SLAC-WP-105

Quantifying the Performance of Charge-Coupled Devices in Ambient Conditions

Ryan Dungee

Office of Science, Science Undergraduate Laboratory Internship (SULI) Program

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internship (SULI) program, under Contract No. DE-AC02-76SF00515.

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Quantifying the Performance of Charge-Coupled Devices in Ambient Conditions

A Tale of Love and Loss

Ryan Dungee

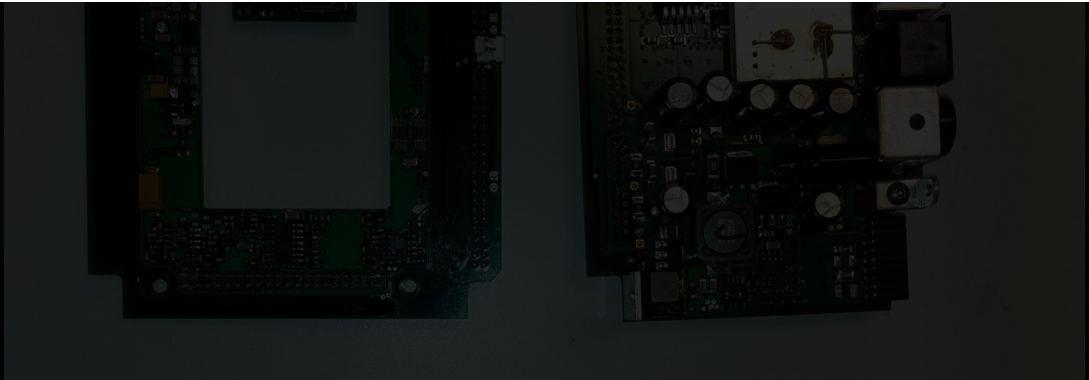
Kitt Peak Observatory, taken by Joe Parks (link)

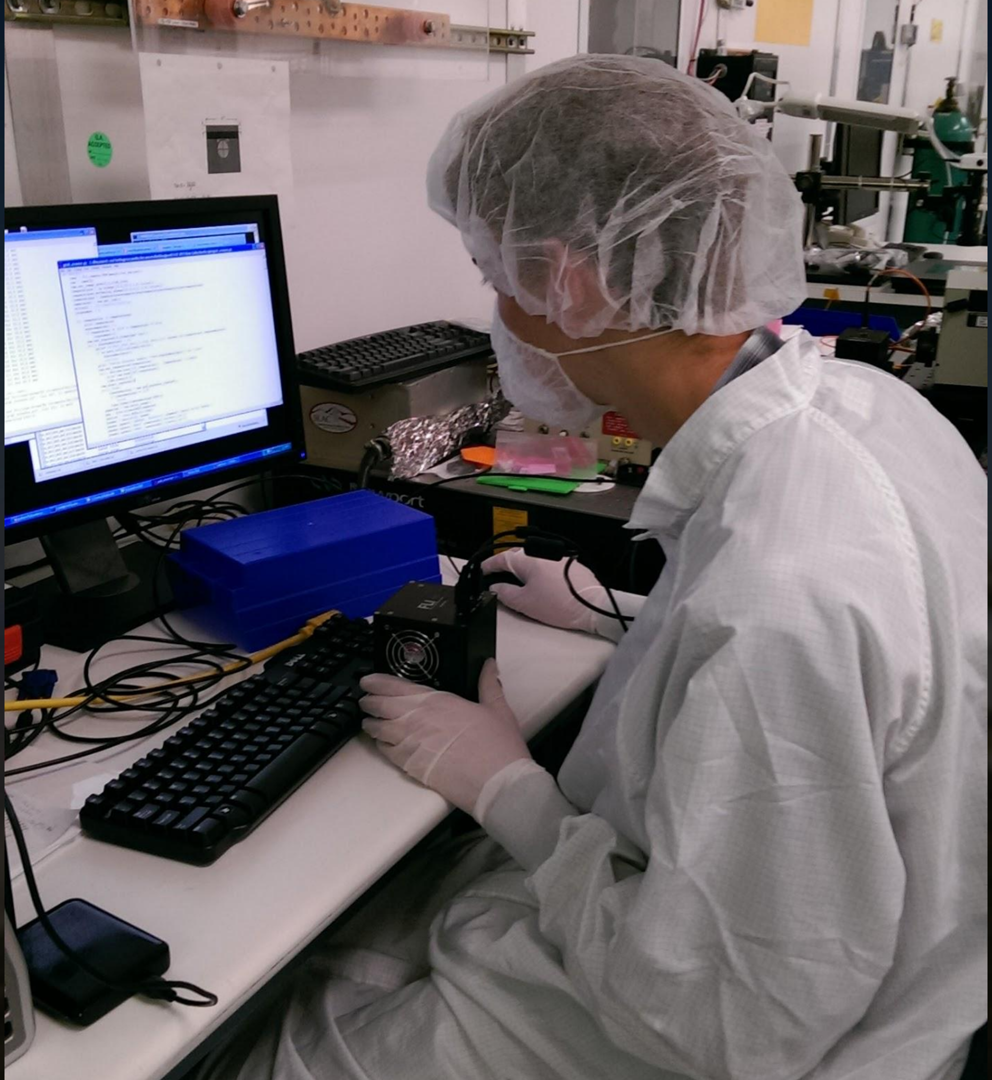
Telescope surveys have given us a great deal of information about our universe, but the images they capture carry with them an inherent limitation. The question then is how do we take this information to the next level? The answer: the Dark Energy Spectroscopic Instrument (DESI). DESI is an instrument that will measure the distance to tens of millions of galaxies in our night sky. This information can be combined with already existing images to construct a three dimensional map of our universe providing a great deal of new opportunities for cosmological research.

