Repackaging and characterizing a HgCdTe CMOS infrared camera for the New Solar Telescope

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ABSTRACT

The 1.6-meter New Solar Telescope (NST) is currently the world’s largest aperture solar telescope. The NST is newly built at Big Bear Solar Observatory (BBSO). Among other instruments, the NST is equipped with several focal plane instruments operating in the near infrared (NIR). In order to satisfy the diverse observational requirements of these scientific instruments, a 1024 \times 1024 HgCdTe TCM8600 CMOS camera manufactured by Rockwell Scientific Company has been repackaged and upgraded at Infrared Laboratories Inc. A new ND-5 dewar was designed to house the TCM8600 array with a low background filter wheel, inverted operation and at least 12 hours of hold time between fills. The repackaged camera will be used for high-resolution NIR photometry at the NST Nasmyth focus on the telescope and high-precision NIR spectro-polarimetry in the NST Coudé Lab below. In March 2010, this repackaged camera was characterized in the Coudé Lab at BBSO. This paper presents the design of new dewar, the detailed process of repackaging and characterizing the camera, and a series of test results.

Keywords: Infrared, CMOS, FPA, Imaging, Solar observation

1. INTRODUCTION

The largest clear aperture solar telescope, a 1.6-meter off-axis New Solar Telescope (NST) has been installed at Big Bear Solar Observatory (BBSO). The NST will be equipped with six facility-class focal plane instruments\textsuperscript{1} for high-resolution spectral and/or imaging observations. The infrared (IR), an unique observational window and tool, will be sampled by three NST instruments: Nasmyth Focus Filtergraphs,\textsuperscript{2} a Cryogenic Infrared Spectrograph, and the Infrared Imaging Magnetograph (IRIM). State-of-the-art IR focal plane array (FPA) camera is an indispensable device for aforementioned instruments. Until recently, the only IR FPA camera available at BBSO was a 1024 \times 1024 HgCdTe TCM8600 CMOS camera manufactured by the Rockwell Scientific Company (RSC, now Teledyne Imaging Sensors) in 2004, configured as shown in the left panel of Figure 1. Although this camera has shown good performance and outstanding capabilities in acquisition of high resolution IR data,\textsuperscript{3,4} it is unable to meet the special needs of the new scientific instrumentation on the NST. First, the dewar for housing TCM8600 FPA is too small to sustain a whole day’s observations, but rather requires frequent refilling with liquid nitrogen (LN\textsubscript{2}) during observational sequences. Second, this camera does not allow inverted operation, which protects LN\textsubscript{2} from spilling when the camera is mounted on a moving telescope. Nasmyth focus observations are not accessible for any IR camera without this feature. Third, the dewar was fitted with a baffled nose piece suitable only for the optics of the old-generation IRIM. The long nose and baffles cause vignetting and other problems in optical setups for current scientific instrumentation. Fourth, the dewar accommodates only one cold blocking filter with a wavelength bandpass from 0.95 to 1.65 \textmu m. This broad wavelength coverage can lead to high thermal background noise, which degrades the signal to noise ratio of IRIM polarimetry measurements. To solve these problems, in collaboration with Infrared Laboratories Inc., we repackaged this TCM8600 FPA in a new ND-5 dewar with a new filter wheel and with inverted operation being enabled. The right panel of Figure 1 shows this IR camera after repackaging. In March 2010, this repackaged camera was characterized in the NST Coudé Lab. In this paper, we present the design of the new dewar, the detailed process of repackaging and characterizing the camera, and a series of test results including linearity, readout noise, gain, full well capacity, hot and defective pixels, bias and flat fields, inverted operation, vacuum and low temperature control, etc..

