A preliminary assessment of an airborne thermal video frame scanning system for environmental engineering surveys

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ABSTRACT : Video based camera systems are being used by an increasing number of remote sensing users. These systems offer several advantages in terms of ease of use, speed of operation, portability and cost. Of particular interest are the thermal video frame scanning (TVFS) systems. These scanners, developed primarily for military purposes, differ considerably in design from the thermal infrared linescanning instruments traditionally used for thermal surveys in remote sensing. One specific example, the Barr and Stroud IR18, is described together with the modifications necessary to mount such a system in a number of light aircraft. Methods of digitally enhancing and classifying single frames of data are discussed. The paper concludes by considering the application of suitably processed imagery for environmental engineering projects such as heat loss monitoring, thermal mapping of roads, geotechnical site investigations and drainage, sewer collapse and utility duct surveys. Further potential areas of application are also identified.

RESUME: Les utilisateurs de télé-détection utilisent de plus en plus l'appareil photographique qui se fonde sur le video. Ces systems offrent plusieurs advantages - facilité d'usage, vitesse d'operation, portabilité, et cout. Les systemès qui se basent sur l'explorateur thermique de cadre video (TVSF) sont d'intéret particulier. Le dessin de ces appareils explorateurs qui étaient dévéloppés pour les buts militaires d'abord différent considérablement des instruments d'exploration thermique et lineaire qu'on emploie d'habitude pour les levés thermiques dans le télé-détection. On décrit un exemple spécifique, le Barr et Stroud IR18, et aussi les modifications nécessaires pour installer un tel système dans quelques avions légers. On discute les méthodes digitales de rehausser et classifier les cadres uniques de données. Le papier conclut de considerer l'application des images traités pour les projets de génie de l'environnement, par exemple, la surveillance de la perte de chaleur, la cartographie thermique de routes, les investigations géotechniques de site et la surface de captation des eaux, l'effondrement des égouts, et les levés des conduits utilitaires. On identifie aussi les autres domaines d'application potentiale.

1 INTRODUCTION

An increasing number of users in recent years have been considering the potential of video based aerial remote sensing systems. A wide variety of data acquisition systems are currently available and a selection of these are reported in section 2, together with some discusssion of the advantages of using video as a recording medium.

One of the most exciting developments however, is in the use of thermal video frame scanners (TVFS) operated from light aircraft. The design features of such instruments, with particular reference to the Barr and Stroud IR18, are discussed in section 3. This is followed by details relating to the mounting of such a system in a variety of light aircraft.

The use of digital image processsing techniques to filter and enhance single frames of thermal data is presented in section 4. The paper concludes by reporting some of the current projects for which the scanner has been used.

2 AIRBORNE VIDEO BASED DATA ACQUISITION SYSTEMS

A summary of previous literature which has reported on the use of video based data acquisition systems is given in Table 1. Several advantages can be cited to demonstrate the benefits of video based systems, which include system portability, near real time verification of data capture, rapid turnaround (since there is no processing stage), low cost of operation and ease of duplication of data (Meisner and Lindstrom, 1985). In view of these perceived advantages a research programme was initiated by the University of Surrey, in conjunction with the University of Glasgow, in August 1984 to evaluate the use of a portable TVFS system for remote sensing applications. Although low resolution thermal imaging systems such as the Aga Thermovision have been used previously (Tice and Larsson, 1978, Geraci, 1983, and Geraci and Caltabiano, 1983) little attention has been focussed on the more expensive, but much higher performance, military forward looking infrared (FLIR) imaging systems.

