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Digital Processing of Analog Thermal Infrared Scanner Data

Greater resolution is obtained at an improved signal-to-noise ratio and with more objective image interpretation.

INTRODUCTION

TWO PROBLEMS are inherent in interpreting normal black-and-white thermal infrared imagery. First, it is subjective because a personal evaluation of the spatial and magnitude distributions of the imaged thermal features, and their implications, is required. Results vary then with the experience of the interpreter and from one interpreter to another. Second, the amount of information retrieved from the photographic format is less than the maximum available due to data smoothing which results from the finite spot size of the oscilloscope tube (flying spot scanner) used to produce the imagery.

ABSTRACT: *A system is described for effective six-bit (64-levels) digitization of recorded analog infrared data which were obtained by using a first-generation Daedalus infrared line scanner. One-hundred twenty-eight samples of the center 90° of each scan line were digitized, and digital data from every eleventh scan line were recorded for computer processing. Initial computer programs used line printer overstrikes to generate a grey scale from which the data subset to be contoured and the contour levels were determined. These data were then used as input to a contour program in order to produce isoradiation contour plots which provided improved thermal detail combined with objectivity.*

Exponential smoothing was also optionally available during digitization and was found to provide a considerable improvement in signal-to-noise ratio with negligible ground peak displacement and without, in most cases, destroying the quantitative relationship of isoradiation level to incident radiation.

Digitization and computer processing of the thermal infrared data allows large sampling rates at high speed with considerable accuracy. The full dynamic range of the scanning system can be accommodated and greater resolution of thermal detail thus can be obtained. Interpretation is less subjective because the spatial and magnitude distributions of the thermal features are clearly and accurately displayed in the form of contour plots and density plots.

THE DAEDALUS INFRARED LINE SCANNER

The Daedalus scanner, which was used in this work, is a first-generation quantitative scanner, and has been described elsewhere (Fleming and Ellyett, 1972; Ellyett and Fleming, 1974). To allow processing of the 8-14 μm, analog infrared signals in the laboratory under controlled conditions, a Lockheed seven-track instrumentation tape deck was used to record the signals and associated video synchronizing pulses.

Scanner optical resolution is ~0.086° (1.5 mrad). However, due to the limited bandwidth of the tape deck (~18 kHz), this figure was degraded to ~0.6° in the scan direction.

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 43, No. 2, February 1977, pp. 145-153.

DIGITIZATION

A block diagram of the digital infrared processing system is shown in Figure 1. Digitization was accomplished by using a multi-channel averager which was also optionally capable of exponential real time smoothing (Keay and Kennewell, 1971) of the sampled data in the flight direction. In order to adequately recover the thermal infrared video signal and its statistics after digitization, careful consideration must be given to sampling rate and quantizing width and this in turn requires a knowledge of the signal characteristics. The requirements for sampling and quantizing have been summarized by Susskind (1957).

The highest significant frequency of the video output from the Lockheed tape deck was approximately 18 to 20 kHz. However, under normal circumstances, the Lockheed tape recorder remained with the scanner in the plane and all digital processing of tapes was done using a modified Revox tape recorder having a 10 kHz bandwidth. From the sampling theorem, a sampling rate of at least 20 kHz was therefore needed with the Revox tape recorder and 36 to 40 kHz with the Lockheed tape recorder. Hardware limitations associated with the averager defined the sampling rate at 30 kHz which gave one sample per 0.72° of scan. Since this is very close to the resolution limit of the scanner when used with the Lockheed tape recorder, and certainly within the scanner's resolution limit using the Revox tape deck, the sampling rate was considered adequate for most applications.

The video output from both tape recorders had a maximum peak-to-peak amplitude of 2 volts. The quantizing requirement (Susskind, 1957) necessitated at least three-bit digitization of the video signal and a quantizing width of 0.25V. Although eight-bit digitization was employed, the digital tape recorder limited the effective digitization to six bits. With the video signal amplified to 10 volts peak-to-peak for maximum input voltage swing to the analog to digital (A/D) converter, the quantizing width was ~0.16 volts.

