Development of Thermal Infrared Imagery to the Detection of Urban Heat Islands

Ronald L. Block
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THE DEVELOPMENT OF THERMAL INFRARED IMAGERY
TO THE DETECTION OF URBAN HEAT ISLANDS

by

Ronald L. Block

A THESIS

Presented to the Faculty of
The Graduate College in the University of Nebraska
In Partial Fulfillment of Requirements
For the Degree of Master of Arts

Department of Geography

Under the Supervision of Dr. Merlin P. Lawson

Lincoln, Nebraska
July, 1978
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Ronald L. Block
ABSTRACT

The primary objective of this study is to demonstrate the scientific validity of using airborne and satellite thermal infrared sensing as a technique for detecting the urban heat islands of selected towns and cities in eastern Nebraska. Emphasis is on the development of the technique, rather than on specific applications of its methodology. Two objectives of application include ascertaining the relationship between: 1) large structural density index values and high density renditions; and 2) increasing city size and increased density ranges.

Several instruments and techniques were used to determine the feasibility of thermal infrared sensing. Density renditions were obtained by use of the point densitometer and the spatial data system and digitized to produce computer isodensity and trend surface maps. The structural density index values for Lincoln were regressed with density renditions to illustrate that a strong relationship exists between these variables. Regression was also employed to indicate a similar correlation between city size and density values. Likewise, color slicing reveals a strong relationship between various land use types and their thermal patterns. However, a qualitative analysis of satellite thermal imagery indicated that current problems in resolution and distance from target render satellite technology incapable of determining intra-urban thermal patterns.
The conclusions of this study may be conveniently grouped into two parts: 1) thermal infrared sensing is superior to traditional temperature measurement techniques as it reveals many interlaced pockets of warm and cool areas that were previously undetected by conventional sensors. As a result, this technique should be utilized for a more accurate evaluation of urban heat island patterns; 2) the photographic graytones that appear on the images might lead one to believe that urban areas have numerous undesirable heat sources that lead to human discomfort and can now be corrected.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements</td>
<td>i</td>
</tr>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>iv</td>
</tr>
<tr>
<td>Table of Figures</td>
<td>v</td>
</tr>
<tr>
<td>Table of Tables</td>
<td>vi</td>
</tr>
<tr>
<td>Chapter I INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Procedure</td>
<td>2</td>
</tr>
<tr>
<td>Objectives</td>
<td>2</td>
</tr>
<tr>
<td>Study Area</td>
<td>3</td>
</tr>
<tr>
<td>Definition of Terms</td>
<td>6</td>
</tr>
<tr>
<td>Evaluation of Temperature Measurement Techniques</td>
<td>11</td>
</tr>
<tr>
<td>Implications for Man</td>
<td>19</td>
</tr>
<tr>
<td>Remote Sensing from Satellites</td>
<td>20</td>
</tr>
<tr>
<td>II A SURVEY OF TRADITIONAL AND THERMAL IR RESEARCH</td>
<td>23</td>
</tr>
<tr>
<td>Of Urban Heat Islands</td>
<td>24</td>
</tr>
<tr>
<td>Conventional Temperature Measurements</td>
<td>26</td>
</tr>
<tr>
<td>Traditional Land Use and City Size Studies</td>
<td>27</td>
</tr>
<tr>
<td>Thermal IR Imagery</td>
<td>33</td>
</tr>
<tr>
<td>Eastern Nebraska Study Area</td>
<td>35</td>
</tr>
<tr>
<td>III THE METHODOLOGY OF THERMAL IR SENSING</td>
<td>35</td>
</tr>
<tr>
<td>Data Collection</td>
<td>35</td>
</tr>
<tr>
<td>Imagery Information</td>
<td>38</td>
</tr>
<tr>
<td>Techniques and Instruments</td>
<td>40</td>
</tr>
<tr>
<td>Review of Methodology</td>
<td>54</td>
</tr>
<tr>
<td>IV THE VALUE OF THERMAL IR IMAGERY TO THE DETECTION</td>
<td>56</td>
</tr>
<tr>
<td>Of Urban Heat Islands</td>
<td>56</td>
</tr>
<tr>
<td>Lincoln, Nebraska</td>
<td>70</td>
</tr>
<tr>
<td>Other Study Sites</td>
<td>86</td>
</tr>
<tr>
<td>Mapping Summary</td>
<td>86</td>
</tr>
<tr>
<td>Color Slicing</td>
<td>93</td>
</tr>
<tr>
<td>City Size</td>
<td>99</td>
</tr>
<tr>
<td>Satellite Imagery</td>
<td>107</td>
</tr>
<tr>
<td>V CONCLUSIONS</td>
<td>113</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>115</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td></td>
</tr>
</tbody>
</table>
## TABLE OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Omaha Metropolitan Study Area</td>
<td>5</td>
</tr>
<tr>
<td>2. Peak Energy Emission at Selected Wavebands</td>
<td>8</td>
</tr>
<tr>
<td>3. The Scanner Operation Principle</td>
<td>15</td>
</tr>
<tr>
<td>4. ITOS-1 Data of Eastern United States Megalopolises</td>
<td>32</td>
</tr>
<tr>
<td>5. Image Distortions of Infrared Imagery Resulting from Aircraft Motion</td>
<td>37</td>
</tr>
<tr>
<td>6. Lincoln, Nebraska Study Area</td>
<td>48</td>
</tr>
<tr>
<td>7. Scattergram of Structural Density Index and Density Values</td>
<td>58</td>
</tr>
<tr>
<td>8. Thermal IR Mosaic of Lincoln CBD</td>
<td>62</td>
</tr>
<tr>
<td>9. Isodensity Map of Lincoln CBD</td>
<td>63</td>
</tr>
<tr>
<td>10. Trend Surface Map of Lincoln CBD</td>
<td>66</td>
</tr>
<tr>
<td>11. Nimbus Satellite Photograph of Nebraska 28 February 1975</td>
<td>67</td>
</tr>
<tr>
<td>12. Isodensity Map of Lincoln City</td>
<td>69</td>
</tr>
<tr>
<td>13. Trend Surface Map of Lincoln City</td>
<td>71</td>
</tr>
<tr>
<td>14. Nimbus Satellite Photographs of Nebraska During the Bellevue to Fremont-Bellevue Area Flightlines</td>
<td>72</td>
</tr>
<tr>
<td>15. Thermal IR Imagery of Capehart Housing Area</td>
<td>73</td>
</tr>
<tr>
<td>16. Isodensity Map of Capehart Housing Area</td>
<td>74</td>
</tr>
<tr>
<td>17. Trend Surface Map of Capehart Housing Area</td>
<td>76</td>
</tr>
<tr>
<td>18. Thermal IR Imagery of Urbanized Bellevue</td>
<td>78</td>
</tr>
<tr>
<td>19. Isodensity Map of Urbanized Bellevue</td>
<td>79</td>
</tr>
<tr>
<td>20. Trend Surface Map of Urbanized Bellevue</td>
<td>81</td>
</tr>
<tr>
<td>21. Thermal IR Imagery of Offutt Air Force Base</td>
<td>82</td>
</tr>
<tr>
<td>22. Isodensity Map of Offutt Air Force Base</td>
<td>83</td>
</tr>
<tr>
<td>23. Trend Surface Map of Offutt Air Force Base</td>
<td>85</td>
</tr>
<tr>
<td>24. Color Slices of Capehart Housing Area</td>
<td>88</td>
</tr>
<tr>
<td>25. Color Slices of Bellevue</td>
<td>89</td>
</tr>
<tr>
<td>27. Scattergram of City Size and Density Values Including Omaha</td>
<td>96</td>
</tr>
<tr>
<td>28. Scattergram of City Size and Density Values Excluding Omaha</td>
<td>97</td>
</tr>
<tr>
<td>29. Isodensity Map of Omaha</td>
<td>98</td>
</tr>
<tr>
<td>30. Land Temperatures of the United States 10 October 1976</td>
<td>100</td>
</tr>
<tr>
<td>31. Land Temperatures of the Midwest, 20 October 1976</td>
<td>101</td>
</tr>
<tr>
<td>32. Land Temperatures of the Midwest, 2 October 1975</td>
<td>102</td>
</tr>
<tr>
<td>33. Land Temperatures of the Midwest, 20 August 1976</td>
<td>103</td>
</tr>
<tr>
<td>34. Land Temperatures of the Midwest, 7 August 1975</td>
<td>105</td>
</tr>
</tbody>
</table>
Table of Tables

Table | Page
--- | ---
1. Infrared Emissivities of Selected Surfaces in Percent | 10
2. The Boundaries of the Nineteen Study Zones | 50
3. The Percentage of Each Land Use Type for the Nineteen Study Zones | 51
4. The Population Density Factor for the Nineteen Study Zones | 52
5. The Structural Density Index Values for the Nineteen Study Zones | 53
6. The Density Excess for the Nineteen Study Zones | 54
7. Density Ranges for Towns Along the Bellevue to Fremont Flightline | 94
CHAPTER I

INTRODUCTION

This thesis will determine if the techniques of low-level air-borne and satellite thermal infrared (thermal IR) imagery are scientifically superior to traditional temperature measurement techniques in a study of urban heat islands in eastern Nebraska.

The climate of a city is noticeably different than that of rural areas. Until man develops more direct methods of controlling the mechanisms of meteorology, his most profound climatic influence will remain the modification of urban areas (Barry and Chorley, 1970:253). The fact that a city is warmer than its surroundings has been known for more than 160 years (Howard, 1818) and it continues to receive considerable attention in literature (Peterson, 1973:264). Comparisons of daily minimum temperatures, which best exemplify this fact, demonstrate temperature differences approaching 10°C (Landsberg, 1956:1974).

An increasing amount of scientific research is being devoted to the analysis of urban heat islands. However, most scientists base their conclusions on traditional temperature measurements which include statistical analyses of short and long term records, and more recently, the mobile automobile traverse. Conversely, the application of thermal IR sensing has been almost entirely neglected in
heat island studies despite the fact that the existence of long wave thermal radiation has been recognized for over 175 years.

Procedure

Towns and cities in eastern Nebraska were evaluated under several temporal and altitude above ground level (AGL) conditions to assess the applicability of airborne thermal IR sensing. Land use as well as city size were examined to illustrate their effect on heat island intensity. Satellite thermal IR imagery of North America was analyzed to determine its present use and future potential for detecting heat island magnitude and distribution.

Note that imagery used in this study was supplied by several sources, implying that the respective imagery was processed under varied conditions. Consequently, there was no comparative analysis of density renditions between images, nor any allusion made to its specific practical application. Because only limited imagery was available to represent any particular condition, the results of this research should not be extrapolated to other studies without further research on the quality control of the film and on the temporal and synoptic conditions of the study in question.

Objectives

The primary purpose of this thesis is to evaluate the techniques of thermal IR sensing in airborne and satellite heat island studies in order to ascertain whether they are justifiable alternatives to traditional temperature measurement techniques. Within the context of this major objective, the intent is to show the feasibility of the technique and not specific applications of it. Examples of its appli-
cation are used only for illustration of the methodology. The primary emphasis is then to demonstrate that airborne low-level thermal IR imagery reveals a more complex and accurate thermal pattern than the simple monolithic model of urban heat islands. A secondary objective is to ascertain the value of satellite thermal IR imagery to evaluate heat island profiles.

Two objectives of application are established: 1) to determine by establishing a relationship between land use types and heat island intensity, that the areas with high structural density index values are the same areas which emit maximum radiation; and 2) to illustrate by comparing several eastern Nebraska towns and cities of similar morphology, that increased city size yields increased thermal contrasts.

Study Area

The eastern Nebraska study area included four of the state's five largest cities and almost half of the 1.5 million residents of Nebraska. Selected sites for analysis ranged from highly urbanized portions of Lincoln and Omaha to a bedroom community of Offutt Air Force Base.

Several towns and cities of varying size within the Omaha metropolitan area were analyzed, including the area from Bellevue to Fremont. Passing through sections of Sarpy and Douglas Counties, this area includes a section of Omaha (355,000), and the towns of Ralston (4,731), LaVista (7,840), Boys Town (989), Elkhorn (1,184), Waterloo (455), and Valley (1,595). The range in population and the similarity in morphology allowed for an analysis of city size as a factor in heat island magnitude. Another separate study centered on Bellevue (21,145),
and included Offutt Air Force Base and Capehart, an air force housing area. The Omaha metropolitan study area is presented in Figure 1.

Lincoln, Nebraska, highlighted in this thesis, contrasts with previous heat island study regions. Lincoln, (with a population of about 150,000 residents) is considerably smaller than other thermal IR study areas described in Chapter II (e.g. Barbados, Baltimore, Phoenix, and Tokyo). This city’s central location places it in the path of most outbreaks of extreme weather. The annual temperature mean is 11.2°C and an annual range of 12°C is expected. Minimal topographic influences make this a good city to study land use and heat island intensity.

Lincoln is an education, government, and transportation center. The main business district and areas of densest residential development occupy the central portion of the city. The central business district (hereafter referred to as the CBD) is essentially linear: a 2.5 kilometer (1.5 mile) extension centered on "O" Street. A major shopping center, Gateway, is located on the periphery.

Building heights in the CBD, University of Nebraska, and contiguous areas extend up to thirty-four stories (130 meters). Elsewhere throughout the city, one and two story structures predominate. Some heavy industry is concentrated on the urban fringe, while parks and other open spaces are generously interspersed throughout the city.
FIGURE 1
Omaha Metropolitan Study Area
Definition of Terms

Urban Heat Island

On an isothermal map a city appears as an island of heat surrounded by a sea of cooler air. This is the urban heat island and is caused by human activities, in conjunction with natural energy production, which yields a special heat balance in urban environments. The temperature anomalies are generally related to urban morphology. Highest temperatures are associated with the densely built-up center and with separate industrial and commercial areas. Generally, the degree of warming diminishes outward from the city center. Kopec (1970:605) remarked that greater homogeneity of air temperature is apparent where the business districts are circular, rectangular, or square rather than linear in shape, as found in Lincoln.

Two primary processes are involved in heat island formation, both of which are seasonally dependent. First, a higher sun angle in summer means that the urban artificial surfaces absorb, store, and emit larger amounts of solar radiation that do rural surfaces. Excessive run-off from the paved urban surfaces means decreased evaporation, and more energy is converted to sensible heat.

Second, in winter the lower sun angle results in less solar intensity per unit area. The contribution of human-induced energy then becomes a comparatively significant addition to the insolation. This energy includes heat escaping from poorly insulated homes, the combination of fossil fuel emission from industry and transportation, and direct human and animal metabolism. Bornstein (1968) analyzed 2.5 years of New York City data and found that this type of energy was more than twice that received from the sun.
Two other factors are important year-round. The blanket of pollutants over a city, especially carbon dioxide and water vapor, absorb part of the long-wave radiation which heats the urban air column. Reduced wind speeds caused by increased surface roughness decrease urban ventilation and inhibit the cooling (mixing) of air. The heat island magnitude is most pronounced at night when light regional winds permit a strong urban circulation pattern to develop.

