Strip Scan Imaging Capability of Wallace Astrophysical Observatory (WAO) 24-inch Telescope

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INTRODUCTION

Time delay integration (TDI) is a CCD image acquisition mode that take advantage of our ability to modify the CCD chip read-out procedure.In the standard CCD image acquisition mode (also called Stare mode), the telescope tracks the movement of celestial bodies while the CCD chip is exposed to the sky. After the exposure is over, the chip is read and the information is transferred to a control computer. By contrast, the telescope tracking is turned off and the telescope stays pointed at a fixed position in TDI (or strip scanning) mode. The CCD chip axes are exactly aligned to the Right Ascension (RA) and Declination axes of the celestial sphere. Additionally, instead of being read at the end of an exposure, the chip is continuously read along the RA axis over the course of the exposure. To make sure that the image is free of star trails, the read-out speed needs to be matched exactly to the sidereal rate, and the read-out direction should be aligned to the direction of the diurnal motion (east to west).

TDI procedure results in several key characteristics of strip scan images. First, since the telescope stays still and the camera continuously scans the sky, a strip scan image can be much bigger in dimension (longer) than a standard CCD image. Second, while a standard image has two sources of tracking error (RA and Declination), a strip scan image only has one source of tracking error caused by inaccuracy of the read-out speed along the RA axis. These two characteristics make it possible to perform more accurate astrometry with strip scan images than possible with standard CCD images. Since KBO occultation predictions greatly benefit from accurate astrometry, strip scan imaging is therefore a very powerful tool for KBO observations.

Until recently, Wallace Astrophysical Observatory (WAO) did not have strip scan imaging capability. Strip scans used for predicting KBO occultations were used to be obtained at partner observatories such as Lowell Observatory in Arizona. Over the course of the summer, I have worked on setting up the CCD camera on the WAO 24-inch telescope for TDI observations, taking test images, optimizing the image quality of the strip scans, and doing photometric analysis on strip scan images.

METHODS AND RESULTS

I spent the first few weeks of the summer learning observational astronomy techniques. This includes learning to use the 24-inch and the shed telescopes at WAO, familiarizing myself with *Winscan* (the TDI control software), and acquiring image reduction and analysis skills using *IRAF*. The research project was then divided into several stages.

1. Setting up the 24-inch for TDI: Aligning the CCD Camera

The first significant step of the project is aligning the CCD camera axes to the Right Ascension and Declination axes of the sky. I began by taking images at *CCDSoft* with the telescope tracking turned off. Under this configuration, stars on the camera field of view are going to drift from east to west during the exposure, resulting in the appearance of star trails on the image. A sample image of trails is shown below:

