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**THERMAL SIGNATURES OF URBAN LAND COVER TYPES: HIGH-RESOLUTION
THERMAL INFRARED REMOTE SENSING OF URBAN HEAT ISLAND
IN HUNTSVILLE,AL.**

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Introduction

The main objective of this research is to apply airborne high-resolution thermal infrared imagery for urban heat island studies, using Huntsville, Al., a medium-sized American city, as the study area. The occurrence of urban heat islands represents human-induced urban/rural contrast, which is caused by deforestation and the replacement of the land surface by non-evaporating and non-porous materials such as asphalt and concrete. The result is reduced evapotranspiration and more rapid runoff of rain water (Carlson 1986, Kim 1992). The urban landscape forms a canopy acting as a transitional zone between the atmosphere and the land surface. The composition and structure of this canopy have a significant impact on the thermal behavior of the urban environment (Goward, 1981).

Research on the trends of surface temperature at rapidly growing urban sites in the United States during the last 30 to 50 years suggests that significant urban heat island effects have caused the temperatures at these sites to rise by 1 to 2 °C. (Cayan and Douglas 1984, Karl et al., 1988). Urban heat islands have caused changes in urban precipitation and temperature that are at least similar to, if not greater than, those predicted to develop over the next 100 years by global change models (Changnon, 1992).

Satellite remote sensing, particularly NOAA AVHRR thermal data, has been used in the study of urban heat islands (e.g., Lee 1993, Matson et al. 1978, Brest 1987, Gallo et al. 1993, Roth et al. 1989). Because of the low spatial resolution (1.1 km at nadir) of the AVHRR data, these studies can only examine and map the phenomenon at the macro-level.

The present research provides the rare opportunity to utilize 5-metre thermal infrared data acquired from an airplane to characterize more accurately the thermal responses of different land cover types in the urban landscape as input to urban heat island studies.

Data Acquisition and Processing

The thermal infrared data were acquired as Mission M424 over the greater Huntsville, Alabama area, on September 7, 1994, a clear day with less than 5 per cent of cloud cover in the sky, using the Advanced Thermal and Land Applications Sensor (ATLAS) sensor system on board a NASA Stennis LearJet. The ATLAS is a 15-channel imaging system which incorporates the bandwidth of the Landsat Thematic Mapper with additional bands in the middle reflective infrared and thermal infrared range (Table 1). All 15-channel data were acquired on the same date at two different scales: 10-metre and 5-metre spatial resolutions. To optimize the detection of warming and cooling of urban land surfaces, the image data were planned to be acquired around solar noon (noon-1:00 p.m.) and 2-3 hours after sunset. In all, starting from 11:00 a.m. local time, nine daytime flight lines were flown from an altitude of 5,000 metres to image at 10-metre resolution, and six daytime flight lines were flown from an altitude of 2,500 metres to image at 5-metre resolution. All these flight lines were repeated at night beginning at 8:30 p.m. Central Time. Color infrared aerial photography was also acquired simultaneously using a Zeiss aerial camera (with 152 mm focal length) during the daytime flights only. Ground data collection, including measurement of surface temperatures at selected sites throughout the city and the concurrent launches of radiosonde were also carried out at the time of overflight. In addition, meteorological station data were obtained from the Army at Redstone Arsenal and at Marshall Space Flight Center during overflights. Portable Ground Atmospheric Measurement System (PGAMS) was also used to collect data for atmospheric correction. Altogether over 10 gb of digital image data were obtained by the flight mission. Despite some bad data in channels 7, 8 and 9 (the mid-infrared channels) and some smears in channel 3, the overall quality of these digital data, particularly the thermal infrared data of channels 10 to 15, was judged to be very good. The CIR photography is excellent in quality, and, because of its superior spatial resolution, provides "ground truth" information against which the digital image data can be checked.

For this particular research, the focus has been on the six thermal infrared bands (Channels 10 to 15, in the spectral range from 8.20 um to 12.2 um) These data have recorded long wave radiation emitted by both

