Pre-Launch Testing of the BRITE Nanosat Instrument

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Issues Affecting the Instrument
Prototype Camera Lab Tests
Pre-Flight System Tests
Readout Noise Tests
Gain Tests
Saturation Level Tests
Linearity Tests
Ground-Based Real Star Field Observing

Lessons from MOST

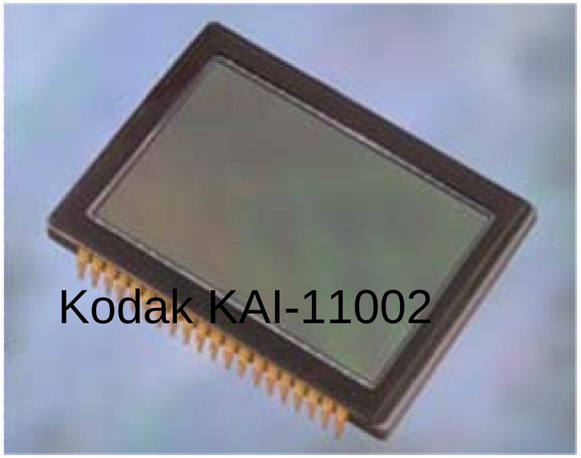
While MOST is a very successful project, we have learned some important lessons. In particular, pre-flight testing and calibration is extremely important.

Nanosats are small enough that:

(a) Spare optics and electronics can be built inexpensively.
(b) The satellite (or a pre-flight model) can observe real star fields before launch.

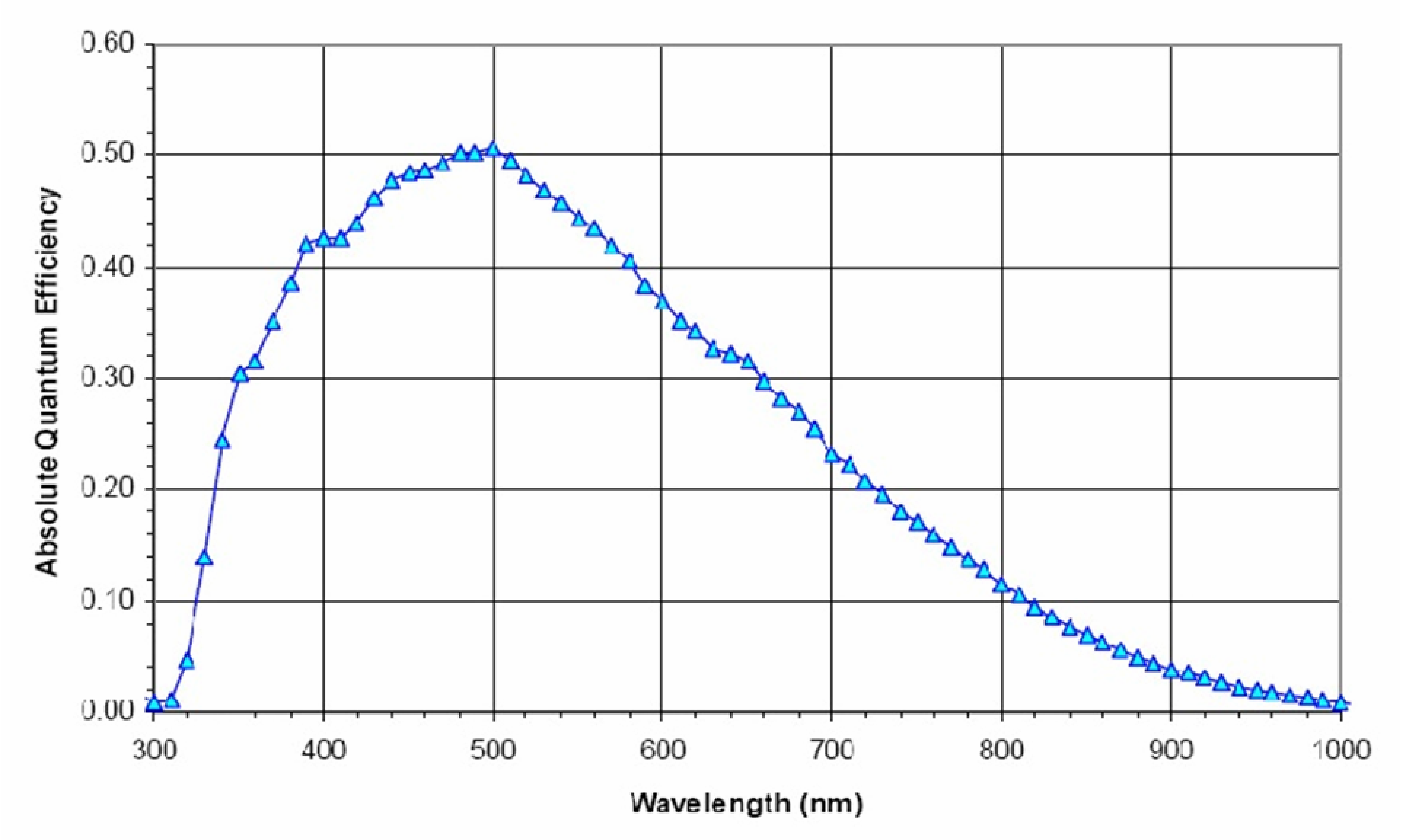
CCD Sensor

Parameter	Value
Imager size	37.25x25.70mm
# of pixels	4072x2720 (Total) 4032x2688 (Effective) 4008x2672 (Active)
Pixel size	9.0µm x9.0µm
Peak quantum efficiency	50%
Saturation Signal	60,000 e$^-$ (90,000 e- VCCD)
Dark current Signal	< 50mV/s



Kodak KAI-11002

Quantum Efficiency Curve for BRITE CCD



Issues affecting sampling of KAI-11002M CCD

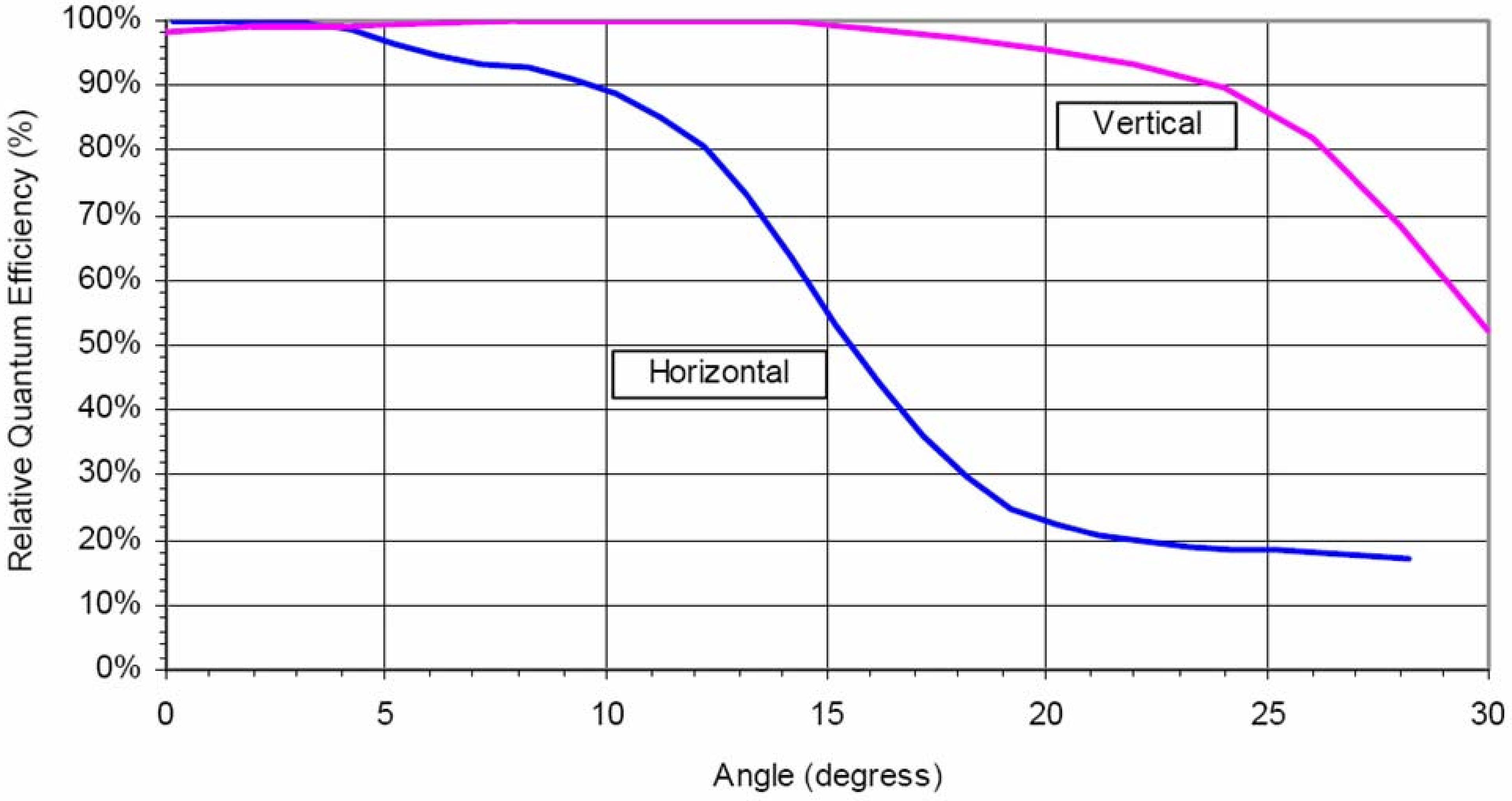
- It is an **INTERLINE TRANSFER** device, which compensates for a CCD without a mechanical shutter.

- It uses **MICROLENSES** to compensate for the 70% dead space. The peak quantum efficiency goes from 16% to 50% when microlenses are fitted, suggesting there should be little effective dead space.

- This means that microlenses probably eliminate most of the “dead space” as far as its contribution to undersampling is concerned. Even back-illuminated CCDs have intra-pixel sensitivity variation.

- The angular response is quite good < 12 degrees.

Variation of Quantum Efficiency with Angle of Incidence in KAI-11002M (Kodak data).



Solar exposure testing

BRITE has no moving parts, hence no safety shutter or flap.

One test has been made to measure the effect of BRITE staring at the Sun, using a non-working engineering chip.Heating was found to not be excessive, confirming engineering calculations.