COMPLETE DIGITAL SYSTEM

Returning now to Figure 1, the video gate circuit was used to provide variable gain and DC offset for adjusting the video signal to a 1 to 10 volt range. To minimize the possibility of aliased high frequency components, the circuit was also used to limit the system bandwidth to ~20 kHz. Exponential RC

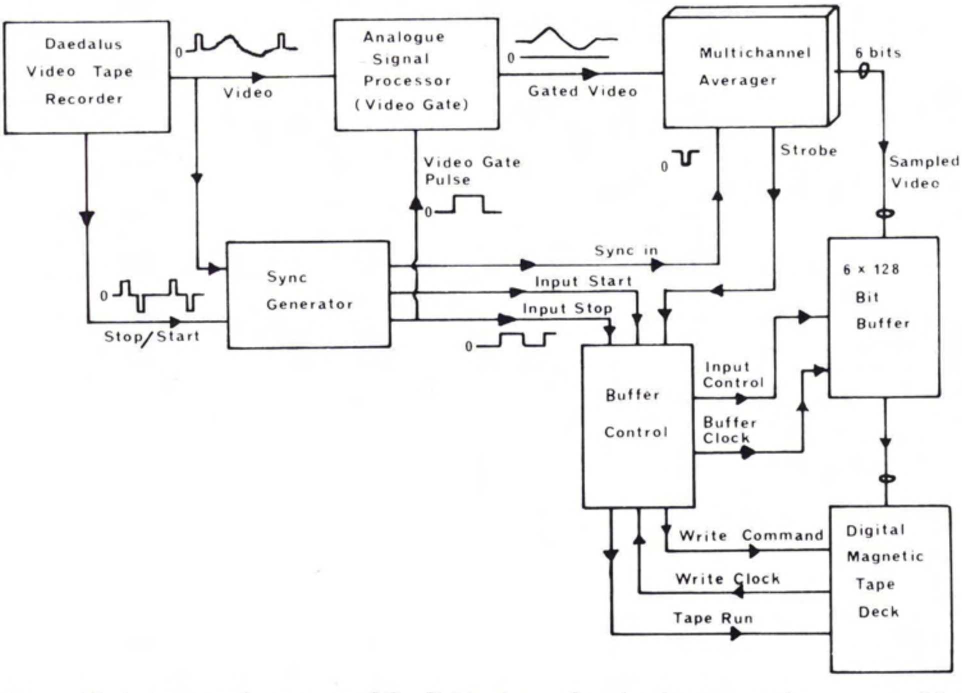

FIG. 1. Block diagram of system used for digitization and optional exponential averaging of the infrared video signals.

(resistance-capacitance) smoothing in the scan direction, corresponding to that provided by the averager in the flight direction, was also optionally provided by the video gate circuit.

The multi-channel averager was initially designed for use in a radar detection system (Kennewell, 1972) to increase its signal-to-noise ratio and was modified for use in this work. The averager was designed so that, following a time delay from the synchronizing pulse, up to 256 samples of the analog input could be taken and stored for exponential averaging with time-coincident pulses relative to the next synchronizing pulse. Normally, in digitizing the analog infrared signals 128 samples were taken which, with an initial 61 sample pulse delay, allowed sampling of the center 90° of scan. A variable sample delay following the synchronizing pulse and a variable sample number were incorporated to provide control over the data density and the position of the sample window relative to the synchronizing pulse. The sync generator provided timing pulses for the complete processing system.

The buffer and buffer control were required to match the 30 kHz output data rate from the multi-channel averager to the 8.34 kHz recording rate (556 characters per inch, 15 I.P.S.) of the Kennedy digital tape recorder which was operated in a semi-incremental mode. For simplicity, a single buffer was used. This restricted data recorded to a maximum of one digitized scan line in eleven, but this was not considered to be a major problem because for an aircraft traveling at 120 knots and at a height of 1,000 ft, this represented ground sampling at about 20 ft intervals in the flight direction. (Cf., at nadir and from 1,000 ft, sampling at intervals of 0.72° in the scan direction represents ground sampling at about 12 ft intervals.) The buffer control also provided variable scan line sampling to a maximum of one scan line in 128.

Figure 2 shows a typical scanner video signal, the sampled output from the A/D converter, and the averager output. The improvement in the signal-to-noise ratio at the averager output can be clearly seen.

Computer Processing

Computer processing of the digitized infrared data was done by using an ICL 1904A computer having 64k words of core storage. The primary aim of the computing work was to obtain isoradiation contour plots. In addition, programs were written for data input and display prior to contouring.

