PEER-REVIEWED ARTICLE

A Spatially Variable Light-Frequency-Selective Component-Based, Airborne Pushbroom Imaging Spectrometer for the Water Environment*

Abstract

A design of a variable interference filter imaging spectrometer (VIFIS) system is described. A set of systematic concepts, including continuous spectral image encoding using a spatially variable light-frequency-selective principle; spectral image data reconstruction using a transputer co-processed video rate pushbroom queue processing algorithm; and complete spectral image information storage and retrieval using video recording, have been adopted in the system. These result in a system that can supply up to 640 spectral bands of 8-bit images within the spectral range from 400 to 700 nm after one flyby. Many other attributes such as compactness of the sensor, simplicity in operation, availability of in-flight image inspection, accessibility of inherent geometric references, and high flexibility in flight height and velocity are other advantages of the system. A preliminary test over the Tay Estuary was performed aboard a Cessna 152 aircraft. The images and spectral profiles obtained show the system to be an effective tool for remote sensing.

Introduction

With the advances of multispectral remote sensing, imaging spectrometry has been emerging as a new and promising research area of remote sensing over the past decade. Imaging spectrometry, which consists of the real-time acquisition of images in many narrow, contiguous spectral bands, generates a hybrid three-dimensional (spatial/spectral) radiance data set. Such hyperspectral image data sets (Vane and Goetz, 1988) allow both that images can be viewed on any given spectral band or band combinations and that the contiguous spectral radiance curve can be manifested at any given pixel or at any associated targeting area. Hence, the composition of surface minerals, water constituents, environmental conditions, and the state of vegetation covering can be identified with increasing degrees of certainty.

An imaging spectrometer here refers to a remote sensing instrument that supplies hyperspectral image data sets. There are four common imaging spectrometers currently in operation: (1) the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) by JPL (Vane, 1987), (2) the Fluorescence Line Imager (FLI)/Programmable Multispectral Imager (PMI) by Moniteq Ltd. of Toronto (Gower *et al.*, 1985), (3) the Compact Airborne Spectral Imager (CASI) by Itres Ltd. of Calgary (Babey and Anger, 1989; Borstad *et al.*, 1989), and (4) the Reflective Optics System Imaging Spectrometer (ROSIS) by MBB of Ottobrunn in Germany (Kunkel *et al.*, 1991). In addition, there are several planned satellite imaging spectrometers: NASA's High Resolution Imaging Spectrometer (HIRIS) (Dozier and Goetz, 1989); ESA's Medium Resolution Imaging Spectrometer (MERIS) (Baudin *et al.*, 1990), and NASA's Moderate Resolution Imaging Spectrometer with Tilt capability (MODIS-T) (Salomonson *et al.*, 1989). A new airborne pushbroom imaging spectrometer, named the Variable-Interference-Filter Imaging Spectrometer (VIFIS), has been developed at the University of Dundee over the past two years. The first airborne engineering test of the VIFIS over the Tay Estuary, U.K. took place in August 1991.

VIFIS was originally intended as a simple imaging spectrometer system with high portability and easy deployment to allow studies of dynamic coastal and estuarine systems in a country like the U.K., which is subject to very rapid changes in weather patterns. The design objectives of VIFIS were as follows: (1) to miniaturize an imaging spectrometer for a light aircraft (a camcorder sized sensor head powered by battery being preferred); (2) to simplify the instrument operation to the level of a manually operated camcorder; (3) to record complete spectral/spatial information in one flyby and hence avoid the usual adjustments of spectral or spatial mode selection and spectral band selection; and (4) to allow short notice deployment in rapidly changing weather conditions.

To fulfill the above objectives, the project was started with a systematic investigation of all possible sampling principles for imaging spectrometery. Conceptual analysis reveals that a spatially variable light-frequency-selective, component-based, airborne pushbroom imaging spectrometer is a promising candidate. The follow-on research of the project considered the design and construction of an airborne VIFIS sensor head and the development of a Personal Computer (PC) based, transputer co-processed VIFIS data processing system. This paper will give brief description of the VIFIS project.

The Sampling Modes of Imaging Spectrometry

Imaging spectrometry deals with the acquisition of a hyperspectral image data set. This data set has a generalized three-dimensional (3D) structure. A normal 3D hybrid reference

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*Presented at the First Thematic Conference on Remote Sensing for Marine and Coastal Environments, New Orleans, Louisiana, 15–17 June 1992.

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Photogrammetric Engineering & Remote Sensing,
Vol. 59, No. 3, March 1993, pp. 399–406.

0099-1112/93/5903–399$03.00/0

frame for this data set is defined as two orthogonal spatial axes which are horizontal and a spectral axis which is perpendicular. This normal reference frame is generally suitable for describing such a hyperspectral data set as a pack of monochromic planar radiance patterns with different spectral bands aligned one by one along the wavelength increment of the spectral dimension.

The hyperspectral image data set can be thought of as a generalized 3D radiance pattern, a sample of photon distribution in a generalized 3D space. A frame of imagery formed on a photo-acquisition plane of a sensor can be abstracted as a thin geometric plane intercept within a defined cube. This description is supported by the fact that a spectral variable can be associated with some spatial variable in some way by using a functional component of an imaging spectrometer. Fortunately, the 2D planar image sensors that are predominantly used in imaging spectrometry instruments have the capability of sampling two-dimensional instantaneous photon distributions. Thereby, it can be inferred that any imaging spectrometer using a planar 2D sensor must employ some kind of generalized displacement to sample a 3D data cube slice by slice in a generalized 3D space. Furthermore, any imaging spectroscopy instrument using a 2D sensor must utilize a time-dividing sampling architecture.

