Remote Sensing Imagery in Urban Energy Program Assessment

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Certain factors that affect urban climate, and hence urban energy use, are much easier to assess using remotely sensed imagery than through traditional ground-level analysis. Examples include surface albedo and percent vegetation cover which can influence the formation of urban heat islands. In each case, accurate, area-wide assessment is essential not only to gauge a city's overall condition and to target particular areas for improvement, but to judge results of modification programs at later stages. The same data can be used in computer simulations of heat islands. Imagery can be acquired from standard government satellite data archives, or on a custom basis using specially equipped aircraft.

This paper demonstrates the comprehensive mapping of accurate albedo and relative tree density across urban areas, using Sacramento and Fresno, California, as sample sites. A combination of multispectral scanning techniques, aerial photography interpretation and the use of a geographic information system (GIS) are utilized to assess the factors contributing to urban heat island formation. The work reported is part of a more comprehensive project in mapping and assessing the urban fabric as it affects energy use. Results will yield excellent and easily understandable maps for use in urban planning and urban policy decision making.

Introduction

The summertime urban heat island (considered here in isolation from its cold-weather counterpart) is a well documented phenomenon. Summer temperature in urban areas often rises several degrees above the background temperature of the surrounding rural region. Causes include the paucity of urban vegetation, effective urban albedos (broad-spectrum reflectivities) that are lower than adjacent rural albedos, the heat exchange properties of urban surfaces combined with the angular geometry of the urban landscape, and waste heat from human activities (cf. Garbesi et al. 1989).

The net effect is that urban regions experience a significantly warmer summer climate overall, and consequently face a larger burden of cooling degree days than would otherwise be the case. Since the urban-rural air temperature difference typically reaches its maximum in the late afternoon and evening, the additional load (that due solely to the heat island temperature differential) coincides with daily peak electric utility loads and contributes significantly to the magnitude of the extreme peak electric loads that define required generating and transmission capacities.

Peak demands are typically met with the least efficient of available generating technologies, which tends to compound the overall energy cost. Akbari (et al. 1990) have estimated the nationwide U.S. dollar cost of peak energy used simply to counteract urban heat island temperature effects at $1 million per hour. That figure does not include the cost of cascade effects such as enhanced smog formation with attendant health and structural damage, or simple human discomfort and stress and its influence on retail activity, worker productivity, civil unrest and psychological and physical health. These costs are avoidable. A clear need for mitigation measures exists.

Several of the mitigation strategies available are simple and low in cost. Examples include substituting light colored (high albedo) surfaces for darker ones, and increasing urban vegetation. However, summertime urban heat islands tend to be patchwork rather than monolithic (Pease et al. 1976). A park may serve to cool its neighborhood, or a railroad switching yard or a particular commercial district might heat its surrounds (Honjo and Takakura 1986). One residential neighborhood might benefit from a particular mitigation strategy far more than another.

Thus while blindly encouraging the use of light-colored paints and roofs and the planting of trees will certainly be beneficial, much more can be done if the urban planner can analyze and respond to the actual pattern of factors within a particular city that foster its individual urban heat island. Once mitigation strategies have been implemented, the planner also needs to assess progress and effectiveness. Those are the needs the present study seeks to address.

Remote sensing in the form of aerial photography has been a standard tool of urban management for decades. Today the advent of both visible and infrared digital imagery allows accurate, quantitative analysis of albedo, vegetative cover and health, and urban surface temperatures at a single moment in time across an entire urban region. For an overview and history of the use of remote sensing in urban heat island studies, see Orvis and Akbari 1992.

Previous studies (e.g. Carlson 1980; Goward et al. 1985; Brest 1987; Henry et al. 1989; Lewis and Carlson 1989; Roth et al. 1989) have for the most part been qualitative in nature and designed to increase understanding of the heat island phenomenon, rather than to aid urban planners. This paper demonstrates techniques used in a pilot study that combines digital imagery of the cities of Fresno and Sacramento, California, with conventional aerial photography to create accurate, regional maps of albedo, tree cover and noon summertime surface temperature. These and maps of several other factors have been co-registered as layers in a raster geographic information system (GIS) to allow detailed analysis.