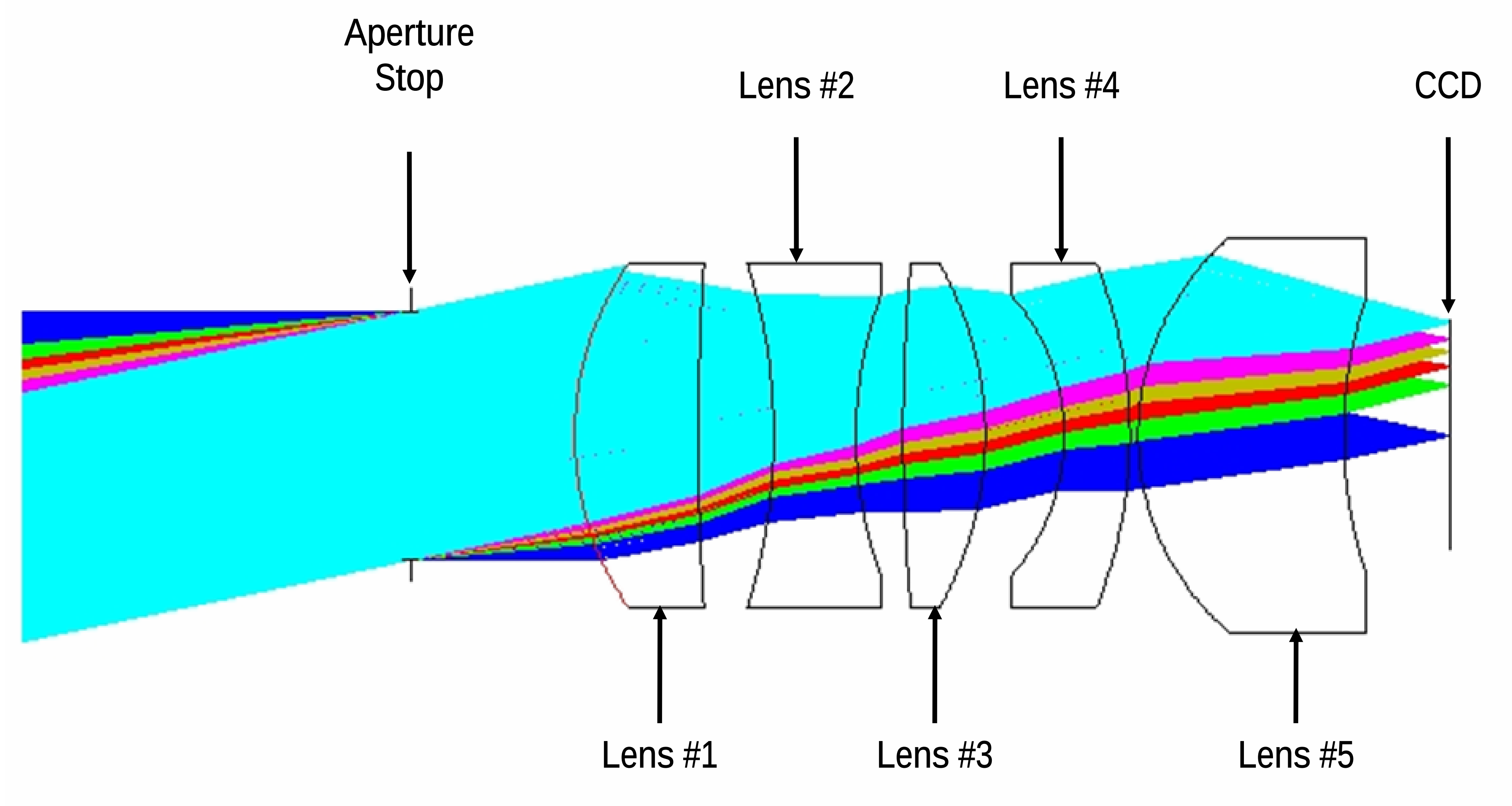
The working Prototype camera will stare at the Sun in the next few weeks.

Telescope

- We chose a 30mm aperture, 70mm focal length, which with a 35mm-format sensor 9µ pixels has an image scale of 26.6 arcsec/pix. This is challenging if undersampling is an issue.
- The field of view is between 22 and 25 degrees.
- The lens design was driven by the need for adequately sampled images and good baffling, which also yielded an image-space telecentric telescope, avoiding vignetting.

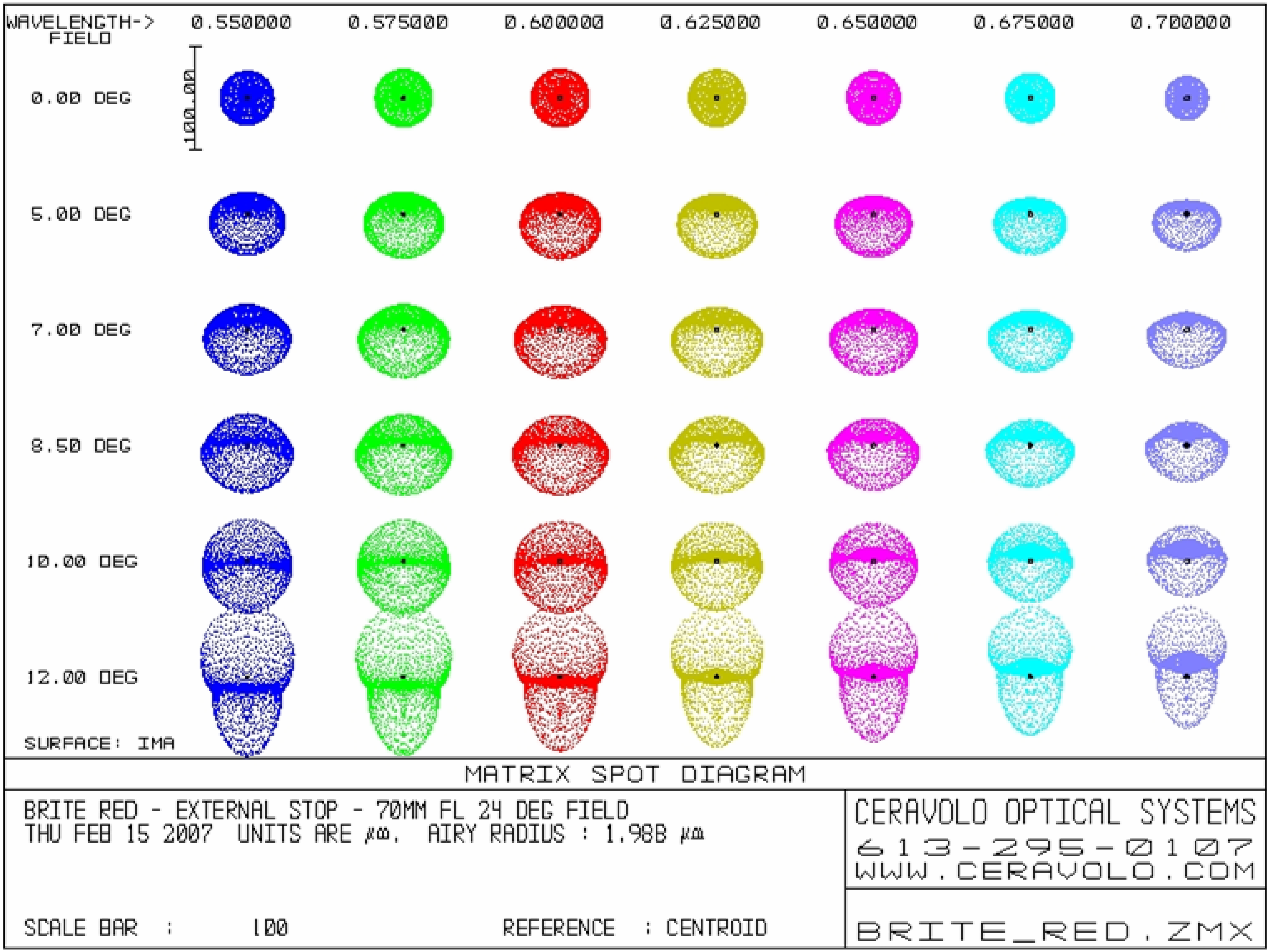
Optical Design (Blue)

Note large bending of rays, leading to aberrations.



Red Brite spot matrix

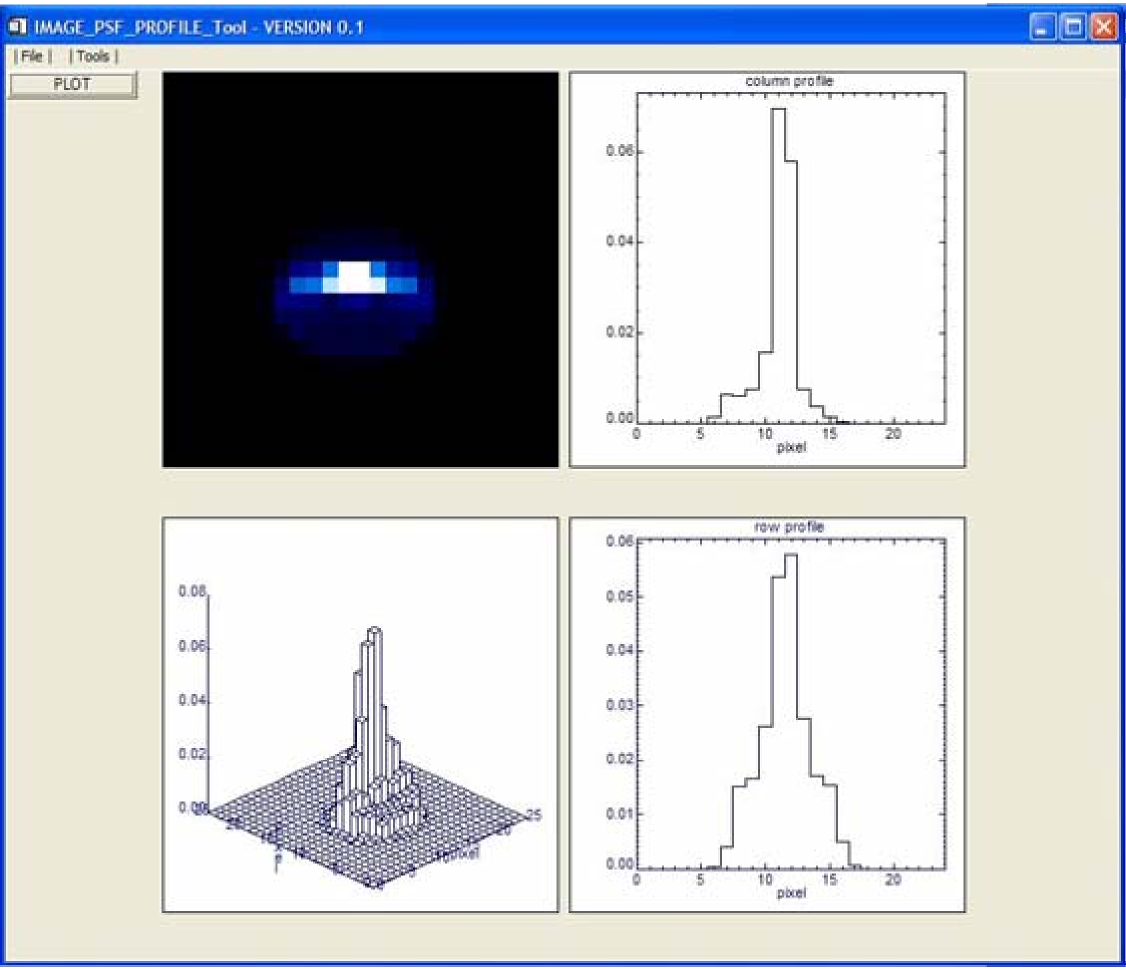
This was deliberately made large to overcome undersampling, but detailed analysis shows there still are SPIKES in the PSF.



