

Design of Image sensors for Hyperspectral Applications

Paul Jerram, David Burt, David Morris, Tim Eaton, Martin Fryer
e2v technologies, Waterhouse Lane. Chelmsford, UK, CM1 2QU

ABSTRACT

The sensor design for Hyperspectral observation is significantly different to many other imaging applications and the various requirements are discussed. An early programme is the MERIS (Medium Resolution Imaging Spectrometer) instrument on ENVISAT, which has been producing high quality Hyperspectral images for the last 7 years. The requirements for MERIS originally led to the development at e2v of both back-thinning technology, to meet the spectral requirements, and the manufacture of devices with a graded antireflection coating, to fully optimize the QE at every spectral band. A number of other hyperspectral missions are being planned or in preparation. For example Sentinel 3 is to be an almost direct repeat of the MERIS instrument and will be followed by Sentinel 4 and 5.

In the future as the technology matures it is likely that Hyperspectral missions will tend to use CMOS sensors rather than CCD. CMOS sensors have a number of potential advantages for Hyperspectral imaging and if these can be successfully exploited then enhanced performance would result. The design of a CMOS sensor is discussed that is targeted at Hyperspectral application to give fully optimized performance at all spectral bands.

Keywords: CCD, Hyperspectral, CMOS, MERIS, Sentinel 3.

1. INTRODUCTION

A Hyperspectral sensor is effectively an array of many linear imaging devices each targeted at a different spectral band, as shown in figure 1. The satellite scans the ground with the spectrum from a narrow strip being split across the imager. The row data from the device then provides spatial information and the column data provides spectral information. Wavelengths of interest generally range from the ultra-violet to near infra-red. Hyperspectral imaging differs from multispectral imaging in that the entire spectrum is distributed across the device and may be divided into bands as required, whereas in multispectral imaging discrete spectral bands are viewed using separate linear arrays.

The challenge for Hyperspectral imaging is that there is a very large variation in intensity between the different spectral bands that may be defined across the spectral range, as shown in figure 2. This causes two significant problems; firstly the detector must be able to operate with a very large range of signal intensities and secondly care must be taken to avoid cross-talk of the high intensity spectral bands with those which are less bright.

Meeting these specific requirements leads to the design of highly dedicated sensors.

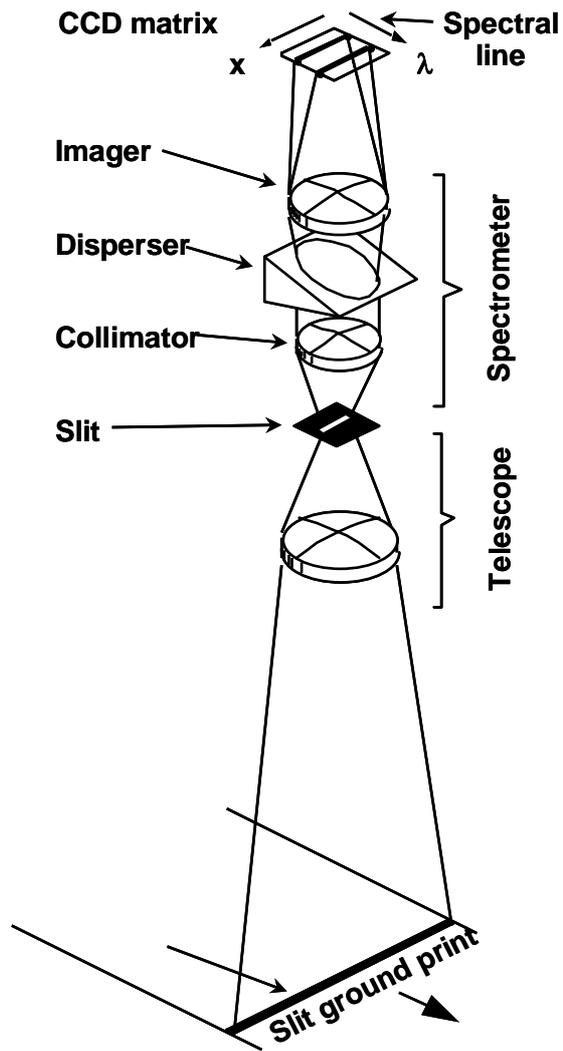


Figure 1: Schematic of Hyperspectral imager

2. DESIGN CHALLENGES

2.1 Spectral line intensity

As stated previously, the main challenge for Hyperspectral imaging arises from the difference in the magnitude of the signals obtained from each of the spectral lines. This is due to the variation of both the detection efficiency of the sensor and the reflectance of the earth. Typical plots of reflectance spectra and the quantum efficiency (QE) of silicon sensors are shown below in figure 2 and 3.

