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A Solid-State Airborne Sensing System for Remote Sensing

The problems of sensor selection, stored array size, and pixel quantization are discussed.

ABSTRACT: *Currently most non-satellite multispectral remote sensing in the visible and near infrared is carried out using clusters of conventional photographic cameras. A project is in progress which exploits microcomputer and solid-state technology in the development of a multispectral scanner to be flown in light aircraft. Such systems offer the potential advantages of improved linearity and dynamic range, extended spectral response, the direct generation of digital data, and the real time display of captured images. The problems of sensor selection, stored array size, and pixel quantization are discussed. A prototype single camera system based on the use of a 100 by 100 element charge coupled device area sensor has recently been flight tested. A four-camera system that will allow the simultaneous capture and storage of 128 by 128 element images in four spectral bands in the 400-1100 nm range is under development.*

INTRODUCTION

REMOTE SENSING FROM LIGHT AIRCRAFT

A PROJECT to develop a multispectral imaging system for remote sensing applications is described. The system is to be flown in light aircraft to calibrate, compensate, and supplement data from Landsat and is based on the use of solid-state array sensors and microprocessor technology. A prototype system incorporating a single array camera has been successfully test flown. Multispectral coverage was obtained by making multiple passes over areas of interest using different filter-camera combinations. A four-camera multispectral sensor system is now in an advanced design stage and will be operational in prototype form in 1980.

In New Zealand, conventional multispectral camera systems with appropriate filters are used for remote sensing and to provide direct underflight data for comparison with Landsat (McDonnell *et al.*, 1977). Such systems have a number of operational disadvantages, including the limited dynamic range and the variable and non-linear response of film. In addition, a scanning microdensitometer is required to generate numerical data. For these reasons, and in the knowledge that solid-state sensor technology was maturing, a research project was established to develop an airborne scanner to meet the outline specification given in Table 1. This led to a comprehensive investigation of sensor characteristics and the development of a charge coupled device (CCD) array camera and a microcomputer based image processing system. The project is part of the national effort in remote sensing (Ellis *et al.*, 1978).

SENSOR/SCANNER SELECTION

The Landsat Multispectral Scanner (MSS) and the Thematic Mapper both use small arrays of discrete point detectors and an electromechanical scanner. There is one array for each spectral band. An oscillating mirror is used to generate the cross-track scan, and the forward motion of the sat-

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TABLE 1. GENERAL SPECIFICATION

Spectral Band Responses:	Band 1—500–600 nm Band 2—600–700 nm Band 3—700–800 nm Band 4—800–1100 nm
Instantaneous Angular Field of View (IFOV):	0.35° (included angle)
Angular Field Subtended by Image:	35° (across track)
Linearity:	±1% of F.S.D.
Dynamic Range:	1000:1 (100:1 acceptable)
Detector Noise Equivalent Signal:	2.0 mW-m sec/m^2
Maximum Target Radiances:	Band 1—2.5 mW/cm^2-sr Band 2—2.0 mW/cm^2-sr Band 3—1.8 mW/cm^2-sr Band 4—4.5 mW/cm^2-sr
Variation of Responsivity over Image area:	2%
Calibration:	In-flight calibration source
Thermal Range of Operation:	−5°C – +35°C
Output Format:	8-bit digital
Power Supply:	24V aircraft supply
Weight:	25 kg

ellite generates the along-track scan. Electromechanical scanning systems for aircraft are commercially available and have the advantage of uniform responsivity over image space. Unfortunately, they tend to be very expensive and, when installed in light aircraft, may require an inertially stabilized platform to compensate for aircraft motion. In contrast, multispectral remote sensing from aircraft is generally performed using clusters of appropriately filtered cameras. These cameras are relatively simple and inexpensive and film sensitivity is such that short exposure times can be used, thus eliminating the need for a stabilized platform. In addition, photographic film combines the sensor function with that of a high density non-volatile image store.

The preceding discussion does not take into account recent advances in array sensor technology. Solid-state, self-scanned arrays suitable for remote sensing have now been developed (Thompson, 1979). The French Earth resources satellite, SPOT, is to use a solid-state linear array in a multispectral sensor (Ducher, 1977). Colvocoresses (1979) has recently suggested the use of a linear array sensor in a proposed mapping satellite. As Tracy and Noll (1979) point out, in changing from mechanical scanning systems to solid-state arrays, "one is trading the idiosyncrasies of a rather complex opto-mechanical dynamic assembly with a single detector for a static assembly containing thousands of detectors." Solid-state array sensors are fabricated using conventional integrated circuit technology and have a multitude of industrial and scientific applications. For these reasons, relative to the specially developed electromechanical scanning systems, they are inexpensive.

