The Application of Remote Sensing Techniques in Microscale Climatology

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Abstract

The climatological study of heat and energy budgets in urban areas has long proved problematic because of incomplete data sources. To meet this contingency this paper illustrates how the use of remotely sensed multispectral data allows evaluation of selected components of the energy budget. Using an area of Indianapolis as a sample region, instantaneous maps of surface albedo and infrared radiant characteristics are derived. Generation of representative cross-sectional energy profiles in selected electromagnetic bands point to the highly variable interface characteristics of the surface. It is concluded that microclimatic analysis using multispectral data holds great promise for quantitative evaluation of the urban energy balance.

One of the fundamental concepts of climatology concerns the energy and heat budget of the earth-atmosphere system. The absorption of solar energy by the earth system is fundamental to the form and function of the earth's climate. While the significance of the sun's role in climatology has been recognized since ancient Greek times, it was only during the last century that the basic physics of radiant energy and its interaction with material substances of the earth were identified (Budyko, 2). It has been shown that the physical properties of the materials present at the interface between the atmosphere and the hydro-lithosphere play a key role in determining amount of energy absorbed and the type of energy conversion from radiation to other forms of energy.

The simplest description of the heat budget is a symbolic expression which identifies the component energy conversions at the interface. This is given by:

$$G = (Q + q)(1 - a) + I\downarrow - I\uparrow - H - LE - F \text{ where:}$$

G = the energy change at any point of the interface
$(Q + q)$ = the sum of direct and diffuse solar radiation
$(1 - a)$ = the percent of shortwave radiation absorbed (a = albedo)
$I\downarrow$ = the longwave radiation emitted from the atmosphere toward the surface
$I\uparrow$ = the longwave outgoing radiation
H = sensible heat
LE = latent heat
F = advected heat

Note that terms in the equation which add energy to the interface are positive whereas terms that remove energy are negative. The object of this paper is to show how remotely sensed data can be used to quantify selected components of the energy flows indicated in the equation.

Quantifying Energy Flows

Measurement of energy flows has only slowly become technically feasible. The earliest measurement devices were simple glass lenses that burnt a paper chart to indicate the duration of intense sunlight. Recently, a variety of electrical and photochemical devices have been developed (Kondratyev, 3). The pyranometer and various radiometers have come into relatively common use in the United States since World War II (Miller, 4). The majority of energy budget studies have been conducted under the methodology developed for other meteorological observations (WMO, 5). A stand of instruments is set up at a selected location under the assumption that the measurements from this location are representative of a larger adjacent region. Unfortunately, this assumption is not strictly valid for heat budget measurements due to the varied nature of earth surface materials. In particular the complex pattern of surface materials in urban areas results in the impossibility of selecting a representative site from which to make such observations.

The most obvious solution to the problem of measuring the heat budget over differential surfaces is to make simultaneous observations over a representative sample area for each surface type (Bach & Patterson, 6). The cost of such a field network of observation stands is extremely high and cross calibration between instruments is never totally successful. Experimental research using aircraft mounted pyranometers and radiometers showed that such airborne measurements could be carried out (Kung, et al., 7; Lenschow and Dutton, 8). These early successes in airborne measurements and contemporary developments in space satellite technology led to the TIROS-NIMBUS-ATS meteorological satellite program (Barrett, 9). The sensors on these satellites measure the reflectance or albedo of the earth and longwave radiant emissions from the earth's surface and atmosphere. The spatial ground resolution of the early aircraft observation and current meteorological satellite observation is too gross (1 to 5 KM) to be used in microclimatic research. However, the spatial perspective of the data provide major insights into the global and regional variations of the energy budget of the earth (Lorenz, 10) and is suggestive of the methodology for energy budget measurements in microscale studies.

Multispectral Scanning

The measuring device that provides the answer to the need for microscale spatial quantification of the heat budget was not developed primarily for climatic research, but for the technical field of remote sensing. In recent years, under the stimulus of military surveillance, technology has advanced to the point that the camera and film are not required to produce an image. Light sensitive sensors are scanned across a scene to measure the variation of radiation flow across the scene. The scanner is calibrated to known light and thermal sources so that the data may be directly converted to physical measures of radiant intensity. The image is produced by sequentially viewing strips of the scene. The width of the strip determines the ground resolution of the scanner.

