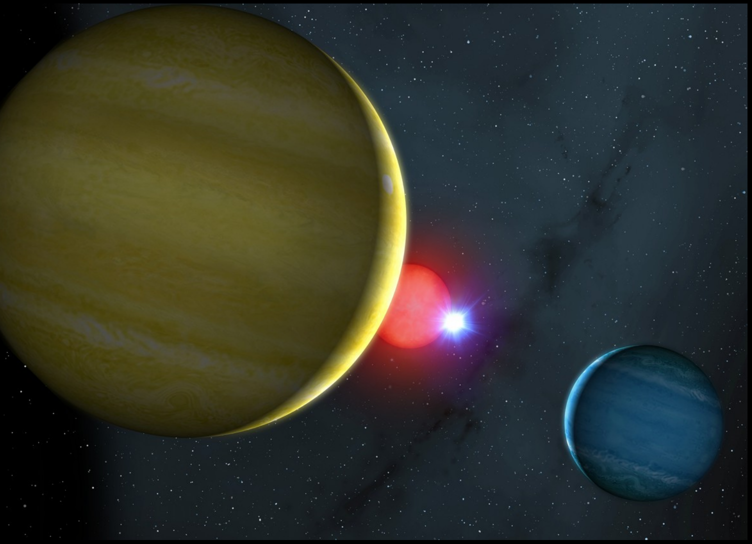

HIGH TIME-RESOLUTION ASTROPHYSICS

OPTICAL INSTRUMENTATION

Vik Dhillon (Sheffield/IAC)

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- The detection of light - an introduction to CCDs
- Instrumentation for high-speed photometry I: ULTRACAM
- ULTRACAM: science highlights

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- High-speed spectroscopy
- An introduction to EMCCDs
- Instrumentation for high-speed spectroscopy: ULTRASPEC on the NTT
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Lecture 4: Data Reduction

- Demonstration of photometric data reduction using the ULTRACAM pipeline

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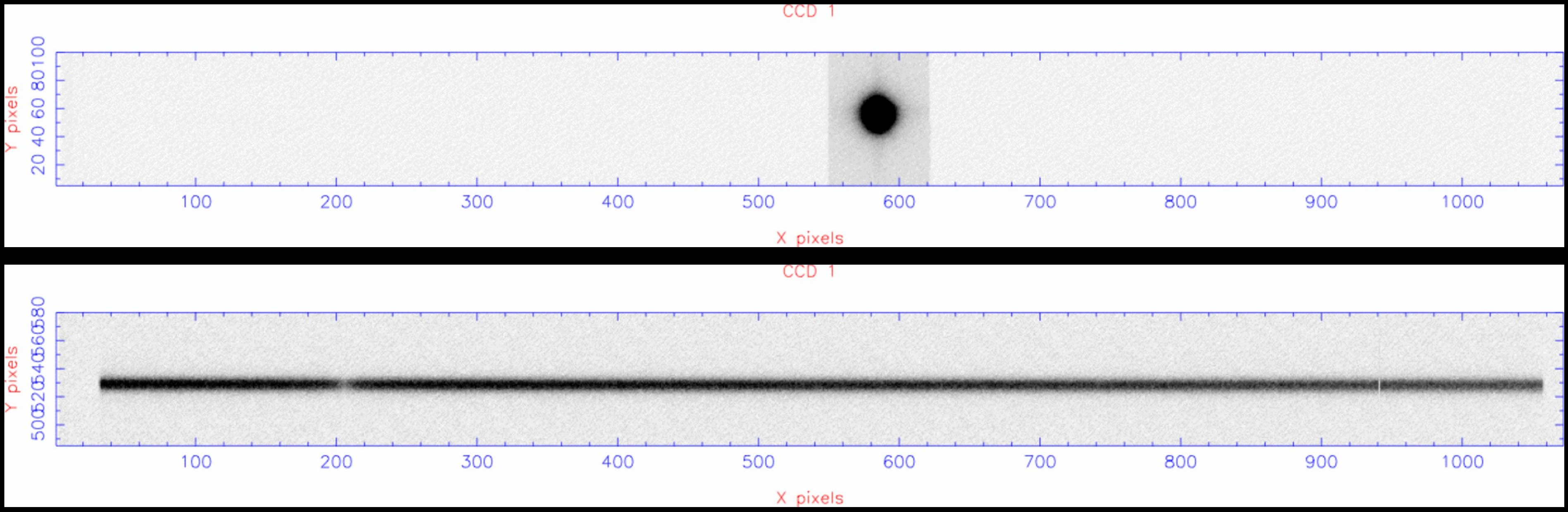
HIGH-SPEED SPECTROSCOPY

- High-speed spectroscopy is an unexplored region of observational parameter space, with many promising applications - see review by Marsh (2007, astro-ph/0706.4246) and talk by Danny Steeghs.
- So we built ULTRASPEC, essentially a spectroscopic version of ULTRACAM.

HIGH-SPEED SPECTROSCOPY

- The reduction of detector noise is much more important in spectroscopy than it is in imaging as the light is spread across the entire length of the detector.
- ULTRASPEC uses a relatively new type of detector - the electron-multiplying CCD (EMCCD).



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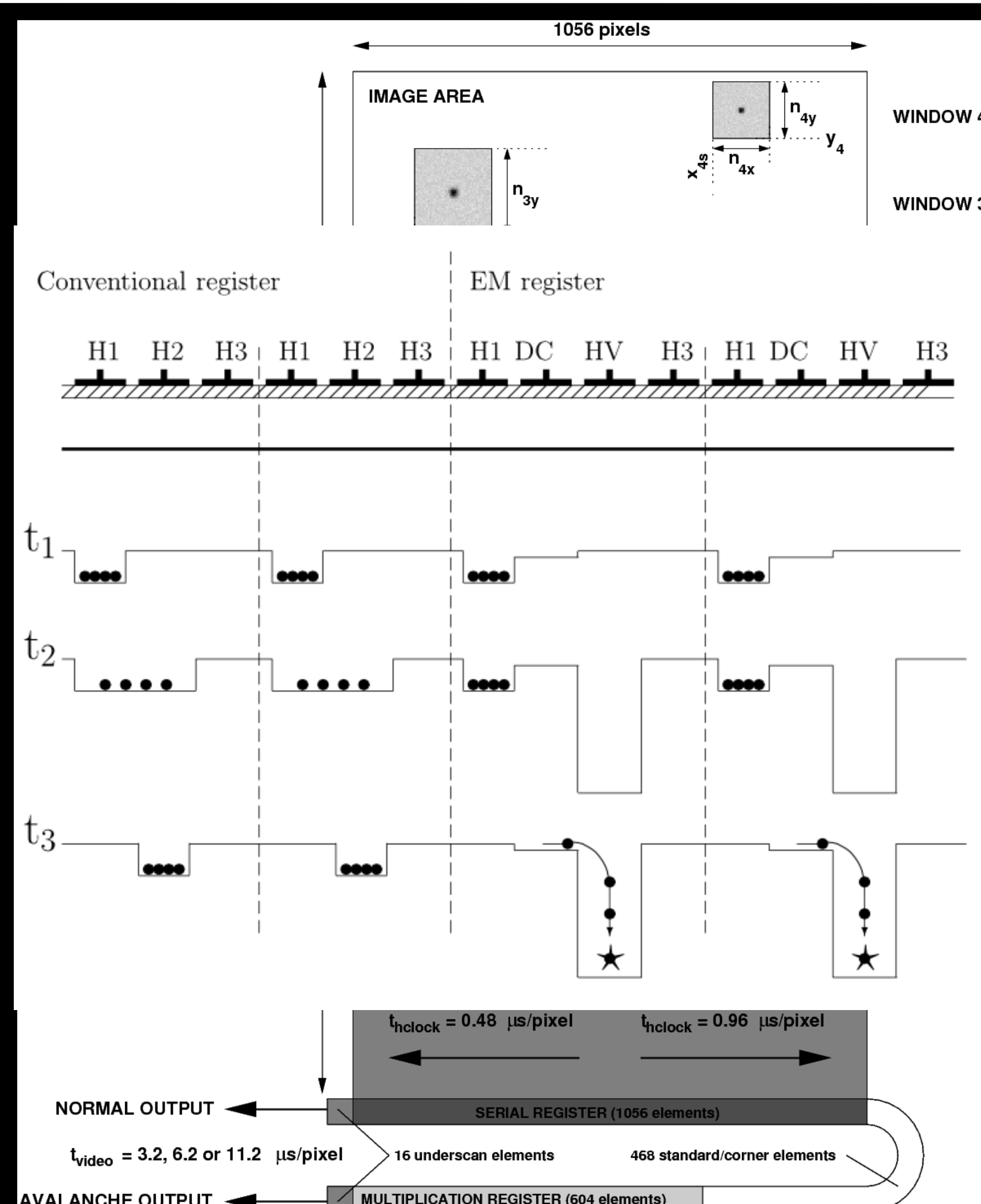
EMCCD STRUCTURE

- Conventional frame-transfer CCD, but with an extended serial register (known as the *electron-multiplication* or *EM register*) .
- Higher voltages are used to transfer the photoelectrons in the EM register, resulting in their multiplication via impact ionisation.
- A single photoelectron entering the EM register will typically be amplified by a factor of 1000, rendering insignificant a readout noise of a few electrons, i.e:
  - with a conventional CCD, one photon results in one photoelectron, which at the CCD output is measured as $1 \pm 3e^-$.
  - with an EMCCD, one photon results in $1000 \pm 3e^-$ at the output.



EMCCD Demo.

EMCCD PROBLEMS I

- A single photoelectron entering the EM register gives rise to a wide range of output signals. This statistical spread constitutes an additional noise source termed *multiplication noise*.
- Multiplication noise doubles the variance of the signal, which is statistically equivalent to halving the QE of the camera.
- One solution is to *photon count*, where a threshold is set to distinguish between 0 and 1 incident photons, although one then needs to ensure sufficiently low light levels that there is an insignificant probability of more than one photon hitting each pixel in an exposure.

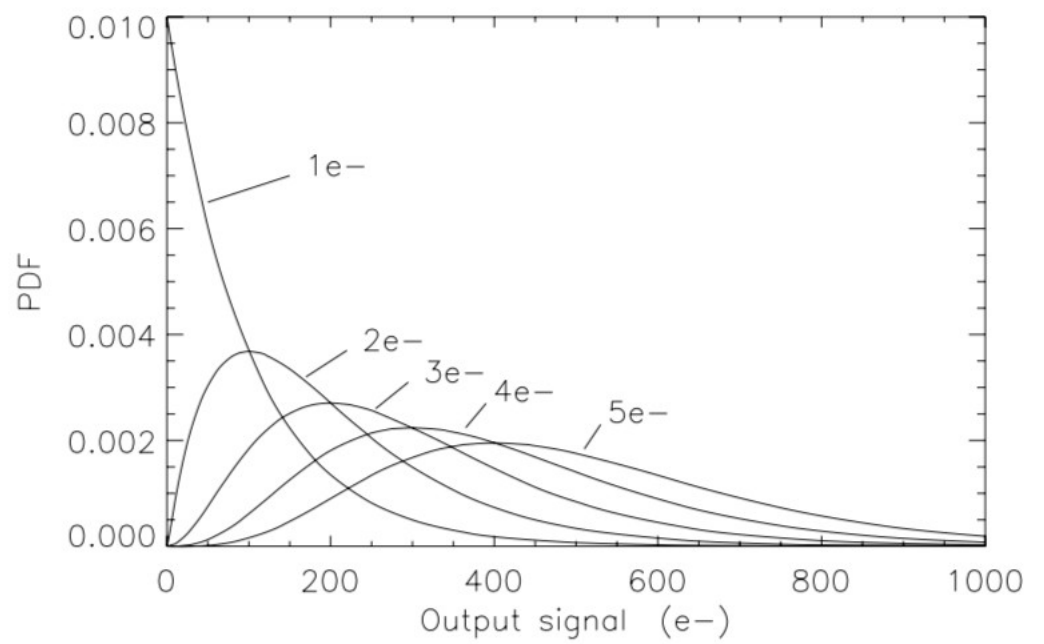
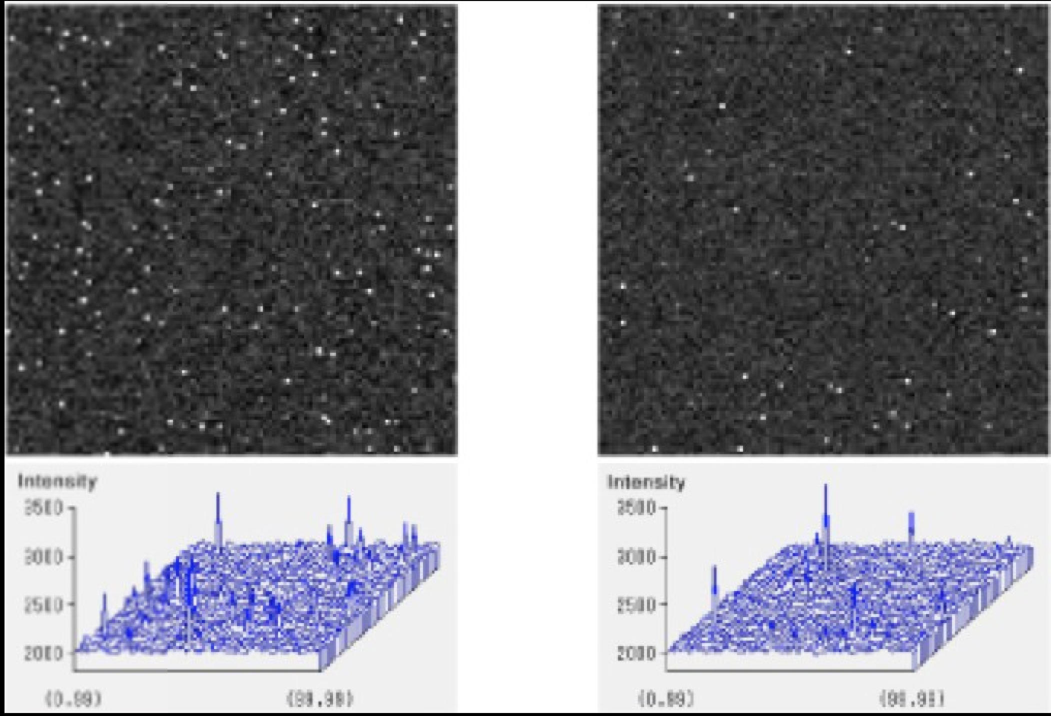


Figure 3. Output of an EM register with $g_A = 100$ in response to a range of inputs from 1 to 5 e^-. The *y*-axis shows the probability density function (PDF) of the output signal, i.e. the fraction of pixels lying within a histogram bin.