Considering the time-dividing nature of a 2D sensor-based imaging spectrometry, steady radiance conditions should exist during the data acquisition. The scene of radiance is said to be steady or time invariant if the surface leaving spectral radiance $R_s(x,y,\lambda,t)$ in the spectral-object space $S_{\{x,y,\lambda\}}$ satisfies

$$R_s(x,y,\lambda,t_1) = R_s(x,y,\lambda,t_2), \qquad t_1,t_2 \in [t_0,t_0 + \Delta T]. \tag{1}$$

It is assumed that steady radiance conditions apply in all the following discussions unless otherwise stated.

The Imaging Spectrometry Process

The imaging spectrometry process can be schematically described as two successive generalized coordinate transformations over the three information spaces, as shown in Figure 1. Surface leaving radiance in the spectral-object space is optically mapped into the photo-acquisition space first and then it is successively mapped into the spectral-image space in digital form.

Generally, an idealized imaging spectrometry process requires that the resultant transformation $\mathbf{\Gamma}$ of the two successive transformations $\mathbf{A},\mathbf{B}$ is in a form of a dilatation matrix or a non-singular diagonal matrix; i.e.,

$$\mathbf{\Gamma} = \mathbf{B}\cdot\mathbf{A} = \begin{pmatrix} \gamma_{11} & 0 & 0 \\ 0 & \gamma_{22} & 0 \\ 0 & 0 & \gamma_{33} \end{pmatrix}. \tag{2}$$

Further it is often required that the elements of $\mathbf{\Gamma}$ satisfy the following:

$$\begin{aligned} \gamma_{11} &= \gamma_{22} = k, \\ \gamma_{33} &= 1. \end{aligned} \tag{3}$$

These ensure that, when mapping generalized coordinates from spectral-object space $S_{\{x,y,\lambda\}}$ into photo-acquisition space $S_{\{X,Y,F\}}$ first and then into spectral-image space $S_{\{x',y',\lambda'\}}$, an imaging spectrometry system will transform the scale of spatial coordinates with a homogeneous magnification k and keep the scale of the spectral coordinate. In other words, no generalized frame rotation occurs after the resultant transformation. These requirements, described by Equations 2 and 3, are termed dilatation requirements.

Under dilatation requirements, it can be derived that (1) the second transformation $\mathbf{B}$ is not independent; (2) the category of imaging spectrometry can be determined by the first transformation $\mathbf{A}$, which is thereby called the key transformation of the imaging spectrometry; and (3) if the first transformation $\mathbf{A}$ is linear, the second transformation $\mathbf{B}$ is also linear. The dilatation requirements are also useful for deducing the second transformation or data reconstruction formulas for any specially designed imaging spectrometry architecture.

Three Types of Imaging Spectroscopy Instruments

According to the orientation of the sampling plane in a normal spectral-objective space, linear imaging spectrometry processes can be catalogued as three and only three kinds when using a 2D sensor. These are horizontal, vertical, and oblique sampling strategies relative to a normal generalized 3D space as shown in Figure 2.

It can be further specified that each of the three sampling models mentioned above can be realized by a particular type of physical instrument. The corresponding instruments, to be briefly described, are shuttering frequency selecting imaging spectrometers, light dispersing imaging spectrometers, and spatially frequency selecting imaging spectrometers, respectively.

The shutter frequency selecting imaging spectrocopy instrument can be realized by using a rotating shutter mechanism that consists of a circular narrow-band interference filter window set mounted on the front of a sensor head. Rotation of the assembly, which is synchronized to successive frame start signals, opens the optical system to different passbands. Clearly, this mechanisms belongs to the horizontal sampling classification shown as Figure 2(A).

The dispersing imaging spectrometer consists of a slit, dispersion unit, and imaging and collimating components. It works when a line of source image formed on the entrance slit is perpendicularly dispersed by a dispersion unit and then re-formed as a 2D spectral imagery of the line scene on the exit focus plane, where the 2D image sensor is placed. By time-dividing and forward shifting sampling, it allows 2D

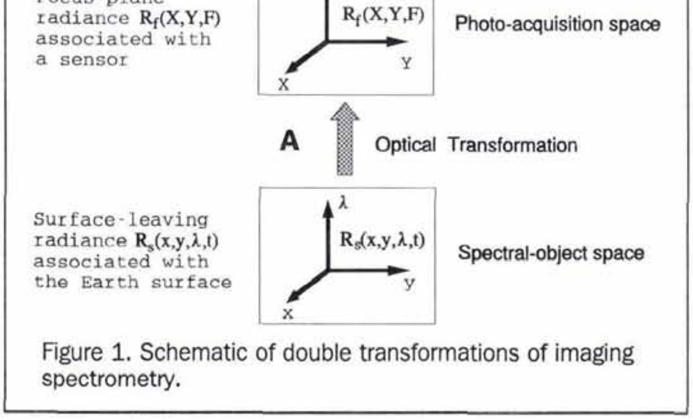


Figure 1. Schematic of double transformations of imaging spectrometry.

spectral imagery of a line scene formed on the focus plane of a sensor to be acquired frame by frame as the ground scene is swept past the entrance slit line by line. This instrument belongs to the vertical sampling category as shown in Figure 2(B).

