WAO Summer 2010 UROP
Photometry Project - Final Report
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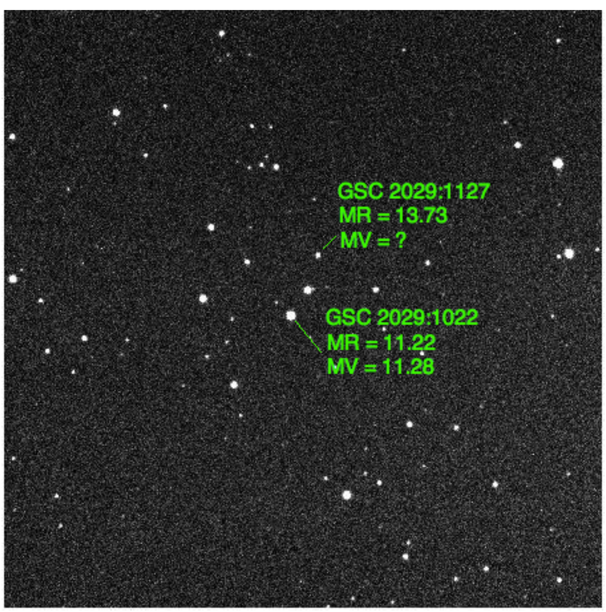
1. Introduction

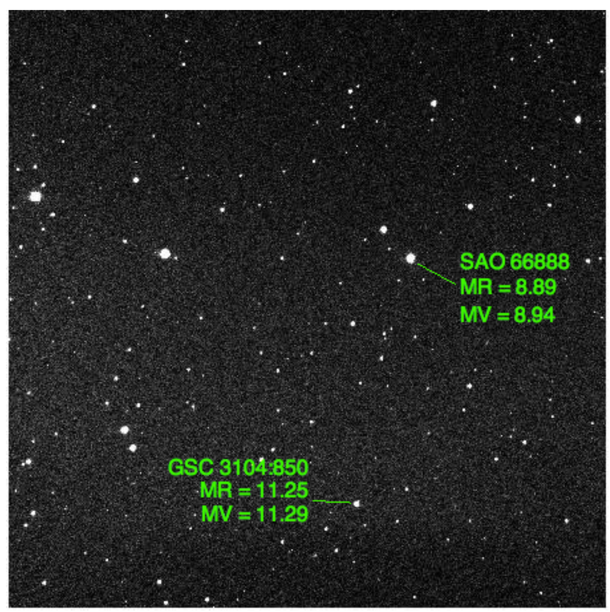
The goal of our project was to determine the technical capabilities of the cameras mounted on Piers 2, 3, and 4. All three telescopes are 14" Celestron C14 Schmidt-Cassegrains; all three cameras are SBIG STL-1001E CCDs. However, due to inevitable manufacturing defects, the cameras have slightly different capabilities. Three quantities were measured as a function of exposure time:

1. Limiting magnitude: The highest (dimmest) apparent magnitude resolvable by the telescope + camera.
2. Signal to noise (S/N): The average ratio of signal to noise for the stars visible in an image.
3. Dark current: The thermal noise in the camera, as measured by dark (closed-shutter) frames.

2. Data Collection



Field 1



Field 2

Before data were collected, we had to determine a set of standard star fields to use. This would allow consistency and easy comparison between data sets; we ultimately decided to use two (in case one field was too bright for a certain filter or was somehow obstructed that night).

The fields had to contain the following things:

- A good (but not crowded) distribution of stars from 11^{th}-16^{th} magnitude (as measured by TheSky software, which doesn't resolve stars above 16^{th})
- Few stars below 9^{th} magnitude (to avoid over-saturation at high exp. times)
- Two comparison stars with M_R and M_V values from a reliable catalogue (Tyc/Hip)
    - A bright one for low exp. times, and a dimmer one (upper 11^{th}-13^{th} magnitude) to avoid saturation at ~240s
    - Field 1 has only two good comp stars, one of which lacks a catalogued M_V value, so we had to use Field 2 for the V filter data

The objective of data collection was to obtain full sets of data on three different filters (Clear, Red and Visible) for all three piers - nine sets in total. I collected the data for Pier 2 and 4, while my partner collected data for Pier 3.

Each set consisted of five science frames taken at each of the following exposure times (in seconds): 0.5, 1, 2.5, 5, 10, 20, 30, 60, 90, 120, 180, 240. In addition, five dark frames were taken at each exp. time during each observing night. For each filter used that night, a set of ten flat frames was taken at a low exp. time (usually 2.5s or 5s) using the dusk/dawn sky.

Data collection took place over the course of June and July. The data used to characterize Piers 2 and 4 was collected over five nights; Field 1 was used for both Clear filters, and Field 2 was used otherwise. Cameras were cooled to -25°C.

3. Data Analysis

The main steps of analysis were:

1. Data reduction using IRAF (commands used: *imcombine, imarith*)
2. Photometry in IRAF + DS9 (*imexam, daofind, phot, txdump*)
3. Magnitude calibration and error correction in Excel
4. Extracting limiting magnitude, S/N, and dark current

Once the raw FITS images from a given night were obtained, they had to be reduced in IRAF before photometry could be performed. Each set of flats and darks was combined using the *imcombine* command, yielding a master dark frame for each exposure time and a master flat frame for each filter used. Using the *imarith* command, the appropriate dark frame was subtracted from each science image as well as the master flats. Each flat was then divided by its mode value (obtained with *imstat*). Finally, each set of science images was divided by the appropriate master flat frame.

To locate the stars in each frame, the *daofind* command was used in batch (non-interactive) mode - there was simply too much data for interactive mode to be a feasible option. Because batch mode was used, there was no way to directly identify false detections (hot pixels, satellites, etc). Therefore, it was essential to make the *daofind* parameters as precise as possible. To accomplish this, the *imexam* command was used in interactive mode, in tandem with the DS9 image viewing program. At each exposure time, the average FWHM was determined holistically, from a large set of manually selected stars, to an accuracy of 0.5 pixels (using an image scale of 1:1). The standard deviation of background noise was also determined holistically, from a large set of manually selected background spots, to an accuracy of a few counts for each exp. time. The FWHM ranged from 2-4 pixels, and sigma ranged from 8-30 pixels (both tended to increase linearly with exposure time). Data sets with much higher FWHM values were discarded.

In addition to FWHM and sigma, the following *daofind* parameters were used at all exposure times:

- max good data value = 55000. counts (to avoid detection of oversaturated stars)
- detection threshold = 5σ

Once .coo (coordinate) files had been obtained from *daofind*, the *phot* command was used in batch mode to obtain photometric data for each star. Once again, choosing the right parameter values was essential in order to obtain the most accurate magnitudes and errors:

- max good data value = 55000. counts
- *salgorithm* (background value sampling) = mode
- *annulus* (distance from center where sky annulus begins) = 15 pixels
- *dannulus* (width of sky annulus) = 5 pixels
- *aperture* (radius of star aperture) = 8,10,12 pixels (three apertures were used, but only the r=10 values were ultimately used)

For other parameters, default values were used.