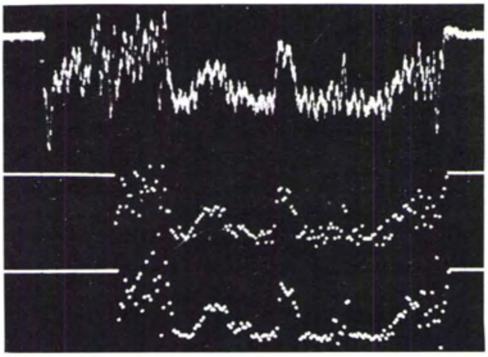

FIG. 2. An example of the digitization (center trace) and averaging (bottom trace) of an infrared video signal (top trace) by the multichannel averager. A total of 157 samples was taken in this example. Because the buffer length was fixed at 128 samples, only the final 128 of the 157 samples were retained and recorded for later processing. With the initial delay before sampling as shown, the initial 128 samples cover the center 90° of active scan.

DATA INPUT TO COMPUTER

For tape security and identification, header and sentinel blocks of standard format were required by the computer at the beginning of each tape. In order to bypass this requirement, a separate assembly language program consisting of three subroutines was written (Wild, 1972) to open, read, and close the non-standard digital tapes. These subroutines were called from the main programs.

The read routine was designed for the sequential row access structure (Hunt, 1972) of the data tape. Each call to the read routine initiated the reading of one data block of 128 characters which, after a binary-to-integer conversion, was stored in an array. If a file mark, used to define the end of a digitizing run, was detected, the first integer in the array was set negative. In all other cases, the resulting integers had values between 0 and 63. For retrieval of data from a specific file, a subroutine was called to search the non-standard tape until a specific number of file marks corresponding to the required file number had been recognized.

MAN-MACHINE INTERACTION

For optimum use of the contour program, the data file subset to be contoured and the contour levels should be accurately defined. This requires a knowledge of the magnitude distribution and extent of data on the digitized infrared data tape. To provide grey level displays for this purpose, two display programs, SYMBOL PLOT and DENSITY PLOT, were developed. Both programs make use of line printer overstrikes to provide the grey levels, and both treated the data block by block and therefore scan-line by scan-line.

SYMBOL PLOT was designed to give a fast, economical first look at the recorded infrared data. Only two line printer overstrikes were used and so, to obtain the fixed eight-level display, both symbol pattern and a limited grey scale transition were used. For ease of identification of areas of interest, both sample (column) and scan line (row) numbers were provided.

DENSITY PLOT used a maximum of 13 line printer overstrikes to obtain an eight-level grey scale. Expansion of the grey scale was possible by optionally setting the eight levels for all or part of the 0 to 63 magnitude range. Options were also included for commencing the plot at any specified block within the data file, for terminating it after a specified number of lines, and for determining its width up to a maximum of 115 samples commencing at any sample position. As with SYMBOL PLOT, both sample (column) and scan line (row) number were included to facilitate the definition of areas to be contoured. Examples of the output from SYMBOL PLOT and DENSITY PLOT for the Mt. Morgan area of Central Eastern Queensland (Figure 3a) are shown in Figures 3b and 3c.

If cost is not a consideration, direct processing of a selected portion of the video data to contours is satisfactory. The overstrike programs represent an intermediate step which was designed to minimize the overall processing costs by allowing a careful and accurate selection of the digitized data subset and contour levels for contouring.

CONTOUR PROGRAM

The contour program (CONTUR) used in this work is based on a contour generator program by Armbrust (1968). An example of its output for the Mt. Morgan area defined in Figure 3c is shown in Figure 4. The program uses a contour-following technique (Crain, 1970) for contouring an equispaced data grid. To ensure that the generated contour lines pass smoothly from one grid box to the next, Lagrangian interpolation is used to calculate points on a subdivided grid. Contouring is then accomplished by linear interpolation between these points.

The requirement for an equispaced data grid is important since the use of a non-equispaced grid introduces considerable interpolation problems (Crain and Bhattacharyya, 1967). Whereas the digitized infrared data were not equispaced, they were regularly spaced with each grid box being a rectangle in reality. This allowed Armbrust's contour generator program to be used, with the square grid box shape being introduced during scaling.

In order to provide a flexible contouring system, subroutines were added to the program to permit file location, variable scaling, and the definition of those parts of the selected data array to be contoured. In areas of rapid thermal change where only a portion of the data was to be contoured, this feature was valuable for saving processor time.