The DESI guidance system consists of 10 detectors called charge-coupled devices (CCDs). Each CCD is made of silicon atoms that emit electrons when struck with light, the electrons are counted and then used to reconstruct an image. But, CCDs suffer from an issue known as 'dark current' which are false counts that come from thermal motions of the silicon atoms. This is particularly problematic since they contribute to the uncertainty of a measurement without contributing to our signal. This causes a drop in the signal to noise ratio, a value that needs to be maximized in order to meet DESI's high precision requirements.

This summer was spent ensuring the DESI guidance system would meet its specifications. Data was collected using a CCD of the same type that would be used on DESI and the effectiveness of dark current removal was tested. Exposures were taken for a wide range of temperatures and exposure lengths and a number of dark current removal methods were implemented. While further testing is required, the initial results are quite promising and the DESI guidance system is on track to meet its specifications.

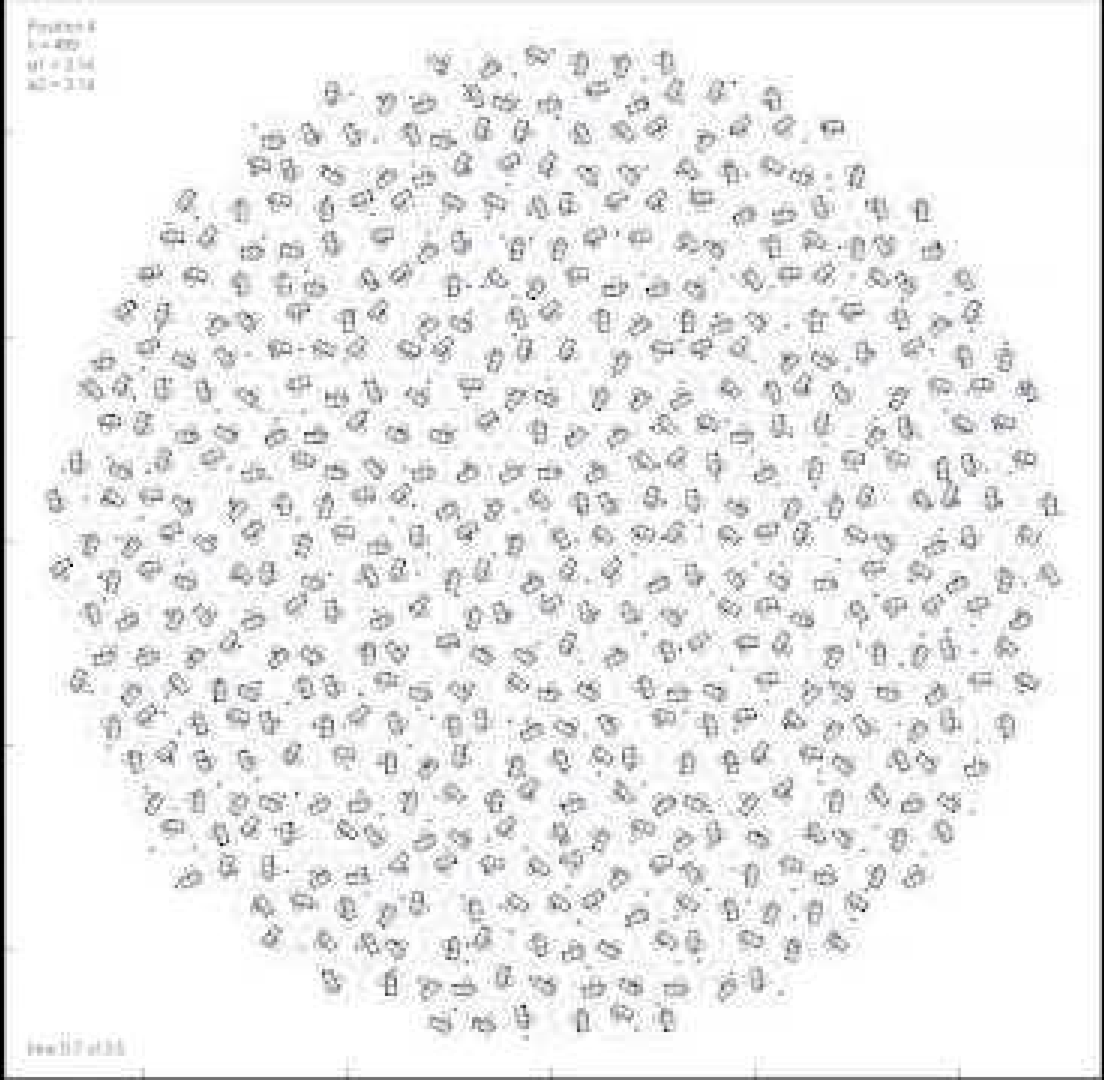
```python

    def set_image_area(self, ul_x, ul_y, lr_x, lr_y):
        #FIXME does this API call actually do anything?
        left, top, right, bottom   = (c_long(ul_x),c_long(ul_y),c_long(lr_x),c_long(lr_y))
        row_width = (right.value - left.value)/self.hbin
        img_rows  = (bottom.value - top.value)/self.vbin
        self._libfli.FLISetImageArea(self._dev, left, top, c_long(left.value + row_width), c_long(top.value + img_rows))

```





What is DESI?