Using the *txdump* command, the coordinates, magnitudes and magnitude errors of all stars were dumped into a text file and imported into Excel. To eliminate false detections, all "stars" with errors above 0.5 magnitudes were eliminated, as well as any data points with calculation errors/INDEF values.

In order to convert instrumental magnitudes (as calculated by *phot*) into apparent magnitudes, the appropriate comparison star was manually identified in each image, and its instrumental magnitude was determined from coordinates. For each image, the calibration factor was found:

$$\textit{calibration factor} = M_{instrumental} \textit{ of comp star} - M_{apparent} \textit{ of comp star}$$

Then the following equations were applied to the data:

$$M_{apparent} = M_{instrumental} - calibration\ factor$$

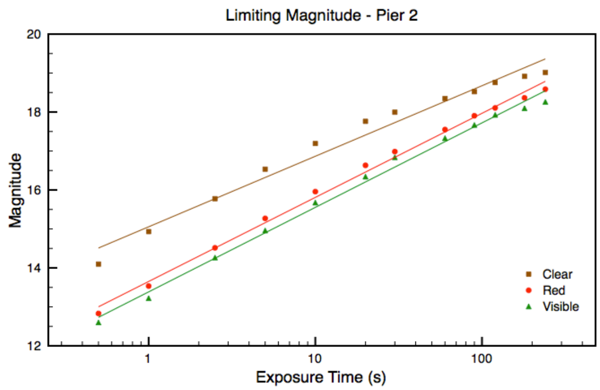
$$S/N = 1/(magnitude\ error)$$

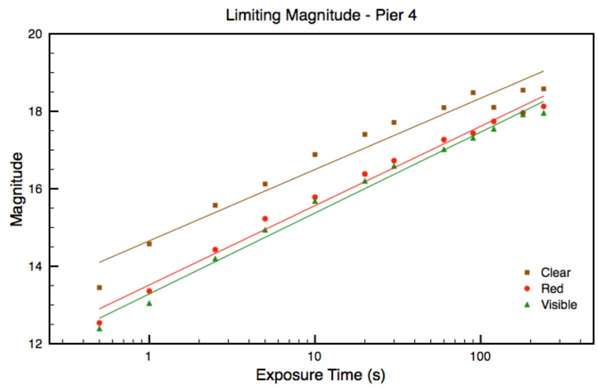
At a given exposure time, each frame had its own limiting magnitude - the median of these was used in the final results. Similarly, each exposure time had its own set of S/N values - these were sorted by magnitude into six lists (see Results). The mean value of each list was used in the final results. These processes were repeated at each exposure time, for each telescope and filter.

In order to obtain dark current data, the *imstat* command was used to obtain the mean dark count value for each master dark frame in a given set. This process was repeated for three sets on each telescope.

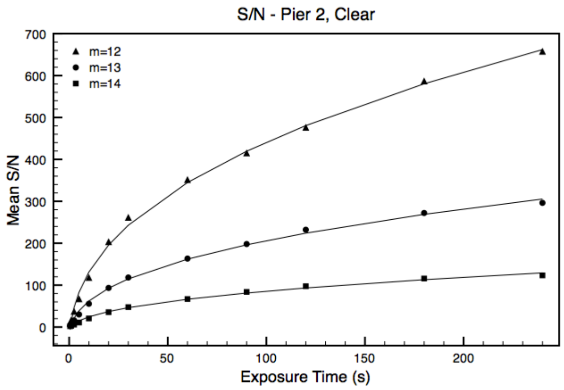
4. Results

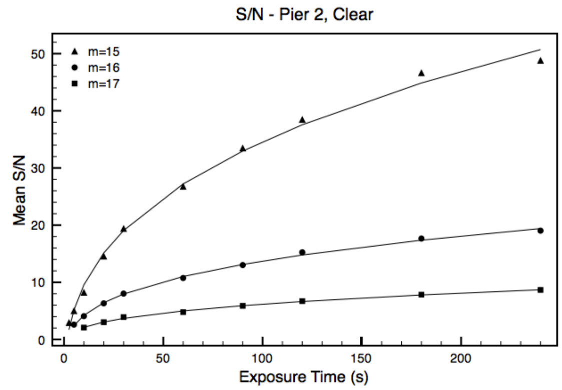
The graphs displayed here are only a small sample. For all graphs, see Appendix A.



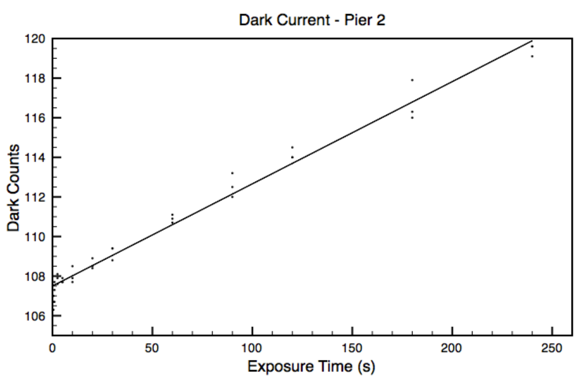


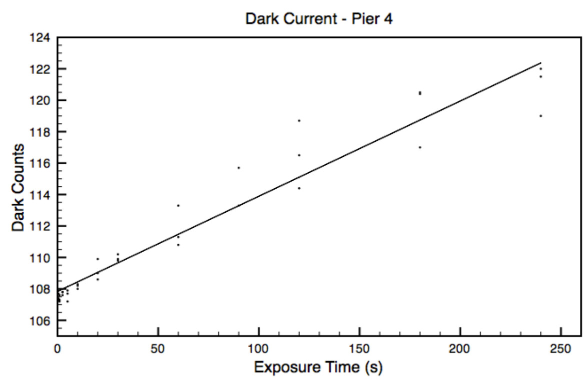
The limiting magnitudes have $\log_{10}$ fits; here, the x-axis is log-scaled to provide a linear appearance. As expected, limiting magnitude increases logarithmically with time, approaching a realistic (although not absolute) limit of what the cameras are capable of. This "hard limit" hovers around 19^{th}-20^{th} magnitude, depending on telescope and filter. The Clear filter is consistently the "best", which reflects its high quantum efficiency across all visible wavelengths. The Visible and Red filters have similar limiting magnitudes (with R being slightly better on P2 and P4, while V is slightly better on P3), although their quantum efficiencies peak in different bands.





In the S/N graphs, it should be noted that "m=12" means "stars of magnitude 12.0-13.0" and so on. Brighter stars tended to "max out" at S/N = 1000 (see Sources of Error); dimmer stars were too scarce. The curves are generalized power fits ($Ax^B + C$), and range from square-root to nearly linear. As expected, mean S/N increases with exposure time and brighter magnitude. All other things being equal, the Clear filter provides the highest S/N; once again, R and V are close in performance. Some sets are better than others; in particular, the R data on P3 is noisy (see Sources of Error).