Table 1 Summary of previous literature - airborne video based data acquisition systems

Spectral Region	Author(s)	Application
(0.4-0.70µm) Panchromatic	Mussakowski, 1983	Water assessment
(0.4-0.7µm) 3 band colour	Vlcek, 1983 Vlcek and Cheung, 1983	Forestry "
(0.4-1.1µm) 3 band 'false' colour	Meisner and Lindstrom, 1985 Everitt and Nixon, 1985 Nixon, Escobar and Menges, 1985	Rangeland studies Vegetation studies
(0.55-1.1µm) 4 band Multispectral	Vlcek and King, 1984 Vlcek, King and Shemilt, 1984	Vegetation Vegetation Mapping
(3-5.6µm, 8-14µm) Thermal Infrared	Tice and Larsson, 1978 Geraci and Caltabiano, 1983 Geraci, 1983 Clement, 1985 Amin, 1986	Heat loss Oil pollution Water quality Water quality Geothermal Mapping

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3 THERMAL VIDEO FRAME SCANNERS (TVFS)

A TVFS system consists of four basic components:
(a) a scanning system which views the scene to be imaged and focusses the incoming infrared radiation,
(b) a ferro-magnetic or semi-conductor detector which measures the thermal variations in the scene,
(c) a CCTV compatible display system where the thermal variations are used to modulate the intensity of an electron beam, and
(d) a video cassette recorder (VCR) to record the thermal imagery.

Unlike thermal IR linescanning systems which are designed specifically for airborne use, the TVFS systems under consideration are designed for both ground and airborne operation. Consequently, the optical configuration, scanning mechanisms and detector arrays differ from those used for thermal linescanning and this leads to significantly different imaging systems being employed.

3.1 Imaging techniques

In general terms a thermal imager operates by mechanically scanning a focussed beam of incoming radiation onto an infrared detector. In its simplest form, such as in a thermal IR linescanner, the scanning is performed in one direction, perpendicular to the direction of flight, by an oscillating mirror or rotating prism. The incoming radiation is then focussed onto a single detector, normally of mercury cadmium telluride (HgCdTe). The 'frame' scanning in this case is performed by the forward motion of the aircraft.

If the imager is to be used from a static platform then some method of scanning in two dimensions is required. There are, however, several practical difficulties with such a single element detector design if a flicker free, high spatial resolution image is to be obtained. Consequently, if high resolution is required it is often more efficient to use a multi-element detector design. Three distinctive arrangements are possible: parallel, serial and matrix scanning.

Parallel scanning involves using a single column of detectors arranged so that each detector element scans a single line in the image. This arrangement reduces the scanning speed. However, the performance of each of the detector elements needs to be similar if the formation of a 'streaky image' is to be avoided. Further significant reductions in scan speed can also be achieved by using band interlaced scanning techniques (Chiari and Morten, 1982).

Serial scanning systems, in contrast, operate by using a single row of detector elements. The cumulative output is obtained by summing the individual signals from each detector. In order to achieve this it is necessary to include separate pre-amplifiers and delay line circuitry for each detector element. Although the electronics of this design are more complex, since the same detector element scans all lines in the image the uniformity of the image is more consistent than with the parallel system.

A compromise arrangement which combines the scene uniformity advantages of the serial scan approach with the high scan speeds of the parallel arrangement is the mixed parallel/serial or 'matrix' design. Inevitably, as the number of detector elements increases, so the number of electrical connections also increases. Although this difficulty, and the consequent signal processing complications can be overcome, the design trend in recent years has been to use SPRITE detectors.

As mentioned previously, with conventional serial scanning the output from each IR detector is pre-amplified, delayed and then added to the signal which is generated in the following element. SPRITE (SIgnal PRocessing In The Element) detectors overcome the need for these separate connections. In the SPRITE design the row of individual detectors is replaced by a single strip of HgCdTe with only two connections and one pre-amplifier. Eight element SPRITE detectors are used in most TVFS systems, such an arrangement is equivalent to a conventional array consisting of 64 discrete elements.

Although SPRITE detectors eliminate many of the connections and much of the circuitry, they still require some form of mechanical scanning to be carried out. An area of considerable interest at present is the development of 'staring arrays' i.e. a matrix of infrared detectors. In this case the function of the optics is simply to focus the incoming radiation onto the matrix of detectors located in the focal plane of the camera. Whilst it is likely that such arrangements will eventually replace the SPRITE design, this is unlikely to occur until very dense matrices can be formed thus enabling high resolution imagery to be produced.

