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DIGITAL PROCESSING OF INFRA-RED SCANNER DATA  
FOR RADIOMETRIC TEMPERATURE ANALYSIS OF THERMAL PLUMES\*

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ABSTRACT

A method for digitally reducing thermal plume data obtained from a Bendix Thermal Mapper is presented. This method includes a distortion removal technique and the calculation of apparent blackbody temperature from the scanner's output film. This method is illustrated using data obtained with a Bendix scanner over the Surry Station nuclear power generating facility located on the James River in Surry, Virginia.

I. INTRODUCTION

One of the primary environmental impacts of water-cooled nuclear reactors is thermal pollution. These nuclear reactors require large quantities of water for cooling, and the usual source is a nearby lake or river. The waste heat from the reactor is transferred to the water which is then returned to its source. The heated water then mixes with the cooler lake or river and affects the local aquatic environment.

There is a need to regularly monitor nuclear power plants which use water cooling, since the effect of thermal pollution on the local aquatic ecosystem can be very serious, particularly when the source of the pollution is located near commercial fishing areas. Many species of fish and crustaceans are adversely effected by a temperature change of only a few degrees, and a water-cooled reactor can potentially cause much more than this. Furthermore, effects vary seasonally as the ambient temperature of the lake or river changes. Whereas local fish species may be able to tolerate a 5°F (2.8°C) increase in water temperature in winter, they may be able to tolerate only a 1 or 2°F (0.6 - 1.1°C) increase in summer.

A convenient method of monitoring the thermal effluent from a water-cooled reactor is to use an airborne infrared scanner that operates in the 8 $\mu$ -14 $\mu$  wavelength range. From scanned data it is possible,

with certain carefully controlled approximations, to determine the apparent blackbody temperature, both of the thermal plume and of the lake or river.

On March 14-15, 1974, a Bendix Thermal Mapper was flown at an altitude of 2,000 ft. (914m) over Surry Station, a nuclear power generating facility located in Surry, Virginia (Figure 1). This power generating facility consists of two steam generating nuclear reactors which use once-through cooling to dissipate waste heat. Water from the James River enters an intake canal, is circulated through the reactor cooling systems, and is then returned to the river some 6 miles (9.6 km) upstream of the intake. This portion of the James River is estuarine, with the salt-fresh water boundary only slightly downstream of the discharge point. As a result, both salt and fresh water species are affected by the thermal gradients caused by the Surry plant, and there is particular concern for the fate of commercial clam beds located downstream.

A problem with the data from the Bendix Thermal Mapper is a nonlinear distortion which must be removed before the data from the scanner can be compared to standard geographic maps. This distortion is particularly serious when the data from several aircraft passes must be mosaiced together to examine a large body of water.

The purpose of this paper is to discuss a digital data reduction method which was designed to remove the distortions produced by the Bendix Thermal Mapper and to calculate temperatures for thermal plume data such as that obtained from the Surry Station flight.

## II. DISTORTION REMOVAL

In the operation of the Bendix scanner, ground emissions are collected by a rotating mirror, passed through a detector filter which is sensitive in the wavelength band of  $8\mu-14\mu$ , and then the light from a glow tube modulated by the detector is imaged onto a cylindrically conformed film. The most serious distortion produced by the scanner is caused by mapping the flat plane of the idealized earth onto this curved film. As illustrated in Figure 2(a), a distance  $L$  on the earth will be mapped into the distance  $\lambda$  on film such that

$$\lambda = \frac{r}{h} \frac{\theta}{\tan \theta} L \quad (1)$$

where  $h$  = the aircraft's altitude above the earth,  
 $r$  = the distance from the thermal scanner's recording optics scan mirror to the curved film,  
 and  $\theta$  = the angle of the scan position from the scan nadir.

The  $\theta/\tan\theta$  term produces the distortion which is most evident in the scanner's representation of linear features. For example, straight roads such as those marked A and C in Figure 2(b) will be undistorted, while a road which crosses the flight path at an angle will appear curved such as that marked B. A less serious distortion occurs if the forward velocity of the aircraft is not matched to the scanner's film recording rate. This distortion causes the imagery to appear stretched or shrunk in the direction of flight.

Scanner imagery is corrected in the following manner. First, the image is digitized on a microdensitometer along the scan direction and output in a computer compatible format. A new, non-uniform picture grid is defined in the computer which corresponds to an undistorted arrangement of the digitized picture. Then, since a display of the data on this new grid would result in an uneven picture with gaps and loss of contrast, picture values are obtained at points on the new rectangular grid by interpolation. The corrected picture is then produced by displaying the interpolated data on a microfilm printer using the new rectangular grid.