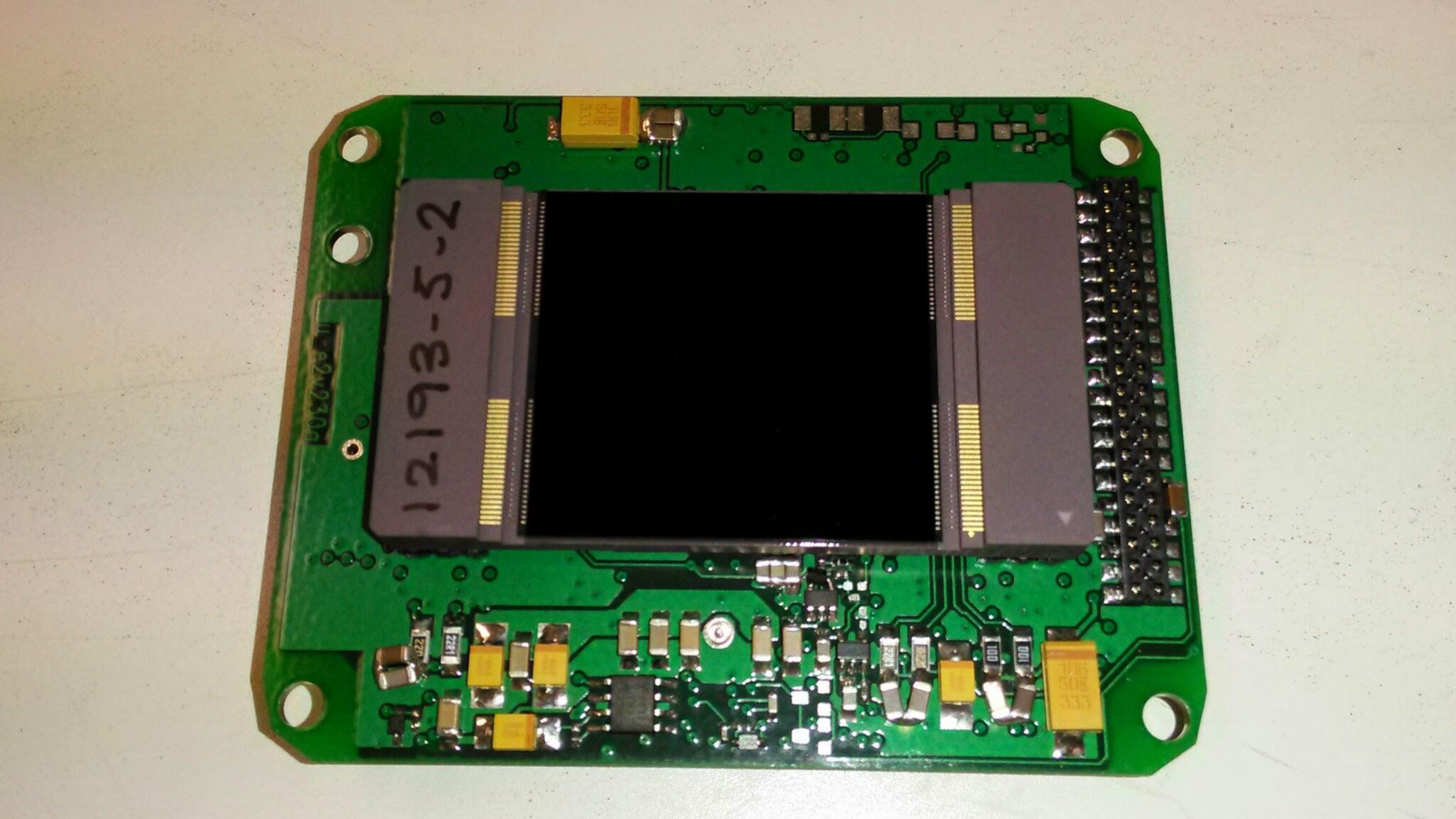
- Dark Energy Spectroscopic Instrument
- Building a 3D map of the Universe
  - Measures distance to the objects
  - Allows for tighter bounds on the expansion history of the Universe
- 5000 Optical Fibers
  - Each fiber receives light from an individual galaxy
  - This is fed into spectrographs to measure the redshift



Animation Credit: (link)
Joseph Silber of Berkeley Lab

What are you pointing at?

- Guidance Focus and Alignment
  - The data will be just sky spectra unless you point in the right direction
- An array of 10 CCDs
  - 6 for guidance - determining what we are looking at
  - 4 for Focus and Alignment - making sure the image is in focus
- High precision requirement
  - Even small misalignments can significantly reduce the brightness of our signal
- Ambient Temperature
  - This minimizes potential introduction of noise during the collection of data