the natural and artificial surfaces in the city of Huntsville. The original image data recorded the radiation as digital number (DN) in 8-bit format with integer values ranging from 0 to 255. Before these image data can be used, they have to be (1) corrected for the attenuation effect of transmitting through the atmosphere (i.e., atmospheric corrections), and (2) calibrated to produce accurate temperature measurements. Atmospheric correction is achieved by applying the MODTRAN program developed by the United States Air Force Geophysics Laboratory, which estimates atmospheric transmittance and radiance for a given atmospheric path at moderate spectral resolution over an operational wavelength region of from 0.25 to 28.5 μm (Berk et al. 1989). The input data to the program for the atmospheric correction are the radiosonde data of atmospheric profiles during the ATLAS overflights. Temperature calibration of the ATLAS sensor for each channel is achieved by using onboard low and high temperature blackbodies which are referenced at the beginning and end of each scan line. With a knowledge of the emittance value for the blackbodies, Planck's equation can be used to calculate the ATLAS reference blackbody radiance for each channel of the sensor system. By combining the outputs of the MODTRAN atmospheric correction program with the high and low blackbodies temperature calibration of the ATLAS sensor system, the Earth Resources Laboratory Applications Software (ELAS) module TRADE converted the 8-bit DN of each pixel of the image data into 32-bit radiance in units of $\text{W cm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (Graham et al., 1986, Luvall et al. 1990, Anderson, 1992). In this paper, to provide a better appreciation of the thermal characteristics of the land cover type, radiance is converted into irradiance, or radiant flux density incident on a surface in W m^{-2} (Monteith, 1973).

This research will make use of the high-resolution 5-metre ATLAS data only because the complexity of human activities in the urban environment requires the highest possible spatial resolution for an accurate characterization of the urban land cover's thermal responses. In view of the need to produce a false color composite image and to compute the normalized difference vegetation index (NDVI), four channels of data (# 2, 3, 6 and 13) were extracted from the five flight lines acquired in the daytime (Table 1), and one channel (#13) from the corresponding five flight lines acquired at night.

Channel 13 (9.60-10.2 μm) is the thermal band of choice mainly because after the atmospheric correction and temperature calibration procedures, Channel 13 data exhibit the best noise-equivalent temperature change (NEDT) of 0.25 $^{\circ}\text{C}$ (i.e., the temperature change across the target that would produce a signal-to-noise ratio of unity in the detector output). According to Wien's Law, the surface temperatures recordable within the waveband limits of Channel 13 are from 284 to 301 K. In other words, the waveband limits of Channel 13 display the maximum energy per unit wavelength of terrestrial radiation. Image data from the other three channels: Channel 2 (0.52-0.60 μm), the green band, Channel 3 (0.60-0.63 μm) the red band, and Channel 6 (0.76-0.90 μm), the reflected infrared band, when displayed through the appropriate blue, green, and red guns of a TV monitor as overlays, will produce a false color composite image (simulating the color infrared) which emphasizes vegetation vigor. When combined with the thermal infrared red band (channel 13) data, the false color composite image will pinpoint hot and cool objects distinctly. As for the night time imagery, images can be recorded clearly only in the six thermal bands. Channel 13 is the band of choice for the night image for comparison with its counterpart in day time. By extracting a smaller number of channels from the original 15-channel image data, the storage capacity requirement has been greatly reduced. However, each 4-channel flight line is about 125 mb data, and the single channel flight line is 25 mb. In short, the volume of image data to be dealt with in this research is large, and only a computer workstation such as Silicon Graphics equipped with optical drives and a large hard-drive capacity can process these digital image data efficiently.

Methodology

In order to make the best use of the high-resolution thermal infrared data, the characteristics of the thermal signatures of each land cover type in the city of Huntsville will be studied. With the aid of the ELAS image processing software running on the Silicon Graphics workstation, the daytime and night-time images of the city are displayed simultaneously. A key of land cover type is developed. From the displayed

images, polygons of homogeneous land cover types are manually delineated from both the daytime and night-time images. These polygons will be analyzed later for their mean radiance values and standard deviations.

Because urban heat island is related to the reduction of evapotranspiration from surface vegetation cover, it is useful to know the relationship between surface vegetation cover and water availability. Recent research has shown that normalized difference vegetation index (NDVI) is a good indicator of surface radiant temperature (Niemani and Running 1989, Gillies and Carlson, 1995). NDVI for the city of Huntsville is therefore computed from the daytime image data using the following formula:

$$\text{NDVI} = (\text{ch6} - \text{ch3}) / (\text{ch6} + \text{ch3})$$

where ch3 is the red band and ch6 is the reflected infrared band of the image data. The NDVI are computed for each of the land cover polygons extracted from the daytime images.

