CASTEL-DETECTORS

Introduction

First of all, the sensor must be capable of providing linear response over some luminance range (otherwise called the full well capacity (FWC)) with a system noise low enough that the dynamic range dictated by the scientific objective is guarranteed (dynamic range is the ratio of the FWC divided by the system noise; its representation in decibels is 20*log 10 of that ratio.) The FWC of the CCD sensor is proportional to the size of the pixels in the CCD (actually it is proportional to the area of each pixel.) The system noise is the result of noise from the CCD, the analog readout electronics and the camera environment- all of which comprise "the way it is operated".
The second major influence on a CCD system is the way the camera is operated. Options include the frame rate and operating temperature. Frame rates depend upon the pixel count and the digitization rate. Spectral provides digitization rates between 50 kHz (for very low noise systems) to 10 MHz for high frame rate systems. Frame rate is driven by application requirements and must be combined with other CCD specific characteristics (pixel size and pixel count) in determining the match between sensor and camera operation modes.
The highest dynamic range is obtained using a CCD with large pixel size, running it very cold and reading it out very slowly. Highest frame rates are obtained using small pixel CCDs with small pixel count (or, on a large pixel count sensor, combining pixels before they are readout.) The importance of pixel size on frame rate is that small pixel size imagers can perform the readout mechanics quicker than larger pixel size imagers.

Constraints on the detector and acquisition system

From the additional scientific objective (solar oscillations), a field of view (FOV) of at least 60” is requested (in order to sample a supergranule or part of an active region). The FOV on the single pixel is fixed to 0.15”/pix, constrained by the Rayleigh criterion and the diffraction limit of the telescope at 400 nm.
As a result, the sensor has to be at least a 512 x 512 pixels.
The mean working temperature is –37° C with -45° C minimum temperature.
The dynamic range suggested by the additional scientific objective is of the order of ≥ 60 db (since 1% oscillations want to be detected with a 10% noise), while since the seeing estimate depends on the contrast of the high resolution structures resolved in the image (> 10%) typically > 40 db detectors and exposure times of less than 20 ms are needed.
The minimum acquisition rate is 0.1 image/s, and the image can also be the result of the summation of many. For high resolution images obtained through summation or long exposure times, a tip-tilting mirror can be introduced (with more complication and additional sensor) or acquisition of many images is needed for successive registering and/or selection.

In the following, we have selected the main characteristics of a camera (sensor + read-out system) in order to define the constraints and compare pros and contras.

Specification		Pro	Contra	Cross specs.
Square pixel	YES	easier reduction		
Pixel Size	< 15 μm		Focal length > 20m	Focal length
# pixels	> 512	supergranule		
Dimension				Filter's diameter
Filling factor	high			Microlenses
QE at 400 nm	> 5%		long exp. time	heating
min[&] FWC*0.7*.9[£]	> 16000 (> 40 db dyn range)			
Shutter	NO	–37° C work. T		
Microlenses			if yes, chromatic aberration	
SNR	see below			
# bit				
Min exp. time	< 20 ms			
Working T	–37° C			
Low T Cabling	Included			

[£]typically the real FWC is 70% of the declared and 90% is used to avoid saturation.
[&]if only photon noise is taken into account.

Quantum Efficiency (QE)

The intrinsic sensitivity of a CCD camera is the ability of each pixel to detect and convert incoming photons to pixellated electrons. If every incoming photon generates a pixellated electron then the sensitivity of that camera is 100%. This is an ideal that can be approached in modern CCD sensors by specialized fabrication processes. This sensitivity metric is known as quantum efficiency (QE) and it is different for each CCD at every wavelength. Quantum efficiency is that percentage of photons reaching the CCD that are converted to electronic signal. The higher the QE the more sensitive the device is in picking up the image. The highest QE is obtained with thinned, back illuminated CCDs. In a back-illuminated CCD, the CCD is "turned over" and processed to remove the substrate so that light enters the pixels from the rear of the pixel structure rather then through the gated electrodes that define (and mask) the pixel on the front side. This arrangement raises the QE to more than 80% for the wavelengths from 550 to 800 nm. Coating are sometimes used to increase the sensitivity in the blue-visible and UV wavelengths. The Roper Scientific uses a Metachrome II coating guarranteed to work at –100° C and not to reduce the spatial resolution.

