FRONTISPIECE. Comparison of a DMSP nighttime image of the eastern United States with a 1970 census map (U.S. Bureau of the Census, 1973) reveals the striking qualitative correlation between population distribution and energy utilization.

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Urbanized Area Energy Utilization Patterns from DMSP Data

There was a high correlation between population, energy utilization, and the brightness distribution of illuminated urban areas recorded on images provided by the Defense Meteorological Satellite Program.

(Abstract on next page)

INTRODUCTION

ENERGY AND ENERGY UTILIZATION are subjects of national concern. One form of energy, electricity, is particularly important to our everyday lives, and in recent years increased costs and demand have caused utilities to urge conservation measures. These conservation measures are of critical significance to the large population centers of the United States, and it appears that a method for monitoring the regional consumption of electricity in relation to population and urban area could contribute to increased efficiency in the allocation of available resources (Hoffman and Wood, 1976). The problem of assessing energy utilization by city and region on a comparative basis, however, is complicated by the absence of a uniform data source. Ideally, a data source which provides an instantaneous regional overview is required.

One potential data source which provides the desired regional overview is the Defense Meteorological Satellite Program (DMSP) (U.S. Air Force, 1974).* Images recorded in the evening reveal the nighttime illumination patterns produced by major cities on a

* The Defense Meteorological Satellite Program (DMSP) was formerly referred to as the Defense System Applications Program (DSAP) from which the data were called Data Acquisition and Processing Program (DAPP) data.

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ABSTRACT: *The Defense Meteorological Satellite Program (DMSP) is providing nighttime images of the world which indicate the qualitative correspondence between population, energy utilization, and the brightness distribution of illuminated urban areas (IUA's) recorded on images in the visual band. Microdensitometer image profiles of 35 cities in the eastern and western United States were used in combination with map boundaries to construct three-dimensional figures (IUA domes) representing the energy utilization of the urban areas in the two regions. Regression equations of the form* $y = ax^b$ *between population, urban energy consumption statistics in kwh provided by utility companies, and IUA dome volumes resulted in correlation coefficients of +0.88 to +0.96. These strong quantitative relationships indicate satellite data such as those provided by the DMSP offer a potential means of monitoring regional urban energy utilization patterns on a uniform basis, perhaps leading to improved efficiency in the allocation of energy resources. Realization of this goal, however, will require sensor systems with improved IFOV, availability of image data in digital formats, and power consumption data in kwh for defined areal boundaries.*

continental basis, and the relative extent of power utilization is easily assessed by the size and shape of the bright spots representing the cities (Croft, 1977; Croft, 1978; Brandli, 1978). A direct comparison of such images with a 1970 map of the urbanized areas of the United States indicates a clear, qualitative correspondence between population and energy utilization (Frontispiece). It also is evident that the energy utilized by a city may be represented by a three-dimensional figure in the form of a rough dome or hemisphere for which the basal plane (x, y plane) conforms to the illuminated urban area (IUA) and the energy utilization at any point is obtained from the z-coordinate value (Figure 1). The volume of the dome is thus a function of area and usage, which in turn are related to population (Welch, 1979). The objective of this study is to describe a methodology which offers potential for the future monitoring of regional urban energy utilization patterns from satellite data.

DMSP Image Characteristics

The DMSP Block 5 satellites are placed in circular, sun-synchronous, near-polar orbits at altitudes of approximately 830 km. Normally, two satellites are maintained in orbit with one providing coverage at dawn and early evening and the other at noon and midnight (Blankenship and Savage, 1974). Several types of environmental sensors are employed; however, the primary sensors are scanning radiometers, operating in visual (0.4-1.1 μm) and thermal infrared (8-13 μm) bands and providing coverage for a swath width of about 2930 km. Within each spectral band data may be recorded in high-resolution (HR, MI) or very high-resolution (VHR, WHR) modes. Nominal instantaneous fields-of-view (IFOV's) of 3.6 and 0.6 km are specified at the satellite sub-point for the high-resolution and very high-resolution visual band modes, respectively. At the lateral image margins these IFOV values degrade to approximately 18 km and 3.6 km due to foreshortening which occurs in the cross-track direction (U.S. Air Force, 1974). Nighttime visual imagery, which must be recorded under conditions of low irradiance, is restricted to the high-resolution mode which employs a silicon detector of sufficient size and sensitivity to produce adequate signal-to-noise ratios for a moonlit scene.