12193-5-2

Tour de France Winning Silicon

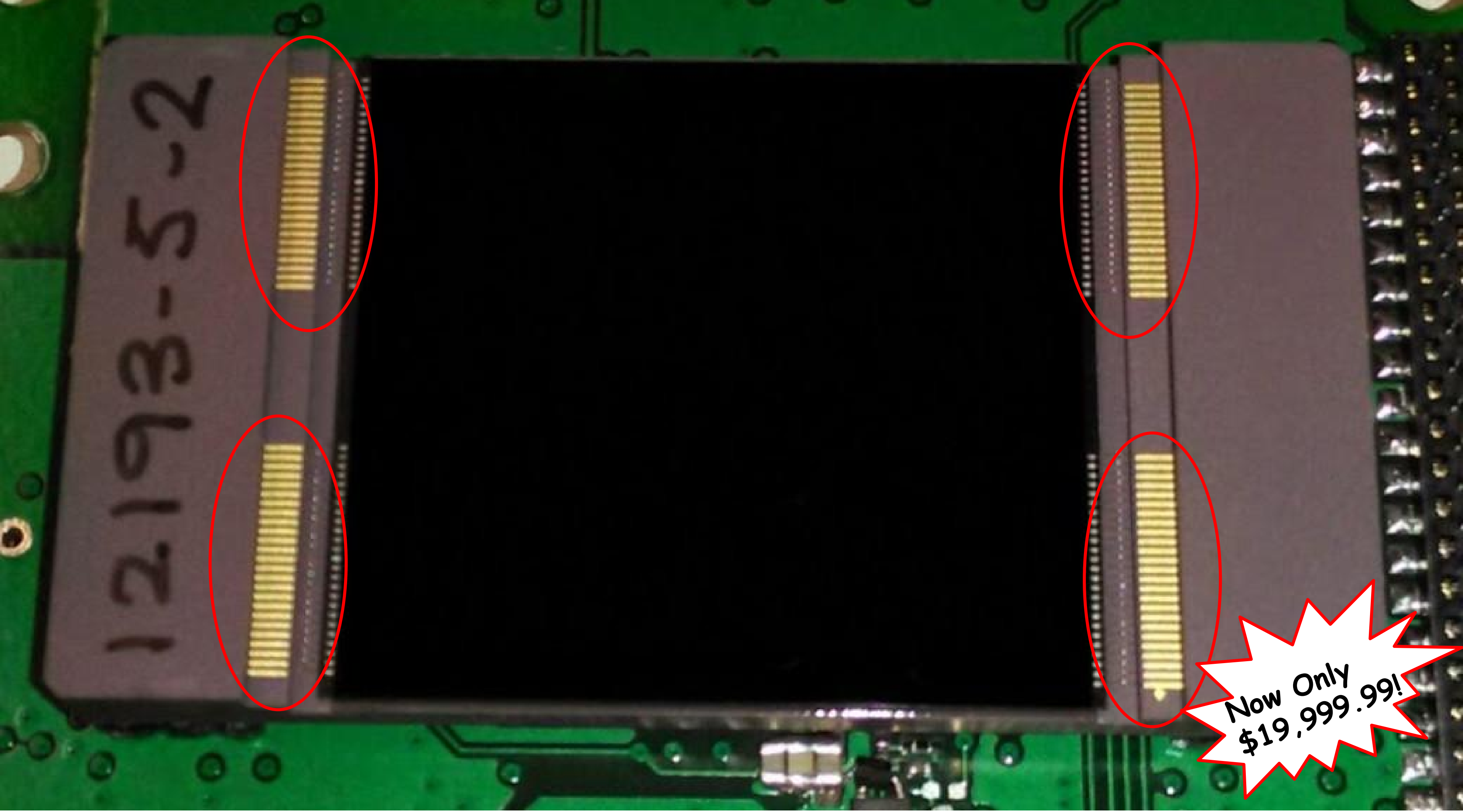
- Charge-Coupled Device
  - CCDs are integrated circuits printed on a silicon substrate
- Photoelectric Effect
  - The silicon is doped in order to make it susceptible to optical wavelengths
- Gates
  - Emitted electrons are pulled to positively charged gates
- Electron Counting
  - The number of electrons a gate receives is counted, one electron is roughly one photon

The Dark Side of Thermodynamics

- Dark current
  - Signal the CCD reads even in perfectly dark conditions
- Thermal physics is not your friend
  - Thermal motions of the atoms in the array can knock electrons free
- The electronics count electrons
  - No way to distinguish thermal electrons from photoelectrons
- Temperature dependence
  - Higher operating temperatures means more dark current

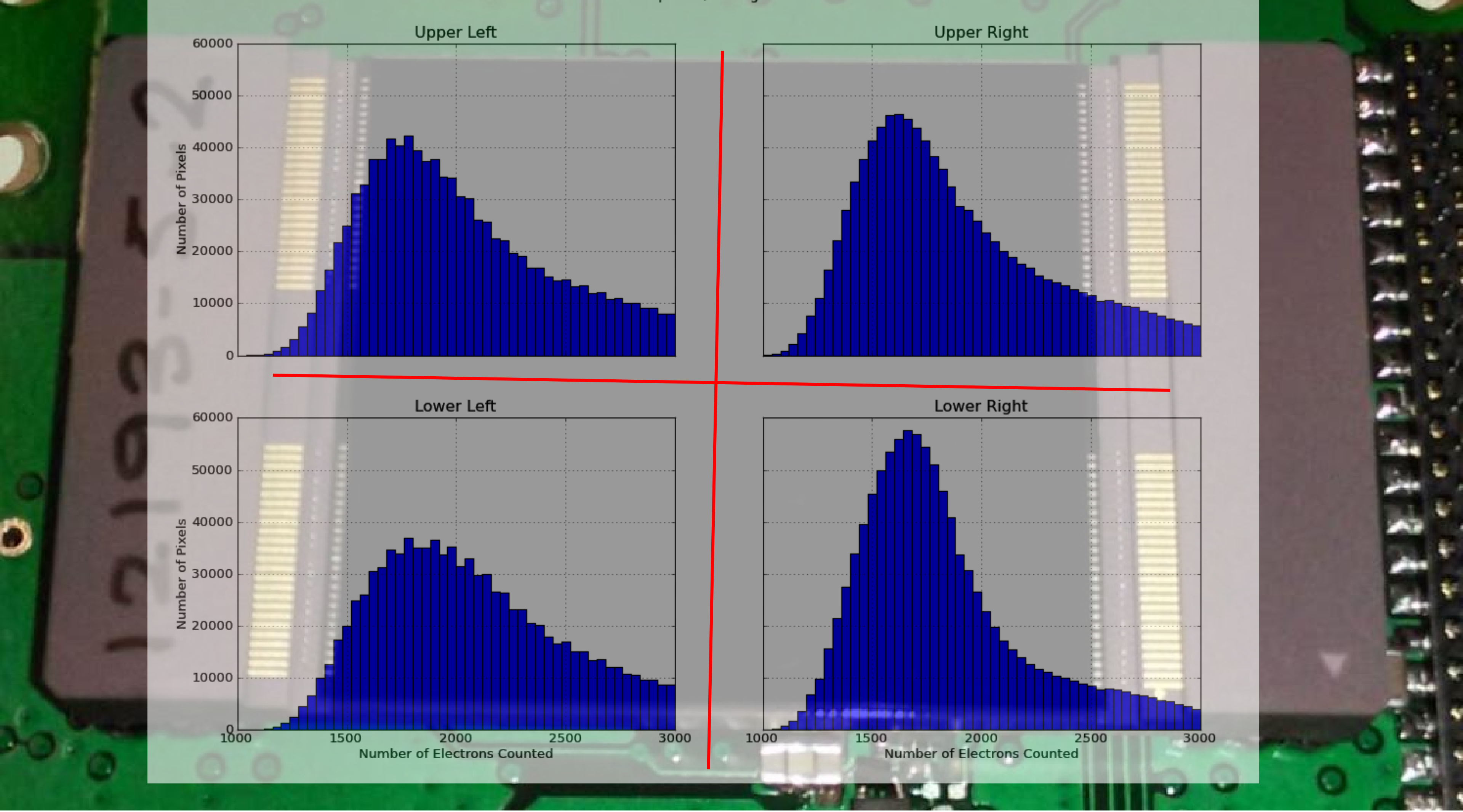
How do you fix this?