The majority of scanning sensors used in remote sensing research are multispectral which refers to the ability of the scanners to measure two or more different segments of the electromagnetic radiation spectrum simultaneously. The advantage in separating the radiation into spectral segments is that certain earth surface features can be easily identified by their response in certain segments of the electromagnetic spectrum. For example, healthy green vegetation reflects intensely in the near infrared (.7mμ-1.5mμ) due to the molecular structure of the vegetation. This spectral separation is a major advantage for climatic research. The shortwave radiation measured covers the wavelength range of the radiant energy emitted from the sun. The longwave radiation is generally measured in one or both of the two longwave radiation "windows" in the atmosphere 4.0mμ-5.0mμ and 7.0mμ-14.0mμ, the latter of which is centered on the peak intensity of radiation emitted by the earth's surface. Since there is little spectral overlap between these shortwave and longwave fluxes the sophisticated multispectral scanner with full spectral response capability provides simultaneous high resolution independent measurements of the reflectance of incoming solar radiation and of outgoing radiant emissions from the earth's surface. These radiant flows are the key factors in heat budget investigations. The synoptic view provided by the scanner allows investigation of microscale spatial variations in these key factors of the heat budget.

Available Sensing Platforms

There are a number of multispectral scanners in use today. The sensors on the TIROS-NIMBUS and LANDSAT satellites are types of multispectral scanners. As noted earlier the TIROS-NIMBUS data resolution is too gross for meso and microscale studies. The resolution of the LANDSAT data (80 meters) would be applicable to regional climatic analysis; however, the spectral range of the current satellites is too narrow (.5mμ-1.1mμ) to provide sufficient information about the surface energy budget. The sensors on future LANDSAT satellites will have increased spectral range including thermal infrared and may be well suited to mesoscale climatic analysis (NASA, 10). Other future satellite projects including the "Heat Capacity Mapping Satellite" show potential in climatic research.

Of more immediate interest are the multispectral scanners mounted in aircraft. One of the most sophisticated of these is the M-7 multispectral scanner developed and operated by the Willow Run Laboratories at the Environmental Research Institute of Michigan (ERIM). The ERIM M-7 multispectral scanner is a 12 channel instrument (12 spectral segments can be measured simultaneously, the spectral segments recorded may be determined by the researcher). The range of spectral sensitivity is from the ultraviolet (.4mμ) to the thermal infrared (14.0 mμ). There are 5 radiation calibration sources. Three for the visible and near infrared radiation range, two for the thermal infrared. When the sensing aircraft is flown at 600 meters (2000′), the ground resolution of the scanner is approximately 2 meters. For each square kilometer of the earth's surface observed from 600 meters, 250,000 independent contiguous measures of the radiation flux are collected. This detailed synoptic view of the radiation flux is ideally suited to the analysis of the microscale spatial variation of the heat budget of the earth's surface.

A Research Approach

Research is currently being pursued at the Remote Sensing Laboratory, Department of Geography and Geology, Indiana State University to further develop the application of ERIM M-7 multispectral scanner to heat budget studies. The ISU Remote Sensing Laboratory (ISURSL) is a research and applications facility which works in close cooperation with The Laboratory for Application of Remote Sensing (LARS) at Purdue University. ISURSL maintains a remote computer terminal to the LARS digital computer system. This facility provides ISU access to a wide range of aircraft and satellite multispectral data and numerous computer programs for processing and analyzing the data.

The study area for this research is a ¾ by 5 mile section of the Indianapolis, Indiana urban region. The long axis of the area follows the course of the White River where it passes through the western side of Indianapolis (Fig. 1). A wide range of urban land use is present in this region including commercial, industrial, residential and recreational activities. The ERIM M-7 scanner data collected from 600 meters on August 10, 1972 and on January 1, 1973 for this region are being utilized in this research.

In order to graphically demonstrate the measurement capability of the multispectral scanner and its applicability to climatic research calibrated data samples from a subregion of the research area for the data collected in August are presented (See Fig. 1).