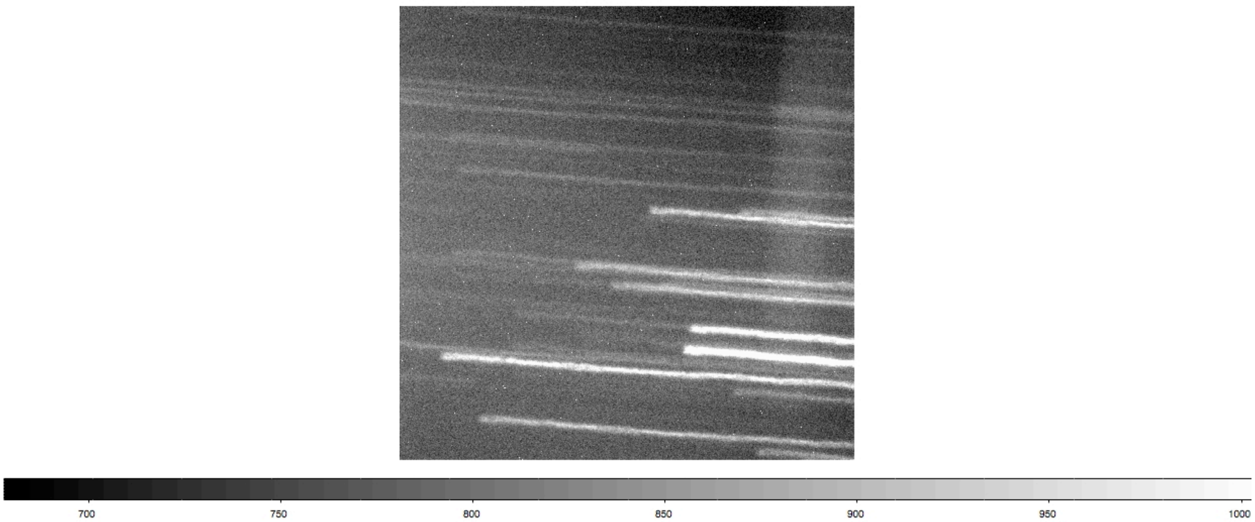


Figure 1: A sample stare mode image of star trails.

To align the CCD camera axes to both RA and Declination axes, I rotated the CCD camera between two successive exposures until the trails were completely vertical. Since there are two possible camera positions that will result in vertical trails, it is necessary to determine the direction of the parallel shift / read-out of the CCD chip. Initially, I assumed that the read-out direction is from top to bottom of the chip and rotated the camera to match that requirement. When I took test strip scan images immediately afterward, the stars appeared as trails, instead of points, and it became obvious that I was operating under the wrong assumption.

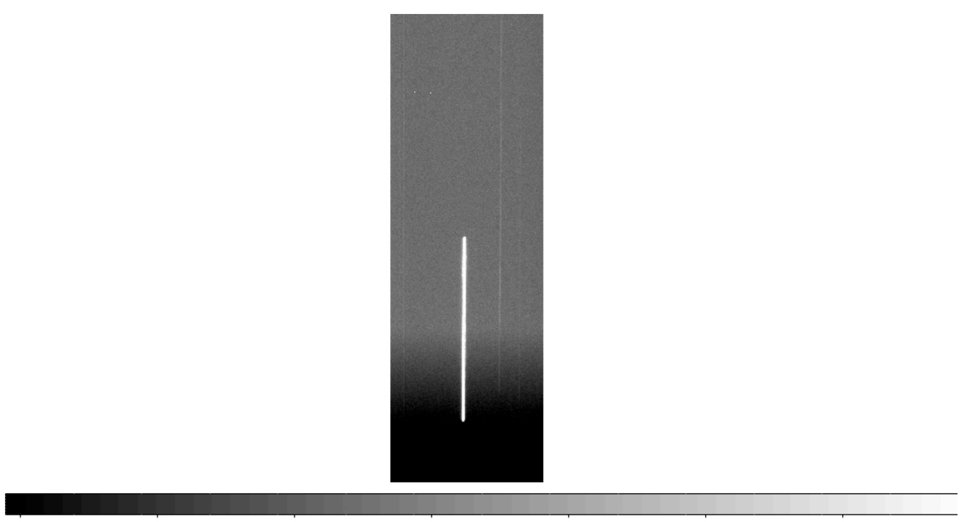


Figure 2 (Previous page,bottom): One of the first TDI trial images that I took. The appearance of a star trail indicated that I was operating under the wrong assumption for the read-out direction (top to bottom). Using the opposite assumption, I was then able to confirm the length of the star trail to within 1% of accuracy. This pointed out that the correct read-out direction was from bottom to top.

On the next observing session, I repeated the procedure and rotated camera to the other possible configuration. Then, I switched to *Winscan* and successfully obtained several working strip scan images.