- Cooling
    - Take advantage of the temperature dependence of dark current
- Dark Frames
    - Take dark exposures using your CCD and subtract these frames from your images
- Interpolation
    - Take dark frames at a specific set of temperatures and interpolate for images if necessary

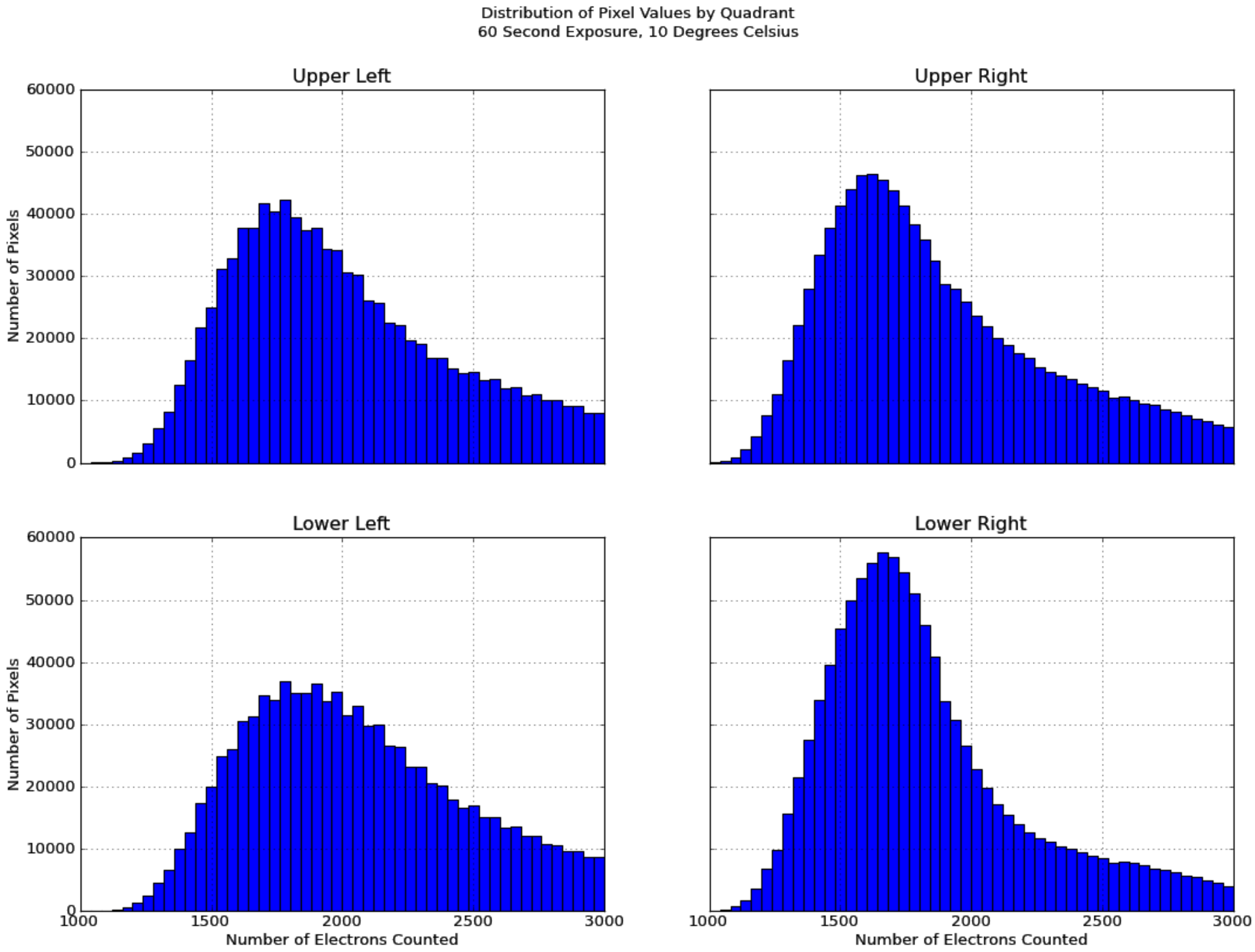

12193-5-2
Now Only
$19,999.99!