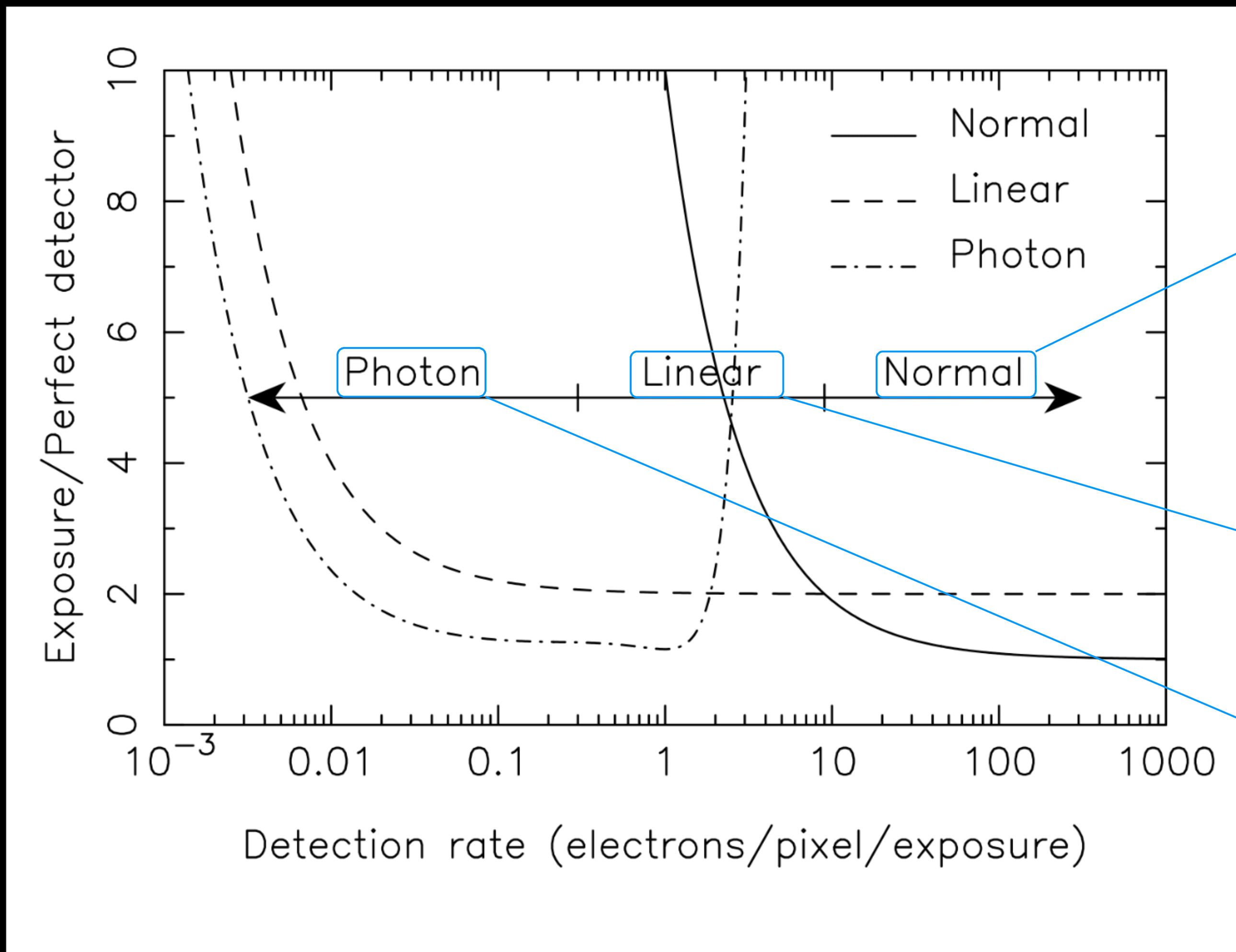
EMCCD PROBLEMS II

- The electron multiplication doesn’t just amplify photoelectrons. It also amplifies dark current and clock-induced charge (CIC). These are indistinguishable from photoelectrons and hence are an additional noise source.
- Dark current can be virtually eliminated by deep cooling (to ~170K).
- CIC can be minimised through careful controller design, although it always remains the limiting noise source in EMCCDs.



THEORETICAL CONSIDERATIONS 1

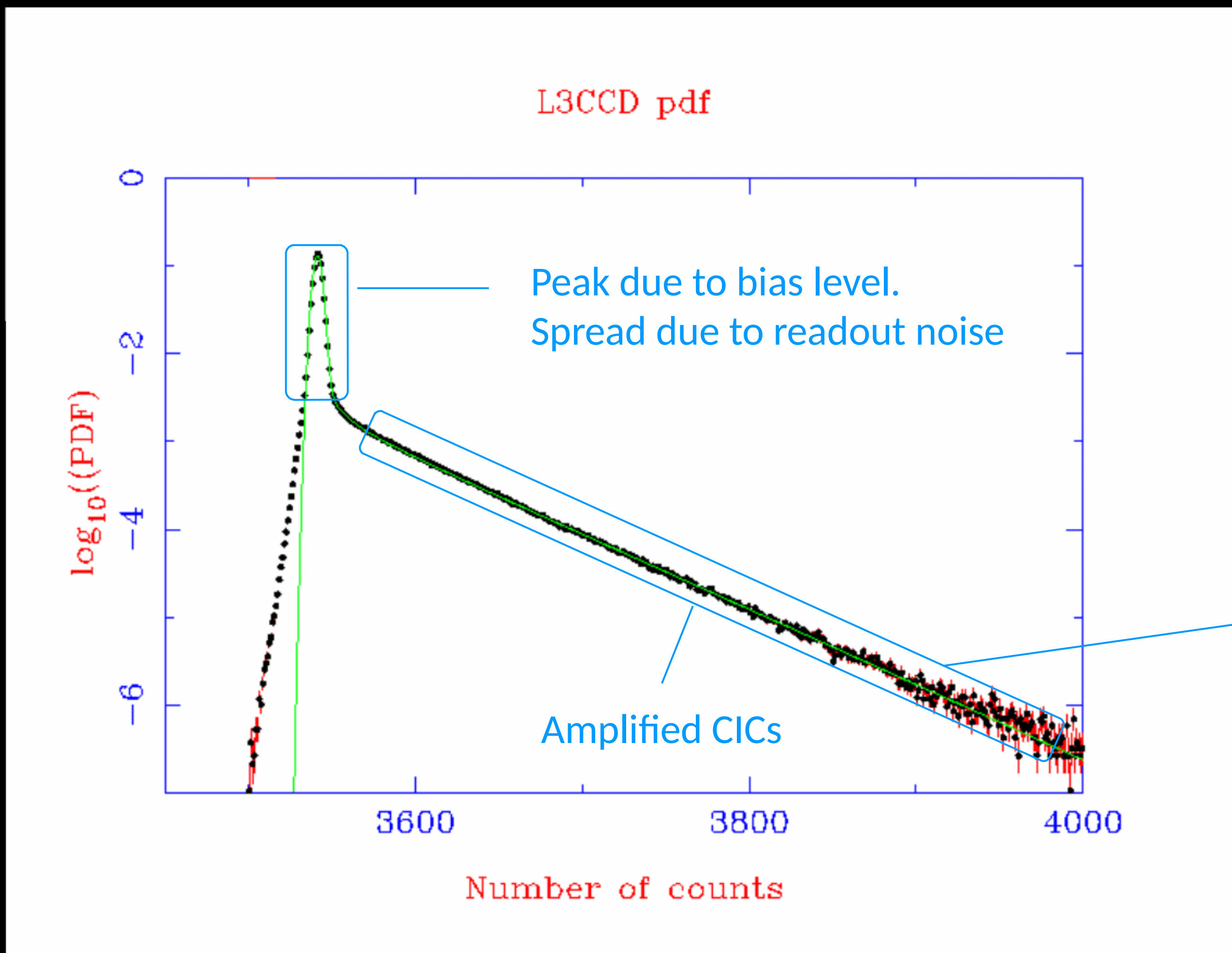
- Exposure time to reach a given SNR compared to a “perfect” detector of identical QE. (CIC = 0.01 e$^-$/pix/exposure)



SNR = signal-to-noise ratio
N = no. of photo-e$^-$/pixel
σ = readout noise in e$^-$/pix
CIC = no. of clock-induced charges in e$^-$/pixel

THEORETICAL CONSIDERATIONS 2

- Histogram of counts in a bias frame with EM gain:

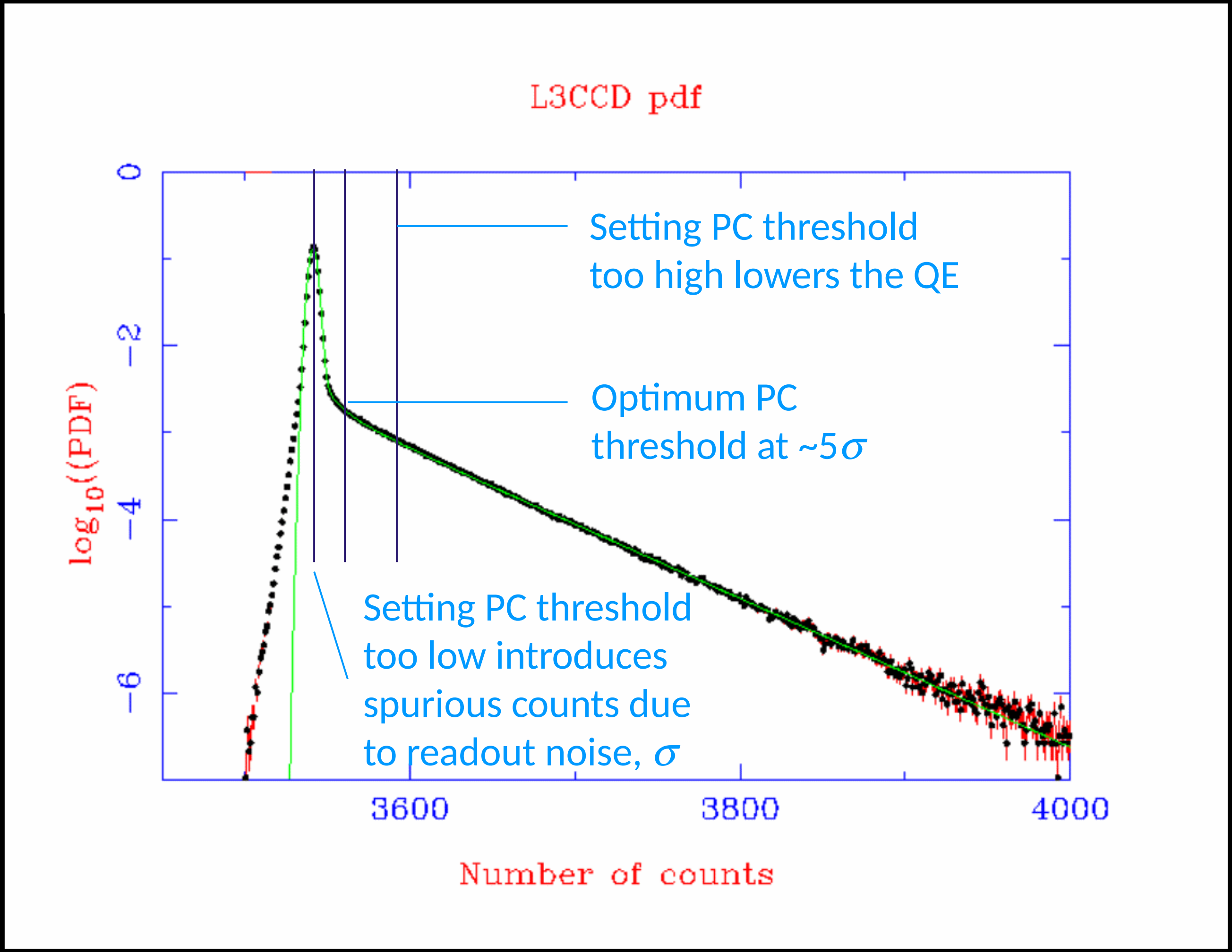


Slope gives the gain

$p_1(x)$ = probability of an output x for a single electron input, with mean gain g

THEORETICAL CONSIDERATIONS 3

- Histogram of counts in a science frame with EM gain:



QE_{old} = quantum efficiency before thresholding

QE_{new} = quantum efficiency after thresholding

T = photon counting (PC) threshold

g = avalanche gain

FURTHER INFORMATION ON EMCCDs

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **411,** 211–225 (2011) doi:10.1111/j.1365-2966.2010.17675.x

On the use of electron-multiplying CCDs for astronomical spectroscopy

S. M. Tulloch★ and V. S. Dhillon★

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Accepted 2010 September 8. Received 2010 August 30; in original form 2010 July 27

ABSTRACT

Conventional CCD detectors have two major disadvantages: they are slow to read out and they suffer from read noise. These problems combine to make high-speed spectroscopy of faint targets the most demanding of astronomical observations. It is possible to overcome these weaknesses by using electron-multiplying CCDs (EMCCDs). EMCCDs are conventional frame-transfer CCDs, but with an extended serial register containing high-voltage electrodes. An avalanche of secondary electrons is produced as the photon-generated electrons are clocked through this register, resulting in signal amplification that renders the read noise negligible. Using a combination of laboratory measurements with the QUCAM2 EMCCD camera and Monte Carlo modelling, we show that it is possible to significantly increase the signal-to-noise ratio of an observation by using an EMCCD, but only if it is optimized and utilized correctly. We also show that even greater gains are possible through the use of photon counting. We present a recipe for astronomers to follow when setting up a typical EMCCD observation which ensures that maximum signal-to-noise ratio is obtained. We also discuss the benefits that EMCCDs would bring if used with the next generation of extremely large telescopes. Although we mainly consider the spectroscopic use of EMCCDs, our conclusions are equally applicable to imaging.

Key words: instrumentation: detectors – methods: data analysis – techniques: spectroscopic.