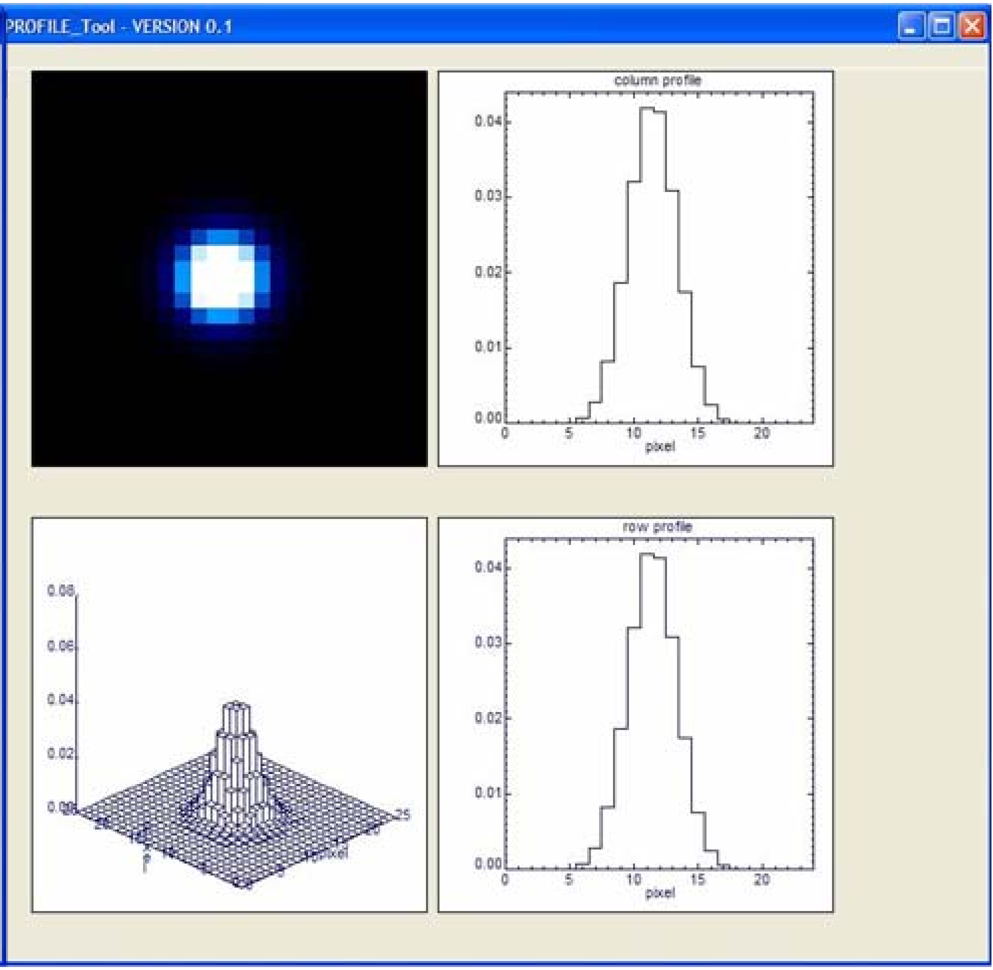
Blue BRITE design PSF simulation by Rainer Kuschnig:

- approximate simulation
- Zemax PSF data resampled/binned to the CCD frame

Zemax PSF **SPIKY!!**

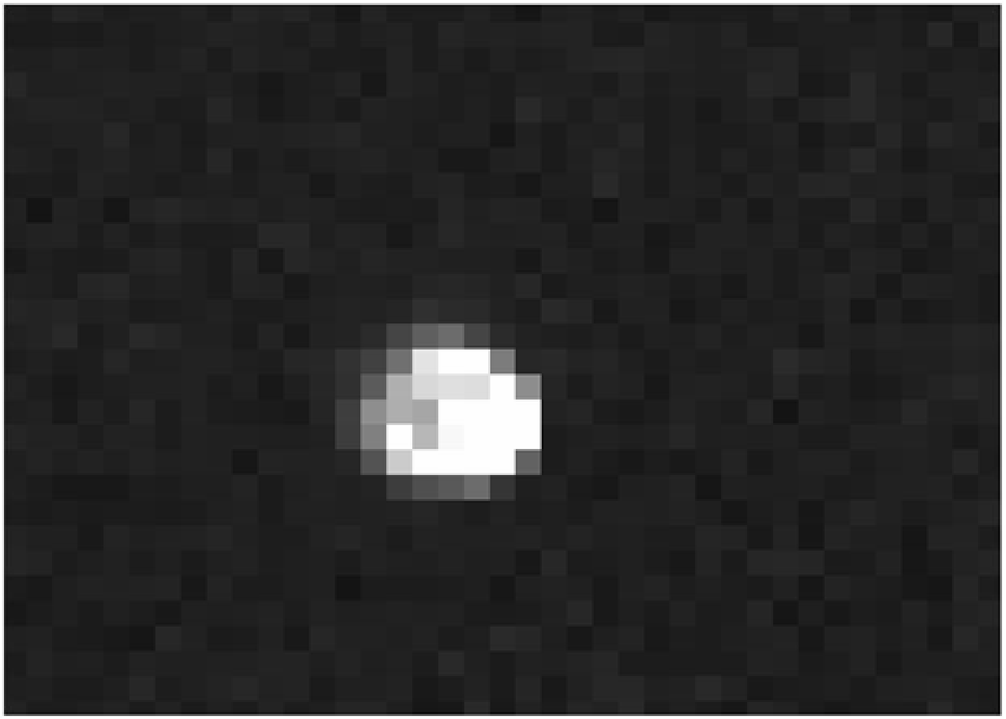


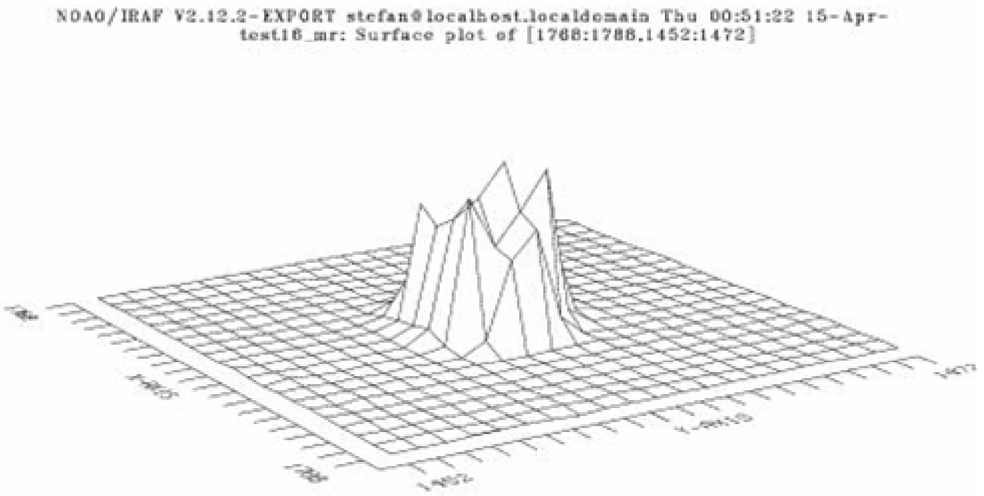
Desired Gaussian PSF

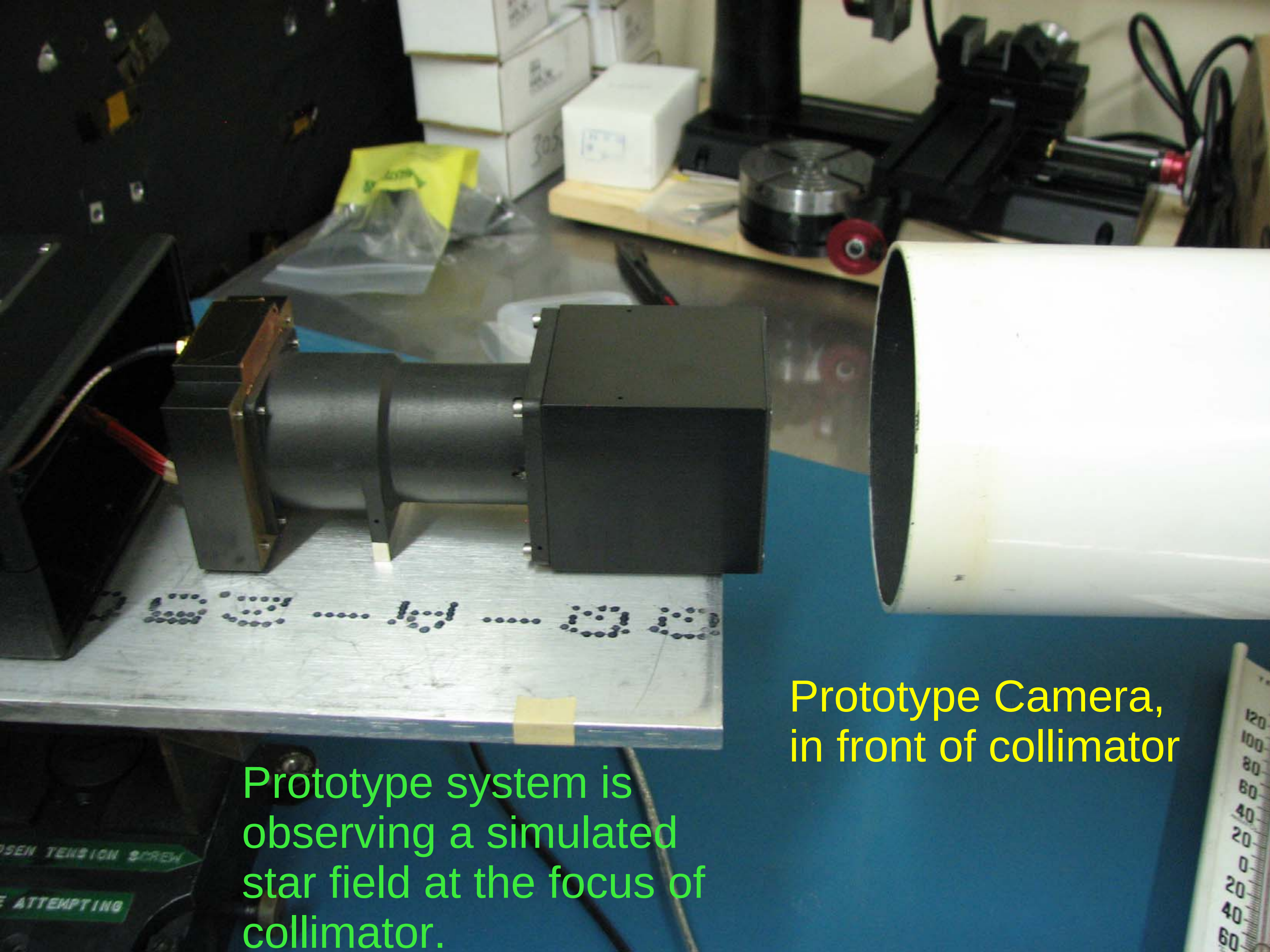


The Undersampling Issue

The sharp features in the already-enlarged PSF means that we must rely on <u>JITTER</u> and some <u>DEFOCUSING</u>. The Austrian team have determined the amount of defocus necessary. The PSF looks like this (real star in Orion):