Figures 2 and 3 are alphanumeric line printer maps of the subregion selected. Each alphanumeric symbol represents one picture element or pixel of the data. Each pixel represents an approximately 5x5 meter (15x15 feet) surface area from which radiant flows are measured. The total number of such measurements made in this approximately ¾x¾ mile area is 44,622. The scanner simultaneously measured 12 spectral components of the radiant flux for each pixel. Two of the spectral components are presented here. Note that in order to reduce the size of figures 2 and 3 every other line and column of pixels has not been displayed. For comparative purposes figure 4 provides an aerial photograph of the study area.

The data displayed in figure 2 are measurements of reflected solar radiation in the 0.55-0.60μm spectral region. They have been calibrated against known internal light sources to produce a simulated display of the percent reflectance of solar radiation from the surface in this spectral region. These data should not be viewed as accurate absolute measurements of percent reflectance or albedo of the surface. Research is still in progress to identify the relation between measured reflectance, incoming solar radiation and the calibration light sources in order to produce accurate percent reflectance-maps. The data in figure 2 have been qualitatively accessed as being accurate to ±10%. The data, however, well demonstrates the magnitude of the relative variance in surface reflectance. Man-made surfaces in general reflect a higher percent of incident solar radiation than natural surfaces. Exceptions are the roof of the ball park grandstand and the parking lot adjacent to the ball park.

FIGURE 1. *A LARS digital (television) image of th study area in Indianapolis. 0.55-0.60um spectral data. Subregion displayed in Figures 2 and 3 and 4 delineated by the rectangle near the top of the image.*

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THE CHARACTER SET USEO FOR OISPLAY IS                    HISTOGRAM BLOCK(S)

 BELOW   2.2              OISPLAYEO AS M
 FROM    2.2 TO     7.9  OISPLAYEO AS M              RUN NUMBER............ 72002600

 FROM    7.9 TO    10.2  OISPLAYEO AS #              LINES........ ( 1150, 1350,  1)

 FROM   10.2 TO    11.4  OISPLAYEO AS H              COLUMNS..... (    1,  222,  1)