**Thermal Infrared Radiation**

The major objective of thermal IR sensing is to detect and record emitted radiation in the far infrared (3.5 to 30.0 micron) portion of the electromagnetic spectrum. This energy is far beyond the threshold level of visible light. Thermal IR energy can be recorded because all matter at a temperature above absolute zero (0°K or -273°C) emits electromagnetic energy due to its atomic and molecular oscillations (Parker and Wolff, 1974:30).

The principles of thermal IR sensing are based on three related laws, namely, the Stefan-Boltzman Law, Wein's Displacement Law, and Planck's Law. The total emitted radiation from a blackbody is proportional to the fourth power of its absolute temperature. This is known as the Stefan-Boltzman Law and is expressed as:

\[ W = kT^4 \]

where \( W \) is emittance, \( k \) is a constant, and \( T^4 \) is the temperature in degrees Kelvin raised to the fourth power. Both the amount and the wavelength distribution of black-body radiation are shown to be functions of temperature.

Figure 2 shows that as a blackbody's temperature increases, the dominant wavelength shifts toward the short wave length end of the
FIGURE 2

Peak Energy Emission at Selected Wavebands

Source: Nunnally, 1979

spectrum. This is an illustration of Wein's Displacement Law expressed as:

\[ \lambda_{\text{max}} = \frac{c}{T} \]

where \( \lambda_{\text{max}} \) is the dominant wavelength in centimeters, \( c \) is a constant \((.2898)\), and \( T \) is the temperature in degrees Kelvin. Wein's Law indicates that the wavelength of peak earth emission (at \(+300^\circ\text{K}\)) is 9.7 microns. Thus the earth is an excellent energy source for a passive sensing device operating in the far infrared wavelengths, beyond what humans can see or cameras with film can record.

Both of these laws are consequences of a more general law, Planck's Radiation Law, which gives the complete distribution of emitted radiant energy from a blackbody at different wavelengths. Planck's "particle concept" illustrates that electromagnetic radiation consists of a flow
of particles or quanta, each quantum having an energy content $E$
determined by:

$$E = hf$$

where $h$ is Planck's constant and $f$ is the frequency of radiation. This
relationship shows that short wavelength (high frequency) energy
such as X-rays, carries more energy per quantum than longer wavelength
energy, such as infrared rays.

Emissivity is defined as the ratio of emittance of a given sur-
face to the emittance of an ideal blackbody at a specified wavelength
and temperature (Rosenberg, 1974:6). Blackbodies are surfaces which
have an emissivity of unity (1.0). Radiometric measurements are
calibrated to blackbody emission and since no surface is a true black-
body (all actual emissivities are less than 1.0), radiometers must
use correction factors to estimate true temperatures.

Emissivity is difficult to measure but according to Kirchoff's
Law, the absorptivity of a surface is equal to the emissivity of that
surface at the respective wavelengths. Therefore if you can measure
absorptivity, then you can determine the emissivity of any surface.
Infrared emissivities of some major urban surfaces are listed in
Table 1.

It is evident from Table 1 that large emissivity differences exist
between the varied urban surfaces and that some of these surfaces have
emissivities that are considerably lower than blackbody emissivity.
Appropriate correction factors must be applied in a final evaluation
of the image. Therefore, researchers should then consider these actual
surface emissivities and take into consideration their effect on the
reduction of energy received by the scanner when they analyze urban
thermal patterns.
**TABLE 1**

INFRARED EMISSIVITIES OF SELECTED SURFACES
IN PERCENT

<table>
<thead>
<tr>
<th>Surface</th>
<th>Emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>94</td>
</tr>
<tr>
<td>Fresh Snow</td>
<td>82-99.5</td>
</tr>
<tr>
<td>Ice</td>
<td>96</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>90</td>
</tr>
<tr>
<td>Wet Sand</td>
<td>95</td>
</tr>
<tr>
<td>Coarse Gravel</td>
<td>92</td>
</tr>
<tr>
<td>Limestone</td>
<td>92</td>
</tr>
<tr>
<td>Dry Concrete</td>
<td>80</td>
</tr>
<tr>
<td>Moist Ground</td>
<td>97</td>
</tr>
<tr>
<td>Dry Grass</td>
<td>90</td>
</tr>
<tr>
<td>Leaves and Plants (10)</td>
<td>98</td>
</tr>
<tr>
<td>Glass Pane</td>
<td>91</td>
</tr>
<tr>
<td>Red Brick</td>
<td>92</td>
</tr>
<tr>
<td>White Plaster</td>
<td>91</td>
</tr>
<tr>
<td>Oak Wood</td>
<td>90</td>
</tr>
<tr>
<td>White Paint</td>
<td>93</td>
</tr>
<tr>
<td>Black Paint</td>
<td>92</td>
</tr>
<tr>
<td>Aluminum Paint</td>
<td>50</td>
</tr>
<tr>
<td>Aluminum Foil</td>
<td>03</td>
</tr>
<tr>
<td>Galvanized Iron</td>
<td>21</td>
</tr>
<tr>
<td>Polished Silver</td>
<td>02</td>
</tr>
<tr>
<td>Human Skin</td>
<td>95</td>
</tr>
</tbody>
</table>

SOURCE: W.D. Sellers (1965)

One factor which strongly influences emissivity is the evaporative cooling effect on moist surfaces which results in a lower temperature than expected. Reradiation and evapo-transpiration of vegetation, the wavelength in which the image is sensed, and the roughness of the imaged surface can also alter the emissivity of a surface.

The resulting density value on an image depends then on the emissivity of the surface and the physical nature of the lowest levels of the troposphere. Basic inherent properties such as albedo, density, heat capacity, and thermal conductivity cause any two different contiguous materials (i.e., concrete versus metal) to have contrasting temperatures. For example Parker (1972:100) cited a concrete highway which absorbs heat at a rapid rate. Because of its high heat capacity, however, its temperature may rise very slowly. Conversely, low-lying vegetation heats up quickly, but its capacity for storing heat is limited. Metal roofs, iron fences, and other surfaces with low emissivities (high reflectivity) will appear much cooler or darker on a
positive print than expected. These thermal properties must be considered in an analysis of thermal IR imagery.

Evaluation of Temperature Measurement Techniques

Conventional Methods

The measurement of temperature has long been accomplished by the use of various devices such as thermometers and thermocouples which require physical contact and are subjected to hazardous environments that affect their accuracy and reliability. Rosenberg (1974:96) pointed out that the earth's surface is, theoretically at least, a two-dimensional plane. Traditional temperature sensors, no matter how small, are three dimensional objects. Therefore, since most urban surfaces are rough and irregular, the integration of surface temperatures would require the placement of many sensors. Lack of equipment and money usually limit this objective.

Auto traverses, the most common method of traditional heat island measurement, record temperature at several discrete points which are assumed to be representative of a spatial mean of temperatures. This highly generalized mode is rarely accurate. These measurements are subjective because direct human involvement is necessary in taking thermometer readings. Unintentional hand movement, for example, can alter both the thermometer angle and the thermometer elevation causing an altered temperature reading.

Ludwig and Keahola (1968) remarked that in field traverses, the diurnal variation in urban effects is often inadequately defined by poor scheduling or terrain features which tend to mask urban effects. Since no two studies employ the identical methodology, comparative analyses are tenuous. For example, Oke (1972) used a thermistor probe
mounted on an automobile at 1.5 meters. Munn et al. (1969) used a volunteer-observer-network which recorded temperatures over a four year period. Fonda et al. (1971) observed temperatures by holding a mercury-in-glass thermometer out of a car window "as far as possible". In all these cases, the differences in technique and degree of subjectivity were a limiting factor. Phenomena such as sun-shade changes, automobile interference, vehicular congestion, and varying automobile speeds can alter recording schedules. Therefore results are frequently and unintentionally altered due to the human element involved in measuring.

Many researchers desire a certain synoptic or temporal condition during the entire traverse. However, the duration of these traverses severely limits this goal. Automobile traverses usually require the interpolation of temperatures to a common time and elevation. The latter involves the reduction of observed temperatures to an "assumed" lapse rate. This degree of subjectivity diminishes the validity of the results.

Certain problems are inherent in the instrumentation. The familiar mercury-in-glass thermometer is fragile and unwieldy in the field, a condition which limits its practical use. Pocket thermometers have low precision and accuracy standards, and all thermometers respond slowly to temperature changes. The way in which instruments are shielded from radiation and air circulation can also produce a variation in the results. Temperature readings are usually estimated to the nearest degree, noticeably affecting the heat island model in certain areas and under certain conditions.
Additional problems of conventional sensors are concerned with money, time and personnel. The use of traditional techniques would, for example, make it very difficult to obtain an instantaneous look of the study area in a few hours or even in a single day. The logistics of fielding personnel and equipment under specified conditions renders the valid collection of data rather dubious. Considerable time and money are required to reduce the data into a workable end product, rendering conventional temperature measurements unfeasible.

**Thermal IR Sensing**

In order to assess the superiority of thermal IR sensing over conventional sensors, the mechanics of this technique must first be described and then it must be shown that radiation temperature measurements afford an accurate representation of the urban heat island profile. This urban thermal pattern is an integration of the surface and near-surface temperatures.

The instrument used in measuring radiation temperature in this study is an AN/AAS-18 infrared mapping system radiometer which is sensitive in the 8-14 micron band of the electromagnetic spectrum. This infrared sensor is a scanning device equipped with a mirror that scans the terrain in continuous strips perpendicular to the flight-line. The scanner receives point data, which strikes a detector element sensitive to thermal IR radiation and produces an electrical current whose amplitude is a function of the surface and near-surface temperature. The voltage from the detector element is electronically amplified to produce an image and then visually displayed on a cathode ray tube (Rudd, 1974:30-31). The final image is then a function of the energy beam emanating from the surface which is an integration of
the emissivity of the target and its surface and near-surface properties (Reeves et al., 1975; Rex Peterson, personal communication).

The attainment of high thermal resolution is a related problem for the scanner operation but one which can be corrected by the procurement of the smallest spot size possible (on the ground) at the scale of the image. The principles of scanning the terrain to obtain a thermal image are illustrated in Figure 3.

The use of the scanner operation enables one to evaluate the accuracy of thermal IR sensing in assessing the urban heat island pattern. Combs et al. (1965) and Wendland and Bryson (1969) have shown that there is little difference between radiometric and actual surface temperatures (see page 29). Rudd (1974) noted that the scanner's detector element is cooled to an extremely low temperature and then enclosed in a heatproof box to insure that the scanner itself does not affect the data. Numerous scientists (i.e., Rudd, 1974) have demonstrated that the effect of atmospheric interference is essentially eliminated by sensing in the 8-14 micron band of the electromagnetic spectrum. In this wavelength region, the "atmospheric window" minimizes solar reflection as well as infrared absorption and emission which can noticeably alter the final image.

Lenshow and Dutton (1964) added that imaging at low AGL's (i.e., below 1000 meters) as done in this study, negates any remaining atmospheric affects. Therefore, thermal IR sensing should present an accurate representation of urban thermal patterns.
FIGURE 3

The Scanner Operation Principle

Source: Rudd, 1974
The Advantages

The use of thermal IR sensing of surface temperature has increased in recent years, despite the fact that it is relatively expensive and complicated. However Lorenz (1966) noted two remarkable advantages of thermal IR sensing. Namely, it is a non-contact method and it does not measure the temperature at one particular point, but provides a mean value for a given area.

Rosenberg (1974:96) remarked that no matter how complex or structured the surface, the temperature measurement is valid since the intensity of radiation received is in integration of points. Despite experimental errors and the uncertainty in emissivities, the accuracy of any point under normal conditions can be determined to within 1°C. This exceeds the maximum accuracy of traditional measurements. Thermal IR radiation has no diurnal restrictions, and it penetrates much haze, fog, and smoke, thereby providing coverage of items not readily detectable by other methods.

Lenshow and Dutton (1964) indicated that since temperature is measured remotely, the radiometer has little effect upon the environment. Because surfaces are sensed from a distance, the complexities of these natural and man-made surfaces do not alter the measurements. Thermal IR mapping allows the presentation of heat sources not normally detectable by conventional means. Pease et al. (1976) indicated that rather than a monolithic plateau, this technique reveals an urban surface that is a patchwork of interlaced warm and cool areas. No other technique is so adept at displaying such temperature discrimination. It is now possible to discern minute temperature variations
previously undetected with traditional measurements. In addition, thermal IR imagery provides good ground resolution which makes interpreting the data relatively easy.

The Disadvantages

However, this technique is not without its drawbacks. The chief atmospheric disadvantages of thermal IR sensing are absorption and emission by atmospheric components, especially by water vapor and carbon dioxide, which can alter the true signal from an object. Greenfield and Kellogg (1960:289) noted that water vapor absorbs much long-wave radiation in the 5-7 micron range and absorbs little radiation in the 8-13 micron range. Beyond 13 microns, absorptivity of gas increases with increasing wavelength. Carbon dioxide has absorption bands at 4.2 microns and at the 14-15 micron range. The emission of carbon dioxide is particularly strong in the 5-7 micron range. Ground reflection, clouds, precipitation, and strong winds are additional atmospheric constraints which also greatly diminish image quality. However, most of these problems can be negated if measurements are recorded during optimum times of the day and within selected wavebands.

There are several inherent problems in the scanning system and in the images it produces. On a positive image, light and dark areas seemingly depict warm and cool thermal signals respectively. However, two surfaces with different emissivities such as asphalt and grass can have the same gray tone on an image while objects with different temperatures such as gravel and concrete can also appear identical on that same image if their emissivities are spaced right. The researcher must recognize such factors as the wavebands that are sensed and the
physical nature of the surface and atmosphere involved in the study which both determine, among other things, the temperature and emissivity of the selected surfaces.

There are other technical problems encountered when working with thermal IR sensing. One of the most confusing situations occurs when an object's temperature is the same as its background and the two surfaces cannot be separated. Such a situation restricts the advantage of this technique.

Poor long-range capabilities, minimal sub-surface detection, and weak stereographic potential are additional constraints on the use of thermal IR sensing. Many problems can occur when the interpreter mistakenly equates heat with density and miscalculates the true value of the density renditions.

At present, major obstacles to thermal IR heat island research are mission costs, which include employment of the airplane, crew, and instrumentation; the processing, duplicating, and computing costs; ground-truth verification; and analysis time. Parker (1972:104) estimated that the final costs of a mission over an area the size of Lincoln can exceed $13,000. Consequently, this technique appears to be economically unfeasible.

A lack of calibrated scanners is another problem of particular note. Because non-calibrated scanners must be used, resultant density values only provide a relative measure of temperature. Ground-truth is needed for the conversion to absolute temperatures.

A final problem is the lack of information that is readily accessible to interested parties. Many climatologists and planners are
still unaware that thermal IR sensing even exists. (The implied objective of this thesis is to educate scientists in the value of this tool.)