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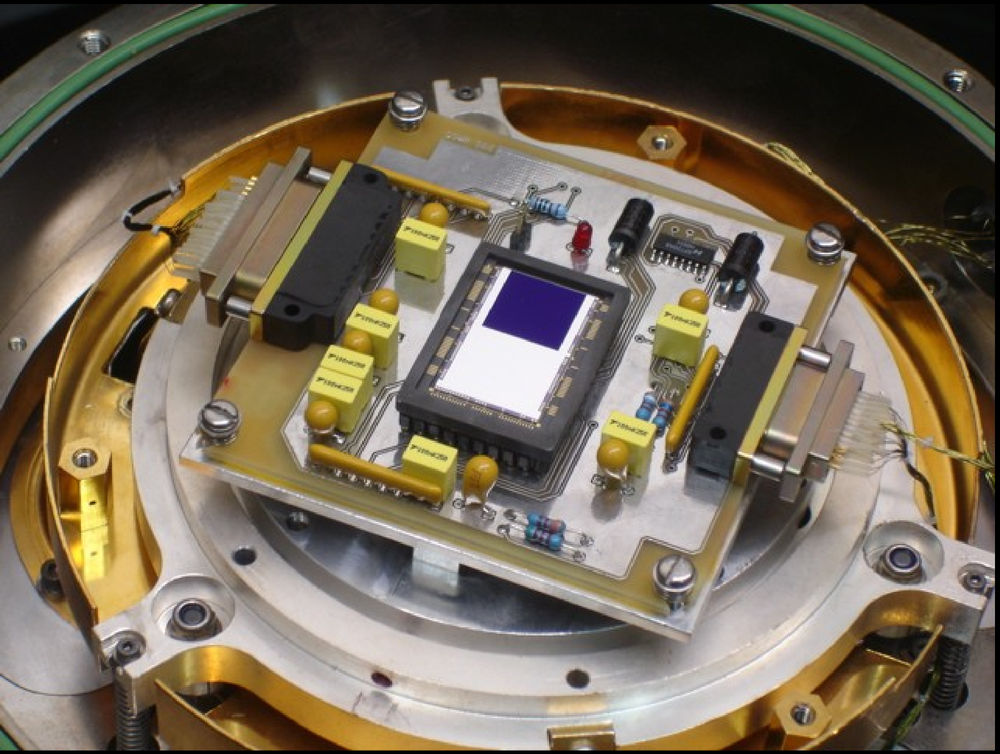
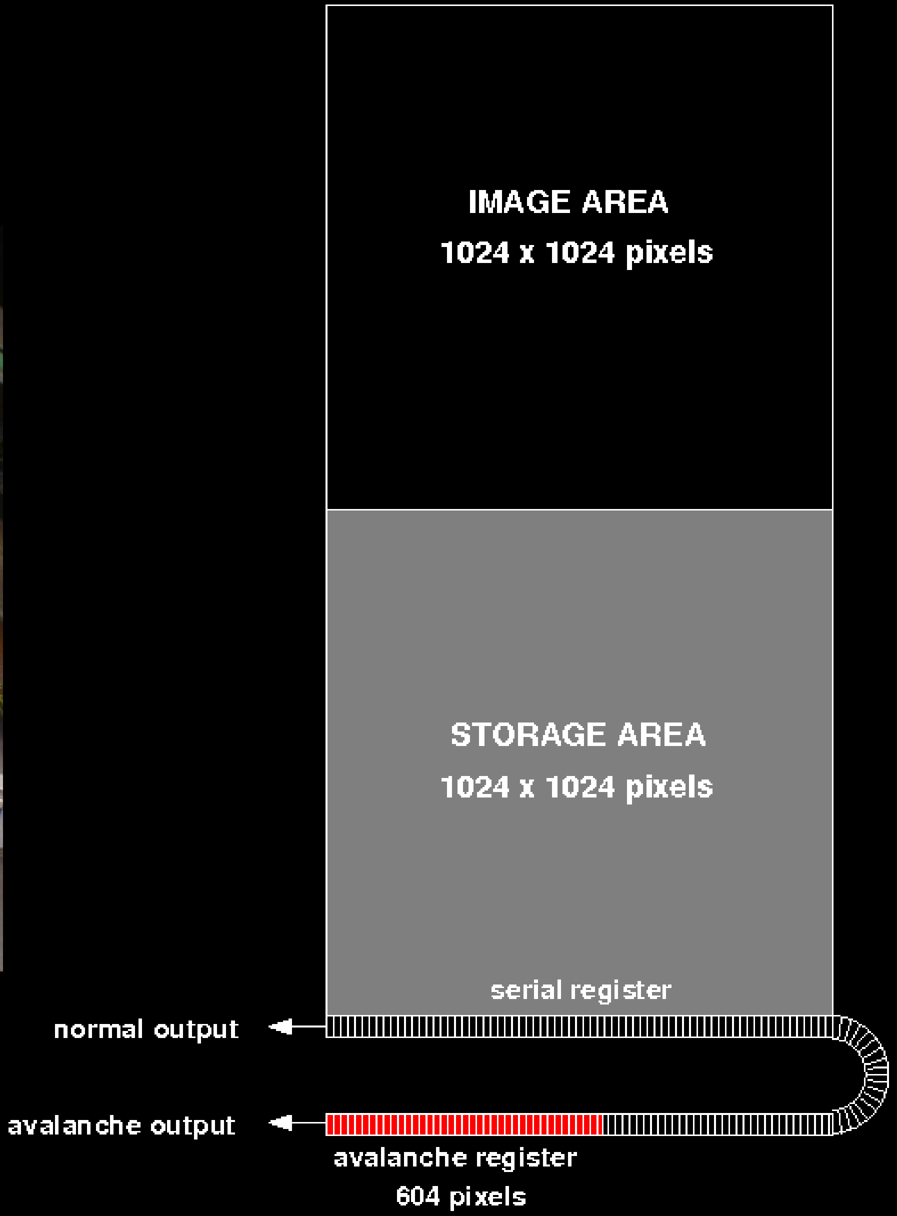
ULTRASPEC

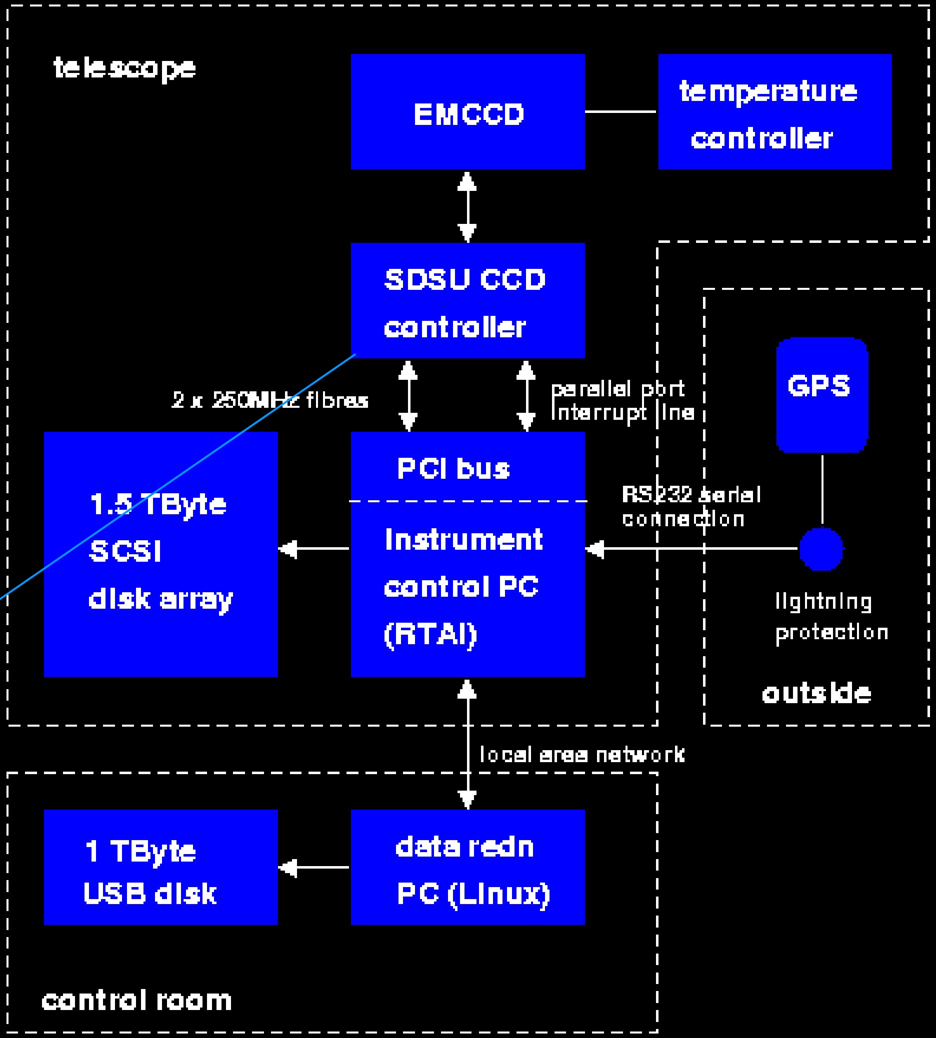
- We replaced the front end of ULTRACAM with a new front end consisting of an EMCCD in a cryostat.
- Downstream of this, ULTRACAM and ULTRASPEC are almost identical. Hence ULTRASPEC is simply a one-arm ULTRACAM with zero readout noise.
- Like ULTRACAM, ULTRASPEC was built by a consortium from the Universities of Sheffield, Warwick and the UK Astronomy Technology Centre, Edinburgh.
- No point building a spectrograph – we used EFOSC2 on the ESO3.6m and 3.5m NTT for 43 nights.

ULTRASPEC EMCCD



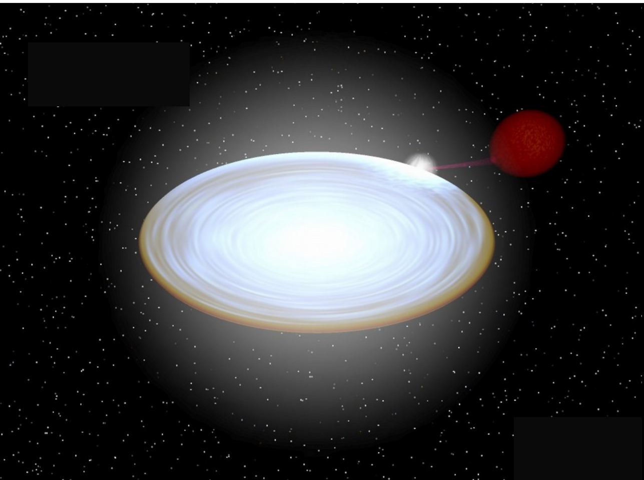


ULTRASPEC DATA ACQUISITION SYSTEM



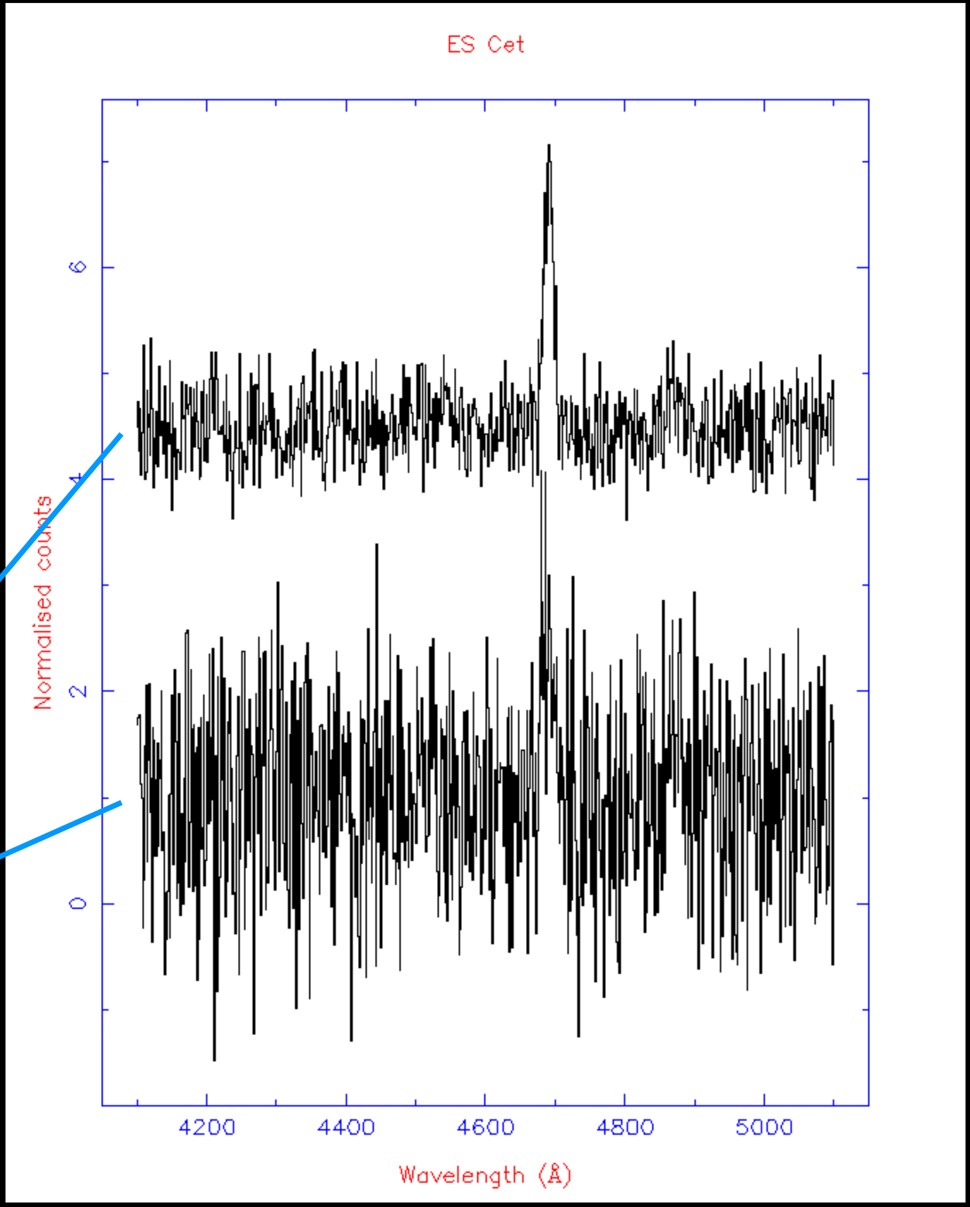
ULTRASPEC Demo.

ULTRASPEC PERFORMANCE



10-second spectrum of the AM CVn star ES Cet using ULTRASPEC on a 3.5m telescope. Increase in signal-to-noise ratio of ~3, equivalent to approximate doubling of the diameter of the telescope!

10-second spectrum taken using a conventional CCD on a 3.5m telescope.



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Tulloch & Dhillon 2011, MNRAS, 411, 211

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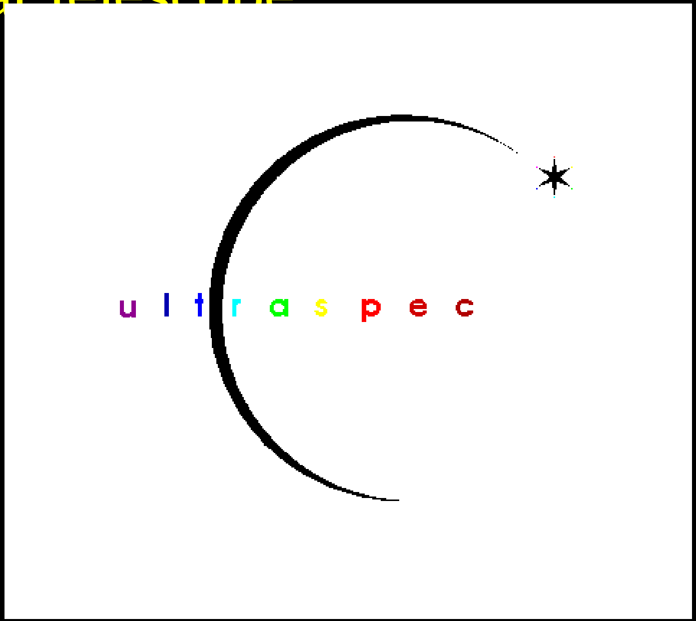
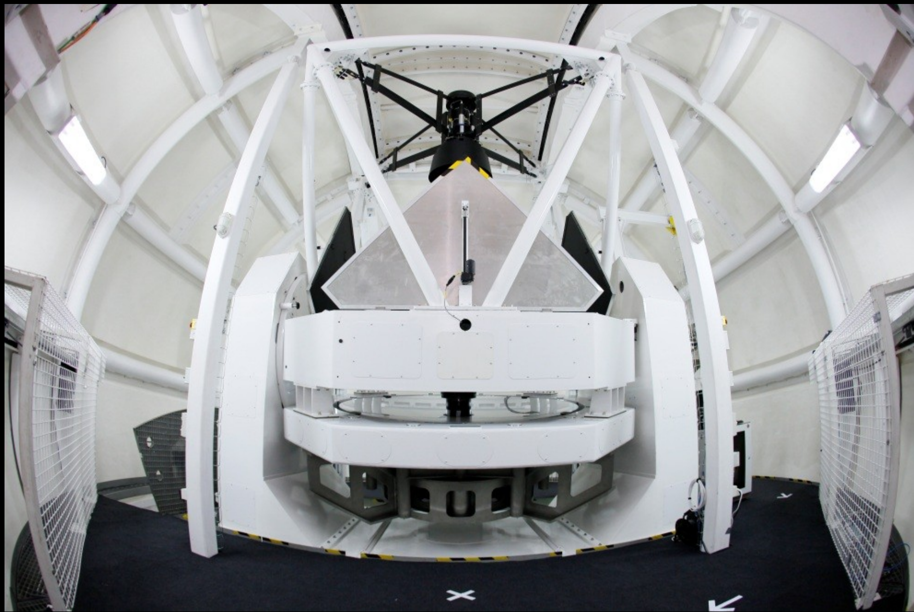
THE CONFUSING HISTORY OF ULTRASPEC

- 2007: ULTRASPEC mounted on the EFOSC2 spectrograph on the ESO 3.6m telescope in Chile for 21 nights.
- 2009: ULTRASPEC mounted on the EFOSC2 spectrograph on the 3.5m NTT in Chile for 22 nights.
- 2013: ULTRASPEC mounted on a custom-made re-imager on the 2.4m Thai National Telescope.