This large difference in signals means that the device must cope with a large dynamic signal range and is therefore very susceptible to cross-talk. Cross-talk can have both optical and electrical components.

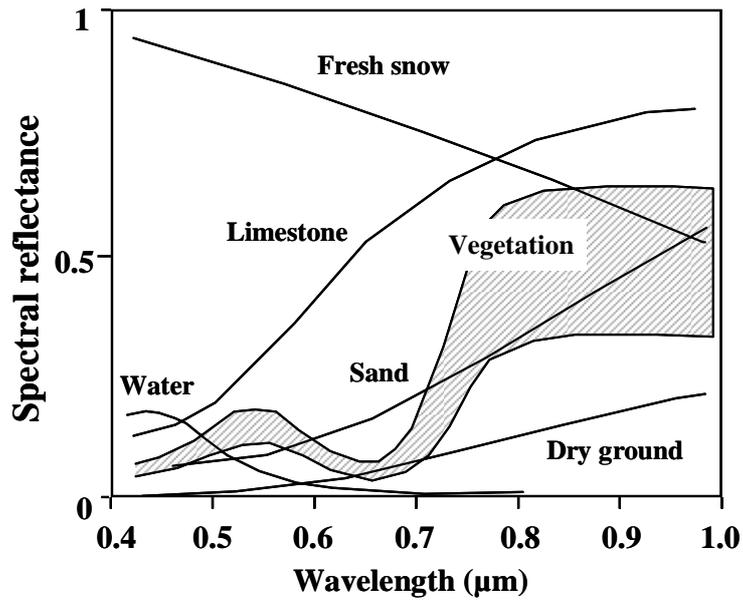


Fig 2: Ground Reflectance spectra

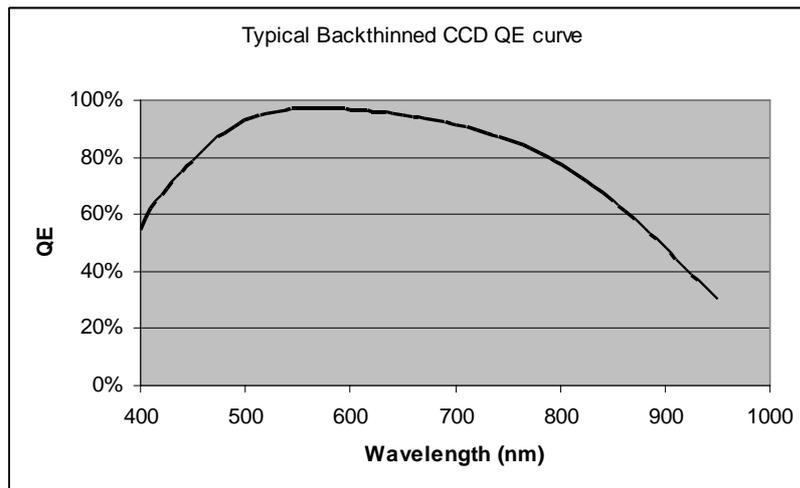


Fig 3: CCD Quantum efficiency

3. CCD DESIGN FOR HYPERSPECTRAL IMAGING

3.1 Dynamic range

As already discussed, there is a need to detect signals with a very high dynamic range, which is generally defined as the ratio of the peak “full-well” signal in electrons to the rms output circuit noise also in electrons.

As the CCD stores charge signals up to a maximum density per unit area, a larger pixel tends to provide a larger peak signal. For a given pixel size, increasing the peak signal can only be achieved by increasing the storage density, which is

possible by adjustment of the gate dielectric and buried channel parameters. A new fabrication process with about 50% increase of capacity is a recent development at e2v, with the added advantage of increased hardness to ionising radiation. For example, achievable pixel peak signals are now typically 300k electrons at 12 μm square, 600k electrons at 15 μm square and 1.7M electrons at 22.5 μm square.