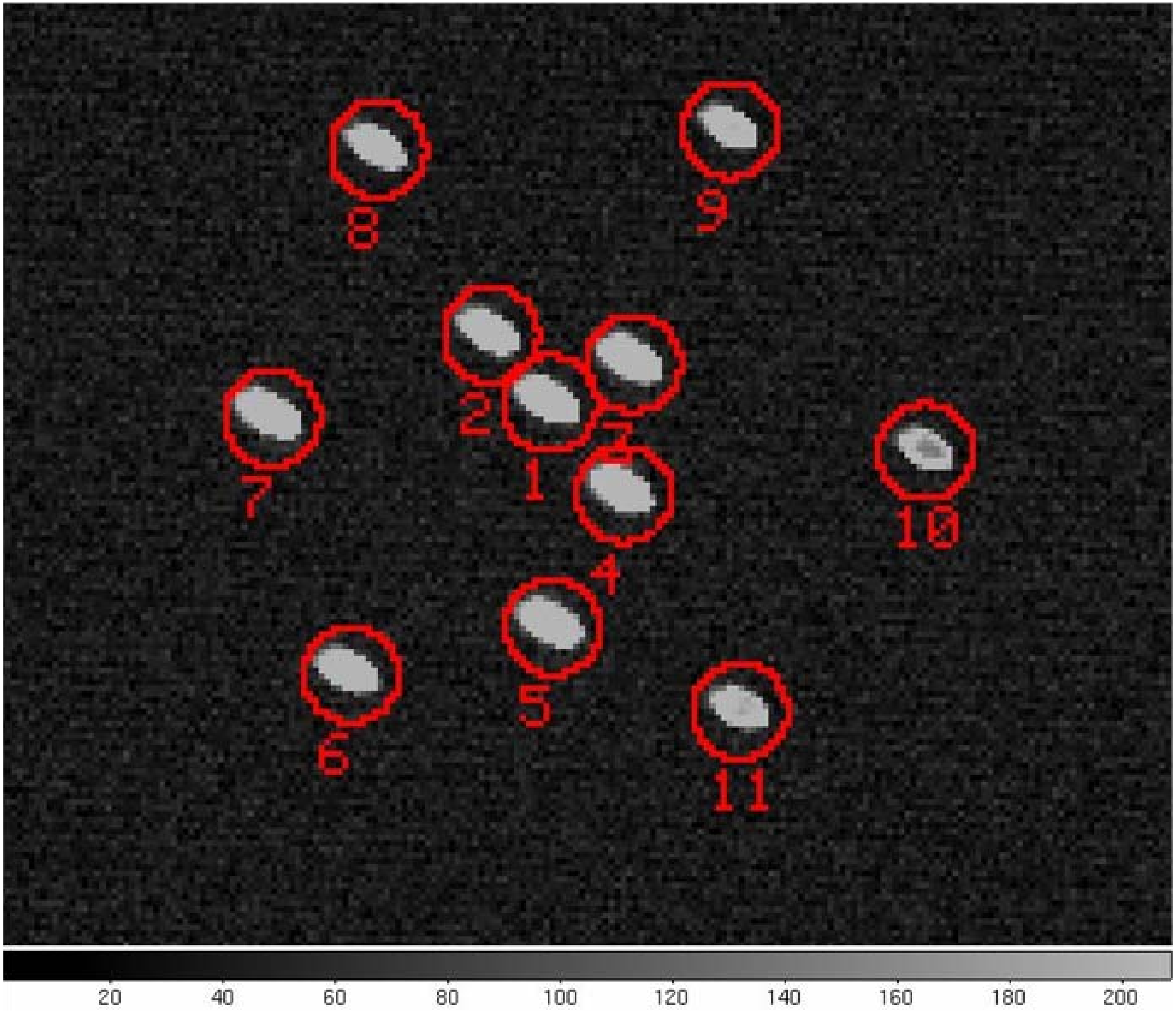




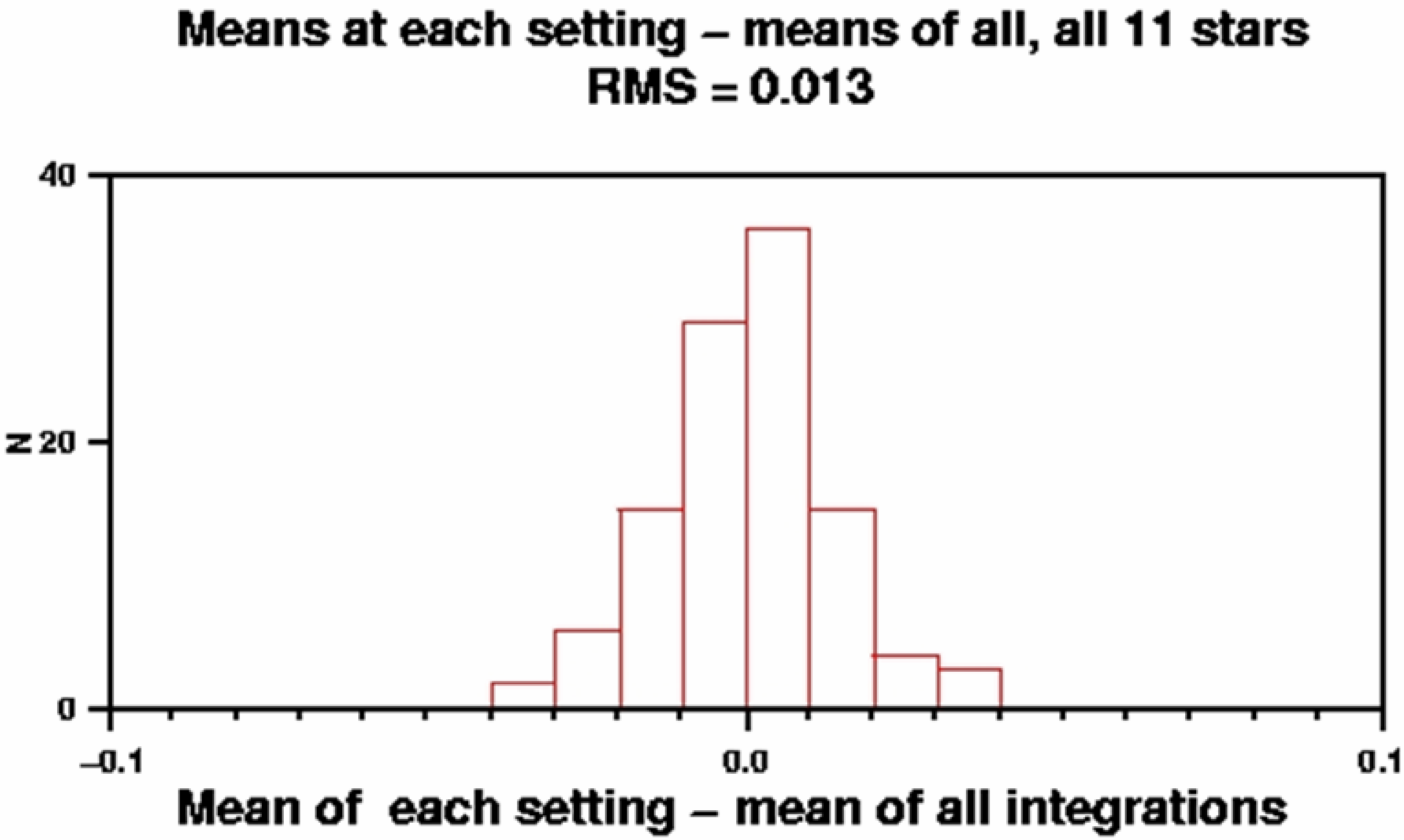
Prototype Camera, in front of collimator

Prototype system is observing a simulated star field at the focus of collimator.

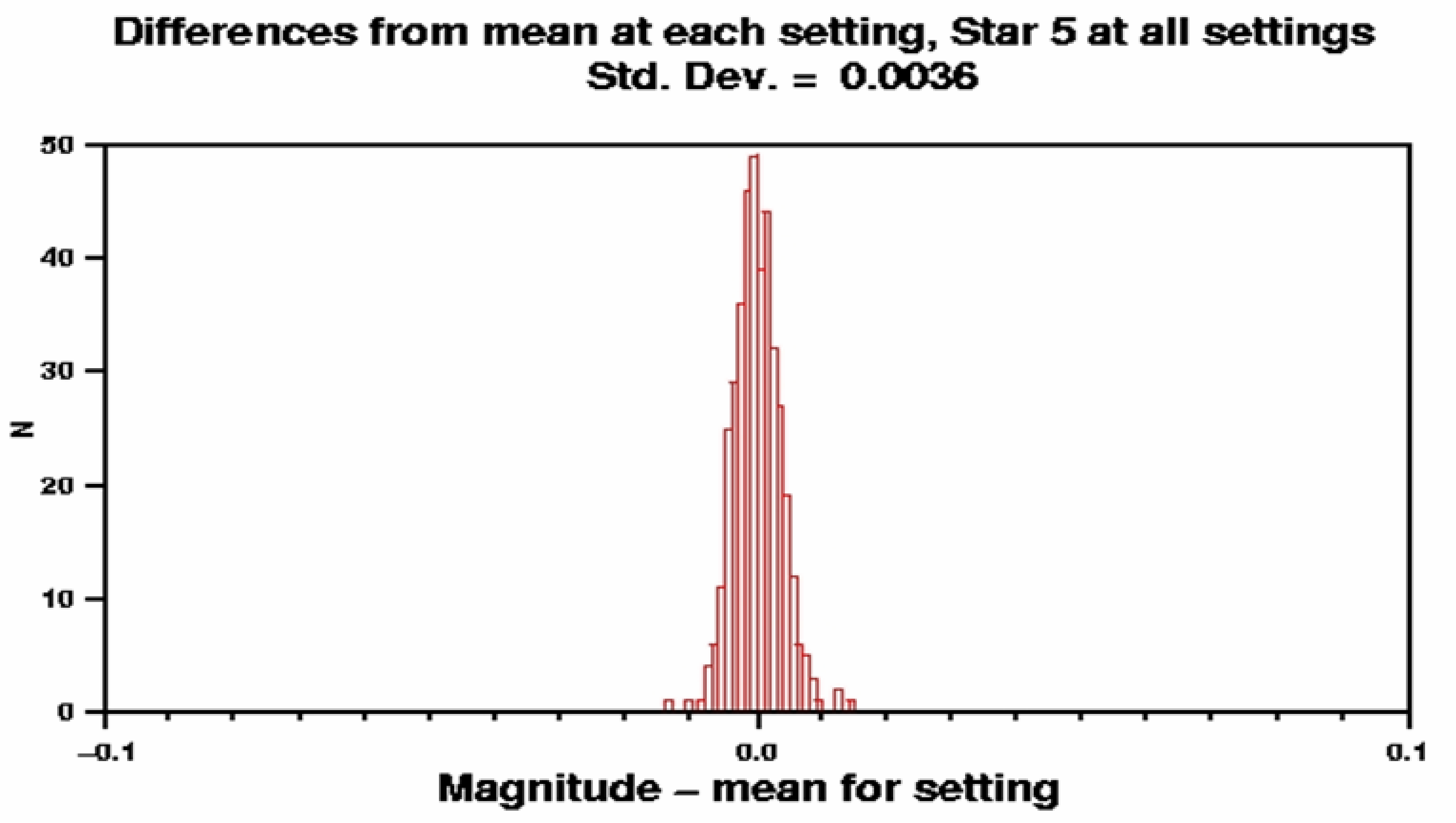
Differential photometry of an artificial star field allows the effects of aliasing (undersampling) to be measured in the lab. This is now also being tested on real star fields.



The effect of undersampling is measured by making many measurements with the image of the star field moving slightly over the detector from exposure to exposure.



Here we see the net effect of aliasing. Each star has been averaged over each setting (40 integrations), and then the total average for that star (400 integrations) is subtracted. The 110 values (11 stars x 10 positions) are distributed as above. This is the net error due to aliasing with this PSF. The error can be reduced to 0.001 with 170 integrations. The distribution looks fairly Gaussian.

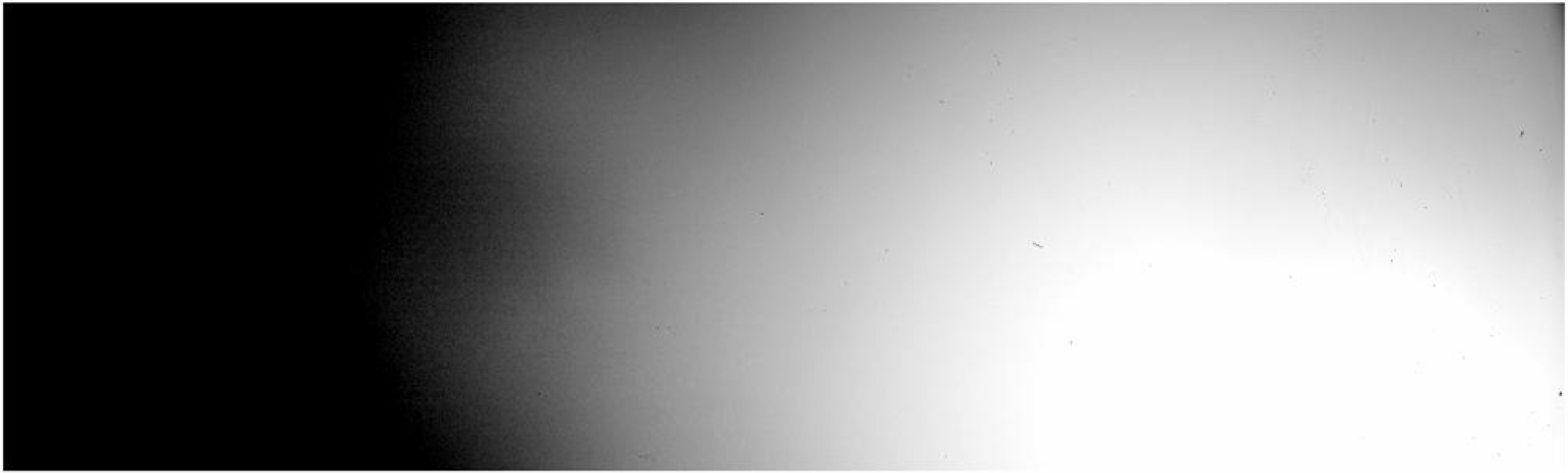


The difference of Star 5 measures and its mean at each setting are shown above. It looks quite Gaussian. The error of the mean here would be 0.001 magnitudes in just 13 integrations (i.e. in the absence of aliasing errors). The standard deviation agrees with what IRAF predicts on the basis of photon and readout noise. Star 5 is one of the brighter artificial stars.

