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Radiometry with Nighttime DMSP Images in Digital Form

The characteristics of DMSP visual-band images in digital form are summarized.

INTRODUCTION

THE USAF DEFENSE METEOROLOGICAL SATELLITE PROGRAM (DMSP) maintained a nearly continuous daily watch on the world for about a decade. This series of spacecraft carried a variety of instruments, of which the most well-known was an imaging system that provided separate but matched observations in the visual and infrared bands. The satellites were sun-synchronous; about half were placed in a dawn-dusk orbit (maintained near the terminator) and most of the others were in noon-midnight orbit lying near the plane that contains the sun. Midnight images in the visual band have proven to be exceptionally interesting from both a geophysical and a demographic standpoint because aurora are widely pictured (e.g., Akasofu, 1974) and because many of the light sources are man-made (e.g., Croft, 1978). Spectral response curves are given in the latter reference.

Our attention here is focused exclusively on the midnight visual pictures. The great majority of such data released by the Air Force are in the form of films that adequately convey locations and general brightness but are poor as a means of preserving radiance values that characterize each picture element (pixel). Some useful radiometric values can be obtained from the films; a definitive paper on that subject was presented by Eather (1979).

The DMSP spacecraft sends images to earth in the form of numbers, each of which represents the radiance of one pixel. Unfortunately, the USAF system does not require preservation of these values, so it has been the common practice to create films (resembling photographs) from the numbers and then to erase the only digital records, the magnetic tapes, for reuse. In part this practice has come about because the original magnetic recordings are in a high-density format that is not yet widely available elsewhere, and one in which tape interchangeability from one facility to another is poor.

While the DMSP images have been widely used, particularly for the study of aurora, their application in research has been hindered by both the lack of digital data and the lack of an authorita-

ABSTRACT: *Nocturnal images of the Earth in the visual band obtained by DMSP satellites are widely used in research. The data are telemetered to Earth digitally, but films have been the only image form available to most investigators. Eather (1979) provided a useful technical paper describing radiometric value recovery from film. To complement Eather's film work, I summarize the characteristics of DMSP visual-band images in digital form.*

Familiarity with the digital imagery should yield a better understanding of the films themselves, particularly with respect to radiometry. Additionally, this information may help others to evaluate the likelihood that digital images would support proposed research projects. For those who obtain digital tapes, I suggest a system for processing that is adapted to analytic work, and provide radiometric interpretation tables that are unavailable elsewhere. While the DMSP was not designed for scientific research, guidelines are drawn from the satellites' characteristics that would warrant consideration if a research-oriented nocturnally imaging satellite were to be designed.

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 47, No. 9, September 1981, pp. 1319-1325.
0099-1112/81/4709-1319$02.25/0

tive source of related technical information. With the exception of a few documents (Dickenson, 1974; Pike, 1975), the available information has resulted from the efforts of research workers who had an opportunity to work with the system. As a source of information about the film form of data, Eather's paper is excellent, but it raises questions about the information content of the original numbers. I will try to provide answers, resulting from my work with six images of the United States in a digital form. These tapes were secured by A. P. Colvocoresses of the Geological Survey and used as the basis for an earlier study (Croft, 1979). The derivation of useful information from the tapes required wide-ranging liaison to obtain the essential background information. Some results of this effort are summarized here.

