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By: THOMAS A. CROFT

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NOTE

DMSP image processing involves the use of the Cassini map projection whereby distances in the cross-track or Y direction are made true to scale. This is the same approach used by Croft in defining the Y direction as described starting on p. 30. However, this results in an affine map projection since scale becomes larger in the along-track or X direction as one moves away from the orbital path center line. The USGS recommends the use of conformal projections such as the Space Oblique Mercator (SOM) rather than the affine Cassini for such applications. The SOM has been implemented thus far only for Landsat imagery.

A. P. Colvocoresses
U.S. Geological Survey

I SUMMARY

The U.S. Air Force has operated its Defense Meteorological Satellite Program (DMSP) for nearly a decade, and film images from the system have been openly available since 1973. Films are well suited for the study of weather, and users of such films have derived much useful data. For many potential remote sensing applications, however, a quantitative measurement of the brightness of the imaged light patterns is needed, and it cannot be extracted with adequte accuracy from the films. Such information is contained in the telemetry from the spacecraft and is retained on digital tapes, which store the images for a few days while they await filming. For practical reasons, it has not heretofore been feasible for the Air Force to provide a remote-sensing user with these digital data, and the quantitative brightness information has been lost with the erasure of tapes for re-use.

For the purpose of evaluation of tapes as a means for remote sensing, the Air Force recently did provide to the author six examples containing records of nighttime DMSP imagery similar to that which has previously been evaluated by SRI International in a film format.[1] The digital data create many new applications for these images, owing to a combination of several factors, the most important of which are the preservation of photometric information and of full spatial resolution. In this evaluation, stress has been placed upon determination of the broad potential value of the data rather than the full exploitation of any one aspect of it. The effort was guided by an objective to develop handling methods for the vast body of numbers--methods which will be practical for use in a research or engineering environment where budgets are limited, and specialized capabilities and image reproduction equipment has not already been developed. We report the degree of success obtained in this effort, pointing out the relative strengths and the relative limitations, as compared to the sophisticated, weather-oriented data processing which is well suited for the Air Force requirements.

Both geometric and photometric calibration methods are evaluated. An image can be considered as a 3-dimensional array, X, Y, Z, in which X and Y are the coordinates of a picture element (pixel) and Z is the brightness at that location. A method of approach to handling these parameters, particularly Y and Z, is developed in a form quite different from that which serves the operational applications.

The user of digital data will need the film images which are generated by the Air Force from the same data as is provided on digital tape. In the first stages of analysis, the films provide both a convenient index and a guide to identification of large patterns in the data. Additionally, the infrared (8 to 13 μ) film provides a valuable indicator of cloud cover.

Two general conclusions are drawn from this study. Firstly, the digital DMSP data have great potential value but their cost, in terms of the interruption of the present operational routine, is quite high. Therefore, if a program is undertaken to provide for the open availability of an archive of digital records, great care must be exercised in selecting only those records which have unusually high value in order that the effort will be cost-effective. Secondly, it is concluded that several aspects of the program, well designed for Air Force operational purposes, are not adapted to earth-sensing needs. This is probably inevitable, since the two applications are largely different and in some ways incompatible. For example, the nighttime visual sensor saturates in the center of major cities and in moderately large fires (such as gas flares). This saturation prevents the analyst from integrating photometric parameters. For weather observation, this inability is unimportant, and acceptance of such saturation makes feasible a decrease in the data rate.

Such limitations in the data will probably be overcome only through modifying the existing system or the implementation of a similar system designed specifically to serve earth-sensing needs.

II BACKGROUND

The Defense Meteorological Satellite Program (DMSP) is based upon a series of earth-orbiting satellites whose primary function is the observation of weather, both day and night, by means of sensors which make images in the visual and infrared bands. The previous work at SRI International, and the current work reported herein, concern only the visual sensor and only those data obtained on that half of each orbit when the imaged surface of the earth is at night. In this condition, and only in this condition, the electromagnetic energy sensed by the system is in a large measure a product of the activities of the men on the surface of the earth. In addition, there are other natural sources of light such as lightning, aurora, and moonlight. In contrast, the infrared sensor primarily detects one kind of radiation--the heat radiation indicative of the temperature of the clouds or of the surfaces, if no clouds mask the view. In a similar simplification, the daytime records from the visual sensor are almost exclusively owing to one source--sunlight reflected from the clouds or the surface. It is the many-faceted character of the sources of "nighttime visual" lights, being attributable to a variety of both natural and man-made phenomena, which leads to their great interest and to the probability that, when properly recorded and processed, nighttime visual images can play an important economic role in the remote sensing of the earth from space.

Work in this field has heretofore been limited by the fact that the only records made available from the U.S. Air Force system to civilian analysts have consisted of film images. While each such image is originally recorded on magnetic tape, the records are generated at a density of approximately 30,000 bits per inch (bpi) in a format which is not transferable to outside computer centers at the present time. The current state-of-the-art in computer tape recording includes 9-track, 1600 bpi tapes which cannot keep up with the data flow during the transmission of DMSP imagery, or their playback from the 30,000 bpi recorders.

In order for the Air Force to release digital magnetic tapes which are compatible with standard computers, it was necessary for the Air Force personnel to execute special computer programs, written only in the last year, by means of which the full information on an original data tape can be transferred to a more conventional format. This entails a considerable effort by both the operational personnel and their computers, already fully engaged in meeting practical needs.

As one of the objects of this evaluation has been the determination of the practical use of digital tapes in place of films, the foregoing mention of the effort required to make computer-compatible digital tapes is relevant. It was clear that the existing facilities, and the personnel assigned to operate them, could not support a major program of supplying tapes. Any program for supplying digital data on a somewhat routine basis will require the implementation of some screening procedure so that only the most useful segments of imagery are digitized.

As a first step in this evaluation of nocturnal images, SRI undertook a study of the films (under a previous contract) with the object of establishing cartographic benchmarks and a systematic identification of the fixed lights which appear on the surface in those images which show land.[1] (Croft, 1977, herein called "report one.") Many bright, fixed lights are the major cities of earth and, somewhat surprisingly, the brightest are those due to the major gas flares which are distressingly plentiful. The other source of cartographic information in nighttime pictures is, of course, moonlight. It illuminates the surface and reveals a picture much like that in daytime. Under such circumstances, little more is needed to aid in identifying geographic locations. On moonless nights, however, the surface bears much resemblance to a star field in the sky; the determination of latitude and longitude then requires a "best fit" of imagery to the locations of known light patterns. An atlas of such light patterns was provided in report one. This work was adjudged to be of significant intrinsic interest, and as a result the author was invited by Scientific American to write an article on the subject.[2] This article in the July 1978 issue probably did more to bring the DMSP to the public awareness than any other single event.

All this preceding work has depended on film exclusively, carrying with it the inherent limitation that pixels cannot be accurately discerned either in latitude, longitude, or brightness. The latitude and longitude dimensions have been satisfactorily (for many purposes) treated through matching of the imagery to known benchmarks.

The Air Force data and filming process is designed so that sensor gain varies in a way which compensates for the changing conditions of lighting, with the object of producing a film whose gray shades are proportional to the albedo of the surface. This approach is ideal for weather sensing; the processing machines produce a final product requiring neither calibration curve applications nor other corrections. The remote sensing worker who wishes to determine source brightness must undertake to determine how the gain of the amplifiers has been varied in order to yield the albedo map; the calculations must then be reversed in order to recover the brightness parameter originally measured by the sensor. In effect, the Air Force system has been made practical through the incorporation of preprocessing (some of which takes place in the satellite); the preprocessing must be reversed to recover the primary information. The reversal is not difficult except in the case of one operational mode called "along scan gain control" (ASGC), in which there is not sufficient recorded information to permit an exact reconstruction of the original measured brightness. Fortunately, ASGC is seldom used in the circumstances which are of interest to this study.

III RAW DATA: THE PRIMARY RECORDS ON TAPE

When supplied to SRI International by the Air Force, each digital record encoded an image which covered a roughly rectangular area having the full width of the DMSP scan (3060 km) and a length of from 5 to 10,000 km. Such a body of data occupied roughly one quarter of a 2400-ft reel of 1/2-inch magnetic tape. In its original form, the image is composed of a single long, uninterrupted string of numbers. The use of such data for analysis requires the application of an orderly approach for access to desired subsets of the numbers. This problem is exacerbated in DMSP data by the lack of an accurate system for relating a pixel to the latitude and longitude it represents. The method for bringing smaller-scale order to the DMSP (which SRI has developed herein) involves sub-dividing the data into "units" and devising a system of relatively simple programs, each of which deals with data in such units. For practical reasons which will become apparent, the SRI units are 72 pixels wide (in the across-track direction, usually east-west) and 64 pixels long (in the along-track direction, generally north-south). One of the computer programs which deals with the unit generates a symbolic listing of all the inherent information in an array laid out like a map. A second program, operating on the same unit, produces a map having variable shades of gray which can be made to match the shading and proportion of the Air Force films.

As one of SRI's purposes was to evaluate the general usefulness of these data, we have made an extra effort to avoid using unique capabilities and to keep these systems both universal and simple. For this reason, all symbol and gray shade plotting is done with a widely available typing mechanism using the "Diablo" element. Similarly, all computer programs are written in "Basic" as it appears to be a widely accepted computer language of today. (In an IBM-equipped research facility, "Selectric" elements could readily be substituted for this system.)[3]

With this preview of what is to come, we return to the raw data tapes which are, basically, exceedingly long lists of numbers. In the original form, the individual bits are organized in groups of three and, as a result, the simplest printouts of the data represent everything in octal digits. An initial listing of the original tapes will then yield pages of octal digits which seemingly exhibit little order. However a closer examination will reveal that there are 2,988 octal digits which exhibit little order followed by 60 which are readily recognized by their repeating patterns of digits. The first set, the 2,988 octal digits, represent 1464 pixels which lie along a single across-track scan. The brightness of each pixel is recorded as two octal digits, or 6 bits. Associated with each across-track scan is a header, comprised of the 60 orderly digits previously mentioned. In this header are given the essential physical parameters required to locate the scan within the body of data, and to record some of the more temporally variable calibration parameters.

After some initial processing of the data, the scans take the form shown as Figure 1. Two and one-half scans are shown here, separated from each other by a blank line. The first line of numbers in any one scan is the header; all the subsequent numbers within each scan are pairs of digits representing the brightness, now converted to decimal (rather than octal) numbers. In the interest of keeping the list short, we have chosen not to put spaces between the pairs of decimal numbers representing the pixel brightness; in practice, when one wishes to read such a list, an overlay is applied which contains vertical lines that separate the numbers into their correct pairings.

In the original data, the pairs of digits which represent brightness were allowed to vary only between the values of 1 and 76, octal. The values 0 and 77, although present in the original data and used in Air Force filming, have been eliminated from the tape-recorded data by changing all 00s to 01s and all 77s to 76s. As a result, the brightness data should never include the successive digits "00" or "77". This is a useful property, since it helps both the computers and the humans to spot the header (which <u>does</u> contain such pairs). In converting these octal

26183638272036393544424548373339364046443023282333383635273434364245433823262829343217164335344534354128353036313735382835384037393
3432464838364137393129443239363736413938272631223732364136273141463330383444474141343127382837523537443634413635433931222338253535
2429383643283842363134322937282536383934283142383431333133384140282131272434323136324235384430233333453835293037304442294537343843
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3142353935303336332739423835172836353548372123202932303931323235444637402537352231414035343051352436342849422835252737302825393441
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2933302745382430282731383944363437453533413730413639363642242435354343393438484640354331383028394436414630333931342931273536433837
4131293431443222324440352844434137313339303238323735473115352728363430283634413338434037464138302324393842364142293436393634403344
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3442433537261 2 4 0 0 0 1302732332026372118291029 32 4 5292933242928241723322922212313 8203322312111254028173328343233323333102941 32
3732374327234649443337534439443126363933223440342825413832404029414839434233392736403739312432172833333236422930353133272936393943
4541272935333442322931284948342840312227263430272933313846373436344036373033302434384034343134363338283033283722284338353542342549
4727262526304045394835363124301722433729413731291929473629373634433739322830212640333229362922343733372732322229343334251836512821
2624273331292635393523302527202119343938322930122640372222223383234313137301635352134282526171834413223192841332418311824352930343 5
3128363930352931251526343822263030263017203830314926141926292124373929382623353627223020263329263134302030262327183434163532233128
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2932313942352424343432353745433839263942394842433537394039324037434636424345343029404744404034343642433536302633344040322128414732
3728273741433127393333414339403744443544463331263541273546424633284240374740324056433543433635364339333534493434373535404642373234
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42412729323842 6 0 0 0 0 632242639222631 18 822182530 61830333031181931307404030252729312331371715153733323428333434303427363931 43
3830303742271934403627313133332313426395239434843323337283039423438302332353730373531364429323128454640413331242629363827243630 32
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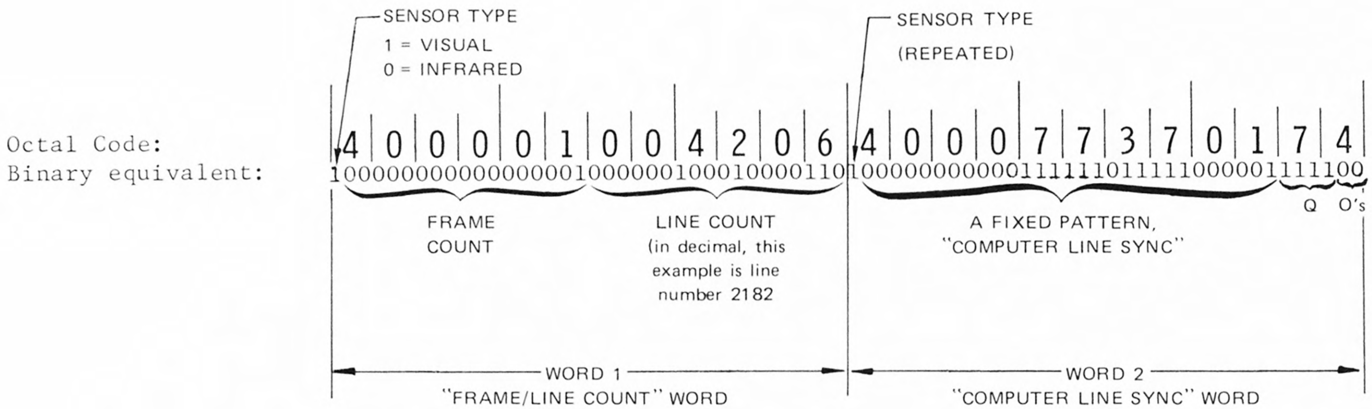
4222312826283033292126343335242330323828233842283030322423254033222124242336273938162527152531283229323318222435353238312837311925
2321292037382239331125381730272523182234331932441725492123301431383138353323241920434032283634382334333536312723293433363641402743

FIGURE 1 DIGITAL DATA FROM THE DMSP MAGNETIC TAPES AFTER MODERATE PROCESSING DESIGNED TO FACILITATE MANUAL EXAMINATION OF THE DATA. About 2-1/2 east-to-west scans are shown; the first line of each scan is a header which provides essential supporting data.

pixel brightness values to decimal, a value of 1 has been subtracted, so that the decimal values range from 0 to 61. Header recognition is then achieved in the SRI system by format control, where it is practical in the scientific application, because a more wasteful tape format can be afforded.

