

# Wide-field photometry at 20 Hz for the TAOS II Project

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## ABSTRACT

The TAOS II Project requires high-speed differential photometry of 10-20 thousand stars over a telescope field of 154mm diameter with 16-micron spatial resolution and good noise performance. We are developing a custom CMOS imager array to accomplish this task.

**Keywords:** photometry, CMOS, imager

## 1. INTRODUCTION

The second-generation Transneptunian Automatic Occultation Survey (TAOS II)<sup>[1]</sup> will use wide-field differential photometry of bright stars to detect randomly occurring occultations by small dark outer Solar-system objects. For the densest fields, we expect up to 20000 candidate stars to fall into our 154mm diameter field of view. As can be seen in Figure 1, at least 20Hz time resolution will be needed to at least partially resolve the lightcurves during typical occultation events for small objects, where diffraction is an important effect.

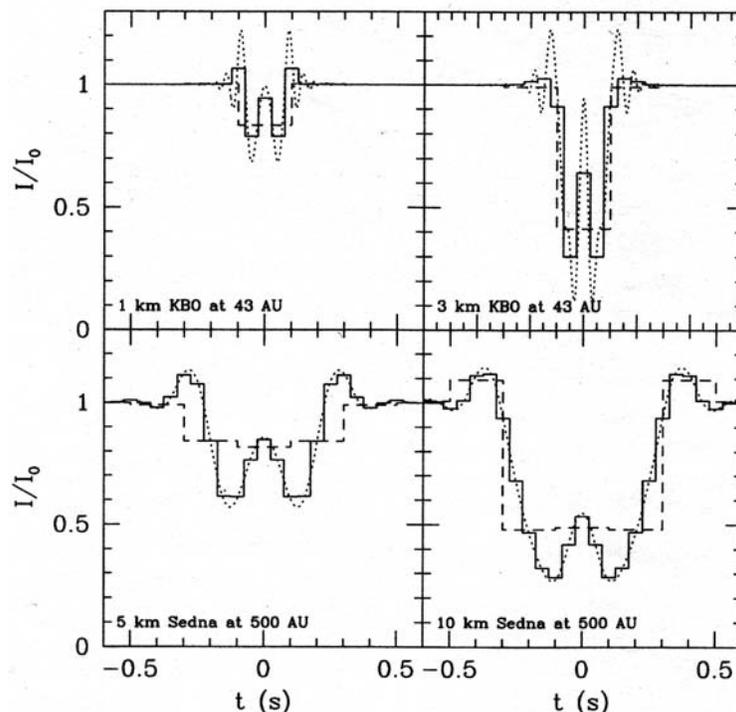


Figure 1. Simulated lightcurves for 1 km and 3 km KBOs at 43 AU and for 5 km and 10 km Extended Disk objects (“Sednas”) at 500 AU. 20Hz sampling (solid lines) is needed to resolve these lightcurves; previous 5Hz attempts (dashed) are clearly insufficient.

We first looked at whether CCD technology could be adapted to rapid framing of this wide field, but this choice seemed both electronically demanding and risky. In order to achieve these high frame rates, we would need to develop custom CCD arrays with many outputs, running at high speeds in the range of 10-20 MHz. But, we also need low noise (5 e- or less), which could only be achieved at high speed with something like L3 electron-multiplying technology, which has

never been implemented on this large a scale with many outputs per device. The downstream electronics to drive all these imagers and process the huge torrent of data would have been very demanding as well.

But, only a very small fraction of the pixels in this field of view contain relevant information. For a focal plane covered by imagers with 16u pixels (ca. 0.6 arcsec for our telescopes) and with a photometric aperture per target star of 6 X 6 pixels (large enough to limit seeing noise), a field with 20000 stars represents just 1% of the total pixels in the field. The other 99% of the pixels can be discarded, but in a CCD, they must be read out anyway. CMOS imagers, on the other hand, can readily skip over uninteresting pixels, dropping the total bandwidth requirements for the readout and signal processing system by corresponding factor of nearly 100. Until recently, however, most CMOS imagers suffered from greatly inferior noise performance compared to CCDs, but a new generation of low-noise devices has now put our requirements within reach.

## 2. THE CUSTOM TAOS CMOS IMAGER

### 2.1 Imager format

In order to achieve a high fill factor on the focal plane, we needed a 3-edge buttable design, with all the pinout along one of the short edges. We also wanted the active length to be approximately half the diameter (about 77mm) and the width as wide as possible, consistent with the size of the photolithography stepper field (i.e. no 2-dimensional stitching, which would drive up costs and risks). For 16u pixels, the resultant format is 1920 columns X 4608 rows overall, with eight independent outputs covering 240 columns each. This latter design requirement comes from our desire to keep the analog signal processing bandwidth down to about 1 MHz per channel, where low noise and low power parts are readily obtainable.

As shown in Figure 2, essentially the entirety of the 154mm focal plane can be covered with 10 such devices. Figure 3 shows a more detailed drawing of the individual device layout.