 FROM   11.4 TO    13.6  OISPLAYEO AS □              CALI RATION COOE............ 4

 FROM   13.6 TO    15.9  OISPLAYEO AS /
 FROM   15.9 TO    19.4  DISPLAYEO AS +
 FROM   19.4 TO    27.4  OISPLAYEO AS .
 FROM   27.4 TO    67.7  OISPLAYEO AS
 ABOVE             67.7  OISPLAYEO AS
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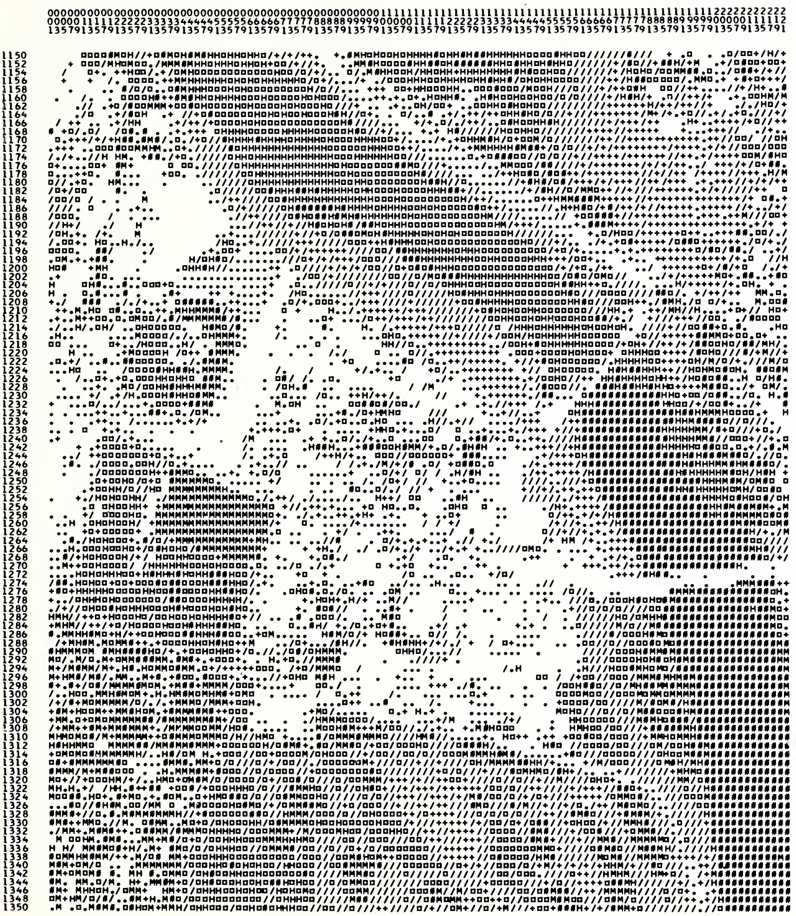
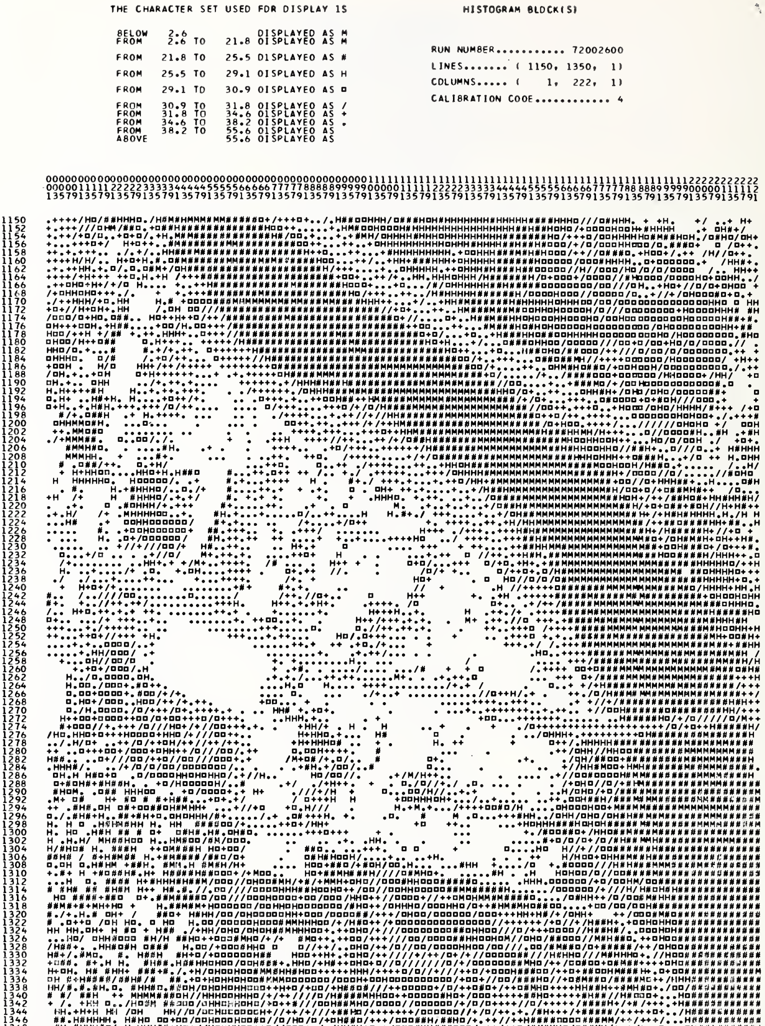


FIGURE 2. *An alphanumeric line printer map of simulated percent reflectance in the 0.55-060um spectral region.*

Figure 3 shows the radiant flux measured in the 9.30-11.7μm thermal infrared region. These data have been calibrated against the two thermal plates in the scanner and converted into radiant surface apparent temperatures. The conversion to surface temperatures is carried out by a non linear calibration function newly developed and implemented in the LARS computer system by the authors as an ongoing step in applying multispectral scanner data to climatological research. The



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THE CHARACTER SET USED FOR DISPLAY IS

BELOW    2.6               DISPLAYED AS M
FROM     2.6  TO   21.8    DISPLAYED AS M

FROM    21.8  TO   25.5    DISPLAYED AS #

FROM    25.5  TO   29.1    DISPLAYED AS H

FROM    29.1  TO   30.9    DISPLAYED AS □

FROM    30.9  TO   31.8    DISPLAYED AS /
FROM    31.8  TO   34.6    DISPLAYED AS +
FROM    34.6  TO   38.2    DISPLAYED AS .
FROM    38.2  TO   55.6    DISPLAYED AS
ABOVE              55.6    DISPLAYED AS
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HISTOGRAM BLOCK(S)