The third sort of instrument, a spatially frequency selective imaging spectrometer, consists of a 2D image sensor and a spatially linear variable filter that is mounted on an imaging plane of the sensor. The imagery formed on the imaging plane of the sensor can be thought of as a mosaic of contiguously varied, monochromic line scenes, each having its own passband, which are logically divided by the linear variable filter. As a flying vehicle moves forward, the mosaic, or the queued monochromic line scenes sensed by the sensor, scans over the ground track as a pushbroom queue sweeps over the ground. The sampling strategy of this instrument is the oblique sampling as shown in Figure 2(C).

The third instrument has the simplest optical and mechanical structure intrinsically. Compared with the first kind of instrument, it has no moving parts. Compared with the second, it is much more compact mechanically and optically. Conceptually, a chip sized variable filter array can be used to substitute for the volume dispersion part of the second. Furthermore, it has an important advantage in the photographic information structure formed on the sensor. In the case of Earth surface remote sensing, the imagery formed on the sensor in this generalized oblique sampling mode remains as a humanly recognizable image. This is because the solar reflective spectral characteristic of a target of the Earth's surface is in general broadband with a slowly varying spectral nature. This particular advantage offers great convenience in direct image inspection and focus state adjustment during a flight mission without needing to employ and operate a digital image reconstruction instrument as an extra paylaod. This advantage also enables post-flight visual inspection of the raw imagery to discover and locate relevant targets easily using standard video equipment. According to the design objectives and above analysis, the third type of instrument has been selected for the projected imaging spectrometer.

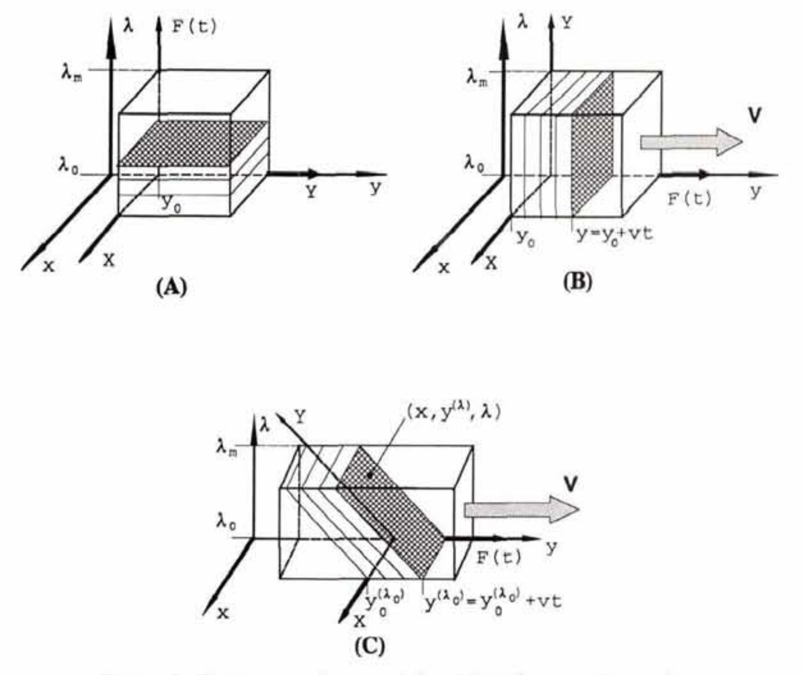
Design of the VIFIS System

The VIFIS system is composed of a CCD imaging spectrometer head, an 8-mm video recording/monitoring unit, and a PC-486 computer hosted real-time data processing setup, in which a transputer based frame grabber/image processing board is embedded. Several concepts, including continuous spectral information encoding onto the focus plane of the CCD sensor by a light-frequency, spatially selecting filter, multispectral image and spectral profile reconstructing using a transputer co-processed video rate pushbroom queue processing algorithm, and complete spatial and spectral information storage and retrieval using video recording have been adopted in the system. The system consists of two parts, the airborne payload and the ground based data processing part, as shown in Figure 3.

The VIFIS Airborne Payload

The VIFIS airborne payload consists of a sensor head and a Sony 8-mm portable video cassette recorder (VCR)—a portable TV monitor combination. The sensor head employs a 756- by 581-pixel silicon CCD shutter camera, TM765, supplied by Pulnix Co., U.K. In front of the camera, a fore-optics set with a variable interference filter is mounted. The 8-mm VCR is used to record the complete spectral/spatial information obtainable from the VIFIS sensor head.

Unlike a dispersion imaging spectrometer, for which primary imagery formed on a sensor is a dispersed line scene and beyond a human's perceptibility if the imagery is directly inspected, the primary imagery that is formed on the sensor of a spatially variable light-frequency-selective, component based, imaging spectrometer remains as humanly recognizable. Using this advantage, no digital image reconstruction equipment is required as part of an airborne



(A)

(B)

(C)

Figure 2. Three sampling models of imaging spectrometry.

payload. This allows an independent, camcorder sized, battery powered, and easily operated imaging spectrometer sensor head to be built.