- **Prototype camera using KAI-11002 chip has been built and is used extensively for testing.**
- **Most important are tests on real star fields and on simulated star fields to measure PSFs and sampling.**
- **We have adjustable bias level and gain. At present bias ~ 100 ADU, gain ~ 3e-/ADU. The gain is shown in photon transfer curves:**

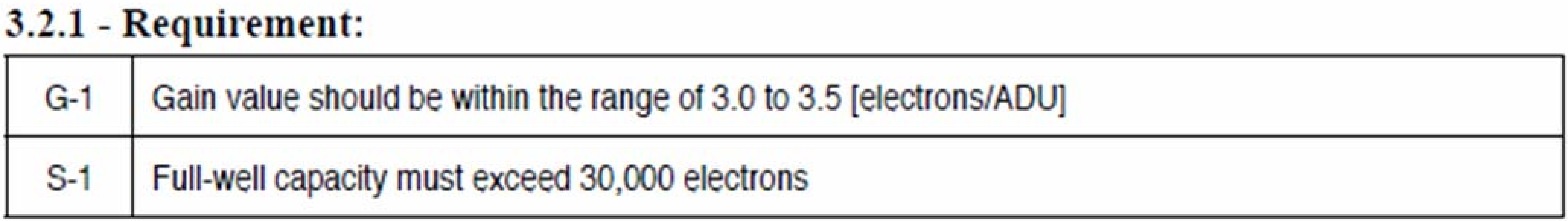
Gain and Readout Noise Determination

The photon transfer curve is simply the plot of variance versus light level of a smoothly-varying scene. About 10 exposures are used to obtain the variance, averaged over a suitable sub-area.



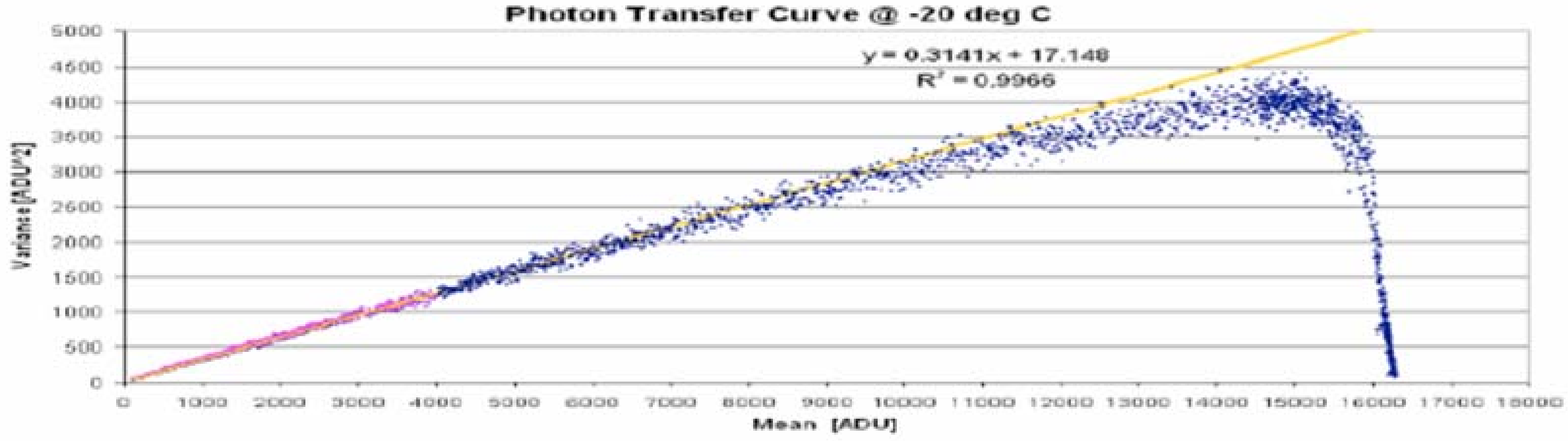
The gain and readout noise are determined from the slope and intercept of variance versus signal in ADU (analog-to-digital converter units). The noise is also given by the variance of the difference between two bias frames, divided by □2.

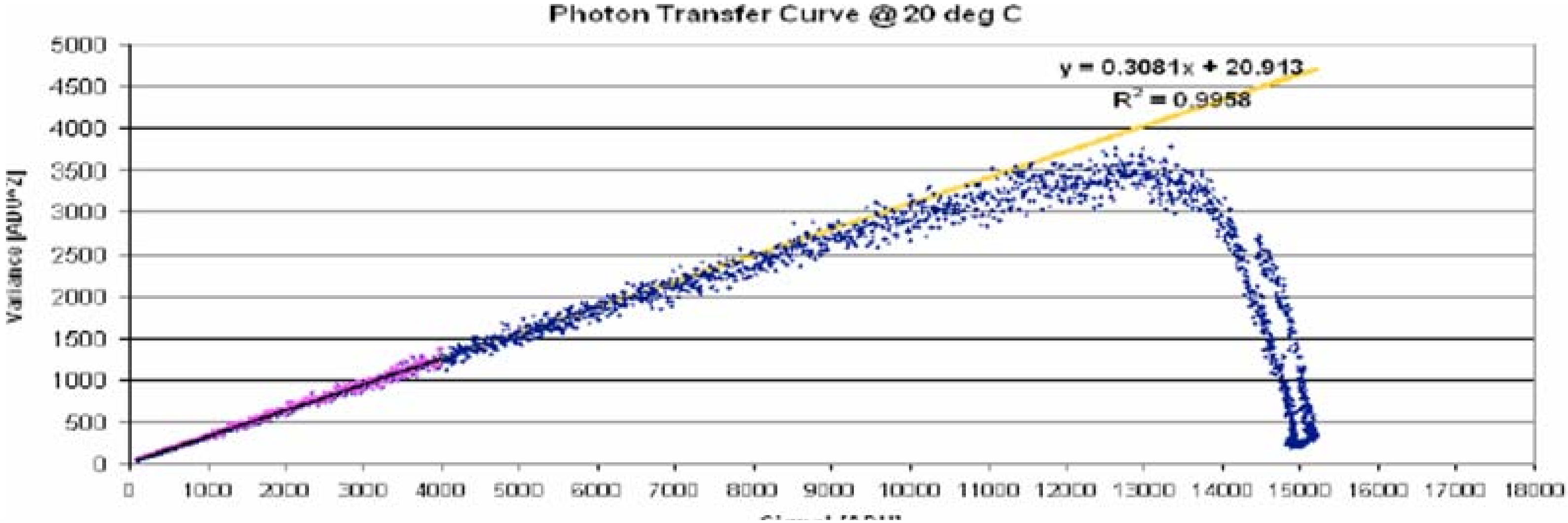
Full photon transfer curves follow to show the variation of saturation with temperature (0.5 or 0.6 second integrations)

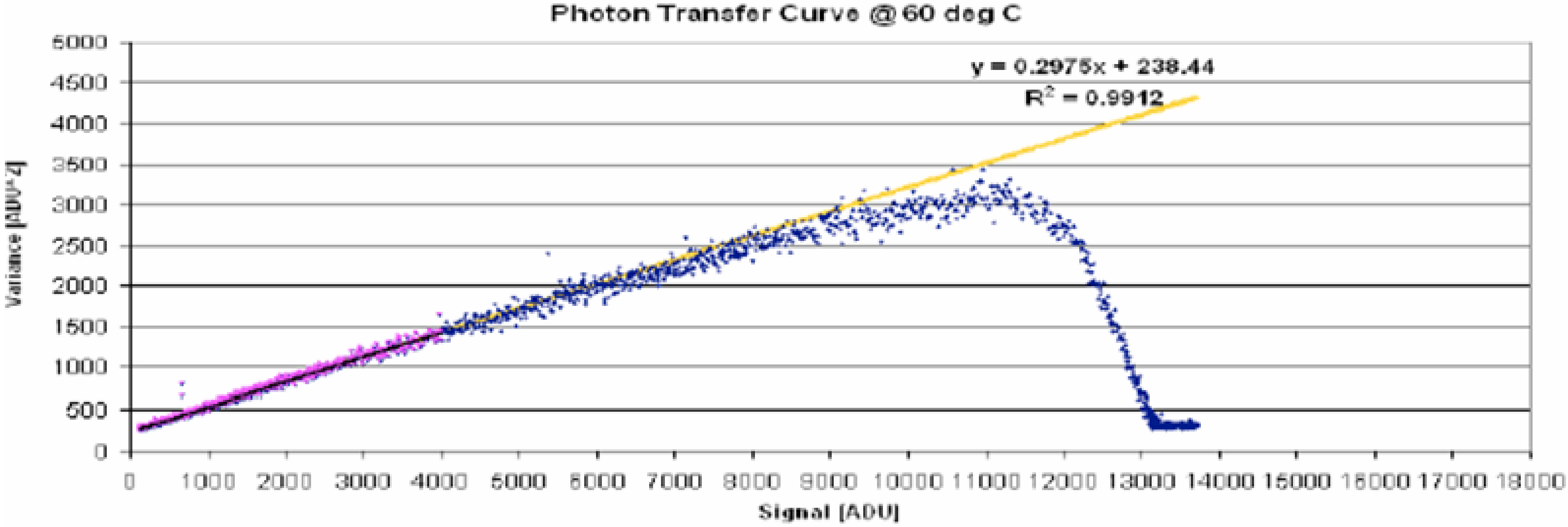


3.2.1 - Requirement:

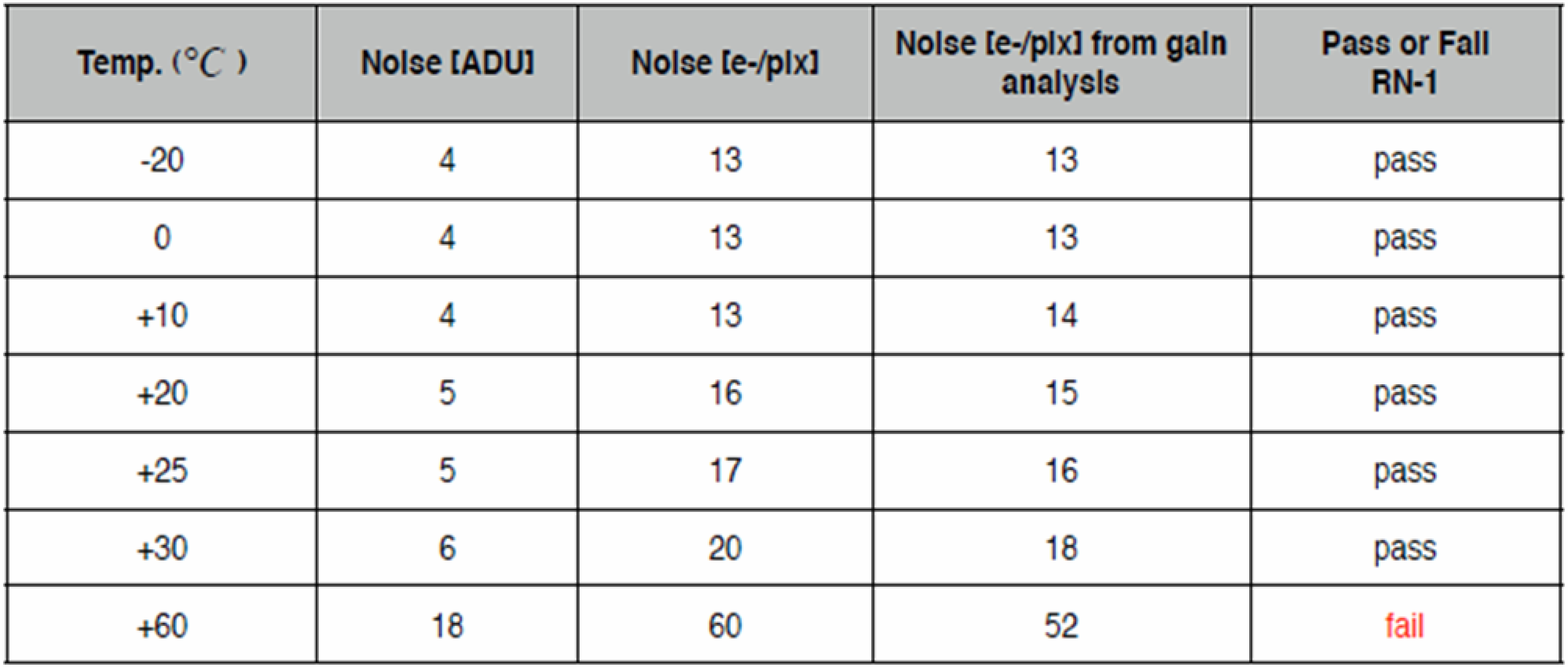
G-1	Gain value should be within the range of 3.0 to 3.5 [electrons/ADU]
S-1	Full-well capacity must exceed 30,000 electrons