The cities of Fresno and Sacramento are both located in California's large Central Valley. They were selected for study because of the hot, dry summer climate, because of previous and ongoing studies in the case of Sacramento, and because both are located in a broad agricultural plain. The intent was to select relatively simple cases to facilitate meaningful analysis of the contributions of observable factors to heating or cooling at neighborhood scales, either in this or subsequent studies.

Data

This study has made an effort to use materials and tools throughout that can be acquired with only moderate investment (on the order of $20,000 to $50,000 initially, less if equipment is at hand; prices are decreasing). Most city governments will already have in hand aerial photographs with better detail than those used herein. The study's digital imagery was acquired from specialized government high-altitude aircraft missions, but the sensor was designed to simulate standard satellite data obtainable from government archives (costs range from several hundred to a few thousand dollars, depending on areal extent and the data source). Certain private companies now offer at competitive rates similar imagery obtained on a custom basis using their aircraft, or they will sell the imaging systems themselves. Aircraft-based imagery offers more detail than satellite imagery, and can of course be acquired at a time and date of a city's choosing.

A typical remote sensor used to produce multispectral digital imagery is analogous to a very slow but accurate and multi-talented television camera. Light enters through a focusing system and falls on a set of electronic sensors that record information about a tiny slice (left to right) of the view below. As the aircraft or satellite moves forward, the ground location of the slice changes, and the image is slowly built up slice by slice, or line by line. Design details vary, and may include reciprocating or rotating mirrors, prisms, diffraction gratings, filters, and anywhere from a few to thousands of specialized photoelectric cells. In all cases, light from different segments of the spectrum (different "bands") is directed to different cells, and the electric charge produced by each cell is recorded as a number. Since the cells are accurately calibrated, the digital image (made up of such individual numbers, hence "digital") yields data on the actual luminance fluxes in the various bands, rather than simple differences in brightness. The most advanced sensors include up to a few hundred bands, and these may extend from the ultraviolet through the visible and infrared to include thermal wavelengths.

Analysis requires a computer workstation and appropriate raster GIS software. A wide variety of appropriate software packages are now available. In most cases one can be obtained that will run on an existing workstation used, for example, for an engineering or planning department's vector GIS. Alternatively, many vendors of GIS software offer custom analytical services.

Aerial Photography

The study used 1:40,000-scale color infrared aerial photographic prints, 23x23 cm (9x9 inches) taken in June of 1987. These are a standard product available from the government; virtually the entire United States is covered. Overlapping photos to allow stereoscopic viewing were obtained for commercial districts only, so that building heights could be estimated. Any similar photographs would serve.

Color-infrared film is often used in aerial photography. Its main advantage is that it shows healthy vegetation much more clearly than similar black-and-white film. The study relied on this capability to distinguish sizable trees from other vegetation at the scale of the photography used. This important distinction could not be made using the study's digital imagery because of its spatial resolution, which was too coarse to identify individual trees. At larger (more detailed) scales, black-and-white prints would suffice.

A second use of the aerial photographs within the present study was to map rough estimates of housing density or, in commercial districts, structural density and building height. For this purpose the 1:40,000 photographic prints used were barely adequate. Most city governments will, however, have much better information already in hand.

Digital Imagery

Digital images were acquired from a multispectral scanner onboard a specialized government aircraft flying at a height of 20 km (65,000 feet). The images were originally made for other studies. The Fresno image was acquired on June 22, 1990 at 11:53 AM, local solar time (LST), the Sacramento on August 5, 1983 at 11:29 AM LST.

The ground area covered by the image in each case was approximately 16.5 km (11 miles) east to west (across the flight path) and 34 km (21 miles) north to south (along the flight path). Because a scanner operates continuously as an aircraft (or satellite) travels, the view near the middle of the flight path is always vertical, shifting to a slight angle left and right. Digital images are composed of individual picture elements (pixels), in this case 716 across by 1,536 long, each of them about 22 meters (72 feet) across when mapped onto the ground.

Multispectral scanners, as explained above, obtain images in several discrete bands simultaneously, the bands somewhat analogous to the colors of our normal perception: color film and television mimic our own color vision by obtaining information in three bands -- red, green and blue. The multispectral scanner that produced the images used in the study recorded information in eleven bands extending from blue in the visible part of the spectrum, through green, red, near- and mid-infrared to the thermal infrared. Where the human eye or photographic film is capable of discerning as many as thirty degrees of brightness at once, this particular scanner could distinguish 256. More evolved digital imaging systems multiply both the number of bands and the levels of brightness several fold.