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2. DESIGN OF THE NEW DEWAR AND THE REPACKAGING PROCESSING

The new ND-5 dewar, designed by Infrared Laboratories Inc., AZ, has dimensions of $13.625'' \times 6.630'' \times 6.630''$. The outer dewar shell is made of gold anodized aluminum with a thickness of $0.313''$. The internal nitrogen vessel provides a reservoir for up to 1.25 liters of $LN_2$, which allows at least 12 hours of hold time under an adequate guard vacuum. A copper cold plate with a thin gold coating acts as the bottom shell of the $LN_2$ vessel to enhance the thermal contact with mounted equipment. TCM8600 FPA and filter wheel are attached to this cold plate that is kept at temperatures around 77 K. Internal radiation shields further isolate the inner cold mounting components from the dewar’s vacuum shell. A charcoal getter bolts directly to the cold work surface. A jar of activated charcoal has been used as an absorbent material and has shown superior performance versus a molecular sieve.

The new dewar features inverted operation to protect $LN_2$ from spilling. Moreover, a specially-designed fill device with a long transfer hose allows us to transport $LN_2$ into the dewar in a convenient way. As a result, the repackaged camera is able to be mounted and perform uninterrupted observations at the Nasmyth focus bench, which is moving with telescope during an observational sequence.

A low-background 4-position filter wheel is included to accommodate cryogenic $JHK$ filters, as well as a cold dark mask. Each hole has dimensions of $\phi 38.0 \text{ mm} \times 5.0 \text{ mm}$. In order to eliminate ghost images, filter slots are designed to have a $3^\circ$ angular tilt. This filter wheel can be adjusted manually. The dial counter indicates the filter or cold dark mask in operation. Currently, we use position 1 for the $H$ filter, 2 for the $J$ filter, 3 for the cold dark mask, 4 for the $K$ filter. A silicon diode temperature sensor (DT-470 series) is mounted on the filter wheel housing. Through a hermetic 6-pin connector, the operating temperature can be read out and displayed on a LakeShore 211s temperature monitor. A fused silica UV grade window is used as the entrance window with an aperture of 2.5''. A pair of field-of-view (FOV) cold baffles have been installed between the entrance window, filter wheel and TCM8600 FPA to reduce stray light. Considering the limitation from the sizes of baffles, filters and FPA, the $f$-ratio of an incoming beam should be slower than $F/12$ to avoid any optical blocking and vignetting.

After the old RSC dewar was opened and disassembled, all electronics including the TCM8600 FPA and RSC controller were directly transferred and installed into the new ND-5 dewar. To ensure a good vacuum seal, a new connector of DB hermetic material was mounted in the vacuum flange with epoxy. The purpose is to allow the existing RSC connector flange to mate to the boss surface of the new ND-5 dewar. Although caution was taken during the transfer of the electronic, there was an accident causing all DAC channels to become non-functional. Diagnosis from Teledyne Imaging Sensors (the successor of Rockwell Scientific Company, RSC) showed that the Bias board was definitely damaged and had to be replaced. After replacement of the Bias board, hardware
integration, and system testing, the repackaged TCM8600 FPA camera was delivered from Infrared Laboratories Inc., AZ to BBSO, CA on March 3, 2010.

3. CHARACTERIZATION OF THE CAMERA

The old RSC TCM8600 camera\(^5\) was characterized at National Solar Observatory/Sacramento Peak in October 2003. The approach to characterization and the results were described in detail by Cao et al.\(^6\) In order to fully understand the performance of the newly repackaged camera, we set up an evaluation system in the BBSO Coudé Lab and characterized the camera during the period from March 25 to March 30, 2010. The camera FPA was illuminated by a stable and uniform light beam in a collimated configuration. The adjustable intensity light source was a mini-optoliner which is able to provide a stable illumination to better than 0.5%. In order to remove the effect of color temperature and quantum efficiency variations, a narrow band interference filter with a bandpass of 5 nm was employed in the optical path. Table 1 lists the specification of RCS TCM8600 camera.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>Hybrid CMOS</td>
</tr>
<tr>
<td>Detector material</td>
<td>HgCdTe</td>
</tr>
<tr>
<td>FPA format</td>
<td>1024 × 1024</td>
</tr>
<tr>
<td>Pixel size</td>
<td>18 µm × 18 µm</td>
</tr>
<tr>
<td>Cutoff wavelength</td>
<td>2.5 µm</td>
</tr>
<tr>
<td>Filling factor</td>
<td>100%</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>≥ 55%</td>
</tr>
<tr>
<td>Well capacity</td>
<td>350,000 e(^-)</td>
</tr>
<tr>
<td>Outputs</td>
<td>8</td>
</tr>
<tr>
<td>Readout mode</td>
<td>Ripple</td>
</tr>
<tr>
<td>ADC</td>
<td>14 bit LVDS</td>
</tr>
<tr>
<td>Frame rate</td>
<td>≤ 30 Hz</td>
</tr>
<tr>
<td>Interface</td>
<td>Camera Link II</td>
</tr>
<tr>
<td>Cooling system</td>
<td>LN(_2)</td>
</tr>
</tbody>
</table>