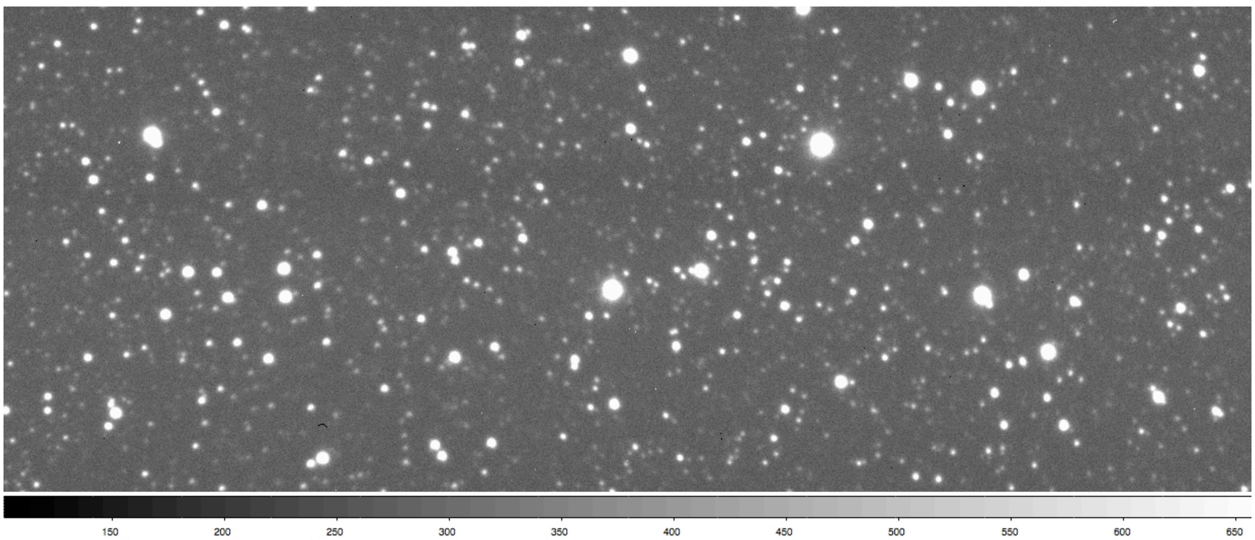


Figure 3: A section of the first working strip scan image I took, rotated by 90 degrees. With current telescope and CCD camera configuration, each strip scan image taken with the 24-inch has an effective exposure time of 35 to 38 seconds, depending of the declination.

2. Optimizing Strip Scan Image Quality

After the CCD camera was set in the right configuration, the next obvious step was to use *Winscan* to optimize the image quality of the strip scan image, as measured by the average Full Width Half Maximum (FWHM) and ellipticity (oblateness of a star's image) values of the strip scan image. Relatively low FWHM and ellipticity values mean that light from a star is more concentrated across a small region of the CCD chip, indicating a read-out speed that matches the sidereal rate.

Using *Winscan,* prior to taking strip scan images, we set the read-out speed by putting in values for the declination of the strip scan field and the focal length of the telescope. These entries affect the image quality of the strip scans: the more accurate the two entries get, the better the image quality becomes. While the declination entry is limited by the accuracy of the telescope pointing, it is possible to find out the focal length entry that will yield the best image quality. On July 20, I took around 20 strip scans of a random area near the celestial equator—each 3,000 lines long—for different focal length entries between 9200 and 9400 mm (the 24-inch telescope information page on the Observatory website gives a focal length value of 9360 mm). The next step involved analyzing each image using the *imexamine* feature on *IRAF* to obtain the average

FWHM and ellipticity values of 10 to 15 stars selected across the field. Finally, the FWHM and ellipticity values are plotted versus focal length entries.

