ULTRACAM — high-speed astrophysics

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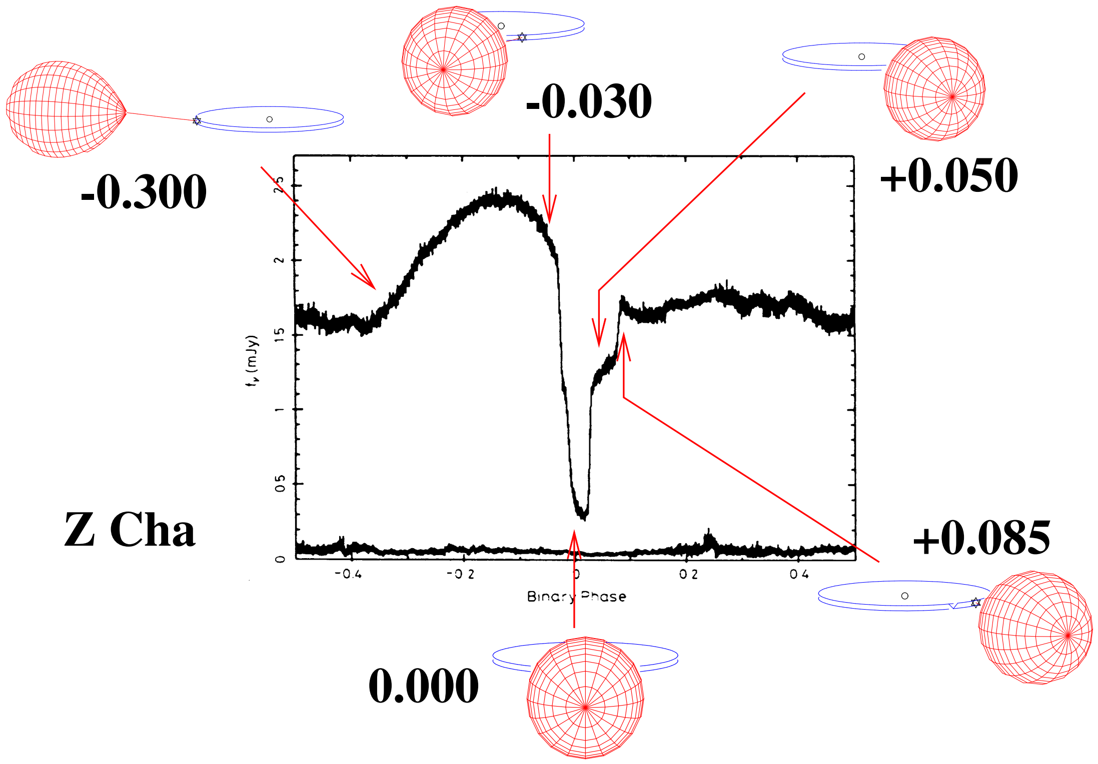
- Astrophysics on short timescales
- Observing at high-speed
- ULTRACAM, a 3-band, high-speed CCD camera

Timescales

$$t_{\rm dyn} = \sqrt{\frac{R^3}{GM}} \approx 30 \left(\frac{M}{\rm M_\odot}\right)^{1/2} \left(\frac{R}{\rm R_\odot}\right)^{3/2} \text{ min.}$$

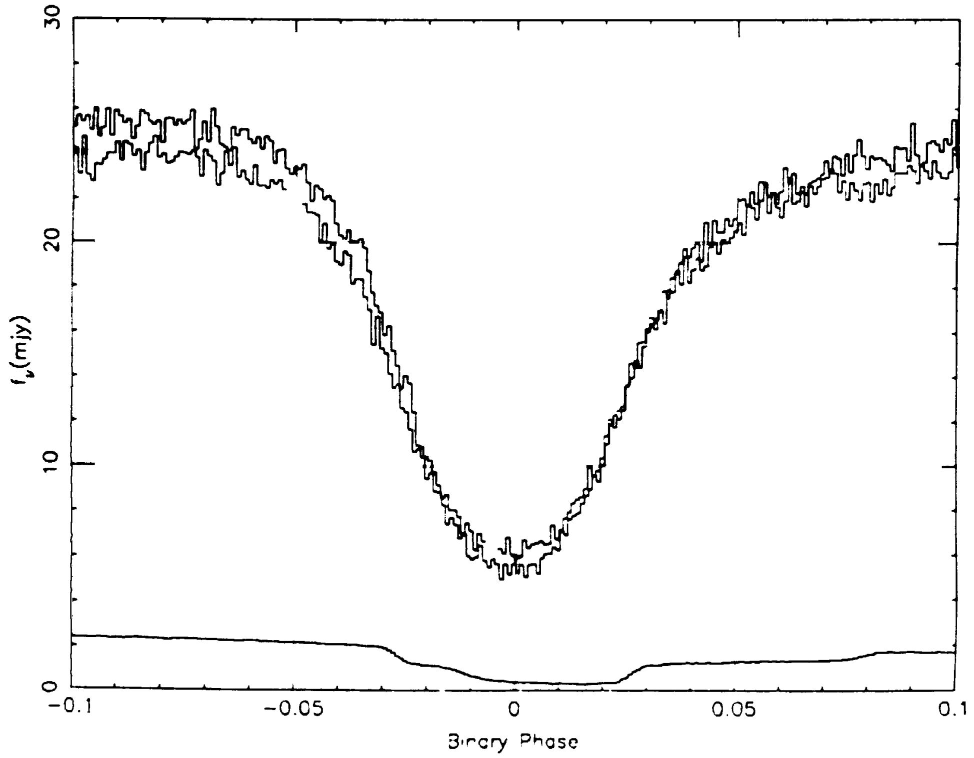
Timescale	Science
1 – 100 s	Eclipses of binary stars Eclipse mapping Asteroseismology White dwarf binaries Flickering in accretion discs DNOs and QPOs
0.01 – 1 s	Echo mapping LMXRB low frequency QPOs Precise timing studies Shift-and-add imaging Speckle imaging Non-redundant mask imaging
< 0.01 s	Neutron star and black-hole inner orbits Lunar occultations