Despite these problems, the disadvantages of conventional temperature measurement techniques still greatly outweigh those identified with thermal IR sensing techniques. As a result, thermal IR sensing is seemingly a justifiable alternative to traditional measurement techniques.

Implications for Man

Thermal IR's utility may have a positive impact on man's increasing manipulation of the urban terrain. Pease et al. (1976) gives an example of a modern tract-home subdivision which lacks tree plantings. Thermal imagery reveals that this subdivision may have environmental thermal responses, i.e. human comfort, nearly as poor as those of the inner city commercial and industrial regions. This fact could be important for decisions relating to the creation of new housing tracts, because older residential areas that form a cold annulus about the city center are often destroyed. Information provided in this thesis can aid concerned parties in the optimum development of urban facilities.

Comparisons of selected airborne and satellite imagery over time, even for only one year, can reveal the effects of new construction on temperature measurements and human comfort in a particular area. Thermal IR measurements can potentially explain the current variation in empirical data, i.e., the seasonal and diurnal variations of the heat island effect. Future studies of the possible urban effects on cli-
mate will command greater attention as man's climatic influence continues to transcend his immediate urban surroundings and will visibly alter areas far beyond city centers.

Remote Sensing from Satellites

The future applications of remote sensing are centered around the need for data collection on a scale either prohibitively expensive or virtually impossible by conventional methods (Yates, 1972). Research in detecting urban temperature patterns will demand simultaneous measurements for comparative analysis of cities separated by great distances. Consequently, the feasibility of employing satellite imagery to urban heat island studies is explored in this paper.

Thermal IR sensing satellites can be divided into three groups. The initial research satellites included the NASA Nimbus series, which carried three advanced radiometric instruments. These satellites made a large number of continuous samplings in order to operate in the presence of a partial cloud cover (Smith, 1968).

NOAA operational satellites came into prominence in the mid-1960's. They differ from the NASA series in that they provide a continuous daily flow of data to specified users. These satellites include the TIROS and ITOS series which were launched in the 1960's and 1970's respectively.

The early 1970's saw the advent of the Synchronous Meteorological Satellite (SMS), and the Geostationary Operational Environmental Satellite (GOES) series, continually viewing the western hemisphere from a height of 35,000 km. The most recent satellite is the Landsat C launched in 1978.
In coverage, the satellite has no peer for remote sensing. Yates (1972) indicated that from an altitude of 1500 km, the NOAA satellites can instantaneously observe about two percent (1300 km) of the surface of the earth. The entire globe can be observed in twelve hours. This extensive and speedy coverage is ideal for comparing heat island magnitude.

However, the disadvantages of distance from target (such as atmospheric interference) and the attendant problems of resolution and sensitivity severely limit the current use of satellite imagery. Wark et al. (1962) pointed out that there are numerous hazards in estimating surface temperatures, and especially emissivities, from satellite measurements alone. Nordberg et al. (1962) noted that the attenuation of ozone is an additional atmospheric problem not encountered by airborne thermal IR sensors. This constituent has a maximum absorption band at 9.6 microns (Greenfield and Kellogg, 1960:286). Consequently, blackbody temperature measurements are underestimated by as much as 200K. Even within the atmospheric windows, considerable absorption can alter actual measurements by as much as twenty-five percent.

In most instances, weight, physical size, and power requirements for space borne sensors must be minimized and even compromised to fall within the capabilities of the satellites which carry them. Yates (1972) cited the ITOS satellite as an example. This spacecraft has solar panels which cause the volume of the sensor box to be several times larger than required.

Power is the most restrictive commodity. Polar orbiters such as Nimbus, ITOS, and TIROS, are in eclipse by the earth nearly half
the time of their orbit. Thus a polar orbiter must have a solar panel capacity at least twice its average power consumption and a battery to sustain the polar orbiter during eclipse.

Two further severe limitations of TIROS were found in its inclined orbit and its spin stabilization. Widger (1966) demonstrated that its coverage of the earth is limited to latitudes equatorward of 65°, while the camera points toward the earth during only one-fourth to one-third of its orbit. In addition, the initial cost of a satellite, say Nimbus, can exceed $65 million. Consequently, power and orbital restrictions will limit the use of satellite thermal IR imagery in the foreseeable future.
CHAPTER II

A SURVEY OF TRADITIONAL AND THERMAL IR RESEARCH
OF URBAN HEAT ISLANDS

The study of temperature changes within a city have dominated
the literature of urban meteorology because temperature was the first
urban climatic anomaly to be discovered and because it has been the
most intensely investigated. Howard's (1818, 1833) analysis of the
temperature of London is generally regarded as the earliest work on
urban climate. His research was based upon a series of simple ther­
mometer measurements taken between 1806 and 1830 at two sites, one
at the city center and the second in open country. Although his work
was monumental (Chandler, 1962:279), the exposures varied considerably.
This factor, as in most subsequent traditional studies, placed doubt on
the validity of the results.

The available literature having any bearing on this subject can be
conveniently grouped into three sections. The first section gives a
brief overview of traditional temperature studies as related to land
use and city size. The second section provides a compendium of the
meager existing literature on airborne and satellite thermal IR sensing
studies of urban heat islands. The final section discusses tradi­
tional and thermal IR research on the eastern Nebraska study area.
This thesis purports to fill a void in the literature on thermal IR
sensing.
Conventional Temperature Measurements

Conventional temperature measurement techniques can be divided into two general types: 1) statistical analysis of short and long term records that are used to establish trends between fixed stations, and 2) mobile automobile traverses.

Statistical Records

Perhaps the most illustrative case involving statistical analysis of long term records was Dettwiller's (1970) study of Paris, France. Long term temperature records (180 years) were kept within a 28 meter deep wine cellar. During the first one-hundred years, there was no measurable temperature change. However, in the last eighty years, the subterranean temperature rose about 1.5°C which included a 1.9°C increase per century in the mean daily minima. This is a remarkable heating effect because the normal temperature wave becomes unmeasurable at about the ten meter depth (Landsberg, 1974).

Temperature recordings at central London and other stations in southeast England were contrasted for the 1920-1960 period (Moffit, 1972). Consistent increases in the range were discovered between these stations with the difference most pronounced in the daily minimum temperature. Lawrence (1968) studied Manchester, England, for the 1940-1960 period. The increases in the mean daily minimum temperatures between the airport and the nearby rural stations correlated positively with the expansion of the urban area.

Dronia (1967) compared temperature trends from sixty-seven paired urban and rural locations for the 1870-1960 period and estimated that the average worldwide urban temperature rise was 0.7°C. Landsberg
(1960) compared thirty years of data for Los Angeles and San Diego and showed that as the difference in population between these cities increased, so did the difference between their mean temperatures. In a second study, Landsberg (1963) analyzed Columbia, Maryland, during the initial two years of its growth. As population increased from 2,000 to 16,000 inhabitants, the spatial temperature ranges within the town increased from 3°C to 4.5°C.

**Automobile Traverses**

The most often used and most successful traditional temperature measurement technique is the mobile automobile traverse. These traverses confirm that the maximum value of the heat island generally occurs on calm, clear nights. Hutcheon et al. (1967) studied Corvallis, Oregon, under these conditions and revealed that a town of only 21,000 residents can produce a thermal anomaly in excess of 5°C. Hutcheon's research confirmed a similar study of Palo Alto, California conducted thirteen years earlier (Duckworth and Sandberg, 1954).

Kratzer (1965) and Ludwig and Keahola (1968) have shown that the magnitude of the daytime heat island may be underestimated. The latter authors made twelve automobile traverses each at San Jose, California; Albuquerque, New Mexico; and New Orleans, Louisiana during the daytime in the summer of 1966. The downtown areas were all at least 0.5°C warmer than the suburbs.

Ludwig (1970) distinguished between the urban atmosphere, perhaps several thousand meters high, and urban surface temperatures, those that an individual senses. An analysis of Dallas, Texas, indicated that the CBD is not the warmest area of the city, especially during temperature maximum; instead, it is the areas of densely packed
three to five story buildings. These buildings display a low-level absorption of the reflected surface insolation.

Toronto, Ontario was studied to show a cause and effect relationship between the lake effect and the heat island pattern (Munn et al., 1969). Strong on-shore winds displaced the daytime heat island maximum downwind from the city center. In three recent investigations, two over New York City (Davidson, 1967; Bornstein, 1968) and one over Cincinatti (Clarke, 1969), helicopters were used to add a third dimension to mobile surveys. In New York City, inversion conditions over built-up areas existed up to about three hundred meters, while in Cincinatti, strong surface inversions were found both upwind and downwind from the CBD. However, within the densely occupied areas, inversions do not begin until about the six-hundred meter level.

Traditional Land Use and City Size Studies

Traditional study methods pervade the meager existing literature on the relationship between land use parameters and heat island magnitude. Duckworth and Sandberg (1954) found that temperatures in Palo Alto, California, increased in direct proportion to building density and that this might be the single most important factor in defining the spatial pattern of urban temperatures. Chandler (1970) noted high correlations between urban air temperatures at a given location in London and the type of land use found within a five-hundred meter radius of that site. At night in areas with strong heat islands, the correlation between heat islands and building density was usually greater than .90.

Clarke and Peterson (1972) observed similar results in Saint Louis through the use of eigenvectors. Myrup (1969) constructed an
energy budget simulation model which indicated that the thermal properties of buildings and pavement are the determining factors in the distribution of heat island intensity.

As previously noted, the monolithic nature of heat islands may be an artifact of ground based measurement systems. Research has been minimal on the application of thermal IR imagery to detect the correlation between land use and heat island intensity. Clarke and Peterson (1972) developed a structural density index (SDI) based on land use patterns which was well correlated with the Saint Louis heat island. The present study combines elements of traditional and modern analysis by refining and applying the SDI to Lincoln, using thermal IR imagery.

Traditional studies that compare city size and heat island magnitude employ models based upon a number of assumptions. In a representative study, Oke (1972) used the variable "background rural temperature" (the average or expected rural temperature) to compare urban-rural thermal differences. This is a subjective evaluation which renders conclusions highly tenuous. Most results are extrapolated to other cities with little qualification made between cities of contrasting morphology. Analysis of the correlation between city size and heat island intensity in the present study is based upon measured thermal radiation. This analysis should verify thermal IR's greater objectivity and subsequent validity.

Thermal IR Imagery

Traditional studies, which pervade the literature, have been restricted by both time and money, severely limiting the number of points in a given area which have been measured. Thermal IR sensing
is a novel technique that can overcome these disadvantages, but current research is negligible as compared with conventional literature and presents a serious gap in the literature. The literature that does exist, though, can also be divided into two parts. The first part surveys case studies of calibrated airborne missions. This thesis does not employ calibrated scanners; however, their advantages and applications are discussed. The second section explores the state of the art of satellite thermal IR imagery.

Airborne Imagery

Case Studies

Fujita and Baralt (1968) conducted research on Tokyo, Japan, using a radiometer to convert measured effective radiant emittance into a corresponding blackbody temperature. Equivalent blackbody temperature was then converted into a corresponding surface temperature. Good agreement was found between surface and estimated values of surface temperature.

Tsuchiya (1974) took four observations of surface temperature in Tokyo using an infrared radiometer. Cooler temperatures, previously undetected by conventional means, were found on the shady side of large green zones and wide rivers. In addition, large correction factors were highly correlated with intensely heated surfaces such as roads and buildings.

Lorenz (1966) computed the difference between true and radiometric measurements for natural surfaces in a study of Frankfurt am Main, Germany. Knowledge of spectral absorptivity and long-wave radiation were required for analysis which could then give an accurate estimation of ground temperatures to within 1°C.
Combs et al. (1965:257) indicated that differences between radiometric and surface temperatures over Phoenix, Arizona, and the contiguous desert ranged from zero to four degrees, depending on elevation. Wendland and Bryson (1969) also found that AGL temperatures of Hudson Bay, Canada, were within four degrees of the water surface temperatures, suggesting no substantial reradiation error. In all these studies the variation between temperatures is small enough to render thermal IR imagery a justifiable expenditure and technique.

Land Use Climatology

Surface energy-exchange phenomena have become important aspects of climatological analysis. Pease, Nichols, Outcalt, and other scientists have extrapolated Myrup's (1969) simulation model to discern the way various land uses interact with local weather to modify surface climates. The combined capabilities afforded by the calibrated remote measurement of surface energy phenomena from above and the simulation modeling of these same phenomena became the basis for a new subdiscipline termed land use climatology (Jenner et al., 1976:3-5).

Simulation models hinge on the ability to calculate various components of the surface energy transfer (Myrup, 1969). Airplane and satellite electro-optical scanners image active meteorological surfaces to obtain surface temperatures by use of the Gray-Window Model. Here, the signal received by the airplane sensor could be converted to a surface value when the mean temperature of the intervening air column and the radiance of a single ground target are known (Jenner et al., 1976:A-3).
The first attempt to map by scanners involved data taken over the island of Barbados (1969) in conjunction with BOMEX, the Barbados Oceanographic and Meteorological Experiment (Pease, 1970). Maps showing the distribution of radiation temperatures and surface radiances were made from a calibrated image of this island and the contiguous area. Atmospheric interference was recognized as the airport runway was underestimated by 10°C at an AGL of 330 meters.

The second mapping experiment imaged data over Baltimore, Maryland. Pease and Nichols (1976) used a multi-spectral scanner to measure surface energy emittance and radiance. Four maps were constructed at a scale of 1:2,500. The map of energy emitted from the land used data from only the thermal (10.0-12.0) range. Albedo maps required a combination of images made in the visual and near infrared. The map of energy absorbed by the surface used the unity-complement of the albedo as a multiplicative modifier of ground based solar radiation. The map of net radiation represented the subtraction of values of energy emitted from values of energy absorbed. The authors found close approximation between radiation measurements and actual surface measurements.

Pease et al. (1976) extended the Baltimore study using thermal IR imagery to ascertain the importance of various land use patterns in influencing climatological variables. Terrain factors such as surface roughness and albedo were estimated for each land use type. Based on these parameters, temperatures for each land use were simulated and plotted on the map. Acquired ground temperatures strongly correlated with simulated temperatures. This study also revealed that the heat intensity of transportation and commercial dominated areas exceeds the heat island intensity of the CBD.
Satellite Thermal IR Imagery

As early as 1959, thermal IR data from Explorer VII revealed that clouds are the dominant factor in determining the radiation patterns (Weinstein and Suomi, 1961:420). Whenever surface lows or fronts are most intense, the cloud tops are higher and colder, substantially reducing the outgoing radiation. Results indicated that the highest radiation readings occurred over areas of surface highs where cloud cover was negligible. Wark et al. and Fritz and Winston (1962) confirmed this fact in related studies. These authors found the best approximation of surface temperatures under clear sky conditions.