Compared with photographic film, solid-state array sensors have a stable and linear response, a wide dynamic range, and a slightly extended spectral response. In using a solid-state array, numerical data and real time displays of captured images can be conveniently generated. Thus, we can generalize that, in changing from photographic film to a solid-state array, one is trading a very compact sensor and information store having highly variable qualities for a sensing system having a very linear response and an improved dynamic range but requiring an external information store.

GROUND RESOLUTION AND STORED ARRAY SIZE

The key parameter of the system is the stored array size. Many remote sensing application do not require high spatial resolution. These include land-use classification, crop inventory, and soil mapping. A prototype aircraft system need not have a ground resolution of better than 30m by 30m to be useful for comparison with the nominal 79m by 79m resolution of the Landsat MSS. An aircraft system with a ground resolution of 30m by 30m per picture element (pixel) and a 10,000 element (100 by 100) stored array size will give a coverage of 9km^2. The resolution can obviously be increased for small targets merely by flying lower.

The specification of a modest array size considerably simplifies data handling, storage, and display requirements. It has made the realization of a practical system possible within the constraints of weight (<25kg) and power supply (<500W) resulting from the use of light aircraft.

PIXEL QUANTIZATION

Even under well controlled laboratory conditions, it is difficult to measure radiance with an absolute accuracy of better than 1 percent. However, in order to calculate differences within a scene, an output resolution of better than 1 percent would be needed. Eight bit conversion, which results in a maximum quantization error of 0.4 percent, is readily achieved with available analog-to-digital (A/D) convertors and is compatible with inexpensive microcomputers.

A Single Band Imaging System (Figure 1)

A single band system has been designed and built as part of the program aimed at the eventual production of a true multispectral system meeting the specifications given in Table 1.

SYSTEM OPERATION

Images are captured by an array camera, converted to digital form, temporarily stored in semiconductor random access memory (RAM), and transferred to magnetic tape for permanent storage. Images stored in RAM can be displayed on a standard television monitor by means of the visual display store interrogator (VDSI). Images that have been stored on tape can be played back into RAM for subsequent display. The key to the low cost and versatility of the system is the incorporation of a microcomputer to control its operation and to provide temporary storage of images prior to storage on tape. The microcomputer is also used to transfer images from tape to conventional computer systems.

The rate of acquisition of data from the present camera, 10,000 eight-bit words in 10 ms, is faster than the maximum data storage rate available in inexpensive tape storage systems. The microcomputer RAM is therefore used to provide buffer storage. Since the basic instruction cycle time of the 8080A microprocessor would not allow data to be stored at the required rate, a direct memory access (DMA) technique has been used. The microcomputer system incorporates an Intel SBC80/10A single board computer, 16k of RAM, and 4k of programmable read only memory (PROM). The PROM is used to store the software that controls the operation of the system.

The operator controls the system from a simple control panel or head, which has three functions:

- Control of the digital cassette recorder;
- Mode selection (images are acquired on demand, under intervalometer control or under the control of a preset timer); and
- The generation of alpha-numeric survey and run identification codes. These are displayed with the capture image on the monitor and stored as an integral part of the image. Under intervalometer and timer control, run numbers are automatically updated.

More comprehensive accounts of the system are given in Hodgson *et al.* (1979) and Cady and Hodgson (1980).

THE CHARGE COUPLED DEVICE CAMERA

The "camera" used in the flight trials incorporates a 100 by 100 element array charge coupled device (CCD) image sensor. In concept, the CCD camera consists of a conventional camera in which a CCD device is mounted in the back focal plane and replaces the film. The solid-state array is used to rapidly (in say 10 ms) capture images at relatively longer intervals (say 10 s). The shorter interval is fixed by the readout rate of the device. This time interval determines the amount of target smear. At 250 kts and an altitude of 21,000 feet, the target smear is 1.2 metres or less than 0.04 pixel. The longer time interval is determined by the amount of overlap required for continuous coverage, with the proviso that the time be long enough to allow the microcomputer system to store the picture data. With the present hardware, a complete picture may be stored in 6 seconds, allowing a 74 percent overlap at the ground speed and altitude given above. The flight trials appear to have established the viability of using solid-state area arrays in this "snapshot mode."