Character of the Digital Form

Each image is essentially a three-dimensional list (X,Y,Z) in which X and Y represent the position coordinates of a pixel and Z is its associated radiance, commonly (but incorrectly) termed its brightness. Because of the large number of pixels, it is not practicable to assign three or even two numbers to each one. Instead, only the value of Z is given and the X-Y position must be deduced from adjunct information. (According to one source (Horowitz and Vostreys, 1980), the newer satellites specify X and Y "to the nearest picture element.") The digital radiance data are supplied in a single long list consisting of successive strings of 1464 pixel values, each of which is six bits long, alternating with background information given in 180-bit "headers." Each string of 1464 pixels comprises one scan of the DMSP visual imager in the X direction, approximately perpendicular to the subsatellite track along the earth. At midlatitudes this scan is nearly east-west. Each scan requires about 0.42 s, so the separation between scans (that is, the Y dimension of a pixel) is the distance that the subsatellite track moves in 0.42 seconds. This is 1.5 nmi or 2.8 km, the nominal pixel dimension and also the dimension of a side of the square area of the DMSP nighttime photomultiplier sensor when projected to Earth near nadir. Because finer resolution is often required in the daytime, another smaller sensor is provided as an option and all scans are performed once each 0.084 seconds. This is five times faster than the apparent nighttime scan rate; groups of five consecutive scans are averaged to obtain the lower rate.

The X axis in the along-scan direction is slightly nonlinear because samples are obtained at equal increments of time while the sensor views Earth via a mirror that springs back and forth in a sinusoidal nodding motion. From the parameters associated with this sinusoid, I calculate that the X value associated with each sample should be

$$X = R \sin^{-1}\left\{\frac{R+H}{R}\cdot\sin\left[a \sin(bn)\right]\right\} - a R \sin(bn),$$

where

X = Surface distance, along scan, from nadir;
R = Radius of Earth;
H = Altitude of the DMSP satellite, about 830 km;
a = 1.0097 radians, the full angle of mirror swing;
b = 0.001822 radians; and
n = Sample number counted outward along scan from nadir.

I checked the accuracy of this formula by locating in a single digital image the centers of 20 cities extending along an east/west line from Savannah, Georgia to Fort Worth, Texas. The number of pixels from city center to nadir was then determined from the DMSP tape while the distance from city center to nadir was measured on a large-scale USGS map. The distance-versus-pixel number matched and served to verify the equation. In film imagery, nonlinearity in the X direction is said to be removed by a similarly nonlinear flying-spot scanner that makes the films.

An evaluation of the scan formula for $n = 1$ will show that X is only about 1.5 km or half the nominal pixel dimension. Yet film users are told that the nadir pixels are roughly 3 by 3 km. The seeming discrepancy arises because the analog signal from the sensor is filtered to 8000 Hz and then sampled 20,480 times per second, at which rate samples occur every 1.5 km at nadir. Herein I call these samples "pixels" but it must be borne in mind that neighboring pixels are not independent; in the X dimension there is smoothing by the 8000 Hz filter while in both X and Y dimensions there is a considerable overlap of the surface areas whose brightness was originally recorded and used as a basis for determining Z. As a result, the operational practice of defining the X dimension of a pixel as 3 km is roughly consistent with the resolving power of the system, and serves as a valid guide for film users.

The determination of pixel radiance requires the numerical value of Z associated with the pixel together with two numbers from the header associated with the scan. One of the header numbers specifies system gain; the other tells the mode of operation of the satellite with respect to the interconnection of brightness amplifiers and the control of their gain. At times, gain is varied along the scan and then the data are inadequate. Unfortunately, along-scan gain control is needed when brightness varies in the east/west direction. Such is the case when the spacecraft views a terminator. Since about half of the DMSP spacecraft have been in dawn-dusk orbits, the practical result is that radiometric values cannot be reconstructed from their tapes. (Auxiliary information from the Air Force may make it possible to perform approximate brightness calculations with along-scan gain control.)

Fortunately, the noon-midnight spacecraft usually operate with gain fixed throughout the scan when they are in the midnight sectors. The resulting system gain is given in the header. In the cited work (Croft, 1979) I derived Tables 1 and 2, which summarize the conversion from pixel value to radiance. A radiance range of 10:1 is called 20 dB in DMSP parlance, because radiance is converted linearly into voltage and then decibel values refer to the resulting electrical signal levels. For representative values of header gain, there is an associated radiance given in Table 1. The second header code tells whether the pixel value is linearly or logarithmically encoded, guiding the choice of columns in Table 2. The pixel value itself is a two-digit octal number but cannot be 00 or 77. Thus, there are 62 possible levels. For representative levels, Table 2 gives the linear or logarithmic multiplier to be applied to the radiance derived from Table 1. The product, then, is the measured radiance averaged over the area represented by the pixel.