3.2 System review

A wide range of thermal imaging systems are currently available and Table 2 outlines the technical specifications associated with a selected sample.

Table 2: Technical Specifications : Thermal Video Frame Scanning Systems.

	Spatial Resolution (mr)	MRTD* (^{0}C)	Spectral Range (µm)
AGA Thermovision	5.8	0.1	3-5.6 8-12
GEC V1010 TICM 11	2.27	0.1	8-13
Hawkeye HT4	2.1	0.15	8-13
Rank Pullin Controls SS600	2.1	0.15	8-13
Inframetrics IRTV-445G	2.0	0.4	8-12
FLIR Systems 1000A	1.87	0.2	8-12
Barr and Stroud IR18	1.73	0.38	8-13

MRTD* = Minimum Resolvable Temperature Difference

As mentioned in the literature review several previous authors have discussed the use of the AGA Thermovision range of instruments for airborne use. These instruments, of which model 782 is the most recent, are single detector, low spatial resolution systems. Two versions of this instrument are available for sensing in the 3 to 5 µm and 8 to 14µm regions of the spectrum. An image consisting of 100 elements/line over a 280 lines/frame format refreshed at 25Hz and interlaced four to one is produced by the scanner. In addition to the low spatial resolution of the instrument the slow refresh rate creates image registration problems when sensing from a moving platform. A further disadvantage is the difficulty of producing a vertical image. In order to achieve this a 45^0 mirror has to be used so as to avoid the liquid nitrogen from the cooling system being expelled.

The Inframetrics IRTV 445G can however be gimbal mounted for airborne use. It uses a 4 element HgCdTe detector and creates a 400 elements/line image over a 445 lines/frame format refreshed at at a frame rate

of 30Hz. Both AGA and Inframetrics have also developed dedicated image processing software for enhancing the imagery and extracting quantitative temperature data.

The majority of high performance TVFS systems operating in the 8 to 13 μm band have been developed for avionic and military applications. Development of the current range of UK military imagers began in 1976 and at that time the decision was made to adopt a modular design philosophy. This is known as the Thermal Imaging Common Module (TICM) programme. The GEC V1010 TICM 11 is representative of this design. Instruments of this type can be mounted in either a fixed wing aircraft or a helicopter, in the latter case the scanner is mounted in a pod to allow a forward looking image to be obtained.

The Rank Pullin Controls (RPC) SS600 thermal imager differs from the conventional TICM scanning design which uses a flapping mirror to scan the field in elevation and a rotating polygon to provide the line scan. In contrast, the RPC design uses two coaxially mounted rotating polygons to form the two dimensional scan pattern. This unique design (Figure 1) is claimed to result in a lighter, more robust and more compact imager suitable for use where severe vibration may be experienced.

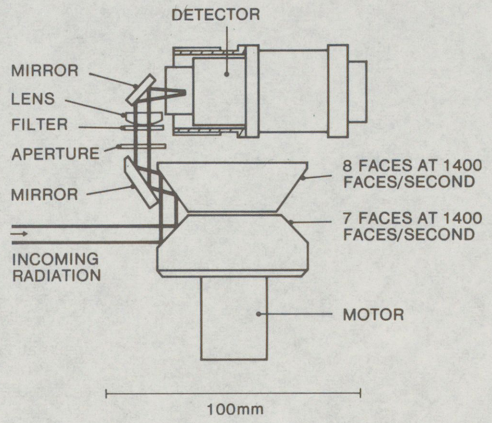

Figure 1. Rank Pullin Controls SS600-scanning system (Lettington, 1985)

The Barr and Stroud IR18 is another TVFS system based on a modular design approach. A narrower scanner field of view is used compared with several other equivalent systems. In this case also a novel optical-mechanical scanning design is used which is discussed in the following section of the paper.