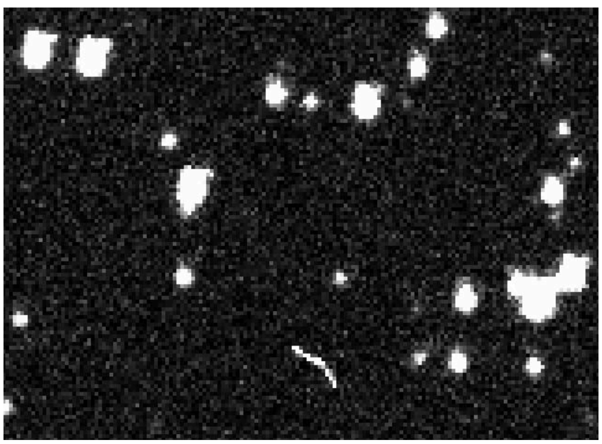
The dark current is expectedly linear and very similar on all three cameras.

5. Sources of Error

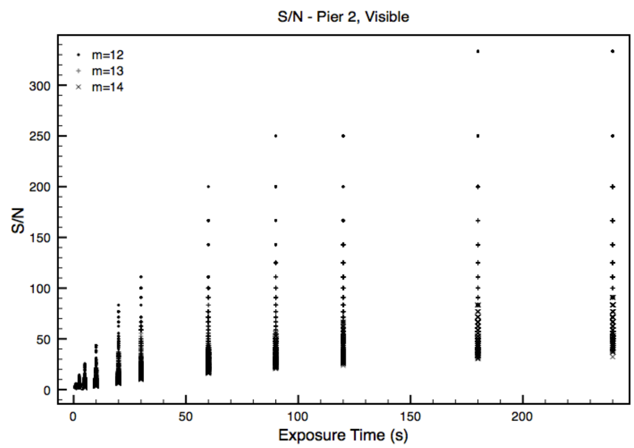
Sources of error fall into two categories - those that affected data collection, and those that affected analysis.

Weather (particularly cloud cover) was a constant problem, especially during July, when no data could be collected for over three weeks due to bad weather. Several times, we went to Wallace expecting clear skies, only to get 'clouded out' in the middle of the night. Records indicate that this happened during P3R data collection, which may explain the noisiness of that data. In order to create better fits, several aberrant data points had to be removed from the P3R data.

In addition, Pier 2 and its Chronos mount had several autoguiding and tracking problems. The autoguider often has difficulty making fine adjustments, leading to "wobbly" stars in long-exposure frames. This led to incorrect FWHM values, multiple detections, and errors during photometry. As a result, we recommend only turning the autoguider on for 120+ second images (to avoid streaking). The mount was also prone to several tracking problems, such as failing to slew, moving to the slew limit when valid paths were available, and not responding for several minutes at a time. It is suspected that the "Find Home" command may have been corrupted, because these issues always arose after attempting to find home. The problems were resolved by syncing the telescope to a bright star before doing anything else (aside from taking dusk flats, which can be done in the parked position). When something went wrong, I would park the telescope and restart everything, which worked well.



Autoguider wobble



S/N quantization

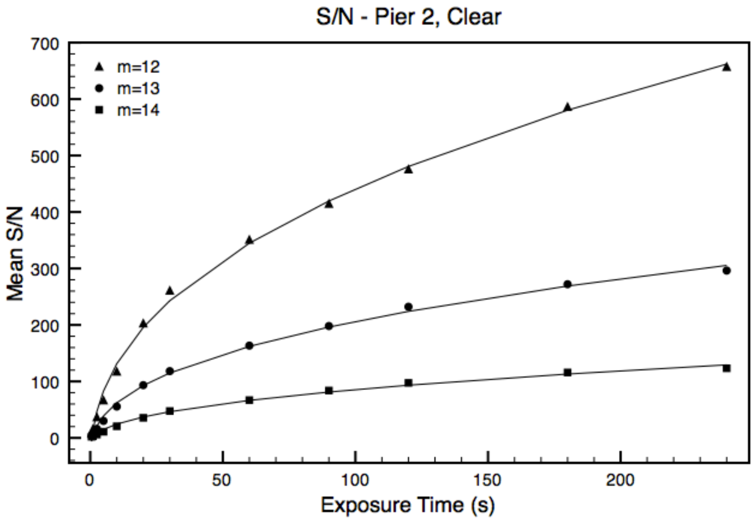
The main obstacle of analysis was presenting the large amount of S/N data in a concise form. Our initial S/N graphs showed discrete "blobs" of data, instead of the expected smooth distribution. This is most likely due to rounding errors made by the *phot* algorithm, which computes magnitude error to 3 decimal places. Sufficiently low errors are limited to values of .001, .002, etc., confining high S/N values to discrete points. For the same reason, S/N maxed out at 1000, because the lowest possible error is .001. In addition, the large amount of data rendered most graphs unreadable. To solve this, the mean S/N was computed for each exposure time.

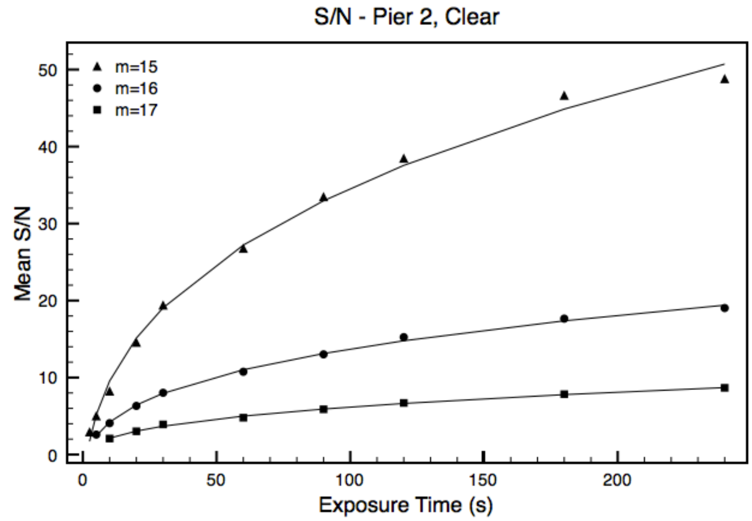
The P3 Clear data was originally very noisy, but we discovered that the darks used to reduce it were nonlinear. The data was re-reduced with linear darks, and the result was a major improvement. The cause on the nonlinearity was most likely equipment failure (e.g. an error with the camera's cooling system).