The variable scaling was of great value in facilitating the comparison of contour plots with air photos and maps. Knowing the height and velocity of the plane, the final plot could be produced at any desired scale. In the scan direction, both linear and tangent θ scaling were optionally available. For linear scaling, it was assumed that the distance between samples at the nadir remained constant as the angle from the nadir increased. For tan θ scaling, which was used to produce distortionless plots, the distance between samples was increased away from the nadir in proportion to the tangent of the angle from the nadir.

The plotting for this work was done on a 74.6 cm plotter using an "offlining" feature of ICL's 1900 series computers.

Typical run times are given in Table 1 as a guide to the relative efficiency of SYMBOL PLOT and DENSITY PLOT and the efficiency of CONTUR under various circumstances. The run time for CONTUR increased markedly with the number of contour levels and the array size.

EXPONENTIAL AVERAGING OF INFRARED SIGNALS

Exponential RC smoothing in the scan (X) direction, corresponding to that provided by the averager in the flight (Y) direction was obtained through analog RC filtering. Determination of the appropriate X time constant for matching of the X and the Y smoothing proved interesting because a continuous and a sampling process having different time scales were involved. Direct comparison of time constants was therefore erroneous and the processes were considered in terms of their spatial filtering effect. To do this, a common parameter, the distance scanned or covered, was introduced.

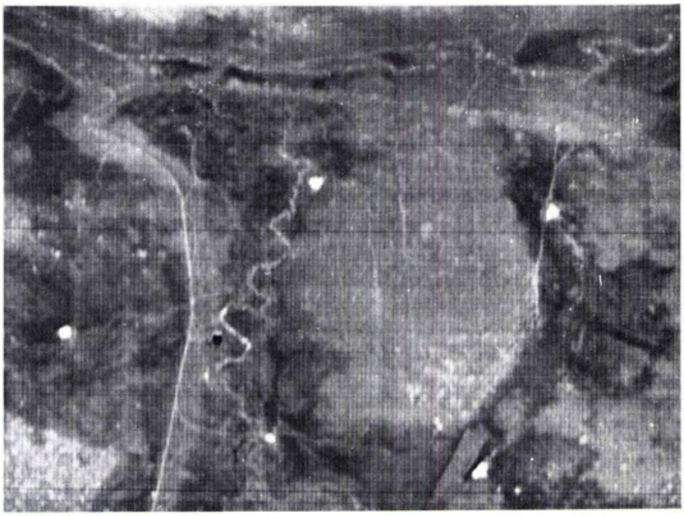

FIG. 3a. Pre-dawn infrared imagery of a wooded area near Mt. Morgan, Queensland. Only the approximate area covered by Figures 3b and 3c is shown.

FIG. 3b Illustration of symbol plot output for the digitized infrared imagery of Mt. Morgan, Queensland.

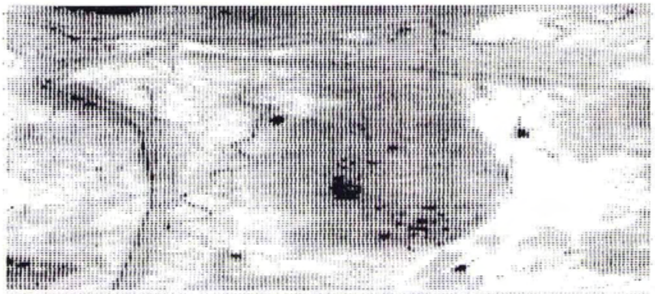

FIG. 3c. Illustration of DENSITY PLOT output for the Mt. Morgan imagery. An expanded grey scale has been used with the eight levels covering equally the data range of 27 to 39

The multichannel averager time constant, τ, is given by Butler, (1974):

$$\tau = 2^k T \qquad (1)$$

where T is the sampling period (1/120th sec for the Daedalus scanner) and k is any positive integer.