In our experiment, the QE is not crucial since we deal with a large photon flux. Nevertheless the seeing estimate fixes the exposure time to values lower than 20 ms. For this reason the exposure time has to be computed taking into account the real characteristics of the optics and camera in order to put a lower limit to the accepted QE from the sensors avaliable on the market.

SNR (from Roper Scientific)

Signal-to-noise ratio (SNR) describes the quality of a measurement. In CCD imaging, SNR refers to the relative magnitude of the signal compared to the uncertainty in that signal on a per-pixel basis. Specifically, it is the ratio of the measured signal to the overall measured noise (frame-to-frame) at that pixel. High SNR is particularly important in applications requiring precise light measurement.

Photons incident on the CCD convert to photoelectrons within the silicon layer. These photoelectrons comprise the signal but also carry a statistical variation of fluctuations in the photon arrival rate at a given point. This phenomenon is known as photon noise and follows Poisson statistics. Additionally, inherent CCD noise sources create electrons that are indistinguishable from the photoelectrons. When calculating overall SNR, all noise sources need to be taken into consideration:

Photon noise refers to the inherent natural variation of the incident photon flux. Photoelectrons collected by a CCD exhibit a Poisson distribution and have a square root relationship between signal and noise (noise= sqrt (signal)).

Read noise refers to the uncertainty introduced during the process of quantifying the electronic signal on the CCD. The major component of readout noise arises from the on-chip preamplifier.

Dark noise arises from the statistical variation of thermally generated electrons within the silicon layers comprising the CCD. Dark current describes the rate of generation of thermal electrons at a given CCD temperature. Dark noise, which also follows a Poisson relationship, is the square root of the number of thermal electrons generated within a given exposure. Cooling the CCD from room temperature to –25° C will reduce dark current by more than 100 times. In addition, many scientific-grade CCDs employ multi-pinned-phase (MPP) technology to even further reduce dark current.

Taken together, the SNR for a CCD camera can be calculated from the following equation:

$$\frac{IQEt}{\sqrt{(IQEt + Ndt + Nr^2)}}$$

where:

I = Photon flux (photons/pixel/second)

QE = Quantum efficiency

t = Integration time (seconds)

Nd = Dark current (electrons/pixel/sec)

Nr = Read noise (electrons)

Under low-light-level conditions, read noise exceeds photon noise and the image data is said to be "read-noise limited." The integration time can be increased until photon noise exceeds both read noise and dark noise. At this point, the image data is said to be "photon limited."

An alternative means of raising the SNR is to use a technique known as binning . Binning is the process of combining charge from adjacent pixels in a CCD during readout into a single "superpixel." Binning neighboring pixels on the CCD array may allow one to reach a photon-limited signal more quickly at the expense of spatial resolution.

Once you have determined acceptable values for SNR, integration time, and the degree to which you are prepared to bin pixels, the above equation can be solved for the minimum photon flux required. This is, therefore, the lowest light level that can be measured for given experimental conditions and camera specifications.

<u>CCD electronics</u> (from Olympus)

Back-thinned, back-illuminated CCD chips

This is a rather expensive and delicate type of chips for high-end scientific-grade CCD cameras which is, to put it simple, mounted upside-down in the camera. The illuminated back is thinned by etching down to about 10 - 15 microns so that it becomes transparent. These sensors have a substantially improved sensitivity over the entire spectral range as compared to standard CCD chips. The quantum efficiency may exceed 80% between about 450 and 650 nm. A substantial downside of this chip type is a readout noise that is usually considerably higher than that of standard chips even at slow digitization speed. The dark noise is higher in cases as well.

Full-frame CCD chips

Full-frame CCD chips consist of a high-density array of photodiodes that convert the incoming photons into electrical potentials. The fill factor is close to 100 percent, which means there is nearly no "empty space" between the diodes and no incoming photons are lost. After image exposure the data readout is performed by shifting the charges in a parallel fashion one row at a time to the serial register. (The charge transfer is similar to the readout of data from the storage array of a frame-transfer chip as depicted below.) The serial register then shifts each row of information sequentially to an output amplifier before it is directed to an A/D signal converter. Unless mechanical shutters or synchronized illumination is used for exposure, smearing artifacts occur because the photodiodes are being continuously illuminated during parallel register readout.