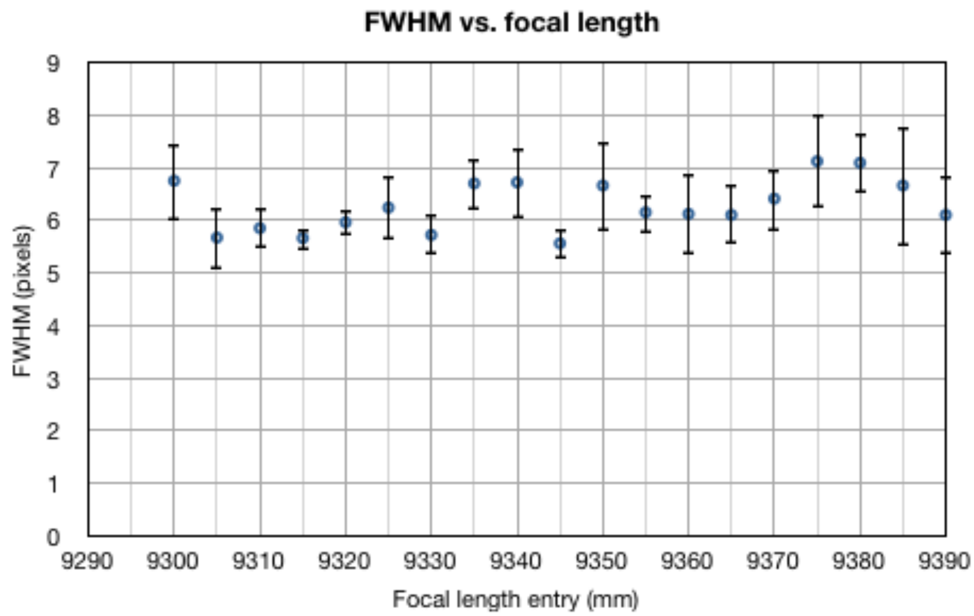


Figure 4: FWHM and Ellipticity vs. focal length. Error bars indicate ±1 sigma. 1 pixel = 0.53”

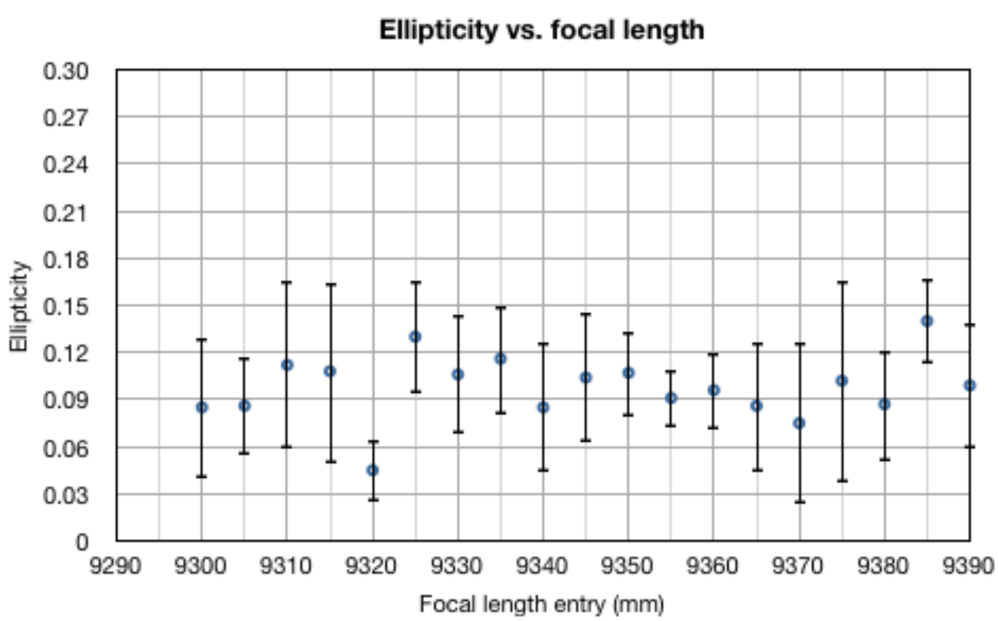


Figure 5: FWHM and Ellipticity vs. focal length. Error bars indicate ±1 sigma.

Figure 4 shows the average Full Width Half Maximum (FWHM) values plotted against different focal length entries for the telescope. The lack of trends on the graph can be explained this way: for the interval 9200-9300 mm, the FWHM is limited mainly by the astronomical seeing. In other words, any changes caused by varying the focal length entry is washed out by the variation of astronomical seeing throughout the observation. On the other hand, Figure 5 shows an obvious dip in average ellipticity at 9320 mm. Also, the relatively small error bar for that data point means that there is less variation of the ellipticity across the strip scan image, indicating that the readout speed closely matches the sidereal rate.