A cross section through the camera is shown on Figure 2. The camera incorporates a Peltier effect thermoelectric cooling device and a solid-state temperature sensor. These devices and a feedback temperature controller allow the CCD array to be maintained at a predetermined temperature in the

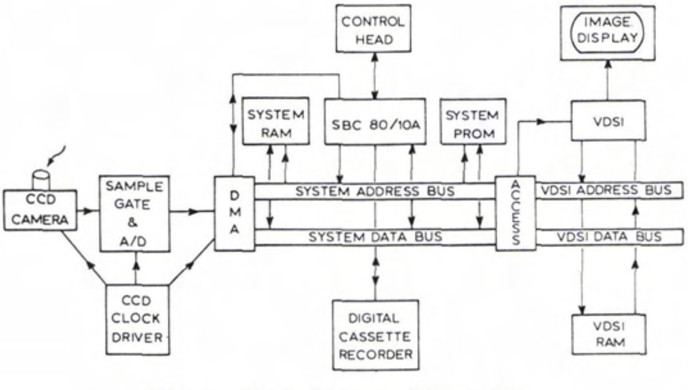

FIG. 1. Block diagram of the system.

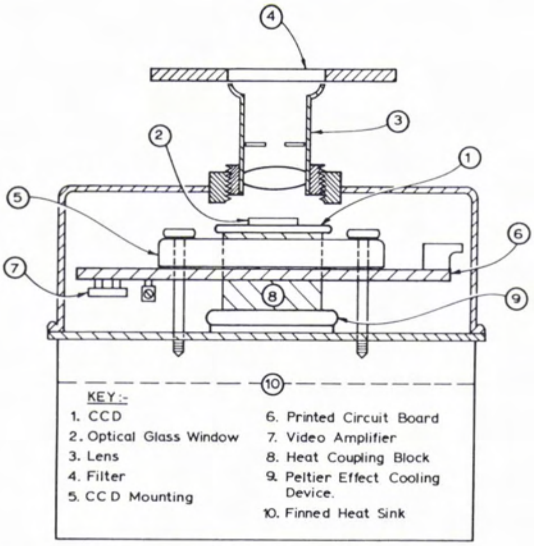

FIG. 2. The solid-state camera.

range −12°C to +30°C. Within the array, each element can be characterized by a dark current and a gain. The dark current is a strong function of temperature, doubling for each 7.05°C increase in temperature. By operating the array at a fixed and controlled temperature, a simple two point calibration is sufficient to establish the basic dark current and gain parameters for each element in the array (Tracy and Noll, 1979). Fixed pattern noise is the term used to describe the predictable variation in the output from an imaging array. The prime source of fixed pattern noise is element-to-element variations in sensitivity. We have found both the fixed pattern noise and the dark signal to be stable with time, but in an operational system data acquisition and calibration are probably best interleaved.

The sensor used in the prototype system is the Fairchild CCD202. It is fabricated using buried channel CCD technology (Walden *et al.*, 1972). The device consists of 10,000 image sensing elements and a system of analog transport registers. During an integration period, incident light passes through the transparent photogate and is absorbed in the substrate generating hole-electron pairs. Minority carriers, in this case electrons, accumulate in the depletion region with the majority carriers being absorbed by the deep substrate. At the end of the integration period a charge has accumulated that is proportional to the integrated light flux incident on the cell. Manipulation of the potentials of the photogate and the adjacent transfer electrode then allows the accumulated charge to be read out. For each scene the video output from the camera consists of a serial train of 10,000 analog pulses. These are digitized and stored as previously discussed.

Although stable and reliable in operation, the CCD camera suffers from two disadvantages both related to the sensor electrode structure. The sensor response is modulated by the spectral transmittance of the polysilicon layers on top of the substrate and by multiple reflections within the layers. The refractive indices of the layers are not matched, resulting in a type of interference filter. This introduces a ripple into the spectral response of the device (Anagnostapoulos and Sadisiv, 1975). Figure 3 shows the measured spectral response for the CCD camera. This problem has been overcome by at least two research teams using tin dioxide gates (Thompson *et al.*, 1978; Schroder, 1978). However, polysilicon is likely to remain the principal gate material used in commercial devices for many years to come. The second disadvantage of this type of CCD sensor is that the presence of the vertical analog transport registers reduces the actual photosensitive area of the sensor to about 45 percent of the nominal area. This lowers the effective quantum efficiency of the device and reduces the accuracy of radiometric measurements.