Frame-transfer CCD chips

Frame-transfer CCDs use two-part chips in which one half is exposed and collects photons while the other is used for temporary data storage only and masked to protect it from incoming light. During the exposure of an image the data of the previous image are readout from the storage array via the serial shift register through an output amplifier and A/D converter. Once exposure and readout are completed the newly accumulated charges are very rapidly moved from the light sensitive half to the emptied storage array; this is termed the frame transfer. Afterwards the cycle can be repeated and the next image acquired. A disadvantage of this principle is the possibility of charge smearing during the parallel transfer if the light influx is continuous throughout.

Interline-transfer CCD chips

On interline-transfer chips each column of individual photodiodes has a light-shielded (masked) vertical transfer shift register directly adjacent to it. The parallel photodiode registers and interline masks are separated by transfer gates. Similar to frame-transfer CCDs there are cycles of simultaneous photodiode exposure and charge transfer channel readout followed by very rapid interline charge transfer from the photodiodes to the emptied shift registers.
Interline-transfer chips are usually equipped with microlense arrays. There is a lens for every pixel to collect photons that would otherwise remain undetected by hitting the interline masks or transfer gates. These lenslet arrays increase the so-called photodiode fill factor by more then a factor of three.

These devices also include an "electron drain" to prevent electron overflow into neighboring pixels by overexposure and the resulting blooming artifacts in the images. Furthermore, electronic shuttering is possible by switching the voltage at the photodiodes in order to prevent photoelectrons that are generated during off-times from reaching the transfer registers.

Electron Multiplying CCD (EMCCD) chips

This is a new on-chip gain technique that can be applied to all current chip types. Such chips feature an additional gain register inserted between shift register and output amplifier through which all electrons are moved serially upon data readout. In each charge transfer step electron multiplication occurs upon impact ionization caused by electrodes with higher voltage amplitude than is necessary for the transfer alone. While the multiplication factor per step might be low, the huge number of steps during serial readout leads to a significant gain. For example, 0.5% gain per step leads to a 165-fold signal increase for 1024 pixels per line. Besides voltage and number of transfer steps the gain factor is also dependent on the chip temperature. The lower the temperature the more probable is the generation of secondary electrons.
The fundamental difference to intensified CCDs is that in those the photoelectrons are multiplied prior to reaching the CCD chip while here the gain is achieved on-chip. Because it is done before readout the read noise is not affected and consequently the signal-to-noise ratio enhanced significantly. On the other hand, dark charges are multiplied together with the photoelectrons, however, the cooling of the CCD keeps this factor low. A certain additional noise factor arises from the probabilistic nature of the secondary electron generation and the uncertainty that goes along.
An advantage over intensified CCDs is that there is no risk of hardware damage due to overexposure and that the spatial resolution is the same as for an analogous standard CCD and not reduced by a photocathode or MCP.