The image data from the DMSP sensors are telemetered to Air Force Global Weather Central (AFGWC), Offutt AFB, Nebraska, or to tactical sites scattered about the world. At AFGWC, the image data are displayed in rec-

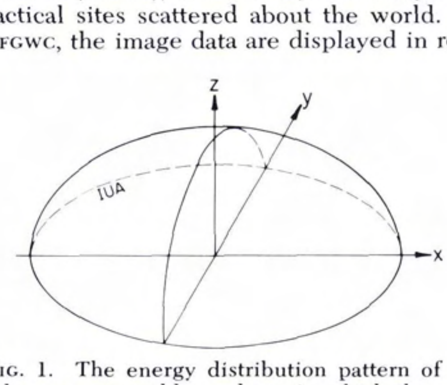

FIG. 1. The energy distribution pattern of an urban area resembles a dome in which the x, y plane represents the illuminated urban area (IUA) and the z axis the energy utilization.

tified, analog form on a video screen and transferred to 9.5 inch positive film at scales of either 1:15,000,000 (normal mode) or 1:7,500,000 (expanded mode). Although the rectification procedure results in images of constant scale, the images of point objects (such as illuminated cities) along the lateral edges appear blurred because of the rectification required to offset the pronounced foreshortening near the limits of the scan. In order to minimize blur, the high-resolution images are generally reproduced at 1:15,000,000 scale (normal mode). Image contrasts may be displayed as a linear distribution of 16 shades of gray for the maximum signal range (the Off Enhancement mode), or the operator may select a switch which will enhance the low, the high, or both extremes of the incoming signal.

Methodology

A number of DMSP archival positive film transparencies of the contiguous United States were obtained from the Space Science and Engineering Center of The University of Wisconsin at Madison. From these transparencies, two images recorded in the visual high-resolution, Off Enhancement mode over the southwestern and eastern United States in the early evening (approximately 9:00 p.m.) of January 15 (West) and February 15 (East), 1975 were identified for further study. Contact duplicate positive film transparencies of the archival images were reproduced in the photographic laboratory, maintaining a gamma of 1.0 to insure faithful reproduction of the archival image gray levels. The duplicate images were then correlated with available map coverage, and a total of 35 cities (including 31 urbanized areas and the incorporated limits of four cities of less than 50,000) recorded as well-defined, reasonably symmetric bright spots were selected for detailed analysis (Figure 2).* Additional data required for the analysis included 1970 census statistics for each urbanized area and 1975 power consumption figures (Table 1). These data were obtained from Bureau of Census publications (1973a, 1973b) and from individual utilities who were contacted by letter and requested to supply information on annual kilowatt hour (kwh) energy consumptions for the urbanized areas. Although response to these requests was excellent, the jurisdictions of the utility companies seldom corresponded

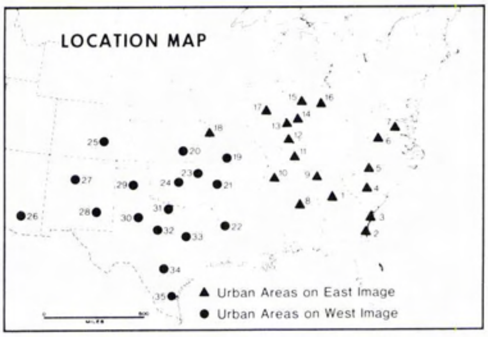

Fig. 2. A location map of the 35 urban areas listed in Table 1.

exactly with the urbanized areas defined by the Bureau of Census. Variability in the data set due to this problem, however, has proved insignificant at the small scales required for plotting and analysis.

In order to explore the relationships between urbanized area, population, and power consumption, a method for analyzing the images of the brightly illuminated cities had to be devised. A first step involved the comparison of the IUA's as recorded on the DMSP images with the corresponding urbanized areas (UA's) portrayed by the Bureau of Census in 1:250,000 scale map format. With the aid of a Bausch and Lomb Transfer Scope, the IUA's and UA's were brought to a common scale of 1:750,000 and superimposed (Figure 3). These superimposed plots revealed a systematic correspondence between the IUA's and UA's, with the IUA's slightly larger due to the effects of halation and system spread function at the small image scales. Additional factors which may contribute to this discrepancy include (1) the possible expansion of the urbanized area in the five-year period between the 1970 census and 1975 imagery, and (2) the IUA is not restricted to the urbanized area boundaries defined by the Bureau of Census. Again, however, at the small scales involved, the effects of these factors could not be ascertained. After the planimetric boundaries of the IUA's were established, the DMSP images were placed in a Joyce Loebl Mark III CS microdensitometer and a series of image density profiles were generated in the x and y directions at 0.4 mm intervals across each IUA. A gear ratio of 20:1 was employed to plot the profiles at 1:750,000 scale so that they could be easily correlated with the boundaries of the IUA's. The density profile axes were then superimposed on the IUA's in the form of an x, y grid and the density of each grid intersection was determined by inter-

* An urbanized area, as defined by the Bureau of Census, includes a central city with a population of 50,000 or more and the surrounding closely settled territory.