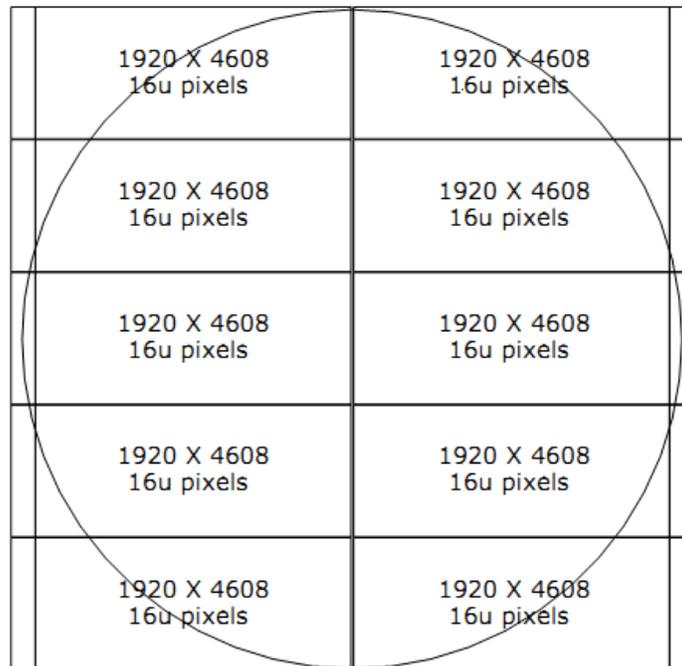


Figure 2. The 154mm TAOS focal plane, populated with ten 3-edge buttable CMOS imagers.



latched while the desired pixel is processed. During the pixel processing time (1 usec for a 1MHz read rate), the address for the next desired column is being clocked in before being latched. Thus, as long as the 8-bit shift time is less that the pixel processing time, there is no lost-time overhead associated with this addressing scheme. The shift register can handle up to 40 MHz clocking or more, allowing even faster pixel rates should that be desirable. A diagram for the layout and clocking of one of the eight independent column address registers is presented in Figure 5.

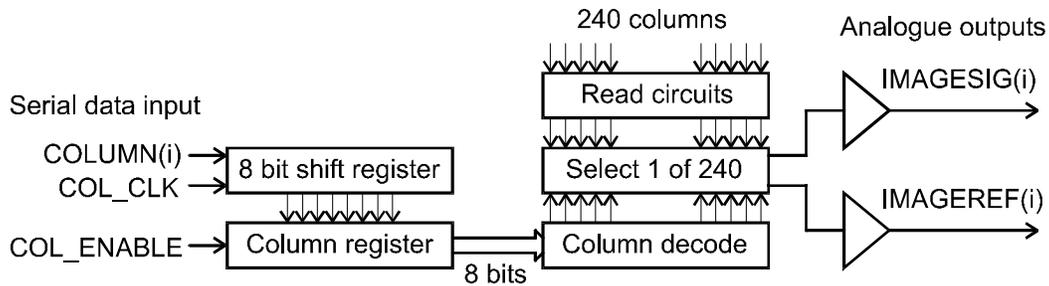


Figure 5. One of eight independent column address registers, with serial-to-parallel input shift register, feeding an 8-bit latch and 1-of-240 column decode and select.

### 2.3 Pixel Architecture

A standard 4T pixel, with transfer gate to allow real-time sampling of both the column baseline and photo signal level is required to meet the noise target and is shown in 6, drawn to show the signals and supplies when in an array. Note that the supplies to the drains of the reset and source follower transistors are separate to allow the use of low noise, very low  $V_t$ , transistors for the source followers. The nominal responsivity is  $80 \mu\text{V}/e^-$ , which we estimate will give a noise level as low as  $5 e^-$  or better. We contemplated but rejected putting in a gain switch, to allow more of the large charge capacity of the 16u pixel to be covered, but the increased shunt capacitance of such a circuit would degrade the noise performance in high-gain mode, where the TAOS science will be done.

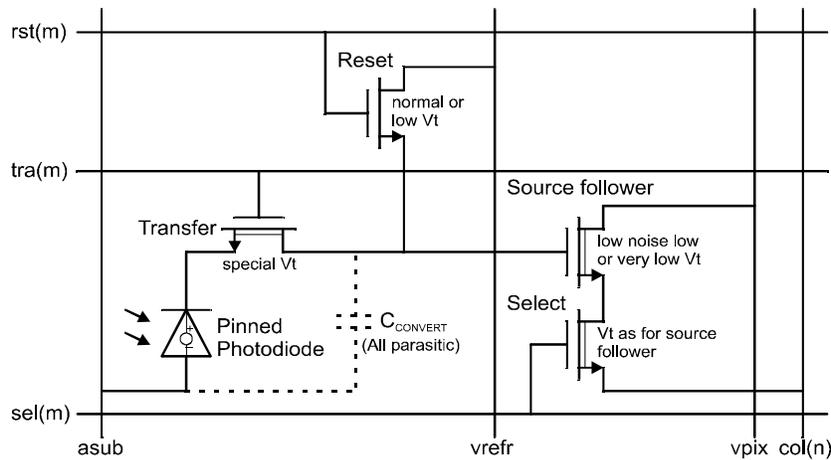


Figure 6. Circuit of 4T pixel.