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LINES....... ( 1150, 1350,  1)

COLUMNS..... (    1,  222,  1)

CALIBRATION CODE........... 4
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FIGURE 3. *An alphanumeric line printer map of calibrated apparent surface radiant temperatures (°C) in the 9.3-11.7um spectral region.*

form of the nonlinear calibration function follows suggestions put forth in Bartolucci et al. (11). The accuracy of the measurement is within ±0.2°C. The highest temperatures are from man made surfaces with the exception of the metal roof to the left of the ball park. This is the result of the low emissivity of the material which markedly reduces the radiant emissions and therefore the surface apparent temperature. In general, the emissivity of the surface materials in the region is between .90 - .98 and does not significantly alter the relation between apparent radiant temperatures and actual kinetic temperatures.

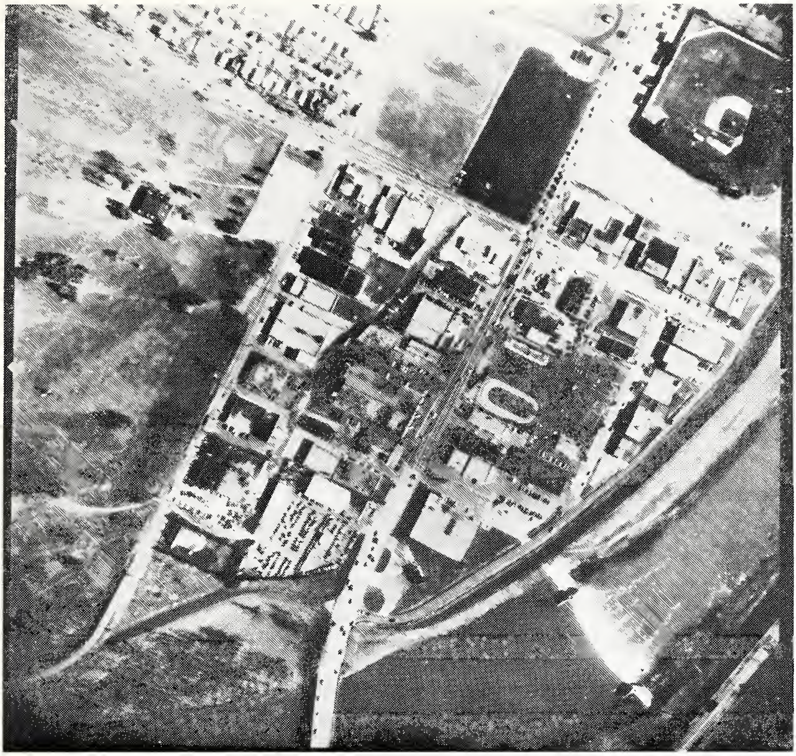
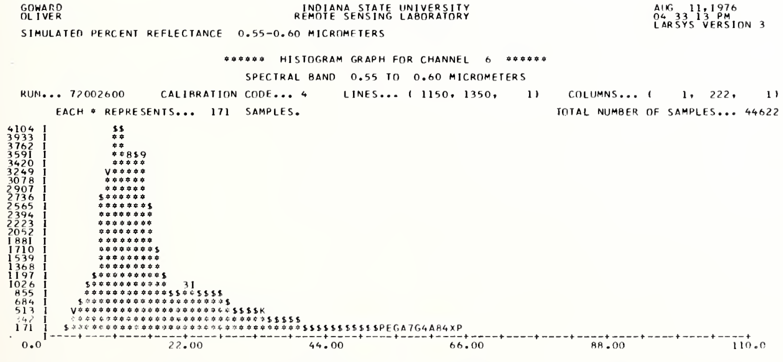


FIGURE 4. *A panchromatic aerial photograph of the region displayed in Figures 2 and 3.*



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GOWARD                                         INDIANA STATE UNIVERSITY                                AUG  11,1976
OLIVER                                        REMOTE SENSING LABORATORY                                04 33 13 PM
SIMULATED PERCENT REFLECTANCE  0.55-0.60 MICROMETERS                                                   LARSYS VERSION 3