CMOS IMAGE SENSORS

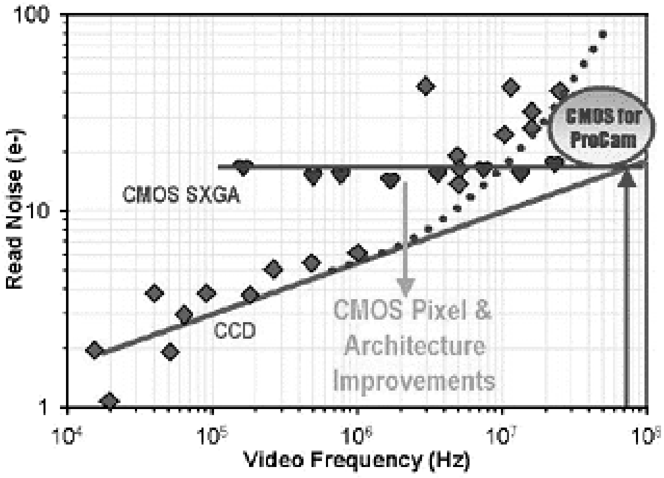
Introduction

Until very recently, nearly all digital cameras are based on the use of a CCD (Charge Coupled Device) sensor. CCD manufacturing uses a process called N-MOS. This complex process makes CCD sensors expensive to manufacture. Another method to produce an image device involves the use of a much more common production technique called CMOS (Complementary Metal Oxide Semiconductor). CMOS is the process by which most of the electronic chips (Random Memory Access chips or microprocessors) are made today. CMOS sensors detect and convert incident light (photons) — first into electronic charge (electrons) and, ultimately, into digital bits. The sensor core is typically an array of photodiodes that detects visible light. Each picture element (pixel) includes co-located CMOS transistors that select, amplify and transfer the signals from each pixel's photodiode. By also surrounding the sensor core with adjunct circuits that dynamically amplify the signal depending on lighting conditions, suppress random and spatial noise, digitize the video signal, and translate the digital video stream into the optimum format for each application, the camera-on-a-chip is now a reality (Rockwell Web Page). CMOS pixel arrays form the core of a CMOS image sensor and are based on either active or passive pixels. Passive pixels use a simpler internal structure, which does not amplify the photodiode's signal within each pixel (PPS). Active-pixel sensors (APS) have an amplifier in each pixel. The APS incorporate transistors in each pixel to convert the photo-generated charge to a voltage, amplify the resulting signal and reduce noise. Adding these components reduces APS fill factor in 0.5 µm processes to about 30 percent at 6µm pixel pitch for square pixels. Microlenses can double or triple the effective fill factor in this case.

CMOS devices incorporating an A/D converter in each pixel are called Digital Pixel Sensor (DPS). In summary, CMOS image devices are in some way very similar to CCDs. Both technologies are based on photosensitive diodes or gates, which are placed in silicon. As previously discussed, in both solid state devices photons are converted into an electronic charge. The main difference between the two technologies lays in the fact that in CMOS it is possible, by using ordinary CMOS components, to integrate a lot of functions into the sensor or into each individual pixel. In CCD technology it's much more complicated to integrate additional functionality into the sensor. By integrating camera functions into the sensor itself, it is possible to create a so called camera on chip.

CMOS APS Read and Dark noise

We report, from the Rockwell Scientific Web page, the read noise (Nr) for the visible CMOS imager having 1280x1024 (SXGA) format. The noise was measured by using a test apparatus comprising a 12-b A/D converter, a Preamble Model 1855 preamplifier with programmable bandwidth as large as 100 MHz, and a personal computer. The SXGA's output driver rise and fall times of 3.5 ns and 7 ns, respectively, allowed operation to ~ 40 MHz. APS noise bandwidth, however, was set at a maximum of 100 kHz. Plotted in figure are the SXGA along with prior CCD read noise data. The SXGA clearly excels at video frequencies. In the basic operating mode used for digital still image capture with sensitivity of about 30μV/e, the read noise is <20 e- to 25 MHz. The visible astronomical imager data, also shown in the figure, represent the lowest read noise.



Comparison of CMOS APS read noise to measured and predicted CCD noise.
From **http://www.rockwellscientific.com/html/cmos.html**

Standard CMOS image sensors suffer from high dark current, and hence dark current noise (thermal noise), of the order of 1 nA/cm^2 at room temperature, often limiting their use to not too long exposure times. For example the STAR250 Rad-hard imager (Fill factory) has an average dark current signal of 4750 e-/s that, for a typical integration time of 20 ms, corresponds to 950 e- of dark current and about 31 e- of dark noise.

In order to achieve a SNR ≈100, for a read noise Nr ≈ 20 e- and a dark noise ≈ 31 e-, we request to collect about 8700 photo-electrons for each pixel. For a typical fill factor × QE = 35% we obtain about 28600 e- for 20 ms (≈143000 e-/s pixel).

The operating temperature

Usually, the operating temperatures for the CMOS devices stay in the range –5 to 60 ^{o}C.

The frame rate (LUPA-1300 FillFactory)

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The frame period of the LUPA-1300 sensor can be calculated as
follows:

Frame period = FOT + (Nr.Lns* (RBT + pixel period * Nr. Pxs / 16)

with: FOT: Frame Overhead Time = 1 us.
Nr. Lns : Number of Lines read out each frame (Y).
Nr. Pxs: Number of pixels read out each line (X).
RBT: Row blanking time = 200 ns (nominal; can be further reduced).
Pixel period: clock_x period/2 (both rising and falling edge are
active edges).
Example read out of the full resolution at nominal speed (40 MHz
pixel rate):
Frame period = 1 us + (1024 * (200 ns + 25 ns * 1280 / 16) = 2.25
ms => 444 fps.
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In the following, we have selected the main characteristics of the LUPA1300 system (FillFactor http://www.fillfactory.com/htm/products/htm/lupa.htm) in order to define the constraints and compare pros and contras.