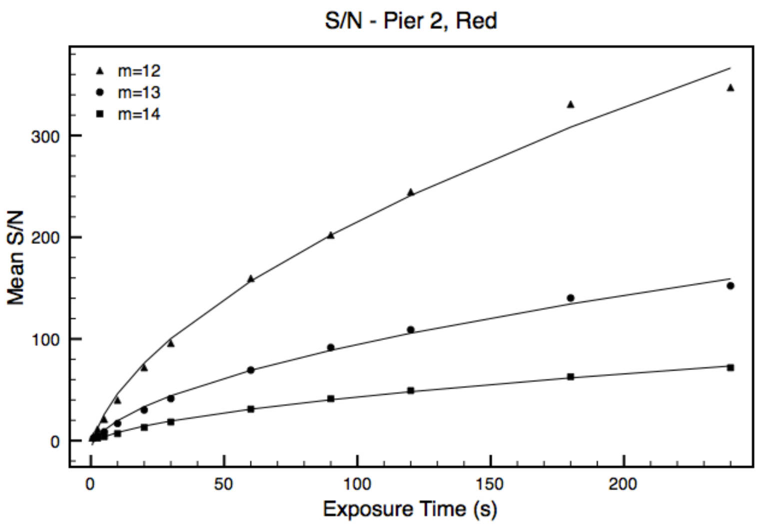
6. Acknowledgements

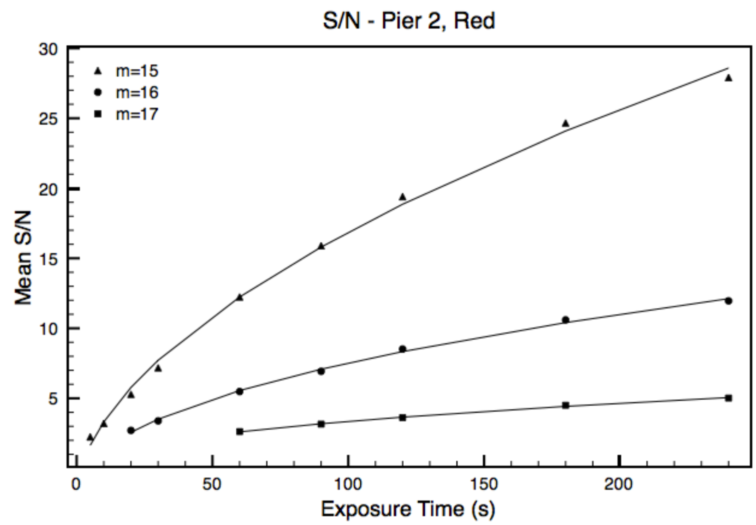
I would like to thank my partner Kathy Tran and the other UROP students, as well as my adviser Dr. Michael Person, Prof. Jim Eliot, and WAO Site Coordinator Tim Brothers.