3.1 Bias, dark and flat fields

Bias is an offset level of the electronics of a detector, which is usually determined without exposure to light, using a total integration time of 0.000 seconds. This camera is capable of computer controlled bias adjustment. There are 8 biases that can be adjusted in an effort to optimize the camera’s performance. The left panel in Figure 2 shows a typical "bias" of the repackaged camera, with numbers denoting the 8 domains of the FPA. We analyzed bias levels for these 8 domains. The right panel in Figure 2 shows histograms of these 8 bias levels. It should be pointed out that the current camera is unable to support 0 seconds exposure and the shortest integration time is 0.013 seconds. As a result, "bias" shown in Figure 2 includes a slight contribution from dark and background emission.

![Figure 2.](image-url)
Flat fields are used to correct for pixel-to-pixel variations in the FPA response as well as any nonuniform illumination of the detector itself. Figure 3 illustrates three typical flat fields taken with an integration time of 5 ms, 15 ms, and 25 ms, with a frame rate of 20 Hz. The dark patterns appearing in flat fields deserve special notice. The positions of the dark patterns depend strictly on the adopted integration time. Two dark patterns emerge initially from the top and bottom, respectively. As the integration time increases, they sweep across FPA bi-directionally toward the detector center. When integration time reaches about 35 ms, the frontiers of two dark patterns arrive at the horizontal middle line at same time. Under an integration time range from 35 ms to 70 ms, dark patterns fill up the whole FPA. They start to move away when integration times are longer than 70 ms and fade fully at 105 ms exposure. The aforementioned procedure repeats with a period of 105 ms integration time. This glitch is suspected to be caused by electronic interference, probably due to imperfect shielding or/and wiring. If the linearity of the detector is good enough, one solution is to correct the observational image with flat fields that must have exactly the same integration time as image exposures.

![Figure 3](image1)

**Figure 3.** Flat fields taken with integration times of 5 ms, 15 ms, and 25 ms.

### 3.2 Linearity

Considering the cumbersome dark patterns, good linearity with exposure is of particular importance in correcting the observational data set with flat fields. Here, we employed the following approach to measure linearity of the repackaged TCM8600 camera: 1. take flat field images with an increasing integration time; 2. select a uniform area (30 × 30 pixels) in domain 3 and plot the mean signal value in ADU (Analog/Digital Units) versus the integration time over the full linear range; 3. fit the data using a linear model by minimizing the chi-square error. The deviation of each point from the fitted line is a measure of the non-linearity of the system.

![Figure 4](image2)

**Figure 4.** Linearity curve of the camera. The device is linear over the output range from 2500 ADU to 10000 ADU.

Figure 4 shows the value of the mean signal versus the exposure over the full linear range. Because one of
the dark patterns sweeps across the selected area near 26 ms exposure time, the curve is no longer a straight line and has two segments instead. We fitted these two segments sequentially. Over an output range from 2500 ADU to 10000 ADU, both of them show good linearity and the nonlinearities are all less than 0.5%.