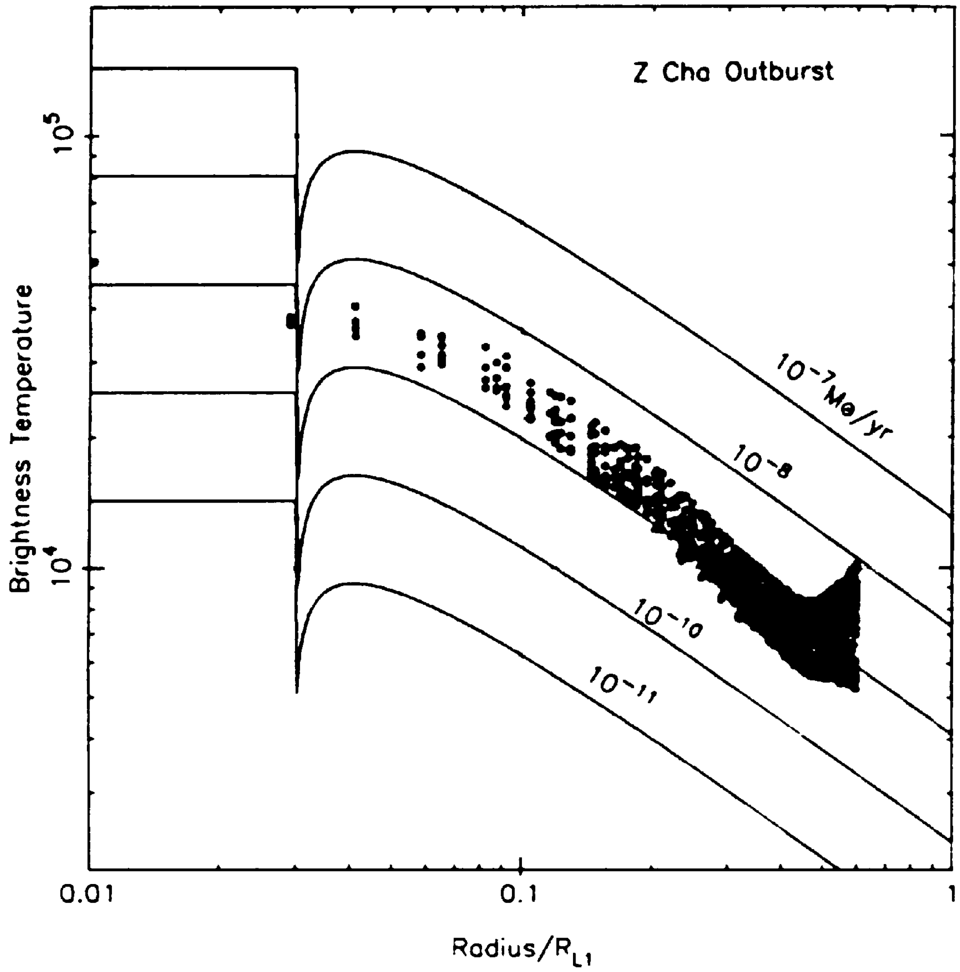
Eclipsing Cataclysmic Variable Stars



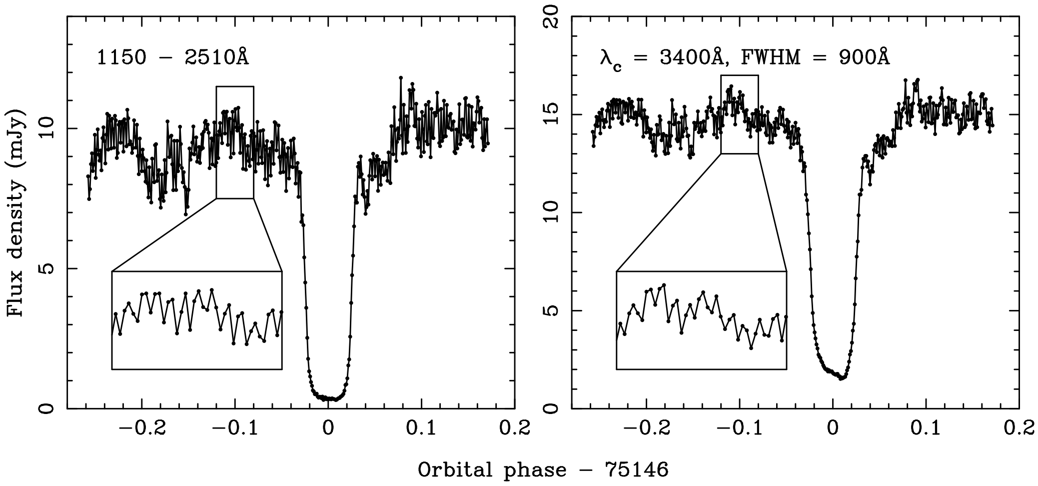
- Sharp eclipse features of the white dwarf and gas stream/disc impact point lead to a complete solution of the system geometry and physical parameters.
- Eclipse transitions take $\sim$ 40 seconds