In the flight direction, the distance, d, covered in time, τ, is:

$$d = V\tau \qquad (2)$$

where V is the aircraft velocity.
In the scan direction, the time t^1, required to scan a distance, d, is:

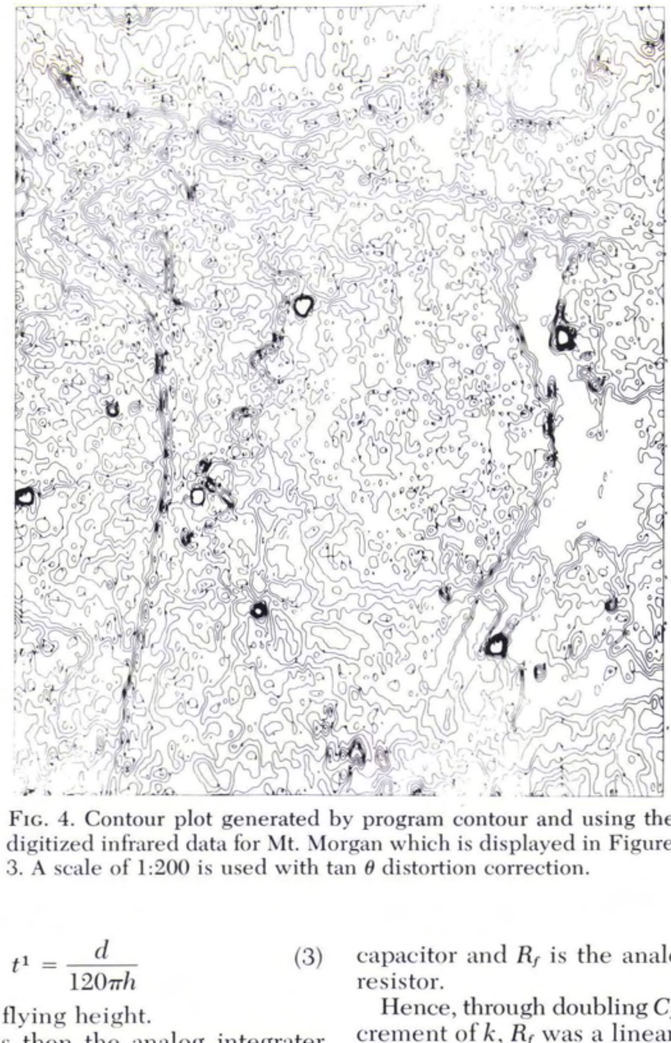

FIG. 4. Contour plot generated by program contour and using the digitized infrared data for Mt. Morgan which is displayed in Figure 3. A scale of 1:200 is used with tan θ distortion correction.

$$t^1 = \frac{d}{120\pi h} \tag{3}$$

where h is the flying height.

The time, t^1, is then the analog integrater time constant.

Substituting Equations 1 and 2 in Equation 3 with $T = 1/120$s. and $t^1 = R_f C_f$ gives

$$R_f C_f = 2^k \left(\frac{V}{h}\right) \frac{1}{(120)^2 \pi} \tag{4}$$

where C_f is the analog RC feedback capacitor and R_f is the analog RC feedback resistor.

Hence, through doubling C_f for each unit increment of k, R_f was a linear function solely of the V/h ratio, and matched X and Y smoothing was possible for various V/h ratios through altering R_f.

EFFECT OF EXPONENTIAL AVERAGING

Since the RC filter is the analog equivalent of the digital averager (Butler, 1974), its

TABLE 1. TYPICAL PROGRAM TIMES

Program	Array Size	Compilation*/ Consolidation (Millsecs)	Run Time (Millsecs)
SYMBOL PLOT	505 × 120	20	230
DENSITY PLOT	490 × 120	18	510
CONTUR**	505 × 120	55	1074
CONTUR***	145 × 120	55	1405

* ICL standard fortran compiler #XFAT used.
100 millsecs = 1 real minute.
** Linear scaling, 5 contour levels.
*** Tan θ scaling, 10 contour levels.

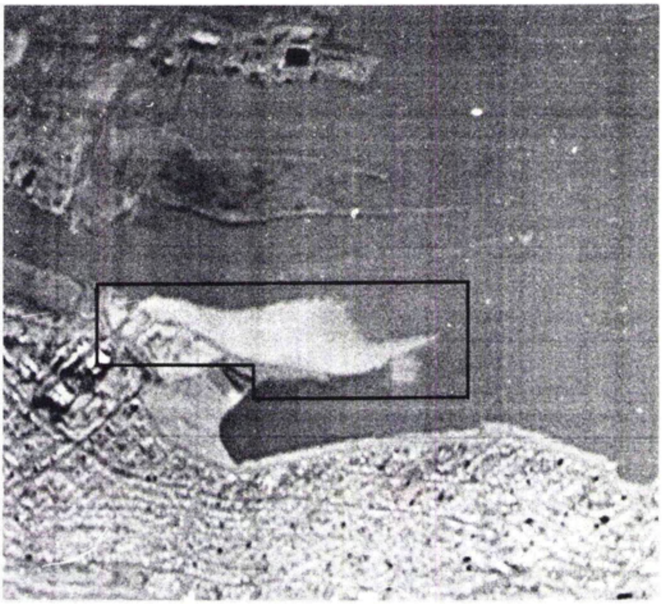

FIG. 5. Thermal infrared imagery of a thermal plume from the Newport power station at the mouth of the Yarra River, Port Melbourne, Victoria. The imagery was flown at 09.00 hrs. from 3500 ft. The area which was contoured is outlined.