3. Limiting Magnitude Photometry

The next stage of the project was to determine the limiting magnitude of the 24” strip scan images. On July 27 and 29 I used the 24-inch to take strip scan images of field around the location Pluto was in 2005. In April 2005, Mike Person took strip scan images of the same field using the Lowell Observatory 18” Astrograph. The rationale behind this was that beside being analyzed for photometry, these strip scan images would be run through the same astrometry pipeline that was used with the earlier 2005 strip scans.

The *IRAF* feature *daophot* is central to the limiting magnitude photometry. After reducing a strip scan image with dark and flat frames, I ran *imexamine* to estimate the average FWHM and sky background standard deviation values. Then, I put these values to *daofind,* an *IRAF* command that identify and listed all stars on the image into a coordinate file. Next, I ran *phot* that ran through the coordinate file and summed the ADU counts of every star and estimated its magnitude (“IRAF magnitude”). Then, I visually identified between 8 to 10 reference stars of various brightnesses and checked the online USNO B1.0 catalogue for their published magnitudes. After some inspection, I found out that the *IRAF* magnitudes closely fit the R1 magnitudes of USNO B1.0 catalogue. On the next step, I subtracted the IRAF magnitudes from the R1 magnitudes of the reference stars. This was followed by calculating the average value of the difference “R1 minus IRAF magnitude” and its corresponding standard deviation. Then, I shifted all the “IRAF magnitudes” on the list by this average value and the result was a list of corrected magnitudes for all stars on the image. Finally, I identified the dimmest star on the list, visually checked the star on *DS9,* recorded its magnitude, and estimated the magnitude error. To estimate the error, I used the error propagation formula with the two error components being the standard deviation of the “R1 minus IRAF magnitude” and the magnitude estimation error of *phot*.

I repeated this process through all of July 29 strip scans, in addition to the July 20 strip scans and July 29 stare images, for the sake of comparison. The limiting magnitude values are listed below:

Date of observation	Image name	Effective exposure time(s)	Limiting magnitude
July 20 (3,000 x1,024 strip scan images)	Image30	35.89	16.17±0.23
	Image25	35.98	16.27 ±0.19
	Image11	36.00	16.23±0.28
	Image24	36.00	16.10±0.25
	Image 21	36.06	16.20 ±0.20
	Image17	36.14	16.13±0.19
	Image16	36.16	16.07±0.24
	Image13	36.21	16.16±0.20
	Image12	36.23	16.14±0.26

Date of observation	Image name	Effective exposure time(s)	Limiting magnitude
July 29 (1,024 x1,024 stare images)	Image02	37.00	16.49±0.29
	Image07	37.00	16.29±0.28
	Image10	37.00	16.34±0.28
	Image14	37.00	16.40±0.28
	Image17	37.00	16.48 ±0.34
July 29 (15,000 x1,024 strip scan images)	Image05	37.47	16.41±0.22
	Image06	37.47	16.50±0.27
	Image08	37.47	16.45±0.24
	Image09	37.47	16.46±0.28
	Image11	37.47	16.50±0.22
	Image12	37.47	16.45 ±0.25
	Image13	37.47	16.45±0.25
	Image15	37.47	16.45±0.26
	Image17	37.47	16.41±0.23

Table 1: Limiting magnitude photometry results. The difference between the limiting magnitude of the July 20 and July 29 strip scans can be explained by the fact that the sky was partially cloudy on July 20 while it was clear on July 29. The dimmest stars recorded here have S/N values of between 5 and 10.