It has been demonstrated (Fritz and Winston, 1962; Nordberg et al., 1962:21) that the "window" data in clear areas approximate temperature at or near the earth's surface. Rao and Winston's (1963) study of TIROS II data recognized several areas where there was a strong similarity between effective temperatures and surface air temperatures. However, measured temperatures were usually underestimated as the largest error occurred over areas of extensive and middle cloudiness and/or snow cover. Again, best estimates of surface temperatures were made over clear, dry land areas.

Rao and Winston concluded that one major problem of satellite data is that radiation values obtained over snow covered regions make them indistinguishable from extensive high and middle cloudiness. Rao (1972:647) studied digitized thermal IR data from ITOS-1 (1970) obtained over the east coast of the United States during the predawn hours. The general location of the four major cities in this region is indicated on Figure 3. The heavily shaded areas represent a region of temperatures from 6°C to 8°C and the vertically hatched
FIGURE 4
ITOS-1 Data of Eastern United States Megalopolises

Source: RAO (1972)
region represents temperatures from 2°C to 50°C. The eastern megalopolis emerges as a relatively warm region compared to surrounding areas.

Carlson et al. (1977) were the first scientists to obtain detailed satellite surface temperature measurements of one city, namely Los Angeles. The NOAA-3 used a Very High Resolution Radiometer (VHRR) which had a resolution of 1 km. at the 0° nadir angle. During the early morning, the highest temperature was found over the industrial area, but by afternoon, the maximum temperature had shifted slightly toward the CBD.

However personal conversation with Carlson (1978) indicated several major difficulties with the results and current attributes of this technique. Only the NOAA Series has the necessary resolution to make an analysis of the urban heat island a viable goal. Advanced computers are essential to process and analyze intra-urban heat patterns extracted from satellite data tapes. Carlson notes that even after two years of computer refinement, satellite thermal IR images still have substantial drawbacks. Despite these limitations, this research indicates that the future of satellite thermal IR imagery is promising, and it is hoped it can provide a quantitative framework for understanding how changes in surface properties can influence the meteorology of cities.

Eastern Nebraska Study Area

Little research has been conducted on heat islands of the northern Great Plains, particularly on towns and cities in eastern Nebraska. Landsberg's (1956) research on Lincoln is unique in that it contradict traditional urban temperature theories. Daytime tempera-
ture readings over a one year period were taken at the rural airport and at the city center weather stations. Whereas daily cold season maxima revealed little difference between the sites, the warm season maxima indicated that temperature readings at the airport were frequently higher than those of the city center. In a later article, Landsberg (1974) pointed out that this procedure always allows for the possibility that micrometeorological settings ascribed to topography might have caused part or all of the observed differences.

Bjorklund, Schmer, and Isakson (1975) collaborated on thermal IR studies concerned with an analysis of rooftop temperatures of Lincoln and other selected towns in this region. Their research placed emphasis on heat losses resulting from inadequate insulation which would give homeowners an opportunity to evaluate their insulation needs. This was the first time that a thermal scanner had been used in an operational program of this type. Such research can be extrapolated to analyze urban heat island profiles.

This review illustrates that there are some very serious gaps in the literature. There is no evidence to indicate that any author has made a comprehensive thermal IR study of one city or compared results between cities of varying size. Likewise, there has been little substantial work accomplished on the variation between contrasting temporal and AGL conditions. Consequently, the monolithic model of heat island distribution still dominates the literature. This thesis should provide a contribution to the field of urban climatology. It represents a recent advance in the study of heat islands and the importance of this technique should increase in future research.
CHAPTER III
THE METHODOLOGY OF THERMAL IR SENSING

This study deals primarily with the development of a technique rather than with its application, and, as such, the methodology chapter must be given special attention. This chapter is divided into three sections. The first part gives the data sources, methods of data collecting, and pertinent information on each thermal IR image. The second part discusses the importance and application of the specific techniques and instruments used in this study. The final part summarizes the methodology used to test each objective in this thesis.

Data Collection

Data Sources

Selected imagery in this study is gathered from five sources: The Central Telephone and Utilities Corporation (CENGAS), Lincoln, Nebraska; the Remote Sensing Laboratory, University of Nebraska, Omaha; and three branches of the United States Department of Commerce—the National Oceanic and Atmospheric Administration (NOAA) in Rockville, Maryland, and two subgroups of NOAA, the National Environmental Satellite Service in Kansas City, Missouri, and the National Climatic Center in Asheville, North Carolina.

CENGAS provided low altitude negatives from its 1975 study which were used to analyze Lincoln (see Bjerklund et al., 1975). The University of Nebraska, Omaha, provided excellent imagery, taken by the U.S. Air Force, of Bellevue and its contiguous area plus imagery...
of the towns and cities between Bellevue and Fremont. The National Climatic Center supplied satellite imagery depicting the synoptic conditions during the respective airborne missions. In addition, this agency supplied imagery to illustrate heat islands in the United States. All three branches of NOAA provided current satellite thermal IR imagery representing various temporal and AGL conditions.

Data: Airplane and Satellite Equipment

Most of the imagery for this study was taken from Phantom II's (McDonnell RF-4C). Roll, pitch, drift, and other airplane deviations cause distortion away from the nadir point. The appearance of scan lines may also obscure the desired data. Therefore, it is necessary to be cautious about the determination of scale from these images. To minimize distortion, analysis is made only on the central two-thirds of the image strip. Various airplane deviations which can alter an image are explained on Figure 5. The airplane scan angle varies from 73 to 120 degrees, and the aircraft speed was always in excess of 150 miles per hour.

The attributes of satellites used in heat island research were discussed on pages 20-22. Sensors on board these satellites include a combination of the following: Scanning Radiometer (SR), Very High Resolution Radiometer (VHRR), Vertical Temperature Profile Radiometer (VTPR), and the Visible and Infrared Spin Scan Radiometer (VISSR).

Generally, the SR sensor can map in the 10.5 to 12.5 micron band of the electromagnetic spectrum and is continually scanning across the horizon with scan steps provided by the forward motion of the spacecraft. Infrared data resolution is approximately 7 km. at nadir.
### FIGURE 5
Image Distortions of Infrared Imagery Resulting from Aircraft Motion

<table>
<thead>
<tr>
<th>Aircraft Motion</th>
<th>Scan Mode</th>
<th>Recording Mode</th>
<th>Identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
<td><img src="image" alt="Scan Raster Displaced Sideways" /></td>
<td><img src="image" alt="Images Displaced Sideways" /></td>
<td>Wavy appearance of straight lines (roads). Cyclic displacement of imagery synching with the aircraft rolling.</td>
</tr>
<tr>
<td>Pitch</td>
<td><img src="image" alt="Uneven Scanline Spacing" /></td>
<td><img src="image" alt="Images Compressed and Stretched" /></td>
<td>Compresses and elongates images of objects (occurs less frequently than roll).</td>
</tr>
<tr>
<td>Yaw</td>
<td><img src="image" alt="Scan Lines Skewed" /></td>
<td><img src="image" alt="Image Edges Skewed or Displaced" /></td>
<td>Compresses and elongates images of objects laterally across the film. Wedging takes place and image edges are skewed.</td>
</tr>
<tr>
<td>Drift</td>
<td><img src="image" alt="Scan Lines Displaced Uniformly" /></td>
<td><img src="image" alt="Images Displaced Uniformly" /></td>
<td>Rectangles are distorted into parallelograms. Angle of distortion is approximately equal to the drift angle. Under normal conditions of drift (less than 10°) this distortion will be quite small.</td>
</tr>
</tbody>
</table>

Source: Parker and Wolff, 1965
The VHRR sensor is similar to the SR sensor except that thermal IR resolutions are approximately 0.8 km. at nadir. Atmospheric soundings of temperature are provided twice daily by the VTPR sensor while the VISSR sensor scans the full disk of the earth in 18.2 minutes at a resolution of 8 km.

Imagery Information

Most authors noted that nighttime imagery is preferable because the effects of differential solar heating and shadowing are eliminated. Ver Stappen (1977:21) disagreed, stating that morning and late afternoon are the most favorable times for thermograph recordings because these times are characterized by a steep temperature gradient. Minimum temperature contrasts (e.g., between water surfaces and land areas) are often reached shortly before sunset.

The following information is a compendium of pertinent facts on the images used in this study.

Airplane Imagery

1. Bellevue to Fremont Negative Transparencies: This mission was flown on 28 November 1975 by the U.S. Air Force, Bellevue. The starting time was 9:00 P.M. C.S.T. and the aircraft used was a RF-4 Phantom II jet flying at an altitude of 1312 meters. The ambient temperature was -4°C and .70 centimeters of precipitation was recorded. Scale along the nadir is 1:2,000.

2. Central Bellevue, Offutt Air Force Base, and Capehart Housing Area Positive Transparencies: These missions were flown on 7 February 1977 by the U.S. Air Force, Bellevue. The starting time was 6:30 A.M. C.S.T., and no precipitation was recorded. There were 95, 149,
and 214 density values recorded respectively. Scale along the nadir is 1:2,000.

3. Lincoln CENGAS Negative Transparencies: These missions were comprised of thirty-eight north-to-south running flight lines and flown in several shifts during the pre-dawn hours from 28 February to 1 March 1975. The mosaic of central Lincoln used in this study was sampled from a portion of the thirty-eight flightlines, namely, 15N and 16N. There were ninety-five points sampled for the structural density index data, and one-hundred points sampled for the central city mosaic. The missions were conducted by the South Dakota Remote Sensing Center at Brookings for CENGAS in Lincoln. The AGL of the private plane was 488 meters. The average ambient temperature was -2°C and cloudless conditions were reported during the missions. Scale along the nadir is 1:3,200.

Satellite Imagery

1. The imagery of 2 August 1975 was taken at 5:00 P.M. C.S.T. by a NOAA-3 satellite. Overcast conditions were reported over Nebraska. Resolution is twenty miles.

2. The imagery of 7 August 1975 were taken at 5:30 P.M. C.S.T. by a NOAA-3 satellite. Near cloudless conditions were reported over Nebraska. Resolution is twenty miles.

3. The imagery of 20 August 1976 was recorded at 12:01 P.M. C.S.T. by a NOAA-3 satellite. Cloudless conditions were reported over Nebraska. Resolution is twenty miles.

4. The imagery of 10 October 1976 was taken at 12:30 A.M. C.S.T. by a GOES satellite. Cloudless conditions were reported over Nebraska. Resolution is twenty miles.
5. The imagery of 20 October 1976 was taken at 12:30 A.M. C.S.T. by a GOES satellite. Overcast conditions were reported over Nebraska. Resolution is twenty miles.

Techniques and Instruments

**Densitometers**

Densitometers are the primary quantitative tools used to measure emitted radiation. This simple machine quantifies both the magnitude and the frequency of tonal change from either film transparencies or paper prints. A trace or point records the change in transmittance of a constant light source. Most densitometers have provisions for measuring both black and white or color densities. Measured densities depend on such characteristics as the recording technique (film/filter combination, optical system), the image processing, and the characteristics of objects such as color, moisture content, and texture (Ver Stappen, 1977;79).

Point densitometers can measure transmitted densities on a relative scale ranging from 0.0 to 4.0 in all parts of the image and can delimit up to twenty-two different gray tones. Film strips are positioned and the transmittance of light is recorded at a particular spot. The strip is then moved to an adjacent spot, and the process is repeated.

The point densitometer used in this study was a Macbeth Quanta­log Transmission Densitometer TD-100, used through the courtesy of the Remote Sensing Center, University of Nebraska, Lincoln. Diffuse transmission density (1 mm aperture) was indicated on a linear meter scale with evenly spaced gradations. After every fourth density rendition, the densitometer was checked to insure that the trans­mission was still calibrated to the initial setting of 3.31. Every
effort was made to record density values at the street level or at least at locations of low-level buildings to guarantee that the measurement of values best represented the surface conditions (refer to Ludwig, 1970). This point densitometer was used to obtain density values from all but the Lincoln city imagery.

Microdensitometers are more sophisticated instruments used to measure the transmission density of microscopically small areas of the image. This machine is an optical scanning system in which the scanning can vary according to need. Scanning occurs along the film, and a trace is recorded in proportion to the amount of measured radiation. Besides the obvious time saved, the density data obtained is presented in the form of a visible graph to facilitate analysis.

**Spatial Data System**

Density measurements of the Lincoln city data were obtained from an image enhancement system used with the consent of the Remote Sensing Center, University of Nebraska, Lincoln. The model used was a 401/704 Spatial Data System, which combines analog enhancement circuitry and closed circuit television techniques to produce both color enhancement and edge enhancement of photographic transparencies. Maximum resolution was obtained by use of a F-16 lens.

Density profilers present a graphic display of density values across a central vertical line in the picture. A vertical white line indicates the cross section of the picture along which the displayed densities are taken. Actual density values vary on a relative scale from 0.0 to 2.99.

The Spatial Data System was also used for color slicing of the images. Ver Stappen (1977:82) stated that this technique is the only
one which allows a completely quantitative analysis of the density distribution of the imagery. The photographic density, as seen by the camera, is divided into levels or contour intervals. Up to twelve levels can be selected, and each level is shown on the color television monitor as one of twelve discrete shades of gray. The borders between colors (or shades of gray) represent contours on the gray scale.

On the television monitor the darker the color or gray tone, the higher the density recorded, and switches on this machine can vary the number of colors or tones. A Minolta camera with Kodak Ektachrome 200 film was used to photograph the images. The primary advantage of this technique is that the equi-densitometric image that is obtained can be interpreted rapidly and conveniently on a television monitor. Density values for the Lincoln city mosaic were also obtained from the Spatial Data System.

Mosaics

Airborne thermal images are recorded with varying degrees of overlap between successive strips of imagery. The purpose of a mosaic is to eliminate this overlap and combine successive photographs in order to obtain an optimum view of the study area. Recognizable points on the image are desired to give optimum fit.

The mosaic used was part of the Lincoln CENGAS data, flightlines 15N and 16N, which traverse the University of Nebraska, warehouse, governmental, and CBD areas of this city. The boundaries of this mosaic are from 3rd to 15th streets, and New Hampshire to D streets. Overlap is twenty-three percent.
CENGAS data were selected because the large scale provided the many identifiable features needed for a detailed densitometric analysis of the CBD to further investigate the traditionally assumed heat island pattern. The mosaic was produced by the Photographic Reproduction Laboratory, University of Nebraska, Lincoln, and constructed with the aid of J.R. Giardino.

**Sampling Methods**

Since it is virtually impossible to measure every density value on an image, the selection of an appropriate sampling method is essential. Samples are required to provide information about the total population and for this reason it is necessary that every member of the population should have an equal chance of being selected. This type of sample is called a random sample. However, random sampling introduces the possibility of producing samples that are overweighted in terms of extreme qualities.

A stratified-random sample used in this study is a way of overcoming the imprecision of simple random sampling. Here the sample is divided into strata which then serve as sub-populations from which samples are drawn. This study used a one-inch grid that was subdivided into thirty-six tracts. Random samples were obtained with the aid of a table of random numbers (Glass and Stanley, 1970: 510-512).