Figure 3 illustrates this distortion removal technique. Figure 3(a) shows imagery obtained with the scanner over the Lawrence Livermore Laboratory in California. The laboratory is laid out on a roughly square grid, but the scanner distorts this badly. Figure 3(b) gives the same imagery corrected for distortions. Rectangularity has been restored, and now these data may be compared to standard maps of the area by preparing overlays from the computer display films.

## III. TEMPERATURE CALCULATION

Thermal information is obtained from the scanner output by making the assumption that the radiant emissions sensed by the scanner are due to gray bodies. That is, the radiance, which is a function of the object plane spatial coordinates  $x$  and  $y$ , is given by:

$$R(x,y) = \epsilon(x,y) 2c^2 h \int_{\lambda_a}^{\lambda_b} \frac{\lambda^{-5} d\lambda}{e^{hc/\lambda kT} - 1} \quad (2)$$

where  $\epsilon(x,y)$  = emissivity  
 $c$  = velocity of light  
 $h$  = Planck's constant  
 $k$  = Boltzmann's constant  
 $T$  = temperature  
 $\lambda$  = wavelength  
 $\lambda_a$  and  $\lambda_b$  = the wavelength limits of the scanner's detector filter.

For thermal plume data, the emissivity is assumed to be equal to one.

Since atmospheric absorption effects are small for the I.R. wavelength band in which this scanner normally operates, the assumption is also made that the energy which reaches the scanner detector is proportional to that emitted by the source. It is further assumed that the energy which actually reaches the scanner film via the glow tube modulated by the detector is proportional to that seen by the detector. Thus, since the photographic density of the scanner output film is proportional to the logarithm of the energy incident on the film (for exposures in the linear portion of the film's H & D curve), the density on the film will be proportional to the logarithm of the radiance emitted by the source. Radiance can thus be obtained from density using simple calibrations, and temperatures may be calculated from radiance by using Equation (2), or by using a simple approximation to Equation (2), such as the Wien approximation. The Wien approximation is valid when the  $hc/\lambda kT$  term in Equation (2) is very much greater than 1. Using Wien's

approximation results in radiance being given by a transcendental equation in temperature, a relationship which can be solved for temperature using Newton's method.

#### IV. PROCESSING THE SURRY STATION DATA

The Surry Station data was recorded on Kodak 2498 RAR film in flight (Figure 4). The detector filter used on the scanner to collect these data was sensitive in the 8.5 $\mu$  to 12.5 $\mu$  wavelength band. At the end of each data scan, the scanner looked at two blackbody calibration sources set at 50.14 $^{\circ}$ F (10.08 $^{\circ}$ C) and 45.23 $^{\circ}$ F (7.35 $^{\circ}$ C). The temperatures of the calibration sources were chosen to bracket the temperatures observed for the plume, and the gain of the scanner was set so that the thermal plume data would be recorded in the linear region of the film's H & D curve. The developed Surry data film was raster scanned on EG&G's Photometric Data Systems 1010A microdensitometer, using a 240 micrometer square aperture and sampling on a square grid every 240 micrometers. This corresponds to approximately one sample every 16 ft. (4.9m) on the ground along the line of flight direction. The output from the microdensitometer was divided into three adjacent segments, each containing 256 x 256 data points, for processing.

The blackbody radiance from the calibration sources was calculated from Equation (2). The corresponding calibration densities on the data film were assigned these radiances, and a density versus the logarithm of the radiance relationship defined for these data. The Wien approximation is valid for these data and was used to calculate temperature from radiance. The error introduced by using this approximation for these data is no more than one percent.

The three Surry data segments containing the data output from the microdensitometer were processed one at a time using a command oriented, CDC 7600 computer program, DISTORT, designed for the purpose. DISTORT consists of an executive command module which directs a series of operation subroutine modules. Each group of operation subroutines obtain a data array of up to 512 x 512 elements from magnetic tape or extended core storage (ECS), performs some function on the data array, then returns the array to tape or ECS. These functions are performed at the request of the user who supplies command cards to the program in the order he wishes to have the functions performed. The functions performed by DISTORT are:

1) Create an N x N picture element array from a black and white microdensitometer output tape. N may be any number up to 512. If an array is requested from a tape which contains fewer elements than the requested array size, the array is filled out with zeros.

2) Read tapes containing output data arrays from several other programs. This allows the pre-processing of data before processing by DISTORT.