For reasons that will become clear, it is desirable to have a single symbol for each of the 62 pixel levels. For this purpose, I devised a "sixol" code (acronym for six-bit symbol) using all the upper and lower case letters, the nine nonzero numbers, and a blank to represent zero. The choice of a blank is made because this level includes all regions too bright to be recorded by the system, and it therefore represents saturation or whiteout. Gas flares and large cities saturate the DMSP (Croft, 1973); this use of a blank renders such landmarks readily visible in sixol listings. The similarity of the number one to the lower-case letter l precludes sixol listing in many type fonts, but ambiguity can be avoided through use of an optical character reading (OCR) font such as that in Figure 1.

TABLE 1. SYSTEM GAIN RELATED TO REFERENCE LEVEL OF RADIANCE

Gain from a Scan Header (dB)	Radiance [watts/cm^2-sr ($\times 10^{-11}$)]
0	2105
1	1876
2	1672
3	1490
—	—
—	—
—	—
62	1.672
63	1.490
Maximum = 63-7/8	1.347

TABLE 2. RADIANCE MULTIPLIER DERIVED FROM PIXEL BRIGHTNESS LEVEL CODE

Level (62 in all)			Radiance Multiplier	
Octal, from Tape	Sixol Code	Decimal	Linear Mode	Logarithmic Mode
00 is not on tape			100	100
01	Blank	0	98.4	93.0
02	1	1	96.8	86.4
03	2	2	95.2	80.3
04	3	3	93.7	74.6
05	4	4	92.1	69.4
06	5	5	90.5	64.5
07	6	6	88.9	59.9
10	7	7	87.3	55.7
11	8	8	85.7	51.8
12	9	9	84.1	48.1
13	a	10	82.5	44.8
14	A	11	81.0	41.6
15	b	12	79.4	38.7
16	B	13	77.8	35.9
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
—	—	—	—	—
74	Y	59	4.76	1.25
75	z	60	3.17	1.16
76	Z	61	1.59	1.08
77 is not on tape			0	1

ISOLATION AND EXAMINATION OF SUBSETS

Each original scan composed of 1464 pixels represents an area on the Earth's surface about 3 km wide and 3000 km long, lying across the track. For most research applications this is somewhat awkward. As an example, in order to determine the value of a neighboring pixel in the along-track direction, one must first read 1463 pixels and a header. To obtain more tractable groups, I have isolated subsets of pixels in standard regions roughly comparable to the geographic size of a Landsat image. These "units" are 72 pixels across and 64 along track; in retrospect, the 64 was an excellent choice but the 72 pixel selection, made because of local hardware considerations, might better have been 61 or 122, because these factor into 1464.

To demonstrate the character of DMSP digital data, three of the more useful processes have been performed on a unit of pixels that includes Washington, D.C., Baltimore, and the region to the

0 {blank}	1 1	2 2	3 3	4 4
5 5	6 6	7 7	8 8	9 9
10 a	11 A	12 b	13 B	14 c
15 C	16 d	17 D	18 e	19 E
20 f	21 F	22 g	23 G	24 h
25 H	26 i	27 I	28 j	29 J
30 k	31 K	32 l	33 L	34 m
35 M	36 n	37 N	38 o	39 O
40 p	41 P	42 q	43 Q	44 r
45 R	46 s	47 S	48 t	49 T
50 u	51 U	52 v	53 V	54 w
55 W	56 x	57 X	58 y	59 Y
60 z	61 Z			

FIG. 1. The 62 sixol symbols (six-bit symbols) and their decimal counterparts, represented in optical character reading (OCR) type font.

north and east. The image was obtained on a moonless night of 3 October 1978 by DMSP satellite "Fl." Figure 2 shows a map constructed of six such units; among these the unit in question is that in the lower-left corner. To create this image I used a specialized typewriter terminal and chose eight of the type elements to represent different shades of grey. For this purpose the Diablo OCR-A print wheel is well adapted because it has an all-black rectangle to represent the dark areas at night. Whatever the mapping approach one may use, it is important to make individual pixels distinguishable. Maps such as Figure 2 serve primarily to locate pixels with respect to local geography. The along-track direction is vertical and is roughly north-south.