Eclipse Mapping



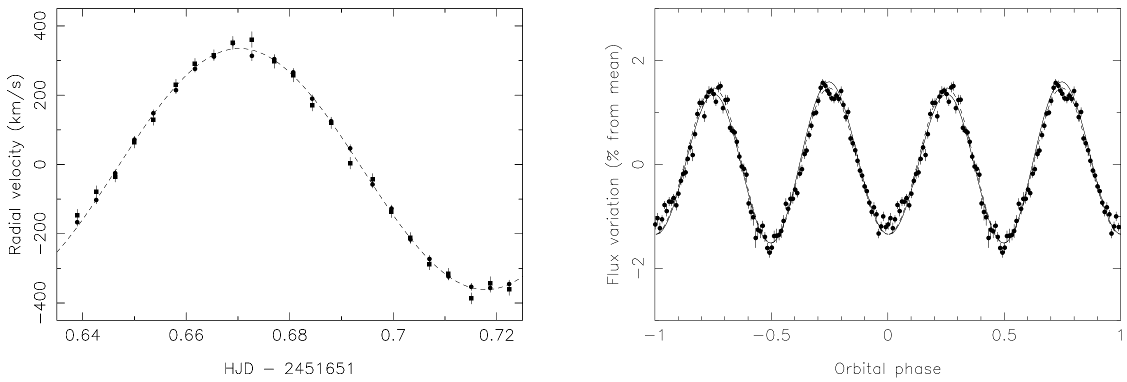


HST spectra of the dwarf nova OY Car



$P = 18$ second oscillations with a peak-to-peak amplitude of 10 to 20%.

KPD 1930+2752 – a Type Ia progenitor



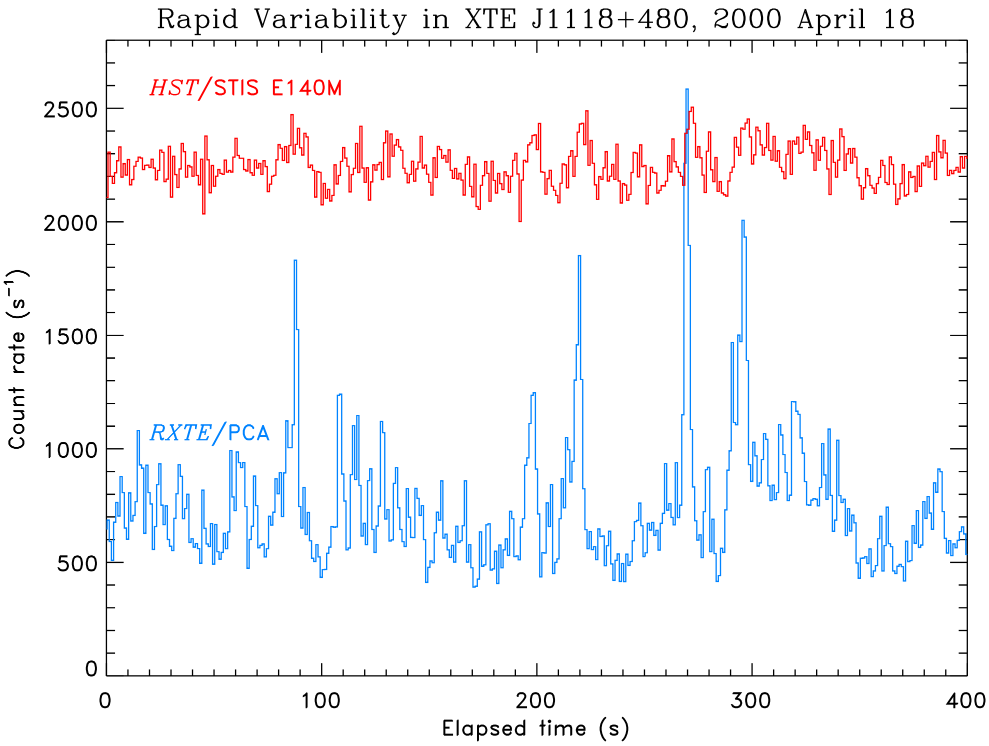
Good Type Ia SN progenitor candidate – sdB + white dwarf.

To confirm mass requires measuring the depth of the white dwarf transit.

Ingress/egress predicted to take ≈ 14 seconds

Precise timing for period change due to GWR.

Echo mapping of X-ray transients



(Courtesy: Rob Hynes)

If X-ray variability drives other wavelengths, can map out structure in the binary – "echo mapping".

Need to detect lags of the order of seconds.

Photometry

Photo-electric photometry:

- Used extensively for high-speed work in the 1970s and 1980s
- Photon-counting: zero readout time and noise.
- Sky background and comparison stars require multiple channels
- Poor QE, 25% at peak, $< 3\%$ at R and I.
- One-band only
- Requires fixed and typically large apertures.

CCD photometry:

- Started in late 1970s
- Simultaneous measurement of sky and comparison stars.
- High QE, up to 95% over wide wavelength range.
- Readout noise and slow readout time.
- One-band only

Key Drivers for ULTRACAM

Here are some key features for competitive high-speed photometry:

