

# **Final Report**

## **Testbed for High-Acuity Imaging and Stable Photometry and Image-Motion Compensation (THAI-SPICE)**

**Program 10214**

**J. A. Gregory**

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## Objectives and Significance

Dr. Eliot Young of Southwest Research institute (SwRI) is the PI of a proposal entitled: Testbed for High-Acuity Imaging and Stable Photometry and Image-Motion Compensation (THAI-SPICE). The main goal of this larger project is to build and demonstrate a fine-pointing system for stratospheric payloads to enable diffraction-limited performance by balloon-borne telescopes. This proposal from MIT Lincoln Laboratory (LL) was as a Co-Investigation of this Sub-Orbital Mission, within the Astronomy and Physics Research and Analysis Program (APRA) and was to furnish to NASA an electronic camera using orthogonal-transfer charge-coupled devices (OTCCD), with a high charge-transfer efficiency (CTE), to stabilize the images acquired by a balloon-borne telescope flying at approximately 120,000 ft. The camera, which has high sensitivity and low noise, will be integrated with the SwRI telescope as government-furnished equipment and will be able to integrate photons arriving from dim stars and other objects over long periods of time. This will enable the acquisition of images with jitter of less than 1 arcsecond. It will be a significant advance for both NASA and astronomy, in general, to have balloon-borne, diffraction-limited telescopes that are free of atmospheric aberrations operating at a much lower cost than similar-aperture satellite-borne telescopes.

MIT LL provided the CCID77 and built the prototype camera, in which it was housed, to SwRI through NASA, in the summer of 2020. The balloon launch was to take place in the fall of 2020, but was delayed until the fall of 2021, due to the COVID-19 pandemic and its effect on the NASA balloon launch schedule. The camera has worked well on the ground and has been integrated into the balloon payload. This has completed the obligations of MIT LL to the program.

## Technical Approach

The OTCCD offers a significant advantage over a conventional CCD in achieving good signal-to-noise ratio and eliminating the apparent motion of an object. Both imagers have an x-y arrangement of pixels, but the conventional CCD can only transfer charge packets in one (e.g., vertical) direction. The OTCCD, on the other hand, can transfer charge both vertically and horizontally in the image array and thus to any location within the array[1,2]. The means of achieving orthogonal transfer is illustrated in Fig. 1. A given pixel is divided into four phases, two of which are right triangles and two are rectangles. To move charge in a vertical direction, gate 4 is held at low potential while high voltages are applied sequentially to gates 1, 2, and 3. To move charge horizontally, gate 1 is held low while high voltages are sequentially applied to gates 2, 3, and 4. This technique has been successfully used to eliminate tip-tilt aberrations on large-aperture terrestrial telescopes, changing the seeing from 0.75 arcsec to 0.5 arcsec and increasing the Strehl ratio[3].

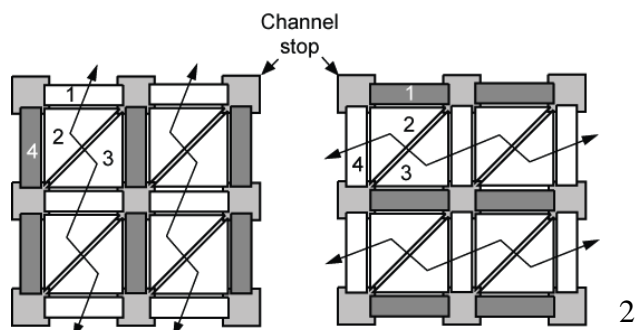


Fig. 1 A schematic representation of a four-pixel region of an OTCCD, showing vertical (left) and horizontal (right) transfer.

The use of a guide-star tracker is illustrated in Fig. 2 to increase the intensity of weak signals, while eliminating the jitter associated with tip-tilt aberrations or platform motion. In this example, a suitable guide star illuminates a pixel in the frame-store region of the CCD and is read out rapidly (on the order of tens of Hz). The position of the guide star is deduced off-chip and compared to the last subframe; the relative change in  $\Delta x$  and  $\Delta y$  is fed back to the science array, where the charge packets are moved by this same  $\Delta x$  and  $\Delta y$ , in anticipation of the next photon arriving at this new site. This simple example is for illustration, as it is obviously more sophisticated tracking algorithms can (and have been) developed; in this proposal (THAI-SPICE), a separate high frame-rate star tracker will be used to update the shifting of the pixels in the OTCCD. At the end of the desired integration period, the charge in the image array pixels is transferred to the frame store region and read out, pixel by pixel, through the serial register.