Capehart housing area (associated with Offutt Air Force Base) was analyzed by dividing the grid into four strata, each of which were subdivided into nine tracts. The tracts were labeled one through nine and three random numbers were selected from each strata. Density values of these three strata were then determined and averaged to smooth out fluctuations.
For the Lincoln city data, each of the nineteen study areas were divided into five equal size regions, and the process was repeated. An average value for each area was obtained. The sampling method for the Offutt Air Force Base and Bellevue data was similar to the above mentioned method, except that sampling was accomplished along a line and only the upper two strata (or eighteen tracts) were sampled. Note that a common resolution between images was attempted, but because no images were directly compared, the attainment of this goal was not deemed essential to this study.

Sample sizes should be such that it is possible to infer accurately from them the character of the respective heat islands. The number of density renditions far exceed the number of thermometer measurements which could be attained by feasible automobile traverses. Therefore, thermal IR imagery seemingly presents a more detailed and accurate urban heat island pattern.

**Computer Mapping**

To be effective, the images must be presented in some graphic form, the most appropriate of which is called SYMAP. SYMAP is a computer program written in FORTRAN IV and used for producing maps which graphically depict spatially disposed quantitative and qualitative information (Harvard University, 1976:1). By assigning values to the coordinate location of data points, three possible types of maps can be produced: contour, conformant, or proximal maps.

Contour (isoline) maps, used in this study, consist of closed curves known as contour lines which connect all points having the same value. Between any two contour lines a continuous variation is
assumed. Therefore, the use of contour maps is restricted to the representation of continuous information such as density values. Conformant (choropleth) and proximal maps are used where the representation of continuous data is inappropriate. Each data point or zone is enclosed by a boundary isopleth to some predefined spatial unit.

The imagery was digitized by methods previously discussed to produce computer isodensity and trend surface maps (see page 41). The complexity and spatial variation of the data plus the accuracy afforded by this technique, necessitated the use of computer mapping as opposed to a manual cartographic display of the data. Selection of a predetermined number of data points controlled the desired degree of refinement.

Isodensity Maps

Density values were plotted on maps of the study areas. A one-inch grid matrix was superimposed on the map, and each point was assigned an "X,Y" coordinate. The outline of the map, the "X,Y" coordinate locations, the density value at each location, the map title, and applicable elective cards were determined. Appropriate computer cards were keypunched and submitted for computer processing. The SYMAP program is outlined in the Appendix and the results are discussed in the next chapter.

Trend Surface Maps

Cole and King (1968:375) remarked that "geographical data often cover whole areas with continuously varying values. These values are usually sampled only at points, although it is the whole undulating surface which is of interest." Trend surface analysis provides a
method whereby mathematical surfaces in three dimensions may be fitted to the data. This technique allows surfaces of increasing complexity, starting with a plane, to be fitted to point observations. The positions of the points are, again, defined relative to a rectangular coordinate grid. Because data are displayed on an aerial basis, this technique is particularly appropriate to geographic studies. Data must be represented on a ratio or interval scale to allow calculations of the sum of squares, which forms the basis of the method.

Chorley and Haggett (1967:717) commented that "methods performed objectively by the computer enable the investigator to divide each map into two or more parts; large scale or regional trends from one edge of the map to the other, and small scale or local effects."

By a reiterative process the original observations may be broken down into a series of progressively smaller extent. The construction of the surfaces was designed to make the sum of the squared residuals as small as possible. Trend surfaces can represent up to six polynomials. The sixth polynomial was selected for all maps because it gave the "best" correlation coefficient. The only addition to this computer program is an elective trend surface card which instructs the computer to print this special map. Results are discussed in the next chapter.

**Structural Density Index**

The establishment of a relationship between land use types and heat island intensity consisted of deriving a correlation between structural density index values (SDI), a measurement of land use influence, and thermal IR density values, a measurement of heat island intensity. SDI is a measure of the amount of heat being radiated from
any given area and shown to be a direct function of the type and amount of each particular land use and the number of people in a given area (Clarke, personal correspondence).

CENGAS thermal IR negatives of Lincoln were selected for analysis because of their large scale (1:3,200) and because of a familiarity with the study area. Such low altitude imagery allowed for the accurate evaluation of the spatial pattern of heat island emittance in Lincoln.

Based on information gathered on land use and population patterns of this city plus comparisons with previous cities (see Clarke and Peterson, 1972), Lincoln was divided into nineteen approximately equal size study areas as indicated in Figure 6. More than nineteen areas would probably be too homogeneous and obscure certain land use types. Fewer than nineteen areas would not provide an in-depth and statistically valid analysis of the subject. Nineteen areas also fit well into Lincoln's boundaries.

Each area was delimited by the percentage of parks, residential (R), industrial (I), and commercial (C) land use types. Residential areas included all dwellings and educational facilities. Commercial areas included all service, transportation, and utility functions. Parks encompassed all open space and athletic fields.

Land use percentages were determined from half-section (320 acres) plat maps provided by the Lincoln City Planning Commission. Half-section maps allowed a detailed analysis of each delimited area and virtually eliminated the possibility of generalization. A grid matrix was developed to quantify the land use data and to provide a uniform data matrix over the study area. In an attempt to reduce
the possibility of some land use types masking the effects of others, a one-inch square grid cell was selected. The use of such a division resulted in 344 total cells for each plat map. The land use data represented the total percentages of the respective land use types in each individual cell. Percentages were obtained by superimposing
the grid matrix on the land use map and visually estimating aerial coverage. The relationship between the land use types is expressed by the following formulæ:

$$\text{SDI} = 2C + I + R(\text{PDF})$$

where $C$, $I$, and $R$ are percentages of commercial, industrial, and residential land use types in each study area and PDF is the population density factor.

An assumption is that commercial land use has twice the weight of an industrial area of equal size. Population density (PDF) was used to determine the weight given to residential areas: i.e., the larger the population density factor, the greater the likelihood of concrete structures. PDF is a relative value which depends on the range of population in a study area. It increases linearly with population from 0.0 to 1.0. Because of its relative measurement, researchers should be cautious about extrapolating a given PDF range to other cities.

Population figures for each block were divided into the respective study areas, and the totals for each zone were compiled and assigned a PDF. These data were acquired from the 1970 Block Statistics of Lincoln available at the City Planning Commission, Lincoln.

The boundaries of the nineteen study zones are displayed in Table 2.

The initial step was to determine the percentage of park, commercial, industrial, and residential land use in each of the study zones. These computations are shown in Table 3.

Population density increases linearly from 0.0 to 1.0. Table 4 shows the PDF for each zone in ascending order.
### Table 2
THE BOUNDARIES OF THE NINETEEN STUDY ZONES

<table>
<thead>
<tr>
<th>Zone</th>
<th>Boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>South 1st to 27th St., city line to Pioneers Blvd.</td>
</tr>
<tr>
<td>02</td>
<td>South 27th to 56th St., city line to Pioneers Blvd.</td>
</tr>
<tr>
<td>03</td>
<td>South 56th to 84th St., city line to Pioneers Blvd.</td>
</tr>
<tr>
<td>04</td>
<td>West 29th to S.W. 6th St., Pioneers Blvd to West A St.</td>
</tr>
<tr>
<td>05</td>
<td>S.W. 6th to S. 27th St., Pioneers Blvd to West A St.</td>
</tr>
<tr>
<td>06</td>
<td>South 27th to 56th St., Pioneers Blvd to East A St.</td>
</tr>
<tr>
<td>07</td>
<td>South 56th to 84th St., Pioneers Blvd to East A St.</td>
</tr>
<tr>
<td>08</td>
<td>West 29th to S.W. 6th St., West A to Holdrege St.</td>
</tr>
<tr>
<td>09</td>
<td>S.W. 6th to 27th St., West A to Holdrege St.</td>
</tr>
<tr>
<td>10</td>
<td>27th to 56th St., East A to Holdrege St.</td>
</tr>
<tr>
<td>11</td>
<td>56th to 84th St., East A to Holdrege St.</td>
</tr>
<tr>
<td>12</td>
<td>N.W. 29th to N.W. 6th St., Holdrege to Benton St.</td>
</tr>
<tr>
<td>13</td>
<td>N.W. 6th to N. 27th St., Holdrege to Benton St.</td>
</tr>
<tr>
<td>14</td>
<td>N. 27th to N. 56th St., Holdrege to Benton St.</td>
</tr>
<tr>
<td>15</td>
<td>N. 56th to N. 84th St., Holdrege to Benton St.</td>
</tr>
<tr>
<td>16</td>
<td>N.W. 29th to N.W. 6th St., Benton St. to city line</td>
</tr>
<tr>
<td>17</td>
<td>N.W. 6th to N.W. 27th St., Benton St. to city line</td>
</tr>
<tr>
<td>18</td>
<td>N. 27th to N. 56th St., Benton St. to city line</td>
</tr>
<tr>
<td>19</td>
<td>N. 56th to N. 84th St., Benton St. to city line</td>
</tr>
</tbody>
</table>

The final computation of each SDI is presented in Table 5.

CENGAS thermal IR density values were derived by methods discussed on pages 43-44. Five density values were obtained from each of the nineteen zones (ninety-five total values) and averaged to smooth out random fluctuations and to obtain the best estimate of heat emittance in each area. The density values were then ranked in descending order, and the density excess of each of the nineteen areas above the lowest obtained density value were derived as shown in Table 6.

The computation of the structural density index and the density excess was now completed for each of the nineteen study areas. The final step was to ascertain the strength of the correlation between
### TABLE 3

**THE PERCENTAGE OF EACH LAND USE TYPE FOR THE NINETEEN STUDY ZONES**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Residential</th>
<th>Parks</th>
<th>Industrial</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>18.25</td>
<td>80.50</td>
<td>00.50</td>
<td>00.75</td>
</tr>
<tr>
<td>02</td>
<td>12.40</td>
<td>85.80</td>
<td>00.40</td>
<td>01.40</td>
</tr>
<tr>
<td>03</td>
<td>26.80</td>
<td>62.60</td>
<td>05.00</td>
<td>05.60</td>
</tr>
<tr>
<td>04</td>
<td>02.90</td>
<td>96.40</td>
<td>00.00</td>
<td>00.70</td>
</tr>
<tr>
<td>05</td>
<td>76.25</td>
<td>17.90</td>
<td>01.00</td>
<td>04.75</td>
</tr>
<tr>
<td>06</td>
<td>39.25</td>
<td>54.90</td>
<td>03.16</td>
<td>02.69</td>
</tr>
<tr>
<td>07</td>
<td>41.50</td>
<td>40.00</td>
<td>00.00</td>
<td>18.50</td>
</tr>
<tr>
<td>08</td>
<td>12.25</td>
<td>61.70</td>
<td>03.25</td>
<td>22.37</td>
</tr>
<tr>
<td>09</td>
<td>40.67</td>
<td>22.67</td>
<td>15.58</td>
<td>21.08</td>
</tr>
<tr>
<td>10</td>
<td>67.75</td>
<td>24.50</td>
<td>04.63</td>
<td>03.12</td>
</tr>
<tr>
<td>11</td>
<td>34.00</td>
<td>57.10</td>
<td>00.40</td>
<td>08.50</td>
</tr>
<tr>
<td>12</td>
<td>57.70</td>
<td>40.20</td>
<td>00.80</td>
<td>01.30</td>
</tr>
<tr>
<td>13</td>
<td>63.80</td>
<td>15.80</td>
<td>09.40</td>
<td>11.00</td>
</tr>
<tr>
<td>14</td>
<td>29.30</td>
<td>58.90</td>
<td>05.50</td>
<td>06.30</td>
</tr>
<tr>
<td>15</td>
<td>06.90</td>
<td>89.30</td>
<td>01.60</td>
<td>02.20</td>
</tr>
<tr>
<td>16</td>
<td>05.90</td>
<td>77.50</td>
<td>06.20</td>
<td>11.20</td>
</tr>
<tr>
<td>17</td>
<td>13.20</td>
<td>86.30</td>
<td>11.50</td>
<td>00.00</td>
</tr>
<tr>
<td>18</td>
<td>02.75</td>
<td>79.30</td>
<td>09.25</td>
<td>08.70</td>
</tr>
<tr>
<td>19</td>
<td>19.20</td>
<td>55.60</td>
<td>10.10</td>
<td>15.20</td>
</tr>
</tbody>
</table>

SDI and density values. Regression was selected as the statistical testing technique, and a computer program was developed to facilitate the analysis of the Lincoln urban heat island.

**Regression**

After a literature review (Clarke and Peterson, 1972) and an analysis of the problem, it was determined that the best method of discerning the existence of a trend was to use linear regression. A regression line is a line of "best linear fit" on a scattergram.
TABLE 4
THE POPULATION DENSITY FACTOR
FOR THE NINETEEN STUDY ZONES

<table>
<thead>
<tr>
<th>Zone</th>
<th>Population</th>
<th>PDF</th>
<th>Zone</th>
<th>Population</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>09</td>
<td>24,604</td>
<td>1.000</td>
<td>03</td>
<td>01,515</td>
<td>0.060</td>
</tr>
<tr>
<td>10</td>
<td>21,773</td>
<td>0.884</td>
<td>08</td>
<td>01,478</td>
<td>0.058</td>
</tr>
<tr>
<td>07</td>
<td>20,667</td>
<td>0.835</td>
<td>17</td>
<td>01,398</td>
<td>0.055</td>
</tr>
<tr>
<td>06</td>
<td>20,622</td>
<td>0.833</td>
<td>18</td>
<td>01,159</td>
<td>0.042</td>
</tr>
<tr>
<td>11</td>
<td>17,886</td>
<td>0.725</td>
<td>02</td>
<td>00,073</td>
<td>0.038</td>
</tr>
<tr>
<td>12</td>
<td>13,774</td>
<td>0.560</td>
<td>01</td>
<td>00,663</td>
<td>0.024</td>
</tr>
<tr>
<td>13</td>
<td>09,834</td>
<td>0.395</td>
<td>04</td>
<td>00,330</td>
<td>0.022</td>
</tr>
<tr>
<td>05</td>
<td>05,183</td>
<td>0.208</td>
<td>15</td>
<td>00,095</td>
<td>0.020</td>
</tr>
<tr>
<td>14</td>
<td>04,521</td>
<td>0.180</td>
<td>16</td>
<td>00,055</td>
<td>0.000</td>
</tr>
<tr>
<td>19</td>
<td>04,135</td>
<td>0.165</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is usually a summary expression of the relationship between two variables used to interpolate or predict unknown values of the variable. Since this study involves only two variables, a simple regression technique expressed by the equation \( Y = a + bX \) was used in this study. The elevation of the "Y" line is called the "Y" intercept and designated by a lower case "a". The slope of the line or coefficient of regression, is designated as "b" while "X" is the magnitude of the independent variable. The variable "b" expresses the change in the dependent variable (density values) as it varies in relation to the independent variable (SDI). Slope direction is indicated by the sign preceeding "b".