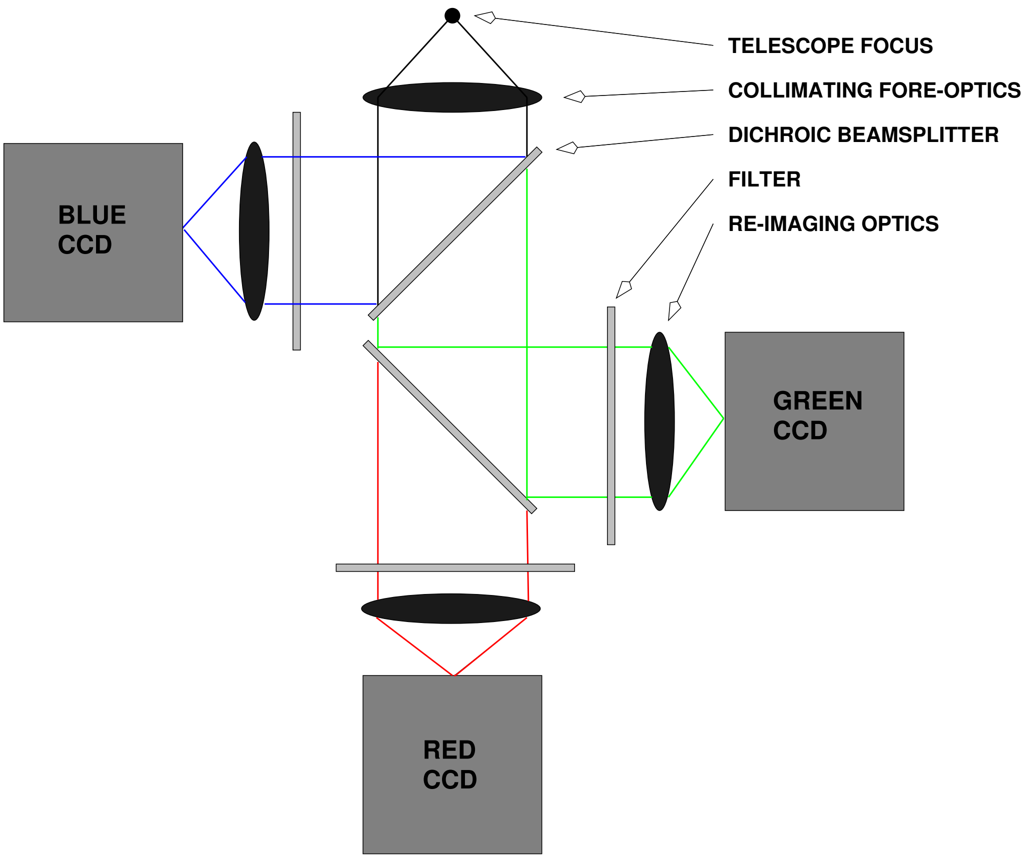
- The capability of taking short exposures with small deadtimes between exposures.
- Multi-channels (3 or more) covering a wide wavelength range in order (minimally) to distinguish a black-body spectrum from a stellar spectrum.
- Simultaneous measurement of the different wavelength bands to avoid problems of stochastic variations ("flickering")
- Imaging capability in order to measure target, comparison stars and sky background in one go and to avoid the need for fixed apertures.
- As high efficiency as possible.

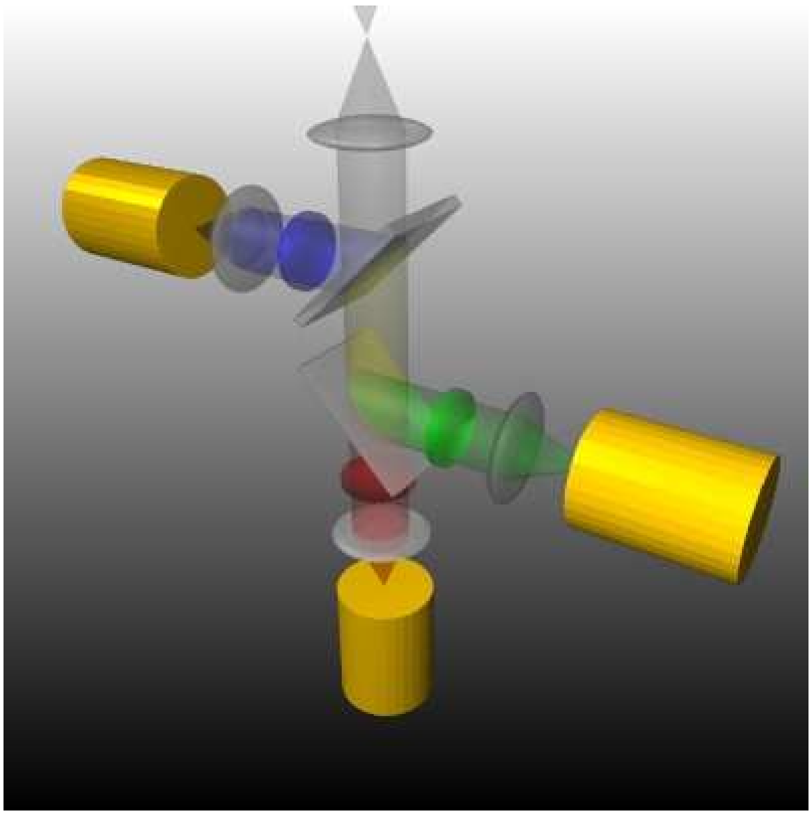
ULTRACAM introduction

ULTRACAM is a 3-channel high-speed CCD imager. Its essential features are:

