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Using DMSP Night-Time Imagery to Evaluate Lighting Practice in the American Southwest

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Abstract. The U.S. Defense Meteorological Satellites provide an opportunity to measure the uplight produced by artificial lighting on the ground. In this study DMSP data are used to measure the integrated at-detector radiance of a number of communities in the American Southwest in an attempt to evaluate the effectiveness of outdoor lighting codes. Use of DMSP data in this manner is complicated by many factors, and some of these are briefly discussed.

1. Introduction

The U.S. Air Force Defense Meteorological Satellite Program (DMSP) satellites orbit Earth in sun-synchronous, low-altitude polar orbits. One orbit is oriented such that the satellite circles the globe approximately over the sunrise/sunset terminator, the other passes over near noon and midnight. The principle purpose of the program is to monitor cloud conditions, but the night-time observations of city lights are what have the attention of the astronomical community.

Other workers have begun using DMSP data to measure uplight produced by cities, including Isobe & Hamamura (1998), Isobe (1998), Falchi & Cinzano (1999) and Cinzano *et al.* (2000). The present study evaluates the possibility of using DMSP data to measure the overall success of light pollution control efforts. Tucson and Flagstaff, Arizona, are two cities in the American Southwest that have a substantial history of light control efforts through outdoor lighting codes. Are these codes working?

2. This Study

The image used in this study is a cloud-free composite of the United States built from many DMSP midnight passes during the dark of the lunar cycle in March 1996 and January-February 1997 (Elvidge *et al.* 1999).

Brightnesses were measured from this image for a sample of towns and cities in Arizona, Utah, Nevada and New Mexico, covering a range in population from under 2000 to almost 2.5 million. The radiance values were summed within rectangular regions around each municipality.

Population figures were taken from the U.S. Census Bureau website, where estimated figures for July 1996 (released in June 1999) are listed. These figures are shown in Table 1 and Figure 1.

Table 1. Radiance (10^{-10} watts/cm^2/sr/μm) and 1996 Population for Southwestern U.S. Cities

Fig. 1	City	State	Population	Radiance
CaV	Camp Verde	AZ	7552	3616
ChV	Chino Valley	AZ	6588	1714
Cot	Cottonwood	AZ	6937	9941
Dou	Douglas	AZ	15015	28288
Flg	Flagstaff	AZ	55094	31110
GiB	Gila Bend	AZ	1695	10447
Hol	Holbrook	AZ	5398	5951
Kin	Kingman	AZ	17270	29998
LHC	Lake Havasu City	AZ	39503	18912
Phx	Phoenix metro[a]	AZ	2427230	1666182
Pre	Prescott	AZ	49760	29693
Sed	Sedona	AZ	9109	5722
SiV	Sierra Vista	AZ	37434	28307
Tuc	Tucson [b]	AZ	472305	396799
TuM	Tucson metro [c]	AZ	729479	396799
Wic	Wickenburg	AZ	5312	4020
Wcx	Willcox	AZ	3533	4005
Wil	Williams	AZ	2706	3588
Win	Winslow	AZ	10420	10257
Bly	Blythe	CA	12982	14855
LVN	Las Vegas[d]	NV	577904	1086814
Mes	Mesquite	NV	6200	22970
Alb	Albuquerque[e]	NM	425526	438288
LaC	Las Cruces	NM	74779	55252
LVM	Las Vegas	NM	16437	18365
Ros	Roswell	NM	47559	45081
StF	Santa Fe	NM	66522	67701
StG	St George	UT	42763	43521

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[a] Includes Apache Jct, Avondale, Chandler, El Mirage, Fountain Hills, Gilbert, Glendale, Goodyear, Guadalupe, Litchfield Park, Mesa, Paradise Valley, Peoria, Scottsdale, Surprise, Tempe, Tolleson, Youngtown.

[b] Includes Oro Valley, South Tucson.

[c] Includes 95% of Pima County population.

[d] Contains three saturated pixels. Includes Henderson, North Las Vegas.

[e] Includes Corrales.