Results of Analysis

(1) Day and Night Contrasts in Irradiance

A total of 351 pairs of polygons covering the city of Huntsville were extracted from six flight lines for 10 broad classes of land cover. The five major land cover types are: residential, agricultural, vegetation, services, and commercial. The fact that agricultural and vegetation feature so prominently indicates their intermingling with services and residential uses in the city. In comparing the day-time irradiance of these 10 broad classes of land cover, commercial, industrial and service uses of the land exhibit the highest irradiance (68-70 W m⁻²) while water, vegetation, and agriculture (in that order) show the lowest (55-58 W m⁻²). Residential uses occupy an intermediate position in irradiance (from 60-70 W m⁻²) because they are composed of buildings and tree cover in varying degrees of mixture. At night, commercial, services, and industrial land cover types cool down rapidly to very similar irradiance (45-46 W m⁻²). On the other hand, water, vegetation, and agricultural land cover types show relatively high irradiance at night (43-52 W m⁻²). Water stands out alone as the warmest land cover while agriculture is the coolest at night. All the 10 categories of land cover are cooler at night than during the day. Residential uses, which are again intermediate in position in irradiance at night (44-46 W m⁻²) show much less variation than that during the day.

(2) Relationships between NDVI and Irradiance of Land Cover Types

The value of NDVI varies from -1 to 1 indicating the amount of vegetation (biomass) that is found in the polygon. In this research, the relationship between surface temperature of the land cover type (as represented by irradiance) and the amount of vegetation (as represented by NDVI) is investigated. Very strong negative correlation exists between NDVI and the daytime irradiance of all broad land cover classes with the exception of transportation, commercial, and industrial uses of the land. NDVI is positively correlated with the irradiance of water during the day, but negatively at night. The highest negative correlation during the day is with the irradiance of transitional or vacant (-0.94), residential (-0.86), agricultural (-0.84), and vegetation (-0.74) land. At night, NDVI is only strongly and negatively correlated with the irradiance of recreation land (-0.91). The implication is that higher vegetation amount in agricultural, residential, and vacant land can bring down the surface temperatures in that land cover type. In other words, residential, agricultural, vegetation, and some vacant/transitional land uses in the city of Huntsville are conducive to lower daytime surface temperatures.

The very strong relationship between NDVI and residential and agricultural uses prompts the author to perform a linear regression analysis. For the relationship between NDVI and residential uses, the adjusted R square value is 0.73 based on 68 polygons. The linear model developed takes the following form:

$$Y_{ire} = 66.87420123 - 22.30358429 * (X_{ndvi})$$

where Y_{ire} and X_{ndvi} are irradiance and NDVI for residential land cover respectively. Similarly, for agricultural uses, the adjusted R square value is 0.70 based on 64 polygons. The linear regression equation is:

$$Y_{iag} = 62.87217884 - 13.91271856 * (X_{ndvi})$$

where Y_{iag} and X_{ndvi} are irradiance and NDVI for agricultural land cover type respectively. By using these equations, the irradiance of residential and agricultural uses can be predicted based on NDVI.

Conclusions

High-resolution thermal infrared image data acquired from the ATLAS sensor system after correction for atmospheric transmittance and path radiance followed by blackbodies temperature calibration produce radiance (or surface temperature) values in 32-bit accuracy for the study of the urban heat island effect. Thermal signatures of different land cover types in the city for day and night help to shed light on their roles in contributing to the urban heat island phenomenon. A study of the relationship between NDVI and the irradiance of each category of land cover reveals the importance of vacant, residential, agricultural, and vegetation land cover types in contributing towards lowering their surface temperatures by virtue of their association with biomass. Because of the intermingling of agricultural and vegetation land cover with commercial and services land cover inside the city, enhanced further by the topographic effect in the east, favorable conditions exist in Huntsville for the development of pockets of day-night temperature differences either between the city center and its rural periphery or between contrasting land cover types inside the city.

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TABLE 1: ATLAS SYSTEM SPECIFICATIONS

Channel No.	Band Width Limits (um)	NER mW/cm² um	NEDT °C	MTF @ 2 mrad	Cooling
1	0.45-0.52	<0.008	N/A	0.5	Ambient
2	0.52-0.60	<0.004	N/A	0.5	Ambient
3	0.60-0.63	<0.006	N/A	0.5	Ambient
4	0.63-0.69	<0.004	N/A	0.5	Ambient
5	0.69-0.76	<0.004	N/A	0.5	Ambient
6	0.76-0.90	<0.005	N/A	0.5	Ambient
7	1.55-1.75	<0.05	N/A	0.5	77 °K
8	2.08-2.35	<0.05	N/A	0.5	77 °K
9	3.35-4.20	N/A	<0.3	0.5	77 °K
10	8.20-8.60	N/A	<0.2	0.5	77 °K
11	8.60-9.00	N/A	<0.2	0.5	77 °K
12	9.00-9.40	N/A	<0.2	0.5	77 °K
13	9.60-10.2	N/A	<0.2	0.5	77 °K
14	10.2-11.2	N/A	<0.2	0.5	77 °K
15	11.2-12.2	N/A	<0.3	0.5	77 °K