The standard error of estimate measures how close the observations are to the regression line. It simply indicates how much of the vari-
TABLE 5

THE STRUCTURAL DENSITY INDEX VALUES
FOR THE NINETEEN STUDY AREAS

Formula: 2C + I + R(PDF) = SDI

<table>
<thead>
<tr>
<th>Zone</th>
<th>2C + I + R(PDF) = SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>2(0.75) + 0.50 + 18.25(.0235) = 02.42</td>
</tr>
<tr>
<td>02</td>
<td>2(1.40) + 0.40 + 12.40(.0038) = 03.67</td>
</tr>
<tr>
<td>03</td>
<td>2(5.60) + 5.40 + 26.80(.0600) = 18.81</td>
</tr>
<tr>
<td>04</td>
<td>2(0.70) + 0.00 + 02.90(.0012) = 01.43</td>
</tr>
<tr>
<td>05</td>
<td>2(4.75) + 1.10 + 76.25(.0208) = 26.46</td>
</tr>
<tr>
<td>06</td>
<td>2(2.69) + 3.16 + 39.25(.0833) = 41.24</td>
</tr>
<tr>
<td>07</td>
<td>2(18.5) + 0.00 + 41.50(.0835) = 71.20</td>
</tr>
<tr>
<td>08</td>
<td>2(22.9) + 3.25 + 12.25(.0058) = 49.71</td>
</tr>
<tr>
<td>09</td>
<td>2(21.1) +15.58 + 40.67(1.000) = 98.41</td>
</tr>
<tr>
<td>10</td>
<td>2(3.12) + 4.63 + 67.75(.0884) = 70.76</td>
</tr>
<tr>
<td>11</td>
<td>2(8.50) + 0.40 + 34.00(.0725) = 42.04</td>
</tr>
<tr>
<td>12</td>
<td>2(1.30) + 0.80 + 57.70(.0560) = 35.70</td>
</tr>
<tr>
<td>13</td>
<td>2(11.0) + 9.40 + 63.80(.0395) = 56.60</td>
</tr>
<tr>
<td>14</td>
<td>2(6.30) + 5.50 + 23.30(.0180) = 23.40</td>
</tr>
<tr>
<td>15</td>
<td>2(2.20) + 1.60 + 06.90(.0020) = 06.01</td>
</tr>
<tr>
<td>16</td>
<td>2(11.2) + 6.20 + 05.10(.0000) = 28.60</td>
</tr>
<tr>
<td>17</td>
<td>2(00.0) + 0.50 + 13.20(.0547) = 01.22</td>
</tr>
<tr>
<td>18</td>
<td>2(8.70) + 9.25 + 02.75(.0042) = 26.76</td>
</tr>
<tr>
<td>19</td>
<td>2(15.1) +10.10 + 19.20(.0165) = 43.42</td>
</tr>
</tbody>
</table>

The dependent variable is not explained by the changing value of the independent variable. With this information, cases which have insignificant variations can be ignored.

The dependent variable is only partially explained by the independent variable, unless both variables correlate perfectly. The Pearson product-moment correlation coefficient (R) expresses the degree of fit and varies from +1.0 to -1.0. It is possible, however, to estimate within a given level of confidence. For this study a ninety-five percent (.05) confidence limit was selected. Because the
TABLE 6

THE DENSITY EXCESS FOR THE NINETEEN STUDY ZONES

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>0:80</td>
<td>0.13</td>
<td>11</td>
<td>1:96</td>
<td>1.29</td>
</tr>
<tr>
<td>02</td>
<td>0:27</td>
<td>0.27</td>
<td>12</td>
<td>1:54</td>
<td>0.87</td>
</tr>
<tr>
<td>03</td>
<td>1:23</td>
<td>0.56</td>
<td>13</td>
<td>2:11</td>
<td>1.44</td>
</tr>
<tr>
<td>04</td>
<td>0:67</td>
<td>0.00</td>
<td>14</td>
<td>1:49</td>
<td>0.82</td>
</tr>
<tr>
<td>05</td>
<td>1:38</td>
<td>0.71</td>
<td>15</td>
<td>0:77</td>
<td>0.10</td>
</tr>
<tr>
<td>06</td>
<td>1:94</td>
<td>1.27</td>
<td>16</td>
<td>1:26</td>
<td>0.59</td>
</tr>
<tr>
<td>07</td>
<td>1:36</td>
<td>0.69</td>
<td>17</td>
<td>0:78</td>
<td>0.11</td>
</tr>
<tr>
<td>08</td>
<td>2:87</td>
<td>2.20</td>
<td>18</td>
<td>1:71</td>
<td>1.04</td>
</tr>
<tr>
<td>09</td>
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</table>

Data were not extremely sensitive, a smaller confidence level was not deemed essential. For the Lincoln study, there were eighteen degrees of freedom, and the critical level of acceptance was 0.444. In the evaluation of city size, six degrees of freedom yielded a critical acceptance level of 0.599.

Review of Methodology

The primary objective of this thesis is to develop the techniques of using thermal IR sensing in airborne and satellite heat island studies in order to determine if it is a justifiable alternative to traditional temperature measurement techniques.
The primary measurements used in this study are derived from a point densitometer and digitized to provide a graphic representation in the form of isodensity and trend surface maps. Construction of a mosaic provides an in-depth analysis of the Lincoln CBD. Color slicing displays varied color combinations in response to the complexity of the heat island profile. The use of regression analysis determines the strength of the relationship between land use or city size factors and density renditions. Satellite thermal IR imagery is used to determine if the state of the art is applicable to heat island studies.
CHAPTER IV

THE VALUE OF THERMAL IR IMAGERY TO THE DETECTION OF URBAN HEAT ISLANDS

This chapter synthesizes the previous discussion on the justification of thermal IR sensing, illustrating specific advantages and applications of this technique for the study of selected towns and cities in Nebraska. Urban heat island patterns are presented for each site, and those factors contributing to the respective thermal patterns are assessed.

The initial section discusses Lincoln and emphasizes: 1) the influence of land use types on density values; and 2) the greater specificity and reliability of thermal IR as a temperature measurement technique. This latter contention should be apparent from an analysis of the computer maps. Both ideas are further advanced in the second section which analyzes the Capehart, Bellevue, and Offutt Air Force Base data to emphasize the advantages of thermal IR sensing over traditional temperature measurements. The third section investigates the role of increased city size as a factor in yielding augmented thermal contrasts. The final section gives a brief qualitative assessment of satellite thermal IR imagery as a tool for detecting urban heat island patterns.

Lincoln, Nebraska

The results of automobile traverses clearly indicate that maximum urban-rural thermal contrasts occur during cloudless evenings.
At this time, the urban artificial surfaces generally release stored-up heat to the atmosphere. Conversely, the peripheral areas with more natural surfaces experience long-wave radiational cooling. Because CENGAS thermal IR data of 28 February to 1 March 1975 were imaged during these ideal conditions, maximum density contrasts should be attained.

Mobile automobile traverses which record similar pre-dawn temperature measurements in any city must contend with such inconveniences as automobile interference, and road detours from assigned routes (because of road construction, high-crime neighborhoods, etc.) all of which potentially render any conventional temperature measurements of Lincoln rather suspect.

Figure 7 is a scattergram which depicts the correlation between structural density index values (SDI) and density renditions. The correlation coefficient (R) is .891, suggesting a very strong relationship between these variables. This number is also substantially larger than the .444 desired for statistical validity at the ninety-five percent (.05) confidence level (Glass and Stanley, 1970:524). A standard error of only .273 implies that most of the variation of the density values has been explained by the changing value of the SDI. Therefore a statistically significant relationship exists between SDI and density values.

Thermal IR research conducted for Lincoln in relation to land use-temperature relationships agrees in many respects with the previously discussed traditional measurement studies. Noteworthy mention is made of the striking similarity between these results and those obtained by Chandler in a study of London (Chandler, 1970). Both authors gaged temperatures during the pre-dawn hours and under similar
FIGURE 7

Scattergram of SDI and Density Values

synoptic conditions. The correlation coefficients are almost identical, intimating that these results could be extrapolated to other cities of varying size to evaluate and provide a basis for correcting any undesirable heat emittance.

The two zones which recorded the highest and lowest density values were analyzed to indicate the importance of land use and popula-
tion factors in determining the SDI. Zone 9 registers the highest density recordings and includes within its boundaries the CBD, University of Nebraska, and governmental areas of Lincoln. The aerial extent of waterproofed surfaces noticeably exceeds that area allotted to natural surfaces.

Less than one-fourth of this zone is classified as open space and this primarily includes parkland rimmed by massive concrete structures. More than one-third of this area consists of either a commercial or industrial land use type. This category includes the central "O" Street shopping district, the railroad switchyards, and numerous warehouse and light industrial concerns on the fringe of the CBD. Middle-density homes are also located on the periphery. Zone 9 encompasses the most densely packed buildings and the most heavily populated neighborhoods in Lincoln. The decreased albedo and the increased thermal conductivity of these artificial surfaces account for much of the augmented heat discharge. Hence, it is no surprise that this zone records the highest density rendition in this study.

Zone 4 represents the opposite extreme in its morphology and, as expected, it records the lowest SDI value. Over four-fifths of this peripheral area is composed of parks, including spacious Pioneers Park, and a substantial area of unused land. Two public facilities, the Men's Reformatory and the State Hospital, along the scattered greenery laden residences, represent only minor deviations from this land use type. It is, in fact, the lack of man-made features, a low population, and especially a deficiency of commercial and industrial features, which result in such low density values.
Zones 4 and 9 reveal the opposite extremes in this study. However, all nineteen zones display a strong relationship between the type of land use in an area and the heat output for that area. Information gleaned in this study has corroborated the findings of Clarke and Peterson (1972) in which strong positive correlations were established between SDI values and temperature values. Strong relationships between building density and high temperatures (Duckworth and Sandberg, 1954) are also substantiated.

Areas such as Zones 9 and 10 circumscribe the most densely packed buildings and have the greatest percentage of waterproofed surfaces. Numerous small (four to five story) buildings dot these zones, and they contribute to a low-level absorption of reflected radiation and a consequent increase in air temperatures. These zones are also among the most heavily populated, and this fact might lead one to assume that the contribution of human metabolism and artificially induced heat (i.e., fuel consumption and home heating) are important variables in evaluating heat island patterns. Because the CENGAS study occurred during the winter season when human-produced heat is at a maximum, this contribution is especially noteworthy.

However, a comparison of Zones 5 and 16, for example, still manifests that the type of land use asserts a greater influence on heat discharge than does the number or concentration of people in an area. Notwithstanding that Zone 16 has the lowest recorded population (fifty-five people) in the study, it still has a substantial SDI of 28.60. This can be attributed to the large percentage of commercial and industrial area comprising this zone. Conversely, Zone 5 has in excess of five-thousand people but considerably fewer commercial and industrial establishments within its boundaries. As a result it
records a SDI of only 26.40. The evidence presented here implies that the type of land use, rather than the number of people, is the primary factor in determining heat island magnitude.

Traditional studies employ temperature excess measurements (see Clarke and Peterson, 1972) as the parameter to be regressed with SDI values. As previously explained, the subjectivity used in attaining these measurements renders their scientific accuracy rather doubtful. With thermal IR sensing methods, one can objectively regress obtained density renditions with SDI values, allowing for an analysis of the relationship between these variables. Therefore, the SDI is refined by using an objectively derived technique to further substantiate the relationship between these variables. Information derived from the SDI can be used for the optimum management and control of undesirable heat emittance.

Lincoln CBD
Isodensity Map

The linear Lincoln CBD includes myriad land use types which result in pronounced contrasts in the density renditions as shown by Figures 8 and 9. Flightline 16N, which encompasses the east side of the Lincoln mosaic, contains the most urbanized section of the city. Density renditions here are considerably higher than those values gaged along flightline 15N, the west side of the mosaic. The latter area is dominated by railroad facilities and encircled by open space.

Several conspicuous heat pockets are noted on this map. When major east-west routes such as "O" Street cross this map, the albedo and thermal conductivity of the surface change dramatically, and higher heat values are detected. A second unusual source of heat is located
This positive print of the Lincoln thermal mosaic includes the north to south flightlines 15N and 16N. Note that variations in exposure between prints did not affect density readings on this negative transparency. Drift of the aircraft caused skewing which necessitated the break-up sections of flightline 16N to attain the proper mosaic. Source: CENGAS, 1975
Isodensity Map of Lincoln CBD

Frequency distribution of data point values in each level

<table>
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<th>LEVEL</th>
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<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 9
in the northwest section of the image, where the railroad tracks, switchyards, and control buildings are located. Higher apparent heat discharge is particularly evident when contrasted to the adjacent open space. This can probably be attributed to the abundance of crushed gravel contiguous to the tracks. The Central Post Office is perceptibly warmer, thus this building can be utilized to illustrate the effect that one structure can have on the microclimate of a compact area.

Conspicuously cooler areas include the northwest section which is primarily railroad-owned wasteland. The metal-roofed city-county building records a lower than expected density rendition. This building, like many others in the central city, has artificial surfaces and roofs (i.e., composed of metal, brick and stone) which lower emissivity and, hence, a lower than expected density value is recorded. Researchers should be cognizant of this fact when evaluating similar data.

In several areas the shaded side of buildings record slightly lower density renditions when compared with the sunnier side. Differential shading attributed to varying building heights causes this anomaly. This detailed variation as well as the general occurrence of isolated pockets of warm and cool areas, presented above, are undetected by traditional sensing methods. In addition, despite the complexity and roughness of this surface, thermal IR measurements are always valid because the intensity of radiation is an integration of all points.

Inaccuracies inherent in traditional measurements such as observer error and temporal restrictions render their validity highly questionable. Therefore, the specificity and accuracy of thermal IR sensing as a temperature measurement tool is again emphasized.
Trend Surface Map

The trend surface map of the Lincoln CBD shows a very distinct regional pattern with heat sources being concentrated in the southeast section of the map and decreasing outward from that point (Figure 10). A primary local trend of high temperatures is the area of railroad switchyards while the area immediately to the north represents a local trend of low temperatures.

Analysis indicates that the central-city area is warmest and that heat concentration diminishes as one moves away from this zone. Because the University of Nebraska with its many altered surfaces occupies the fringe of this urban corridor, high heat concentration extends to the northern edge of the map. This contrasts with the Capehart data, for example, in which no such linear concentration of man-made surfaces exists. Note that high heat emittance is concentrated in a north to south direction. This fact reflects the traditional Lincoln city plan which emphasizes building away from the westward situated Salt Creek with its flooding potential.