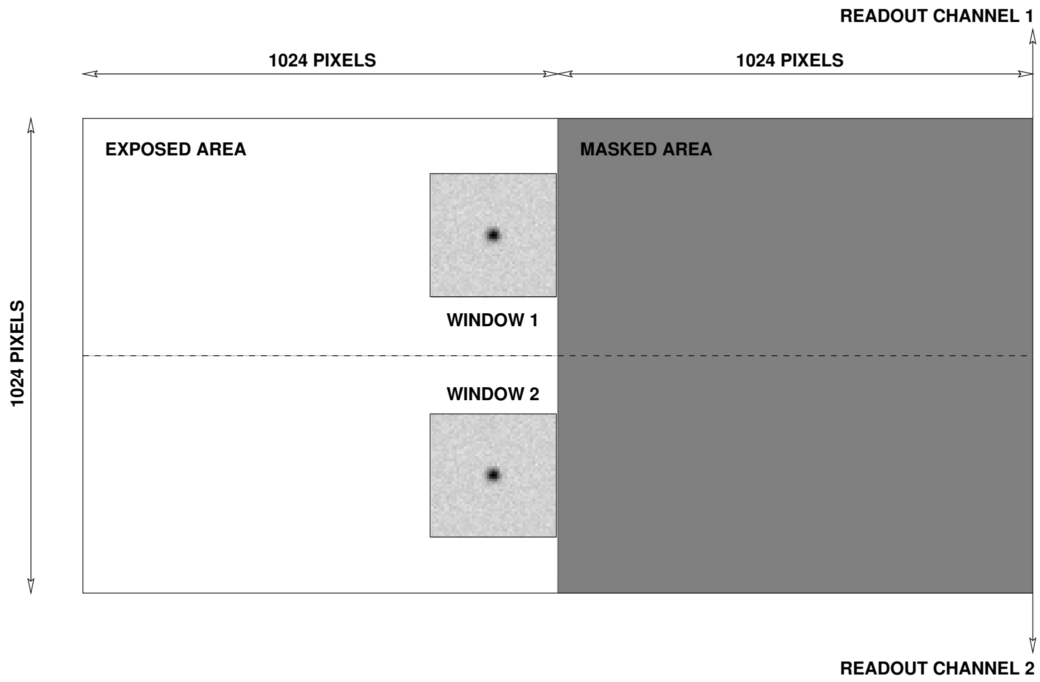
- $3\times$ frame transfer Marconi 47-20 CCDs.
- Imaging area 1024×1024 pixels.
- Dichroic beam-splitters to divide spectrum.
- For most projects, the dead-time will be set by the shifting time, < 5 milli-seconds.

Schematic views of ULTRACAM





Frame Transfer



SHIFTING	$\approx 5\,\mu\text{s}/\text{column}$
	$\approx 0.7\,\mu\text{s}/\text{pixel}$
READOUT	$\approx 3\,\mu\text{s}/\text{pixel}/\text{readout channel}$

Two readout channels handle half the data each.

Example Deadtime Calculations

FULL-FRAME:

Shift by 1024	$1024 \times 5 \times 10^{-6} = 0.005\,\mathrm{s}$
Shift 1024^2 pixels	$1024^2 \times 0.7 \times 10^{-6}/2 = 0.37\,\mathrm{s}$
Readout 1024^2 pixels	$1024^2 \times 3 \times 10^{-6}/2 = 1.57\,\mathrm{s}$

$$\text{Deadtime} = \max(0.005, 1.945 - t_{\text{exp}}) \text{ seconds}$$

e.g. 1 s exposure, deadtime 1 s; 2 s exposure, deadtime 0.005 s.

100×100 WINDOW:

Non drift-mode:

Shift by 1024	$1024 \times 5 \times 10^{-6} = 0.005\,\mathrm{s}$
Shift 100×1024 pix	$100 \times 1024 \times 0.7 \times 10^{-6}/2 = 0.036\,\mathrm{s}$
Readout 100^2 pix	$100^2 \times 3 \times 10^{-6}/2 = 0.015\,\mathrm{s}$

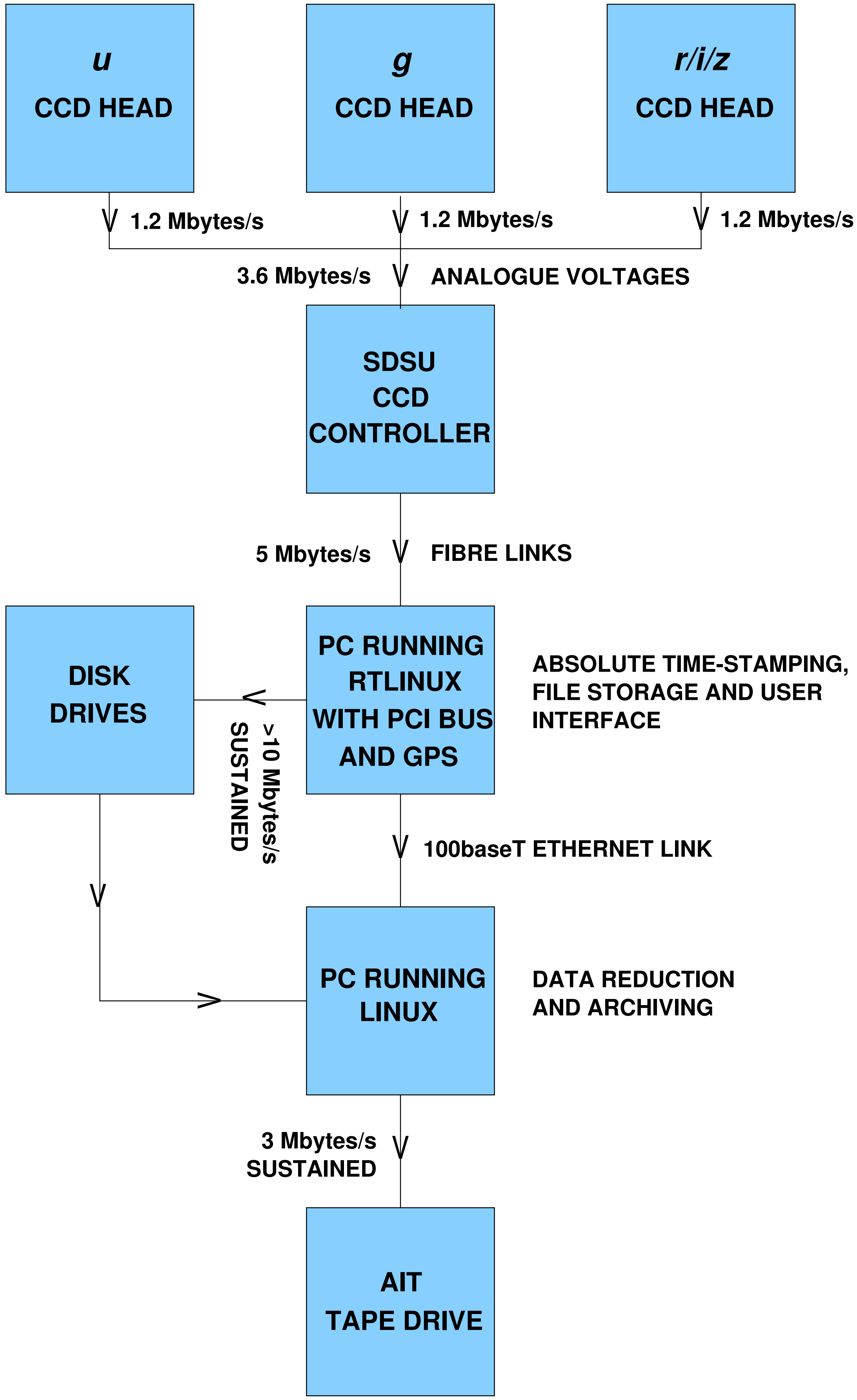
$$\text{Deadtime} = \max(0.005, 0.056 - t_{\text{exp}}) \text{ seconds}$$