Photon Transfer Curve @ -20 deg C
y = 0.3141x + 17.148
$R^2 = 0.9966$
Variance [ADU^2]
Mean [ADU]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000


Photon Transfer Curve @ 20 deg C
y = 0.3081x + 20.913
$R^2 = 0.9958$
Variance [ADU^2]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000

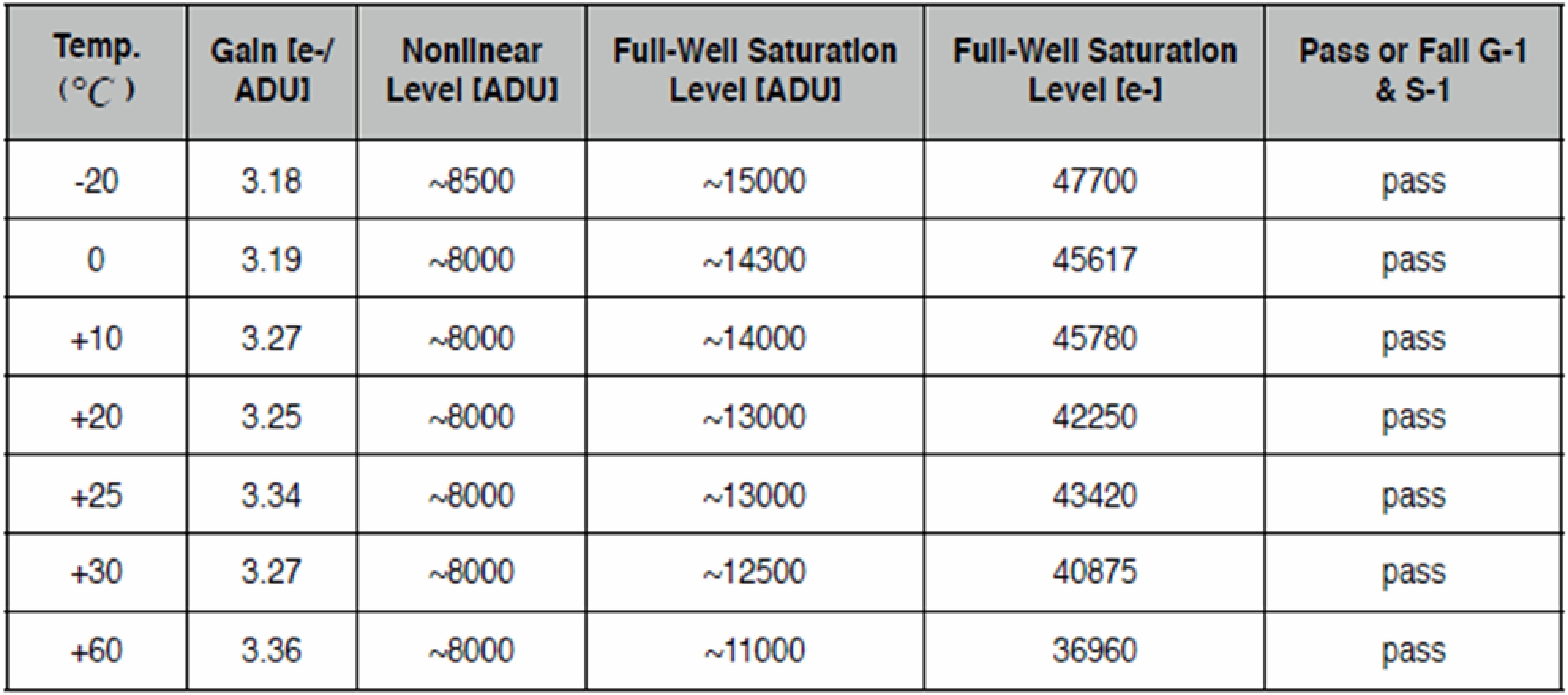

Photon Transfer Curve @ 60 deg C
y = 0.2975x + 238.44
$R^2 = 0.9912$
Variance [ADU^2]
Signal [ADU]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000

Readout Noise as function of Temperature



Temp. (°C)	Noise [ADU]	Noise [e-/pix]	Noise [e-/pix] from gain analysis	Pass or Fail RN-1
-20	4	13	13	pass
0	4	13	13	pass
+10	4	13	14	pass
+20	5	16	15	pass
+25	5	17	16	pass
+30	6	20	18	pass
+60	18	60	52	fail

Gain and saturation as function of Temperature



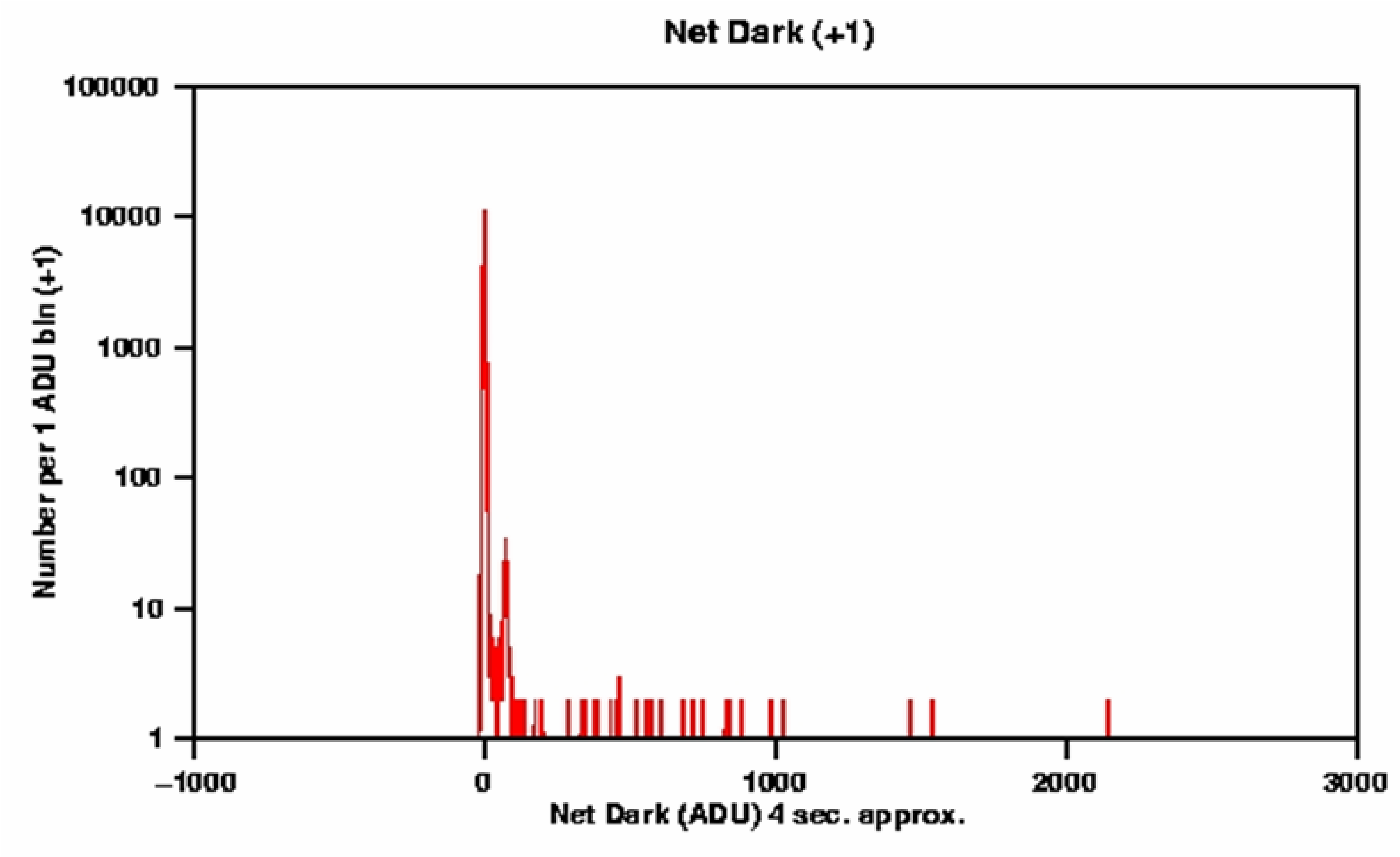
Temp. (°C)	Gain [e-/ADU]	Nonlinear Level [ADU]	Full-Well Saturation Level [ADU]	Full-Well Saturation Level [e-]	Pass or Fail G-1 & S-1
-20	3.18	~8500	~15000	47700	pass
0	3.19	~8000	~14300	45617	pass
+10	3.27	~8000	~14000	45780	pass
+20	3.25	~8000	~13000	42250	pass
+25	3.34	~8000	~13000	43420	pass
+30	3.27	~8000	~12500	40875	pass
+60	3.36	~8000	~11000	36960	pass

For the 60C case, a slightly illuminated portion of the detector shows the elevated bias level (general dark current) in a 0.6 sec. Integration, with hot pixels as at lower temperatures. (Approx. 500-pixel long strip shown).