Lincoln City

Point densitometric analysis of the Lincoln CBD mosaic shows a concentration of heat in the most urbanized section of the city and a reduction of heat away from this central area. However, this mosaic depicts only a small area of this city. Consequently, all of Lincoln was analyzed using the Spatial Data System to ascertain if the results obtained with the mosaic can be extrapolated to include the entire city. Figure 11 is a pre-dawn satellite photograph illustrating the synoptic conditions over the United States on 28 February 1975. The cloudless conditions which existed over Lincoln enabled the exposure of maximum density constrasts.
FIGURE 11

Nimbus Satellite Photograph of Nebraska, 28 February 1975

SOURCE: NOAA, 1977
Resolution: Unknown
Isodensity Map

On the isodensity map of Lincoln (Figure 12) those areas with the highest density values coincide with Zones 7, 8, 9, 10, and 12 which are all located in close proximity to the CBD. Conversely Zones 1, 2, 4, 15 and 16 record the lowest density renditions.

The neighborhood of highest density renditions is the square-shaped area located along the west-central portion of the map. Comprising the heavily industrialized Zone 9, this area also includes Lincoln's foremost east-west thoroughfare, "O" Street, which again is evident as an island of heat. The distribution of high density areas closely coincides with the distribution of commercial enterprises. Gateway Shopping Center, which is contiguous to "O" Street and situated on the urban fringe, assumes a significant role in extending high density renditions to the periphery of Lincoln.

High density recordings are also found to the north of the main business center and in the university-state fairgrounds area. Most of the natural surfaces have been modified; brick, concrete, and stone dominate the area. Other greenery-laden surfaces in the vicinity make the contrast of this area on the map particularly apparent. Other areas of anomalously high density values are the airport (northwest), and the Antelope Park area (central), which includes many medium density homes.

Conspicuously lower density renditions are gaged in the southern one-third of Lincoln, a condition which can be attributed to a plethora of open space and a minimal alteration of the natural surface. Likewise, the eastern periphery and the West Lincoln areas record low density values. West Lincoln is in close proximity to several indus-
trial complexes, but because it is dominated by open space and greenery, lower than expected density values are recorded.

**Trend Surface Map**

Density values for each area are obtained and presented on a trend surface map to smooth out fluctuations and to present an overall representation of the Lincoln heat island as shown in Figure 13. The trend surface map of Lincoln bears a strong resemblance to traditional heat island maps. These maps present a pattern referred to in the literature as the concentric zone model in which the center of the city is warmest and heat distribution decreases away from a central point in a series of concentric rings. The regional trend is west to east toward the newer, peripheral areas where a high percentage of the land remains in a natural state. This result is not surprising when one considers that random fluctuations are smoothed out and that generally the central and peripheral areas record the highest and lowest density values respectively.

**Other Study Sites**

The imagery on which this data is based was produced during cloudless weather conditions which permit the presentation of maximum density contrasts. Figure 14 (a and b) are Nimbus satellite photographs of the synoptic conditions during the mission.

**Capehart Housing Area**

**Isodensity Map**

Figure 15 (a and b) are two thermal images of the Capehart study area. The isodensity map exhibits isolated heat sources which are strongly correlated with land use distribution as indicated in Figure 16.
TREND SURFACE MAP OF LINCOLN

FIGURE 13

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

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SCALE 1:2700

N

FIGURE 13
FIGURE 14
Nimbus Satellite Photographs of Nebraska

Bellevue and contiguous area imagery, 7 February 1975
Source: NOAA, 1977. Resolution Unknown

Bellevue to Fremont Mission, 28 November 1975
Source: NOAA, 1977. Resolution Unknown
FIGURE 15
Thermal IR Imagery of Capehart Housing Area

Source: U.N.O. Remote Sensing Laboratory
Scale 1:2000
Heat concentration is centered in the northeast portion of the map where several man-made structures including a theater, playhouse, youth center, and service station are located. Construction of these features has radically altered the urban surface and, as a result, they are distinct as isolated islands of heat.

Analogous thermal patterns are demonstrated by a large elementary school and a chapel in the southeast section and by a secondary elementary school in the southwest portion of the image. Contiguous and perpendicular to this second school building are the heavily traversed Whiteman and Kennedy Drives. Density renditions along these roads are perceptibly higher than along most other streets reflecting an increase in vehicular traffic. The higher measurements in the north central area represent closely spaced, medium density homes which have more man-made surfaces and less greenery than do the low density homes. In almost every case, the lowest recorded values occur in areas dominated by these spacious low density dwellings.

Trend Surface Map

The Capehart trend surface map indicates three primary regional patterns reflecting the previously discussed heat concentration regions (Figure 17). One area extends outward from the theater complex (northeast) and slopes toward the center of the map. Emanating from the west central section, the second area extends outward from the elementary school and Whiteman Drive. The final area extends from the second elementary school toward the center.

Two local variations of anomalously high heat discharge are detected in the northwest and southwest sections of the map. These surfaces imply that the Capehart heat island is not a monolithic
plateau; rather it consists of several isolated warmer regions surrounded by numerous cooler regions. Furthermore, this trend surface can be directly correlated with the distribution of particular land use types and the alteration of the natural surface in the area. Traditional surveys would not perceive this complex pattern because of generalities inherent in the measurement process.

**Bellevue**

**Isodensity**

This image encompasses the southern one-third and most urbanized section of Bellevue (Figures 18a, 18b and 19). However, low density homes dominate this image and can be detected by lower recorded density renditions found throughout the map. An area of middle density homes is positioned in the southeast section and is detectable by slightly higher renditions.

Located along the north central area, the CBD records substantially higher density values than does the surrounding area. These renditions would be even higher were it not for the many metal and brick surfaces with lower emissivity values. The compactness of this area has occasionally necessitated the measurement of rooftop temperatures which also produces lower than expected values. Lincoln CENGAS data displayed similar problems. Two other aberrant areas of higher values are associated with school buildings which are surrounded by man-made surfaces. Decreased albedo values found along these asphalt surfaces permit a maximum heat discharge.
FIGURE 18

Thermal IR Imagery of Urbanized Bellevue

Source: U.N.O. Remote Sensing Laboratory
Scale 1:2000
Isodensity Map of Urbanized Bellevue

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

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<tr>
<td>LOWEST VALUE</td>
<td>FIGURE 19</td>
<td>HIGHEST VALUE</td>
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Scale 1:2000
Trend Surface Map

The trend surface map presents a complex picture of heat island concentration (Figure 20). An obvious apex of heat concentration is noted in the city-center, and this area is encircled by somewhat cooler sites. The location of lowest values extends from the west central portion toward the northwest edge of the map. Temperatures are highest in the center and lessen in intensity toward the northwest and southeast borders of Bellevue.

An anomalous local heat trend is perceptible in the southeast section of the city where a school and other cultural facilities have radically modified the natural surfaces. The very complex thermal patterns demonstrated on both Bellevue maps are clearly more detailed than those found on traditional heat island maps and demonstrate the influence of land use types on the varied microclimates of this city.

Offutt Air Force Base

Isodensity Map

Offutt Air Force Base data also refute the traditional monolithic heat island pattern as noted by Figures 21 (a and b) and 22. There is a pronounced concentration of high density values in the northeast section of the map. This area corresponds to the Aerospace Museum where the contiguous concrete-dominated surface is markedly different from the surrounding area. Runway surfaces are also distinguished by high density renditions as compared with contiguous grass surfaces.

In both places, artificial surfaces record lower than expected density values due apparently to their lower emissivities. This fact
FIGURE 21

Thermal IR Imagery of Offutt Air Force Base

Source: U.N.O. Remote Sensing Laboratory
Scale 1:2000
might lead one to assume that the true density values were underestimated and that the actual values are somewhat higher. This dilemma in interpretation is one of the primary drawbacks of utilizing thermal IR sensing. The researcher must also be careful not to equate density with heat.

Those sections of the air force base which are laden with greenery record conspicuously lower density values. Building complexes interspersed throughout these areas cause isolated higher density renditions. One noteworthy example of thermal IR's precision is found along the west central portion of the map where two aircraft are preparing for takeoff. The exhaust and heat emitted from these aircraft is reflected by the higher density values measured on the wing and tail area. The results of this analysis exemplify the ability of this technique to detect detailed thermal variations within a minute area.

Trend Surface Map

Trend surface analysis of the air force base demonstrates a regional heat concentration in close proximity to the Aerospace Museum, and a gradual dissipation of heat as one moves away from this point (Figure 23). Lowest values are attained near the center where natural surfaces dominate, and then they gradually rise toward the western edge of the map where artificial surfaces dominate the image.

A decreasing regional trend is experienced from the center of the map, along the runway area, to the southeast edge where there is little alteration of natural surfaces. The entire northernmost portion of the map, the airbase fringe, displays a low-level trend.
FIGURE 23

TREND SURFACE MAP
of
OFFUTT AIR FORCE
BASE

SCALE 1:1600

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

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Mapping Summary

Because the heat island is primarily determined by the type of land use and the number of people in a given area, it is expected that maximum heat emittance should be concentrated in the most urbanized sections of Lincoln; and following this logic, the generalized trend surface map should appear in a concentric pattern. Because the towns other than Lincoln were studied in more detail (greater resolution), unfeasable with traditional sensors, their trend surface patterns are obscured, if not obliterated. What is surprising and, coincidentally, paramount to the justification of this thesis, is the occurrence of many interlaced pockets of warm and cool areas found on the isodensity maps in response to variations in the man-made and natural environment.

Thermal IR sensing can measure every point on the surface in a very brief time; hence, anomalies previously undetected by automobile traverses are manifested by this method and can be used to refute the highly generalized monolithic heat island pattern. This technique is also helpful in pinpointing artificial surfaces because of their respective radiating efficiencies. If for any reason an electrical or other artificial heat source is temporarily discontinued (i.e., a blackout) the use of thermal IR sensing would become an aid in the prompt detection of varied urban heat sources. Despite the disadvantages of this technique (refer to page 17) thermal IR sensing is found to be superior to traditional sensing methods.

Color Slicing

Color slicing divides the urban surface into various color combinations in response to the density values of the respective surface.
Before discussing the specific attributes of color density slicing, note that in this analysis the north and south edges of the respective images (Figures 24, 25, and 26) are eliminated from discussion as their anomalous colors (primarily yellow) are obviously attributed to distortion. The images should be interpreted to mean that when the color is darker, there is seemingly more heat being emitted from the observed point.

Capehart Housing Area

Color slicing of the Capehart imagery demonstrates that many thoroughfares are distinguished by their light blue colors (Figure 24). The most heavily travelled sections of these roads are depicted by increasingly darker shades of blue. Similar color schemes are also established in the northeast corner where the youth center complex is located and along the east central area where a middle density housing complex is evident. The yellow color which rims the elementary school buildings in the southwest section is conspicuous as a heat source area. Throughout these images, those areas laden with greenery are strikingly apparent by their white color.

Color slicing shows a similarity in heat emittance between roads and other man-made features. These surfaces are composed of materials such as concrete and asphalt which record analogous emissivities and possess similar radiating efficiencies. Natural surfaces discharge very meager amounts of heat; so their color scheme differs greatly from those of buildings and roads.
FIGURE 24
Color Slices of Capehart Housing Area

Scale 1:2000
Source: U.N.O. Remote Sensing Laboratory
FIGURE 25

Color Slices of Bellevue

Scale 1:2000

Source: U.N.O. Remote Sensing Laboratory
FIGURE 26
Color Slices of Offutt Air Force Base

Scale 1:2000
Source: U.N.C. Remote Sensing Laboratory
Bellevue

The Bellevue color slices show the street pattern of this city, as denoted by the progressive shades of blue (Figure 25). Increasingly darker colors correspond to the increasing width and utilization of the CBD routes. When one travels away from this area (north center), this pattern becomes increasingly less visible. The CBD itself is clearly marked by varying shades of yellow, while those areas of highest building density appear as purple. Several educational and commercial facilities which emit sizeable quantities of heat are perceptible throughout the slices because of their dark blue to yellow colors.

Bellevue's town boundary is distinct on this map as variations of blue and white within the city change abruptly to an all white color. This change denotes the boundary between predominantly man-made surfaces and natural surfaces. The only exceptions are the railroad contiguous to the city line and several linear features which seem to be power lines. These features appear as light blue lines in the large expanse of white.

Offutt Air Force Base

The color slices present a picture that is materially more complicated than that found in either town. In the upper-slice several features are distinguished by their various shades of blue, including a pronounced residential section of Bellevue that is located along the eastern corner of the map. The runway adjacent to the airbase museum is also blue, but where the active runway begins, there is a drastic change to yellow and purple. These colors reflect a constant amount of heat being discharged by aircraft using this runway. Yellow
Colorslicing also appears in the northwest section of the upper slice (Figure 26) where several building complexes are located. These buildings are in turn encircled by varying shades of white and blue in response to myriad contrasting surfaces present in this compact area. Greenery laden surfaces are situated between the runway and are conspicuous by their white color.

The lower slice (Figure 26) is even more complex. The major runway of the air force base appears distinctly purple and black, reflecting its surface composition and the omni-present heat being released along it by aircraft movement. The parking ramp is yellow; however, that area where the two aircraft are preparing for a mission is purple in response to the heat emission from their warmed-up engines. As noted in an earlier section, this variation (color as related to density) exemplifies the detailed differences in heat discharge that can be detected, further establishing the superiority of thermal IR sensing. Color variations are also detected at the building complex (northwest corner), and this blue to yellow range can be ascribed to thermal variations within the buildings.

The Offutt color slices are similar to those of Capehart and Bellevue in that surfaces with similar emissivity and composition display similar colors. However, the complexity and range of the colors is far greater in the Offutt slices. Heat-laden runways, middle density homes, and numerous large and small building complexes, all in close proximity to each other, account for this difference.

Color Slicing Summary

The color slices of Capehart, Bellevue and Offutt Air Force Base illustrate the similarity in amounts of heat emission (as shown by the
colors) between man-made surfaces. The darkest colors are usually associated with commercial and industrial facilities. Traffic density of particular roadways is reflected by the varying shades of blue, while areas dominated by natural surfaces are conspicuous by their bright white color. Hence, a division of these colors into white and non-white might best represent an overall panorama of the respective heat islands. Interlaced regions of warm and cool areas, which can be contoured by color slicing are easily detected. Thermal IR color slicing is a technique which can display a very sharp delineation of land use types.

These color slices can vividly illustrate those areas where, for example, further urbanization can have severe ramifications with respect to human discomfort and work efficiency. In addition, pivotal areas can be earmarked for the planting of urban greenery which is needed to ameliorate undesirable heat emission. Because thermal IR sensing measures every point on the surface within the limits of the resolution for the particular study, even the smallest heat source is presented on the slice.

City Size

A densitometric analysis of six towns and an urbanized section of Omaha are accomplished to determine the variation in city size in altering the range of density values in the study area. This technique
can potentially determine the future magnitudes of heat islands and, therefore, aid in planning decisions aimed at predicting and minimizing undesirable heat emittance.

All the sites analyzed in this city size study are taken from the Bellevue to Fremont airborne mission (refer to page 38). The range of density values for each town in terms of diffuse transmission density is shown in Table 7. The ordering of these sites is determined by their location along a flightline.