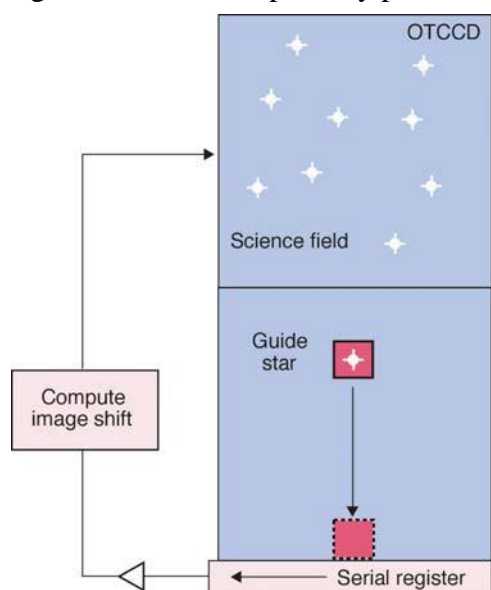


Fig. 2. Use of image array (upper, science field) and frame store (lower) to provide feedback for orthogonal in the image array science field.

Using such a system, the intensity of dim stars can be raised above the readout noise of the CCD (typically 2 to 6  $e^-$  in a LL CCD[1], at readout rates up to several MHz), increasing the signal-to-noise ratio. As mentioned above, the guide star position is read out every few milliseconds (faster than the Greenwood frequency of the atmosphere) and the change in position is relayed to the science array where charge shifts can occur every few microseconds, allowing integrations to take many seconds, without blurring of the image (provided a shutter is employed during transfer from image array to frame store to serial register). It is estimated that with this approach, the pointing accuracy of the telescope will be on the order of 0.1 arcsec, enabling diffraction-limited imaging.

The OTCCD used (the CCID77) has 3100 columns and 1550 rows, in adjacent sections of in the image array (IA) and 1550 rows and 3100 columns in each of two frame store (FS) region, one

below and one above the image arrays; this is referred to as a split-frame transfer architecture. A line diagram of the imager is shown in Fig. 3