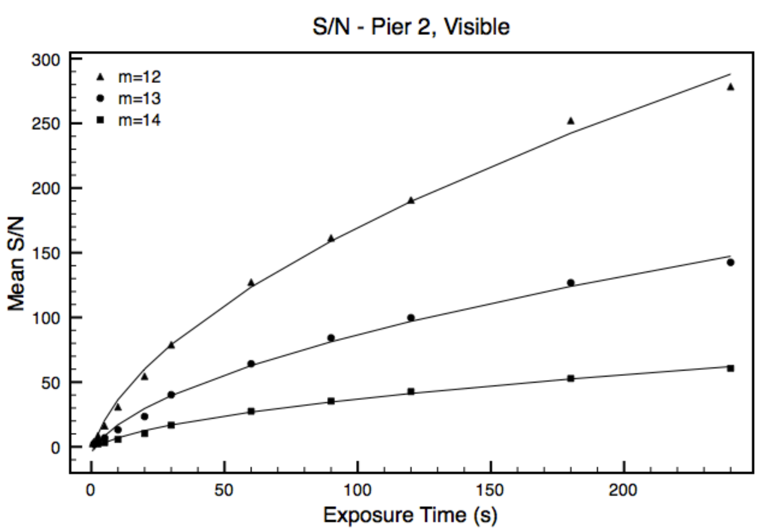
Appendix A. Graphs

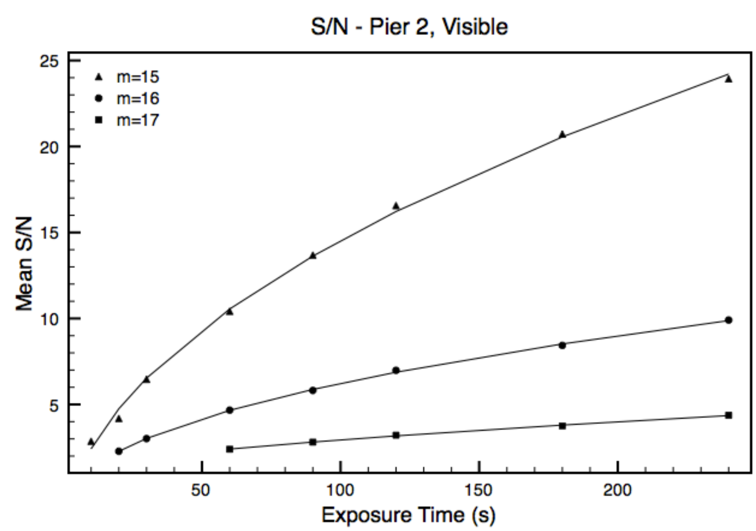


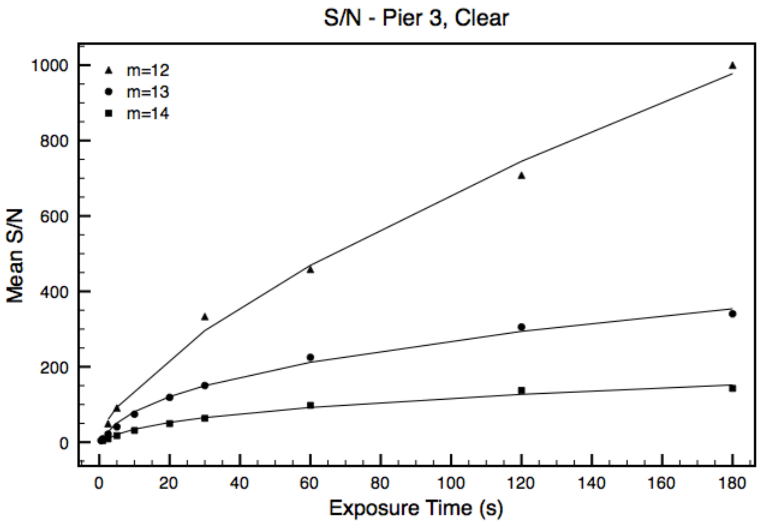


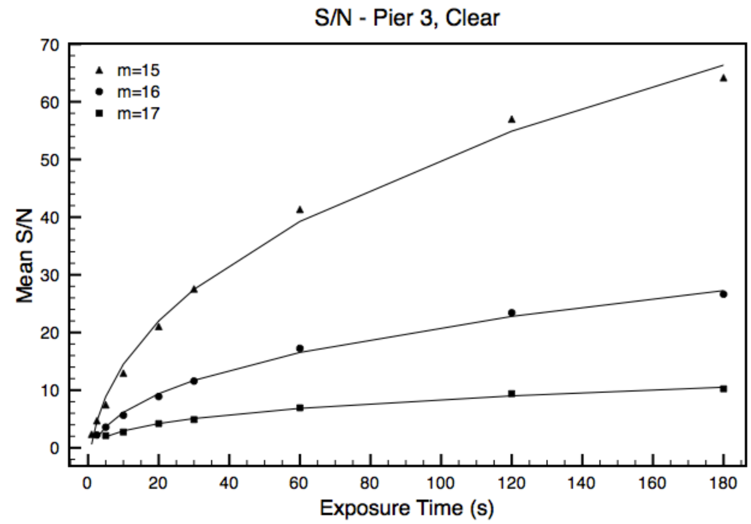


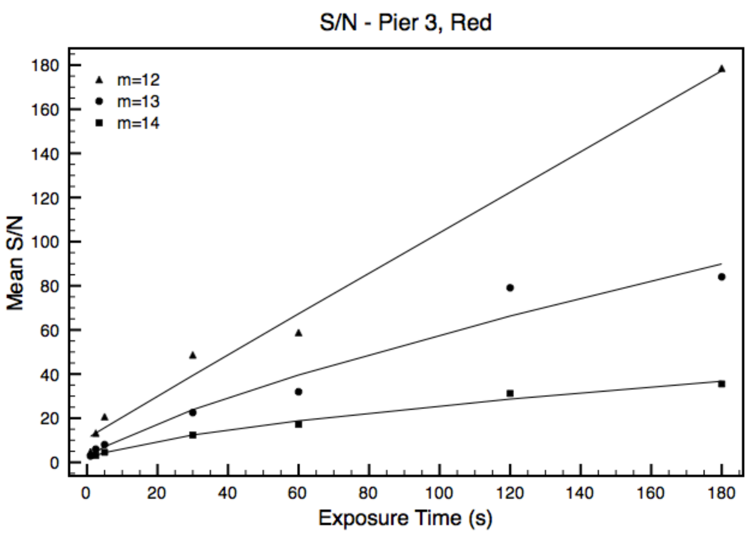


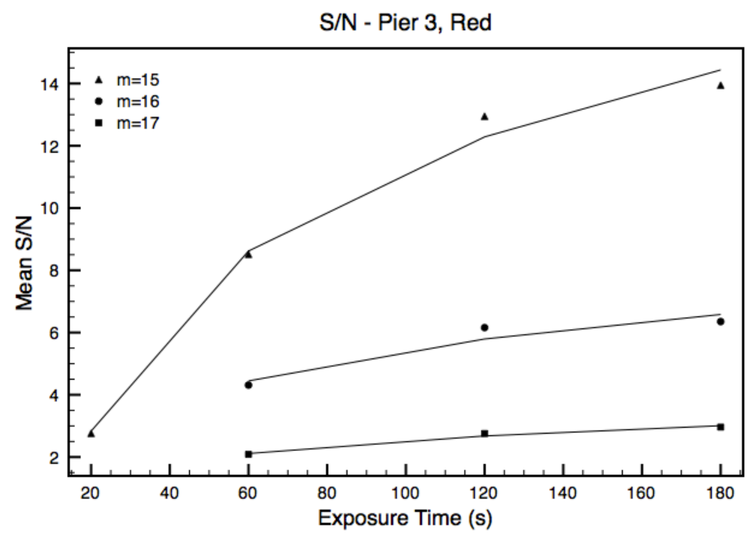


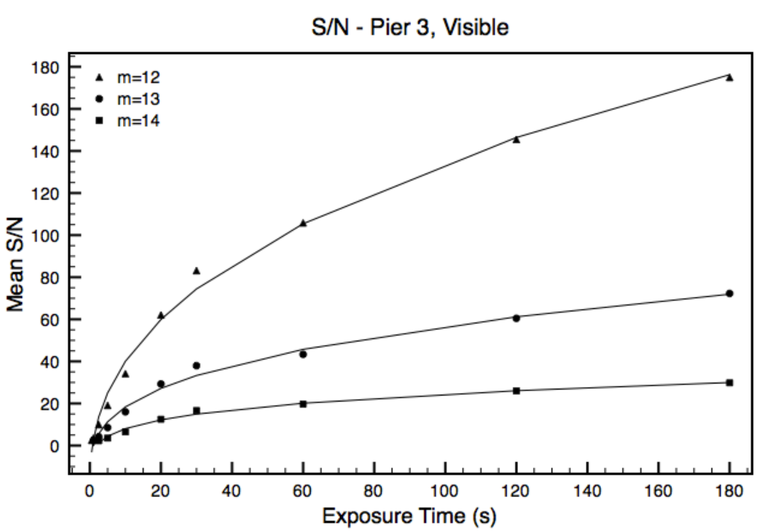


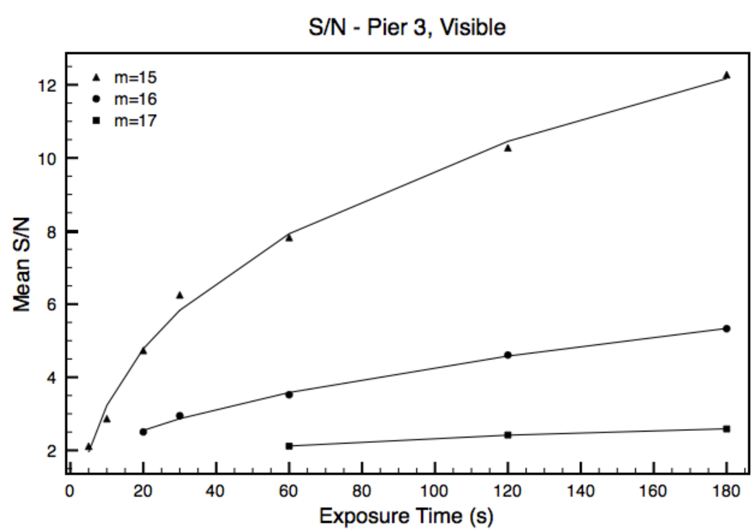

S/N - Pier 3, Clear
m=12
m=13
m=14
Mean S/N
Exposure Time (s)


S/N - Pier 3, Clear
m=15
m=16
m=17
Mean S/N
Exposure Time (s)


S/N - Pier 3, Red
m=12
m=13
m=14
Mean S/N
Exposure Time (s)


S/N - Pier 3, Red
m=15
m=16
m=17
Mean S/N
Exposure Time (s)


S/N - Pier 3, Visible
m=12
m=13
m=14
Mean S/N
Exposure Time (s)