### 2.4 Readout Architecture

In order to achieve very low noise, the signal from the 4T pixel needs to be processed with a correlated double-sampling (CDS) circuit, removing the otherwise debilitating  $1/f$  noise sources as well as the  $kTC$  noise of the column bus line. For this purpose, we use two sample-and-hold circuits on each column, one sampling the level of the column line before transferring charge to the output transistor node (the reference level) and one sampling after transfer (the signal level). Once latched, the output nodes for all columns in the selected row are reset, beginning the next integration interval.

Because there is a settling time of about 10 usec associated with the CDS sampling circuits which would adversely cut into the available time to process and digitize the desired pixels in that row, we will employ a two-channel version of this CDS scheme, shown in Figure 7.

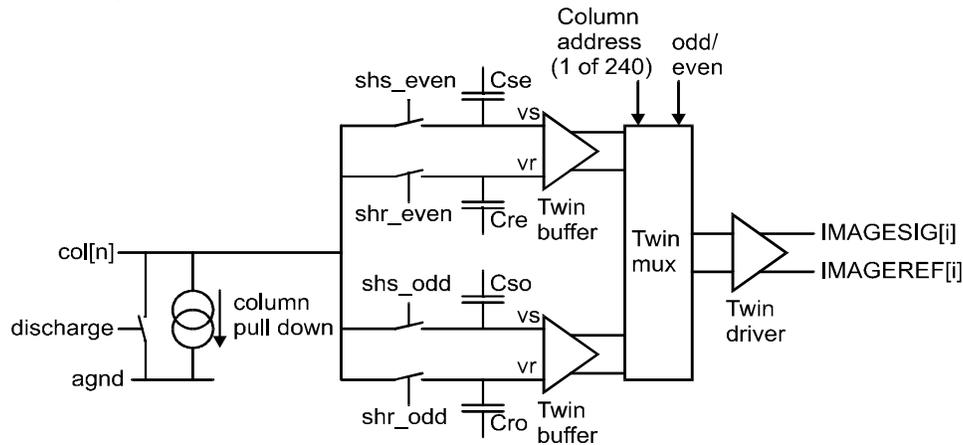


Figure 7. Two-channel dual buffered CDS circuits, with a two-state "ping-pong" multiplexer (mux).

The action of this circuit is as follows:

1. Select the desired row(n), which enables all columns in that half of the imager.
2. Use the shr\_even and shs\_even switches above to sample the reference and signal levels, respectively.
3. After sampling, reset the entire row, starting a new integration.
4. Initiate processing of the differential video for selected columns (1 of 240 per block). During this time, the next desired row(n+x) is being selected, and the other half of the two-channel circuit is being sampled in a similar fashion, using shr\_odd and shs\_odd above.

### 3. OBSERVING CADENCE CONSIDERATIONS

We feel confident that for almost all star fields we may encounter, this imager will be able to readily process differential photometry on all stars bright enough to provide the requisite signal-to-noise. The faint star limit is set by shot noise considerations from this size telescope, as well as the ensemble read noise of the imager over the pixel patch assigned to each target (as one cannot coadd pixels noiselessly in CMOS imagers). This limit will probably be about  $M_v=15-16$  or so at a 20Hz cadence for small occulters, and perhaps as faint as  $M_v=16.5$  for objects or 10 km size or larger, where diffraction is less important.

Looking at Figure 1 again, you can see that framing at an even higher frequency would be desirable, to better sample the occultation waveform and extract more information on size and distance to the object. At about 40 Hz we achieve near-Nyquist sampling, but of course the number of possible target stars is correspondingly reduced. Also, looking at the coverage of the focal plane in Figure 2, we see that the outermost four imagers have only about half their area utilized. We may choose to frame these devices at a more rapid rate, as the number of targets to be covered there is always less than for the interior imagers.

TAOS II will use three identical 1.3 meter f/4 telescopes, staring at the same fields simultaneously. This provides a coincidence filter to help reject false-positives caused by seeing noise for all targets, plus shot noise for the faintest targets. In addition, because the telescopes will be separated from each other by distances of approximately 100-300 meters, occultation events will be shifted in time by a small amount between the three, depending on the geometric relationship of each telescope to the event shadow as it sweeps by. Simulations seem to indicate time shifts between perceived events of order a few tens of milliseconds, or a major fraction of each sampling interval. This may provide additional waveform information because of the phase shift between the three samples of the event.

### REFERENCES

- [1] "The Transneptunian Automated Occultation Survey (TAOS II)", M.J. Lehner et al., Proc. SPIE 8444-11, Amsterdam (2012).