As depicted in Figure 1, each header consists of two parts separated by a space. In the original records, the first part of this header preceded the scan of data and the second part followed it. The header is explained in greater detail in Figure 2, where each octal digit has been broken down into its three component binary bits, shown directly underneath. The meanings of the bits or the octal digits are explained under the heavy brackets. The following comments about these parameters are offered as a rough guide, although we have not attempted to provide a complete explanation here. (Such explanations will presumably be provided with digital tapes to those users who receive them.)[4,5]

- The first binary digit will always be 1 since only visual data are contemplated herein.
- The frame count, although it occupies many binary bits, seldom gets larger than a few. The author speculates that the long string of bits, being mostly zeros, provide a primary recognition feature for finding the header in the original digital data strings.
- The line count simply counts the across-track scans and thus it will increase by unity in each successive header.
- Word two has never varied from the value shown in this figure, among the examples thus far witnessed by the author. The parameter Q gives a small-scale scan correction, already incorporated in the data and not needed in this work.
- Universal time of day is specified in word 125.
- The gain of the amplifiers is G and the mode of operation is M. These will be discussed later.



BETWEEN WORDS 2 AND 125 ARE 122 WORDS OF DATA, 732 PIXELS OF 6 BITS EACH, CONSTITUTING ONE LINE SCAN. (Other tapes from DMSP may contain 61 or 244 such words.)

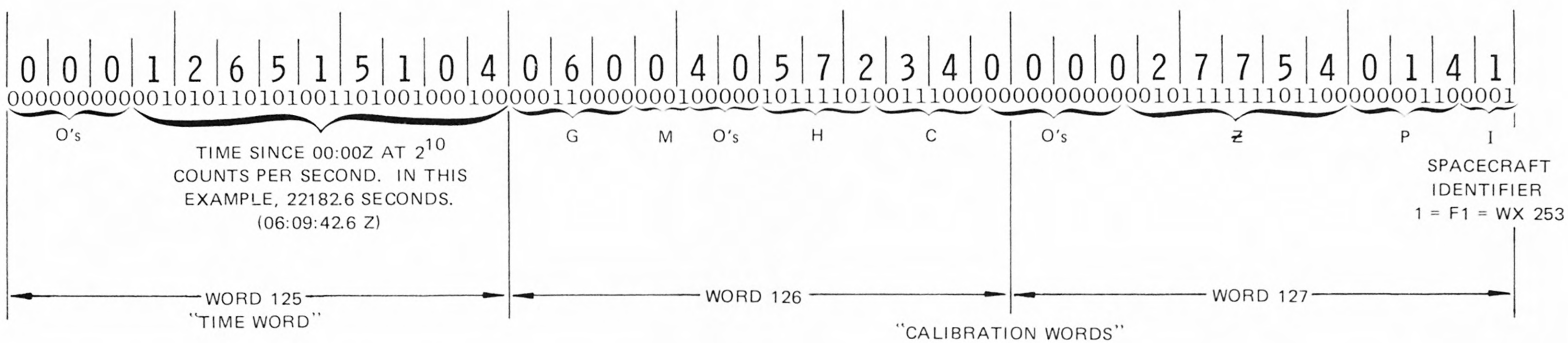


FIGURE 2 CONVENTIONAL IDENTIFICATION OF THE PARTS OF THE HEADER ASSOCIATED WITH EACH SCAN. In its original form, the header was split in two parts, one leading, and one following the data. Letters designate parameters defined in the text. Word numbering shown applies to "2 x 2 averaged" data.

The parameters H and C concern the infrared sensor. Spacecraft altitude above earth and attitude relative to the sun are coded in parameter Z and a photomultiplier calibration is given by P; only the altitude was needed in this study. (Image positions were adequately determined by interpolation among known locations.)

Many of the important header parameters are not adequately represented by the octal digits. In particular, some of the parameters require the octals to be broken into binary equivalents. Subsets, no longer in the original groups of three, must then be extracted. We have, therefore, implemented one further step in the processing of the header which is designed to make Basic data handling practical. This step is described by Figure 3, in which an octal header is converted to the SRI system, a mixture of binary, octal, and decimal representations. The treatment of line count preserves the frame digit as an initial number, a matter of convenience. Parameters Q and M are rendered in binary, because in that form their interpretation is clearest. Time, probably the key parameter, is preserved both in its original octal form (useful when referring back to more primitive data listings), and it is converted to decimal and then divided by 1024, in which form it is simply the number of seconds past U.T. midnight. The gain (G) is converted to decimal as the most convenient form; however, H and C and some zeros are maintained in their octal form as we do not expect to use them. Parameters Z and P will be needed in future computer programs and we have therefore converted them to decimal, the form which is needed by Basic programs. Finally (I), which identifies the spacecraft, has not been preserved in the SRI system. The spacecraft identification is inherently included in the overall data file titling system.

Figure 3 thus illustrates how the header is converted into nine numbers, each of which is in a convenient format. In the next stage of processing in the SRI system, the scans are divided into successive groups of 64. Associated with this group of scans, the 64 headers are preserved as a single entity. The 64 scans are called a "register" and so the group of 64 headers are called the "register headers," identified by a register number and an image number. The register size of 64 was

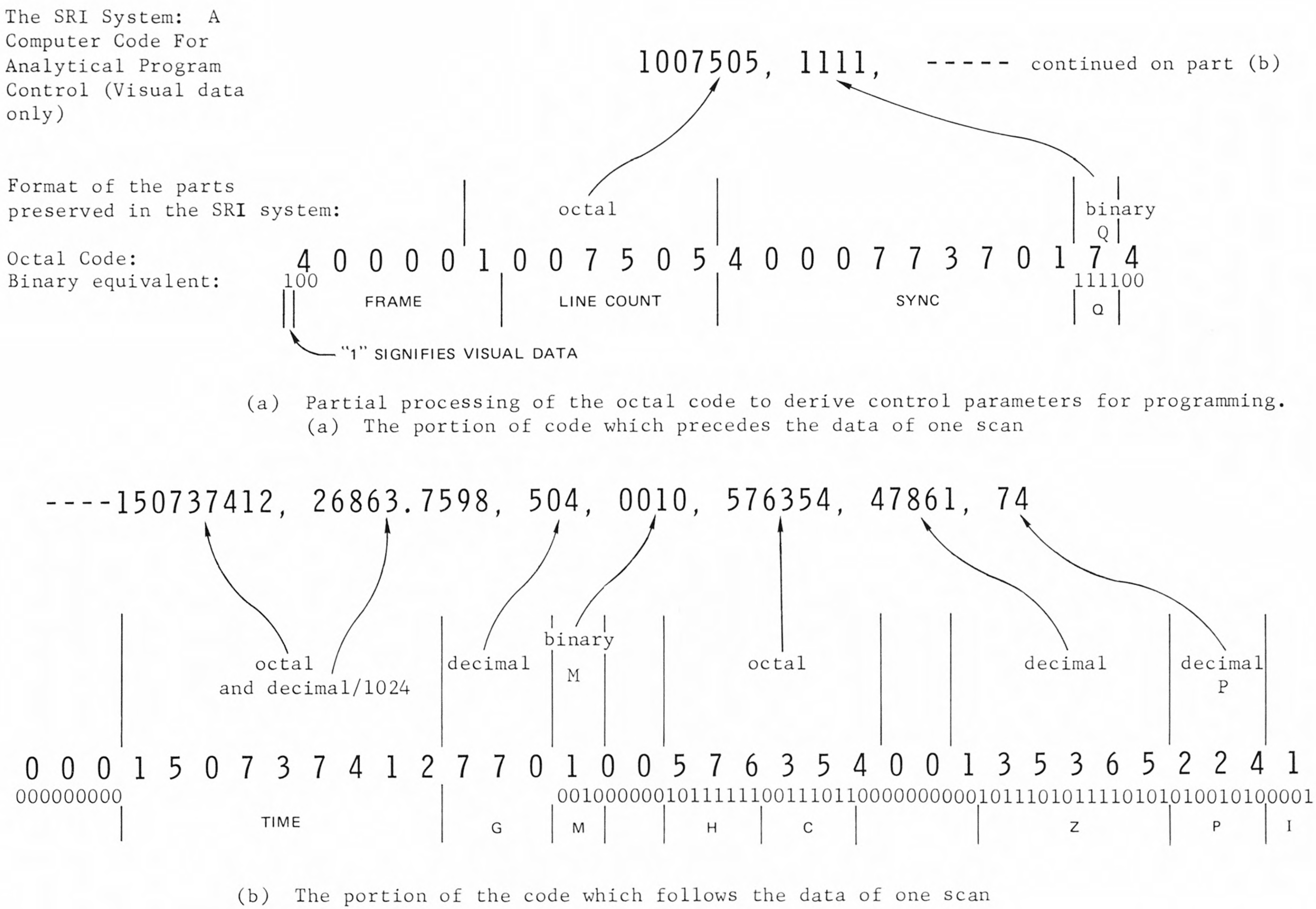


FIGURE 3 CONVERSION OF THE HEADER TO A PARTIALLY DECODED FROM IN THE SRI SYSTEM, USING AN APPROACH DESIGNED FOR THE VISUAL DATA. Parts of the header are rendered in binary, octal, or decimal, according to their meanings.

chosen because our digital tapes are inherently organized by successive groups of 64 scans. Two other coincidences supported this choice of 64; firstly, the map display was judged to be most convenient if the units of data were not much longer than 64. Secondly, SRI had earlier been provided with Air Force tapes in which groups of 4 pixels had been averaged together, ("2 x 2 averaged") and in such tapes the records (that is, the groups of numbers separated by gaps on the magnetic tape) contained 128 scans having precisely the same number of pixels as does the aforementioned register. By defining a register as equivalent to a record in the 2 x 2 averaged tapes, several convenient numbers describing the data became whole numbers. The significance of this decision as a guide to future work probably does not lie in the fact that SRI chose 64 scans, but rather in the experience that an optimum choice of unit size can simplify much of the work that follows. The choice of 64, which worked well in this exercise, might not be optimum if the tape formats change. Such a change does not seem unlikely, and partly for this reason we have made no attempt herein to provide a detailed mapping from the original tapes into the units of data.

The first few scans from a unit of data are depicted in Figure 4 where they take the form of a Basic data set. This was formed automatically, by the same computer program which read the original Air Force tape. In this set, the first line is a remark which provides a numerical identification for the unit, encoding its location both with respect to the along-track and across-track directions on the original film and the identity of the original film. This numbering system has worked well. The set of data is called a "unit" meaning that it lists the brightness of its pixels in two-digit decimal numbers ranging from 0 to 61. The designation "Unit.9.61.154" means that it is the ninth unit in the across-track direction, that it is from register 61, and that it is derived from the image identified as SRI number 154. The associated film supplied by the Air Force is also identified as SRI number 154.

The second line in the unit provides the repetitive part from the first and last headers, and is included in order to give confidence that no data artifacts occurred in the register. On one occasion, in one tape, three anomalous pixel values were found in one register, causing an

```
 990  REM     THIS IS   UNIT.9.61.156
1000  REM  40000100751140007737O174 40000100741240007737O174   949   878
1010  DATA 30,37,25,18,27,39,39,35,34,32,34,43,35,41,47,31,44,43
1020  DATA 31,31,34,35,44,42,33,37,38,29,41,32,27,47,39,37,36,35
1030  DATA 32,39,38,32,43,34,25,31,43,42,22,26,36,44,34,29,26,31
1040  DATA 36,42,32,32,35,32,34,50,38,22,38,37,45,33,29,42,35,28
1050  DATA 33,13,17,24,26,32,36,40,41,40,46,41,44,30,34,37,43,44
1060  DATA 46,35,27,36,40,39,37,39,38,41,44,44,42,43,43,38,38,42
1070  DATA 36,38,48,42,37,39,31,27,40,31,38,46,46,25,25,36,40,43
1080  DATA 40,32,27,38,41,38,50,33,45,39,24,34,33,40,44,39,38,33
1090  DATA 40,32,24,18,20,40,33,28,22,31,38,39,32,40,43,44,42,32
1100  DATA 28,35,48,48,39,33,37,37,40,43,43,39,31,47,46,36,35,31
1110  DATA 34,36,20,40,36,37,34,42,42,43,37,35,46,48,46,37,39,29
1120  DATA 32,28,37,37,27,38,47,36,33,44,35,37,27,27,43,30,40,43
1130  DATA 18,33,35,34,27,22,38,37,23,28,24,37,25,37,44,37,34,37
1140  DATA 32,36,43,42,42,36,38,42,28,36,43,32,28,36,42,38,30,36
1150  DATA 28,40,42,34,32,37,42,46,40,35,35,37,34,34,49,34,35,33
1160  DATA 39,43,36,35,36,43,43,35,43,56,40,32,40,47,37,40,42,28
1170  DATA 23,26,31,25,26,23,27,25,29,31,28,30,30,24,28,33,38,32
1180  DATA 37,28,45,39,32,25,37,34,34,39,38,33,37,40,36,34,35,38
1190  DATA 33,24,41,44,33,40,34,36,39,36,34,29,42,41,36,42,38,39
1200  DATA 24,23,30,38,41,46,37,40,43,38,33,41,34,36,28,30,34,36
1210  DATA 13,22,20,15,8,13,16,29,27,22,39,38,34,19,28,36,20,22
1220  DATA 33,21,29,34,33,39,34,32,39,44,34,29,33,42,41,37,39,39
1230  DATA 37,30,36,43,38,34,37,45,29,42,44,30,37,30,29,35,38,45
1240  DATA 33,33,23,30,44,38,35,42,32,36,31,32,34,24,27,31,21,28
1250  DATA 7,19,10,21,30,29,18,44,45,24,20,35,35,31,33,30,33,36
1260  DATA 39,41,43,40,28,27,27,23,35,45,44,37,37,37,39,43,35,30
1270  DATA 38,29,38,42,43,33,40,33,27,38,31,39,34,30,35,36,37,36
1280  DATA 37,28,25,34,40,38,27,36,37,33,32,42,41,41,44,50,39,20
1290  DATA 2,2,1,8,16,21,22,28,27,27,38,30,30,23,22,33,38,39
1300  DATA 34,22,30,42,22,34,36,29,36,33,34,40,41,41,39,44,30,29
```

FIGURE 4 PARTIAL HEADER AND FIRST FEW SCANS OF DMSP DATA AS PRESERVED IN ONE UNIT OF THE SRI SYSTEM. Unit includes all information for a region 72 pixels in the across-track direction and 64 pixels in the along-track direction. Four data lines comprise one scan.

illogical interpretation of all subsequent numbers. No repetition of this error has yet been found, but if it occurred it would upset the reading sequence, and this second line in the unit would then be changed.

The last two numbers in the second line of the unit provide the count of the included pixels in the across-track direction. The count begins from the eastern edge of the picture, even though the scan began from the western edge. This unconventional ordering is caused by the fact that the spacecraft recorded the image on a tape recorder that did not rewind before playback; rather, the numbers were sent to earth during playback in the reverse direction, so that the order of all numbers (that is, the sequence of pairs of octal digits) representing pixel brightness was reversed. The header information was not reversed, however. In the SRI units of data, this reversal has been again reversed so that the numbers read from left to right and from top to bottom (that is, from west to east and from north to south). Registers are still numbered from south to north.