THAI NATIONAL TELESCOPE

- ULTRASPEC now permanently mounted on TNT in exchange for 25 nights per year.
- 2.4m *f*/10 Ritchey-Chretien on Doi Inthanon (2,457m).
- High quality telescope, with 4-port Nasmyth focus.
- Dark (*B*=22.5) site in a national park with excellent seeing (0.85” median).
- Use in ~7-month dry season (Oct-Apr).



OPTICAL DESIGN

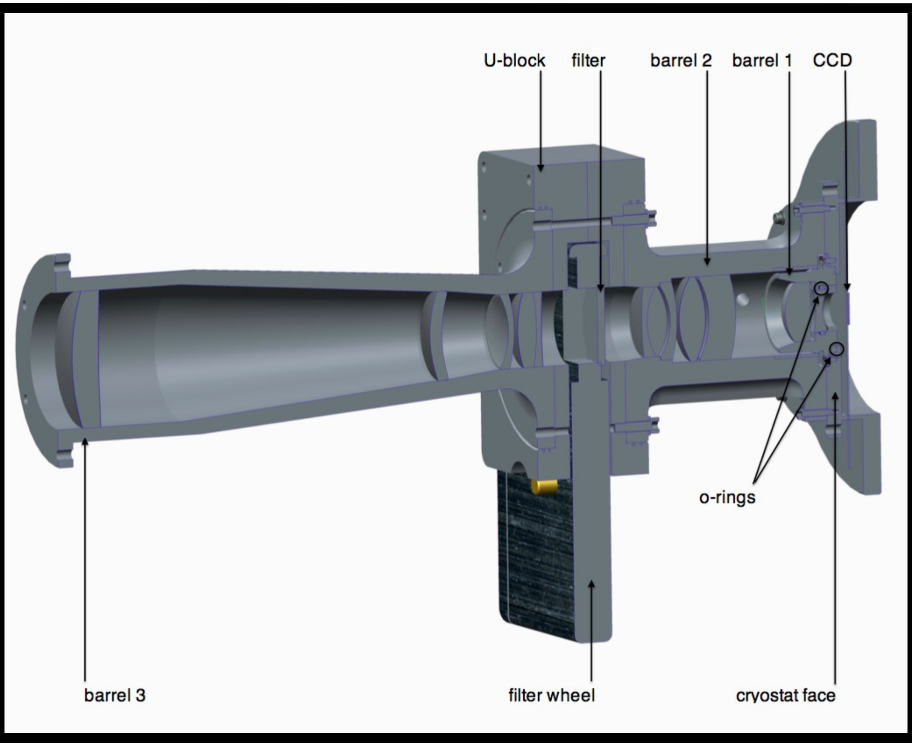
- The median seeing at the TNT is ~0.9”. To critically sample this seeing requires a platescale of 0.45”/pixel.
- With ULTRASPEC’s 1024x1024 pixel EMCCD, this would result in a field of view of 7.7’x7.7’, giving an 80% probability of finding a comparison star of R = 11 mag.
- TNT is 2.4m *f*/10, so focal length is 24m, and plate scale is 206265/24000 = 8.6”/mm.
- Placing the bare ULTRASPEC EMCCD (with 13μm pixels) at the Nasmyth focus of the TNT would therefore have given us a platescale of 0.11”/pixel.
- Hence we designed a 4x focal reducer for ULTRASPEC to provide the required platescale of 0.45”/pixel, which can work across the desired wavelength range of 330-1000 nm.

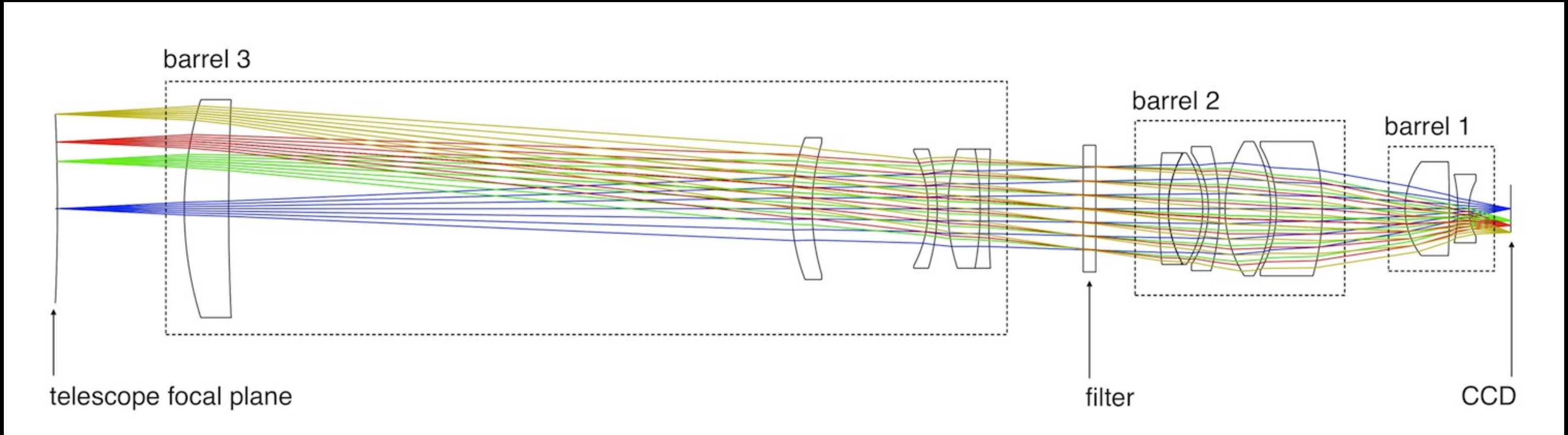
ULTRASPEC ON THE TNT

- Mounted on the Nasmyth “cube”.
- Re-imager (not spectroscopy!), giving 8’x8’ FoV and 0.45”/pixel platescale.
- 6-position filter wheel with 14 broad- and narrow-band filters to choose from.
- New data acquisition system, giving up to 200 Hz frame rates.
- New opto-mechanical chassis.
- First light in Nov 2013, with two successful observing seasons now complete.
- Science: compact objects, transients, e.g. optical follow-up of Fast Radio Bursts.

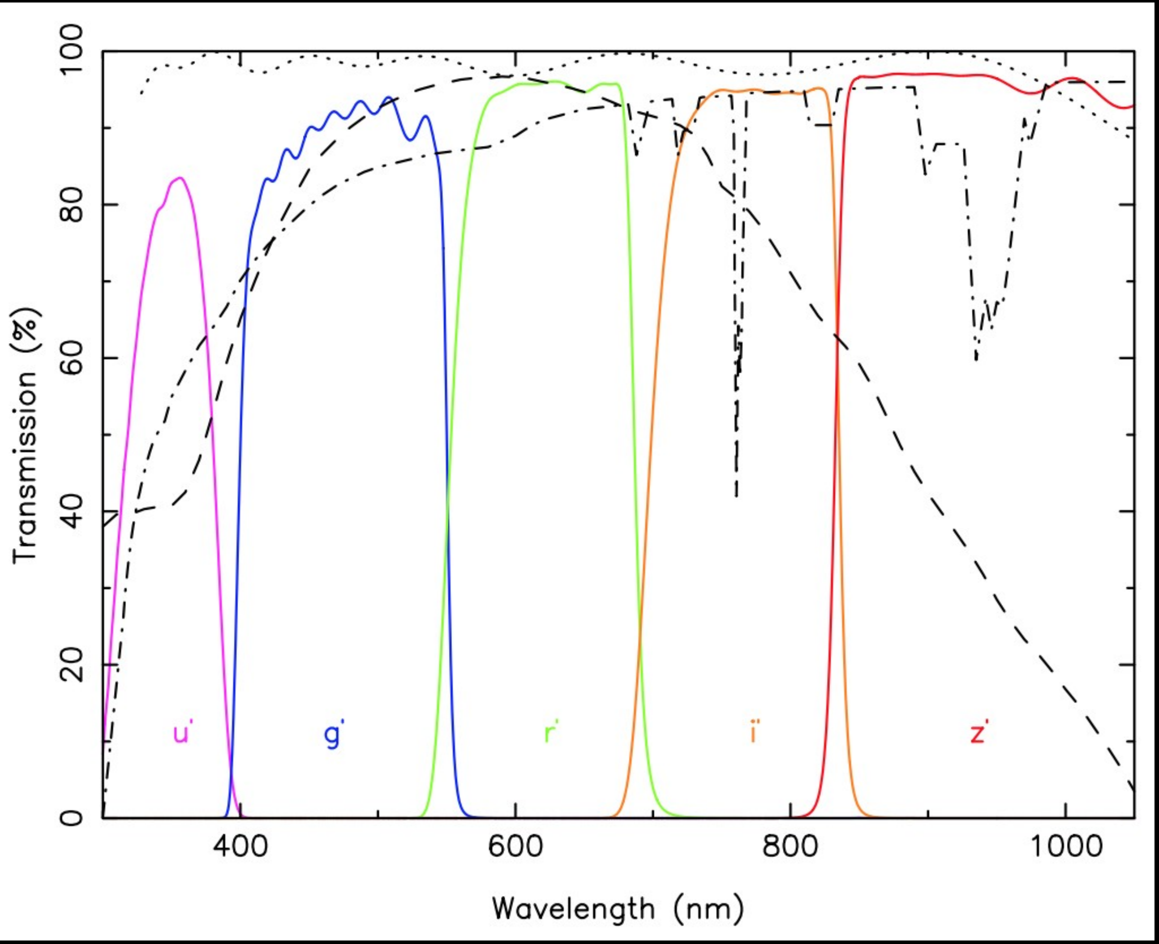
OPTICS

4x focal reducer





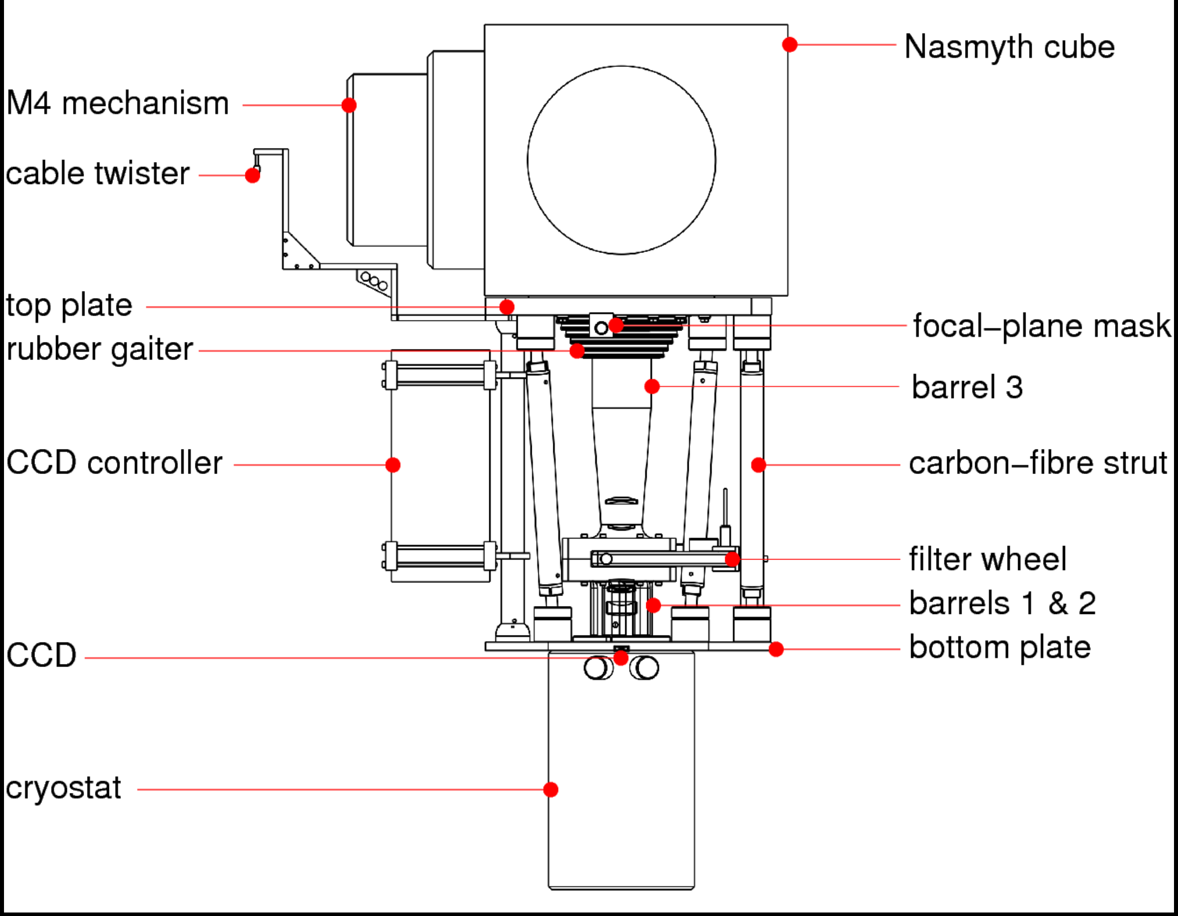
FILTERS

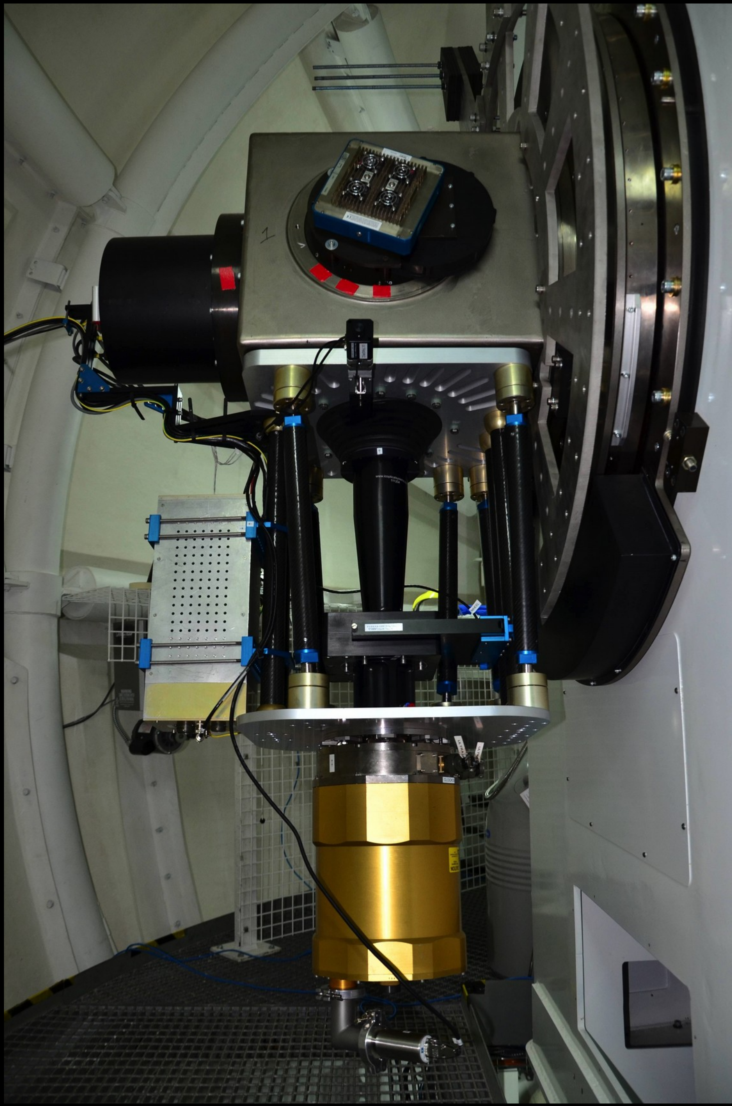


Filter	λ_c (nm)	$\Delta\lambda$ (nm)
u'	355.7	59.9
g'	482.5	137.9
r'	626.1	138.2
i'	767.2	153.5
z'	909.7	137.0
Clear	–	–
Schott KG5	507.5	360.5
$i' + z'$	838.5	290.5
CIII/NIII+HeII	465.7	11.2
Blue continuum	514.9	15.8
NaI	591.1	31.2
Red continuum	601.0	11.8
Hα wide	655.4	9.4
Hα narrow	656.4	5.4