The most useful representation of the DMSP data is the sixol array exemplified in Figure 3. One sixol symbol is used for each pixel and, as a fortunate result, there is a one-to-one correspondence between the symbols on the map in Figure 2 and the sixols in Figure 3. Washington and Baltimore can be clearly seen because the saturation due to bright lights in the city centers results in blank areas on the sixol array matching those on the map in Figure 2.

It deserves emphasis that the sixol array preserves all the radiometric information available in the taped DMSP digital data. One requires only the header information, which can typically be represented by a few numbers. A sixol array in OCR font like Figure 3 could serve as a ready means for communicating digital imagery to any user in possession of a suitable optical character reader. In this instance, the header said that the pixel gain was linear and that Table 1 should be entered with a value of 57 dB. It follows that the reference level was 2.97×10^{-11} watts/cm^2-sr. Table 2 then tells that a blank sixol represents 98.4 percent of this radiance; all we know about the blank city centers is that their radiance equaled or exceeded this value. For other pixels, radiance is specified within a narrow range by the pixel levels, that is, by the sixols. The minimum value, with sixol Z, is seldom found because the system gain is programmed by the Air Force in order to avoid values too near the bottom of the scale.

The number of pixels at each of the 62 radiance levels is depicted by the histogram in Figure 4 for the same unit of data. In populated regions, such histograms typically consist of two distinguishable parts—the natural and the man-made lights. The man-made lights are brighter and are distributed somewhat uniformly in the histogram. On moonless nights the naturally lighted pixels are typically dim and concentrated in a distribution that appears to be Gaussian, much like that between levels 35 and 50 in the example. Eather has summarized the reasons for inferring that airglow is often the main source of this light on moonless nights. When the moon is nearly full, its light reflected from clouds or snow may become comparatively bright, but still the pixels containing man-made sources will be brighter. Even when albedo is low, the reflected lunar light exceeds the airglow. The origin of lights in various groups that may occur in a histogram can readily be determined by reference to the sixol array or to a brightness map. By plotting sixols or maps with a limitation that only those radiometric values within some particular range are to be included, one can readily locate the sources of the different histogram groupings.

STRENGTHS AND WEAKNESSES IN RESEARCH APPLICATIONS

Daily coverage of the entire world is one of the great advantages of the system. Other imaging satellites that provide only occasional opportunities to look at any given site are often foiled by bad weather and may not obtain a useful image of that site for months.

Fine-scale analysis is rendered difficult by the rather large size and ever-changing shape of the DMSP pixel area. At the nadir, the nominal and exemplary pixel area is a square with boundaries set by the square area of the sensitive element at the focal plane of the DMSP satellite telescope. As the scan progresses, the square area of view rotates because scanning is performed by oscillating a mirror in the field of view of a telescope that initially looks horizontally along the track. Thus, as the view departs from the nadir, the pixel area grows, rotates, and becomes diagonal. As the mirror nears the end of its sinusoidal oscillation and its angular rate decreases, the large size and the overlap of pixels would become objectionable. To mitigate these unwanted features, a portion of the focal-plane sensor is disabled during the outer portion of each scan. While these pixel area changes are repeatable and subject to calculation, nevertheless they render analysis of light from small sources more difficult to perform.