A complication will arise when data become available from the newest DMSP satellite (F4) because it makes its nighttime passage while traveling from south to north! In the SRI system, concern about these matters is minimized, because the units of data are always preserved as described, occurring in the same orderly system that words appear on this page. The complication of dealing with all the possibilities of order is then relegated to the computer program which generates the units.

Summary of the Data Handling Procedure--We have described a program for unitizing a long stream of numbers by means of a system that lends itself to simplified processing without compromising quality. All of the essential information is preserved. The map area, as represented in the original image by a film, can be visualized as subdivided into small rectangular areas, herein called units. Roughly, a unit width of 72 pixels is about 100 miles, and approximately 20 units are required to compose an entire across-track scan. A unit length of 64 pixels is, also roughly, 100 miles. The processing of areas larger than a unit requires the separate treatment of several units and the subsequent blending of results. Many examples of this will be depicted here.

IV MAKING PHOTOMETRIC DETAIL ACCESSIBLE

In the study of a picture, the questions which arise are largely in this form: the analyst examines an image and then, from pattern recognition within the image, inquires concerning the brightness of comparatively small subsets of pixels. Usually the outline of these subsets does not follow a mathematically simple form, but rather it is in a form which follows the outline of the surface phenomenology. In most instances, we expect that the user of DMSP digital images will need a capability to pluck (from the discernible data) the brightness values of individual pixels selected from a map. If it were necessary to do this by computer programming, the problem could become quite complex. SRI has endeavored to develop a practical alternative in the form of a symbol plot and a corresponding map, having a one-to-one geometric layout similarity. The user may then examine the map, determine the regions of interest and refer to the symbol plot to determine the original photometric values, pixel by pixel.

The "Sixol" Plot--It will be recalled that the original DMSP brightnesses were included in two octal digits but that the values 00 and 77 were not included. Here, this numbering system will be called "modified octal," as it includes only 62 values. In the units of data, SRI found it convenient to represent these 62 values by the decimal numbers 0 to 61. Each of these values, when plotted on a map, will yield one symbol. A convenience therefore arises if we form a system of 62 individual symbols to represent the 62 brightness levels. This was done as depicted in Figure 5, showing decimal, modified octal, and "sixol." The latter term is an abbreviation of "six-bit symbol" which we introduce here in a form having only 62 assigned values. Other applications for sixol will require all 64 values, achieved through the use of two more symbols which follow Z.

Decimal	DMSP {modified octal}	Sixol {introduced here}
0	1	0 or blank
1	2	1
2	3	2
3	4	3
4	5	4
5	6	5
6	7	6
7	10	7
8	11	8
9	12	9
10	13	a
11	14	A
12	15	b
13	16	B
14	17	c
15	20	C
16	21	d
17	22	D
18	23	e
19	24	E
20	25	f
21	26	F
22	27	g
23	30	G
24	31	h
25	32	H
26	33	i
27	34	I
28	35	j
29	36	J
30	37	k
31	40	K
32	41	l
33	42	L
34	43	m
35	44	M
36	45	n
37	46	N
38	47	o
39	50	O
40	51	p
41	52	P
42	53	q
43	54	Q
44	55	r
45	56	R
46	57	s
47	60	S
48	61	t
49	62	T
50	63	u
51	64	U
52	65	v
53	66	V
54	67	w
55	70	W
56	71	x
57	72	X
58	73	y
59	74	Y
60	75	z
61	76	Z

FIGURE 5 A 62-ELEMENT DIGITAL CODE, CALLED "SIXOL," DEVISED TO PRESERVE THE FULL DETAIL OF DMSP DATA IN MAPLIKE ARRAY

The sixols are in effect a natural extension of the 4-bit symbols called hexadecimal. Similarly, 3-bit symbols are called octal and 1-bit symbols are called binary. From the author's studies on this matter, it appears that 7-bit symbols are not practical because of the limitations of both symbolism and mechanisms. Therefore, sixol probably represents the ultimate achievable numbers of bits which can be converted into a single-character code. (Superimposed pairs of symbols could serve to encode 7 or 8 bits, if a need arises.)

In order to make possible the use of the sixol symbols as depicted in Figure 5, it is necessary to use a type font which distinguishes between zero and the letter oh, and which distinguishes between the number one and lower case letter el. From experimentation with the machines which were already available within the author's facility, it was determined that 3 or 4 type fonts met the criterion, but that the optical character reading (OCR) version of the Diablo wheel was the best for purposes of publication. This has been used to generate Figure 5 and all the plots given herein. This approach offers an additional advantage; any reader equipped with the necessary mechanism to read OCR symbols can then reconvert these sixol plots back into numbers, and thereby recover the DMSP digital data in their full detail. Since the printed page is a compact form for the presentation of such data, it is the writer's expectation that future computer centers will include optical character printers and readers as a normal means for the preservation and communication of data.

A unit of data in a sixol array is given in Figure 6. The blank region in the lower edge is Dallas and Fort Worth, whose central lights were so bright that the DMSP sensor saturated, yielding all zeros (which are here represented by blanks, in order to increase the visibility of saturated regions). The seeming featurelessness of this array, except for the blank region noted, is misleading. A careful examination will reveal many small regions that are brighter than others, but such an examination is tedious and time-consuming. We shall see that a slight modification of the array yields a black and white map which makes the features stand out much as they do in a film image. Then from a

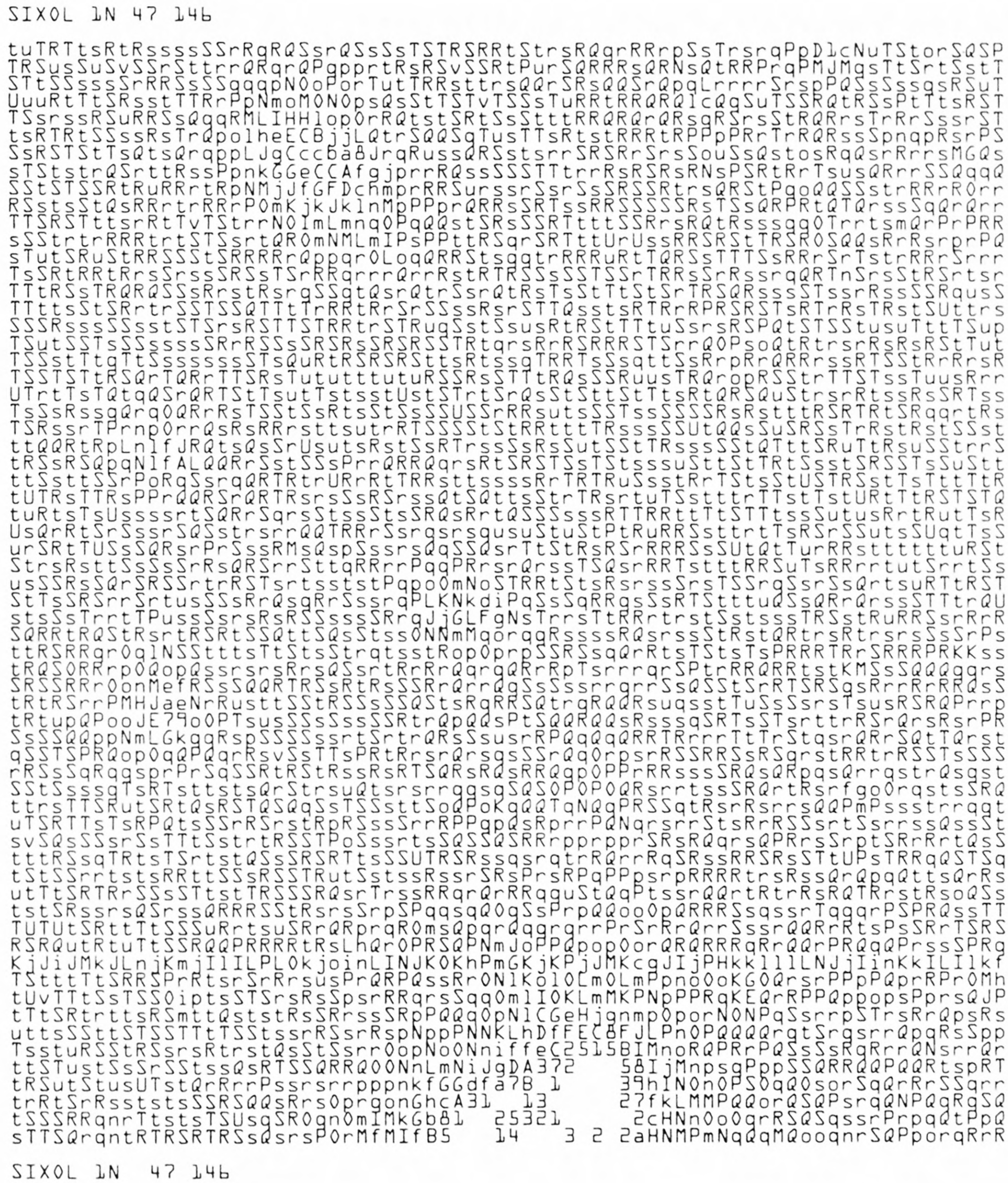


FIGURE 6 ONE UNIT OF DMSP DATA CONVERTED TO SIXOL SYMBOLS, ARRAYED AS A MAP. When accompanied by a gray-scale map and appropriate calibration data from headers, this chart permits the viewer to reconstruct detailed photometric data inherent in a DMSP image.

side-by-side comparison of the map and this sixol array, the user can identify those symbols which contain desired photometric information, extract them, and thereby determine individual pixel brightnesses.

The generation of a sixol array such as Figure 6 is simple, largely because the data are already appropriately organized in the unit. Figure 7 shows the complete Basic program necessary to convert one unit of data into one sixol array. The program consists of two parts. First, a list having 62 spaces is filled with 62 sixols, in order, from pixel value 0 to 61. Next, groups of 72 values are read from a unit of data and the corresponding groups of 72 sixols are stacked in horizontal lines for printing. After 64 such lines are printed, the task is completed. The program required to do this is shown in its entirety, written in such simple Basic code that it should work on most Basic compilers without modification. (Some compilers will not accept zero as an index; for such compilers a minor modification of the program will be needed.)

```
10  REMARK    Sixol.decimal     February 1979    Croft   SRI
30  REMARK      set unit label at 760
50  REMARK      place sixols in W$ for decimal data
60  DIM W${62}
80  FOR K=0 TO 61
100 READ W${K}
130 NEXT K
160 DATA ' ','1','2','3','4','5','6','7','8','9'
170 DATA 'a','A','b','B','c','C','d','D','e','E'
180 DATA 'f','F','g','G','h','H','i','I','j','J'
190 DATA 'k','K','l','L','m','M','n','N','o','O'
200 DATA 'p','P','q','Q','r','R','s','S','t','T'
210 DATA 'u','U','v','V','w','W','x','X','y','Y'
220 DATA 'z','Z'
250 GOSUB 750
260 REMARK     print sixols,  72 across and 64 down
270 FOR M=1 TO 64
280 A$=''
290 FOR N=1 TO 72
300 READ D
310 A$=A$+W${D}
320 NEXT N
330 PRINT A$
370 NEXT M
380 GOSUB 750
390 GOTO 799
750 PRINT
760 PRINT 'UNIT.8.102.156'
770 PRINT
780 RETURN
799 END
```

FIGURE 7 COMPUTER PROGRAM CONVERTING THE DMSP DATA UNITS TO SIXOL ARRAYS

V THE GENERATION OF GRAY-SCALE MAPS

In order to generate gray-scale maps of the same information shown on the units, SRI set as its objective the application of the same Diablo OCR element used for the sixol plots. As a first step for achieving this objective, every OCR character was repeatedly printed in a rectangular array, from which a small portion of the resulting record is shown in Figure 8. This chart was then examined by means of a photometer (United Detector Technology, Inc., 80X Opto-Meter, with sensor 6288), and the brightness of the reflective light from each rectangular array was objectively determined. Each OCR character was thus associated with a certain level of darkness that would appear if that character were used to represent a certain range of the available 62 photometric values.

The human eye cannot perceive 62 shades of gray in light reflected from a page, nor do the OCR symbols provide 62 levels. Typically, in these plots, we attempt to provide nine or ten levels of gray. Better gradation was achieved in trials using two-symbol overstrikes, but for simplicity the single symbols are used here.

Using the OCR symbol thus selected by direct photometric measurement, the generation of a visually pleasing image from the units of digital data requires only a modification of the sixol plotting algorithm. A range of digital values must now lead to a single symbol. For convenience, a one-unit array of such symbols is here called a "map." By such means, and using only seven symbols (of which the blank is one), a digital image (map) of Atlanta, Georgia has been printed with Diablo OCR characters in Figure 9(a). In this map, one can see the outline of the city, the major access roads, and the smaller cities around it.

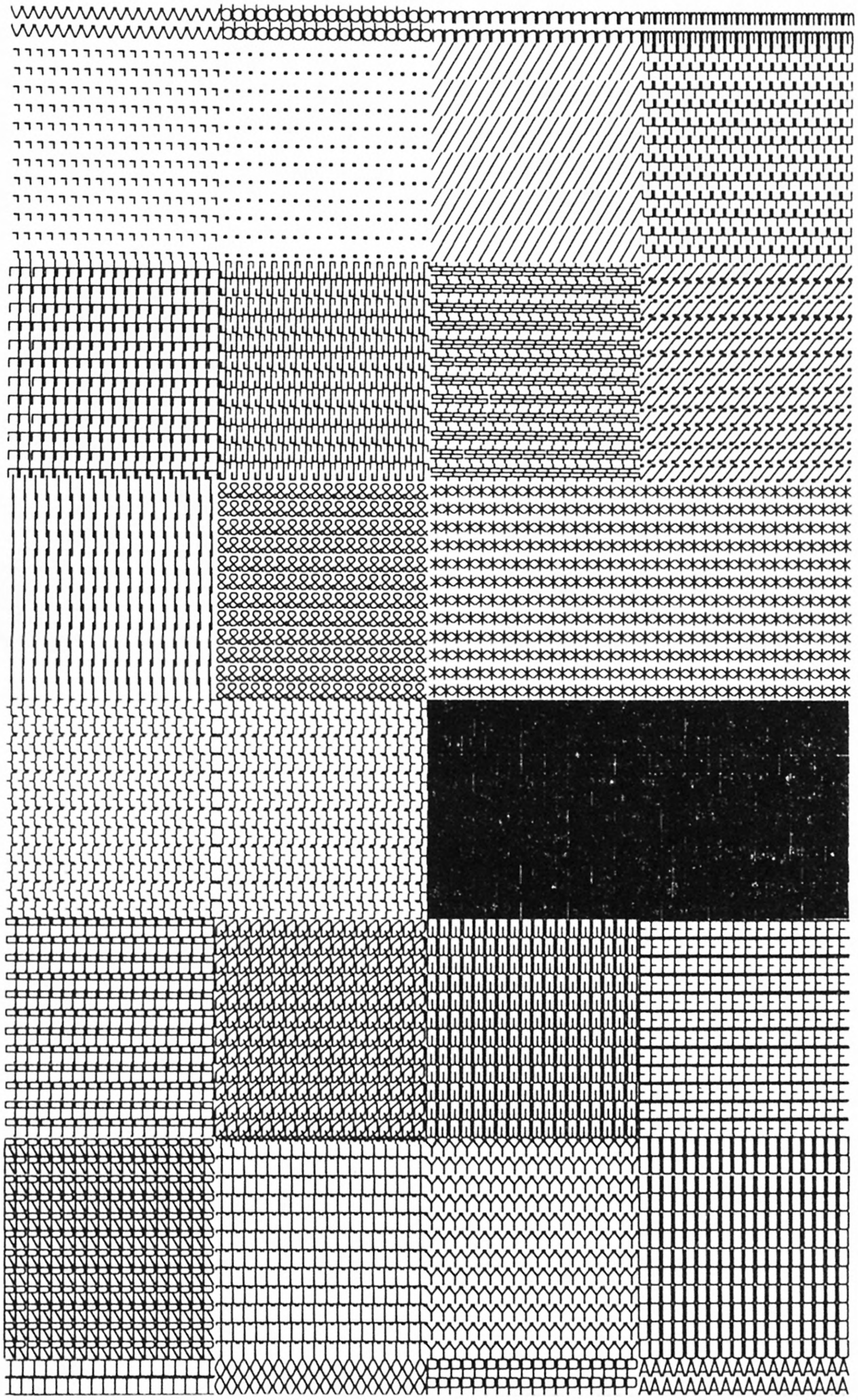


FIGURE 8 REPRESENTATIVE ARRAYS OF SYMBOLS USED IN PHOTOMETRIC MEASUREMENTS TO DETERMINE THE APPEARANCE OF DARKNESS (the Gray Scale) IMPARTED TO PAPER THROUGH PRINTING OF THOSE SYMBOLS. Results of photometric darkness measurements were used for selecting grayness symbols used in subsequent DMSP image generation (herein called "mapping").