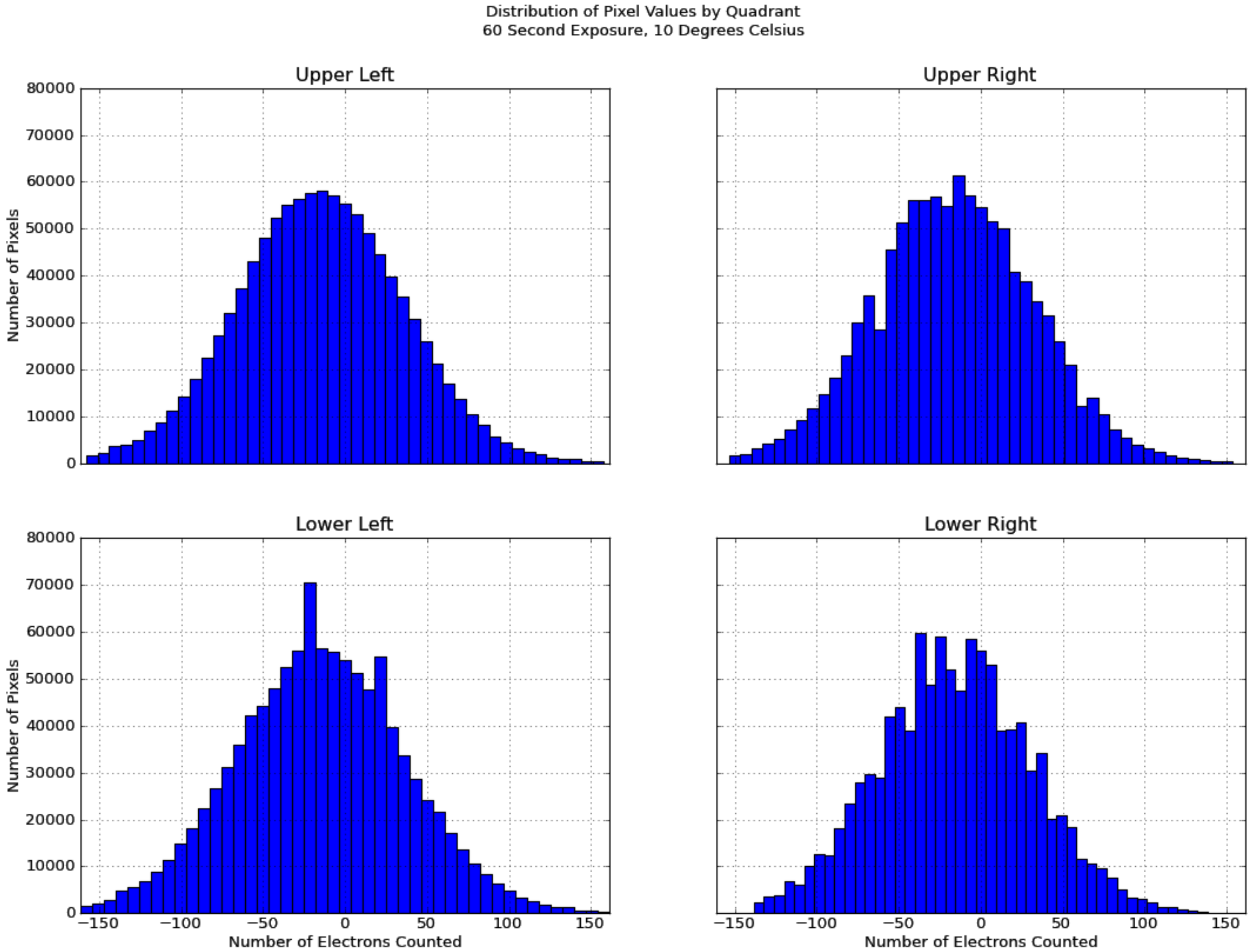
What am I looking at?

- Four channel readout
  - One CCD effectively operating as four independent, but smaller CCDs
- Different circuitry
  - Each channel has its own circuitry and thus its own biases/uncertainties
- Four subplots
  - Each quadrant has information plotted for it individually