Specification		Pro	Contra	Cross
Square pixel	YES	easier		
Pixel Size	14 μm		Focal length > 20m	Focal length
# pixels	1280 ×1024	supergranule		
Dimension	17.9 × 14.3 [mm]			Filter's diameter
Filling factor	high			Microlenses
Fillfactor×QE @ 700 nm	15%			
full well capacity	60000 e-			
Shutter	synchronous			
Dynamic Range	62 db			
noise	45 e- RMS			
# bit	dual slope			
Frame-transfer	450 fps	high		
Full-frame				
Min exp. time	2 ms			
Working T	?		probably –5/+60 C	
Low T Cabling	?			

The exposure time for the system at Dome C

For ground based observations, the atmospheric condition is a crucial parameter for the determination of the exposure time. In fact, the sky transparency plays a dominant role due to its large variations during the day (mainly due to the different elevetion of the observed object in the sky) and at timescales of 1/100 seconds (due to the atmospheric turbolence).
In the case of solar observations, the amount of incident light is usually not a problem, while the acquition rate could be a limit due when large images want to be stored.
In order to estimate the exposure time through the CASTEL (Concordiastro Solar Telescope), we first compute the number of photons incoming on the detector
The solar spectrum incoming on the ground at the average distance from the sun is reported in figure 1. This spectrum changes less than a part over 10000 due to the relative Earth-Sun distance during the year. In the figure the changes during the solar cycle (11 years) are also shown and they are strongly dependent on the wavelength.

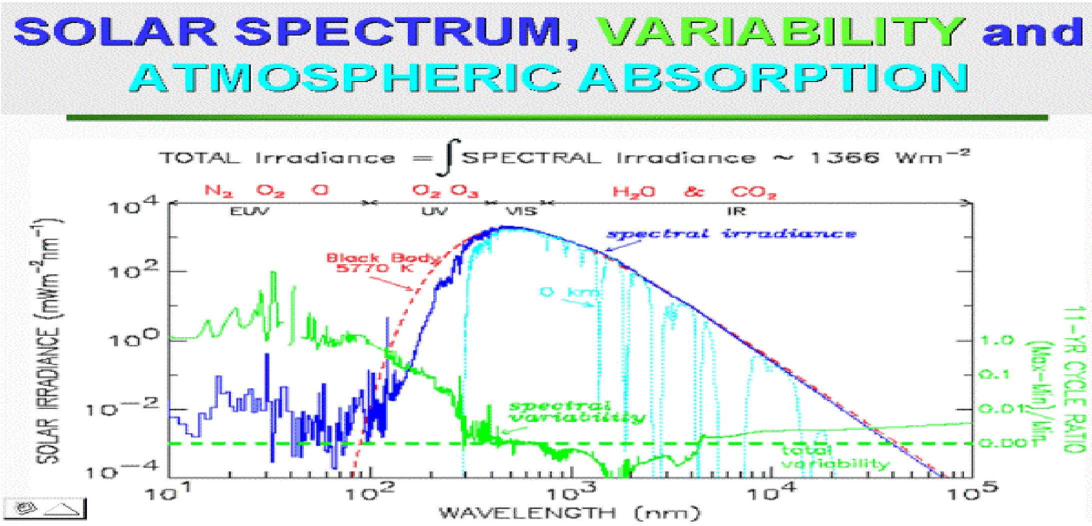


Figure 1: mean solar spectrum on the ground (blue), its variations (green) and black body spectrum at 5770 K (red).