### TABLE 7

DENSITY RANGES FOR TOWNS ALONG THE BELLEVUE TO FREMONT FLIGHTLINE

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<th>Population</th>
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<th>Difference in Range</th>
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<tr>
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<td>004,731</td>
<td>0.10-1.00</td>
<td>0.90</td>
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<tr>
<td>Omaha</td>
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<td>0.20-2.40</td>
<td>2.20</td>
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<tr>
<td>Boys Town</td>
<td>000,989</td>
<td>0.20-0.70</td>
<td>0.50</td>
</tr>
<tr>
<td>Elkhorn</td>
<td>001,184</td>
<td>0.20-0.95</td>
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<tr>
<td>Waterloo</td>
<td>000,455</td>
<td>0.10-0.40</td>
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<tr>
<td>Valley</td>
<td>001,595</td>
<td>0.15-0.85</td>
<td>0.70</td>
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</table>
The six towns range in size from 455 to 7840 people and are considered suburban residential communities of Omaha (355,000 residents). They possess a similar morphology as their land use consists primarily of low and medium density residences. City-size - density-range relationships of these towns are also compared with an urbanized section of Omaha in an attempt to further corroborate the previous findings.

Figure 27 is a scattergram of the regression equation between city size, as indicated by population, and the range of density values. The correlation coefficient is .830, which is considerably larger than the .599 needed for statistical acceptance at the ninety-five percent (.05) confidence level (Glass and Stanley, 1970:525). Much of the difference in the dependent variable, density values, is explained because the standard error is only .400.

When Omaha is discounted from analysis and only the six towns of relatively comparable size are regressed (Figure 28) the correlation coefficient is increased to .944 (.661 is needed for acceptance) and the standard error is decreased to .151. The results compare favorably with Oke's (1972) contentions in a similar traditional measurement study in Canada. These regression equations verify the positive relationship between increased city size and increased density ranges. This scattergram can be extrapolated to predict the relationship between these factors for other urban areas.

The Omaha section of the flightline is also used to further illustrate inadequacies of conventional measurement techniques (Figure 29). A considerable variety of land use types is discernable on this image and, as expected, much of the surface in the urbanized center of the map is radically altered. The concrete and asphalt dominated
FIGURE 27
Scattergram of City Size and Density Values
Including Omaha
FIGURE 28
Scattergram of City Size and Density Values
Excluding Omaha
Figure 29
Isodensity Map of Omaha

FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN EACH LEVEL

<table>
<thead>
<tr>
<th>LEVEL</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

SYMBOLS

Low

High

Scale: 1,2000
surfaces emitted much heat while at the same time, the more rural surfaces, located on the northern and southern edges of the map, produced primarily radiative cooling. These marked contrasts yield many interlaced nodes of warm and cool areas.

These variations in the density values found in Omaha are not readily apparent in the other study sites. However, augmented density ranges in conjunction with the increased size of the respective towns can be attributed to the existence of scattered commercial and industrial facilities. Consequently city size data fulfill the objective of application stated on page 3. The ramifications of increased thermal contrasts that are associated with parallel increases in urbanization, are shown to lead to large-scale inconvenience and human discomfort and should be considered in future planning decisions.

Satellite Imagery

Figures 30 and 31 illustrate that satellite thermal IR sensing can easily discern regional heat concentrations. These October 1975 GOES images indicate that water is warmer (lighter) than land as shown by the higher heat emittance of the Great Lakes. The southern or warm half of the country is clearly delineated by its heat discharge. The moderating influence of the ocean is evident by the northward advance of the warm tongue along the east coast of the United States. However, urban thermal patterns of any scale are not distinguished on this image.

Satellite thermal IR imagery can also present a more detailed picture of ground temperatures for the sub-region of interest. Figures 32 and 33 are enlargements of a large portion of the American corn and
FIGURE 30
Land Temperatures of the United States, 10 October 1976

Source: NOAA, 1977
FIGURE 31
Land Temperatures of the Midwest, 20 October 1976

Source: NOAA, 1977
FIGURE 32

Land Temperatures of the Midwest, 2 October 1975

Source: NOAA, 1977
FIGURE 33

Land Temperatures of the Midwest, 20 August 1976

Source: NOAA, 1977
wheat belts taken from NOAA-3 satellites. In Figure 32, where dark areas represent high heat emittance, complex variations in ground temperatures are visible. However, it is difficult to distinguish the urban environment (or intra-urban thermal patterns) from non-urban areas because of the extremely small scale.

Figure 33 shows that the larger cities of the central United States (i.e., Chicago, Milwaukee, Saint Louis, and Indianapolis) are discernable by their high radiant emission and can be identified by their size. However, intra-urban thermal patterns are still imperceptible, again because of scale, and one can not discern, for example, which sections of Chicago are warmest.

Urban areas are highlighted on the final NOAA-3 image (Figure 34) by their higher thermal density readings. Chicago, as expected, is most evident as noted by the largest black mark in the image. The darker colors of Milwaukee and Saint Louis distinguish these cities from the surrounding rural landscape, but heat island patterns are still imperceptible on this image.

Satellite imagery presented in this chapter has seemingly demonstrated the ability to discriminate both land temperatures and urban areas by their high thermal discharge. However, this thesis is concerned with the capability of this technique to detect intra-urban heat island patterns. Carlson (1978) was cited (see page 33-34) as indicating that at present, satellite imagery is not feasible. The author concurs with Carlson as the imagery presented in this paper has failed to indicate even a general monolithic heat island model, much less one in which isolated pockets of warm and cool nodes are
FIGURE 34
Land Temperatures of the Midwest, 7 August 1975

Source: NOAA, 1977
evident, Satellite thermal IR imagery is found to be infeasible as a technique for the study of intra-urban thermal patterns.

As noted in an earlier chapter, the many restrictions of this technique are manifested in an evaluation of these images. The distance from target and the attendant problems of resolution severely limit the competency of the respective satellites to discern the intra-urban thermal patterns. Emissivities are often noticeably altered which renders a comparative analysis of temperature profiles rather tenuous. However, many of these exposure problems should be negated in the near future as increasing amounts of time and money are being appropriated to this end.
CHAPTER V

CONCLUSIONS

The data presented in this thesis have demonstrated that thermal IR sensing is a scientifically feasible and accurate temperature measurement technique. Several illustrations of its application also confirm that thermal IR sensing is superior to traditional temperature recorders. Justification of this paper is supported by comparing both traditional and thermal IR measuring devices.

Conventional temperature sensors have their primary drawback in the overall intrinsic generalizations that must be assumed in all such measurements. These dilemmas include the fact that many thermometric recorders must be positioned to obtain an accurate measurement of any sizeable study area. The duration of automobile traverses requires that recordings must be interpolated to a common time, which introduces inadvertent subjectivity. Time factors also initiate the possibility of varied synoptic conditions which can nullify a comparative analysis of points along that traverse. Automobile interference and solar changes can also seriously alter recording schedules.

Frequently, more than one person is involved in the handling of the instruments and in the analyzing of the data for a particular study. Because of inadvertent hand movement and because direct interpretation of the data by human beings is required, results are often unintentionally altered. Another related problem is the inconsistent shielding of instruments from air and water movement, which limits
objective analysis. Perhaps the most overlooked dilemma is that comparative evaluations are necessarily tenuous because all traditional studies encounter these problems.

Conversely, thermal IR sensing is a non-contact method where the average, and thereby the more accurate, measurement of temperature for a given area is possible. The degree of refinement desired is easily controlled by the number of points selected for measurement. Since temperatures are gaged remotely, the complexities and roughness of the urban surface do not alter the recordings. The time savings afforded by thermal IR studies also eliminate the automobile traverse problems presented in the preceding paragraphs.

Thermal IR sensing is not without its disadvantages. The low emissivities of some man-made surfaces often cause the true radiating efficiency of such a surface to be underestimated. Natural surfaces (i.e., vegetation and grass) which approach blackbody emissivity, can then appear as anomalous hot spots on the imagery. There is also the problem of equating heat emission with density renditions which can result in an inaccurate evaluation of the urban surface. The emission and absorption of atmospheric components such as clouds and water vapor can also skew the actual density values on an image.

However, the advantages of this technique essentially outweigh any disadvantages discussed in this study. Inaccuracies ascribed to instrument inconsistencies and human subjectivity are virtually removed. The principal atmospheric disadvantages of signal attenuation are minimized by exposing in the 8-12 micron window. Finally, the accuracy of this technique in depicting a more complex pattern of isolated warm and cool pockets, rather than a monolithic urban plateau,
renders thermal IR sensing a superior temperature measurement technique.

The point densitometer is the primary quantitative instrument utilized to demonstrate thermal IR's application to real world situations. Densitometers are easy to manipulate, and, with proper calibration, objectivity of the results is virtually assured. The Spatial Data System is an alternative to the densitometer, and it provides the obvious advantage of increased efficiency.

Computer isodensity and trend surface maps use digitized density data to illustrate the complexity of this temperature sensor. The structural density index (SDI) regresses land use and density values to illustrate the strong positive relationship that exists between these two variables. Demonstration of the accuracy and latitude of these instruments in determining temperature values is essential to this study.

The SDI results for Lincoln corroborated previous research (Clarke and Peterson, 1972) on the positive relationship between these two variables. Areas dominated by artificial surfaces, i.e., commercial and industrial areas, were found to emit the greatest radiation values. These surfaces were most often located in close proximity to the CBD, but they were also represented by isolated warm and cool pockets interspersed throughout the city. Because these were objectively derived results, the land use - temperature relationship is further strengthened.

The mosaic was found to be a microcosm of the entire city as heat discharge varied in response to the changing surface. Several surfaces of high heat emittance were responsible for extending the urban heat concentration to selected areas of the urban fringe.
However, since sampling methods serve the function of smoothing out anomalies, the concentric pattern of heat distribution was still expected.

The smaller areas of Capehart, Bellevue, and Offutt Air Force Base were computer analyzed to ascertain if their heat island panoramas also dispute the monolithic pattern. The Capehart housing area clearly demonstrates isolated heat sources in response to buildings and roadways. Bellevue exhibits a similar pattern, but it possesses a CBD conspicuous by its high heat renditions.

Offutt Air Force Base is more complex than Capehart and Bellevue with its many isolated cultural features interspersed among greenery laden surfaces. All three sites reveal an intricate thermal pattern of warm and cool areas distinctly similar to the larger city of Lincoln. This situation further illustrates the greater precision of thermal IR sensing.

Color slicing enhances the similarities in heat emittance between various man-made surfaces. The overall picture indicates increasingly darker colors in response to increasing building density and artificial surfaces. Areas laden with natural surfaces are distinguished by their white colors. The advantages of color slicing lie in its ability to highlight vividly those areas of undesirable heat emission and to indicate those neighborhoods where urban greenery should be introduced to ameliorate disagreeable conditions. This technique affords yet another example where thermal IR sensing is more accurate than traditional temperature measurements.

The analysis of satellite thermal IR imagery indicates that this technique has the potential, but not the present capability, to discern
intra-urban heat island patterns. More research is needed on improving satellite technology before this technique can provide the large-scale benefits currently demonstrated in low-level airborne studies. The major shortcomings concern the distance from target, poor resolution, and a lowered emissivity. However, current research should resolve most of the attendant problems in the near future.

Pease et al. (1976) and other climatologists have begun to apply the various techniques of thermal IR sensing to heat island studies. A salient feature of this research is its all-encompassing nature which combines many thermal IR techniques to justify its scientific validity. In time, scientific advancements will make this technique more accurate and more economical which will increase the feasibility of satellite thermal IR imagery.

Research presented in this paper also fills a void in the urban climatic literature of the Great Plains Region. Suggestions for future research include the use of thermal IR sensing to depict urban heat island patterns in tropical or arctic cities. Many of these areas possess a delicate and unstable environment, and the alleviation of undesirable thermal anomalies (warm or cold) might yield results that are potentially even more beneficial than those results currently gleaned from western cities. Future research should also attempt to refine calibrated scanners to augment the capabilities of this technique.

The potential value of this technique as a forecaster of possible micro- and meso-climatic trends has been illustrated. Comparison of thermal images, even over a brief time period, can reveal the effects
of increased urbanization and its undesirable side-effects. Based on these images, the estimation of future urban contributions to human discomfort should be possible. As the world is becoming increasingly urbanized, the greater our knowledge of the nature of urban climatic effects, the greater will be our ability to develop and choose among viable alternatives for the construction and use of cities.
APPENDIX

Sample SYMAP Program

job cards

//RBLOCK JOB (GEOGAA692411,1795), SYMAP, MSGLEVEL=1, PRTY=2, CLASS=D
//*JOBPARM K=0
//KJL EXEC SYMAP, TIME=2
//SYMAP, SYMAP DD *

A-OUTLINE

Outline card define borders of the map. The first card which is the upper left hand border is repeated. The Y coordinate is punched in columns 11-20 and the X coordinate in columns 21-30.

B-DATA POINTS

The data points are the "X,Y" coordinates of all measured density values. One card is allotted for each value. The punched columns are the same as the A-OUTLINE cards.

E-VALUES

These are the values at each of the coordinate points punched in columns 11-20.

F-MAP

These cards instruct the map what the print and the specific electives desired.

Card 1---Title of Map, i.e. Trend Surface Map of Bellevue
Card 2---Authors Name
Card 3---Blank Card
Card 4---Indicates map size. The number one (1) is punched in column 5 and the dimensions are punched in columns 11-20 and 21-30 respectively.
Card 5---Indicates class intervals desired. The number three (3) is punched in column 5 and the interval in columns 11-20.
Card 6---Indicates minimum value in study. The number four (4) is punched in column 5 and the value in columns 11-20.
Card 7---Indicates maximum value in study. The number five (5) is punched in column 5 and the value in columns 11-20.
Card 8---is used if trend surface map is desired. The elective 38 is punched in columns 4-5 and the number of polynomials desired is punched in column 11.

SPSS COMPUTER PROGRAM

The use of an SPSS computer program allowed for the determination of a regression analysis. SPSS (Statistical Package for the Social Science) uses prepared packages to describe each variable in this study. SPSS has the advantage of being simple, easy to learn, and does not require much knowledge about the computer. The following SPSS program was utilized to determine the relationship between SDI and density values in Lincoln:

```
//RBLOCK JOB (GEOGAA692400), SPSS, PRTY=0, CLASS=D
/*/JOBPARM BIB=L901
// SPSS EXEC SPSS, TIME=(2,0)
// SYSIN DD*

column
16

RUN NAME SCATTERGRAM
FILE NAME RON BLOCK
DATA LIST FIXED/1 SDI 1-5, DNST 6-10
INPUT MEDIUM CARD
N OF CASES 19
VAR LABELS SDI, STRUCTURAL DENSITY INDEX/
STATISTICS DNST, DENSITY VALUES
SCATTERGRAM DNST with SDI
OPTIONS ALL
STATISTICS ALL
READ INPUT DATA data
FINISH /*
```
BIBLIOGRAPHY


Periodicals


Conference Papers, Government Publications and Other Sources