Many of the limitations of DMSP are indirect consequences of the world-wide daily imagery—and that in itself is probably the greatest virtue of the system. Among these limitations I would cite:

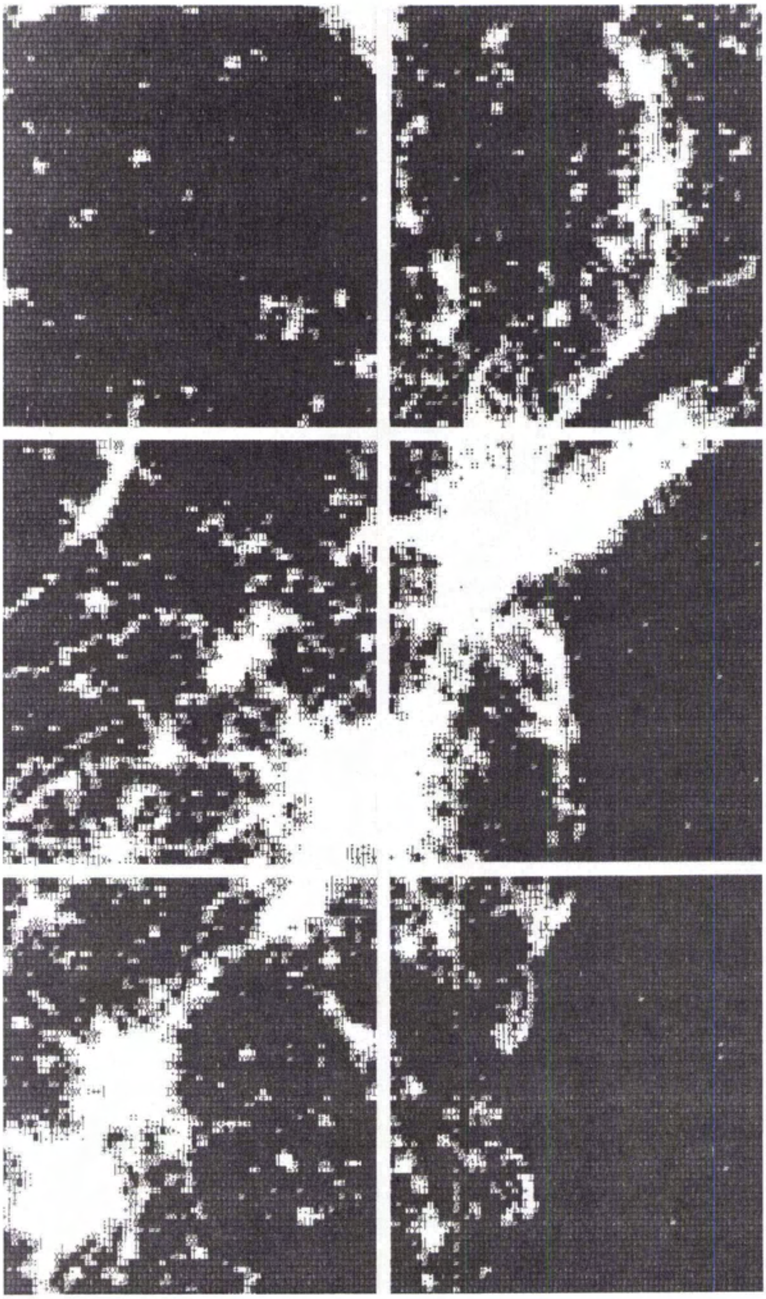

FIG. 2. Six units of DMSP digital data, each 72 by 64 pixels, represented by typing for each pixel one from among eight symbols that exhibit different shades of grey when thus assembled. The major white regions depict DMSP saturation by lights in Washington, Baltimore, Philadelphia, and New York.

- Pixel Saturation; at any given time, a radiance range of only 100 to 1 is telemetered to the ground. When the range is set to reveal weather patterns, measurements of many auroral and man-made light sources are lost due to saturation.
- Pixels are too large for many purposes. (The large pixels and limited radiance range both serve to minimize the amount of digital data.)
- Radiometry at the sides of the image, 1500 km from the nadir, is hindered by the oblique path

FIG. 3. A unit of DMSP imagery in sixol preserving all the photometric information from the digital tape. Large letters designate Washington (W), Baltimore (B), York (Y), and Dover (D). Except for the northernmost scan, system gain was 57 dB and the pixel gain was linear.

through the atmosphere. Nevertheless, this oblique view is necessary if successive orbital images are to overlap.