3) Perform distortion removal by the technique described above. This creates a new N x N, undistorted picture element array.

4) Computes radiance point by point from a density array given a density-versus-the-logarithm-of-the-radiance relationship for the data.

5) Computes temperature point by point from a radiance array using the Wien approximation and Newton's method.

6) Outputs the data in several tape formats compatible with other programs.

7) Outputs the data arrays on either of two microfilm plotter devices, a Stromberg Carlson 4020 microfilm plotter, or an Information International FR-80 microfilm plotter. These output displays may be of several types. Output to the Stromberg Carlson 4020 microfilm plotter generates either 17 gray level, black and white half-tone displays, or multi-level pseudocolor displays. The pseudocolor displays are created by writing three half-tone pictures using red, green, and blue filters, and any one of five color schemes. Output to the FR-80 generates 64 gray level, black and white displays. These displays are not half-tones, but controlled gray level reproductions.

8) Outputs data arrays to a magnetic tape which can then be used to reconstruct the data on the P.D.S. 1010A microdensitometer. The reconstructions from the P.D.S are very high quality, black and white transparencies containing 256 levels of gray from black to white.

For all the output displays from DISTORT, the user has complete control over what data values are assigned to the gray levels or colors output. The user may also choose to let the program distribute the data among the gray levels or colors using certain built-in statistical functions. In running DISTORT, the user also has the option of running his own subroutines, either under the control of the DISTORT command module, or by writing his own driver for the DISTORT operation subroutine modules.

The digitized Surry data segments were corrected for distortions, converted to radiance and then temperature, and displayed. The original temperature displays were pseudocolor displays that linearly assigned colors to temperature in 21 levels from violet to red. For the purposes of publication, Figure 5 shows a black and white representation of the color-displayed, mosaiced temperature data. Hand drawn temperature contours have been included with these data.

## V. RESULTS AND CONCLUSIONS

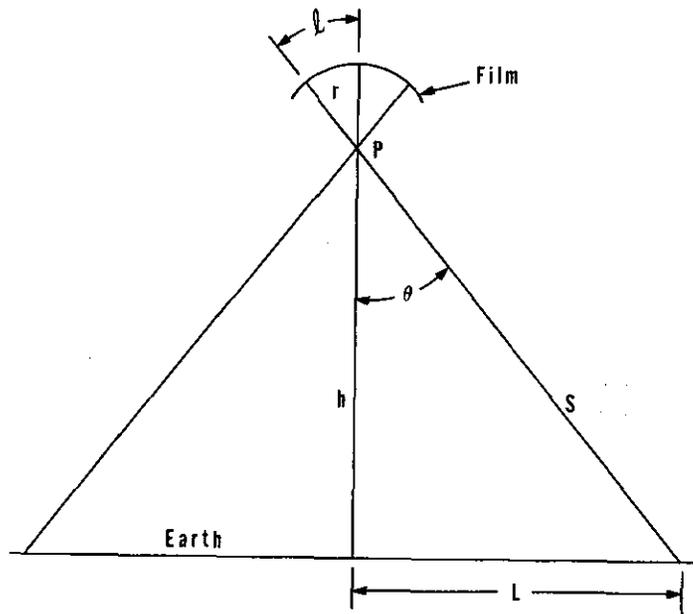
Ground truth information gathered from an instrument tower (labeled Station 6 in Figure 1), on the day after the Mission A Surry Flight, indicates that the temperature calculations for the Surry data are accurate to about 1°C. The primary error is probably due to the assumption that the water is a blackbody (emissivity = 1). Certain conditions, such as chemical pollution in the river, reduce the emissivity to slightly less than one, and thus introduce this error into the calculations. However, without additional information about the river's chemical makeup, or more extensive ground truth, it is not possible to correct for this error.

This purely digital data reduction method appears expensive and cumbersome in relation to certain video-analog methods such as density slicing. However, the digital approach has the advantages that the distortion introduced by the scanner may be removed, air transmission and shading corrections (not done here, but well understood) may be calculated, and a detailed temperature calculation which accounts for the nonlinear relationship between photographic density and temperature may be performed. This latter advantage is particularly important, since assuming a linear relationship between density and temperature may introduce errors that in certain conditions may exceed state and federal environmental monitoring standards.