VARIABLE INTERFERENCE FILTER AND SENSOR HEAD

An interference filter is a multi-layer thin film device which is arranged as a single or multiple Fabry Perot interferometer. A single Fabry Perot interferometer is constructed as a cavity (a dielectric spacing) sandwiched between two partially reflecting layers or reflectors. This device obeys the multiple beam interference principle of a thin film and selectively transmits or rejects incident light depending upon its wavelength. For better performance, quarter-wave dielectric stacks are almost universally used as the reflectors on either side of the cavity in VNIR regions. By varying the reflectivity of the reflectors, the thickness of the spacing, and the number of Fabry Perot cavities, a wide variety of bandwidths and beam shapes are achievable. The basic series of films deposited on a substrate forms a simple unblocked Fabry Perot interferometer which, depending on its design, will have sidebands on both sides of the desired transmission band. These sidebands can be eliminated by blocking filters. The simple Fabry Perot and the necessary blocking filters are cemented together to form the complete filter. It is not difficult to find commercial, monochromic, all-dielectric interferences filters with halfwidths down to 0.5 percent of peak wavelength.

If the thickness of all the layers of an all-dielectric interference filter varies in proportion across the substrate, the position of the transmission peak will vary in the same way. This filter is termed a variable interference filter (VIF). VIFs are available in linear and circular versions.

A particular VIF that is suitable for the VIFIS instrument is a linear variable narrowband interference filter. Its wavelength position λ of the transmission peak is directly proportional to the geometric position Y along its length. This relationship can be expressed as

$$Y = w(\lambda - \lambda_0), \tag{4}$$

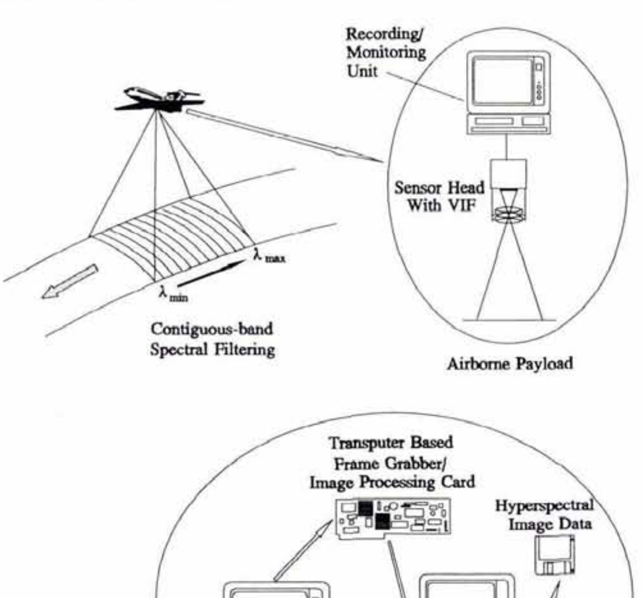


Figure 3. Schematic of VIFIS system.

where w, the VIF constant or linear dispersion, is written as

$$w = \frac{L}{\lambda_m - \lambda_0} \tag{5}$$

where L is the effective length of the filter, and λ_o and λ_m are the minimum and maximum wavelengths of the transmission peak, respectively. If both the filter and the sensor are on the image plane of a camera lens, Y can also be expressed as follows:

$$Y = \frac{f}{H}(y^{(\lambda)} - y^{(\lambda o)}), \tag{6}$$

where f is the focus length of the lens, H is the height of the sensor, and $y^{(\lambda)}$ and $y^{(\lambda o)}$ are the y-axis coordinates of the object which are selected by a general wavelength passband and the minimum wavelength passband, respectively, as shown in Figure 2(C).

From Equations 4 and 6, we have

$$w(\lambda - \lambda_0) - \frac{f}{H}(y^{(\lambda)} - y^{(\lambda o)}) = 0. \tag{7}$$

Obviously, this equation describes a generalized oblique plane as shown in Figure 2(C). While the sampling plane moves ahead, it will acquire 3D information by intercepting the space slice by slice with the increasing $y^{(\lambda o)}$.

Assigning the reference frame as shown in Figure 2(C), the matrix form of the generalized coordinate transformation from the spectral-object space $S_{\{x,y,\lambda\}}$ to the photo-acquisition space $S_{\{X,Y,F\}}$ can be written as

$$\begin{pmatrix} X \\ Y \\ F \end{pmatrix} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ 0 & 0 & \alpha_{23} \\ 0 & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{pmatrix} x \\ y^{(\lambda)} - y_0^{(\lambda o)} \\ \lambda - \lambda_0 \end{pmatrix}, \tag{8}$$

where $y_o^{(\lambda o)}$ is the y-axis coordinate of the left bottom edge of the oblique sampling prism, and F is the frame number or the F-axis coordinate. The generalized geometric meanings of all the coordinates can be found in Figure 2(C). Furthermore, four non-zero matrix elements are derived as

$$\begin{aligned} \alpha_{11} &= \frac{f}{H}, \\ \alpha_{23} &= \frac{L}{\lambda_m - \lambda_o} = w, \\ \alpha_{32} &= \frac{\nu_f}{v}, \\ \alpha_{33} &= -w\frac{\nu_f H}{v f}, \end{aligned} \tag{9}$$

where ν_f and v are the frame frequency of the sensor and the relative velocity between the sensor and ground, respectively.