3.3 The Barr and Stroud IR18 Mk II Thermal Video Frame Scanner

The scanner used in these tests was developed initially for military use, but it is now available for commercial remote sensing applications. Table 2 outlines some of the technical specifications of the sensor and Figure 2 illustrates the principle of operation of the scanner.

To achieve a video compatible image, two main criteria have to be met: firstly, the resultant image must be rectilinear and, secondly, it should have a 625 line CCTV output (525 lines in the USA). In order to achieve this, banded scanning is carried out using a high speed rotor, turning at 39,000 rpm, to give

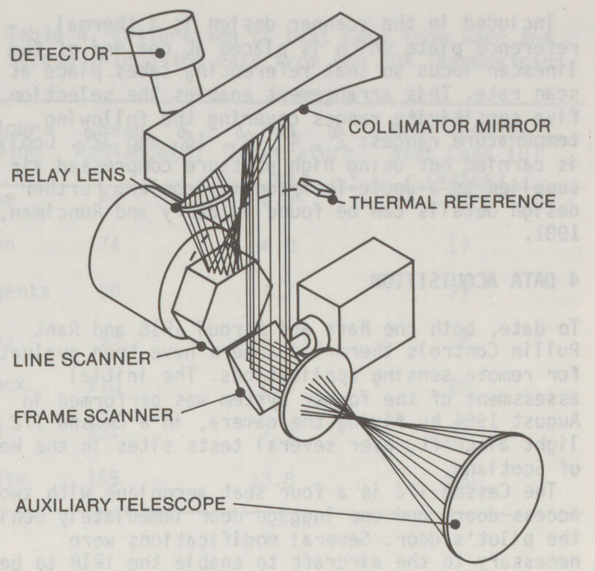

Figure 2. Barr and Stroud IR18 Mk 11 thermal video frame scanner - principle of operation (Berry and Runciman, 1981)

the line format, and a slower galvanometer driven rotor to achieve the frame transfer at 50Hz. Petrie (1983) has estimated that the system has a data collection rate equivalent to 19 X 10^6 pixels/second.

The optics of the IR18 are used to collimate the incoming radiation and, by using afocal telescopes, enable a variety of magnification ratios to be used, so producing various object field of views (Table 3). Such an arrangement ensures that the incident radiation forms a bundle of parallel rays which can then be focussed onto the frame scanning rotor. A concave mirror then re-collimates the image onto the rotating hexagonal rotor and subsequently onto the detector.

Table 3: Barr and Stroud IR18 - object field of view with various auxiliary telescopes

Magnification Ratio	Object Field of View (H^0 X V^0)
1	38.0 25.5
1.5	25.3 17.0
6	6.30 4.25
9	4.22 2.8
14	2.7 1.8

The detector used is an eight-element Mullard 'SPRITE', although four elements are normally preselected for use. The scanning sequence is such that on each successive frame scan a different element (of the four active elements) scans the same part of the scene. A consequence of this is that if the imager output is integrated over a number of frames, detector non-uniformity errors can be eliminated. Complex microprocessor controlled circuitry controls the synchronisation of the rotor speeds and signal outputs and the transfer of the data onto video tape. A conventional U-Matic video tape recorder is used to store the imagery.

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Included in the scanner design is a thermal reference plate which is placed at one end of the linescan locus so that referencing takes place at the scan rate. This arrangement enables the selection of five sensitivity ranges covering the following temperature ranges: 2^0, 4^0, 8^0, 16^0 and 32^0. Cooling is carried out using high pressure compressed air supplied to a Joule-Thompson minicooler. Further design details can be found in Berry and Runciman, 1981.

4 DATA ACQUISITION

To date, both the Barr and Stroud IR18 and Rank Pullin Controls thermal scanners have been evaluated for remote sensing applications. The initial assessment of the former system was performed in August 1984 by flying the camera, in a Cessna 172 light aircraft, over several tests sites in the West of Scotland.