Drift-mode:

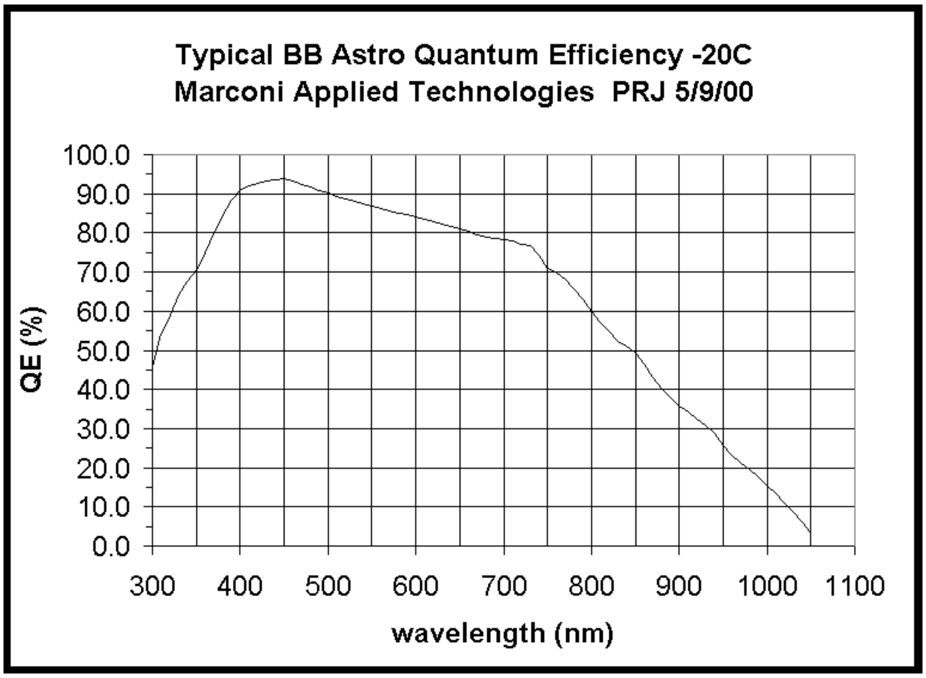
Shift by 100	$100 \times 5 \times 10^{-6} = 0.0005\,\mathrm{s}$
Shift 100×1024 pix	$100 \times 1024 \times 0.7 \times 10^{-6}/2 = 0.036\,\mathrm{s}$
Readout 100^2 pix	$100^2 \times 3 \times 10^{-6}/2 = 0.015\,\mathrm{s}$

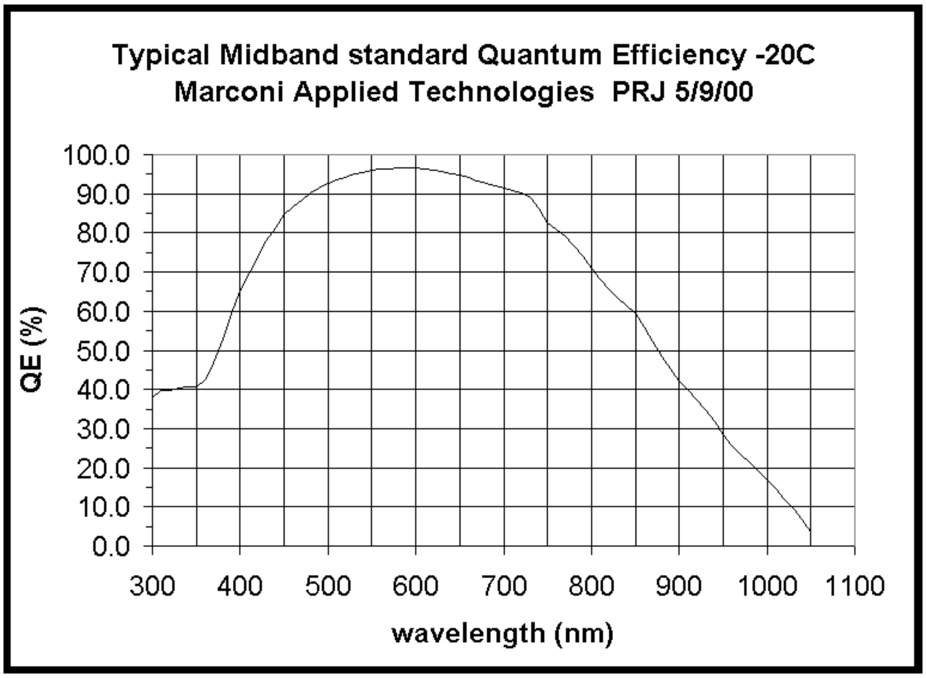
$$\text{Deadtime} = \max(0.0005, 0.056 - t_{\text{exp}}) \text{ seconds}$$