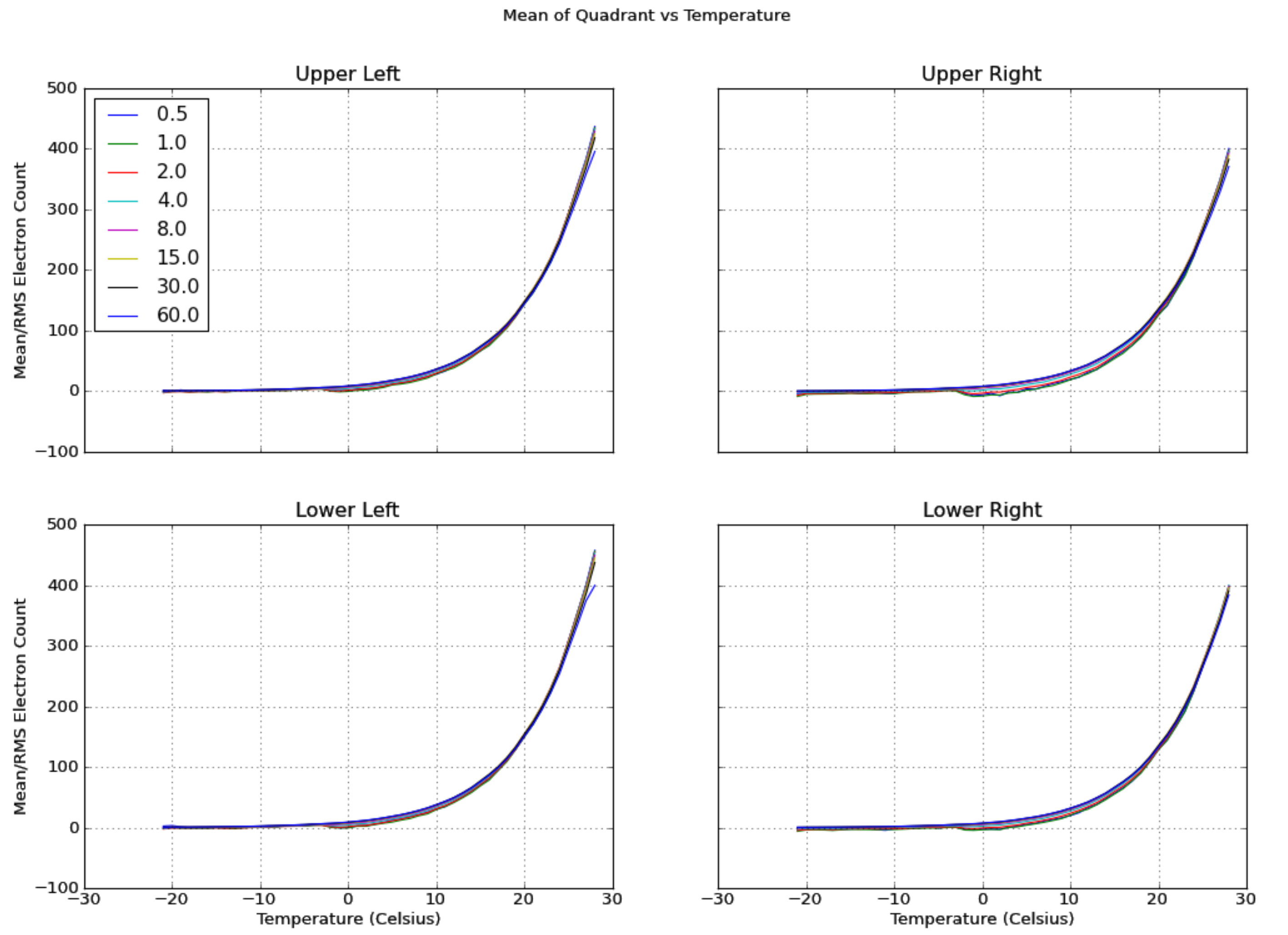


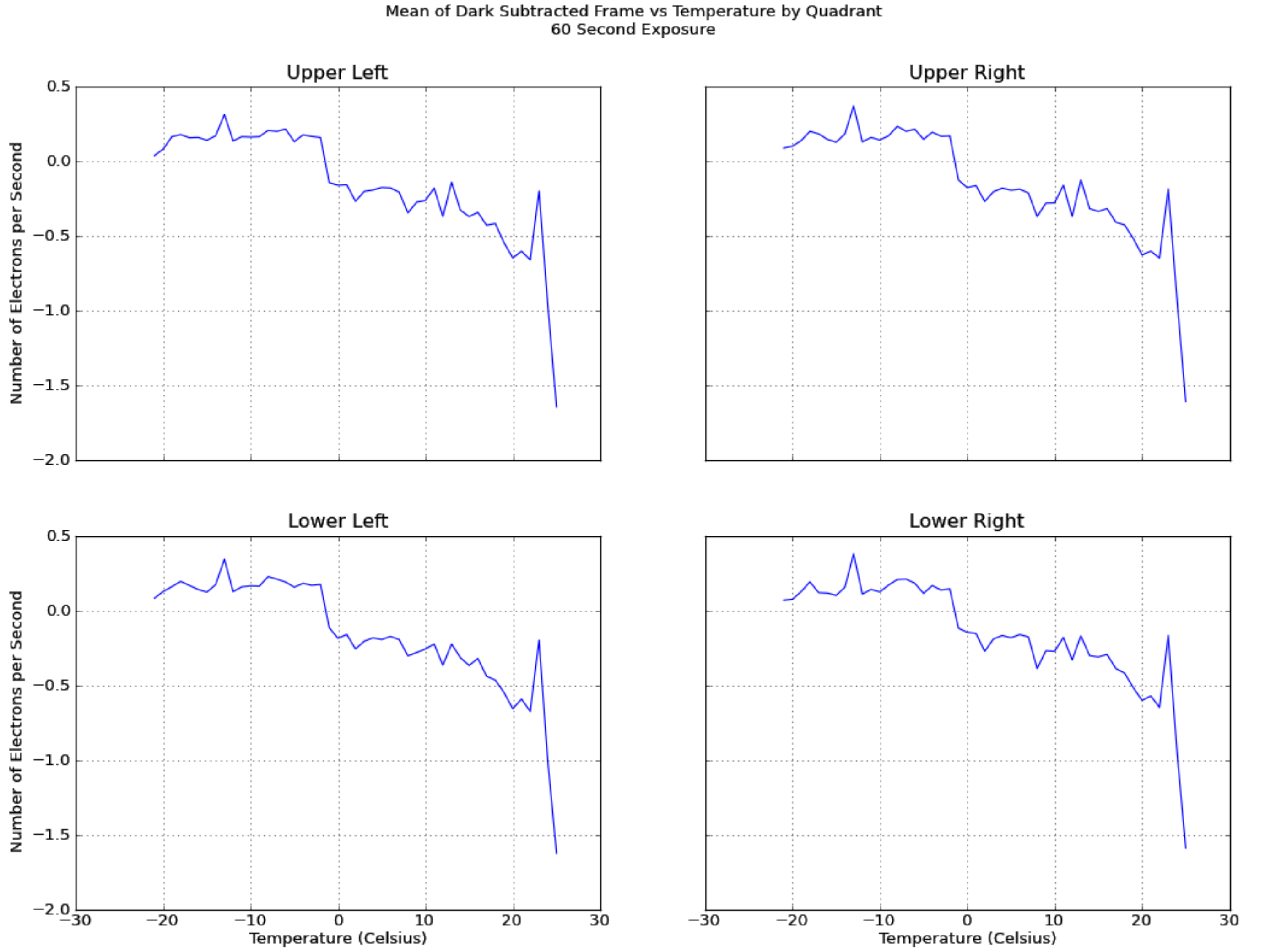
Upper Left
Upper Right
Lower Left
Lower Right
Number of Pixels
Number of Electrons Counted
0
10000
20000
30000
40000
50000
60000
1000
1500
2000
2500
3000