A charge signal of N electrons is “detected” on a node capacitance C_N at the device output to give a voltage signal of GNq/C_N , where G is the voltage gain of the following amplifier and q is the charge on the electron. The overall responsivity is Gq/C_N volts per electron. Bias levels typically limit the maximum swing at the node to about 3 volts, thus for a maximum signal of N_M electrons, the minimum possible value for C_N is $qN_M/3$ Farads. Since with correct optimisation the output noise is proportional to $\sqrt{C_N}$, the dynamic range is also proportional to $\sqrt{C_N}$. This does however lead to an unfortunate trade-off: a device designed for very high signal levels with large C_N cannot also have the lowest possible noise. A solution to this problem that is suitable for many applications is to design a high responsivity circuit with a low value of C_N to detect the smaller signal levels, but have a facility to switch in extra capacitance to increase the value of C_N to detect larger signal levels. A factor three is provided in several e2v devices intended for astronomical applications, but there is no reason why higher factors could not be used. A penalty is that the noise increases in the ratio of capacitance, but this is largely offset by the higher signal levels. As an example, a device designed with $C_N = 10$ fF to give a responsivity of about $8 \mu\text{V}/\text{electron}$ with $G=0.5$ will have a low frequency noise floor of less than 2 electrons and peak signal capacity of about 200k electrons; a dynamic range of about 10^5 . By switching in an extra 20 fF the peak signal increases to 600k electrons (with noise floor now about 6 electrons). If faint spectral lines are then read at the higher gain and bright lines at the lower gain the effective dynamic range of the sensor is increased by a factor of three.

3.2 Wedge coating for minimising optical cross-talk

Optical cross-talk can be significantly reduced by minimizing reflections within the system. In MERIS and Sentinel 3 this is carried out at the device level by the implementation of a “wedge” or graded anti-reflection coating. The thickness of a single layer AR coating is varied across the device to change at the same rate as the spectrum and be a quarter wavelength for every spectral line. A coating of this nature results in almost no reflection from the sensitive back surface of the device. At wavelengths higher than about 750 nm, however, reflections are possible from the front surface of the device from light that has passed all the way through the silicon without being absorbed, and these cannot easily be reduced. Figure 4 shows the expected reflection from a device with a wedge coating as compared to a device with a uniform coating. A side benefit of the use of a wedge coating is that the QE is fully optimized at every wavelength.

A wedge coating can only be easily implemented on devices where the height is reasonably large. An alternative for smaller devices could be to use a two layer or multi-layer AR coating over the whole active area. However the benefit of a two layer (or multiplayer) AR coating is very small as the level of reflection will be increased in the centre of the band where the signal is likely to be higher.

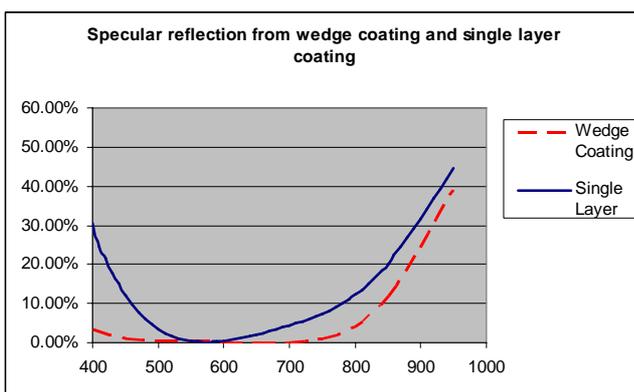


Fig 4: Reflectance from wedge and single layer coatings

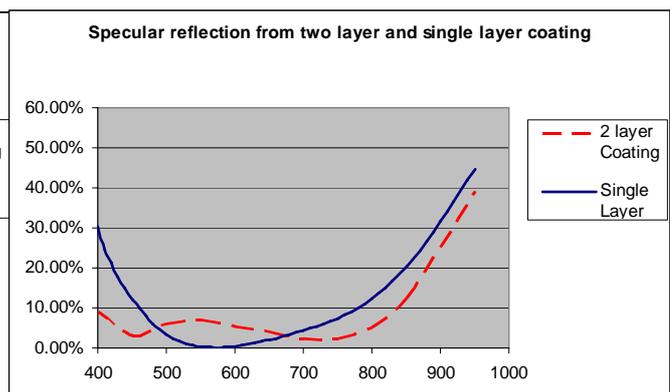


Fig 5: Reflectance from a single and two-layer coating

3.3 Frame transfer

For many Hyperspectral applications, e.g. MERIS, it is convenient to use the frame-transfer architecture for signal read-out. This does however lead to the well-known problem of “frame-shift smear”, with spurious charge signals being picked up by the potential wells as they move through bright regions in the image during the frame transfer operation. Since the quantity of spurious charge depends on the time a potential well is in the vicinity of a bright region, a faster frame transfer will reduce the amount of pick-up and thereby the degree of cross-talk. A faster frame transfer frequency can be possible by providing metal tracks to minimise the series resistance of the polysilicon electrodes. An added advantage can be a reduction of the fraction of the CV^2f clock power that is dissipated on-chip.