                                ******  HISTOGRAM GRAPH FOR CHANNEL  6  ******

                                     SPECTRAL BAND  0.55 TO  0.60 MICROMETERS

RUN... 72002600     CALIBRATION CODE... 4     LINES... ( 1150, 1350,    1)    COLUMNS... (    1,  222,    1)

     EACH * REPRESENTS...  171  SAMPLES.                                          TOTAL NUMBER OF SAMPLES... 44622

4104 I         $$
3933 I         **
3762 I         **
3591 I         **8$9
3420 I         *****
3249 I        V*****
3078 I        ******
2907 I        ******
2736 I       $******
2565 I       *******$
2394 I       ********
2223 I       ********
2052 I       ********
1881 I       ********
1710 I       ********$
1539 I       *********
1368 I       *********
1197 I      $*********$
1026 I     $***********  31
 855 I     ************$$**$$$$
 684 I    $********************$
 513 I   V**********************$$$$K
 342 I   ****************************$$$$$
 171 I  $*********************************$$$$$$$$$$$PEGA7G4A84XP
 .   I----+----+----+----+----+----+----+----+----+----+----+----+----+----+----+----+----+----+----+----+----+
  0.0                  22.00               44.00               66.00               88.00               110.0
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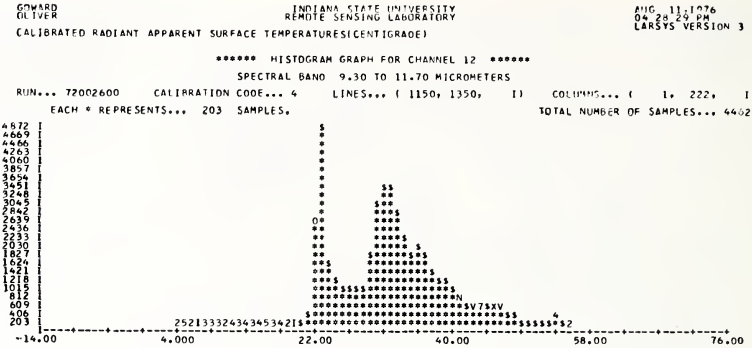
FIGURE 5. *A histogram of the distribution of simulated percent reflectance in figure 2. 0.55-0.60um spectral region.*



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GOWARD                              INDIANA STATE UNIVERSITY                        AUG  11,1976
OLIVER                              REMOTE SENSING LABORATORY                       04 28 29 PM
CALIBRATED RADIANT  APPARENT  SURFACE  TEMPERATURES(CENTIGRADE)                     LARSYS VERSION 3

                          ******  HISTOGRAM GRAPH FOR CHANNEL 12  ******
                            SPECTRAL BAND  9.30 TO 11.70 MICROMETERS
RUN... 72002600    CALIBRATION CODE... 4    LINES... ( 1150, 1350,    1)   COLUMNS... (    1,  222,    1)
    EACH * REPRESENTS...  203  SAMPLES.                               TOTAL NUMBER OF SAMPLES... 44622
```

FIGURE 6. *A histogram of the distribution of calibrated apparent surface temperatures (°C) in figure 3. 9.3-11.7um spectral region.*

Figures 5 and 6 are histograms of the distribution of radiant flux intensity of data displayed in figures 2 and 3 respectively. The range of percent reflectance (Fig. 5) is from 2% to over 60% with the majority of the surface reflecting between 10%-20% coincident with the river and vegetated surfaces. The long tail of responses between 20% and 60% is coincident with the majority of man made surfaces in the region. The temperature range (Fig. 6) is between 4°C and 56°C. The low end of the distribution, between 4°C and 20°C, is primarily from the metal roof building. The marked peak at 20°C is the river water and trees. The second peak between 25°C and 35°C is short grass vegetation in the parks and a golf course. The tail from 35°C-56°C are all responses from man made surfaces in the region.

A further view of differences in energy flows across the surface is seen in cross-sectional profiles. Figures 7 and 8 are graphs of line 1222 of the reflectance and emissive data respectively. These graphs represent a typical line of data as viewed by the scanning element of the instrument. Line 1222 is about ⅓ the way down from the top of the alphanumeric displays in figures 4 and 5. Note the low reflectance of the ball park roof in columns 47-53 and the high reflectance of the road surface in columns 91-93 of figure 7. The river channel is in columns 147 to 183. It shows low reflectance with the exception of the waterfall in columns 165-167. Figure 8 is a line graph of the temperature variation across the scene. Note the high temperature of the ball park roof in columns 47-51 and low river temperatures in columns 147-183.

Conclusions

The presented graphics demonstrate the qualitative and quantitative nature of the data. The high resolution of the data provides a unique answer to the problem of investigating synoptic variations in the surface components of the heat or energy budget. The information presented here is a progress report on research which is currently well under way to investigate the impact of urban land use on modifying the energy budget of the earth's surface. Preliminary observations drawn