Thus an immense amount of data is stored in such a digital image, and a wide variety of information can be retrieved through appropriate analysis. The present study required information pertinent to the surface energy budget: albedo, the preponderance of transpiring vegetation, and surface temperature.

Analysis

The phase of the study reported herein focused primarily on preparing and extracting information from the two primary sets of data, and then merging them both into a GIS. At that stage subsequent analysis could be performed using maps generated by the GIS such as those presented with this paper (reproduction prohibits inclusion in the proceedings), or using the GIS directly either as a visual aid or a tool for numerical analysis. This section covers the preparation and merging of data.

Structural Geometry and Tree Cover

The intent of analyzing the aerial photographs was to map aspects of the urban landscape that were important to the study but that would not show up in the digital imagery used because of its limited spatial resolution. Note that the same limitation would apply to a photograph taken from an equivalent altitude; on the other hand, higher-resolution digital imagery would serve as well, but would be cumbersome to analyze on today's computers. An analyst classified the image area of each city, neighborhood by neighborhood, mapping the classifications onto standard 1:24,000 scale 7.5-minute topographic sheets.

The analyst defined twenty categories (Table 1), most denoting degrees of structural density (in either detached residential or commercial) and tree cover. In addition, categories for agricultural land, open water and rural small-holdings allowed comprehensive mapping. The mapped categories were later digitized as polygons from the topographic sheets using GIS software, in Universal Transverse Mercator (UTM) coordinate space. Some editing was necessary since the Sacramento digital image was acquired several years before, and the Fresno image after, the aerial photographs were taken. For the most part this consisted simply of remapping new development as the agricultural land it had formerly been, or vice-versa. Tree growth in three or four years is minimal, while other vegetation in this area is dormant in summer unless irrigated, so natural rainfall history makes little difference.

In a subsequent step the polygon files were resampled, using GIS software, to create raster GIS layers corresponding to particular parameters: density of trees taller than one story, roof area index as an indication of structural density, and neighborhood structure heights. Sampling was performed at 22 meters to match the resolution of the digital images, but the layers were still mapped to the UTM coordinate system.

Table 1. Categories Used in Classifying from the 1:40,000-scale Aerial Photographs. Note that no truly forested residential areas, nor commercial with any significant tree cover, were found. Tree-cover categories are visual and subjective.

	Category	Structural Density	Density of Trees Larger than a Single-story Residence
1.	Open agriculture	Miniscule	Rare to absent
2.	Spaced residential with open canopy	Lot frontages > 20 m (65')	Dominant
3.	Intermediate residential with open canopy	Lot frontages 13-20 m (45-65')	Dominant
4.	Dense residential with open canopy	Lot frontages < 13 m (45')	Dominant
5.	Spaced residential with broken canopy	Lot frontages > 20 m (65')	Rare to sub-dominant
6.	Intermediate residential with broken canopy	Lot frontages 13-20 m (45-65')	Rare to sub-dominant
7.	Dense residential with broken canopy	Lot frontages < 13 m (45')	Rare to sub-dominant
8.	Spaced residential without canopy	Lot frontages > 20 m (65')	Rare to Absent
9.	Intermediate residential without canopy	Lot frontages 13-20 m (45-65')	Rare to absent
10.	Dense residential without canopy	Lot frontages < 13 m (45')	Rare to absent
11.	Open commercial	Roof area < 10%	Occasional to absent
12.	Intermediate commercial	Roof area 10-70%	Occasional to absent
13.	Dense commercial	Roof area > 70%	Occasional to absent
14.	Open multistory commercial	Roof area < 10%	Occasional to absent
15.	Intermediate multistory commercial	Roof area 10-70%	Occasional to absent
16.	Dense multistory commercial	Roof area > 70%	Occasional to absent
17.	Parkland with trees, other forested areas	Very low	Dominant to somewhat open
18.	Open parkland	Very low	Occasional to absent
19.	Semi-rural	Roof area < 5%	Present
20.	Open water	Zero	None

The Digital Images

For many purposes digital imagery can be used as is, or else slightly enhanced to allow easy visual interpretation of the picture itself. Since the goal of the present study includes the accurate recovery of numerical attributes such as surface temperature and albedo, some initial steps are required. Once these are performed and the attributes themselves extracted, the results can be resampled as above, to produce additional GIS layers that also are UTM-coordinate maps.