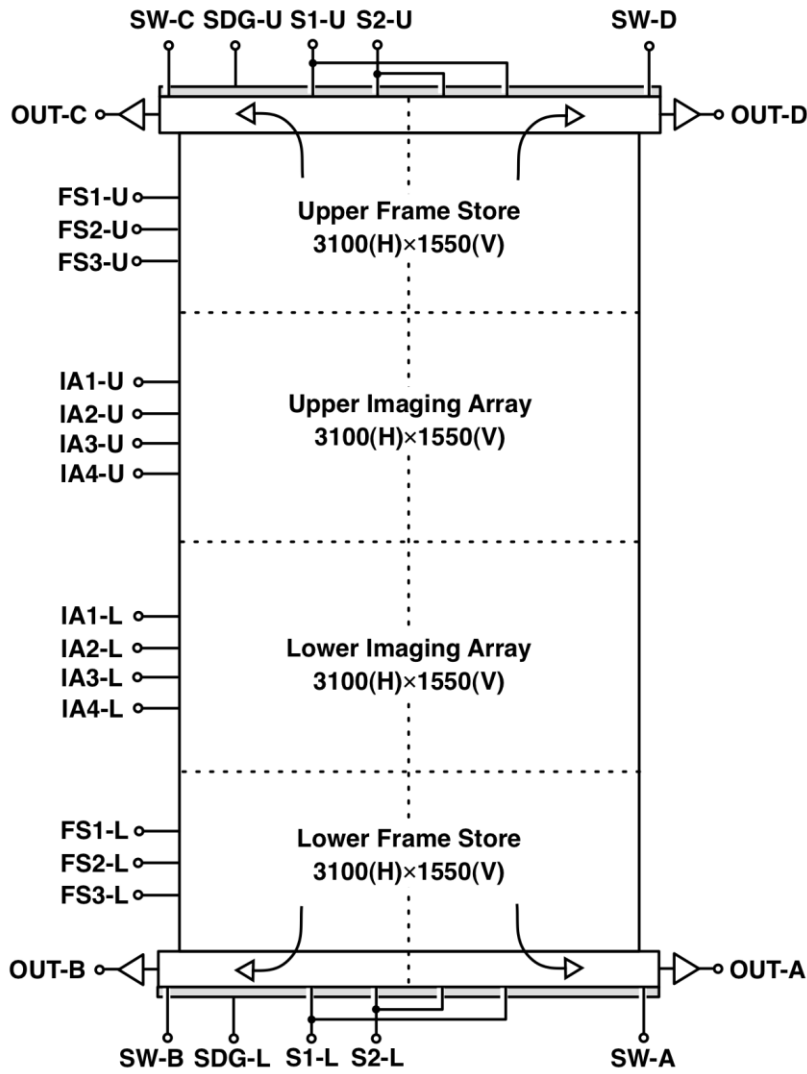


Fig. 3. Layout of CCID77 OTCCD imager.

The upper parallel IA ( $1550 \times 3100$ ) collects science data while the lower array ( $1550 \times 3100$ ) allows the readout of guide stars; this readout can be quite rapid ( $>30$  Hz) if, once a guide star is identified, the user chooses to use a smaller window, typically  $\approx 100 \times 100$  pixels. This is an optional mode of operation, which may augment the use of a star tracker camera and controller to feed back pixel-shifting commands to the OTCCD.

The FS regions accept charge from the abutting IAs as they are read out; this being a relatively long integration in the science IA and a short one in the guide star IA. This use of a monolithic piece of silicon reduces the weight and complexity of the camera by eliminating moving components.

The effectiveness of the OTCCD to transfer charge with high CTE, while maintaining low noise was demonstrated in Kitt Peak[3]. In this ground-based case, the signal to noise ratio increased by a factor of 1.7 and the FWHM of the peaks decreased from 0.73 arcsec to 0.50 arcsec.

Some of the other attributes of the LL OTCCD are high quantum efficiency (QE) and low noise. The CCID77 used for this program will be back illuminated (BI) leading to high QE [4]; the basic advantage of back illumination of a CCD over front illumination is, in the latter, the photons are subject to absorption in the polysilicon gates of the device, while in the former, the photon is absorbed in the single-crystal Si of the body of the imager. With a two-layer antireflection coating deposited on the illuminated surface, transmission can be tuned to nearly 100% over a band of wavelengths; it is often peaked near 800 nm, to minimize scatter in the telescope of the OH lines present in the atmosphere. For a 75- $\mu\text{m}$  thick BI imager, the QE at 950 nm can be over 50%, with the falloff due to the long absorption length of Si at that wavelength.

A view of the completed camera is shown in Fig. 4. The front to back distance is about 150 mm and the height and width are about 180 mm and the CCID77 OTCCD used for this activity (obscured by thermal cooling straps) was mounted to the front panel.

The camera was adapted with appropriate thermal control to survive the balloon ascent and operate at the high altitudes necessary to reduce atmospheric aberrations to negligible levels. This camera mates to the SwRI telescope and uses a radiator integral to the gondola design to keep the OTCCD at  $\approx -30$  °C. The camera weighs about 10 kg, occupies about 8 liters, and consumes less than 25 W of power. The camera has appropriate I/O to relay the guide star image, accept shift controls from the balloon payload, and relay the science image. It is also possible to incorporate shift commands from an inertial guidance unit in the payload.

The charge transfer efficiency (CTE) of the CCID77 OTCCD was estimated to be  $> 0.99999$ , for a combination of horizontal and vertical transfers, observed for finely focused light spot illuminating pixels and then moved across the IA in a serpentine path. This compares well with the CTE of 0.999999 typical of vertical transfers in a standard LL CCD. It is, however, a lower-bound estimate because the standard techniques of capturing the charge packet from the decay of a  $^{55}\text{Fe}$  isotope do not lend themselves well to the two-dimensional path taken by an OTCCD under

a test of horizontal and vertical transfers. In the  $^{55}\text{Fe}$  test, many x-ray events are captured by the IA and moving one charge packet from an event across the initial location of other events may confound the process.