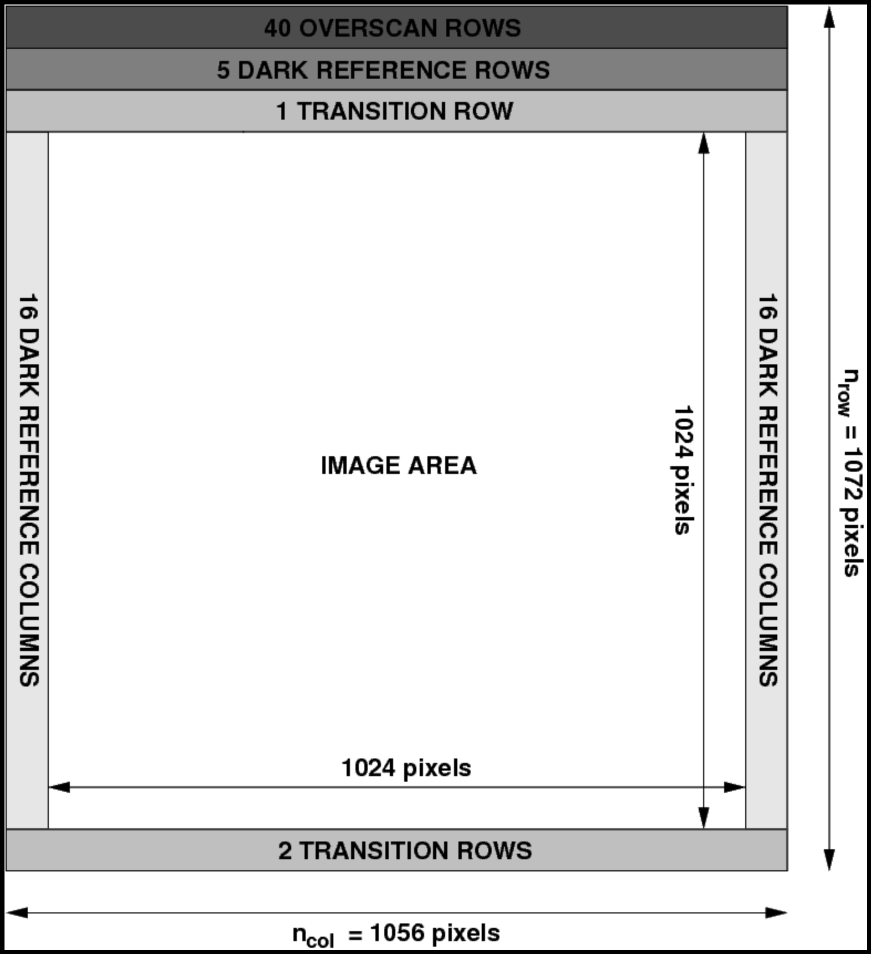
All filters (except KG5) have the same optical thickness, so refocussing is not required.

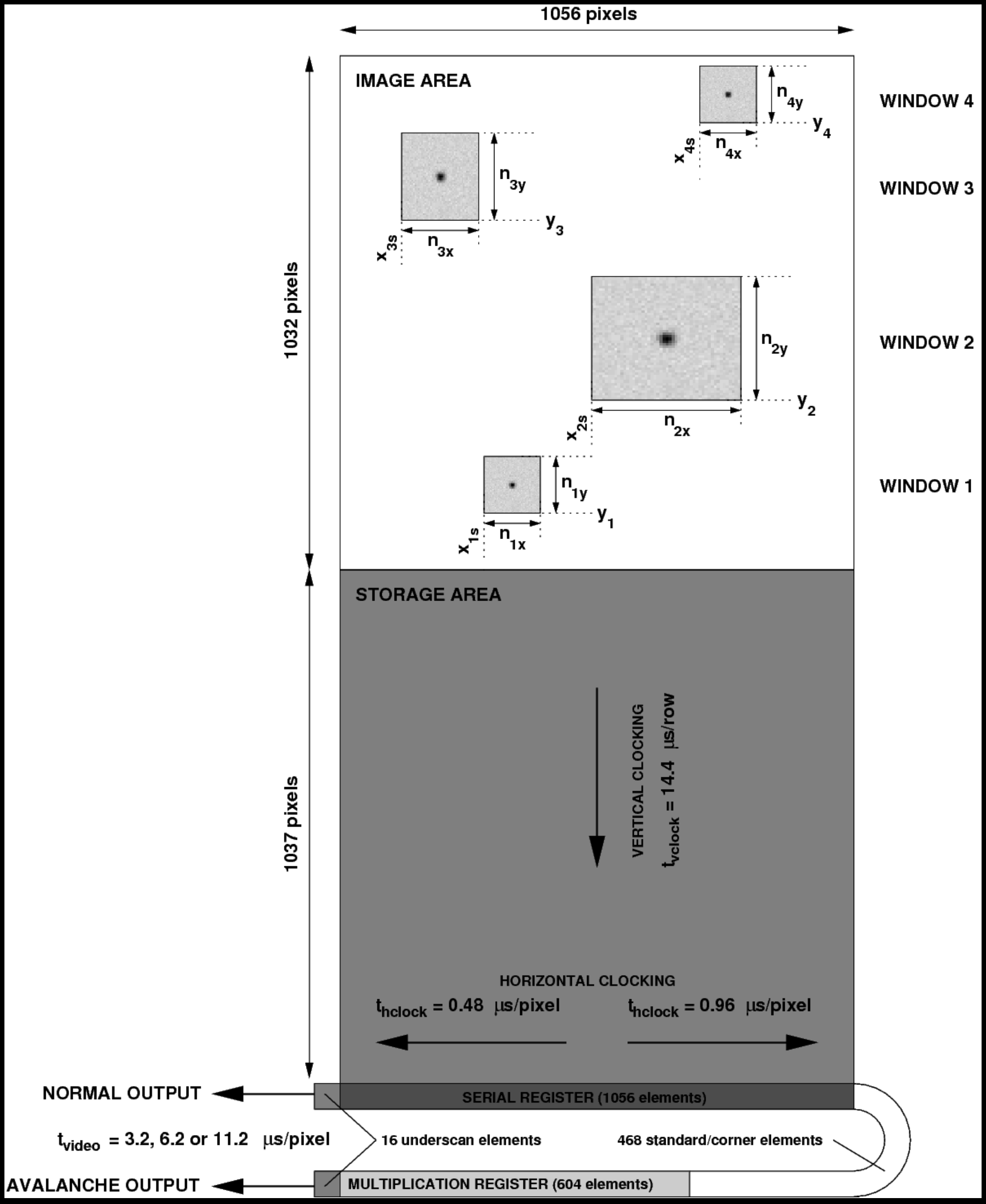
MECHANICAL DESIGN





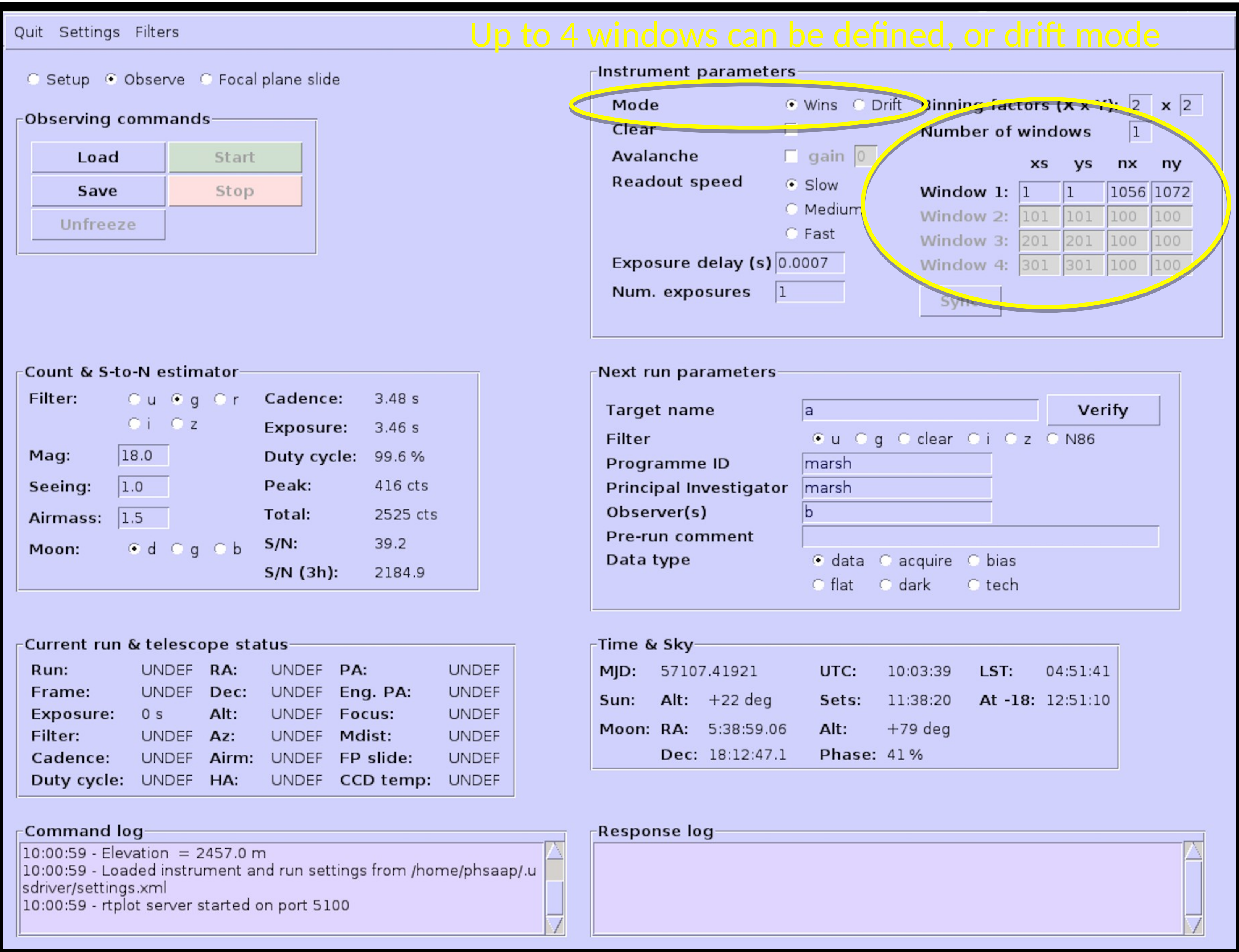
THE ULTRASPEC EMCCD DETECTOR





e2v CCD201-20, EMCCD, thinned, back-illuminated, AR-coated, 13 micron pixels, operated at 160K.

OBSERVING WITH ULTRASPEC



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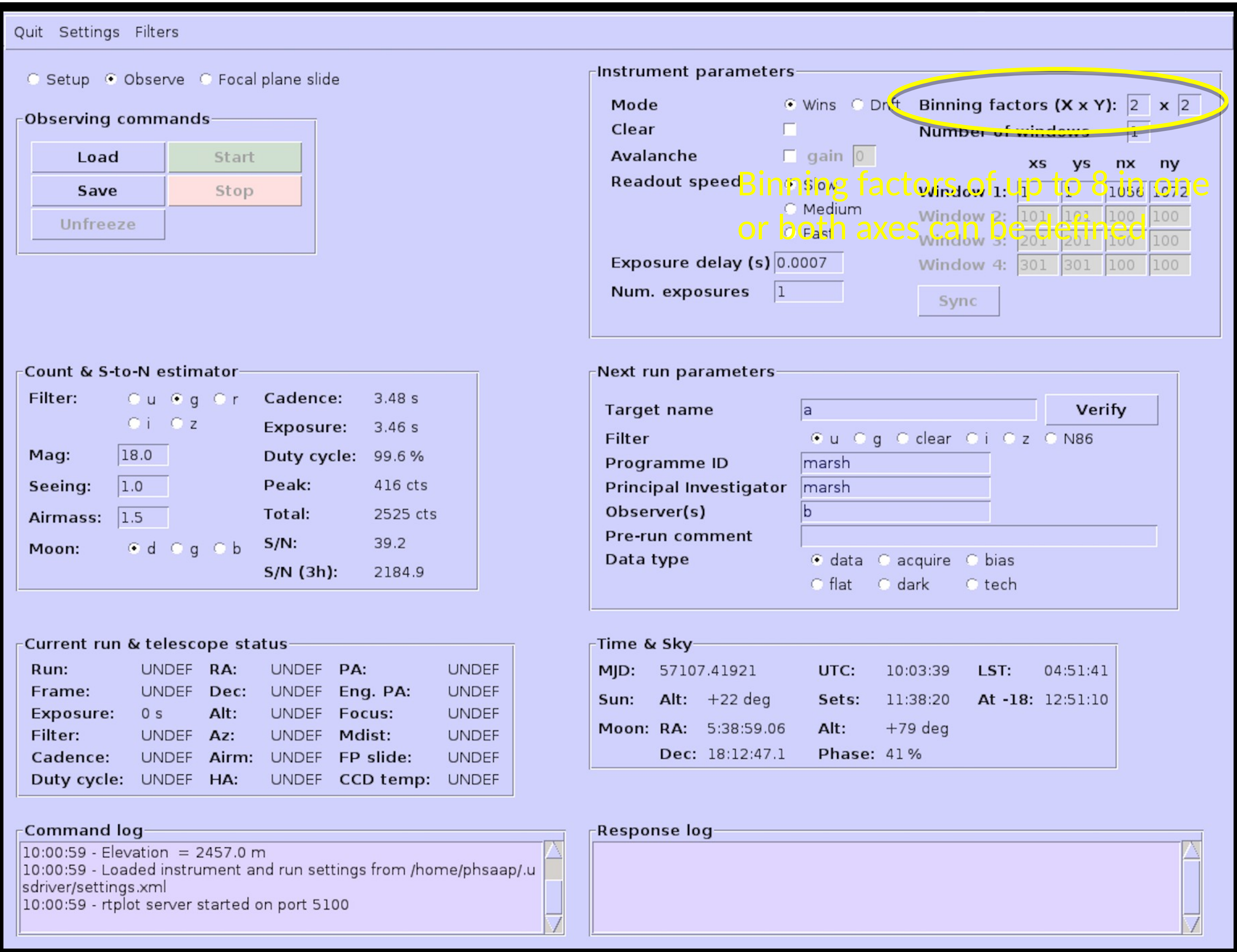