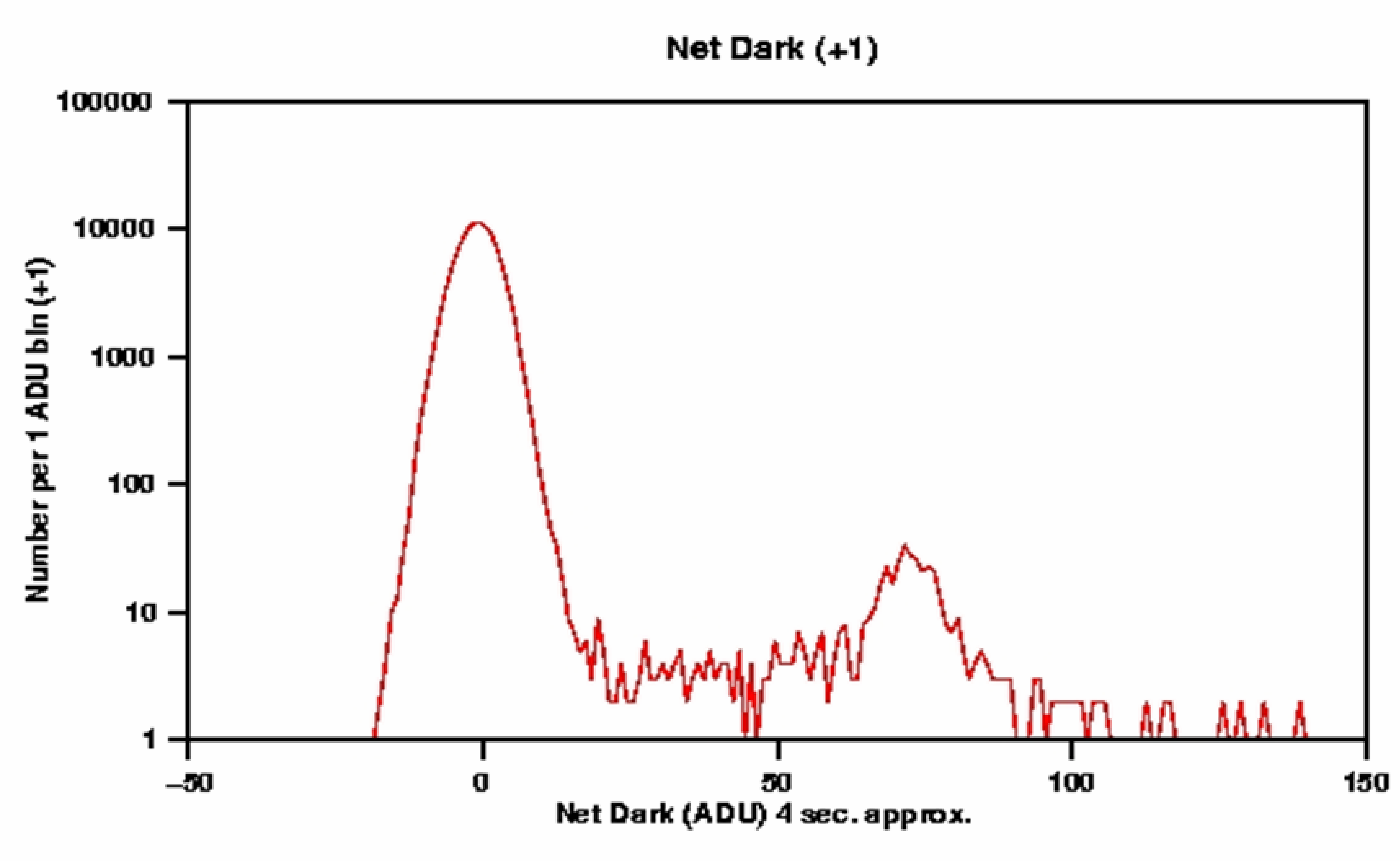
(Note small number of “hot” pixels)

Darks (determination of Dark Current)

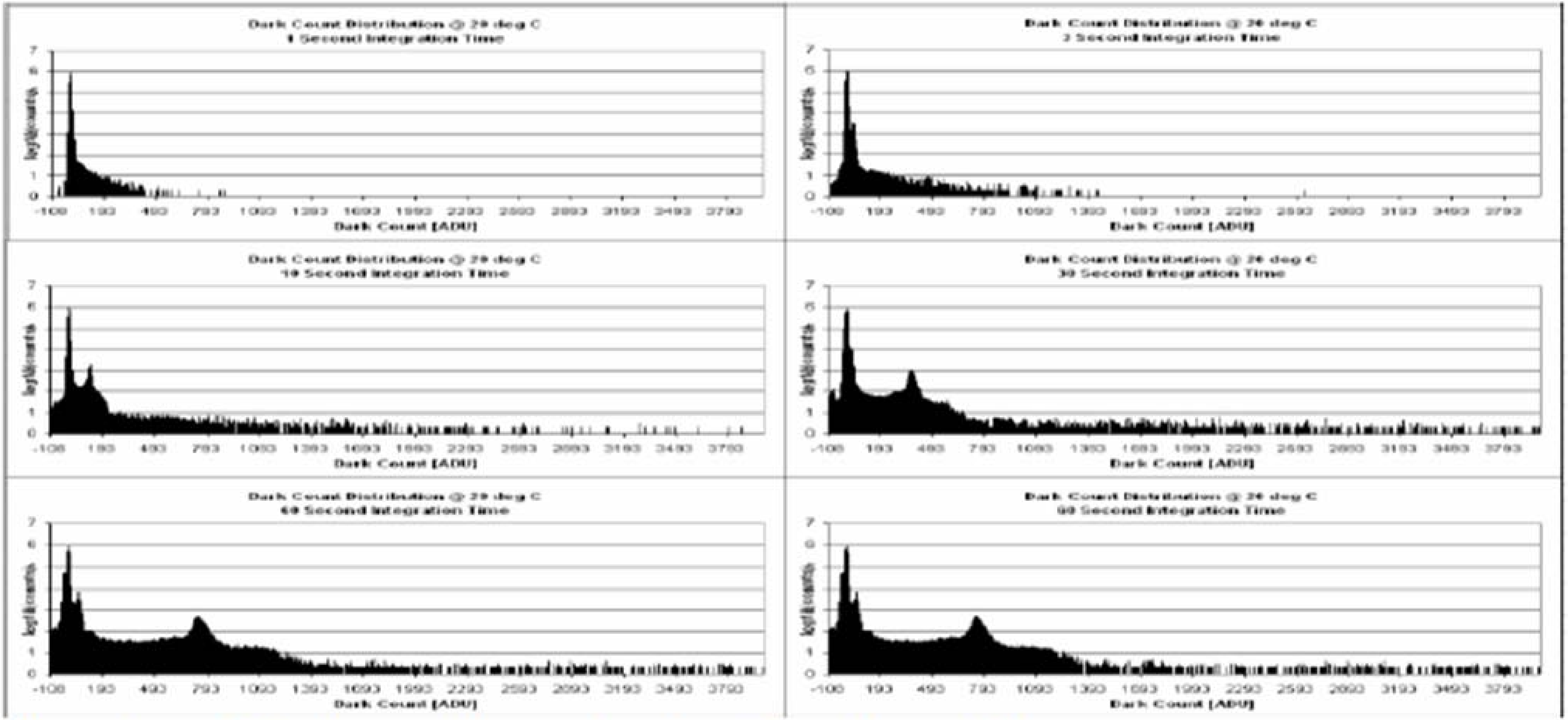
A histograms of dark counts per pixel (bias subtracted) is shown below:



The low end of the distribution of average net dark is shown below, on a logarithmic plot (hence 1 has been added to avoid zero counts). Only 0.5% of pixels have more than 17 ADU dark count in approx. 4 seconds at 71 F (21.7 C), and 0.04% have over 100 ADU.



Preflight camera: Dark current distributions at 20 C for exposures of 1, 3 10, 30, 60 and 90 seconds.



Above: from top left to bottom right: 1sec, 3sec, 10sec, 30sec, 60sec, and 90sec integration time

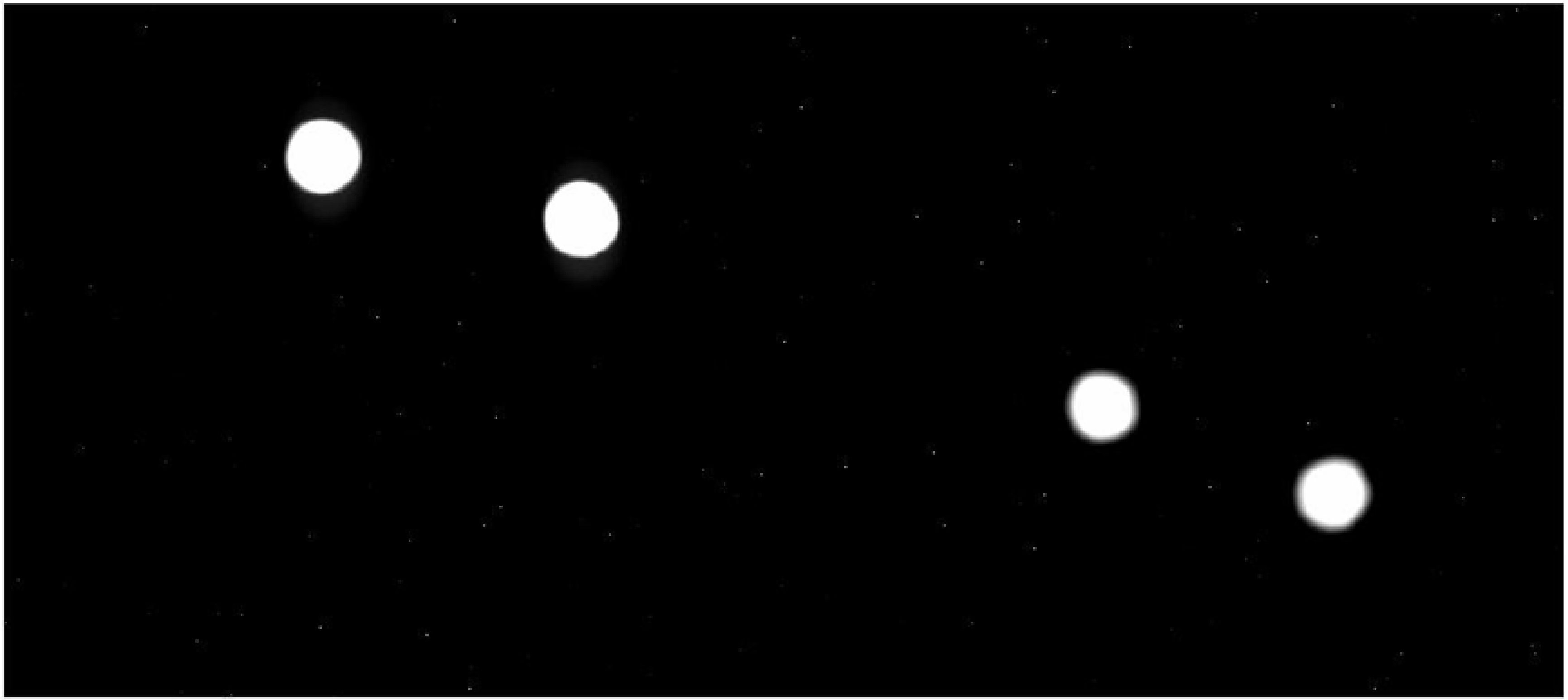
Such distributions have been obtained between -20 C and +60 C.

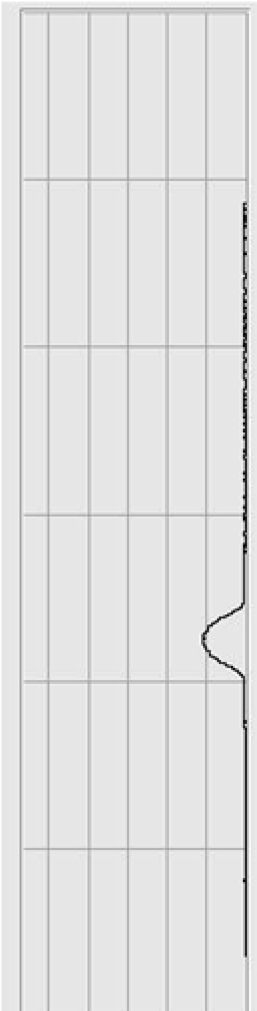
The conclusion is that exposures of tens of seconds are possible even with the camera at 20C e or more. The “hot” pixels, less than 1%, can be avoided or removed in the analysis.

A map of “hot” pixels will be made before launch and updated during the mission.