frequency response function is the same as that of the multi-channel averager out to the Nyquist frequency. Its effect on the infrared signals in the scan direction will therefore be the same as that of the averager in the flight direction. Hence in this section, only the effect of the multi-channel averager on the infrared signals is discussed.

The properties of the averager were derived and discussed by Butler (1974) and may be summarized:

(1) the mean of the output is equal to the mean of the input;
(2) for independent input samples (noise), the output variance is reduced by $1/(2^{(k+1)} - 1)$. Correlated signals are preserved;
(3) filtering is exponential with the system having a comb filter frequency response function given by:

$$|H(e^{j\omega t})| = \frac{a}{(1 + b^2 - 2b\cos \omega T)^{1/2}} \quad (5)$$

where T = sample period
$a = 1/2^k$
$b = (1 - a)$

(4) Peak amplitude is reduced and maximum amplitude occurs when input and output amplitudes are equal. This implies some shifting of peak position (systematic error).

The signal-to-noise ratio improvement produced by equal exponential averaging in both the scan and flight directions can be seen in the contour plots of a thermal plume (Figure 5) shown in Figures 6 a-d where k values 0-3 have been used.

Sampling the averager output at a rate of 11 per second* implies, from the sampling theorem, the need for the system to be band-limited to ~5.5 Hz. From Equation 5, it can be shown that the infrared signal bandwidth in the flight direction is reduced by the averager from 60 Hz to ~14, 5.5, and 2.5 Hz for divisor constants, k, of 1, 2, and 3 respectively. Therefore, only the $k = 2, 3$ smoothed plots should be free from aliasing effects (cf., Figure 6a) and so only these k values were used during data analysis.

Ideally, if smoothing is to be used in quantitative work, it should remove noise only, leaving the target unaltered. However, while exponential averager divisor constants of 2 and 3 remove aliasing effects and improve the S/N ratio of the contour plots, their effect on amplitude reduction and systematic er-

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* Although 120 samples from each scan line were taken by the averager, only the samples from every eleventh scan line could be taken from the averager and recorded. Since the scan rate was 120/second, this implies sampling the averager output ~ 11 times per second.