Atmospheric Correction. Distant mountains look blue and featureless because of the atmosphere's effect on light traveling along the path between the mountains and our eyes. Some is lost to scattering and absorption, while other light is scattered *into* the path. Remember that the blue "sky" is nothing but scattered light obscuring the deep black of space. A satellite looking downwards confronts almost the same brightness, with the planet's surface dim beyond it.

To correct for atmospheric effects, the radiance measurements recorded by the scanner must be accurately adjusted. First, extra light scattered into the path (or in the case of some infrared bands, emitted by the air along the path) must be subtracted, and then the result increased to compensate for absorption and scattering losses. The exact amounts depend not only on the wavelengths of the band involved, but on the atmosphere: its depth, and also its temperature, humidity, dust content and so on.

The complex calculations involved were accomplished using a unique public-domain program called Lowtran-7 (Kneizys et al. 1988). For each case, an atmospheric profile was constructed using local weather data for the date and time; lower atmosphere data from the date's nearest California Air Resources Board sounding flight; and upper atmosphere data bracketing the time, from the nearest U.S. Weather Service radiosonde station (Oakland, California). Using the atmospheric profile, sun position and image geometry as input, Lowtran-7 calculated path radiance and transmittance for each sensor band. This information, along with the sensor's calibration data, allowed accurate estimation of band-specific image radiance at ground level.

A secondary atmospheric effect is the adjacency effect, a slight blurring of images caused by forward scattering of light from its true source to appear in nearby pixels. Present corrections for this problem are approximate, and the errors introduced are relatively minor. Treatment will be excluded from this discussion.

Apparent Albedo. In order to estimate albedo, an additional set of information is required. The atmospheric correction described above yields a series of accurate band-specific radiance images. In order to calculate reflectivity, downwelling radiance must also be known. Lowtran-7 was used for this purpose as well.

Using the same atmospheric profiles discussed above, Lowtran-7 was used to calculate both direct sunlight and a series of sky radiances at particular locations in the sky. These were then weighted to approximate the whole-sky integrated radiance falling on a horizontal surface. When calculating sky radiances Lowtran-7 included a component representing back-scattered light originally reflected upward from the ground. The sum of direct and indirect components together yielded downwelling radiance.

At that stage, apparent reflectivity could be readily calculated by dividing band-specific upwelling radiance, pixel by pixel, by the band-specific downwelling radiance. Unfortunately, most present-day multispectral scanners do not have contiguous bands across the whole spectrum. Instead, gaps in the spectrum exist whose reflectivities must be estimated. This was done by using Lowtran-7 to improve on the method of Brest and Goward (1987). In general the reflectivities of materials in adjacent portions of the spectrum is similar: thus reflectivities within gaps could be estimated from that in adjacent bands.

An important exception is the reflective behavior of green vegetation in the near infrared, which differs markedly from that of most materials. Thus the near infrared must be separated out and the three resulting sections of the spectrum weighted separately (Brest and Goward 1987) according to the insolation assigned overall to that spectral section by Lowtran-7, adjusted in the near infrared according to the strength of the vegetative signature.

The sum of the weighted and adjusted reflectivities is an estimate of apparent full-spectrum reflectivity, or albedo. The word "apparent" represents two important caveats. First, the image was made from directly above, so that the occasional specular or shiny surface encountered in an urban landscape, reflecting light somewhat like a mirror, would appear very bright if it reflected the beam of the sun into the sensor, or dark otherwise. Either case produces an error in estimating albedo. Second, the vertical view also limits the surfaces in view (see Ellefsen 1989; compare Carnahan and Larson 1990). Vertical surfaces disappear, while shadows cast by upright structures can darken the surfaces viewed.

Initial results compare favorably with previous work (e.g., Goward et al. 1985; Brest 1987; Lewis and Carlson 1989). Non-water albedos range from below 0.1 (a large coal yard, and certain parking lots) to well in excess of 0.5 (new, reflective roof coatings on large warehouses). Saturation due to spectral reflection was an occasional problem, usually easily identified, as any significant spectral reflection tended to yield "albedo" values well in excess of 1.0.