TABLE 1. POPULATION AND ENERGY CONSUMPTION DATA (kwh) FOR THE URBAN AREAS RECORDED ON THE DMSP IMAGES

East			West		
City	Urbanized Area Population-1970	kwh-1975 (in thousands)	City	Urbanized Area Population-1970	kwh-1975 (in thousands)
1 Atlanta, GA	1,172,778	11,235,198	19 Springfield, MO	121,340	989,382
2 Brunswick, GA	19,585*	190,458	20 Wichita, KS	302,334	3,510,015
3 Savannah, GA	163,753	1,919,851	21 Ft. Smith, AR	75,517	370,000
4 Columbia, SC	241,781	824,194	22 Shreveport, LA	234,564	1,500,823
5 Charlotte, NC	279,530	3,591,557	23 Tulsa, OK	371,499	4,150,166
6 Roanoke, VA	156,621	674,245	24 Oklahoma City, OK	579,788	6,250,000
7 Fredericksburg, VA	—	626,268	25 Pueblo, CO	103,300	500,894
8 Birmingham, AL	558,099	3,312,146	26 Tucson, AZ	294,184	3,609,387
9 Chattanooga, TN	223,580	4,961,302	27 Albuquerque, NM	297,451	2,558,894
10 Jackson, TN	39,996*	667,597	28 Roswell, NM	33,908*	174,419
11 Bowling Green, KY	36,253*	419,986	29 Amarillo, TX	127,010	843,954
12 Evansville, IN	142,476	2,346,277	30 Lubbock, TX	150,135	676,623
13 Terre Haute, IN	80,908	1,289,176	31 Wichita Falls, TX	97,564	904,319
14 Indianapolis, IN	820,259	7,675,183	32 Abilene, TX	90,571	708,213
15 Ft. Wayne, IN	225,184	3,641,395	33 Waco, TX	118,843	923,611
16 Lima, OH	70,295	1,958,707	34 San Antonio, TX	772,513	5,717,143
17 Decatur, IL	99,693	1,227,063	35 Corpus Christie, TX	212,820	2,351,002
18 Kansas City, MO	1,107,787	7,247,442			

* Population for the incorporated limits of the city.

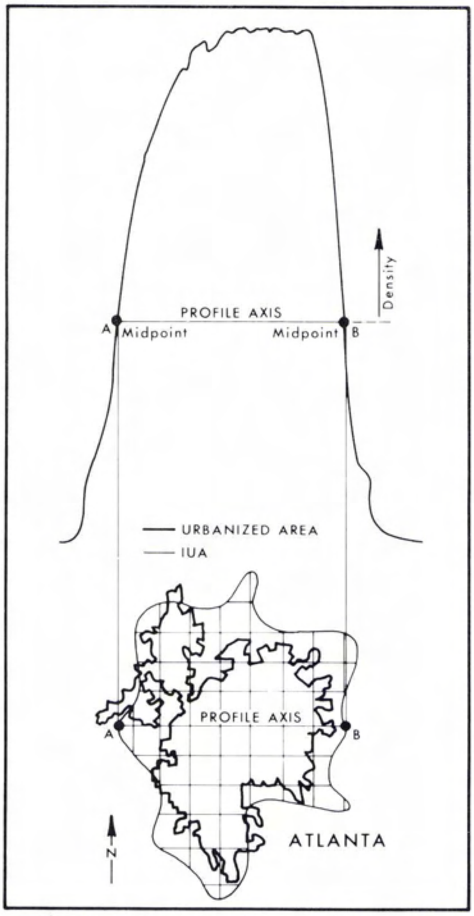

FIG. 3. The correlation between the illuminated urban area (IUA) and the urbanized area defined by the Bureau of Census for Atlanta, GA. The x, y, z (density) values at the grid intersections of microdensitometer profiles are employed to construct the perspective IUA domes represented in Figure 4.

polation after scaling the midpoints of each profile edge to the boundaries of the IUA's as shown in Figure 3. The x, y, and density (z) values were then used in conjunction with the Calcomp THREE-D software package, operational on the University of Georgia IBM 370/158 computer system to produce perspective drawings of the cities (Figure 4). These drawings allow qualitative visual comparisons of the energy utilization patterns of the cities.