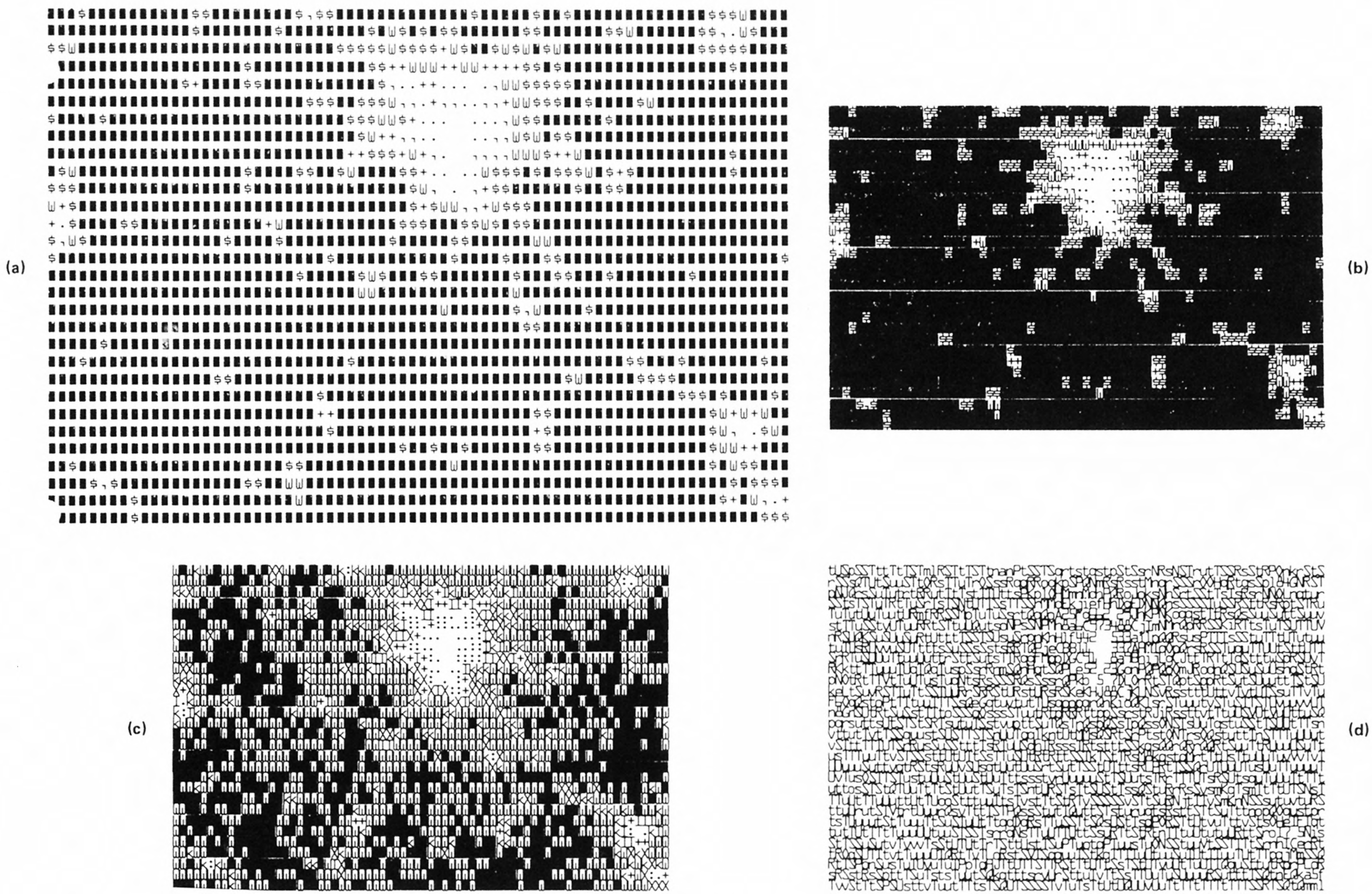


FIGURE 9 MAPS OF THE REGION AROUND ATLANTA DEMONSTRATING SEVERAL ASPECTS OF THE PLOTTING (refer to text). (a) Grayness symbols clearly separated; (b) Grayness symbols, placed contiguously; (c) Different gray levels assigned to the DMSP digital codes; (d) Sixol symbols, printed with the same density as plot symbols.

The spaces between the plotted symbols hinder pattern perception, and so, using a convenient feature of the DTC computer terminal, we have eliminated the spaces in Figure 9(b). In this map, one of the earliest examples of the SRI trial imagery from a DMSP tape, the outline of Atlanta and its neighboring population centers becomes readily apparent.

As an illustration of the kind of qualitative map change which is easily accomplished with these methods, Figure 9(c) shows the same digital information now represented by 9 shades of gray and with a digital partitioning which yields a lighter image. This is equivalent to an increase of the exposure of the film or, alternatively, a change in the gain settings of the DMSP. A marked change occurs in the appearance of the map and, in fact, similar qualitative changes are often observed in the film imagery. At times, such exposure changes make the recognition of familiar cities and gas flares more difficult. The value of such scale changes in the study of digital data lies in the fact that the limited range of visually perceptible gray variation can be fully utilized by adapting the digital partitioning to the particular needs of each image. In this case, for example, a requirement to locate cities and roads would best be met by the partitioning of Figure 9(b) while a requirement to study the darker details or the albedo of the surrounding countryside would be better served by Figure 9(c).

The elimination of spaces among the plotting symbols is not advisable when sixols are to be plotted. The example in Figure 9(d) shows the same information as in 9(b) or (c), plotted to the same size, and the sixols become difficult to identify. The sixol symbols must be kept separated, as in the example of Figure 6. This is only a minor inconvenience, as the analyst can readily relate individual sixols to individual gray map symbols, despite the different proportions of the sixol and map plots. By photo reduction, it is possible to make the sixol plot and the map of equal size, but this serves only the somewhat "cosmetic" purpose of appearance and is not necessary in a working environment.

Owing to slight imperfections in the symbol printing locations, we have found it advisable to compress the map symbols even farther than the examples of Figure 9(b) and (c). The remainder of the figures in this report have horizontal rows of symbols which overlap slightly.

A computer program which produces gray scale plots, or maps, is presented in Figure 10, together with the first part of a unit of data. Notice that the label, printed by statement 362, includes a space between every contiguous letter. In this manner, the label will assume a normal appearance when laid above the map with the symbols set close together. The program of Figure 10 is seen to be similar to the earlier program which makes sixol plots, except for the fact that the array is filled with only nine symbols which are assigned to blocks of numbers. Once this array is filled, the process of laying down the map is virtually identical to the process of laying down the sixol array.

```
10   REM     GRAY.DECIMAL        JULY 79     CROFT
20   REM        SET LABEL IN 370
30   DIM B${62}
40   B${0}=' '
50   FOR K=1 TO 3
60   B${K}='.'
70   NEXT K
80   FOR K=4 TO 6
90   B${K}=':'
100  NEXT K
110  FOR K=7 TO 9
120  B${K}='+'
130  NEXT K
140  FOR K=10 TO 12
150  B${K}='|'
160  NEXT K
170  FOR K=13 TO 15
180  B${K}='I'
190  NEXT K
200  FOR K=16 TO 18
210  B${K}='X'
220  NEXT K
230  FOR K=19 TO 21
240  B${K}='W'
250  NEXT K
260  FOR K=22 TO 61
270  B${K}='█'
280  NEXT K
300  REM   The B$ list is filled with plot symbols
350  Z=0
360  PRINT
362  PRINT 'A l b e r t a ,   S R I   1 5 6'
364  PRINT
370  PRINT 'MAP.9.101.156'
373  IF Z=1 THEN 600
377  Z=1
380  PRINT
400  FOR M=1 TO 64
405  A$=''
410  FOR N=1 TO 72
420  READ A
430  A$=A$+B${A}
440  NEXT N
450  PRINT A$
510  NEXT M
520  REM        DMSP data follow:
590  GOTO 364
600  PRINT
799  END
1000 REM  40000200071240007737017 4 40000200061340007737017 4    949   878
1010 DATA 49,33,25,31,32,23,20,22,22,28,8,14,8,25,26,8,20,28
1020 DATA 34,22,24,22,21,17,27,25,25,16,18,18,29,17,8,30,13,19
1030 DATA 21,13,20,29,29,17,26,16,27,37,30,21,16,5,0,2,11,16
1040 DATA 11,9,13,8,20,28,22,22,20,31,23,24,29,30,22,6,15,25
1050 DATA 48,48,31,32,39,37,35,29,38,26,8,12,22,23,14,20,25,25
1060 DATA 20,18,23,16,17,28,17,8,16,25,43,31,22,30,38,36,31,20
1070 DATA 16,18,29,18,13,25,26,21,10,1,25,34,6,11,19,14,13,16
1080 DATA 18,21,30,38,21,15,26,23,16,26,37,33,25,22,16,8,20,12
1090 DATA 27,29,24,32,29,32,39,45,42,36,35,25,19,19,34,40,27,18
1100 DATA 31,21,31,33,31,22,9,14,11,17,17,27,31,18,20,24,39,30
1110 DATA 20,19,18,23,18,19,16,25,14,17,29,31,8,24,32,14,19,27
1120 DATA 30,20,0,17,24,23,18,19,27,27,27,24,27,16,21,22,21,36
1130 DATA 27,24,36,27,23,33,41,38,38,29,27,35,16,15,27,27,38,36
11
```

FIGURE 10 COMPUTER PROGRAM WHICH MADE THE MAPS SHOWN IN THIS REPORT, AND A FEW SCANS OF DMSP DATA FROM ONE UNIT (four printed lines per scan)

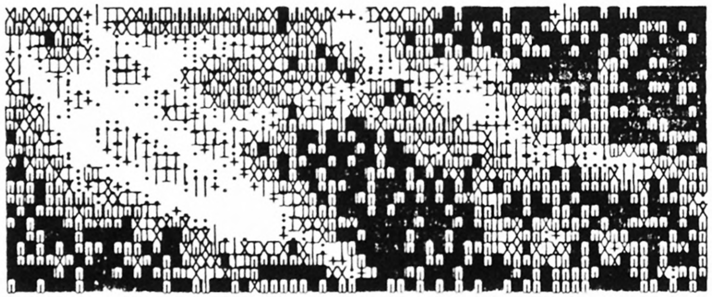
VI IMAGES DERIVED FROM DIGITAL DATA

In order to lessen the quantity of numbers which must be handled, many of the Air Force operational processes make use of "2 x 2 averaging," in which a single brightness value is derived from the average of 4 of the original values. Because the initial pixel size is nominally 1.5 nautical miles on a side, this averaging yields a resolution of 3 nautical miles. Because of the nonuniform scan speed, these nominal values differ from the true pixel size in some regions of the image. A more detailed discussion of the lateral scan geometry will be given shortly.

A. The Two Resolution Scales

Two images of San Francisco and the surrounding cities are given in Figures 11 (a) and (b). The former was obtained on September 8, 1978, and is a 2 x 2 average, having 3 nautical miles resolution. The latter was obtained on October 3, 1978, and it preserves the full 1.5 nautical miles resolution. The greater detail of the full resolution image is clearly shown by this comparison. It is concluded from a study of both types of data that the remote sensing community will, for most purposes, be willing to pay the price of dealing with a larger mass of numbers in order to achieve the 1.5 nautical mile resolution. Any averaging that may be desirable for the purposes of specific study will readily be performed by the investigator. The utility of the 3-nautical-mile tapes is based solely upon fact that they are less expensive to process per unit area on the surface, and this criterion is comparatively unimportant in this work, whereas it is of paramount importance to the operational community. One of the conclusions of this study, therefore, is that the digital data user will prefer the 1.5-nautical-mile tape rather than the 3-nautical-mile averages.

(a)



(b)

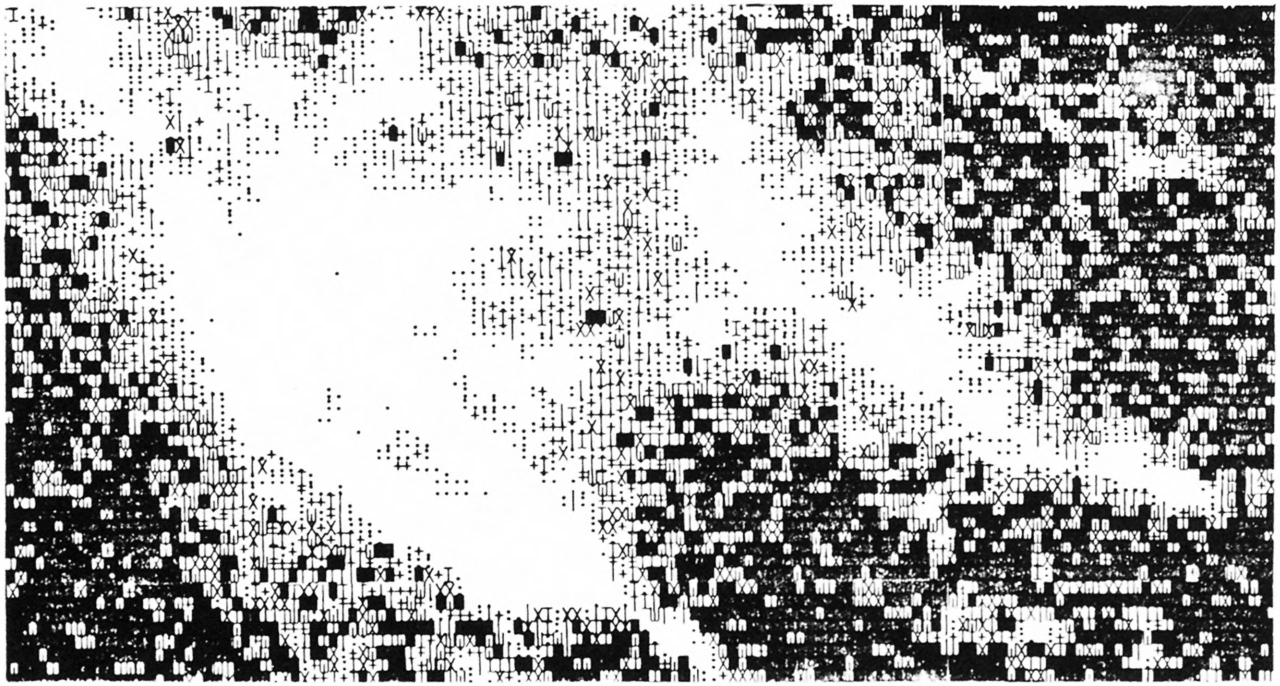


FIGURE 11 COMPARISON OF THE TWO TYPES OF DMSP DATA; THOSE WITH NOMINAL 3-NAUTICAL-MILE PIXELS (Part a), AND WITH 1.5-NAUTICAL-MILE PIXELS (Part b). Both images show cities of northern California, including San Francisco.