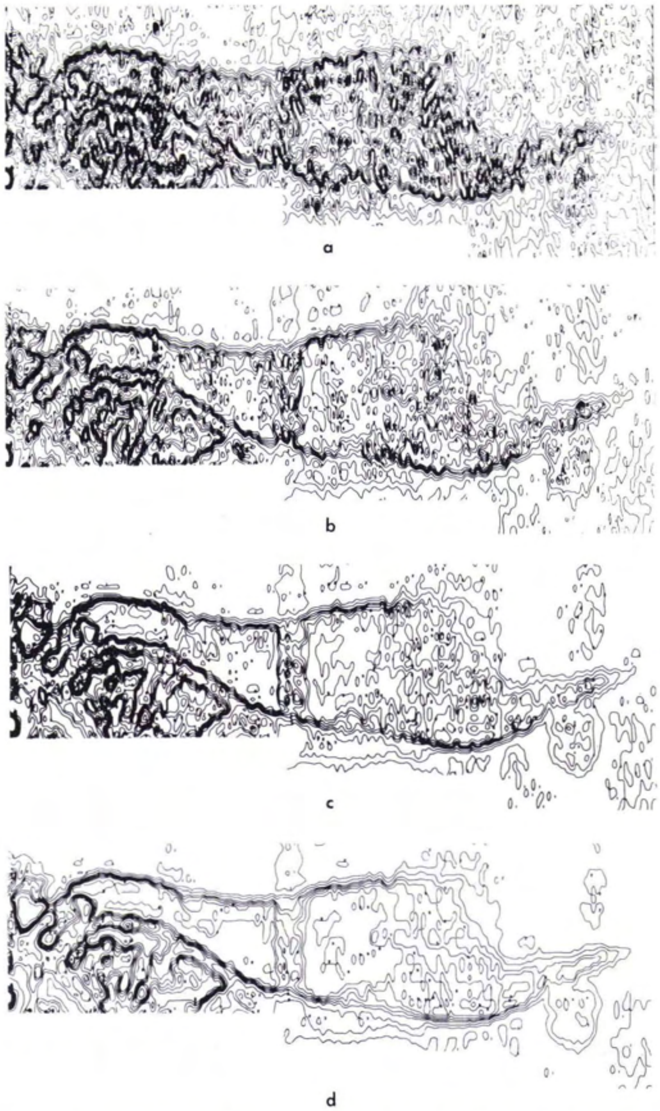

FIG. 6. Contour plots of Newport power station thermal plume from digitized infrared data; (a) unsmoothed ($k = 0$), (b)-(d) with averager constants k of 1, 2, and 3 respectively. Note that D.C. drift in this system appearing as vertical bands was a problem over water. The scanner has since been modified to eliminate D.C. drift effects.

rors is greater than for $k = 1$. The amplitude reduction factor depends greatly on target size as compared with the effective smoothing length of the averager, and also on the rate of signal rise. Butler (1974) quotes an effective smoothing length of 7 and 15 samples for $k = 2$ and 3 respectively. Thus, if the target is slowly varying and greater than seven sample periods (i.e., seven scans) in width, the effect of the averager on the target amplitude will be minimal.

For all diviser constants, some shift in peak position is inevitable. In aeromagnetic and similar geophysical surveys, where flight lines are typically at 0.5 mile intervals, the displacement of an anomaly peak by even one or two samples by smoothing can be a significant error. In this work, a peak displacement of 15 samples with $k = 3$ would be extreme. With a scanner resolution of 1.5 mrad in the flight direction, contiguous scans, and a flying height of 1,000 ft, instantaneous ground resolution width is 1.5 ft and the smoothing induced displacement would be 22.5 ft, which is a negligible distance. Therefore, a major objection to exponential smoothing in geophysics is not applicable in this case. It should be noted, however, that the degradation in scanner optical resolution in the scan direction due to bandwidth constraints associated with the analog magnetic tape, can lead to a significant peak displacement in the scan direction. For the system described here, a typical displacement of about five to seven samples would introduce a manageable displacement of 500 to 700 ft, which is very much less than the corresponding 2 to 3 mile displacement which would arise in geophysical surveys with 0.5 mile sampling and exponential smoothing.

CONCLUSIONS

A considerable improvement in thermal detail is provided by the contour plots. The facilities within the system for plot linearization and scaling have been extremely useful for matching the quantized infrared imagery with air photos, thus allowing easy identification of thermal features. Whereas the plots make imagery interpretation more objective, some experience is still required for efficient plot interpretation, particularly of linear features. The use of five to eight contour levels normally provided the best compromise between cost and improved display and interpretability. Areas of rapidly changing thermal slope can be enhanced with 10 to 15 levels. The exponential smoothing provides an excellent signal-to-noise improvement with negligible ground peak displacement. It has been useful in preventing possible aliasing effects due to inadequate sampling in the flight direction and, if the target size is greater than the effective averager length, as is mostly the case, peak amplitude reduction is minimal.

Finally, through studying the application of contoured thermal imagery to geology and hydrology (Goldsbrough, 1974), the contouring technique was found to be most useful for temperature contouring of water bodies. A smoothing constant, k of 2 or 3 was found to be desirable for increasing the signal-to-noise ratio. Contouring of infrared imagery of land areas required considerable processor time due to the detail involved and this application appears to be limited to areas where thermal detail is required.

ACKNOWLEDGMENTS

I would like to express my appreciation to Professor C. D. Ellyett, Physics Department, Newcastle University, for his advice, suggestions, and support throughout this work. My appreciation is also expressed to the members of the electronics workshop of the Physics Department, Newcastle University—Mr. E. C. McLaughlan, Mr. P. McNabb, Mr. A. James, and Mr. J. Davis—for their advice and assistance with the construction of the infrared digital processing equipment. Thanks are extended to Geopeko Limited for permission to use their infrared imagery of Mt. Morgan, Queensland, and also the Victorian Electricity Commission for permission to use their infrared imagery of the thermal plume. Finally, the assistance of a Commonwealth Post-Graduate Research award is gratefully acknowledged.

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