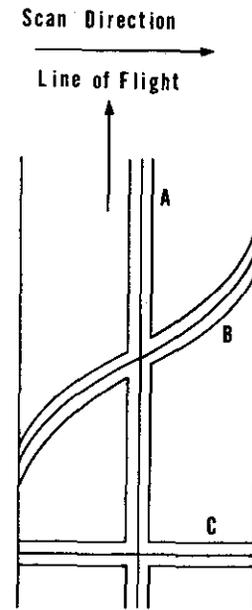
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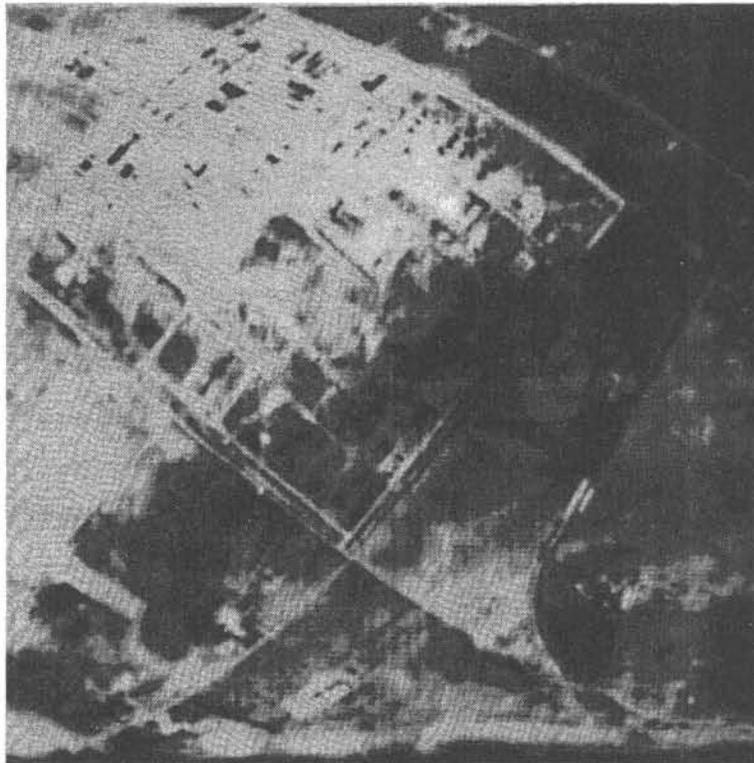