B. Pixel Saturation and its Consequences

The population center of America is depicted in Figure 12 at 1.5 nautical miles resolution, derived from the digital image obtained on October 3, 1978. The more southerly rectangular section of this image is composed of five units across and two units down, while the upper rectangle is composed of three units across and two units down. Thus, the image contains 16 units in all. On the far left is Pittsburgh, Pennsylvania; at the bottom is Washington, D.C., and from there toward the upper right one sees Baltimore, Philadelphia, New York, and Boston. This map illustrates the severity of the pixel saturation problem; all the white areas on this image are composed of pixels which are fully saturated and thus uninformative. The extent of our knowledge is that the white regions were brighter than the maximum recorded value, but this is not a very useful parameter. The presence of so many saturated pixels prevents the analyst from integrating the light output from cities. Since there are many potential practical applications of such a procedure, the saturation is unfortunate. At the present time, we are requesting a special run of a DMSP satellite in a mode which will not saturate at city centers, but it is a mode which does not serve the primary function of the DMSP satellite.

C. The Y Dimension: Details of the Scan

With each digital tape, the Air Force kindly supplies a film image. In Figure 13, we demonstrate the similarity between the images derived by OCR character mapping (a) and those derived from film (b). Here, a dozen units of data have been converted into a strip of image which extends from the Dallas-Fort Worth population center all the way to the sea, beyond Savannah, Georgia. This is an especially valuable region for study, because a line of cities extends in a roughly east-west direction which happens to be nearly colinear with the DMSP scan.

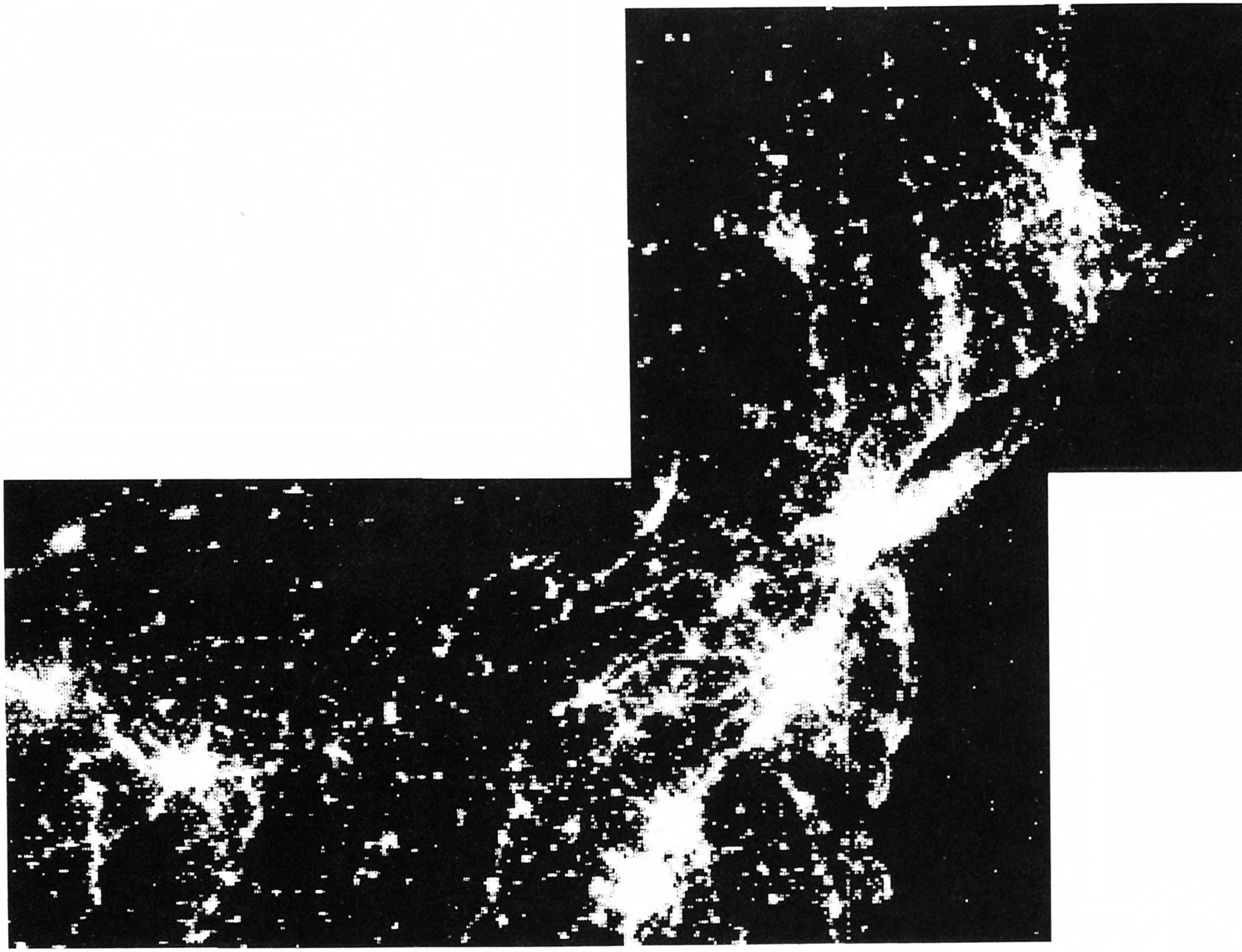


FIGURE 12 SIXTEEN UNITS OF DMSP DATA ON A CLEAR NIGHT SHOWING SOME MAJOR CITIES OF AMERICA. Pittsburgh (left), Washington, D.C. (bottom), and Boston (upper right).

(a)

(b)

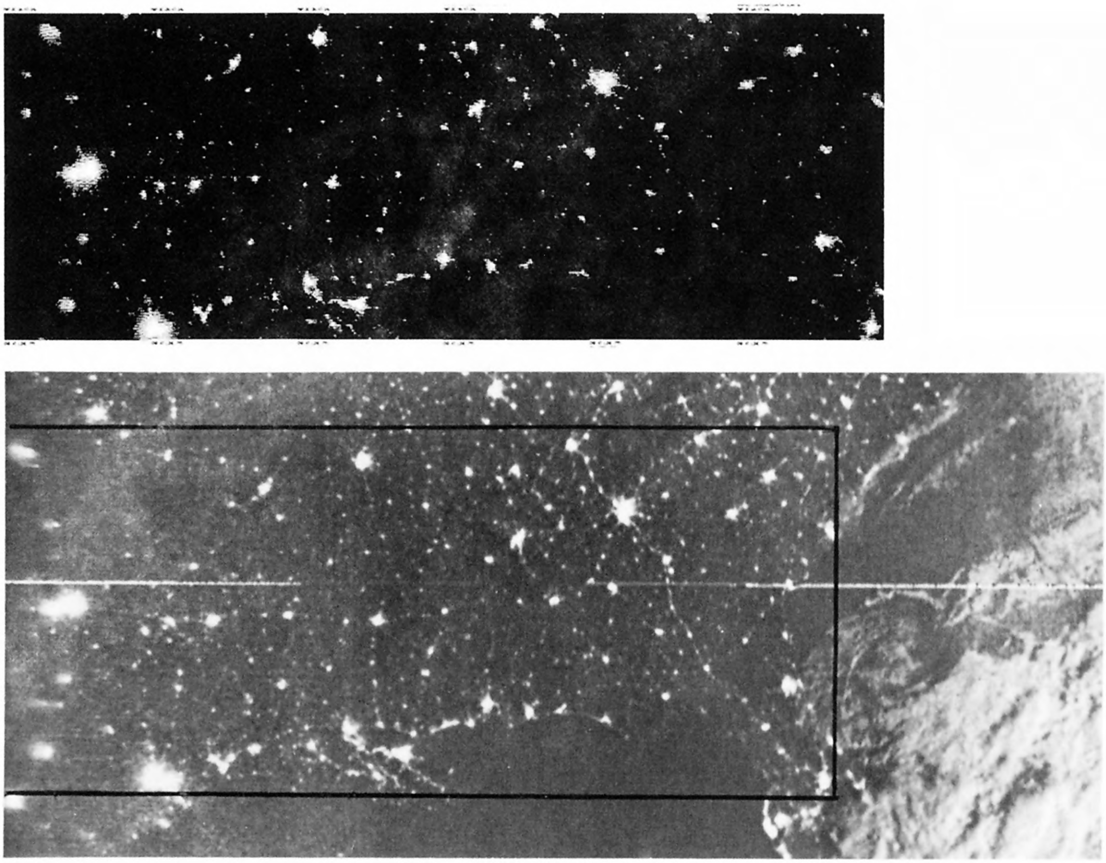


FIGURE 13 COMPARISON OF FILM VERSION AND DIGITAL MAP OF THE SAME DMSP IMAGE ACROSS AMERICA FROM DALLAS EAST TO THE SEA. Larger image is the Air Force film; map is composed from a dozen DMSP units, using system described herein.

By measuring the locations of these cities geographically, and by determining their pixel number along the scan, we have undertaken to evaluate the optimum method for pixel-by-pixel determination of along-scan location. Figure 14 shows the resulting comparison. The drawn line shows the calculated relationship between lateral geographic distance D from the nadir (the abscissa) and the pixel number n, (the ordinate):

$$D = R \cdot \frac{\pi}{180} \left\{ 90 - \cos^{-1} \left[\frac{R + H}{R} \cdot \sin\left(a \sin (bn)\right) \right] - a \sin (bn) \right\} ,$$

where D = surface distance, along scan, from nadir

R = radius of earth. D and R are in the same units

H = altitude of the DMSP satellite, in the same units

a = 57.85°, the full angle of mirror swing

b = 0.20888 for 3 n.mi. pixels; twice that for 1.5 n.mi.

n = pixel number counted outward along scan from nadir.

Each of the major cities, from Fort Worth and Dallas to the sea, is then shown by a dot which was located, with respect to the ordinate, by determining the pixel number of the city center on the DMSP image. The location of each dot, relative to the abscissa, was determined by measuring the geographic distance of the city from the subsatellite track. A few of the cities were east of the track, but most were west.

As the satellite passes overhead, it sees the earth by means of a mirror which is suspended on springs and is oscillating from side to side. In engineering parlance, this mirror spring system has a Q of approximately 500, from which parameter an engineer will conclude that the oscillating mirror position as a function of time is very close to the ideal sinusoidal.

The calculated line on Figure 14 was determined by the above formula, which relates the sinusoidal oscillation of the mirror to the distance along the surface from the nadir, assuming a nominal satellite altitude, and accounting for earth curvature as if earth were a 6370 km sphere.

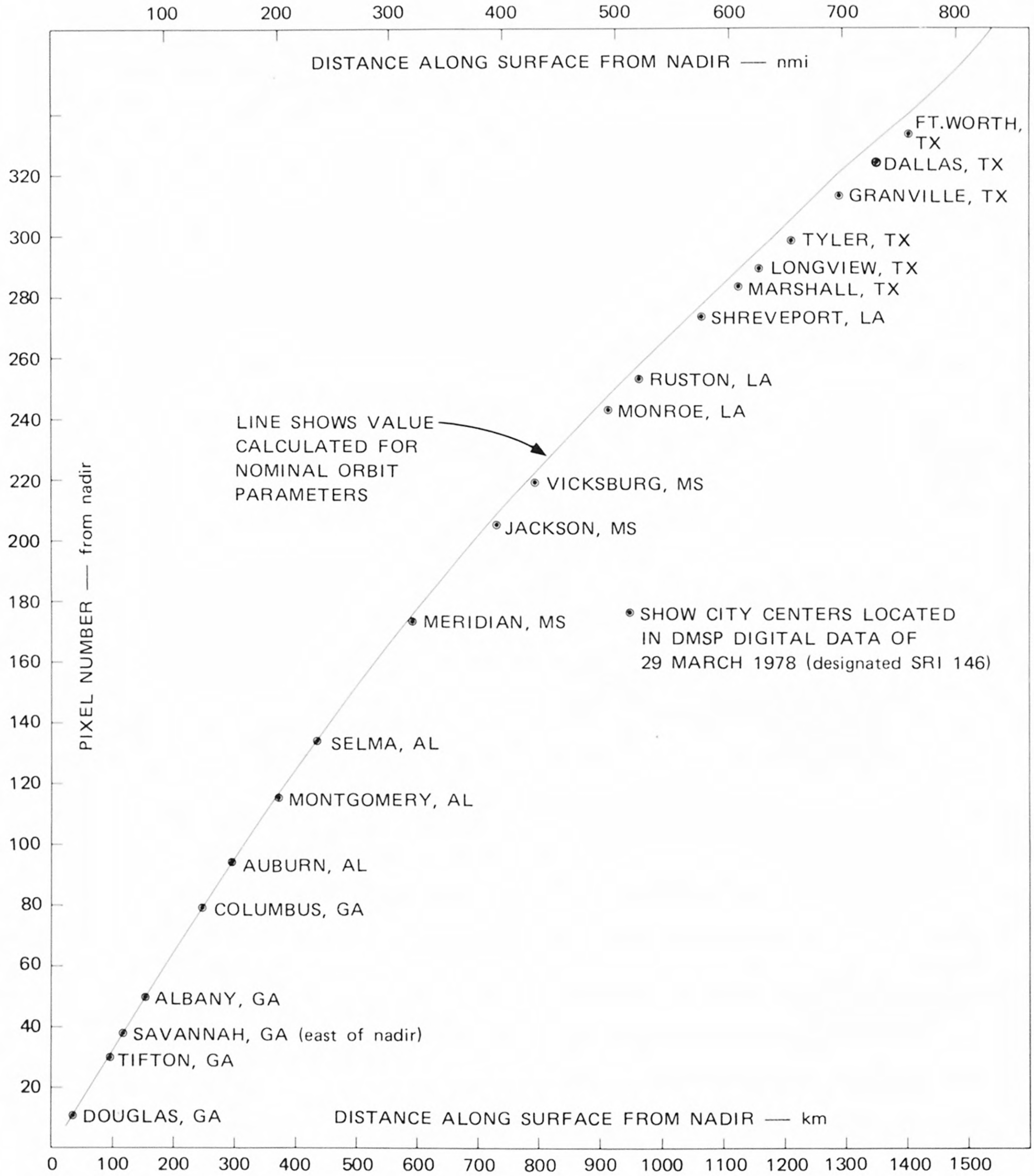


FIGURE 14 COMPARISON OF ACROSS-TRACK DISTANCE (calculated from mathematical description of the instrument scan) AND THE SAME DISTANCES DERIVED BY LOCATING SPECIFIC CITIES ON A DIGITAL IMAGE AND USGS MAP. The small, but gradually increasing separation of the curve (theory), from the dots (measurement) is attributable to altitude of the DMSP satellite (not nominal at the time of this observation).