Linearity Tests

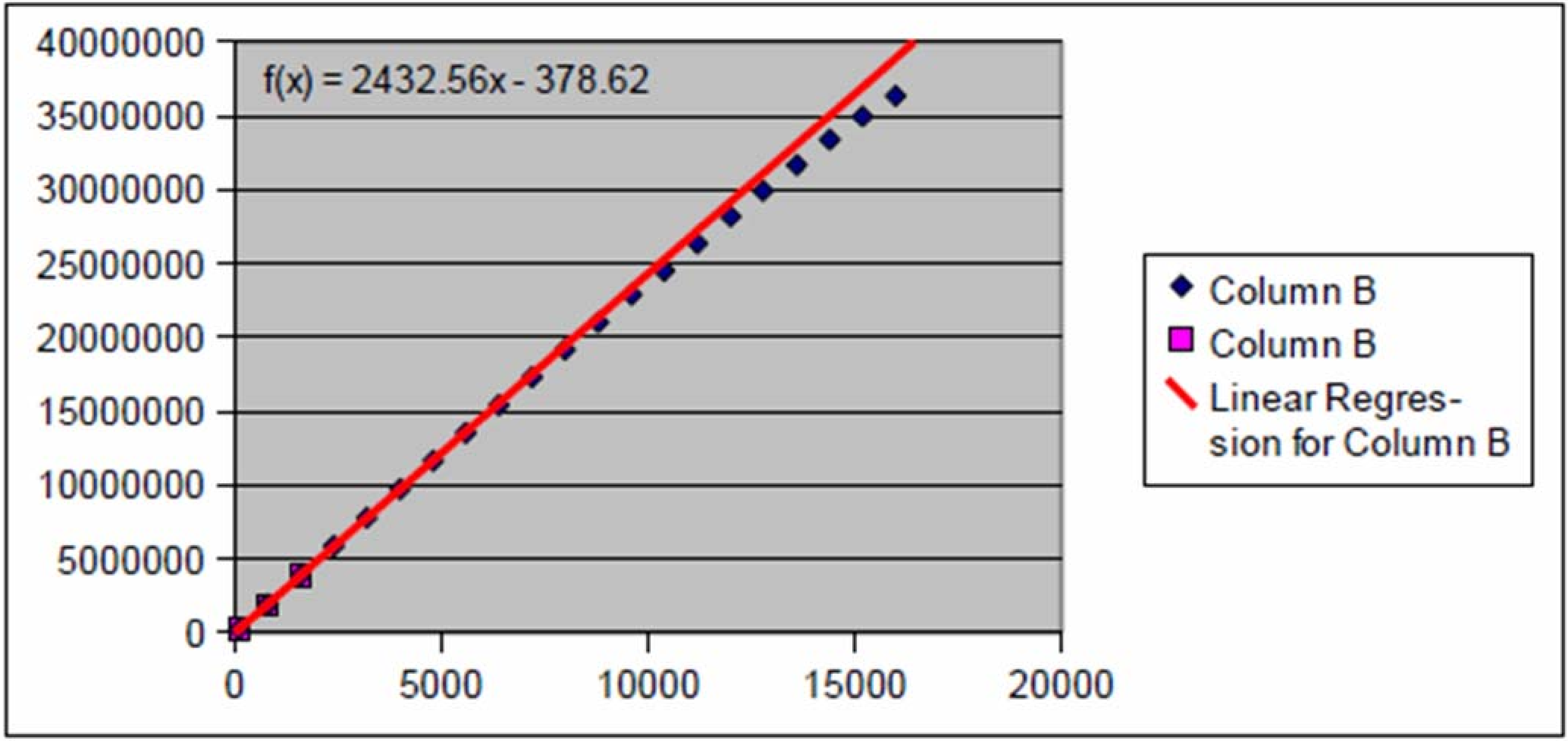
- Ratios of average signals in apertures at many illumination levels used to determine non-linearity. (Relative illuminations fixed).



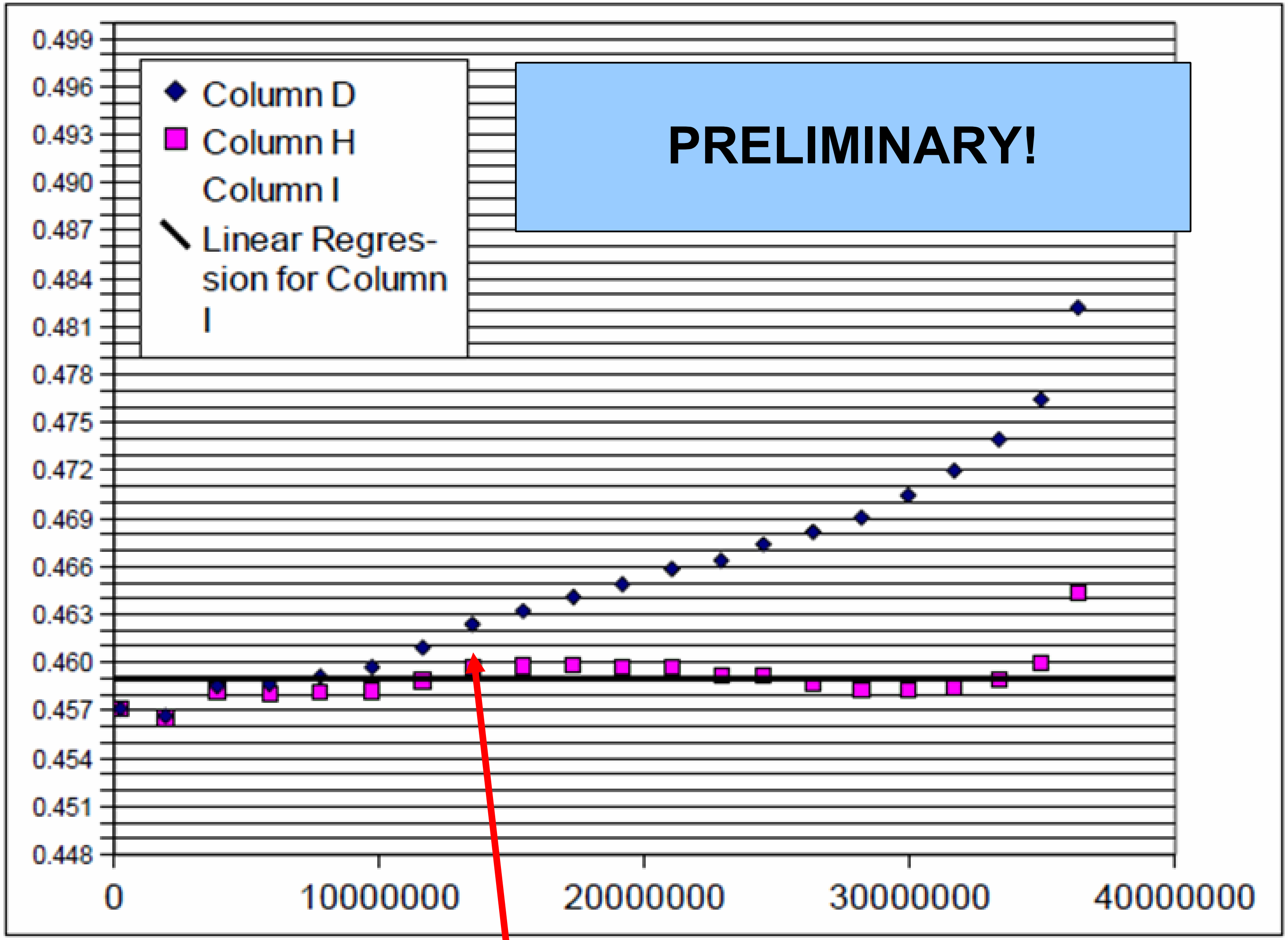


A preliminary look at Linearity

Total signal in one aperture vs. avg. signal per pixel in a brighter aperture



Deviation from Linearity



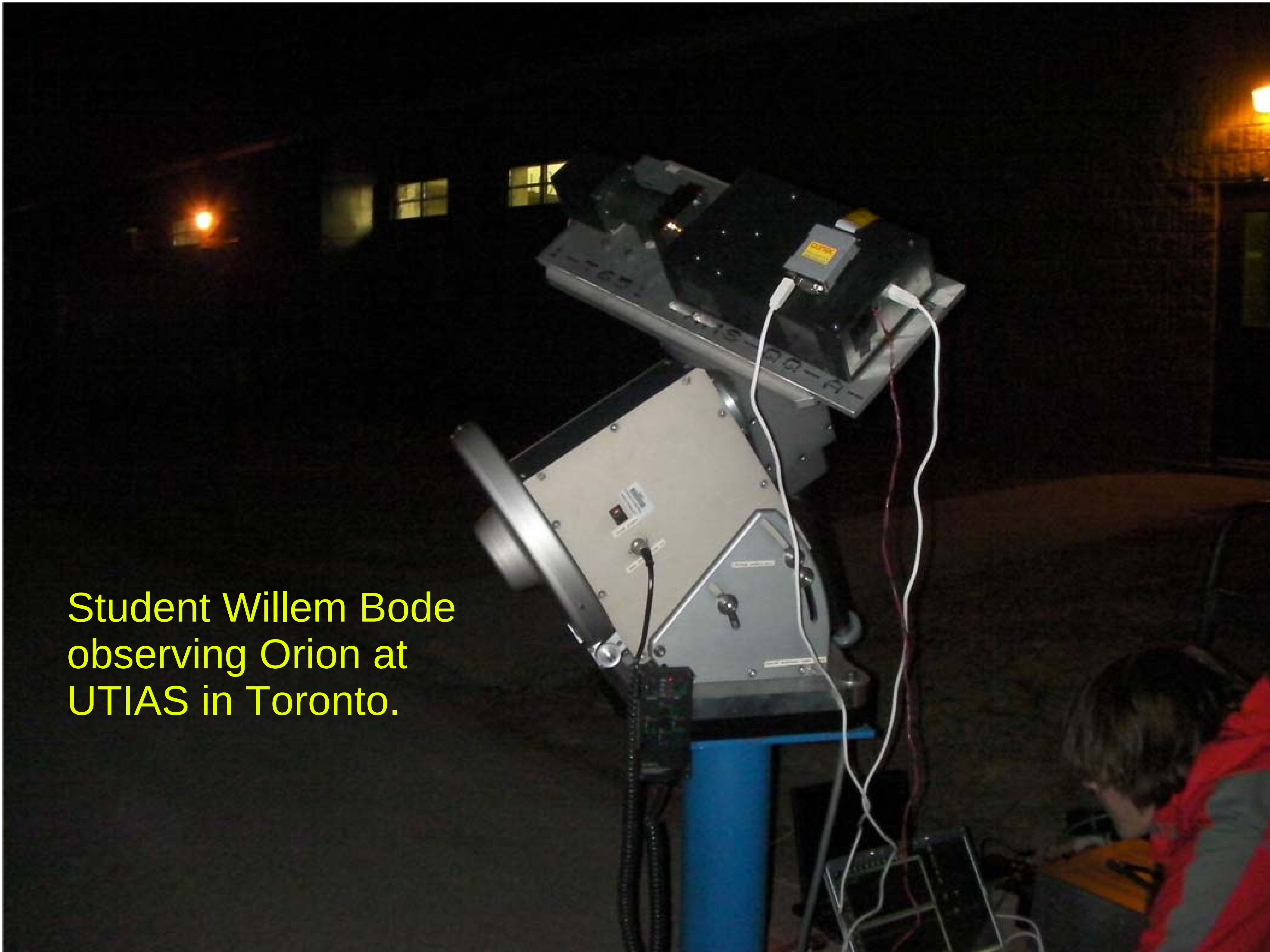
PRELIMINARY!

Non-linear fitting being done

Further measurements have been made but still need to be analysed, involving a non-linear fitting technique to obtain the actual non-linearity from the ratio method used here.

So far, the non-linearity does not appear to be severe, but will need to be accurately calibrated.

In Progress: Observations on real star fields, using a Paramount tracking platform on loan from RMC, Kingston. This is testing for response and undersampling errors.



Student Willem Bode observing Orion at UTIAS in Toronto.

Orion's Belt, observed at UTIAS. This is only a fraction of the field.

Conclusion

Ground-based pre-launch testing of the BRITE instrument is possible both in the lab and outside looking at real stars. Testing has involved characterisation of the instrument as well as formal engineering acceptance testing to ensure that specifications are met. This will now be followed by pre-launch calibrations.