The Cessna 172 is a four seat aeroplane with two access doors and one luggage door immediately behind the pilot's door. Several modifications were necessary to the aircraft to enable the IR18 to be used for the production of vertical imagery. The main features of the design which was used are described in Ekin (1984). Briefly the approach adopted by Ekin was to design a retractable camera carriage, attached to the luggage door, which could be extended in flight by the camera operator. A pair of rails, on which four wheels with V - shaped groves ran ensured the smooth movement of the rig into the extended position. Figure 4 illustrates the IR18 mounted in a slightly modified version of the rig described.

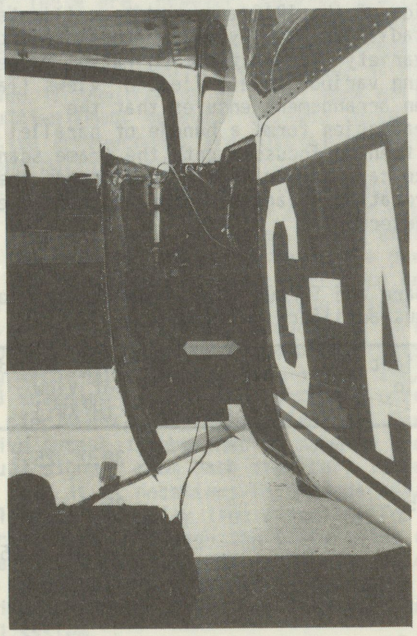

Figure 4: Barr and Stroud IR18 mounted on retractable camera rig in a Cessna 172 light aircraft.

The adoption of a light aircraft and an easily manipulated TVFS system of the type described offers several advantages to the user. Firstly, by using widely available light aircraft the operational costs of the survey can be significantly reduced. Secondly, once the site of interest has been located and the camera rig extended, the scanner operator can view, via a small monitor, the area being imaged by the instrument. Thirdly, after the survey has been completed immediate confirmation that the data has been recorded successfully can be achieved by playing back the video tape, either in flight, or more commonly when the aircraft returns to base.

For other applications however, it may be unacceptable to use the scanner from a light aircraft, either because of the need for a more stable platform, or the need to use the camera in conjunction with several other sensors. More recent experience of using the IR18, for defence and commercial applications by ERSAC Ltd. has involved using the IR18 in a purpose built camera mount in a twin engined Piper Aztec aircraft. For maximum flexibility of operations and integration with a standard aerial camera, a special adapter plate was designed and deveolped by ERSAC and Barr and Stroud to enable the IR18 to be mounted and operated through a standard Wild RC8 aerial camera mount. This configuration is illustrated in Figure 4. The most significant advantage of this design is the capability for full yaw control; this enables higher precision to be achieved when flying parallel flightpaths for the acquisition of imagery over large areas

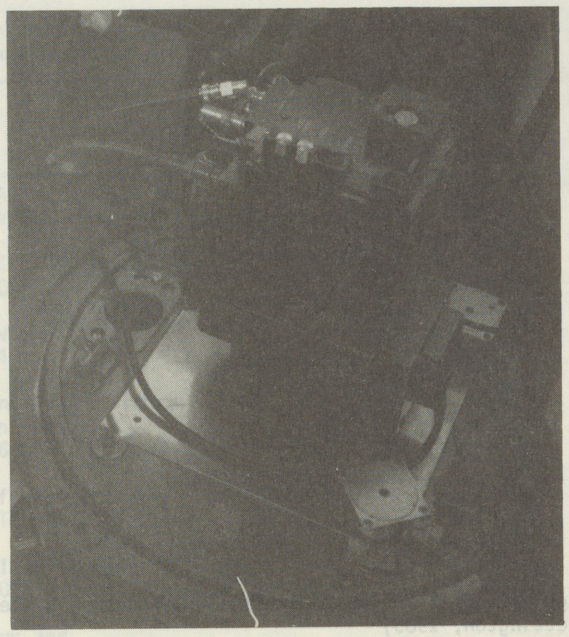

Figure 5: Barr and Stroud IR18 in an adapted Wild RC8 aerial camera mount in a Piper Aztec aircraft

5 DATA PROCESSING

The processing of video based thermal data consists of three distinct phases:

(a) conversion of the analogue video recording to a digital format,

(b) pre-processing of the digital data to remove image inconsistencies, and/or to rectify and geometrically correct the image, and

(c) processing and analysis of the data using conventional image processing techniques.