Some of the limitations of the present system arise because it is designed to serve operational needs exclusively. The unavailability of digital forms of imagery originally stemmed from a lack of recording capability; there was no equipment or software available that would produce standard computer-compatible digital magnetic tapes of the images prior to mid-1978. Even though this technical problem is now solved, there still does not exist any administrative avenue by which a researcher can obtain the digital data, although there are two such avenues for film. It deserves emphasis that DMSP tapes are difficult or impossible to obtain and there is no documentation written to guide users who are outside the system. In contrast the NOAA operational satellites in polar and in geostationary orbits provide routine environmental imagery that is in many respects comparable to DMSP data (e.g., Matson and Dozier, 1980).

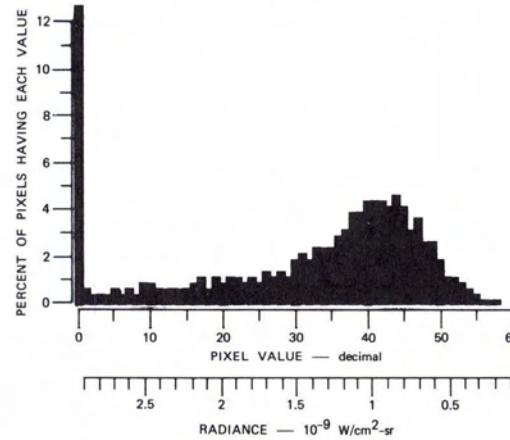

FIG. 4. The number of pixels at each level in the same unit of imagery.

A NEW SYSTEM

If one were to design a nocturnal imager to serve research and ultimately to meet pragmatic civil requirements, then several aspects of the DMSP example could provide guidelines. For example, it is clear that most films serve only as a means to determine that conditions were somehow less than optimum. The user of nocturnal imagery must be more selective than the user of daytime imagery. The presence or absence of moonlight, partial sunlight, clouds, aurora, or lightning may dictate the usefulness of any given image. One may examine hundreds of images to find one that serves a particular purpose. Furthermore, the setting and operation of the instrumentation appear to be more critical at night.

For the purpose of examining large quantities of data, one needs film, not digits. Only after a rather small data subset has been selected are the numbers of use. Any archival organization that supports the satellite must then be prepared to supply catalogs of inexpensive images plus small quantities of high-quality film images and digital data.

A provision for multiple colors at night would be helpful. For example, the DMSP often reveals a mixture of gas flares and cities; a division of the spectrum into neighboring bands, represented by colors, would render these sources distinguishable. Such use of two thermal infrared bands to identify gas flares was demonstrated by Matson and Dozier (1981 (see pages 1311-1318 of this issue)). Among the present images, there is no unambiguous basis for distinguishing between sources having spectra that are far different.

For selected times and areas, smaller pixels would often be desirable. However, the resulting volume of digital data would prove impracticable if worldwide imagery were to be obtained. Ideally, selected areas could be imaged at high resolution on command only when weather is good and other lighting requirements are met.

Some purposes could be served better from a near-stationary orbit where the progress of events could be observed for several hours. Recent weather satellites have made this advantage abundantly clear. The studies of auroral lifetime (Krukonis and Whalen, 1980) could not have been performed with DMSP images for this reason, so the task was done by photography from an aircraft. Many other forms of natural and man-made lights that are clearly represented in DMSP images could likewise be more usefully recorded if their changing patterns through the night could be monitored.

Acknowledgments

I thank the many USAF personnel who provided much of the information needed to make use of the tapes. In particular, I would cite Mr. A. W. Kimball of Westinghouse for his breadth and depth of technical knowledge about the DMSP. I thank Mr. A. P. Colvocoresses of the USGS, who perceived the importance of digital information and arranged for the provision of tapes. This work was supported by NASA.

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(Received 3 November 1980; accepted 18 February 1981; revised 6 April 1981)

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