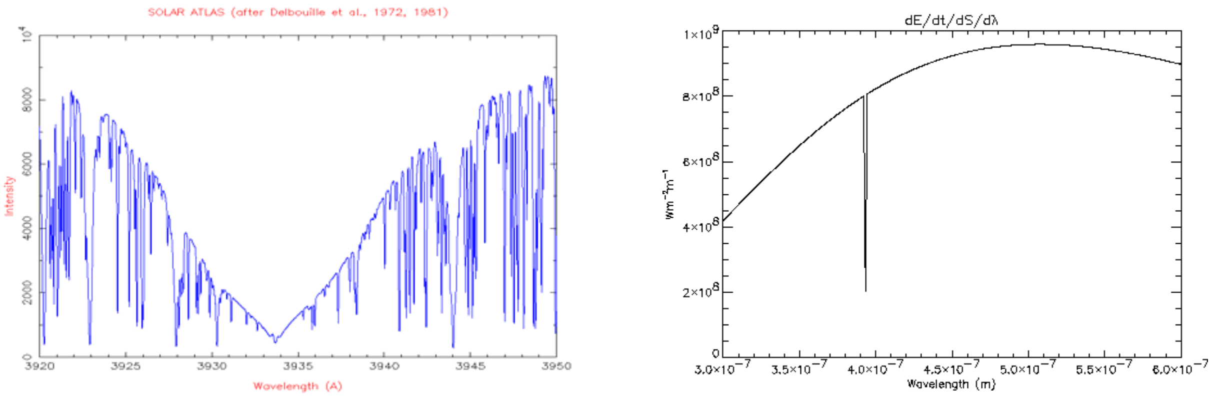


Figure 2: Ca K spectrum at 393.7 nm as measured on the ground (Bass 2000 archive and Utrecht University data, left) and irradiance simulation above the Earth atmosphere (right).

The largest variability of the solar spectrum incoming on the ground is due to the sky transparency. We estimated from 0.5 (below this value usually no observing run is usually performed) to 0.9.
The CASTEL will operate at blue wavelengths, and in particular along the Ca K line at 393.37 nm (see figure 2), and no emission is considered in this model to estimate the exposure time.
The flux spectrum incoming on the telescope is S = a dE/dt/dλ/dS, where a is the sky transparency (depending on the wavelenght).

The transmission through the optics takes into account the additional lenses, filters with the real transmission profiles. a telescope efficient aperture of 40 cm with a 10% transmission has been considered.

The incoming photons on the detector is ∫dλ S*(tel area*filters trans*optics trans)/hc/λ.

In order to compute the exposure time we now need some characteristics of the detector: the resolution on pixel, the QE and the FWC. We consider only 70% of the declared wells as usable in the linear range and the 90% of them not to reach saturation.

In the following, we report two examples for different sensors from Apogee, using a Barr 0.3 nm FWHM filter and ND Andover filters. Any change can be easily scaled.

Dome C & CASTEL characteristics

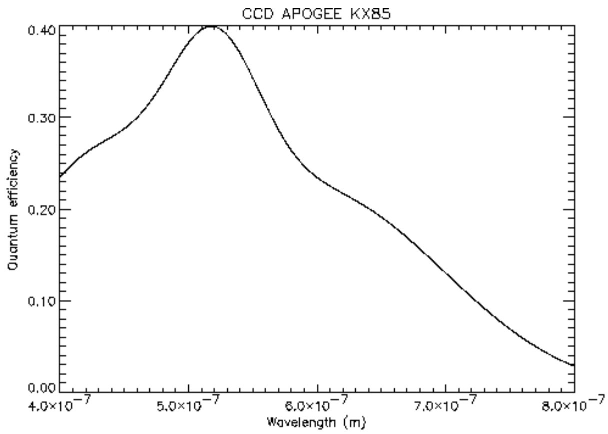
Telescope diameter	Telescope transmission	Spatial res. on pixel	Atmospheric ransparency	Optics transmission	Filter's peak transmission at 393.7 nm	Filter's FWHM at 393.7 nm
40 cm	0.1	0.15"	0.8	0.85	0.6	0.3 nm

With Apogee KX85 (min exposure time = 2 ms)

FWC	QE at 400 nm	ND	**Exp time**
16500	0.24	2.3	1.6 ms

With Apogee ALTA U2000 (min exposure time = 1 μs)

FWC	QE at 400 nm	ND	**Exp time**
40000	0.47	2.3	1.9 ms



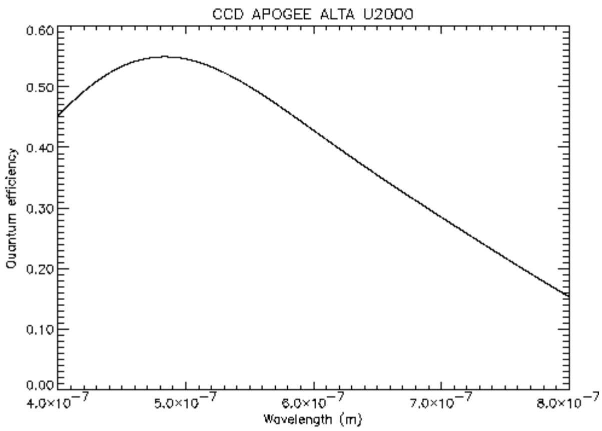


Figure 3: QE spectra for the KX 85 (left) and Alta U2000 (right).