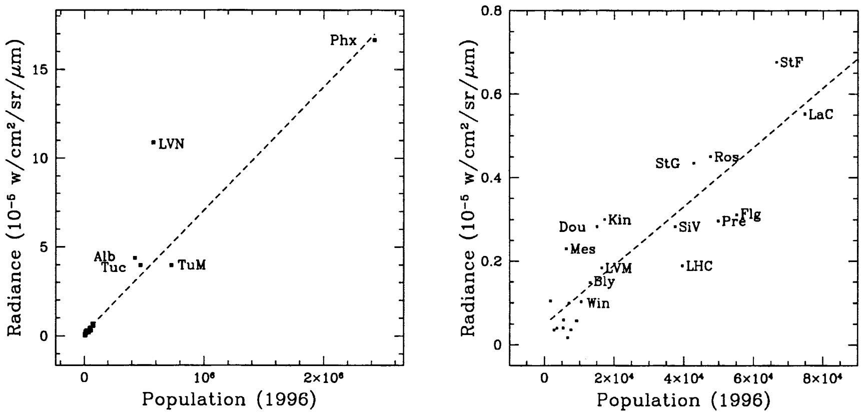

Figure 1. Integrated radiance *vs.* population for all measured cities (left) and smaller cities (right). The dashed line is a first-order fit to the data below 80,000 population. Letter abbreviations are in Table 1.

3. Discussion

Though there are many uncertainties in these data and their interpretation (see below), the measured integrated radiance of Flagstaff, AZ falls near the lower limit for cities of similar size. Flagstaff has had a long history of outdoor lighting controls, beginning in 1958 with the first lighting code addressing astronomical interests anywhere in the world, and followed by regular updates to the present time. The integrated radiance of Flagstaff is approximately that of an average town of population about 37,000, or about 67% as much as an average city of its size in these data.

But other communities without strict lighting codes appear fainter than the average as well (e.g. Prescott, AZ), and this leaves the question whether the moderate brightness of Flagstaff can be attributed to its lighting codes.

Another city with a similar long history of outdoor lighting codes is Tucson. There are few cities of similar size in the region against which to compare its brightness, and therefore the brightness of an "average" city of this size is hard to define. In Figure 1, the Census Bureau population figure and the integrated DMSP radiance place Tucson close to the line connecting the small cities to the single large metropolitan area of Phoenix; it also appears comparable to the similarly sized Albuquerque. But Tucson has a large polulation in adjacent areas of Pima County, outside the city limits on which the official population is based. Tucson planners estimate that presently the population of the Tucson metropolitan region is 95% of the Pima County population. Applying this fraction to the Census Bureau 1996 estimate for Pima County (767,873) would put Tucson at 729,479, and therefore considerably fainter *per capita.*

There is scant indication in these figures for a decreasing uplight *per capita* as population increases, as seen by Falchi & Cinzano (1999), nor is there any apparent tendency to decreased *per capita* output with increasing population, as reported by Garstang (1986). A first-order fit to the cities of less than 80,000 nearly exactly intercepts the largest and brightest city measured.

3.1. Sources of Error

Assuming there are no residual clouds in the composite image, and neglecting photometric calibration uncertainties in the DMSP photometric equipment and processing, the following are some of the effects that will influence the *per capita* apparent brightness of cities in the DMSP data:

Population Uncertainties. Population figures are uncertain for many communities, since what the Census Bureau defines as a given city does not always correspond with what appears to be the city extent in the DMSP image. The example of Tucson presented here, where the true figures may be more than 50% higher than Census Bureau figures, may be generally indicative of the magnitude of this source of error. A proper approach will require a detailed community-by-community population analysis.

Angular Dependence. The light emitted from cities is not likely to be independent of direction. Reflected uplight might be approximately lambertian (ignoring blocking effects) but direct uplight is likely to have strong angular dependencies. Garstang (1986) assumes an intensity dependence of direct uplight proportional to the fourth power of the zenith angle. Although the raw DMSP scans contain observations over a range of zenith angels on an east-west line, it is not clear how such a limited sample of altitude and azimuth measures can be applied to evaluating the entire upward hemisphere.

Ground-Level Obscuration. Variable amounts of obscuration from vegetation and structures will affect the apparent brightness of cities as viewed from different angles. This effect may increase toward the horizon but it has not been measured. The degree of this effect may also be correlated with city size as larger cities have taller buildings.

Albedo Variations. Varying reflectivity of the ground, the relation of such variation to lighting use, and the presence or absence of snow cause further uncertainities. These effects, particularly of snow, could be large.

Extinction. The zenith angle of DMSP observations as viewed from the ground varies from 0 deg to about 60 deg, leading to a 1 to 2 range in airmass between the source and detector. Atmospheric extinction coefficients vary from approximately 0.35 mag/airmass near the blue limit of the detector to 0.1 mag/airmass or less near the red limit. This effect has not been removed from these data, and sufficient information may not be available to do it.

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