The pixel number is based upon the fact that the pixels are obtained at equal increments of time. The line was thus derived and found to provide a close approximation to the city positions, except for a slow drift away from the correct value as the nadir distance increases. (Figure 14, upper right.) From header parameter Z (Figure 2), it was found that the spacecraft was higher than the nominal altitude at the time of this test, by the amount which correctly accounts for the mismatch between the lines and the dots on Figure 14.

In the Air Force film imagery, the along-track pixels are reproduced at equal intervals, but the across-track pixels (the ordinate in Figure 14) are nonuniformly spaced across the film to maximize the similarity between distance on the film and distance along the earth's surface. The objective of the film-making system has been to simplify the task of the personnel who search these records for evidence of weather. For the digital data user, our study indicates that a more accurate across-track pixel location can be achieved (at the expense of more processing) through the use of the aforementioned formula of the sinusoidal scan. All plots derived from digital data in this report make use of uniformly spaced pixels in the across-track direction. As compared to the surface geography, these plots contain a geometric distortion matching that of the line on Figure 14. Some of this effect can be seen in film-to-map, the comparison shown in Figure 13, where the horizontal-to-vertical proportion (ratio) changes with respect to the east-west position. It is indeed fortunate that the scan of the DMSP mirror is so perfectly sinusoidal, making it possible to determine across-track direction accurately through the use of a fairly simple formula. The correction for satellite altitude, exemplified by Figure 14, could be obtained either from the comparative lateral positions of several fixed lights or it could be obtained from parameter Z in the scan header.

D. An Example of the Versatility of Digital Unit Processing

As an illustration of the ease with which the units of digital data can be processed, we wish to demonstrate the removal of an artifact from the DMSP data. In the film version in Figure 13, just north of the Dallas-Fort Worth complex, a horizontal streak runs across the image. In Figure 15, we show the unit of data from the upper left corner of Figure 13 as it was originally mapped. The unit was in Figure 6, where the artifact details may be seen. It contains a single line of picture elements which are defective.

This was a 3-nautical-mile digital tape consisting of 2 x 2 averages, and so a test was first conducted to see if only a single one of the original two 1.5 n. mile scans had been all-zero or had incurred some form of systematic error. From a study of the numbers which make up the streak in Figure 15, as compared to the numbers which make up the lines above and below, it was determined that there was no sensible pattern within the artifact. The values for each picture element in the streaked area, therefore, were obtained by averaging together the values of the picture elements above and below.

This process is much like that which takes place in television image generation, using the delay device called a "dropout compensator." In the television systems of today, such compensation merely substitutes the values in the preceding line if the current line appears to be defective. (The primary cause of such a defect is a tape "drop-out" and thereby the name is coined.) Our process, benefiting from the luxury of digital computer implementation, is one step better; the missing data are refilled by interpolation between the values before and after, rather than by simple repetition of the values before. The digital images of Figure 13 lack this defective streak because it has been removed by this form of compensation. This removal required the writing of approximately 20 lines of code into the computer program presented in Figure 10. Despite this demonstration of the ease of correcting the appearance of an artifact, it must be kept in mind that the information thus inserted in the streak is artificial; this correction is useful only as a matter

MAP.1N.47.146

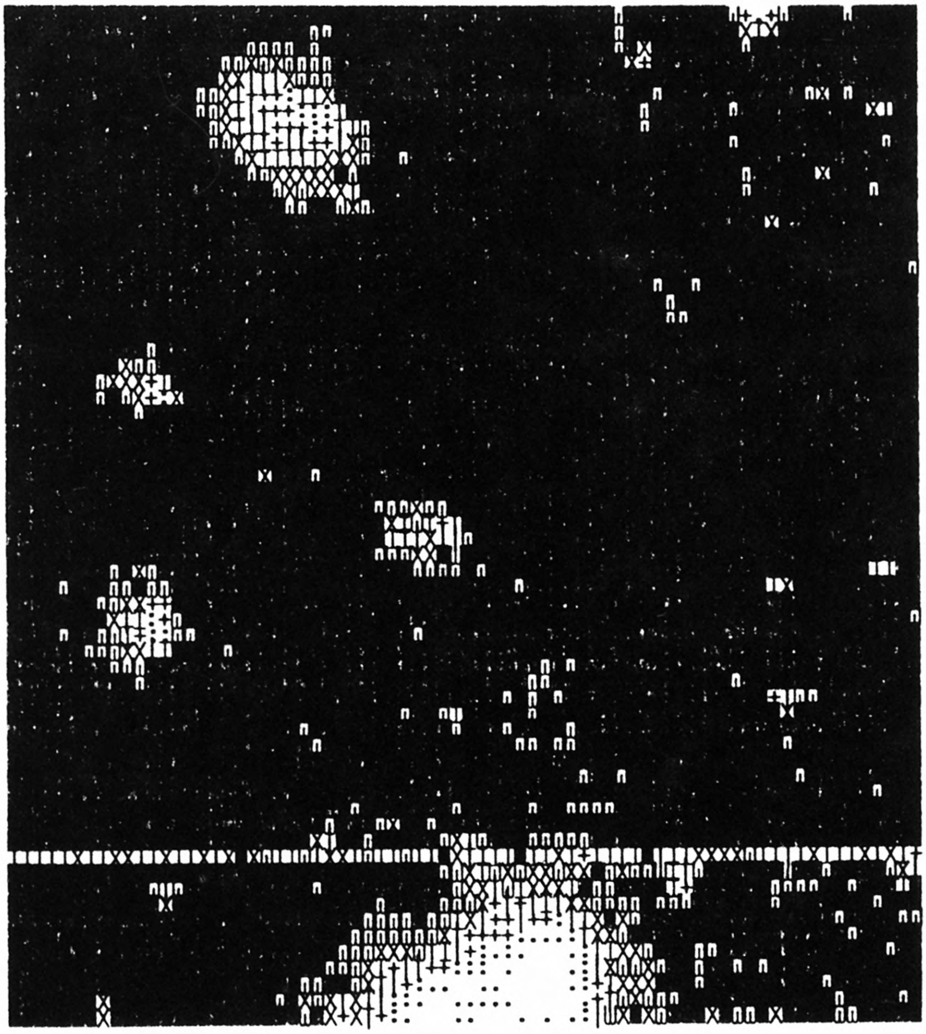


FIGURE 15 NORTHWEST UNIT FROM THE MAP OF FIGURE 13 BEFORE CORRECTION OF THE IMAGE ARTIFACT (shown as a streak) OCCURRING JUST NORTH OF DALLAS (corresponding unit is in Figure 6). A correction algorithm, described in the text, was used to remove this defect and generate the map in Figure 13.

of appearance. A subsequent numerical analysis of the pixels would have to be conducted with caution, lest the insertion of the artificial line of averages should alter the derived pixel statistics.

E. Waste Gas Flares and Lightning

In the Gulf of Campeche (near Tabasco), Mexico has discovered extensive oil fields, and it is flaring a great deal of waste gas there. Figure 16 is a 1.5-nautical-mile representation of this region. As compared to city lights, the gas flares are regions of saturation immediately adjacent to dark regions. In the case of cities, there is normally a gradual change from brightness to darkness as one moves away from the city center. Individual gas flares, which have a spectral output closely matching the response of the DMSP nighttime scanner, can readily saturate the sensor even though, on the next adjacent scan, there is no response. This is what leads to the appearance of isolated saturated pixels on the imagery.

At the time of Figure 16, the corresponding infrared image showed that a cloud covered the lower right corner of this region and swept up to the right, where a horizontal streak is seen. This horizontal streak is a classic signature of lightning on the DMSP images, but this one has the distinction of being the first to be revealed to us in its full digital representation. Notice that the lightning affected several successive scans, and it therefore must have lasted approximately one second. (The scans occur once each 0.42 second.) This is probably a fairly lengthy cloud stroke of the type which is often seen in the DMSP data, although it is seen less by surface observers, owing to the intervening clouds below the lightning. As opportunity permits, SRI plans to study the physical significance of these lightning stroke records using the sixol plots. In this example, the 2 units on the right of Figure 16 will yield the details of the light along the streak which is caused by this lightning event.

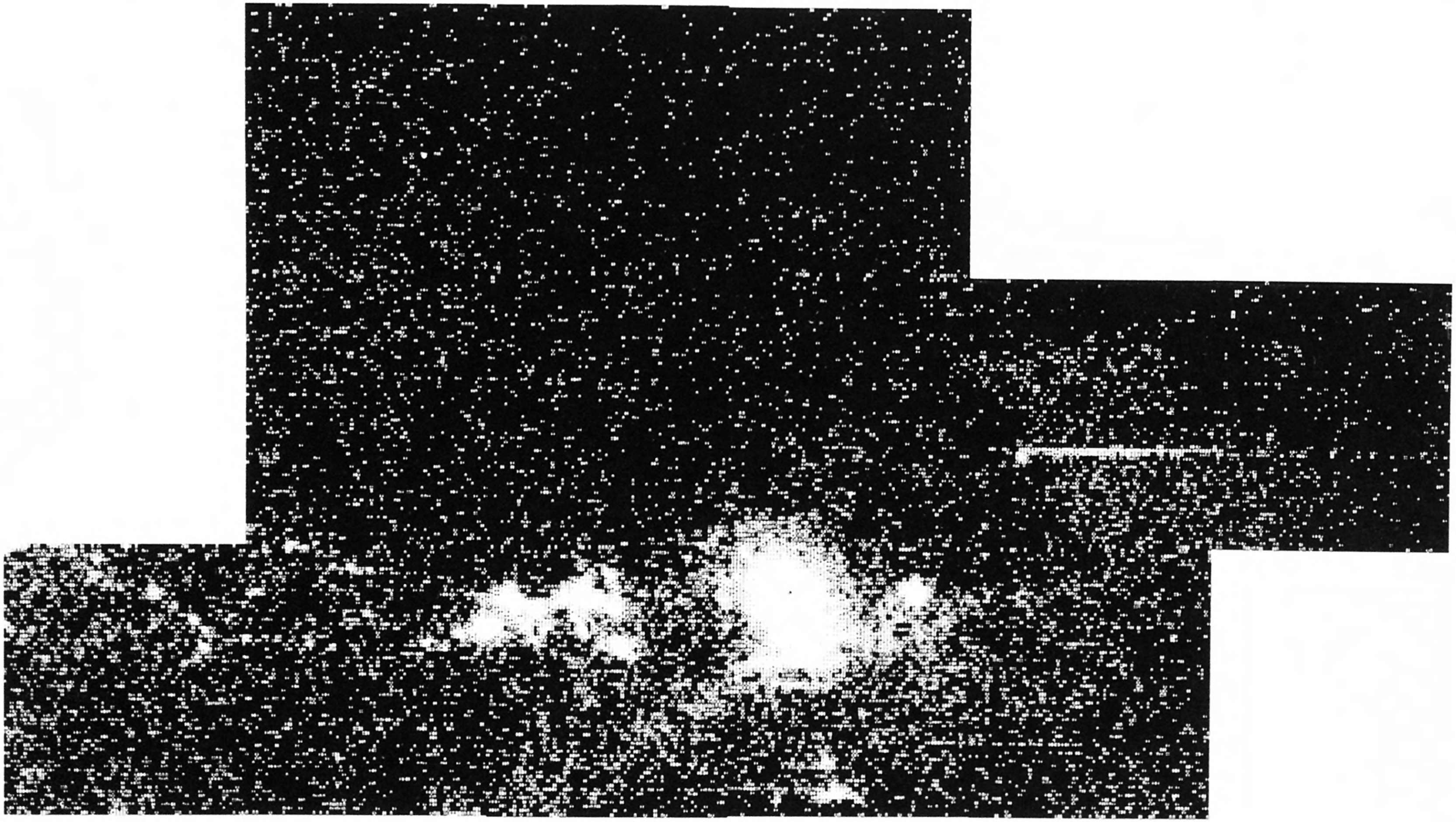
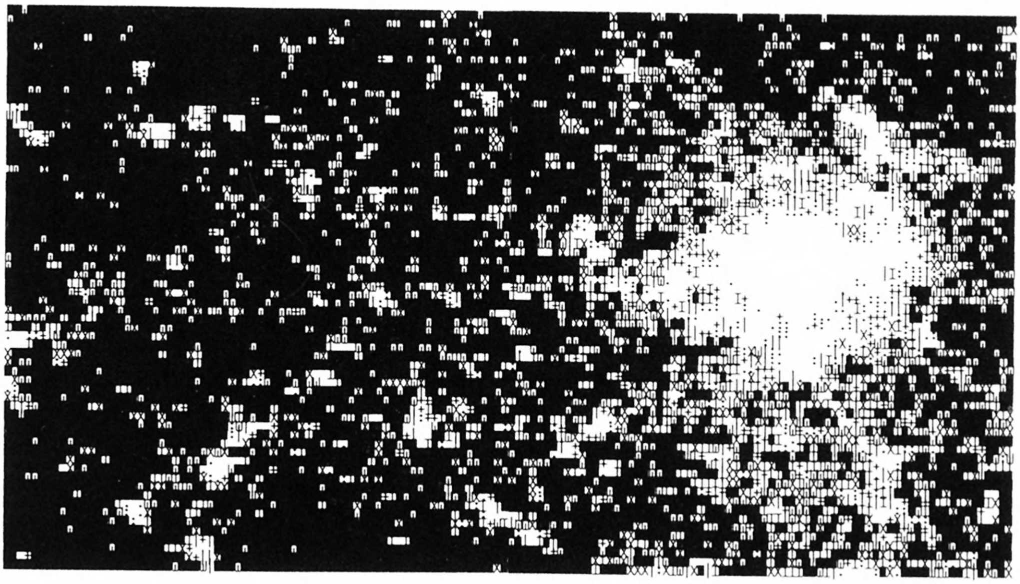


FIGURE 16 GAS FLARES OF THE GULF OF CAMPECHE IN MEXICO. In the two units on the right, a horizontal streak shows the typical DMSP response to lightning.

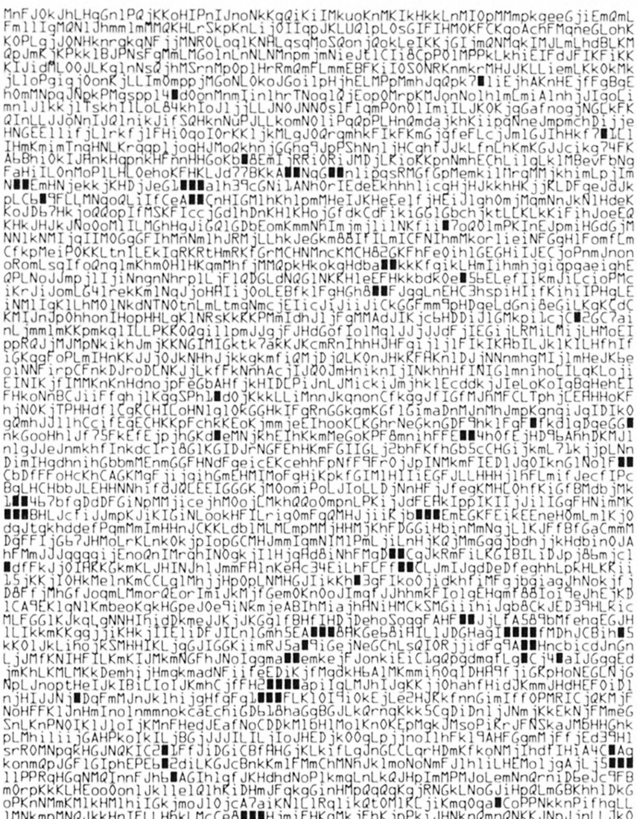
F. Flare Location by Computer

Another large gas flaring region is shown in Figure 17(a), in which the large bright region is Edmonton, Alberta. To the south and west of Edmonton lies a large gas and oil field, in which a great deal of gas flaring has long been visible in the DMSP images. Figure 17 provides a first look at this region in digital data. Immediately, one sees a characteristic which is unlike that of the populated regions of earth; there are small isolated spots so bright that they saturate the sensor. The clue to this is the presence of blank regions (digital code zero) with black regions immediately above and below.