Ideally, a specifically designed variable interference filter or micro filter array would be directly cemented or coated onto the CCD sensor. However, in the prototype VIFIS sensor head, a commercially available linear VIF, VERIL S 60, supplied by Schott Glaswerke, Germany, is used for the engineering test. The spectral range of VERIL S 60 is continuously linear, running from 400 to 700 nm. The halfwidth in midrange is 10 to 14 nm. The transmission also varies with wavelength. However, the flatness of the spectral transmission is reasonable. In mid-range it is greater than 45 percent and at the sides it is only lower by about 5 percent. The average value of the unwanted spectral transmittance is less than 10^{-4} within the blocked range (from UV to 1.4 μm). Because the size of VERIL S 60 does not match the size of the front face of a 2/3-inch CCD sensor, a double imaging optical layout is employed in the prototype instrument.

FREQUENCY MODULATION VIDEO RECORDING

Although digital image storage is characterized as noise free in data copy and transmission, the analog frequency modulation (FM) video tape recorder is an economic bulk storage device with reasonably good quality. The common domestic VCR, such as the Sony 8-mm recorder, can record video data with a signal-to-noise ratio (SNR) better than 44 dB using a normal quality video tape. The SNR of FM recording is determined by the bandwidth of the modulation frequency deviation and the coercivity and particle packing density of a video tape. When a high grade video tape is used, SNR value can increase by about 3 to 6 dB. This enables the SNR of 8-mm video recording to be approximately equal to the theoretical limit of 48 dB that an 8-bit digital equipment can reach. By expanding the frequency deviation from the 1.2 Mhz of Sony 8-mm video recording to the 2.0 Mhz of Sony Hi8 video recording, the SNR can be further improved. Furthermore, one 90-minute Hi8 format video tape can store the equivalent of about 40,000 mega-bytes of digital image data. These two attributes allow the VCR to record the complete imaging spectrometry information (with both high spatial and high spectral resolutions) in one flight mission with the SNR no worse than that of 8-bit digital equipment. It should be stressed that the strategy of the VIFIS instrument is to realize full imaging spectrometry data recording with simplicity in structure and ease of operations on a light aircraft. Accordingly, an industrial quality, portable, 8-mm FM helical scanning video recorder, Sony EVO-520P VCR, is used for this purpose.

Ground Based Data Processing System

The ground based data processing part of VIFIS system employs a PC-486 computer that controls a T805 transputer based frame grabber/imaging processing plug-in board. The task of the ground based system is to digitize, process, and re-organize the VIFIS primary video data to the normalized hyperspectral image data set in real time. The data can be produced to be compatible with some commercial imaging spectral software. A suitable imaging spectrometry software is T-spectral developed by Terra-Mar Resource Information Services, Inc.. The data system is also designed to supply end products in VIFIS' own data format for a transputer based graphic environment.

HARDWARE OF DATA PROCESSING SYSTEM

For hyperspectral image data generation or reconstruction, a real-time digital video capturing, processing, and displaying (VCPD) equipment is required. With the emergence of transputer and other parallel μP and DSP based fast and intelligent VCPD plug-in cards for host computers, a general purpose Personal Computer (PC) can be converted to be a powerful and flexible imaging spectrometery data processing system.

A VCPD plug-in board for an IBM PC/AT, the MosaiQ-M, which is manufactured by Quintek Ltd. in Bristol, was chosen. The MosaiQ-M is a single T805-20 transputer based monochrome frame grabbing/image processing board. It is designed to grab, process, and display standard or non-standard video images in real-time. The basic model used is equipped with 2-MByte dual-ported video RAM (VRAM) and 4-Mbyte dynamic RAM (DRAM). However, up to 4-Mbyte shared VRAM and 8-MByte DRAM as well as two Zoran vector co-processors, ZR34325, can be added onto the board to give out 75-MFLOP performance. Furthermore, four TRAM slots on the board can be used to extend its processing or communications (global data transfer) capabilities. The MosaiQ-M is compatible with the Inmos B008 mother board description. This enables it to be programmed under many popular transputer software environments.

The IMS T805-20 transputer adopted by MosaiQ-M is a 20-MIPS, 32-bit single chip scientific microcomputer belonging to the T800 family. Its 32-bit wide memory interface can directly access a linear address space of up to 4-Gbyte external memory with a sustained data rate of 26 Mbytes/sec. A configurable memory controller supports a wide variety of mixed memory systems. By mapping the VRAM address into T805 addressing space, it can access the VRAM concurrently during the digitizing process. Its four serial links give the potential to transfer hyperspectral image data to external devices each at about 20 Mbits/sec. With its parallel programming environments, appropriately processing TRAMs can be added to give a better performance.

The MosaiQ-M board has been tested in a PC-486 AT compatible and PC-386 notebook computer with an expansion box. In fact, the hardware configuration is not only suitable as a VIFIS ground based data system, but also can be a part of an airborne payload to allow real-time processing in-flight.