Distribution of Pixel Values by Quadrant
60 Second Exposure, 10 Degrees Celsius
Upper Left
Upper Right
Lower Left
Lower Right
Number of Pixels
Number of Electrons Counted
0
10000
20000
30000
40000
50000
60000
1000
1500
2000
2500
3000

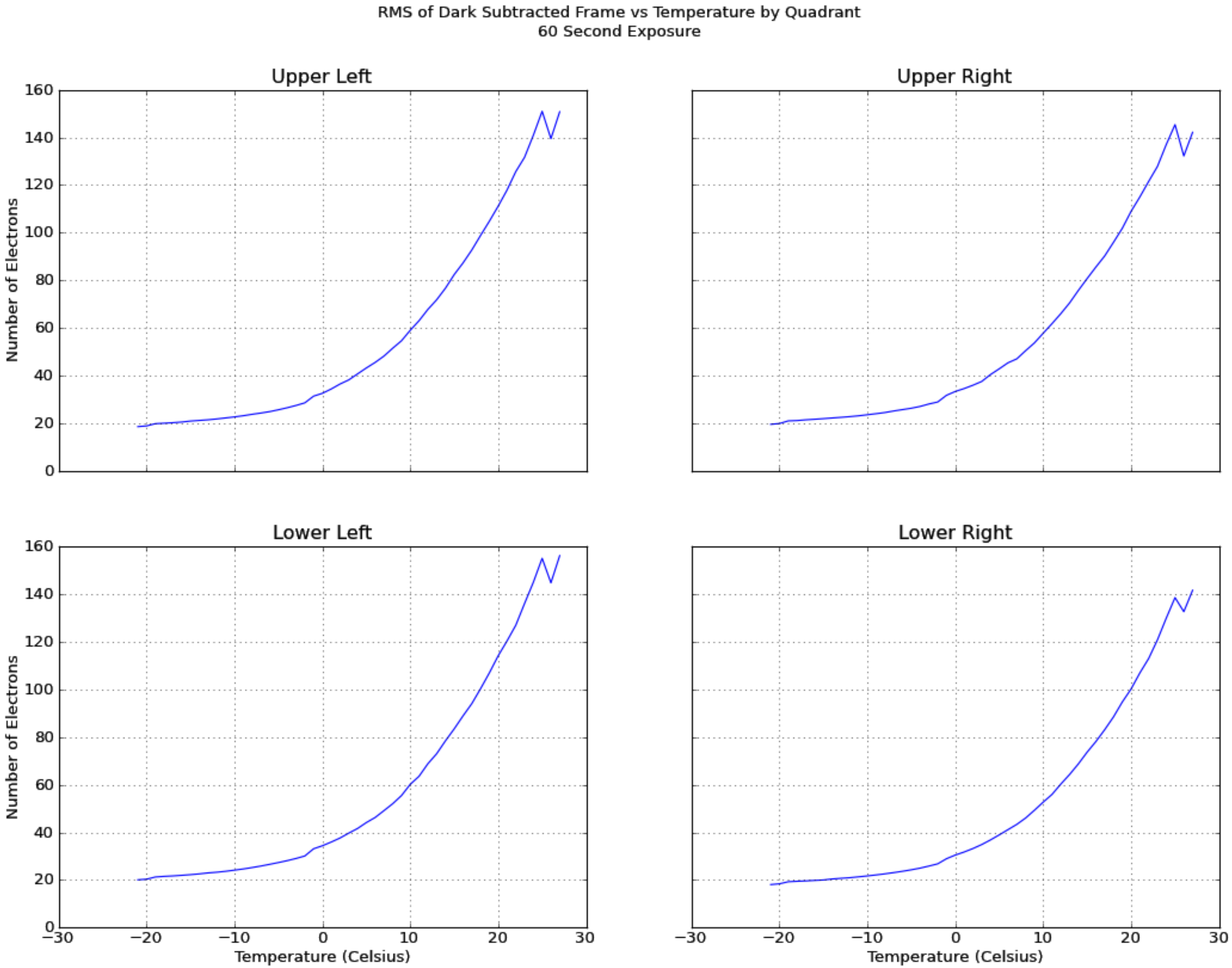


Distribution of Pixel Values by Quadrant
60 Second Exposure, 10 Degrees Celsius
Upper Left
Upper Right
Lower Left
Lower Right
Number of Pixels
Number of Electrons Counted
0
10000
20000
30000
40000
50000
60000
70000
80000
−150
−100
−50
0
50
100
150


Mean of Quadrant vs Temperature
Upper Left
Upper Right
Lower Left
Lower Right
0.5
1.0
2.0
4.0
8.0
15.0
30.0
60.0
Mean/RMS Electron Count
Temperature (Celsius)
500
400
300
200
100
0
−100
−30
−20
−10
0
10
20
30



Mean of Dark Subtracted Frame vs Temperature by Quadrant
60 Second Exposure
Upper Left
Upper Right
Lower Left
Lower Right
Number of Electrons per Second
Temperature (Celsius)
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−30
−20
−10
0
10
20
30


RMS of Dark Subtracted Frame vs Temperature by Quadrant
60 Second Exposure
Upper Left
Upper Right
Lower Left
Lower Right
Number of Electrons
Temperature (Celsius)
0
20
40
60
80
100
120
140
160
−30
−20
−10
0
10
20
30

Conclusions and Acknowledgements

- Trust but verify your open source software
- Thermal Physics is not your friend, but you can still beat it
- Cooling will not be necessary for DESI

- Department of Energy/SULI
- Enrique Cuellar and Maria Mastrokyriakos
- Kevin Reil