To demonstrate this isolation of zeros, the sixol plotting program was modified. In statement 160 of Figure 7, the zero sixol was changed from a blank to a filled black rectangle. Using this program, the western unit of Figure 17(a) has been rendered as a sixol array, shown in Figure 17(b). Now the gas flares stand out clearly as black spots that are isolated. From this, a pattern never evident among the lights of cities away from oil fields, it is clear that a computerized pattern recognition program could readily be devised to locate the flares.



(a)



(b)

FIGURE 17 GAS FLARING IN THE VICINITY OF EDMONTON AND CALGARY IN ALBERTA, CANADA (a) AS SEEN IN A MAP. Modified sixol plot (b) shows these flares readily identified because they saturate the sensor while affecting only small regions. Other light sources saturate only when they affect larger regions.

VII PATTERN RECOGNITION IN THE IMAGERY

Typically, the analysis of these data can proceed only after the sources of the imaged light have been identified. Such image identification is straightforward on moonlit nights, requiring only comparison to a map, while at moonless times it may become truly puzzling. In any case, the identification phases of the project probably require the use of the Air Force visual or IR films, unless the analyst has resources sufficient to construct an equivalent image. A complete reconstruction by units is impractical; the units have been devised for small-area studies of, say, 1000 miles or less in extent.

On moonless nights, the lights are first identified with respect to the known locations of cities and fires. It is a great aid to have several images of the same region taken at different times, because the changing locations of some lights reveal them to be transient. (The rate of change in brightness or location is often a major clue to identification.) One such example is illustrated in Figure 18, using three images taken on the first three midnights of 1978. Off the west coast of New Zealand, there are bright lights which change in position on successive nights. Lacking other data, one would be hard pressed to explain these lights. As it happens, the author knew in advance that they would be there, and obtained these images as a result of forewarning. These examples provide evidence that, at times, the images alone do not provide enough clues to make identification possible. One must then resort to ad hoc measures.

The author first saw larger but similar lights in the Sea of Japan. By coincidence, one of the author's colleagues, Dr. E. T. Pierce (now deceased) was an internationally recognized thunderstorm expert who lived for a time in Japan and wrote about the "eccentric" thunderstorms in this same region of the Sea of Japan.[8] When the Japanese sea images

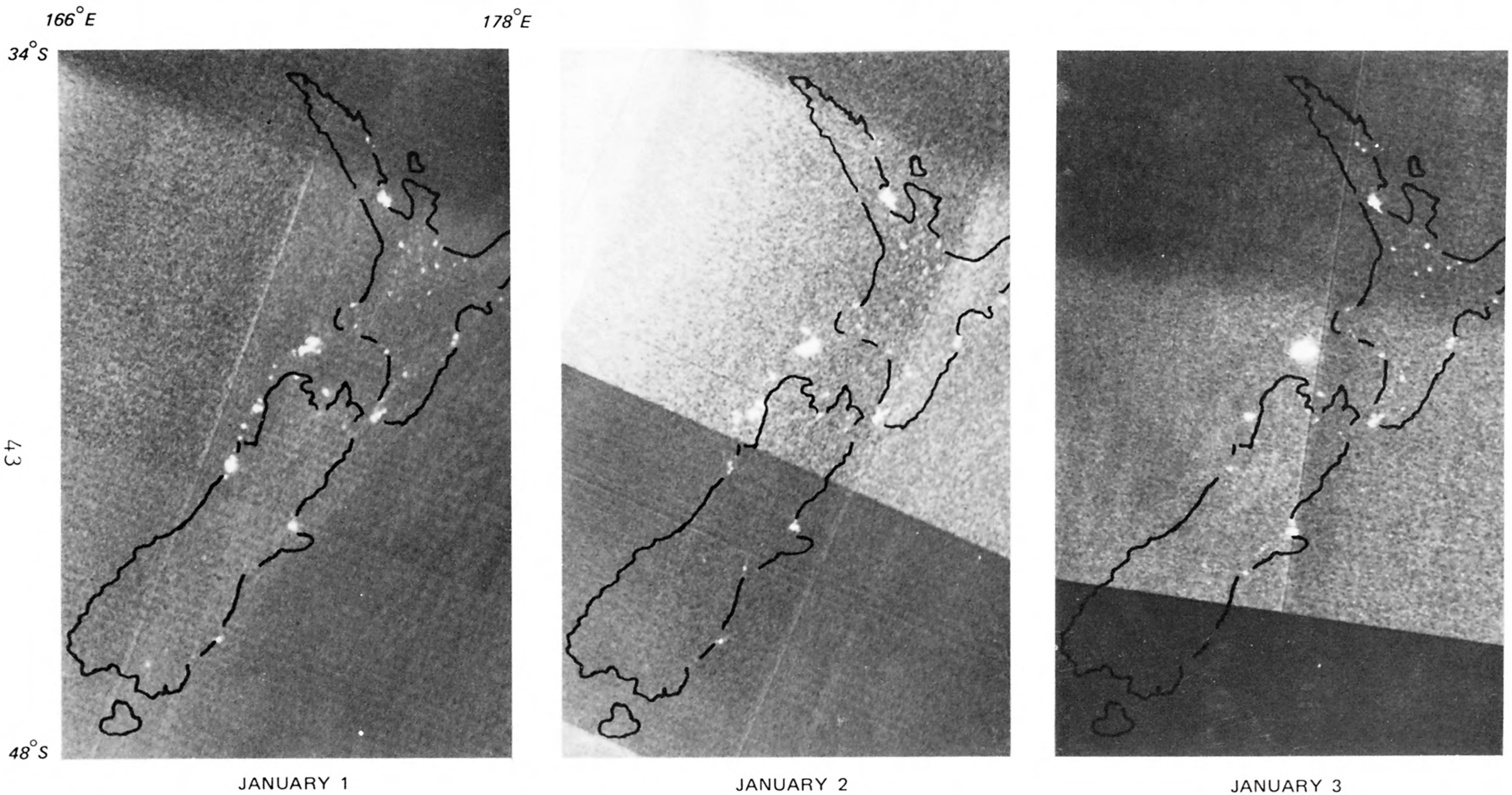


FIGURE 18 JAPANESE SQUID FISHING FLEETS OFF THE WESTERN SHORES OF SOUTH ISLAND, NEW ZEALAND. Larger fleets operate in the Sea of Japan. The large bright region centered in Cook Strait (between islands) may be due to flaring in the Maui gas field.

were included in report one, it was tentatively speculated that the lights might be some peculiar manifestation of eccentric thunderstorms. However, by the time of the Scientific American article[2] we had received confirmation from the Japanese Fisheries Agency that the lights were due to the squid fishing fleets equipped with incandescent lights of great power.[9] The changing locations of the lights followed the known patterns of the changing locations of the fishing fleets in that sea. The fleets seek squid whose locations are dependent on the thermal conditions of the water. Their positions can be determined with some useful degree of confidence from an examination of the DMSP infrared pictures which show water temperature.[10] The same Japanese Fisheries experts advised us that a smaller fleet worked near New Zealand, and the Scientific American article attracted letters from New Zealanders who had witnessed the fleet. Recently, in tracking down a UFO incident that occurred in New Zealand, Shaeffer[11] investigated the possibility that the UFO lights which had been reported were actually due to the Japanese fleet, with the light travelling under peculiar propagation conditions. In response to technical advice from the author, Mr. Shaeffer obtained a DMSP image (the central one shown in Figure 18) and kindly provided a copy of it to the author.

The location of the fleet as revealed in these three images is much like that reported by another correspondent[12] who said that the Japanese fished off the west coast of South Island. Because the boats clustered along the 12-mile limit, he suggested that DMSP image examiners might mistake them for a coastal population strip; indeed, a slight error in drawing the coastline in Figure 18 would lead to such erroneous conclusions. Mr. Wilkes advised that the lights were very bright--that "even 12-miles away they throw distinct shadows, and if there are enough boats offshore it is possible to read a newspaper outside on a moonless night." Later in the season, the fleet heads toward the east side of South Island and apparently becomes more dispersed. During the period depicted in Figure 18, Mr. Wilkes reports observations of a fleet numbering about 200, concentrated between 12 and 25 nautical miles offshore between the towns of Westport and Hokitika. (The bright spot between islands is located at the Maui gas field, and may be a flare.)

VIII CONVERTING A SIXOL TO A BRIGHTNESS LEVEL

In the operation of a typical scientific instrument, equipment settings are varied when necessary to keep the responses in the range where the best performance is achieved. The numbers which come back from the instrument are seldom viewed as being completed physical measurements; rather, they are treated as a code from which one will derive useful numbers through the application of calibration curves, scale corrections, and the like. This "data processing" is cumbersome perhaps and expensive, but it is often the best way to derive maximum accuracy with limited data.

For a practical, around-the-clock operational system, the post-measurement data processing workload must be held to a minimum. With this objective, the DMSP ground and space systems are constructed so that most of the necessary scale factors are applied, and adjustments are made, as the observations are conducted aboard the spacecraft; as a result, the numbers sent to earth are directly useful. Precomputed tables and computerized algorithms are used to vary the gain of the spacecraft amplifiers in order to achieve this goal. A crew of operators is constantly engaged in evaluating the data, evaluating the requirements for new data, and determining the gain-setting commands which should be sent to the spacecraft to control these amplifiers in the coming days or weeks. As compared to the typical research measurements, comparatively little processing occurs after the measurements are telemetered to the ground. Through the control of amplifier operation and the selection of scale factors, the six-bit numbers sent from spacecraft to ground and subsequently recorded on magnetic tape or on film represent the albedo of the surface. No need exists for any further digital computer processing of the light intensity data.

This operational approach represents a point of departure between the practical needs of the U. S. Air Force and the contrasting needs of remote sensing workers for comparatively small amounts of the same data. The latter wish to know the brightness of the light coming up from the surface in absolute terms, i.e., in watts per square centimeter per steradian, and as a function of wavelength. In nocturnal images, much light originates at the surface and then the very concept of albedo is inappropriate. As a result, the digital data user needs to take the sixols and convert them into some measure of radiance.

A. A Decibel Trap

It is convenient to digress briefly, to review the rationale for the decibel, because we shall see that the concept is used in a potentially confusing manner during DMSP brightness control calculations. This usage permeates the documentation of the system. In electrical calculations, one often deals with a power ratio that equals the square of a corresponding voltage ratio. For example, a power ratio of 100 results from a voltage ratio of 10. As many technical descriptions concern ratios of powers or voltages, there is ample opportunity for error to arise from imprecise wording, with the result that a number intended to represent power ratios would be applied to voltages or vice versa.

Use of the decibel precludes such errors. Ratio identifications are clarified because the decibel is formulated differently for voltage than for power. The decibel is 20 times the log of a voltage ratio but only 10 times the log of a power ratio. A statement in decibels is therefore unambiguous.

In the DMSP spacecraft, the fluctuating level of power in the light seen by the spacecraft is converted linearly into a voltage; therein lies the key to this discussion. In subsequent amplifications of this signal, changes in the voltage level are expressed in decibels, using the voltage formula which incorporates a 20-multiplier. The same decibel count applies to the power ratio in the light, for which one would use a 10-multiplier. Readers of USAF DMSP literature should be aware of this convention. All decibels herein refer to the voltage; thus, a 20 dB change represents a ratio of ten in light power.

B. Level Changes

The visual sensor for the F1 spacecraft, which provided all the digital data discussed in this report, was able to operate in four modes, each of which provided a different range of brightness. In sunlight, a solid state detector is used (but it will not be discussed, because our attention is restricted to imagery near midnight.) The remaining three modes of operation make use of a photomultiplier tube (PMT). Roughly speaking, the sensor area within this PMT can be adjusted to full size, or one-ninth size. Three modes of operation are called PMT high, PMT low, and PMT 1/9; the latter uses one-ninth of the PMT.

The process of controlling the gains of the amplifiers to achieve the desired result requires the separate setting of amplifiers, choices of modes, and the synthesis of many considerations. In contrast, the derivation of a brightness level from a pixel value (that is, from a sixol) is fairly simple. It begins with a reference level of radiance and requires simply the multiplication by three numbers which are gathered from various sources.

1. The reference level for spacecraft F1 is 0.042 watts/cm^2-sr. Each spacecraft has a unique reference level, but one which is generally within a few percent of this value; furthermore, the radiance is determined based upon the spectrum of sunlight. For moonlight, a slightly different value of radiance would apply because of the different spectrum of moonlight. The photomultiplier tube of each spacecraft in the DMSP series is measured to determine its spectral response, and the relative response to moonlight and to sunlight is then determined. Generally, the difference is only a few percent. For satellite F1, the moonlight radiance values are 4% lower than those for sunlight. We shall neglect this small difference.

2. Associated with each mode of operation, there is a compensating amplifier having a gain which, once more, is unique to each spacecraft. All of the data herein was obtained in the most sensitive mode, PMT high, for which the compensating gain of F1 is 86 dB; the first radiance multiplier is then -86 dB, or a factor of $10^{-86/20}$.

3. Operating under command from the ground is a video digital gain amplifier (VDGA) whose gain can vary between zero and 63-7/8 db, in 1/8 dB steps. The imagery presented herein was obtained under a computer control mode known as "along-track gain control (ATGC)", under which the VDGA gain remains at a fixed value throughout each whole scan. The value of gain is recorded in the header and identified as G. (This will be found in Figures 2 and 3.) In the SRI system, the number has been converted to a whole decimal number which must subsequently be divided by 8, in order to derive the second multiplier, the decibel setting of the VDGA. For ready reference, the reference level and the first two gain values have been combined in Table 1, giving a value of radiance associated with each whole dB of VDGA gain, and also a value for the maximum, 63-7/8 dB. This table provides half of the necessary information for a manual conversion of pixel code into brightness. A different table would apply to each spacecraft, but the values therein would differ by only a few percent from those given here.

4. Lastly, the pixel value encodes the third multiplier, telemetered from the spacecraft, and preserved herein as a sixol. If the first binary bit of header parameter M is zero, then the code is linear and the pixel value represents a gain between unity and zero in 64 equal steps. Alternatively, if the first bit of parameter M is unity, then an additional logarithmic amplifier was used. As a result, the pixel value represents a gain between unity and 1/100, in 64 logarithmically equal steps. As expressed in decibels, the use of the logarithmic amplifier subdivides 40 dB into 64 equal steps; therefore, each step represents $10^{-1/31.5}$, or about 7.5% in terms of radiance. This third type of gain, herein called "pixel gain", is fully evaluated in Table 2, which applies to all spacecraft. When used together with Table 1, this mechanizes the conversion from pixel value (either in octal or sixol) to radiance. It is only necessary to multiply the radiance from Table 1 by the gain from Table 2. (Alternatively, the radiance conversion could easily be performed by computer or calculator.)