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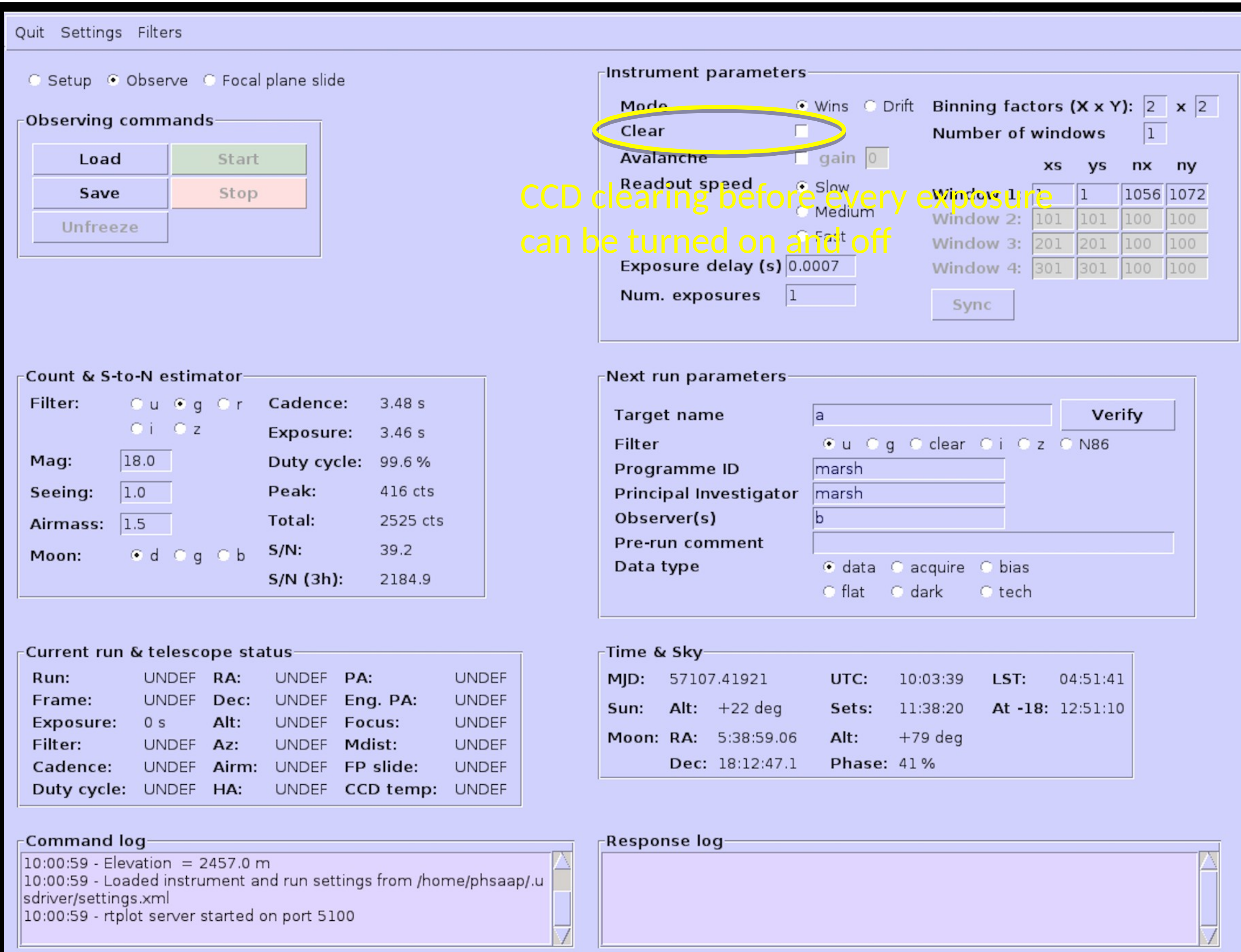

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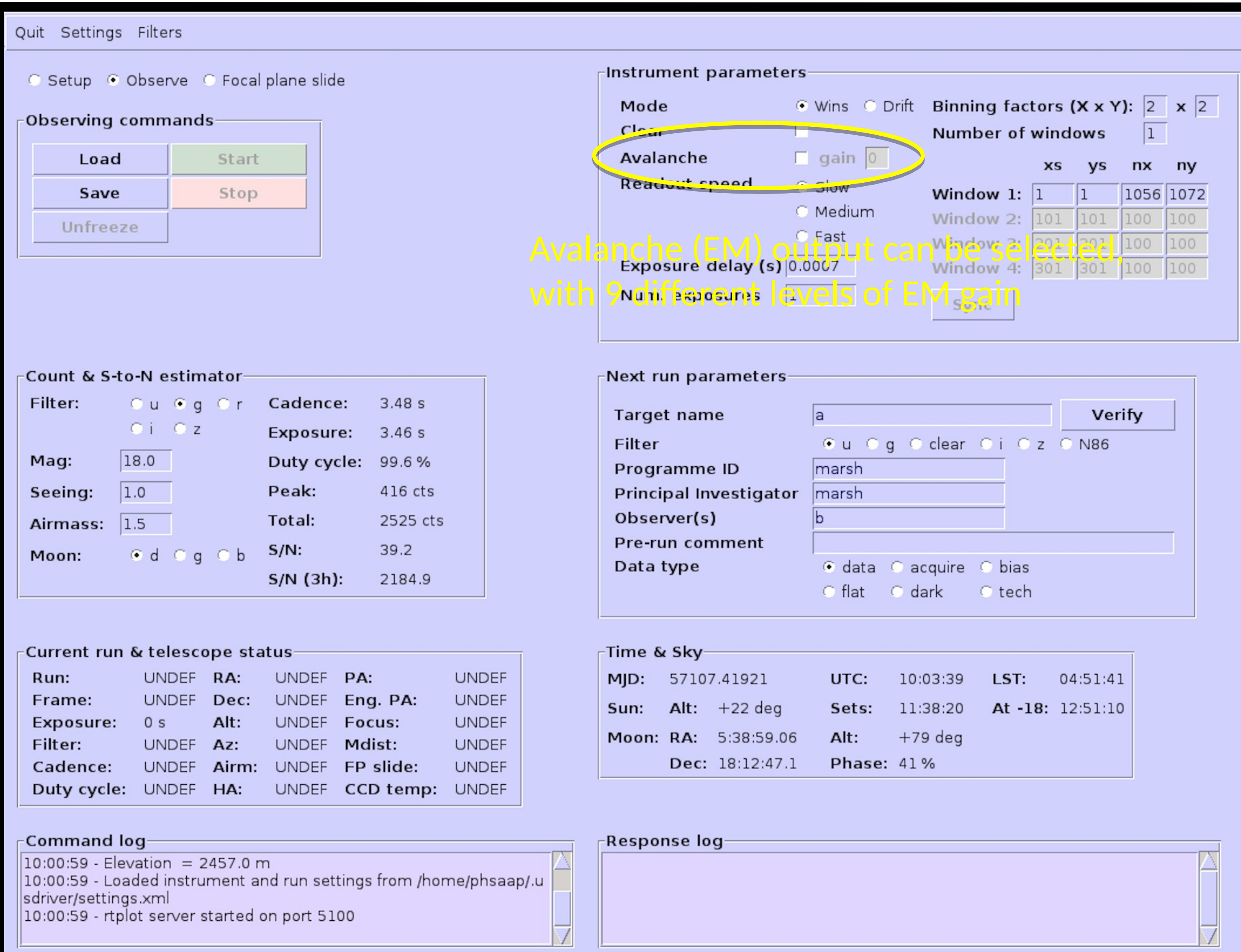
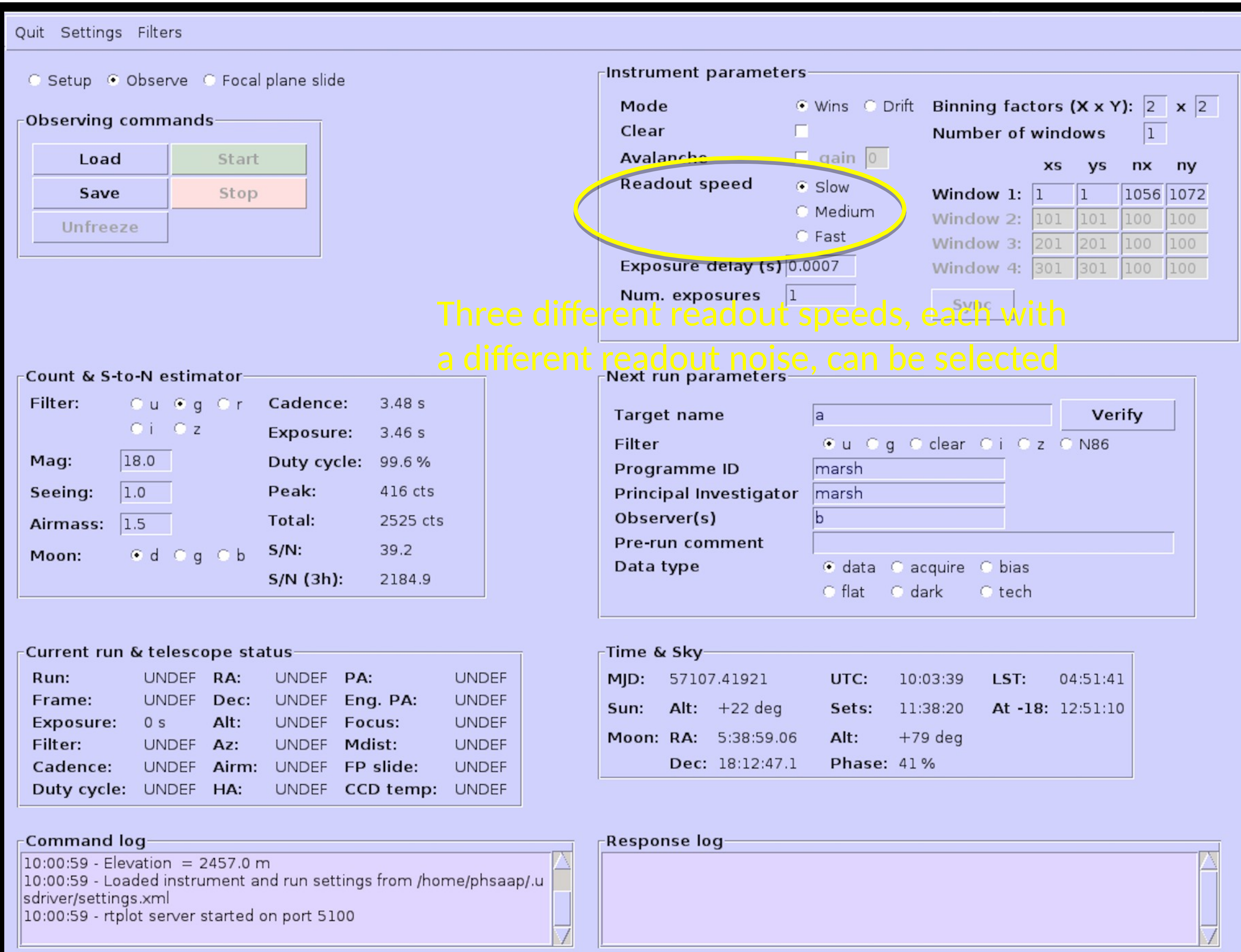


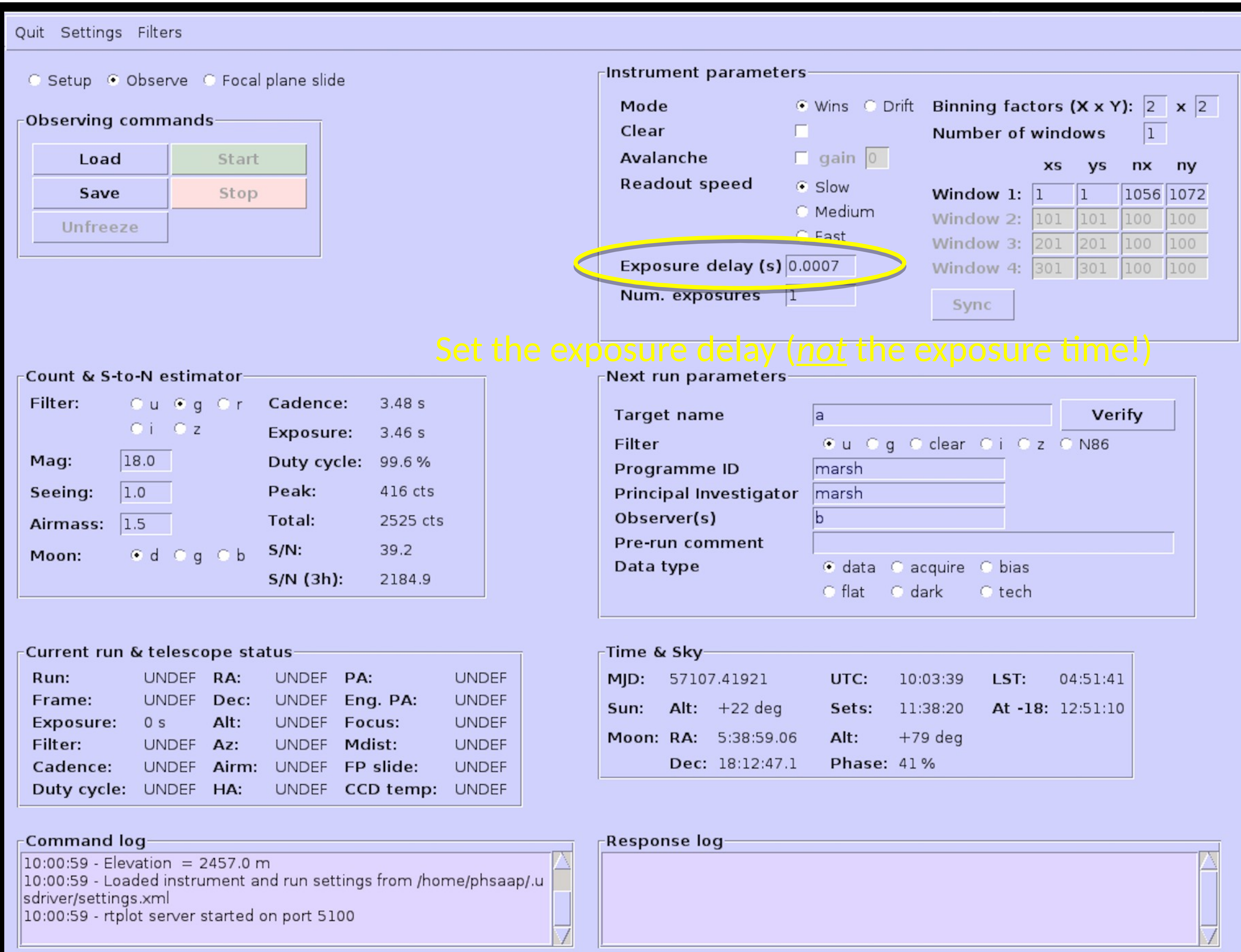
Avalanche (EM) output can be selected, with 9 different levels of EM gain

OBSERVING WITH ULTRASPEC



Three different readout speeds, each with a different readout noise, can be selected