Quantitative relationships were established by computing the mean volumes (V) of the IUA domes in mm³ from both the x and y profiles with the aid of Simpson's Rule:

$$V = h/3\,(A_0 + 4A_1 + 2A_2 + 4A_3 + 2A_4 + \cdots + 2A_{n-2} + 4A_{n-1} + A_n)$$

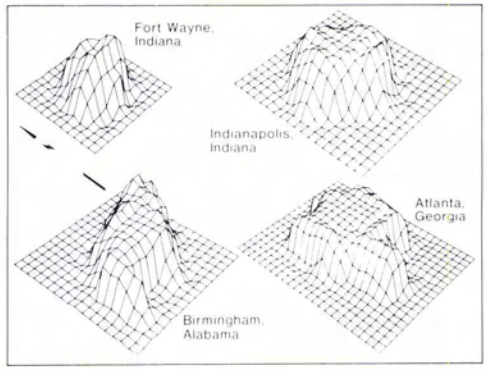

FIG. 4. Computed generated perspective drawings of the IUA domes of four cities on the east image.

where h = distance between microdensitometer profiles at the map scale (8.0 mm), and
A = area under each microdensitometer profile above the midpoints of the profile edges in mm² as measured by digital planimeter.

Scattergrams of the relationships between 1975 energy consumption in kwh and volume and between kwh and the populations of the urbanized areas in 1970, were developed on doubly logarithmic paper. Regression lines computed to fit the apparent straight-line relationships by the methods of least squares were of the form $y = ax^b$ (Figure 5)

where y = dependent variable such as population or energy consumption (kwh),
a = coefficient (y intercept),
x = independent variable such as kwh or volume of the IUA dome (mm³), and
b = exponent (slope of regression line).

POPULATION, KWH, AND IUA DOME VOLUME CORRELATIONS

The qualitative observation that population and energy consumption are closely related is confirmed by the graphs in Figure 5a which exhibit correlation coefficients of +0.88 and +0.96 for the urban areas portrayed on the east and west images. The urban areas in the west represent a more homogeneous sample in terms of population, urban area, terrain, and energy consumption figures which undoubtedly accounts for the higher correlation coefficient. These graphs indicate that (a) population and power utilization