```
****** GRAPH OF LINE 1222 ******

RUN NUMBER............ 72002600            DATE DATA TAKEN... AUG  10,1972
FLIGHT LINE... WABASH BASIN 28             TIME DATA TAKEN..... 1612 HOURS
DATA TAPE/FILE NUMBER.. 1020/ 1            PLATFORM ALTITUDE..   2000 FEET
REFORMATTING DATE. SEPT 21,1972            GROUND HEADING..... 345 DEGREES

CHANNEL  6   SPECTRAL BAND  0.55  TO  0.60 MICROMETERS   DISPLAYED  AS..6   CALCODE = 4   CO = 0.0       C1 =  25.00
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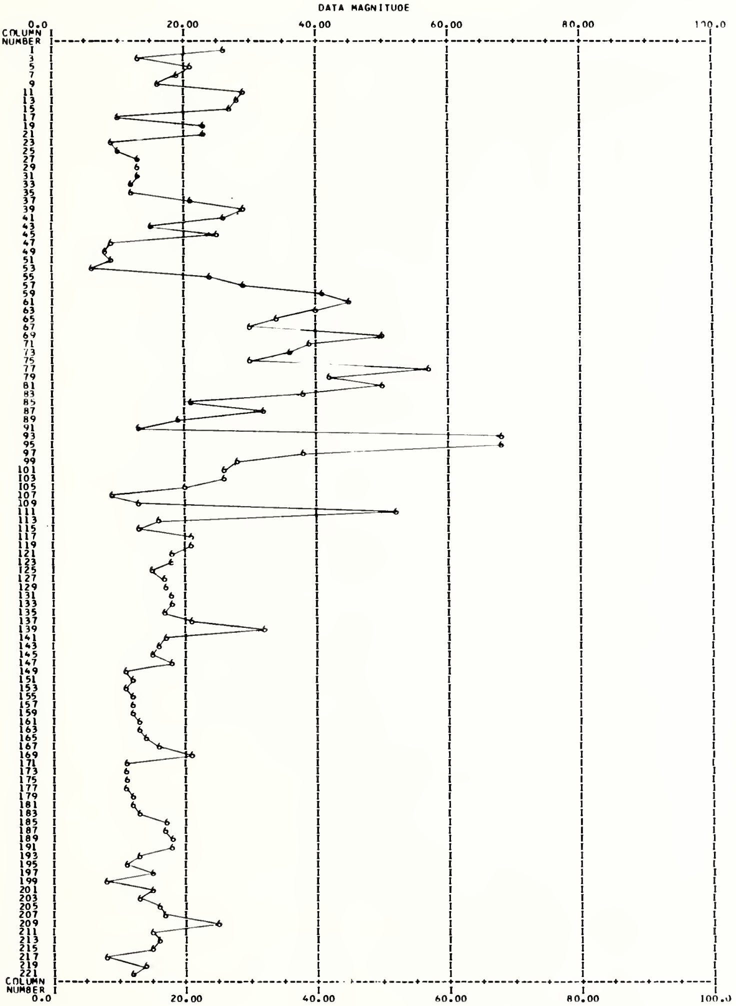

```
                    CALIBRATION FOR LINE   1222

                       CO                C1                C2
CHANNEL        MEAN  VARIANCE    MEAN  VARIANCE    MEAN  VARIANCE
   6            0.0    0.0       25.0    0.0       15.8    4.0

                  ROLL WAS NOT CALCULATED FOR THIS DATA.
```

FIGURE 7. *A graph of simulated percent reflectance in line 1222 of figure 2. 0.55-0.60um spectral region.*

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                    ******  GRAPH OF LINE 1222  ******