The analogue to digital (A to D) conversion of video tape is carried out using a digital frame store (DFS) or 'frame grabber'. These instruments are now widely available at relatively low cost. The particular model used for these investigations was the Quantel 3001 DFS controlled by an IDP 3000 image processing system.

The pre-processing, and processing stages, were carried out on a GEMS image processing system. One particularly useful pre-processing technique is that

of de-striping. This was performed by running a rectangular box filter across the image. The advantage of such a process is to produce a more consistent image. However, since the filter cannot discriminate between small scene variations and systematic and random noise, both tend to be removed or reduced in amplitude.

For applications where there is an interest in the detection of subtle linear features, (for example the identification of subterranean field drains), it has been found useful to perform a variable filter edge enhancement, the filter size being dependant on the particular feature of interest. The most commonly used filters range from 3 X 3 to 15 X 15 pixels in dimension. Once the feature of interest has been enhanced by this process it has also been found useful to apply a median filter; this resamples the data in a 3 X 3 box. By using this process isolated pixels caused by the edge enhancement procedure tend to be removed.

A further processing operation is required if the project requires quantitative absolute temperature values. In order to obtain such information calibration of the imagery needs to be carried out using ground temperature measurements obtained at the time of the aircraft overpass. Correlation of these ground measurements with the unstretched digital numbers can be used to establish the limits for a quantitative density slice representing discrete temperature levels. The application of this technique to heat loss monitoring is presented in section 6.

6 APPLICATIONS

As mentioned previously several flights of the Barr and Stroud IR18 TVFS were performed during August 1984 as part of a preliminary research assessment of the instrument. As a consequence of early morning mist these flights took place from late morning until late afternoon rather than, as planned, during the post-sunset/ pre-dawn period. The imagery obtained was, nevertheless, useful since it enabled the potential of the imagery to be assessed together with methods of processing the imagery (Dale, 1985)

More recently both the Barr and Stroud and RPC TVFS systems have been flown, for a variety of projects by ERSAC Ltd. The following material reports some of the most significant applications to date.

6.1 Heat Loss Monitoring.

Several projects have been carried out using the Barr and Stroud IR18 to assess heat loss from industrial and residential buildings. As mentioned above, in order to provide quantitative estimates of localised heat loss from TVFS imagery it is necessary to establish calibration data to relate the grey scale variations on the image to emitted radiance and eventually to estimates of heat emission. In addition to deriving emitted temperature it is also necessary to evaluate the variations in emissivity over the scene.

Ground temperature measurements can be obtained using either conventional in-situ temperature probes (e.g. thermistors or thermometers) or alternatively by using ground based radiometric measurements from instruments such as the AGA Thermovision. As mentioned earlier the AGA Thermovision is a low spatial resolution system; however, it is possible, by using a blackbody reference, to obtain ground temperature measurements. By using the Stefan-Boltzmann law the heat loss for a particular temperature value can be derived and a suitable density slice for the IR18 imagery obtained. The results of one particular set of data are shown in Table 4.

If the computed heat losses (Q) from Table 4 are regressed on the mean digital number indicating emitted radiance (R) from the IR18, then a regression coeffiecient (r) of 0.924 is obtained. The

Table 4. Calibration of Heat Loss from Barr and Stroud IR18 using data from the AGA Thermovision

Colour Coding	Mean Radiance(R)	AGA Temperature (^{0}c)	Mean Computed Heat Loss (Q) (Watts)
Blue	44	2.5	11
Cyan	74	4.0	17
Magenta	80	4.7	21
Grey	95	6.3	28
Black	110	6.5	29
Red	131	7.6	33
White	155	13.8	63

coefficient of determination (r^2) is 0.854, indicating that 85% of the computed heat losses from the calibration results above can be explained by the corresponding radiance values (R) as recorded and digitised from the IR18 sensor data. The resulting heat loss regression equation for the IR18, for the 8^0c gain setting was of the form;

$$Q = 0.4185R - 12.537 \quad ....(1)$$

with a standard error of ±6 watts.