FLIGHT TRIALS

In late August 1979 the prototype system was installed in a Rockwell Turbo Commander aircraft of New Zealand Aerial Mapping Services and test flown along part of the Hawke's Bay coast north of the Wairoa River. The CCD camera was substituted for one of the conventional cameras of the four-camera cluster described by McDonnell *et al.*, (1977). This enabled the simultaneous capture of photographic and electronic images under intervalometer control. The system operated satisfactorily and the results of the tests are under study. Figures 4 and 5 are photographs of a CCD derived image and a conventional photograph of the same region, respectively.

A FOUR BAND SENSOR SYSTEM

A four-camera sensor system is now in an advanced design stage. This will enable the simulta-

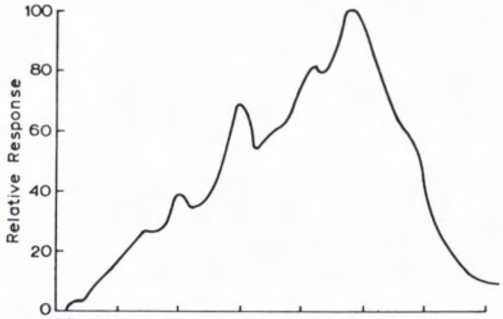

FIG. 3. The measured spectral response of the CCD camera.

FIG. 4. CCD derived image of the coastal region including a lagoon (Landsat band 5). This was obtained by photographing the system monitor and does not do justice to the quality of the stored images. At a later stage a "Colorwrite" machine will be used to give high quality hard copy.

neous capture of up to four images. This system uses four Fairchild CCD211 190 by 244 element CCD array sensors having a spectral response and noise performance similar to the CCD202. Only 128 by 128 elements of each array will be utilized, and again each pixel will be quantized to eight bits resulting in a storage requirement of 16K bytes per picture. The 128 by 128 array is compatible with our existing storage and display systems and probably represents the current practical limit for 8 bit microcomputer systems having 64K of address space. A block diagram for the system is shown in Figure 6.

DISCUSSION AND CONCLUSIONS

We have discussed progress on a project which has recently started to yield useful hardware that incorporates a microcomputer and a solid-state array sensor. Flight trials have demonstrated the viability of remote sensing using these relatively inexpensive components. The concept of operating an airborne array sensor in the snapshot or framing mode appears to have been proven. However, further work needs to be done to show that radiometric information can be derived from this type of sensor. At the time of writing, the usable array size is limited by the rate at which data can be recorded using lightweight and inexpensive recording devices. Digital storage technology is developing rapidly, so this limitation is unlikely to persist. The four-band sensing system uses software generated sensor clocking and drive waveforms. This scheme will facilitate the use of a wide range of alternative sensors or even a mixture of sensor types.

FIG. 5. A conventional photograph of the same region (Landsat band 5).

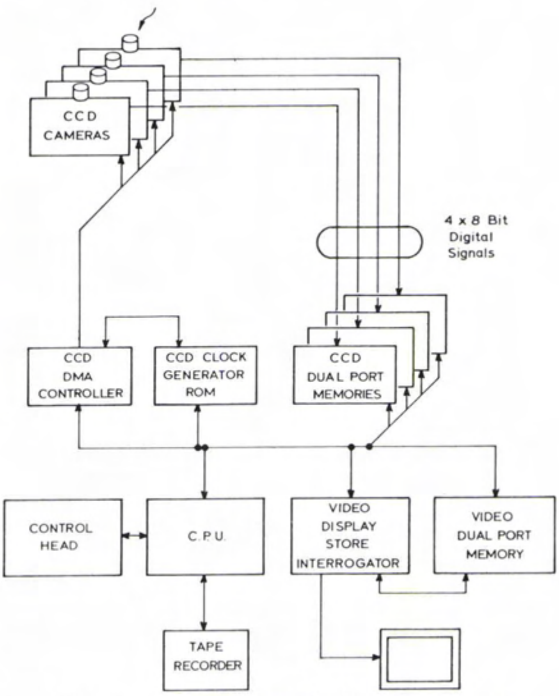

FIG. 6. Block diagram of a four channel MSS.

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