S/N - Pier 3, Visible
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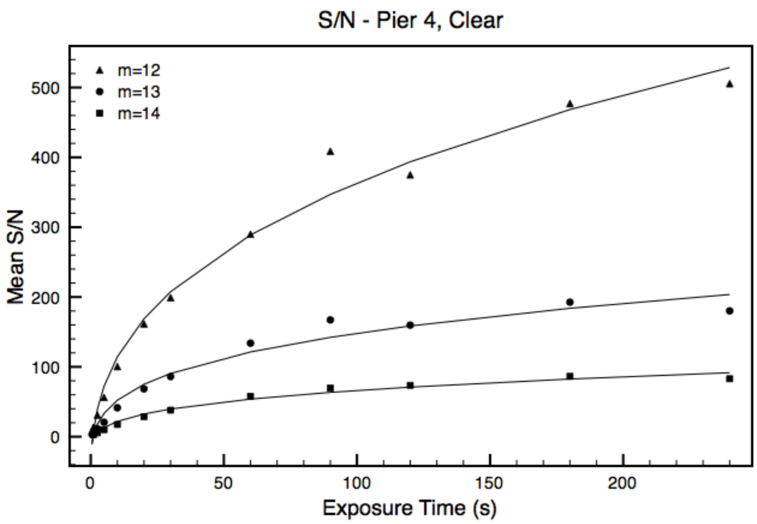
m=16
m=17
Mean S/N
Exposure Time (s)


S/N - Pier 4, Clear
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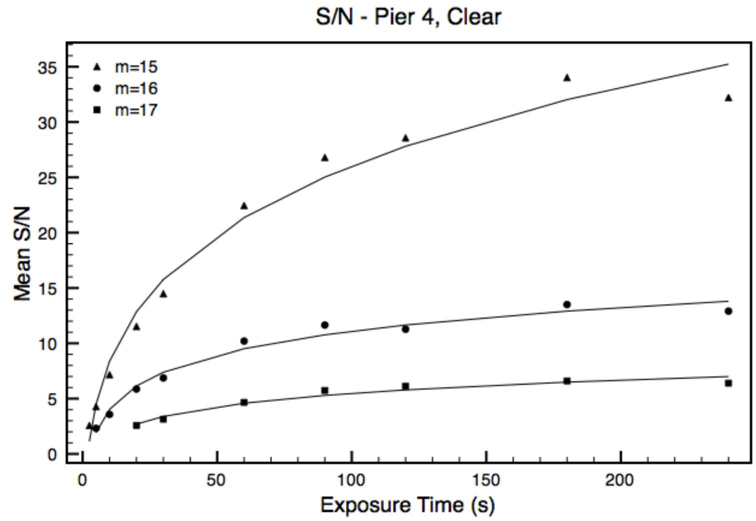
m=13
m=14
Mean S/N
Exposure Time (s)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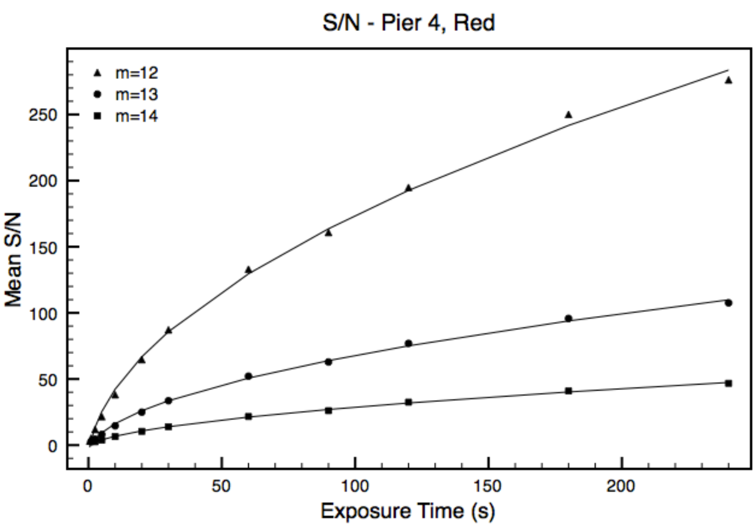
m=16
m=17
Mean S/N
Exposure Time (s)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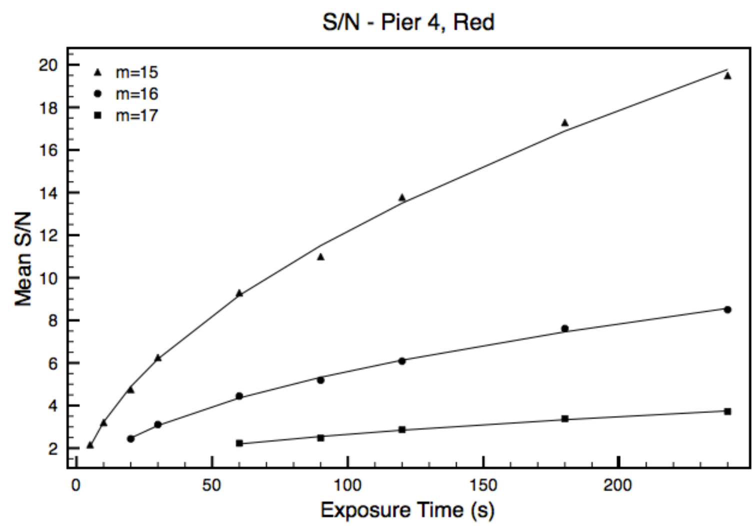
m=13
m=14
Mean S/N
Exposure Time (s)


S/N - Pier 4, Red
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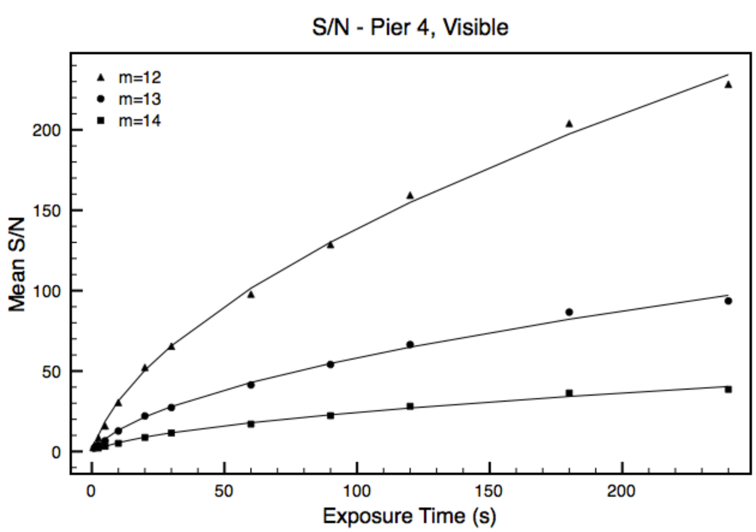
m=16
m=17
Mean S/N
Exposure Time (s)