6.2 Thermal Mapping of Roads

A novel environmental engineering application of the IR18 TVFS system has involved thermal mapping of road surfaces in winter to identify accident black spots. The primary objective of this night-time aerial survey work was to assist road engineers in the siting of ground sensors to monitor ice conditions around high accident risk sections of road. It is also hoped that the data will enable improvements and ecomomies in road gritting operations to be achieved.

The survey was carried out in Scotland in February 1986. Ground temperature measurements were obtained and used to determine calibration data for the IR18. By using this data in conjunction with the GEMS image processing system it was possible to digitise and calibrate a selected number of frames of data. Using a digital to analogue converter it was then possible to create from these selected scenes, a density sliced video image of the original analogue tape. This feature has been shown to be of considerable benefit to non specialists viewing the imagery.

6.3 Geotechnical Site Investigations

An assessment of the potential of the IR18 to detect solution features in chalk will be carried out during the summer of 1986. Solution features are a serious geotechnical hazard and generally provide unreliable bearing capacity for foundations. A review of the significance of solution features and the use of remote sensing techniques for their detection is provided in Kennie and Edmonds (1986). The relative performance of TVFS and thermal infrared linescanning techniques will also be investigated during this exercise.

6.4 Drainage, Sewer Collapse and Utilities Surveys

A recent application of the IR18 has involved the detection of subsurface utilities and problems associated with such features. In this case the TVFS was mounted on a boom attached to a car and was used in conjunction with a ground impulse radar system (λ = 6 to 330 centimetres).

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This work was carried out in London during June 1985 (Stove, 1985) with the aim of identifying leaking water mains, sewer collapses and piperuns below the pavement surface. The main conclusion from this work was the complementary nature of the two systems since the impulse radar provides information relating to the depth of features beneath the terrain, that is in the vertical plane, whereas the TVFS provides data about the spatial extent of the phenomenon in the horizontal plane. For example, at one particular sewer site the ground impulse radar indicated a marked discontinuity between the structure of the road and the fill material beneath; normally this is indicative of poor compaction or voiding in this zone. Also, a reduction in the radar signal velocity occurred which indicated that the material in this zone was of a much higher moisture content than the surroundings. Analysis of the TVFS imagery over the same area was carried out by density slicing the thermal emissions to indicate 1^0c temperature intervals. A clear indication of the size of the sewer was obtained and a marked increase in emission was detected corresponding to the discontinuity recorded by the ground impulse radar.

The work on this particular application is at an early stage of development and a method of automating the measurement of any correlation between the data from these two complementary sensors is currently being considered. One possible solution may be to reformat the output from the ground impulse radar and record this on videotape (Stove, 1985). The radar data could then be digitally formed into image form and registered with the TVFS data.

6.5 Further Applications

In addition to the projects outlined above TVFS systems have potential application for many other environmental engineering projects including: oil pollution monitoring, monitoring of spontaneous combustion of waste tips, power station cooling water discharge monitoring, ground water and spring detection and hydraulic leakage from dams.

7 CONCLUSIONS

TVFS systems differ considerably both in optical design and in radiometric characteristics from thermal linescanning instruments. A wide range of instruments are currently available using distinctive imaging techniques. Such instruments provide an alternative method of acquiring thermal data and, in general, at lower cost, if a light aircraft is used as the measuring platform. By using suitable image processing techniques and ground temperature measurements for calibration purposes quantitative thermal characteristics of the terrain can be deduced. It is suggested that TVFS systems have a significant role to play in the acquisition of thermal data for environmental engineering projects particularly when used in conjunction with other complementary remote sensing or geophysical sensors.

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