3.4 Sensor design for Sentinel 4 and 5

The definition of the sensors to be used for Sentinel 4 and Sentinel 5 is still in progress. However the requirements for increased dynamic range and reduced cross-talk mean that it is likely that if these missions are to use CCDs then many of the performance enhancements discussed in this paper will be required.

4. EXAMPLES OF CCD DESIGN FOR HYPERSPECTRAL IMAGING

4.1 MERIS

The first space-based Hyperspectral image programme with which e2v were involved was the MERIS instrument on ENVISAT and this has been successfully operating for over seven years. MERIS used a standard CCD25 device that was modified for this mission. The CCD25 is a frame transfer sensor with 770×576 pixels in the image section, each $22.5 \mu\text{m}$ square, and a further 770×576 elements in the store [1].

The CCD25 was one of the first e2v devices to employ back-face technology (i.e. light input through the back thinned silicon). At that time (1992) the process was relatively new and involved cutting the wafer into individual die before thinning, which was a very labour intensive procedure. It did however mean that it was relatively simple to deposit a wedge coating on each device. The programme to manufacture a repeat of the MERIS device (designated Sentinel 3), now uses a more-recent production-scale whole-wafer back-thinning process that is less labour intensive, but makes the implementation of a wedge coating on many different devices across a wafer very much more difficult. Complicated masking is required.

MERIS is continuing to produce impressive images and science data and has been an extremely successful instrument. An example image from the ESA website is shown in figure 6 below [2].



Fig 6: MERIS Hyperspectral image of the Nile Delta

4.2 Other Hyperspectral Missions

There are a number of other Hyperspectral missions that have used a CCD similar to that used for MERIS. These include CHRIS (Compact High Resolution Imaging Spectrometer) on PROBA [3] which has recently completed 5 years of operation and OMI (Ozone Monitoring Instrument) [4] which operates in the UV spectral region from 270 to 500 nm monitoring pollution. An Image of the sulphur dioxide produced from a volcanic eruption is shown in figure 7 [5].

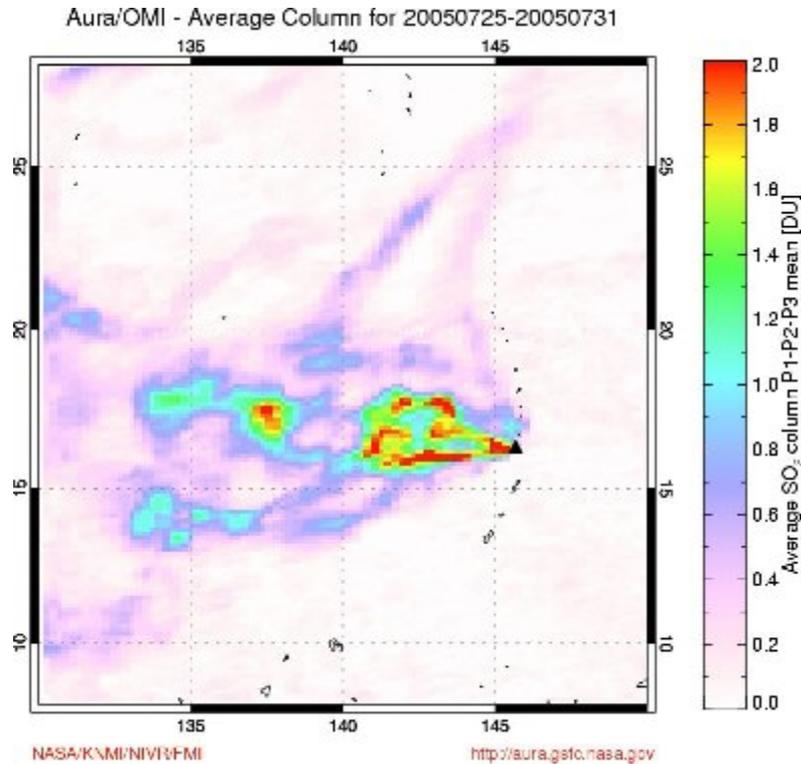


Fig 7: OMI Sulphur Dioxide image of the eruption of Anatahan

5. CMOS DEVICES FOR HYPERSPECTRAL IMAGING

CMOS imagers nowadays use pixels containing a photo-detector, a buffer amplifier and a switch to drive a column output track when selected. This gives two fundamental advantages over CCD. Firstly, each pixel is read directly and not through many other pixels, removing smear effects, and secondly, rows can be read and reset in any order to allow extension of the saturation level on a line-by-line basis. By having the means to selectively increase saturation levels, a high sensitivity basic pixel can be used to minimise noise.