Vegetation Index. As mentioned above, the overall reflectance curve of healthy green vegetation is distinct from that of other materials in the near infrared (NIR). In particular, vegetation reflects very strongly at NIR wavelengths close to the visible end of the NIR segment of the spectrum, but absorbs strongly at adjacent visible red wavelengths. Thus the ratio of reflectances in two bands, one covering each of those two spectral regions, serves as an excellent indicator of the preponderance of healthy green leaf area within any given pixel. Among non-vegetal materials, the NIR/Red ratio very rarely exceeds one, whereas the ratio for pure vegetation seldom drops below two. Particularly useful is the fact that this ratio is quite independent of leaf color, plant morphology and other possible sources of confusion.

Because of that fact, however, it is not possible to distinguish between trees and lawn or shrubbery within an urban context. The more complex spectral signatures used in classifying crops and wildland vegetation are rendered useless by the extreme complexity and heterogeneity of the urban landscape, given the 22-meter pixel dimension of the images used in the study (cf. Forster 1983). Because of the very different contributions to near-ground meteorology of large trees versus low vegetation, especially lawn, it was necessary to analyze tree densities separately (above).

Again, initial results compare favorably with published data (Forster 1985; Goward et al. 1985; Honjo and Takakura 1986). A ratio between the two image bands that included the peak red/NIR differences that typify green leaves yielded a result that depicted vegetation density accurately and uniquely in the urban landscape. This was not the case with other ratios or single-band measures, and was equal to more complex statistical approaches (e.g., Forster 1985).

Surface Temperature. Retrieving surface temperature from thermal infrared data, after atmospheric correction including correction for atmospheric radiance, is a simple matter of applying the Planck equation. Emissivities of most urban materials are near unity at thermal wavelengths. A few bright metal surfaces with relatively low emissivities (typically 0.2-0.3 when new) induce some error.

Despite sensor calibration difficulties with the Fresno data, excellent thermal images were obtained from which calibrated surface temperature could be read directly. Initial overall patterns resemble those depicted in the literature (Carlson et al. 1977; Balling and Brazel 1988; Dousset 1989; Roth et al. 1989). Temperatures vary widely, with lack of vegetation, surface pavement and structural crowding all of evident importance in yielding elevated temperatures.

Creating Maps

At this stage, data from analysis of aerial photography had already been converted to raster GIS layers, already defined in UTM coordinate map space. A final step for the digital image products involved resampling the computed and other corrected images in UTM coordinates as well. This is easily accomplished using almost any GIS software, and mainly involves correcting the direction of north, plus expanding the east and west edges of the image somewhat to compensate for the viewing angle.

That done, maps of albedo and surface temperature could be output directly, while the map of arboreal vegetation first required combining the vegetation map derived from the digital image with the tree preponderance map derived from the aerial photography. One useful aspect of a raster GIS is its inherent flexibility when it comes to creating a product. Scale is arbitrary; maps can be produced to match any existing products. Depiction is also arbitrary. Albedo, for example, can be shown as a gray scale image, as an image map in a color continuum, or mapped in colored gradient steps or even contours.

Of course, many other products are also possible, such as simple color or color infrared ("false color") image maps of the city, or more complex concepts such as a map showing where albedo and surface temperature do and do not vary inversely with one another. The stage is also set for more sophisticated analysis, such as that under way in the present study. In the meantime, however, the initial maps themselves provide a powerful tool for the urban planner intent on identifying particular areas where investment in heat island mitigation projects would be most effective, or at later stages, comparing results with original data.

Discussion

The intent of this paper is primarily to introduce an available technology to an interested community. As such, neither a technical discussion of remote sensing nor detailed discussion of methodology is within its scope. Readers are encouraged to contact the authors for further information.

Unfortunately imagery and image maps of the type under discussion are beyond the publication capabilities of the conference proceedings. A limited number of sample color photocopies will be available at the conference, or by mail from the author. It is hoped that even without appropriate illustration this paper will help to educate interested readers in both the power and the challenges posed by utilizing remote sensing technology as an aid in summertime urban heat island analysis.

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