S/N - Pier 4, Visible
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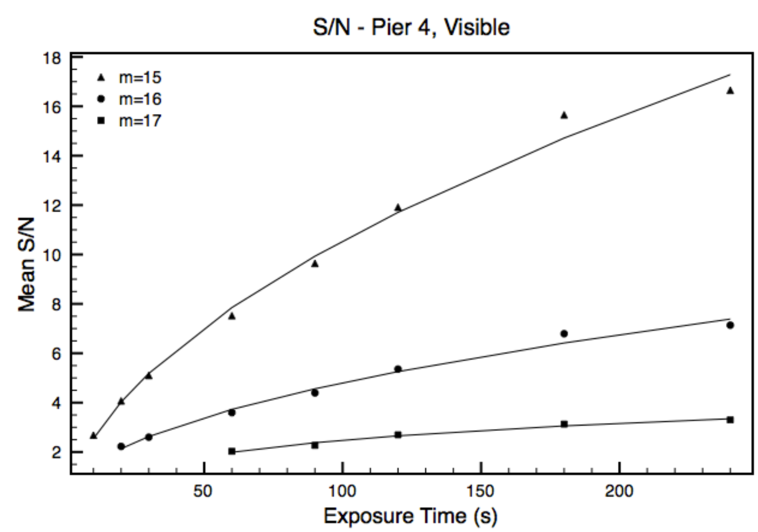
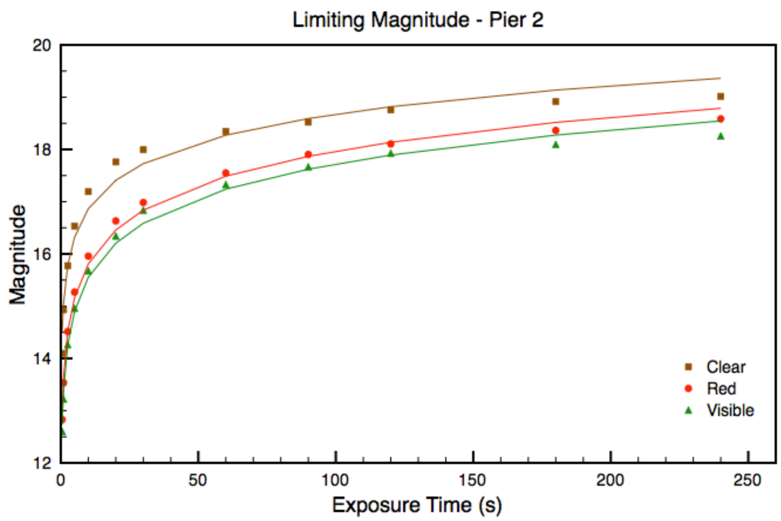
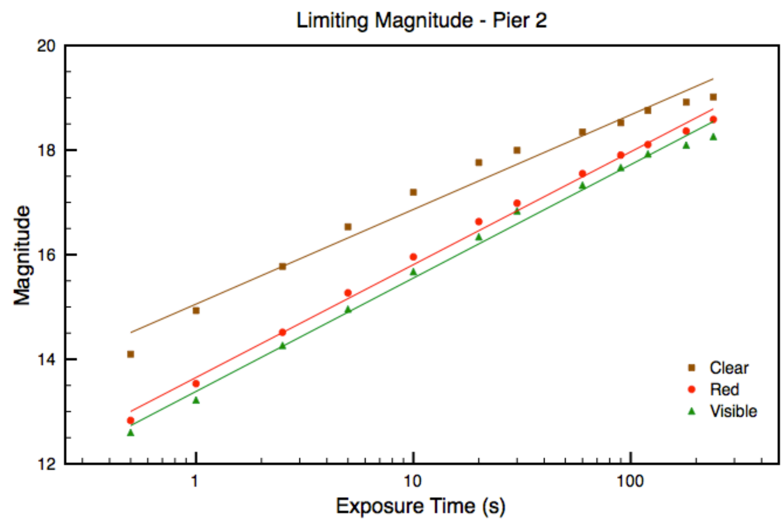
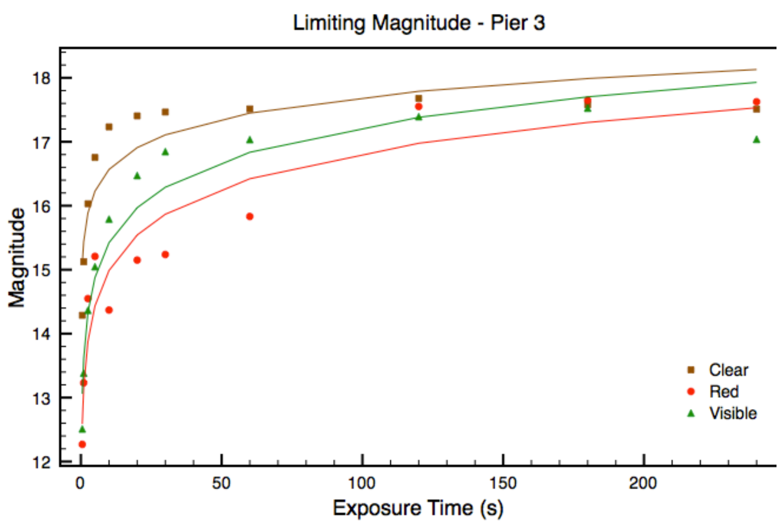
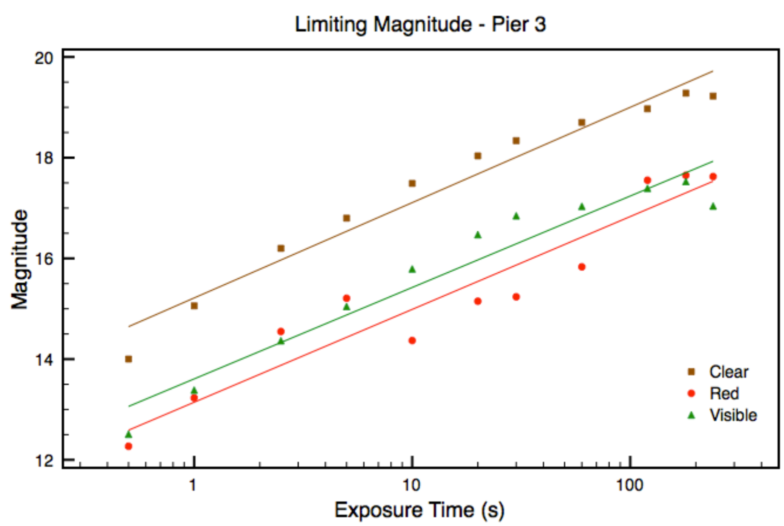
m=13
m=14
Mean S/N
Exposure Time (s)

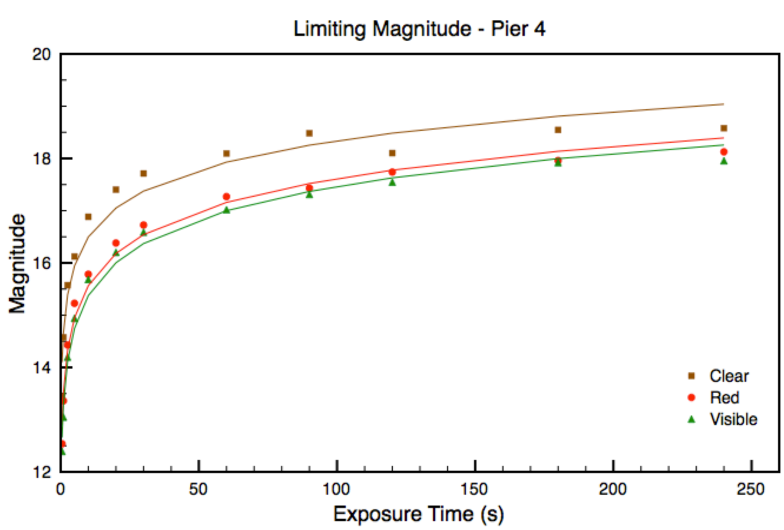

S/N - Pier 4, Visible
m=15
m=16
m=17
Mean S/N
Exposure Time (s)