DISCUSSION

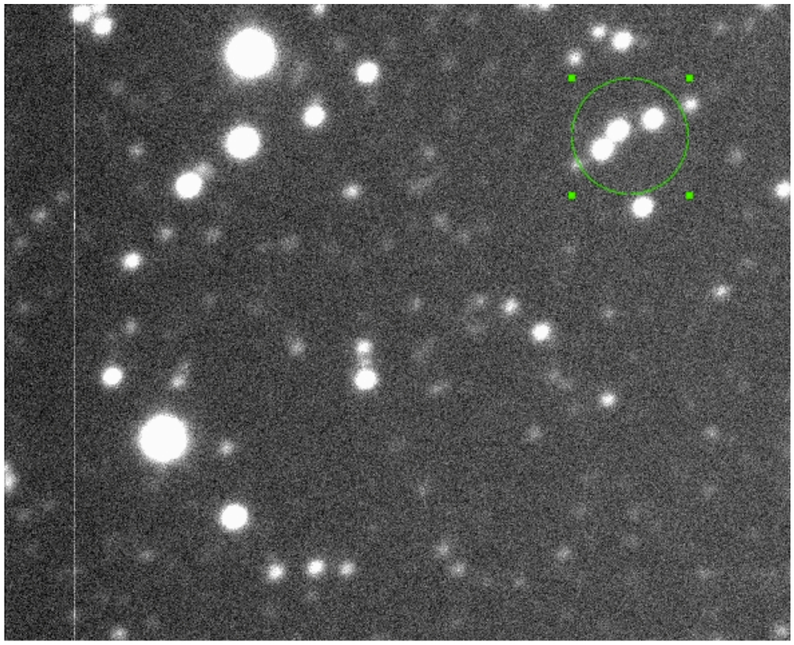
My summer work at Wallace Observatory shows that major KBOs such as Pluto are within reach of strip scan images taken with the 24-inch telescope. It is possible to increase the limiting magnitude of the strip scans by adding a focal reducer to the optical system, therefore increasing the field of view and the effective exposure time on TDI mode. Additionally, an electronic instrument rotator will make setting up the TDI camera a much easier process in the future. It remains to be seen how good the astrometric fit of the strips scans are: at the time of the writing the strip scans are yet to be run through the astrometry pipeline.

ACKNOWLEDGEMENT

I would like to thank the UROP office for funding this project. I would also like to thank Mike Person, Tim Brothers, Jim Elliot, Carlos Zuluaga, and fellow UROP researchers for their support to this project.

APPENDIX

A comparison between one of the July 29 strip scans and the 2005 Lowell Observatory strip scans is shown below:



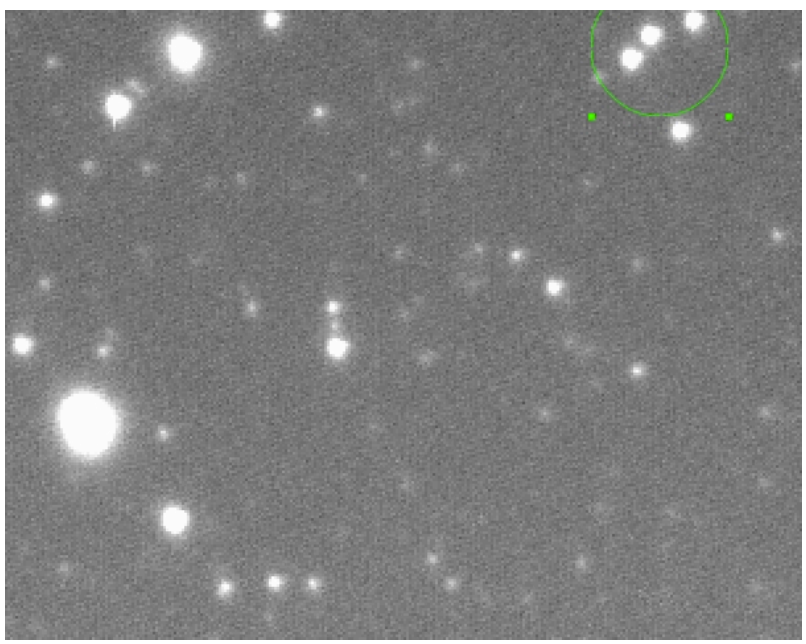


Figure 6: The top image is from a small fragment from one of my July 29 strip scan images, while the bottom image is the same patch of sky taken from the 2005 Lowell strip scans. Compare the region inside the green circles: the Lowell strip scans benefit from better astronomical seeing at Lowell Observatory (the 3 stars are better separated on the bottom image). On the other hand, the top image record fainter stars that are undetected on the bottom image, thanks to the bigger aperture of 24-inch telescope.