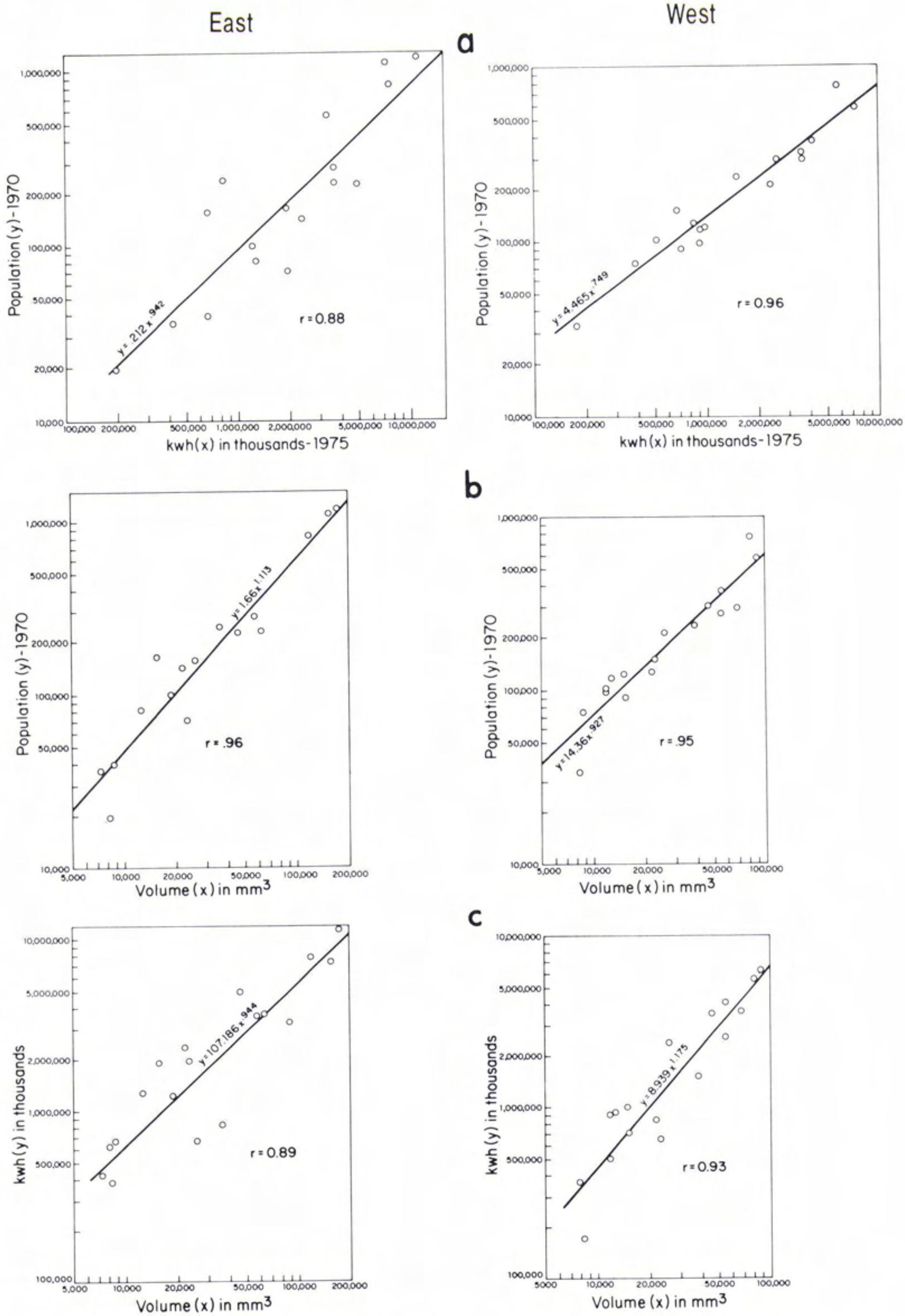

FIG. 5. Regression equations between population and energy utilization in kwh (5a), population and IUA dome volume (5b), and energy utilization and IUA dome volume (5c) for the urbanized areas recorded on the DMSP images of the east and west study areas. Correlation coefficients (*r*) of +0.88 to +0.96 indicate the promise of analyzing regional urban energy utilization patterns from satellite data.

patterns are strongly related on a regional base, and (b) it should be possible to correlate the image derived IUA dome volumes with both population and energy utilization statistics.

The relationships between population, energy utilization, and IUA dome volume are reflected by the regression lines in Figures 5b and 5c. Population vs. volume produces the highest correlation coefficients ($r = +0.96$ and $+0.95$) because of the uniform definition of urban areas and the consistent relationship between the planimetric map boundaries of the urban areas and the boundaries of the IUA's transferred from the DMSP images.

The correlation between energy utilization in kwh and IUA dome volume ($r = +0.89$ and $+0.93$), while slightly weaker than population vs. volume, is still remarkably strong considering the variables in the recording process and power utilization data. At this scale of application the impact of these variables is reduced and it appears possible to conduct broad regional comparisons of power utilization which could lead to the more efficient allocation of resources.

Conclusion

Satellite reconnaissance systems such as those employed in the DMSP provide a potential means of obtaining data for the analysis and comparison of regional urban energy utilization patterns as a function of population and built-up area. Regression equations show the relationships between energy consumption as determined from utility company statistics and the volume of IUA domes constructed from microdensitometer profiles across the nighttime images.

The potential of this procedure will be considerably enhanced, however, if methods can be devised to determine energy consumption within the defined urbanized area of larger cities and if satellite data can be improved. Based on the experience gained in this study, an array or line scan sensor with an IFOV of about 0.5 km used to record mid-evening data encoded to 6 or 7 bits would permit a more accurate and practical representation of the IUA as a matrix of x, y, z values. The IUA domes could be interpolated from these values. For this type of application, however, it is desirable that the sensor field-of-view remain sufficiently large in order to near-simultaneously record urban areas on a regional basis. In the future, correlation of nighttime visual data with that recorded in the thermal infrared by DMSP or Heat Capacity Mapping Mission type spacecraft may enhance the possibilities of modeling regional urban energy utilization patterns from satellite data.

Acknowledgments

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