OBSERVING WITH ULTRASPEC



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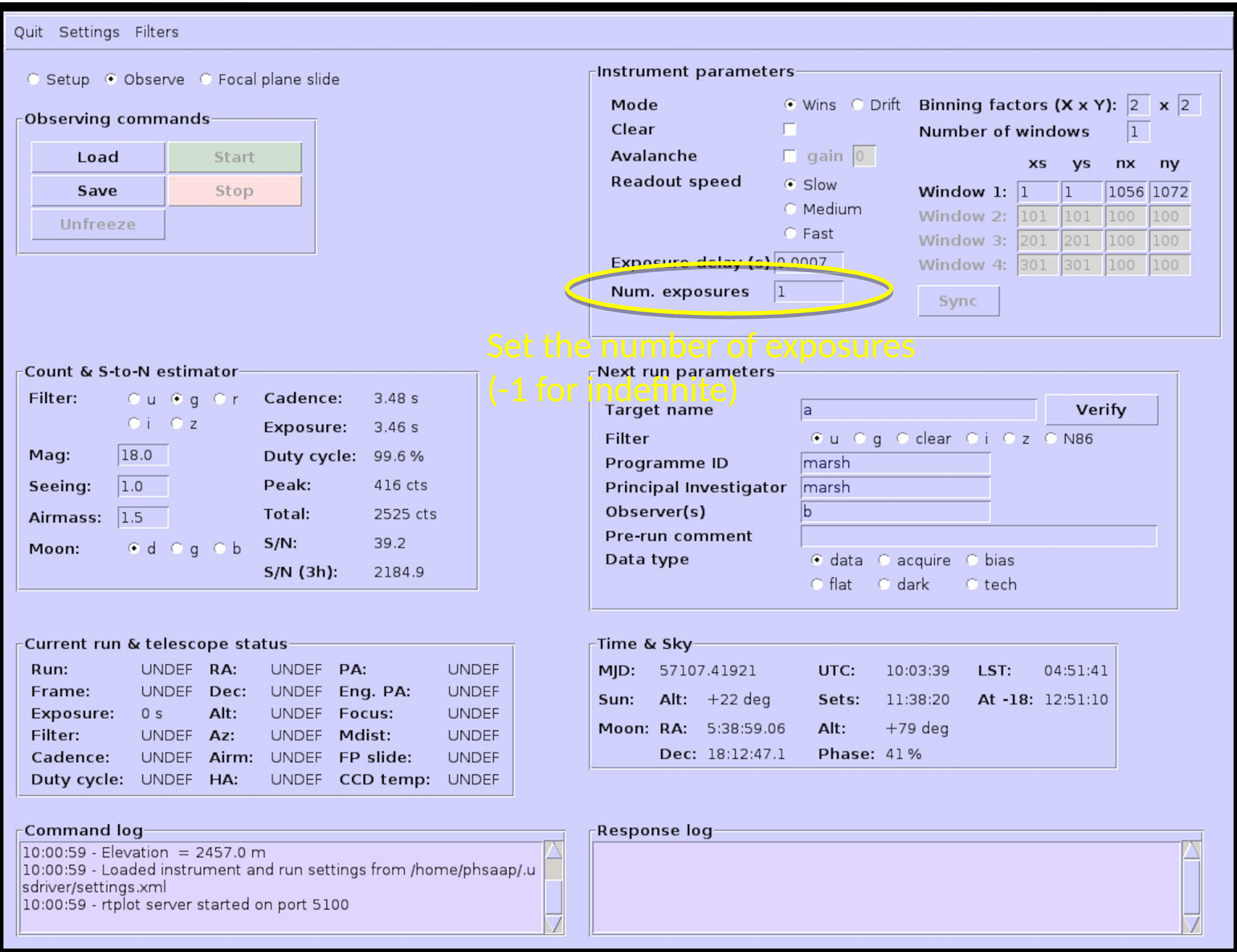

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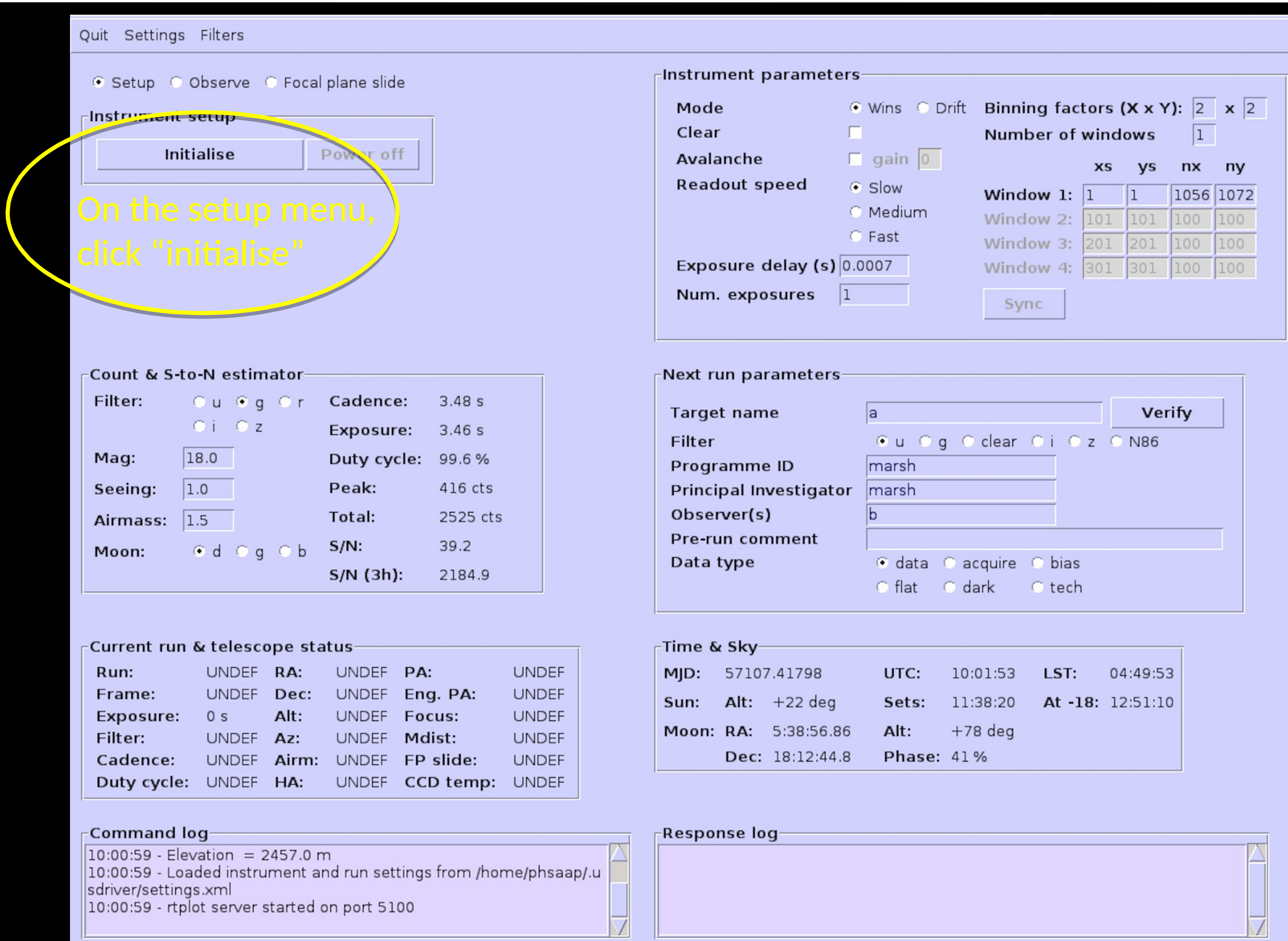

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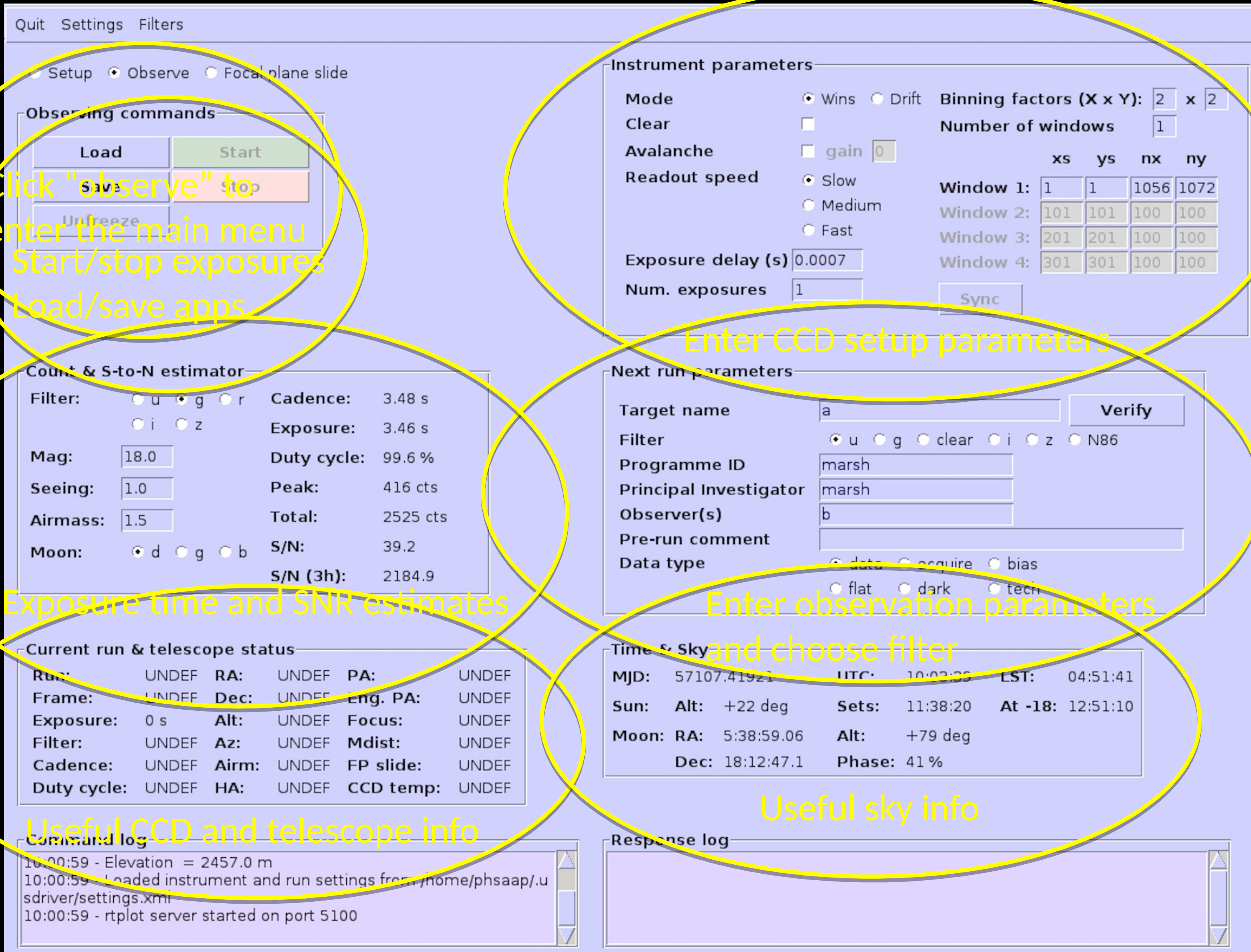
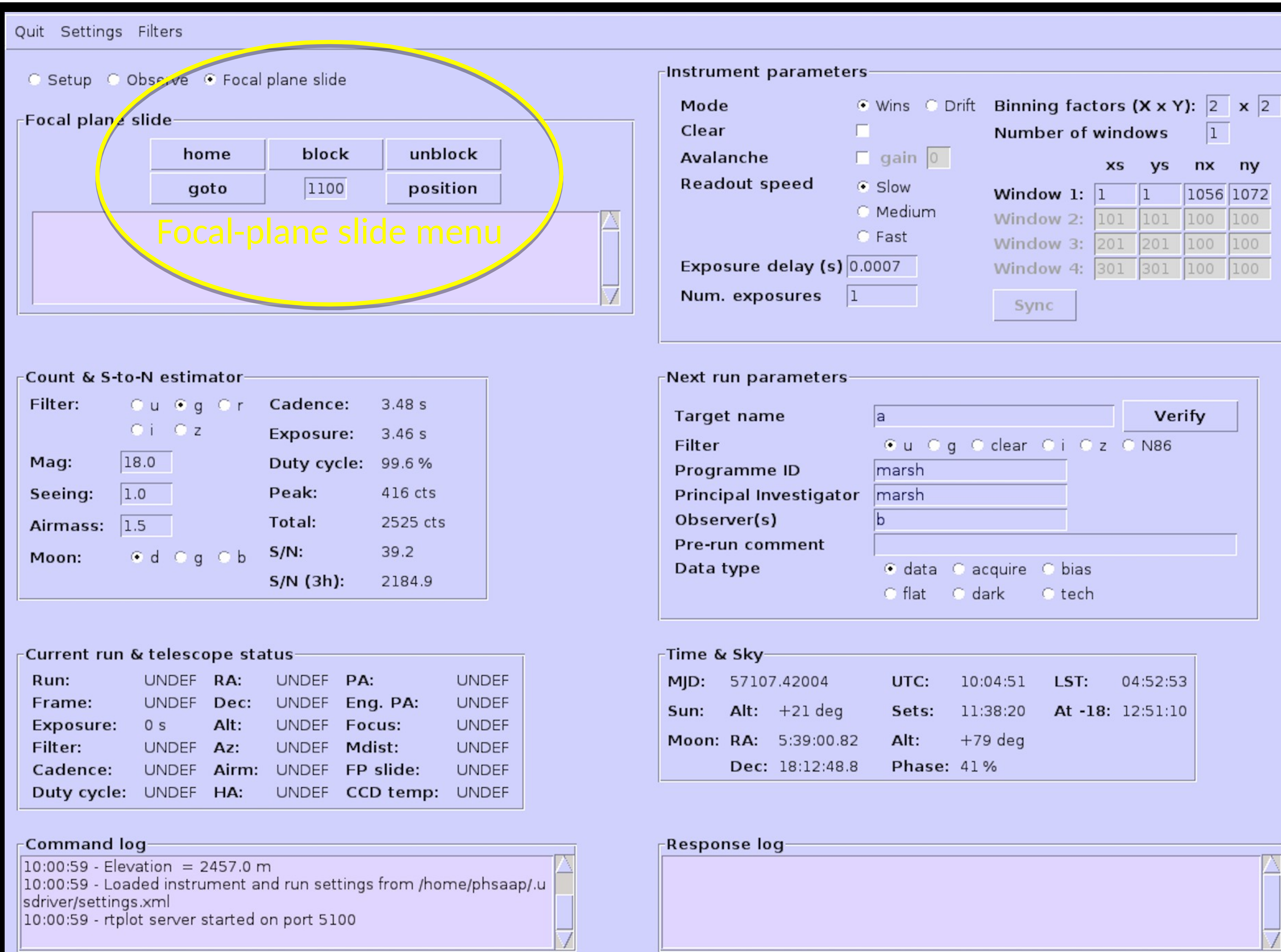


