMS data for the area surrounding Tortugas Mountain (Figure 14a) and a second area several miles to the north of Tortugas Mountain (Figure 14b). Both areas are known to exhibit anomalous subsurface temperatures. Elevated temperatures up to about 65°C at 250 to 300 meters and significant fluid quantities estimated to be producible at a rate of 1,000 to 2,000 gallons/minute have been found at both locations (Icerman and Lohse, 1983; Lohse, 1984). Figure 15 illustrates the same area as Figure 14 but with the geothermal temperature contour lines overlaid upon the HCCM data rather than the TIMS data. For comparative purposes, Figure 16 shows the geothermal temperature contours only over the same area.

In Figure 14a, a slight pattern similarity may be observed between the TIMS data and the geothermal temperature contour lines. The warm areas (i.e., red) appear to correlate with the highest temperature contours around Tortugas Mountain. To the northwest of Tortugas Mountain, the green TIMS data exhibit somewhat similar patterns with the temperature contour lines. This similarity becomes more pronounced when the blue color trend on the west edge of Figure 14a is considered. The correlation between the TIMS and the geothermal subsurface data appears to be more tenuous to the east and north of Tortugas Mountain.

In Figure 14b, the geothermal and the TIMS data are compared for an area north of Tortugas Mountain. There are no similarities that are readily apparent between the two data sets. Indeed, the warmest geothermal area, in the center of the temperature contour lines, correlates best with the blue pattern which represents the coldest surface temperatures. The TIMS data are apparently recording the

a. Tortugas Mountain area

b. North of Tortugas Mountain

Figure 14. TIMS data overlaid with geothermal temperature contours.

a. Tortugas Mountain area

b. Tortugas Mountain and area to the north

Figure 15. HCCM data overlaid with geothermal temperature contours.

TEMPERATURE CONTOUR MAP AT 30 METERS BELOW GROUND SURFACE

TEMPERATURE(°C) CONTOURS
(1°C CONTOUR INTERVALS)

LOCATION AND TEMPERATURE(°C)
AT 30 METERS DEPTH +27.8

Figure 16. Temperature contours at a 30-meter depth in the area surrounding Tortugas Mountain (Icerman and Lohse, 1983).

topographic and near-surface hydrologic features of an arroyo that passes through the vicinity.

The discrepancy found in Figures 14a and b (i.e., the apparent correlation between the geothermal and the TIMS data in the Tortugas Mountain area and the complete lack of any similarity north of Tortugas Mountain) may be attributed to surface effects masking any possible geothermal surface expression. The elevated temperatures in the TIMS data correlating to Tortugas Mountain in Figure 14a are most likely caused by solar-induced heating and heat retention in the massive rock formation. The cold area that shows in Figure 14b, where the geothermal data indicate an anomaly, is thought to be caused by near-surface hydrology. These two effects are predominant throughout the entire study area and seem to be masking any surface temperature effects from geothermal anomalies.

In Figures 15a and b, the HCCM data are compared with subsurface temperature data at 30 meters for the Tortugas Mountain area and the geothermally anomalous area several miles to the north of Tortugas Mountain. In Figure 15a, the HCCM data temperature trends appear to be correlated with the temperature trends indicated by the TIMS data. In addition, the HCCM data appear to correlate well with the geothermal temperature contours surrounding Tortugas Mountain; however, this correlation may well be spurious because of heat retention in the massive rock formation. The lack of correlation in Figure 15b is similar to the observations based on the TIMS data. Again, the temperature anomaly indicated in the HCCM images is probably the result of solar-induced temperature effects.

5.0 SUMMARY

This investigation demonstrated similar temperature relationships between both the HCMM and the TIMS data and surface features. There is consistency in thermal mapping using both scanners and only a difference in ground resolution. The temperature to feature relationships were not found to be consistent in the identification of subsurface temperatures. The TIMS data showed that a single spectral channel was as effective as several spectral channels for all interpretations except soil classification and that a broad spectral band was as effective in providing data as a narrow one. This result should reduce the cost of further thermal data acquisitions for future applications.

Results of this preliminary analysis suggest that the TIMS data may have been of such high resolution (i.e., 10 meters) that features were detected which masked surface expressions of subsurface thermal anomalies. Vegetation density, although the variation in the vegetative cover was small, obscured any subsurface temperature indications by highlighting the more densely vegetated drainages. Although features such as vegetation concentrations cannot be effectively removed, varying the resolution could help. By decreasing the resolution of the thermal IR scanner or resampling the data to a larger unit (e.g., 100 meters), the impact of a vegetation mask could be reduced because the spectral response of the masking feature is averaged within a larger area, therefore, having less influence on a single resolution element. If a continuous cover of dense vegetation exists, the change in resolution size would have little effect in an effort to remove or reduce the masking.