RUN NUMBER............ 72002600          DATE DATA TAKEN... AUG  10,1972
FLIGHT LINE... WABASH BASIN 28           TIME DATA TAKEN..... 1612 HOURS
DATA TAPE/FILE NUMBER.. 1020/ 1          PLATFORM ALTITUDE..   2000 FEET
REFORMATTING DATE. SEPT 21,1972          GROUND HEADING..... 345 DEGREES

CHANNEL 12   SPECTRAL BAND  9.30  TO 11.70 MICROMETERS   DISPLAYED  AS..C   CALCODE = 4   CO =  1.839   CI =  2.346
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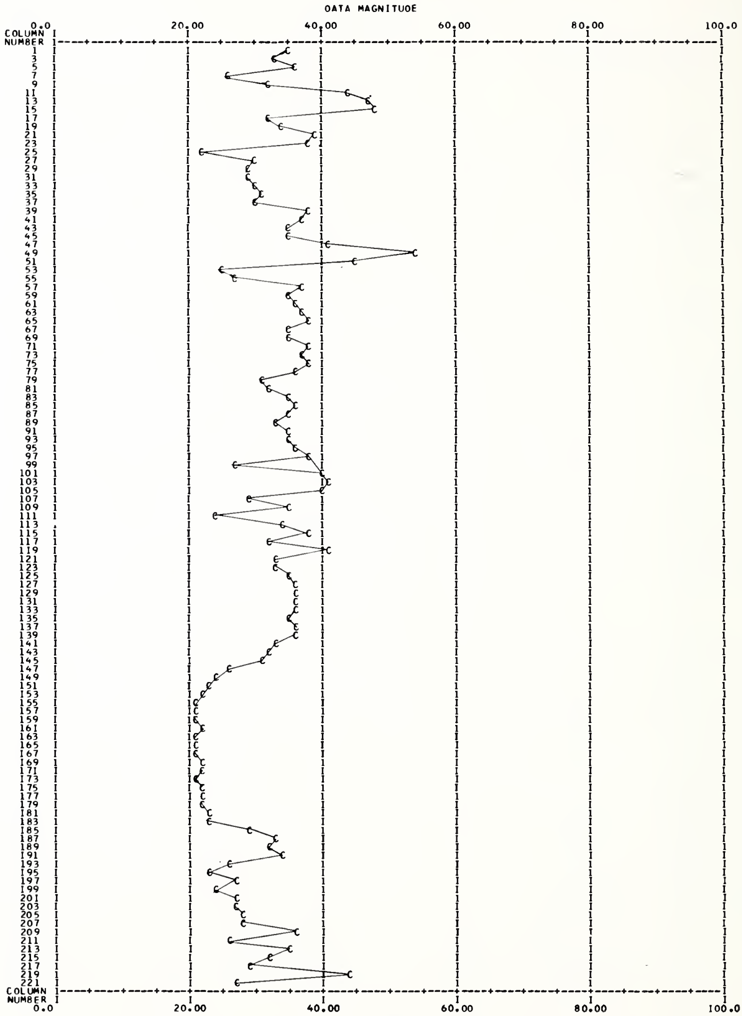

FIGURE 8. *A graph of calibrated apparent surface temperatures (°C) in line 1222 of figure 3. 9.3-11.7um spectral region.*

from August, 1972 data are that urban land use alters surface albedo through increasing the variance of albedo by a factor of 2 to 3 when compared with vegetated surfaces. Man made surfaces on a mid summer afternoon have temperatures which are 2 to 3 times higher than adjacent vegetated areas.

Although a variety of questions related to the temporal variations of the heat budget remain to be answered, the basic methodology by which the detailed synoptic or spatial variations of the energy budget may be identified has been developed by this research conducted at the Indiana State University Remote Sensing Laboratory. The proposed extension of current research is to carry out a coordinated ground and air observation program of a diurnal sequence to investigate the impact of urban land use on the regional climate in detail. It is anticipated that with the LANDSAT C satellite, to be launched in September, 1977, that mesoscale regional studies may also be conducted due to the inclusion of a thermal infrared scanner for the first time in the ERTS-LANDSAT program. Ideally a coordinated research effort relating ground, aircraft and satellite observations will be carried out to make full use of these new multispectral scanners in climatic research.

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