C. The Maximum Detectable Signal

The maximum detectable signal (radiance) is not quite 0.042 watts/cm^2-sr; that value is the zero intercept of a straight line which represents the response of the system, and as a result it is a convenient reference number. To avoid citing this unattainable reference, many system descriptions make use of a reference level of 0.0212, at which response point the pixel value is roughly 6 to 9, depending on the spacecraft.

Table 1. THE RADIANCE OF A SATURATED PIXEL FOR DIFFERING VALUES OF VDGA GAIN

(This applies only to satellite F1, since it assumes a reference level of 0.042 watts/cm^2-sr and PMT high gain of 86 dB.)

VDGA GAIN as dB (-)	VDGA GAIN as inverse factor	RADIANCE watts/cm2-sr (pixel=000000)
0	1	2.10495E-06
1	1.12202	1.87604E-06
2	1.25893	1.67202E-06
3	1.41254	1.49019E-06
4	1.58490	1.32813E-06
5	1.77828	1.18370E-06
6	1.99527	1.05497E-06
7	2.23873	9.40244E-07
8	2.51189	8.37993E-07
9	2.81839	7.46862E-07
10	3.16228	6.65642E-07
11	3.54814	5.93254E-07
12	3.98108	5.28738E-07
13	4.46685	4.71238E-07
14	5.01189	4.19991E-07
15	5.62343	3.74317E-07
16	6.30960	3.33611E-07
17	7.07949	2.97331E-07
18	7.94331	2.64996E-07
19	8.91255	2.36178E-07
20	10.0000	2.10494E-07
21	11.2202	1.87603E-07
22	12.5893	1.67201E-07
23	14.1255	1.49018E-07
24	15.8490	1.32813E-07
25	17.7829	1.18369E-07
26	19.9527	1.05497E-07
27	22.3874	9.40240E-08
28	25.1190	8.37990E-08
29	28.1840	7.46859E-08
30	31.6230	6.65639E-08
31	35.4816	5.93251E-08
32	39.8110	5.28735E-08
33	44.6687	4.71236E-08
34	50.1191	4.19989E-08
35	56.2346	3.74316E-08
36	63.0962	3.33609E-08
37	70.7951	2.97330E-08
38	79.4335	2.64995E-08
39	89.1258	2.36177E-08
40	100.001	2.10493E-08
41	112.203	1.87602E-08
42	125.894	1.67201E-08
43	141.255	1.49018E-08
44	158.491	1.32812E-08
45	177.830	1.18369E-08
46	199.528	1.05496E-08
47	223.875	9.40236E-09
48	251.191	8.37986E-09
49	281.842	7.46855E-09
50	316.231	6.65636E-09
51	354.818	5.93248E-09
52	398.112	5.28733E-09
53	446.689	4.71233E-09
54	501.193	4.19987E-09
55	562.348	3.74314E-09
56	630.965	3.33608E-09
57	707.955	2.97328E-09
58	794.338	2.64994E-09
59	891.262	2.36176E-09
60	1000.01	2.10492E-09
61	1122.03	1.87601E-09
62	1258.94	1.67200E-09
63	1412.56	1.49017E-09
63.875	1562.27	1.34737E-09

Table 2. THE GAIN ASSOCIATED WITH EACH PIXEL VALUE IN THE LINEAR AND LOGARITHMIC MODES OF OPERATION

(When multiplied by the radiance from Table 1, this yields the pixel radiance.)

Sixol	Octal	Gain{lin}	Gain{log}
none	0	1	1
	1	.984127	.92951
1	2	.968254	.863988
2	3	.952381	.803085
3	4	.936508	.746476
4	5	.920635	.693856
5	6	.904762	.644946
6	7	.888889	.599484
7	10	.873016	.557226
8	11	.857143	.517947
9	12	.841270	.481437
a	13	.825397	.447500
A	14	.809524	.415956
b	15	.793651	.386635
B	16	.777778	.359381
c	17	.761905	.334048
C	20	.746032	.310501
d	21	.730159	.288613
D	22	.714286	.268269
e	23	.698413	.249359
E	24	.682540	.231781
f	25	.666667	.215443
F	26	.650794	.200256
g	27	.634921	.186140
G	30	.619048	.173019
h	31	.603175	.160823
H	32	.587302	.149486
i	33	.571429	.138949
I	34	.555556	.129155
j	35	.539683	.120050
J	36	.523810	.111588
k	37	.507937	.103722
K	40	.492064	.096410
l	41	.476191	.089614
L	42	.460318	.083297
m	43	.444445	.077426
M	44	.428572	.071968
n	45	.412698	.066895
N	46	.396825	.062179
o	47	.380952	.057796
O	50	.365079	.053722
p	51	.349206	.049935
P	52	.333333	.046415
q	53	.317460	.043143
Q	54	.301587	.040102
r	55	.285714	.037275
R	56	.269841	.034648
s	57	.253968	.032205
S	60	.238095	.029935
t	61	.222222	.027825
T	62	.206349	.025864
u	63	.190476	.024040
U	64	.174603	.022346
v	65	.158730	.020771
V	66	.142857	.019306
w	67	.126984	.017945
W	70	.111111	.016680
x	71	.095238	.015505
X	72	.079365	.014412
y	73	.063492	.013396
Y	74	.047619	.012451
z	75	.031746	.011574
Z	76	.015873	.010758
none	77	0	.01

The 0.0212 radiance is about the brightest that one could expect in a daytime scene, corresponding to a cloud having an albedo of 0.8, lambertian reflectance, and no absorption of light in the intervening atmosphere. This alternative reference point is not of practical significance at night, but it is often mentioned in the DMSP literature, and hopefully this brief mention will tie together the two explanations. For the present purpose, it is simpler to specify the intercept, 0.042 for F1, with a brief note in passing that the gain of a system cannot be zero dB in the modes of operation commonly employed.

D. The Minimum Detectable Level

At midnight the "PMT high" gain of F1 would be 86 dB, and the VDGA gain might reach 63-7/8 dB. A pixel value of binary 000000 (signifying a pixel gain of unity) would thus represent a brightness level of

$$0.042 \cdot 10^{-\frac{86}{20}} \cdot 10^{-\frac{63\ 7/8}{20}} = 1.35 \times 10^{-9} \text{ watts/cm}^2\text{-sr.}$$

The DMSP can subdivide this radiance to 1/63 in the linear mode, or 1/100 in the logarithmic mode. To determine the true minimum detectable scene brightness available on tape, it is necessary to account for the fact that the lowest level, binary 111111, has not been preserved. The lowest recorded value is 111110, octal 76. In turn, this is not a measure of brightness, as the value indicates only that the recorded scene was that dark, or darker. The measurable minimum, therefore, is represented by pixel value of binary 111101 or octal 75. In the linear mode of operation, this represents 4.3×10^{-11} watts/cm^2-sr. In the logarithmic mode, this represents 1.6×10^{-11} watts/cm^2-sr. These are the minimum detectable levels for the instrument, but such low levels have not been detected in the tapes available to this study; noise and natural light sources exceed this level.

A more typical value found on the tapes is a value of G equal to 440 which, when divided by 8, yields the VDGA gain of 55 dB. In Figure 6, a sixol symbol S is fairly typical. From the first bit in header parameter M, we know that the gain control was linear and so the brightness of a parameter having sixol S was $(3.74314 \times 10^{-9})(0.238095)$, or about 10^{-9} watts/cm^2-sr. In DMSP descriptions, this level is often cited as the threshold.

E. Comparison to Landsat

As was described in report one, Landsat has been operated at night, with the result that most of the pixels were completely unexcited; that is, zero in all colors. The exception was caused by gas flares which strongly excited the sensors; many pixels were fully saturated. The details of the pixel illumination patterns as a function of latitude, longitude, and spectrum, were included in report one. At that time, we lacked information concerning the photometric parameters of the DMSP and therefore a comparison was not possible.

Among the sensors on the Landsat satellite, the most sensitive should be that associated with band 5 of the multispectral sensor. When operated in its high gain mode, this band exhibits a maximum radiance of 0.00067 watts/cm^2-sr.[13] The telemetered output is a 6-bit number, but the sensitivity to the dim light is somewhat increased through the use of "compression," by which means the numbers of a 7-bit code (0-127) are non-linearly mapped into a 6-bit code (0-63). Examination of the "decompression tables" reveals that this mapping is linear for the first few codes (the dimmest) so that, from the standpoint of determining the minimum light level detectable by Landsat, it is equivalent to the use of a 7-bit code.[14]

The minimum among the minima is then achieved by band 5 when it is in a high gain mode, at which time the maximum radiance (all binary 1s) corresponds to 0.00067 watts/cm^2-sr. The minimum detectable level is then 1/128 of this amount, or about 5.2×10^{-6} watts/cm^2-sr. The reason for the relative appearance of insensitivity of the Landsat records at night is thus made clear; it is 4 orders of magnitude less sensitive than DMSP.

To put this number further in perspective, it may be recalled that the city centers are saturated in the DMSP records. In such records, the "PMT high" amplifier was used (86 dB) and the VDGA was set at 55 dB. In this circumstance, full saturation with pixel gain unity represents about 4×10^{-9} watts/cm^2-sr, a light level some thousand times weaker than the weakest detectable Landsat signal.

The Landsat was never intended for use at night, and these numbers are offered here only because they tend to provide a quantitative explanation for the emptiness of the pixels among the three nighttime Landsat pictures which have been attempted. One, from the New York area at night, is said to have revealed all zeros. Another, taken over Algeria, was described in report one,[5] where the response to gas flares was reported. (Some pixels were saturated; i.e., fully bright.) A third, taken in the Los Angeles-San Diego area, again revealed all zeros. While it is difficult to prove a negative point, these sensitivity figures nevertheless tend to support the claim bv some who have said that the Landsat is incapable of detecting cities at night.

IX CONCLUSIONS

The digital data which can be provided by the Air Force are of practical use, and they have potential value. For the most part, this benefit stems from the preservation of the photometric parameters. In this study we have endeavored to develop a method for orderly handling of the digital data, and to develop the techniques for recovering photometric data--at least to the point where the practicality of the recovery could be assessed. The scale of this effort has occupied all our resources, with the result that we have not had the opportunity to apply the method to a specific study at the time of this writing. It is clear, nevertheless, that the potential value is there. Examples are the unique lightning-stroke record on the right of Figure 16, and the gas flare signature statistics in Figure 17. Given the present state of our development of these data, it would be a straightforward matter to perform a quantitative analysis of either phenomenon by direct manipulation of the units of data. If further digital records of the same regions could be made available at useful intervals of time, we could then measure the temporal evolution of gas-flaring through the comparison of successive images. For such a study, the digital records would be essential.

The moderately large size of the DMSP pixels (as compared to those of Landsat, for example) offers the user some benefit, in that the quantity of numbers which must be handled is not overwhelming. With Landsat, we would be dealing with about ten million numbers to represent an area equivalent to one unit (having 4608 pixels) in this study. One of our conclusions has been that the analysis of DMSP data is indeed practicable. The main element lacking is an avenue by which the digital data may be obtained. To our knowledge, the image tapes supplied for this analysis are the only ones ever released for unclassified study.

We have further concluded that potential applications for nighttime imagery exist which cannot be met by the DMSP. In the main, this conclusion stems from the limited range of values of brightness which are retained, coupled with the weather-oriented requirements which alone dictate the brightness range to be recorded. As a result, the brighter regions are typically saturated and one is prevented from making potentially productive observations. Large cities are not imaged at all, and they are one of the more important regions from the standpoint of the economic value of such data.

There is little likelihood that the design of the Air Force satellite system will be compromised with the object of meeting this need, since it is irrelevant to the mission of the DMSP. The most obvious cure, an increase in the recorded range of radiance, would necessarily increase the telemetry data rate, which is already a limiting operational factor. It seems likely, therefore, that the optimization of a nighttime sensor for remote sensing of surface lights will not occur until such time as a special sensor is built and flown for this purpose. To this end, SRI has been appraising many applications of the images which have come to our attention, largely as a result of the *Scientific American*[2] article. Many letters were received from technically sophisticated readers; for example, an Italian scientist inquired concerning the use of DMSP midnight images as a means for selecting an astronomical telescope site in Italy. For that purpose, the imagery would be well suited. Most applications are more obvious, tending to relate to monitoring of natural resources, society, or geophysical phenomena.

The DMSP system is truly an outstanding performer in the realm of remote sensing. In this report, attention is restricted to use of the visual sensor at night, forming one small aspect of the DMSP performance spectrum and one which is, as a matter of fact, considered by the Air Force to be a minor part. Another wealth of information resides in the infrared imagery, both in the night and the day, and the daylight visual images contain still another story. In addition, the DMSP carries non-imaging sensors of variety and versatile capability. We wish to close with this note of admiration for the excellence of the system, and with an expression of gratefulness for the help provided to us by the personnel who work the system.

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REFERENCES

1. T. A. Croft, "Nocturnal Images of the Earth from Space," Final Report, SRI International, Number 68197 (March 1977).

2. T. A. Croft, "Nighttime Images of the Earth from Space," Scientific American, Vol. 239, No. 1 (July 1978).

3. T. A. Croft, "Plotting Shades of Gray with a Standard Computer Terminal," Technical Report 3208-1, Stanford Electronics Laboratories, Stanford University, Stanford, California (March 1974).

4. Maj. Lee G. Dickenson, Defense Meteorological Satellite Program (DMSP) User's Guide, AWS-TR-74-250 (Air Weather Service, Scott Air Force Base, Illinois, December 1974).

5. C. P. Pike, Auroral User's Guide for DMSP, Air Force Systems Command, USAF (AFCRL, Hanscom AFB, Massachusetts, April 1975).

6. T. A. Croft, "Burning Waste Gas in Oil Fields," Nature, Vol. 245, No. 5425, pp. 375-376 (October 1973).

7. M. Brook and T. Ogawa, "The Cloud Discharge," in Physics of Lightning, R. H. Golde, ed., Vol. 1 (Academic Press, San Francisco, California, 1977).

8. E. T. Pierce, "Winter Thunderstorms in Japan--A Hazard to Aviation," Naval Research Reviews, Vol. 29, No. 6, pp. 12-16 (June 1976).

9. A. Suda and S. Kasahara (private communication).

10. R. W. Fett, "Fishing Fleet Activities Revealed by Night-Time Data from the Defense Meteorological Satellite Program (DMSP)," Marine Fisheries Review, Vol. 37, No. 4, MFR Paper 1131 (April 1975).

11. R. Shaeffer (private communication).

12. O. Wilkes (private communication).

13. Landsat Data User's Handbook, NASA Earth Resources Program, Document 76SDS4258 (Goddard Space Flight Center, Greenbelt, Maryland, September 1976).

14. P. F. Holkenbrink, Manual on Characteristics of Landsat Computer Compatible Tapes Produced by the EROS Data Center Digital Image Processing System (USGS, Sioux Falls, South Dakota, December 1978).

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