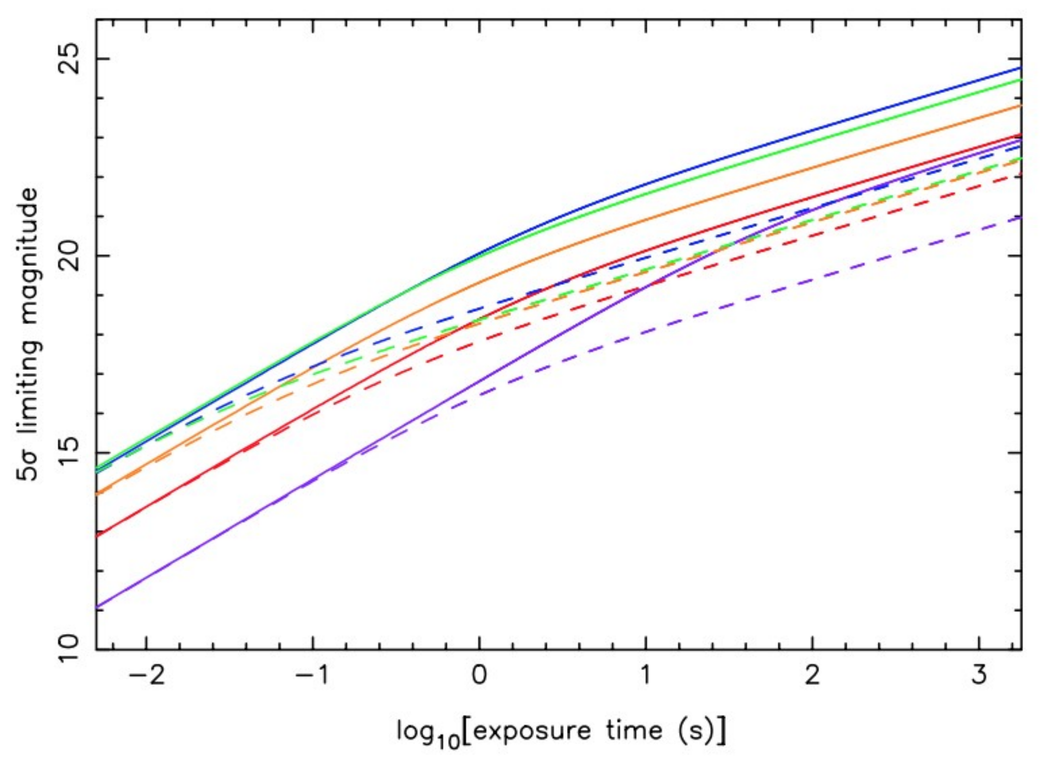
USDRIVER


Quit Settings Filters
Setup Observe Focal plane slide
Focal plane slide
home block unblock
goto 1100 position
Focal-plane slide menu
Instrument parameters
Mode Wins Drift
Clear
Avalanche gain 0
Readout speed Slow Medium Fast
Exposure delay (s) 0.0007
Num. exposures 1
Binning factors (X x Y): 2 x 2
Number of windows 1
xs ys nx ny
Window 1: 1 1 1056 1072
Window 2: 101 101 100 100
Window 3: 201 201 100 100
Window 4: 301 301 100 100
Sync
Count & S-to-N estimator
Filter: u g r i z
Mag: 18.0
Seeing: 1.0
Airmass: 1.5
Moon: d g b
Cadence: 3.48 s
Exposure: 3.46 s
Duty cycle: 99.6 %
Peak: 416 cts
Total: 2525 cts
S/N: 39.2
S/N (3h): 2184.9
Next run parameters
Target name a
Verify
Filter u g clear i z N86
Programme ID marsh
Principal Investigator marsh
Observer(s) b
Pre-run comment
Data type data acquire bias flat dark tech
Current run & telescope status
Run: UNDEF RA: UNDEF PA: UNDEF
Frame: UNDEF Dec: UNDEF Eng. PA: UNDEF
Exposure: 0 s Alt: UNDEF Focus: UNDEF
Filter: UNDEF Az: UNDEF Mdist: UNDEF
Cadence: UNDEF Airm: UNDEF FP slide: UNDEF
Duty cycle: UNDEF HA: UNDEF CCD temp: UNDEF
Time & Sky
MJD: 57107.42004 UTC: 10:04:51 LST: 04:52:53
Sun: Alt: +21 deg Sets: 11:38:20 At -18: 12:51:10
Moon: RA: 5:39:00.82 Alt: +79 deg
Dec: 18:12:48.8 Phase: 41 %
Command log
10:00:59 - Elevation = 2457.0 m
10:00:59 - Loaded instrument and run settings from /home/phsaap/.usdriver/settings.xml
10:00:59 - rtplot server started on port 5100
Response log

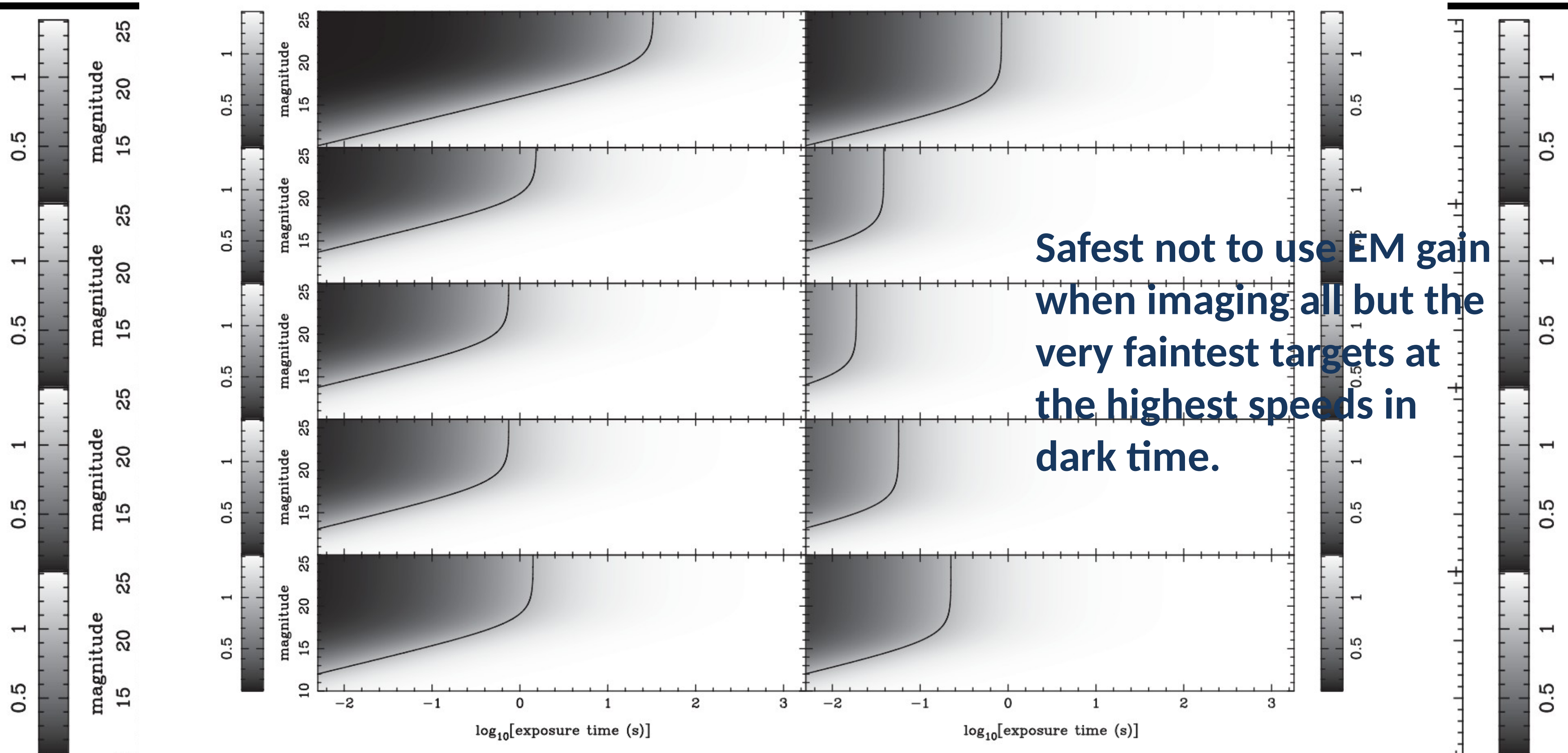
ULTRASPEC+TNT PERFORMANCE

First light with ULTRASPEC+TNT: the Nautilus Galaxy (NGC 772).

5-sigma limiting magnitudes. Solid curves: dark time; dashed curves: bright time.



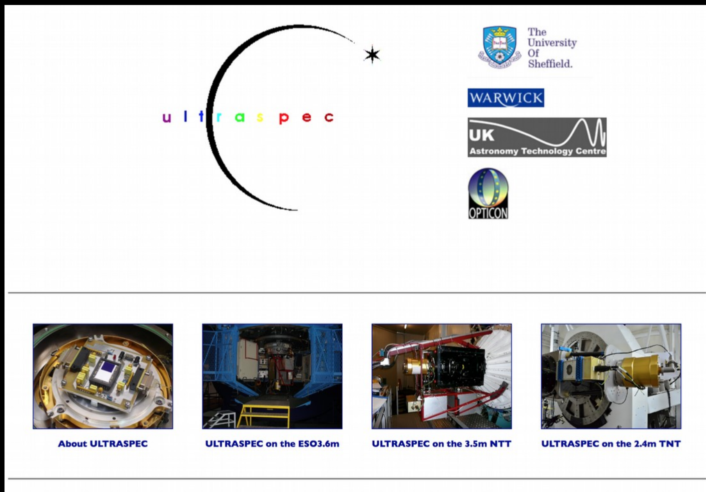
WHEN SHOULD YOU TURN ON EM GAIN?



Safest not to use EM gain when imaging all but the very faintest targets at the highest speeds in dark time.

Figure 10. Grey-scale showing the ratio of the SNR obtained from the normal output of ULTRASPEC on the TNT to that obtained with the avalanche output, as a function of object magnitude and exposure time. The curved line in each panel indicates where both outputs would give identical SNR. Hence the white regions to the right of this line indicate where the normal output would result in superior SNR and the black regions to the left of this line indicate where the avalanche output would result in superior SNR. The left- and right-hand columns show the SNRs obtained in dark and bright time, respectively. The rows show, from top to bottom, the SNRs obtained with the u', g', r', i' and z' filters. Black and white in each panel correspond to values of 0.085 and 1.414, respectively, as indicated in the grey-scale wedges. The calculations assume seeing of 1 arcsec, unity airmass and no CCD binning. For the normal output, readout noise of 2.3 e^- is assumed. For the avalanche output, we assume linear (or proportional) mode is used, where the readout noise is assumed to be zero and the QE of the EMCCD is effectively halved due to the presence of multiplication noise (see Tulloch & Dhillon 2011 for details). As discussed by the latter authors, some of this effective QE loss can in principle be regained through photon counting, but it is difficult to avoid coincidence losses due to the high sky background when imaging at all but the highest frame rates in blue filters during dark time.

FURTHER INFORMATION ON ULTRASPEC



ULTRASPEC WEB PAGE:
http://www.vikdhillon.staff.shef.ac.uk/ultraspec/ultraspec.html

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ULTRASPEC: a high-speed imaging photometer on the 2.4-m Thai National Telescope

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ABSTRACT
ULTRASPEC is a high-speed imaging photometer mounted permanently at one of the Nasmyth focii of the 2.4-m Thai National Telescope (TNT) on Doi Inthanon, Thailand's highest mountain. ULTRASPEC employs a 1024×1024 pixel frame-transfer, electron-multiplying CCD (EMCCD) in conjunction with re-imaging optics to image a field of 7.7'×7.7' at (windowed) frame rates of up to ~200 Hz. The EMCCD has two outputs – a normal output that provides a readout noise of 2.3 e^- and an avalanche output that can provide essentially zero readout noise. A six-position filter wheel enables narrow-band and broad-band imaging over the wavelength range 330–1000 nm. The instrument saw first light on the TNT in November 2013 and will be used to study rapid variability in the Universe. In this paper we describe the scientific motivation behind ULTRASPEC, present an outline of its design and report on its measured performance on the TNT.

Key words: instrumentation: detectors – instrumentation: photometers – techniques: photometric

1 Introduction

High-speed optical photometry can be defined as photometry obtained on timescales of tens of seconds and below. This is a technological definition, based on the fact that the conventional CCDs found on the vast majority of the world's largest telescopes take tens of seconds or longer to read out. Hence if one wishes to perform high-speed optical photometry on large telescopes, it is usually necessary to build specialised instruments dedicated to the task. A list of some of the world's high-speed optical photometers is given by Dhillon et al. (2007b).

High-speed photometry enables the study of compact objects, such as white dwarfs, neutron stars and black holes. This is because the dynamical timescales of these stellar remnants range from seconds to milliseconds, so that their rotation, pulsation, and the motion of any material in close proximity to them (e.g. in an accretion disc), tends to occur on these short timescales. Hence only by observing at high speeds can the variability of compact objects be resolved, and in this variability one finds encoded a wealth of information, such as their structure, radii, masses and emission mechanisms, e.g. Littlefair et al. (2006).

The study of white dwarfs, neutron stars and black holes, both isolated and in binary systems, is of great importance in astrophysics. For example, they allow us to test theories of fundamental physics to their limits: black holes give us the chance to study the effects of strong-field general relativity, and neutron stars and white dwarfs enable the study of exotic states of matter predicted by quantum mechanics. Black holes, neutron stars and white dwarfs also

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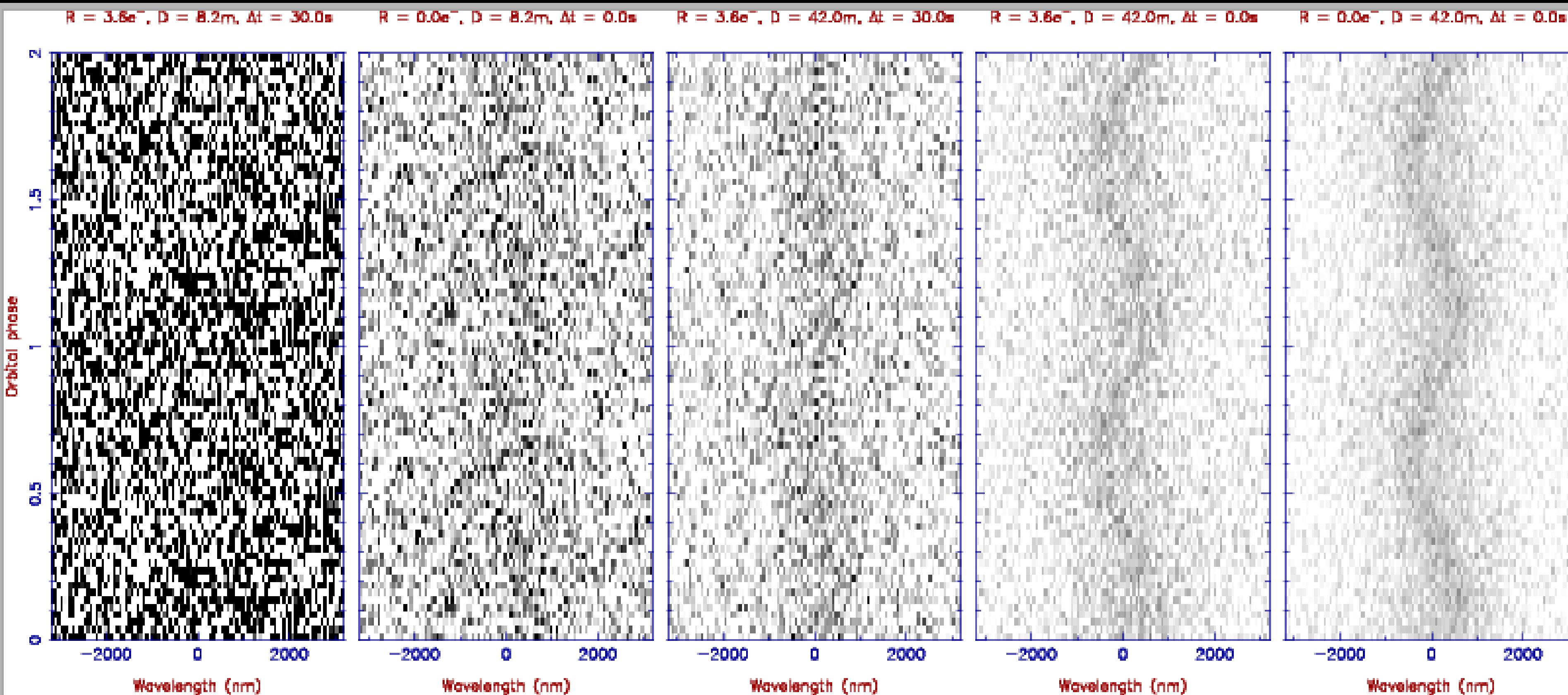
Dhillon et al, 2014, MNRAS, 444, 3504

THE FUTURE OF EMCCD SPECTROSCOPY

VLT+FORS+CCD VLT+FORS+EMCCD ELT+FORS+CCD ELT+FORS+FTCCD ELT+FORS+EMCCD



Simulated trailed spectra of the HeII 4686A emission line in the V=21.1 ultra-compact binary HM Cnc. 8 hours of 8 sec exposures, folded into 40 phase bins on the 322 sec period.

The End.