DATA RECONSTRUCTION PRINCIPLE

As mentioned earlier, data reconstruction for imaging spectrometry is a generalized coordinate transformation from the photo-acquisition space to spectral-image space. According to the dilatation requirements, the matrix formula of the second transformation can be written as

$$\begin{pmatrix} x' \\ y' \\ \lambda - \lambda_0 \end{pmatrix} = \begin{pmatrix} \beta_{11} & 0 & 0 \\ 0 & \beta_{22} & \beta_{23} \\ 0 & \beta_{32} & 0 \end{pmatrix} \begin{pmatrix} X \\ Y \\ F \end{pmatrix}. \tag{10}$$

It can be further derived that the elements of the transformation matrix **B** are as follows:

$$\begin{aligned} \beta_{11} &= 1, \\ \beta_{22} &= 1, \\ \beta_{23} &= \frac{f}{H}\frac{v}{\nu_f}, \\ \beta_{32} &= 1/w. \end{aligned} \tag{11}$$

Solving the inverse of **B**, *we obtain*

$$\begin{aligned} X &= x', \\ Y &= w(\lambda - \lambda_0), \\ F &= \frac{H}{f}\frac{\nu_f}{v}y' - w\frac{H}{f}\frac{\nu_f}{v}(\lambda - \lambda_0). \end{aligned} \tag{12}$$

These are the general guides for the data reconstruction of the VIFIS instrument.

To rebuild a monochrome image at the passband with the transmission peak $\lambda = \lambda_i$ in the area of $x' \in [0,a_2]$, $y' \in [b_1,b_2]$. Equation 12 can be further specified as

$$\begin{aligned} X &= x', \\ Y &= w(\lambda_i - \lambda_0) = C1, \\ F &= \frac{H}{f}\frac{\nu_f}{v}y' - w\frac{H}{f}\frac{\nu_f}{v}(\lambda_i - \lambda_0) = \frac{H}{f}\frac{\nu_f}{v}y' - C2. \end{aligned} \tag{13}$$

The physical meaning of Equation 13 is that by fixing the row coordinate Y of the sensor and the frame start reference at the parametric values of $C1$ and $C2$, respectively, which are determined by different passband λ_i, a monochrome track-recovery image is built up by retrieving column coordinate X and frame number F according to Equation 13. To rebuild a spectral radiance curve associated with a pixel at $(x',y') = (x'_i,y'_i)$, a set of formulae can be derived from Equation 12 by the similar procedures above and they are left to the interested readers.

ALGORITHM

The basic task of the VIFIS data processing algorithms is to reconstruct the primary videograph sequences into the normally structured spectral images, which have been organized according to Equation 13, such that monochrome images with different spectral bands aligned over the same area one by one along the wavelength increment of the spectral dimension are produced. It should be stressed that, if the monochrome bandwidth can be tolerated to a wider coverage, which corresponds to the geometric coverage of a narrow strip of the VIFIS sensor with the several line width, m, along the in-track direction, then Equation 13 can be modified as

$$\begin{aligned} X &= x', \\ Y &= w(\lambda_i - \lambda_0) = C1, \\ F &= \frac{H}{f}\frac{\nu_f}{v}my' - w\frac{H}{f}\frac{\nu_f}{v}(\lambda_i - \lambda_0) = \frac{H}{f}\frac{\nu_f}{v}my' - C2. \end{aligned} \tag{14}$$

This modification gives a specific flexibility to the VIFIS instrument in that the track-recovery images can be built in flexibly sized partitions by selecting m, which is equivalent to extending the maximum of the programmable frame frequency ν_f by m times to suit more flexible flight parameters, v and H, in practical applications.

A VIFIS data processing algorithm for the transputer based VCPD unit called pushbroom queue processing (PQP) algorithm has been developed. It transforms the primary videograph data sequences generated by the VIFIS sensor to multiple aligned monochrome images simultaneously on the basis of the Equation 14. The computation procedures of this transputer algorithm include the following. The first procedure is the system initiation which includes the channel definition (giving m) and the channel selection (giving the set, $\{C1|\lambda_i, C2|\lambda_i; \lambda_i = \lambda_1,\lambda_2,\ldots,\lambda_m\}$) as well as booting of a range of control registers for digitizing and displaying timing, input and output look-up-table setting, along with some other default operations. The second procedure is multi-channel data distribution. During a continuous digitizing, the incoming primary video frames under the control of digitizing logic are arranged to be sent into a dual-ported VRAM buffer which is also mapped into transputed addressing space. The transputer distributes the defined primitive frame segments in the VRAM buffer(s) to several DRAM buffers via the 32-bit wide local data bus on the MosaiQ-M board at a fast rate. After successive data distribution synchronized by video timing, multiple channels of track-recovery images are concurrently built up in the DRAM buffers, segment by segment, from the fast refreshed primitive frames in the VRAM. More details of the algorithm can be found in a previous paper (Sun and Anderson, 1991).

A slight modification of the algorithm since the previous paper is that the ping-pong operated VRAM buffers have been optimized to a single VRAM buffer distribution after computation timing analysis. This optimization improves the data distribution process so that up to six bands of track-recovery images in 512 by 1024 format (at $m \leq 32$) can be concurrently generated in the on-board local memory in real time during the video replay. By replaying the aerial video tape as required, up to 640 spectral images within the spectral range from 400 to 700 nm can be reconstructed in this prototype instrument using the post-flight pushbroom queue processing software.

Preliminary Test and Performance of The VIFIS System

A preliminary test of the VIFIS system over the Tay Estuary was undertaken aboard a Cessna 152 aircraft in August 1991. In the test, the VIFIS sensor head was horizontally clamped to a side door of the aircraft. A 90-degree angle mirror attachment enables the sensor to point to the nadir or in an oblique direction. In the experiment, near nadir orientation was chosen. The experimental setup is as shown in Figure 4. The specification of the VIFIS system is listed in Table 1.