Randomly selected row addressing can also be used to read out only one or more spectral windows (regions of interest) to increase the frame rate.

Typical hyperspectral imagers have a large pixel, at around $24 \mu\text{m}$ square, so it is possible to add extra transistors and capacitors to a 3T CMOS APS pixel without significantly degrading fill factor. These extra components can be used to give both a global snapshot shutter and a switch-selected choice of conversion gains. By back-thinning, the fill factor can be improved to 100 % – twice the factor often seen with front face 3T pixels. CMOS sensors from a number of different foundries have already been successfully back-thinned by e2v and have demonstrated a fill factor approaching 100% [6].

Switched conversion gains with a 3:1 ratio are possible by using a mosfet to connect a capacitor in parallel with the photodiode. By using a MIM structure this capacitor will not have any spurious sensitivity itself; the source and drain of

the switch will be sensitive, but their volume is a tiny fraction of the total pixel photosensitive volume and with back illumination only red and NIR will penetrate right through the silicon. Further increases in the charge capacity of some spectral lines can be achieved by adding extra read and reset cycles to those lines and summing the results digitally.

As with CCD, the long wavelength response can be improved by using thicker epitaxial silicon. To retain good MTF this requires higher resistivity to increase the depletion depth. These two changes from a standard CMOS process can limit the foundry choice, with the need for stitching often adding a third constraint.

Metal mirrors can be placed on the front of each pixel to reflect any radiation that has passed through the entire silicon thickness, to improve QE. Many foundries use a TiN barrier layer under each metal and this predominantly reflects the red or NIR radiation. This is not a problem with a back illuminated Hyperspectral imager as the other wavelengths are absorbed in the silicon before they can reach the mirror.

As CMOS sensors continue to mature it is likely that they will become the preferred choice of sensor for Hyperspectral applications.

An imager in design at e2v will offer the following key parameters:

| Parameter | Value | Comments |
|---|--|--|
| Number of rows (spectral lines) | 256 | |
| Number of columns (spatial resolution) | 1024 | Can be stitched to other sizes in 512 column increments. |
| Pixel size | 24 μm square | |
| Frame rate (full frame) | 250 fps | Windowing can allow faster rates. |
| Windowing (ROI) | Spectral direction only. | Rows can be randomly selected. |
| Peak signal | 100k or 300k electrons | Run time programmable, either global or row-by-row. |
| Shutter type | Global snapshot or rolling or row-by-row randomly addressed. | Snapshot gives best motion-stopping. Rolling shutter can include CDS to reduce kTC noise. Row-by-row allows both read-with-reset or NDR. |
| Charge to Voltage conversion gain at 100k electrons setting | 13 μV /electrons at photodiode. | 10 μV /electrons at imager pin. |
| Output type | Analogue | 12 bit external ADC recommended. |
| Number of outputs | 8 | One for each group of 128 columns. |
| Read-out Noise | \sim 15 electrons rms | At 100k electrons setting with CDS. |

ACKNOWLEDGEMENTS

Our thanks to Olivier Staint-Pe for useful background information and sketches on Hyperspectral imaging

REFERENCES

[1] Cutter, M.A., Pool, P. and Burt, D. "Development of a Backthinned CCD for the Medium Resolution Imaging Spectrometer" 1993 Image Sensors Workshop.

[2] <http://envisat.esa.int/instruments/meris/>

[3] <http://earth.esa.int/proba/>

[4]

http://www.knmi.nl/omi/research/news/newsWrap.php?language=only_en&timeFrame=latest&choise=page&path=research

[5] NASA image courtesy Simon Carn, [Joint Center for Earth Systems Technology](#) (JCET), University of Maryland Baltimore County (UMBC)

[6] Bréart de Boisanger, M, Saint-Pe, O, Larnaudie, F, Guiry, S, Magnan, P, Gonthier, P.M., Corbière, F, Huger N and Guyatt N. "COBRA, a CMOS Space Qualified Detector Family Covering the need for many LEO and GEO Optical Instruments ICSO 2008.