The HCMM data, in turn, offer too low a resolution (i.e., 600 meters) to provide the necessary nighttime surface expression of subsurface temperatures. Landforms are well delineated, however. Dona Ana Peak and Goat Mountain are clearly shown as are alluvial fans and basins. Surface temperatures appear to be related to rock outcrops and lithology rather than to geothermal phenomena.

Overall, the thermal data were found to provide a wide range of information of an indirect nature useful to geothermal exploration. The surface hydrology (i.e., drainage) was readily identifiable and provided supporting data to recent faulting found in the alluvium. The offset in drainages within the alluvium indicates the presence of recent faulting and also indicates points along the fault trace. This structural information, shown by drainage offsets as well as vegetation boundaries, is enhanced by thermal data. Subsurface hydrology expression appears to be enhanced by both data collection systems but in particular by the HCMM data. The area around Goat Mountain, for example, indicates a temperature pattern which could relate to possible subsurface drainage between the mountain and Dona Ana Peak. The temperature pattern extends around the mountain and appears to indicate the movement of groundwater from the northeast, above the Isaacs Lake area, flowing to the west southwest joining the Dona Ana Arroyo leading into the Rio Grande Valley.

Soil and vegetation are delineated quite well using the TIMS data. The base overlay of soils mapped at the series level could be correlated in selected cases to classified the TIMS data. Temperature patterns appeared to be highly correlated with vegetation density in many areas, especially in the Tortugas Mountain area.

Ground temperatures during the TIMS data collection were some of the highest for a diurnal cycle during the year. Had the data been acquired during the cold and dry winter season, the thermal impact of the sun would have been lower because the long, cold nights would have reduced the daytime thermal buildup much more so than during the summer season.

6.0 RECOMMENDATIONS

This study addressed the direct application of airborne and spaceborne thermal scanner data for the exploration of geothermal resources. Although a direct association can not reliably be made, there are a number of associated exploration tools which may be enhanced using such data. The Landsat 5 satellite offers a broad-band thermal scanner with a ground resolution of 120 meters (U. S. Geological Survey, 1982). This resolution value is between the ground resolution of the HCMM and the TIMS data and can provide large area coverage at low cost. The Landsat data should be of interest to geothermal exploration teams because of the potential for providing landform and structural data as well as possible information on near-surface hydrology.

The HCMM data should be further examined for subsurface hydrology indicators and for regional and statewide landform mapping. Lithologic units may be related to temperature in areas of low vegetative cover.

The TIMS data offer a detailed look at small areas potentially for soil classification and for recent structural information, such as Late-Quaternary faulting along the existing geothermal fields. The TIMS data have been acquired for much of the known geothermal fields adjacent to Las Cruces. A comparison of the TIMS data acquired during a

cold and dry winter period with the data collected during the summer months could advance the understanding of high-resolution scanner data as a geothermal exploration tool. Data sets collected in winter and summer seasons should be useful in evaluating the impact of vegetation as a mask on elevated subsurface temperatures.

With little cost going to data acquisition, an extension of this study to include the use of thermal data in the development or enhancement of geothermal exploration tools could be performed. Image processing techniques now being developed by research scientists at NASA and the United States Geological Survey for the TIMS data could make a great difference upon the evaluation and interpretation for temperature anomalies and for geologic, soil, and structural information (Krohn, 1984). The most useful technique is the decorrelation stretch. This procedure is used to remove the high interband correlation between the thermal IR channels that are related to surface temperature. A three-step procedure uses: (1) an initial rotation of the bands into principal component axes; (2) normalization of the three principal component axes to Gaussian distributions; and (3) the inverse of the initial principal component rotation. The purpose of this enhancement is to view the uncorrelated axes in a color rendition that is related to the original bands.

Comparison of thermal scan data over different seasons and day/night data comparisons would be a logical extension of this study. A more comprehensive approach is necessary to evaluate thermal IR data thoroughly and to collect indirect or ancillary data, (e.g., recent faulting) useful in geothermal exploration efforts. As the amount of data and geographical extent of the geothermal anomalies grow, there

should be a better method for handling and integrating exploration data. A geographic information system for the geothermal fields in the Las Cruces area would better support correlations between data sets and graphically show the geothermal resource areas by temperature, ownership, elevation, geology, and a number of other factors. This process would require the input of existing data into a computer-based geographic system.

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