A sample set of the track-recovery imagery acquired by the VIFIS instrument is as shown in Figure 5. The scene was taken just over a sewage outfall area of the Tay Estuary, U.K. Figure 5C is a set of VIFIS spectral images taken at 10-nm intervals between 440 and 670 nm. Figure 5A is a monochrome image centered at the wavelength band of 570 nm, which is the exact four-times enlargement of the second image from the upper-left corner of Figure 5C. Figure 5B demonstrates two pixel-spectral plots, α and β, averaged in 5- by 5-pixel

Figure 4. The photograph of prototype VIFIS mounted on a Cessna 152 aircraft.

TABLE 1. SPECIFICATION OF VIFIS SYSTEM.

Image Sensor:	Type: 2/3" interline transfer CCD Resolution: 756 by 581 pixel Dynamic Range: 67dB Video SNR: better than 50dB
Spectral Parameters:	Variable Interference Filter: VERIL S 60 Spectral Range: 400-700nm Spectral Resolution: 10-14nm
Field of View:	18°
Flight Height:	Variable, 1000ft upwards
Airborne Payload:	Mass: 4kg Power Consumption: 19W (DC 12V) Recording: sony EVO-520P 8mm VCR
Digital Data Format:	Sizes: 512 by 1024 (6-band concurrent reconstruction) Grey Level Resolution: 8 bit Logical Spectral Bands: up to 640

windows, centered at the pixel coordinates of (100, 200) and (292, 76) and cursor-designated as α and β in Figure 5A, respectively. The spectral plot α, which was acquired over the less turbid water, is directly built up from the average radiance values at the pixel coordinates of (100, 200) from all the bands except at the pixel coordinates of (85, 200) in band 2, where a patch of sun glint occurred at the pixel coordinates of (100, 200); hence, a slight coordinate shift was chosen to avoid the sun glint. The spectral plots β, which were acquired over a patch of more turbid water, are built up from the average radiance values at the same patch from the all bands. Because the windy conditions, which can be perceived by looking at the wave pattern of Figure 5A, caused changes in both the aircraft attitude and the position of the small patch which were not negligible, a rubber stretching operation, which is equivalent to stretching the target to the reasonable location, was taken to ensure the patch spectrum is properly built up.

Discussion

Three kinds of imaging spectrometer—dispersing, variable shutter filtering, and variable pixel filtering imaging spectrometers—can be used to generate hyperspectral image data sets. However, the imaging and spectral sampling strategies of these instruments are quite different on aspects of spectral/spatial sampling concurrency and, hence, the inherent quality of spectral images. These points are now discussed in this section.

Concurrency of Sampling

Intrinsically, each of the three kinds of imaging spectrometry instruments is of a certain kind of concurrency. Such concurrency depends on the orientation of the sampling plane in Figure 3. In the case of the dispersion imaging spectrometer, the sampling is inherent in spectral concurrency. This means that a profile of the pixel spectrum is measured contemporarily. For the shutter filter imaging spectrometer, the sampling is of an inherently spatial concurrency. This means that all the pixels within any one of the spectral images are captured simultaneously. However, what kind of concurrency is associated with the VIFIS instrument?

In the case of the VIFIS instrument, the concurrency of the measurement is not as straightforward as those of the first two instruments. There is neither pure spectral concurrency nor idealized spatial concurrency in the monochromic sense according to the VIFIS sampling mode. Both of the humanly preferred monochromic images and pixel spectra need to be rebuilt by time-sequenced data accessing. When the effect of changes in aircraft attitude (pitch, roll, and yaw) is not negligible, both the track-recovery images and the time-sequentially reconstructed spectra may be distorted unless an elaborate gyro-stabilized mount is used. Such distortion may degrade the spectral measurement seriously if the target is of a fine structure. Over and above this, if the steady radiance condition is not satisfied, errors in spectral measurement will also be introduced.

The concurrency plane in VIFIS mode is relatively intricate. However, the basic fact is that a primary videograph, which is the spatially continuous, spectral-image-segment mosaic or the linear variable filtered ordinary photographic image, is concurrently recorded. Such an image remains as geometrically distortion free and can be taken as a reference frame for the geometric rectification to the relevant track-recovery images. Dispersion imaging spectrometry has no such reference. The scale of the track-recovery image of the dispersion instrument in the in-track direction must be deter-