(a) Schematic of Scan Recording Geometry

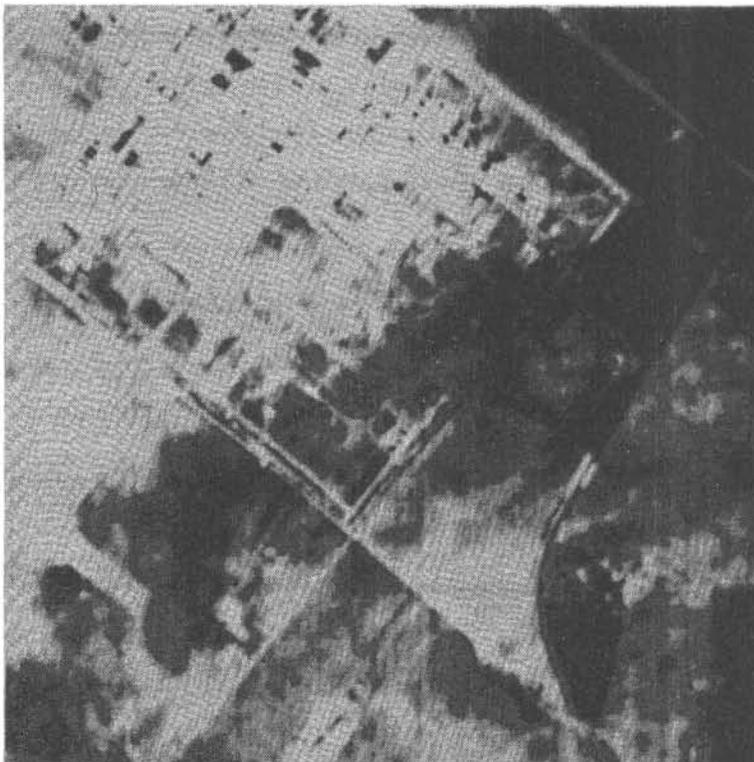


(b) Film Distortion

Figure 2. Scan Recording Geometry



(a) Raw Scanner Imagery of the Lawrence Livermore Laboratory



(b) Scanner Imagery with Distortions Removed

Figure 3. Infrared Scanner Images

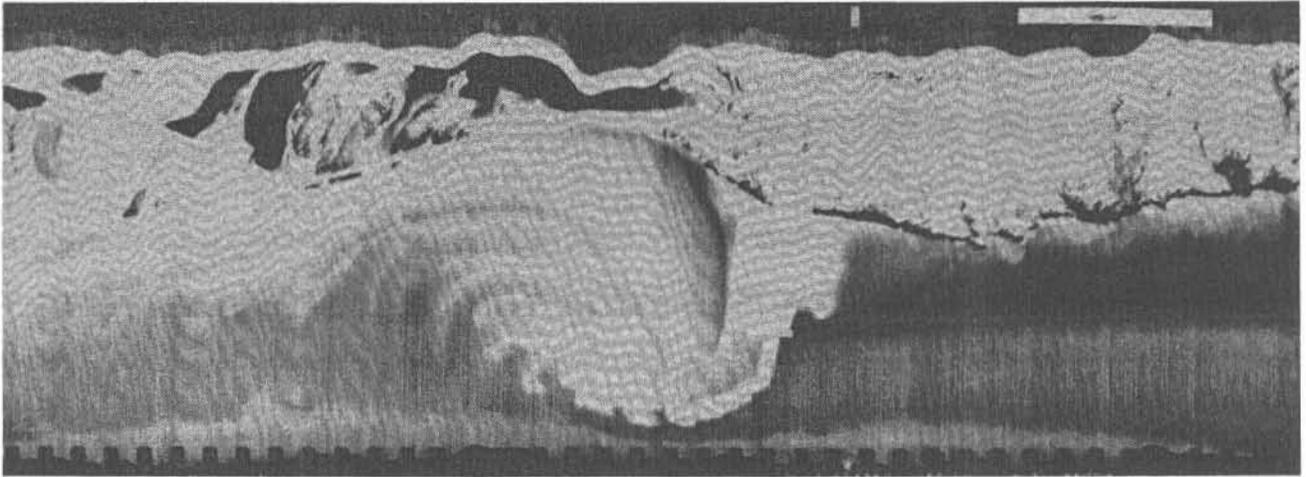


Figure 4. Raw Infrared Scanner Imagery from Flight over Surry Station

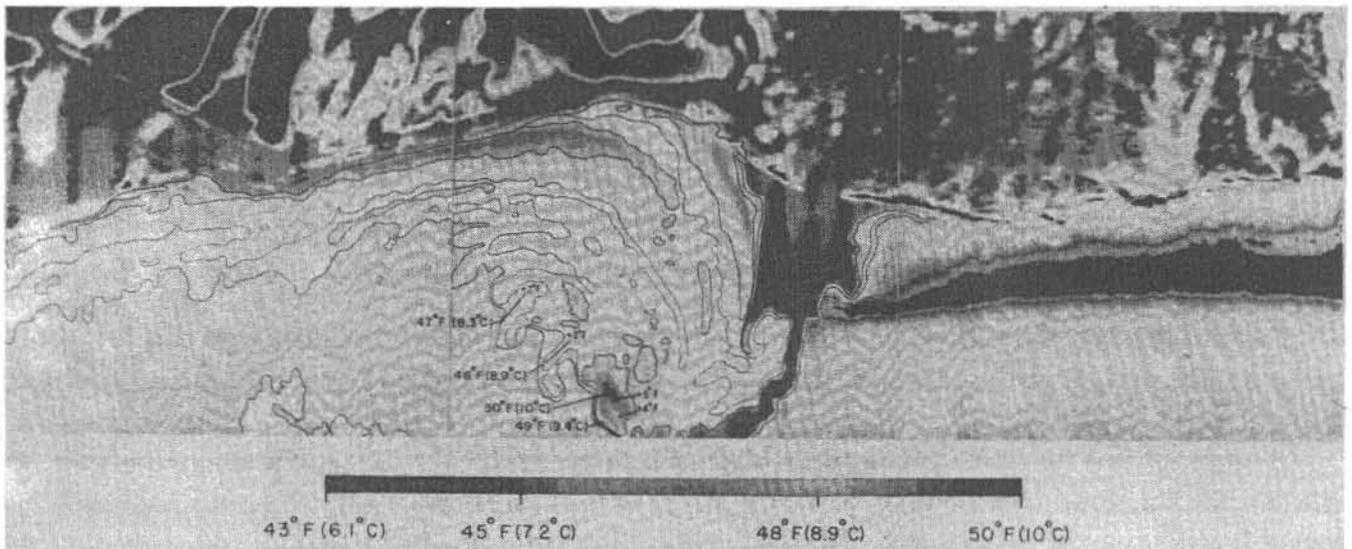


Figure 5. Reduced Surry Station Data with Temperature Contours