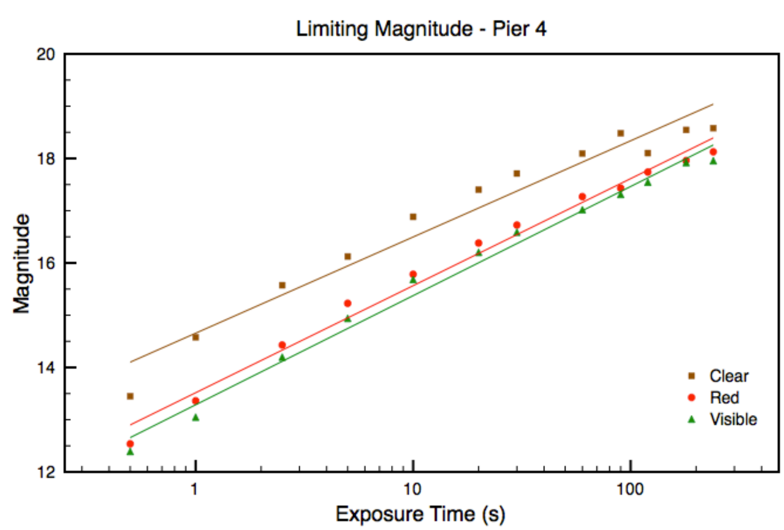

Limiting Magnitude - Pier 2
Magnitude
Exposure Time (s)
Clear
Red
Visible

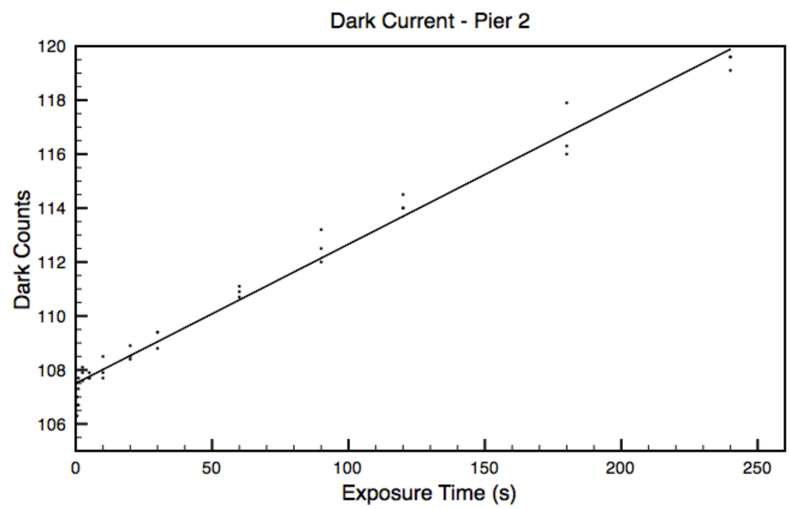

Limiting Magnitude - Pier 2
Magnitude
Exposure Time (s)
Clear
Red
Visible


Limiting Magnitude - Pier 3
Magnitude
Exposure Time (s)
Clear
Red
Visible

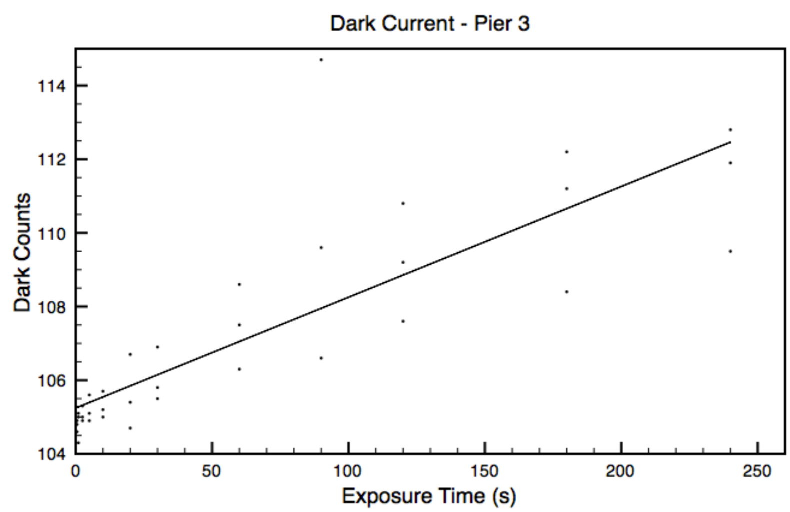

Limiting Magnitude - Pier 3
Magnitude
Exposure Time (s)
Clear
Red
Visible


Limiting Magnitude - Pier 4
Magnitude
Exposure Time (s)
Clear
Red
Visible

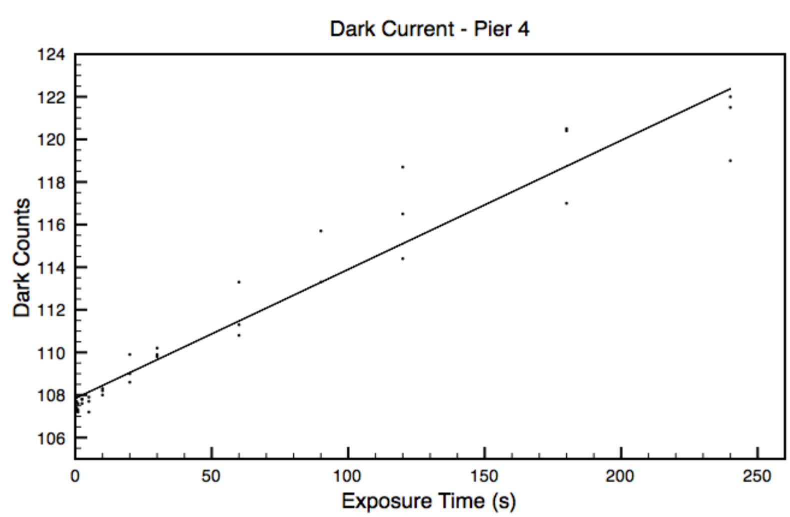

Limiting Magnitude - Pier 4
Magnitude
Exposure Time (s)
Clear
Red
Visible



Dark Current - Pier 2
Dark Counts
Exposure Time (s)
120
118
116
114
112
110
108
106
0
50
100
150
200
250



Dark Current - Pier 3
Dark Counts
Exposure Time (s)
114
112
110
108
106
104
0
50
100
150
200
250



Dark Current - Pier 4
Dark Counts
Exposure Time (s)
124
122
120
118
116
114
112
110
108
106
0
50
100
150
200
250