#### Impact on the Field and Relevance to NASA

This camera is an essential element of the larger SwRI proposal for balloon-borne telescopes, since it will help to achieve the fine pointing accuracy necessary for diffraction-limited performance of the telescope. Such a system would enable NASA to launch large telescopes with many scientific missions, with apertures greater than 1 m, at a relatively low cost compared to a satellite-borne telescope, opening the field to much greater activity. It could be possible to include such telescopes on free-flying balloons or dirigibles.

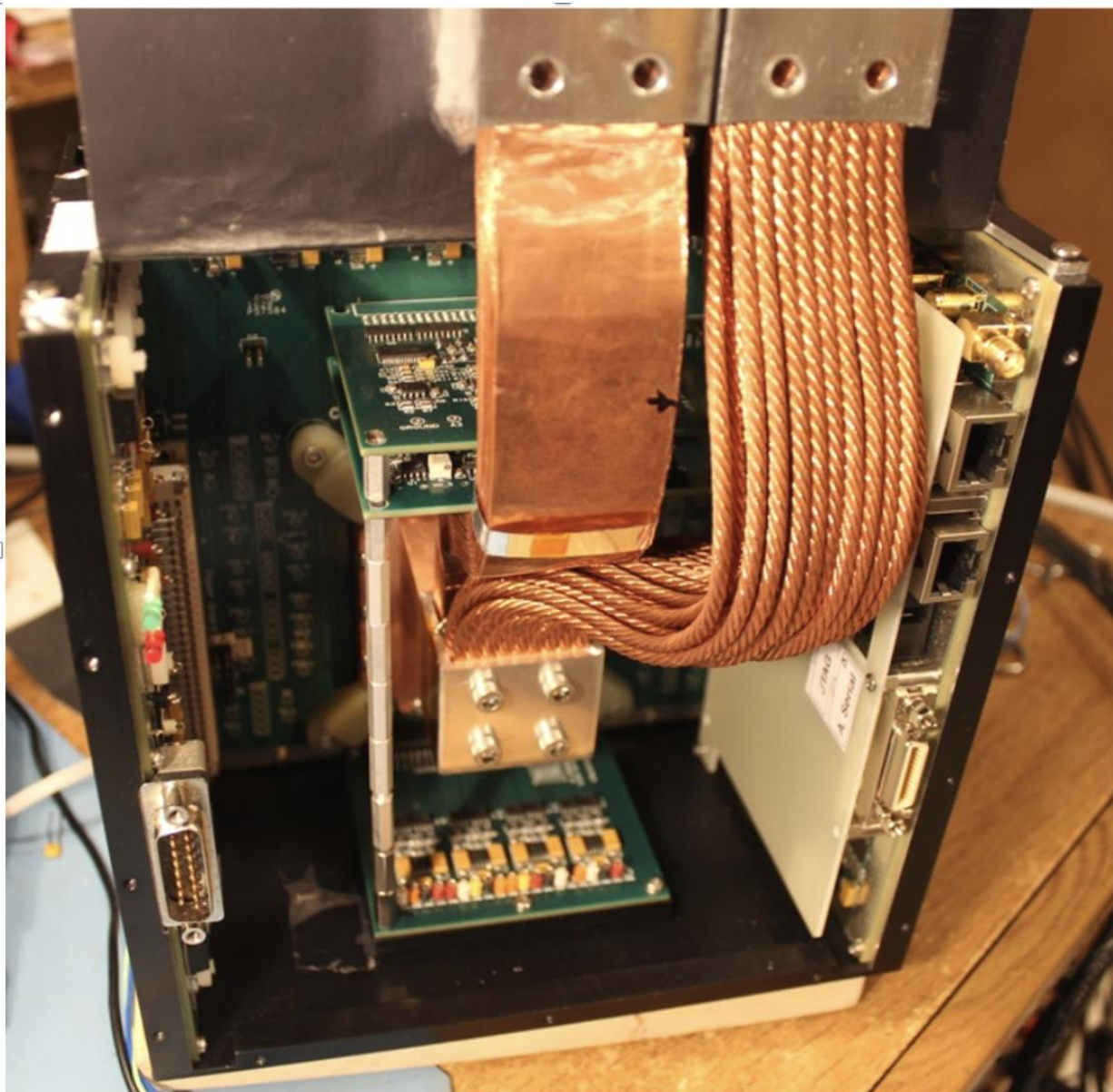


Fig. 4. Interior view of CCID77 OTCCD camera.

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