Data Acquisistion System

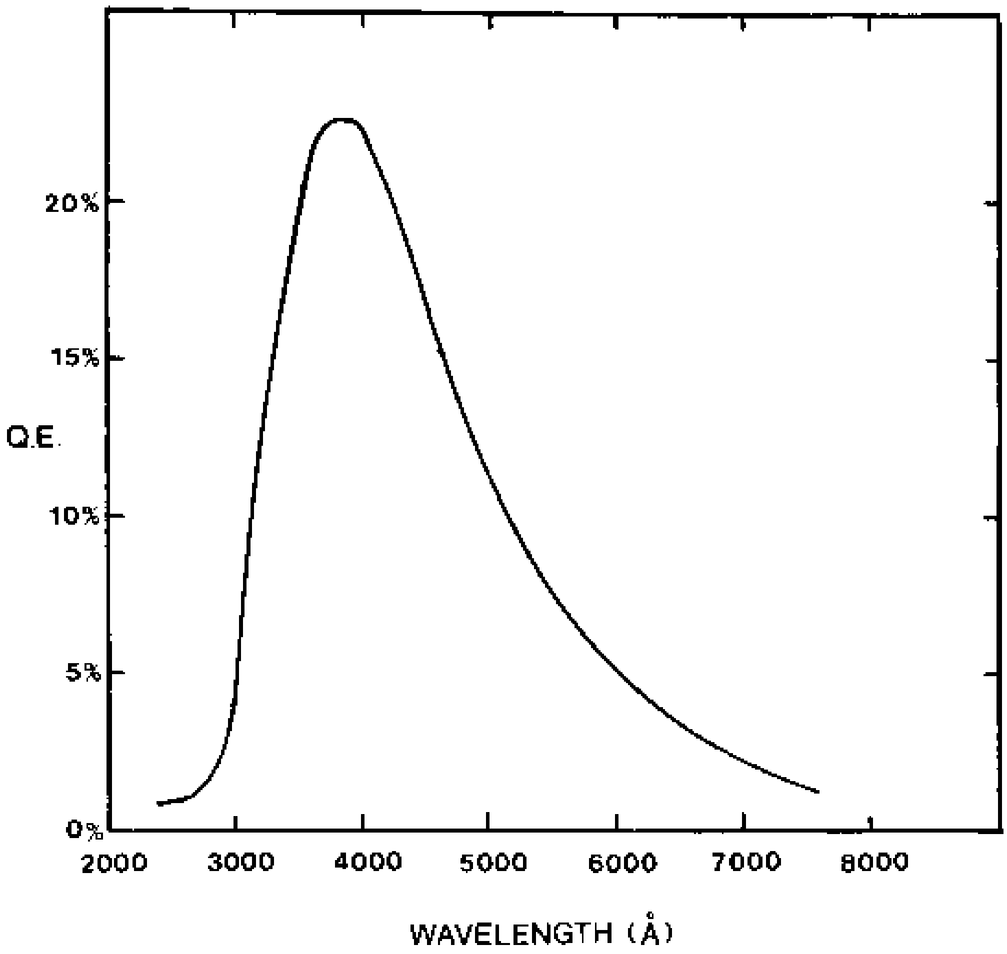


CCD Quantum Efficiencies

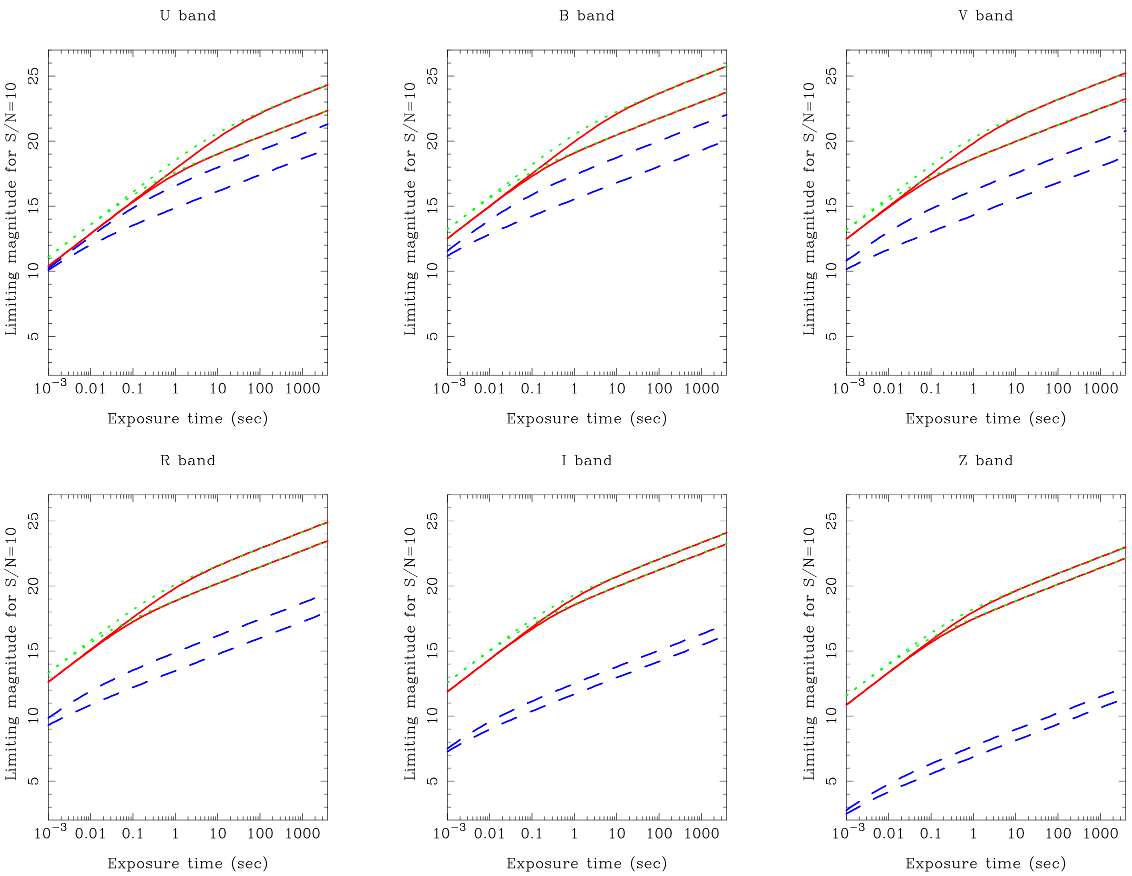




Typical S20 Photocathode Response



ULTRACAM sensitivity

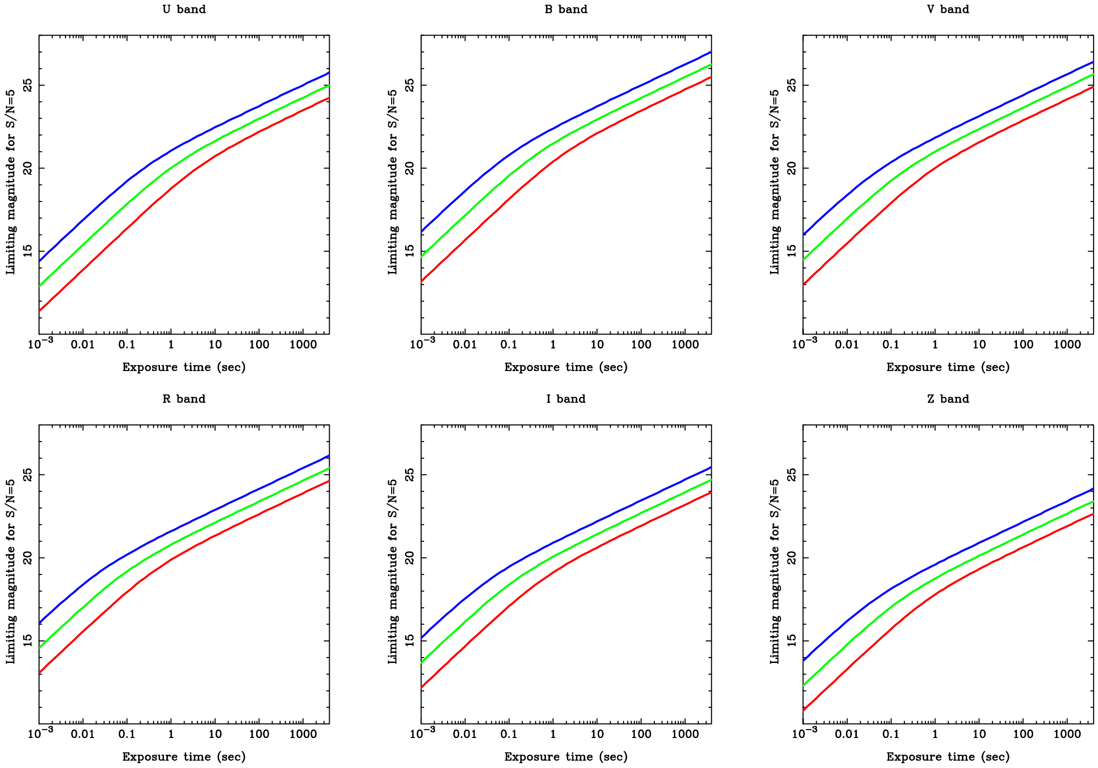


— ULTRACAM (binned)

— ULTRACAM (unbinned)

— Photoelectric photometer

Sensitivity vs telescope aperture



— 8m telescope

— 4m telescope

— 2m telescope

ULTRACAM details

DETECTOR SYSTEM		
3× Marconi 47-20 frame transfer CCDs. Back-thinned non-IMO, AR-coated. 13 μ m pixels.	0.3"/pixel	£48k
Readout noise at slowest readout speed	3 e^- at 10 μs/pixel/channel	
Readout noise at fastest readout speed	6 e^- at 3.3 μs/pixel/channel	
3-stage Peltier cooling	Dark current 0.1 e^-/pixels/sec	
DATA ACQUISITION		
SDSU CCD controller, including VME interface card, 12 slot chassis, 3 clock cards, 3 video cards.	Data rates of up to 2 MByte/sec	£37k
VME hardware	Absolute timing to 1 milli-second	£17.5k
SUN Sparc Ultra-10; 512 Mbytes memory; 109 GBytes hard disk; 144 GBytes DDS3 DAT drive.	Data storage for 1 night at fastest data rates. Reduction rates of at least 1 Mbyte/sec.	£18k
OPTICS		£30k
1× collimating fore-optics		
3× re-imaging optics		
2× dichroics		
UBVRIZ filters		
MECHANICAL COMPONENTS		£1k
Chassis; kinematic mounts for the CCDs; exchangable mounting flange for different foci.		

Summary

Ground-based high-speed photometry has fallen into dis-use with the advent of CCDs and their usually slow readout.

Single CCDs can only observe in one-band and miss vital colour information.

ULTRACAM

- is a 3-channel CCD imager.
- uses frame-transfer CCDs for high-speed.
- uses high QE CCDs for efficiency.
- avoids the fixed apertures that make photometry with photomultipliers difficult at faint magnitudes and in crowded fields.
- is due for comissioning from Autumn/Winter 2001.