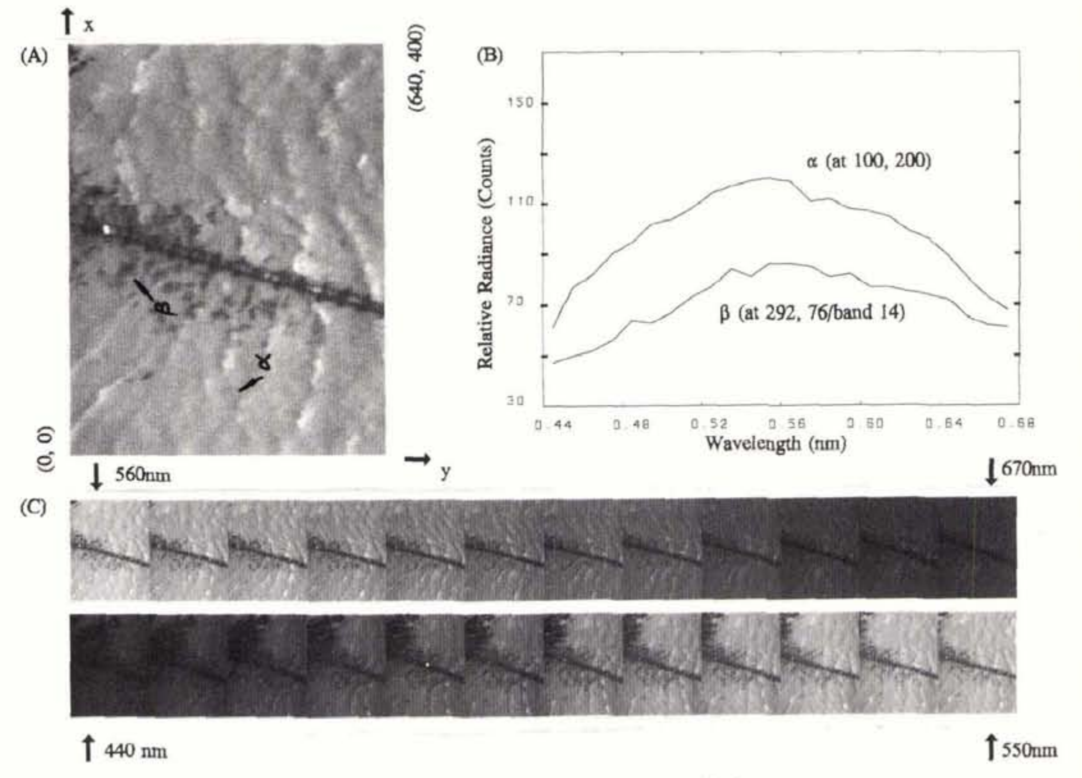


Figure 5. A set of VIFIS imagery over a sewage discharge area.

mined by calculating the flying parameters of the aircraft in general. These parameters may be time varying or inaccessible to the image reconstruction. Besides, with the VIFIS instrument, if there are any homogeneous areas in the sensed track, the history of the illumination variation can be disclosed according to the VIFIS sampling principle. The shutter filter imaging spectrometer has no such advantage. These two attributes suggest a potential advantage of VIFIS over dispersion and shutter filtering imaging spectrometers if proper pattern recognition and artificial intelligent algorithms could be developed.

Inherent Quality of Spectral Images

A highly useful parameter in evaluating the performance of an optical system is the modulation transfer function (MTF), which is less than 1.0 in general. When an optical system has more than one independent linear component, the overall MTF of the whole system is the product of the component MTFs. That is, the more optical components, the worse is the overall MTF.

With a dispersion imaging spectrometer, an independent dispersion unit with a narrow slit is unavoidable. If the spatial frequency of the image of a target is sufficiently high that the dimension of the image detail is less than the slit width, it will not be resolved along the in-track direction across the sensor array because of the blurring of the triangle spectral dispersion. This means that the cut-off of the MTF of the spectrometer is determined by the slit width if the image of the slit width on the sensor is larger than the corresponding dimension of the photo site of the sensor. By avoiding the image degradation caused by the extra MTF of an independent dispersion unit, the spatial resolution of the filtering imaging spectrometry is in general better than that of the dispersion imaging spectrometer.

Another major difference between the VIFIS instrument and the dispersion imaging spectrometer lies in the intrinsic nature of the mosaic segment of the track-recovery images. No matter how wide the slit width, one frame of primary videograph of the dispersion imaging spectrometer can be used to produce only a line scene. With the VIFIS instrument, the sampling principle allows the mosaic segment to be defined in different widths of line bunches. In addition, with the intrinsic geometric reference, VIFIS allows much greater flexibility in flight height and velocity. Even at a very low altitude, such as during aircraft takeoff or landing, the VIFIS acquire good images. In fact, the spectral images of the sewage discharge area of Figure 5 were taken during the aircraft descent.

To conclude this discussion, it should be pointed out that each of the three kinds of instrument has its own intrinsic merits and limitations. The major advantages of the VIFIS instrument are the simple structure, the great convenience in operation, the humanly recognizable nature and geometric distortion free nature of the primary videograph, the great tolerance allowed for the variable flight parameters, the good image resolution, and, finally, the unambiguous spectrum with no problems of overlapping orders. However, it has neither the absolute spectral concurrency nor the idealized monochromic spatial concurrency possessed by the dispersion and variable shutter filtering imaging spectrometers, respectively. It is an instrument midway between these two from the sampling concurrency viewpoint. Though the intrinsic geometric distortion free references can be used to achieve the hybrid merits of the other two, it requires heavy computation resources to be realized in future.

Conclusion

A set of systematic concepts, including spatially variable light-frequency-selective imaging spectroscopy, transputer real time pushbroom queue processing algorithm for spectral image reconstruction, and complete hyperspectral image information storage and retrieval using video recording, have been validated by the VIFIS project. These result in an inexpensive and effective VIFIS instrument with a battery operated, camcorder sized, airborne payload weighing only 4 kg. As an innovative prototype, the VIFIS system can supply up to 640 spectral bands of 8-bit images within the spectral range from 400 to 700 nm after one flyby. Other design objectives, including simplicity in operation, in-flight image inspection, and high flexibility in flight height and velocity are also demonstrated by the engineering test of the VIFIS prototype. It is concluded that the VIFIS is a promising tool for the water environment and other applications.

Acknowledgments

The first author is financially supported by an Overseas Research Studentship from the CVCP of the Universities of the U.K. and Dundee University Research Studentship award during the course of this work.

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