3.3 Gain and readout noise

The classical Photon Transfer Curve (PTC) approach,\textsuperscript{7,8} is used to characterize the gain and readout noise, and has been used for well over a decade. A typical CCD/CMOS camera system generally contains three distinct noise characteristics: readout noise, shot noise, and fixed pattern noise. Readout noise is the random noise, only associated with the camera output amplifier and signal processing electronics. It represents the baseline noise of a camera. Shot noise does not originate from the camera. It results from the statistical nature of the input light itself, and is proportional to the root square of the input illumination. Fixed pattern noise is caused by differences in sensitivity among pixels, which dominates at higher level of input light. In order to measure gain and readout noise more precisely with the PTC, we eliminated the contribution from fixed pattern noise during measurement. This processing was accomplished by subtracting two consecutive frames having the same integration time. The characterization method and data collection procedure were described in detail by Cao et al.\textsuperscript{5}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{Photon Transfer Curve plotted with a uniform area (30 × 30 pixels) in domain 3 with a frame rate of 20 Hz.}
\end{figure}

Figure 5 shows a sample of PTC, which was generated in a uniform area (30 × 30 pixels) in domain 3 under a frame rate of 20 Hz. The slope of fitting line in PTC allows the gain and readout noise to be obtained by measuring the noise level at zero illumination. The measured gain and readout noise are 24.4 $e^-$/ADU and 46.5 $e^-$, respectively. This measurement was applied to the eight domains because eight individual ADCs are used for camera output. The measured results are summarized in Table 2.

\begin{table}[h]
\centering
\begin{tabular}{lcccccccc}
\hline
Domain & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\hline
Readout noise ($e^-$) & 40.29 & 39.41 & 46.48 & 44.22 & 41.22 & 42.91 & 42.01 & 40.40 \\
\hline
\end{tabular}
\caption{The measured gains and readout noises of eight domains.}
\end{table}

3.4 Full well and dynamic range

Full well capacity defines the number of electrons an individual pixel can hold before spilling-over into adjacent pixels. As shown in Figure 4 and Figure 5, the camera saturates around a level of input signal between 10000 and 11000 ADUs. Taking an averaged gain of 24.3 $e^-$/ADU into account, a conservative estimate of the full
well capacity is about 250,000 $e^-$.

The dynamic range is calculated as full well capacity divided by the smallest detectable signal. If we consider the averaged readout noise of 42.12 $e^-$ as this lower limit, the dynamic range is 75.47 dB for a frame rate of 20 Hz.

### 3.5 Vacuum and hold time

One purpose of repackaging the camera is to improve the $LN_2$ holding capability and cold time of the dewar so as to sustain a whole day’s observations. Apart from thermal dissipation of the FPA electronics itself, the hold time depends on the status of the dewar vacuum in operation. In consideration of safety and efficiency, a VARIAN turbo mini pumping system (Turbo-V70) has been purchased for pumping the dewar. Turbo-V70 is a portable, totally oil-free turbo-molecular pumping system with pumping speeds from 40 to 70 liters/s. Testing was performed with the dewar standing in a horizontal configuration, as shown in Figure 1. $LN_2$ was filled into the new dewar after the internal vacuum was pumped down to $5 \times 10^{-6}$ torr. When the internal temperature dropped to a low level, the charcoal getter inside the dewar was activated to absorb the outgas products. As a result, the internal vacuum was further reduced to $7 \times 10^{-7}$ torr.

![Figure 6](image_url)

Figure 6. Cooling speed and hold time of the new dewar after one $LN_2$ full filling. Solid line plots the mean signal value of FPA versus the time consumed. Dotted line plots the filter wheel temperature versus the time consumed.

Figure 6 illustrates the cooling speed and hold time of the new dewar after one $LN_2$ full filling. We monitored the temperature variation of the FPA by recording the mean signal value of dark images every 15 seconds, which was plotted with solid line in Figure 6. The FPA requires one and a half hours to attain a $LN_2$ temperature equilibrium down from room temperature. The temperature variation of the filter wheel was recorded every 1 minute by reading a LakeShore 211s temperature monitor, as plotted with dotted line in Figure 6. Due to its large volume and the extended distance from cold plate, the filter wheel has to spend at least 4 hours to reach a temperature equilibrium at 83.5 K. The hold time of the new dewar is over 14 hours.

### 3.6 Hot and Defective Pixels

Hot and defective pixels are those individual sensors on FPA that fail to sense input light levels correctly. They display obviously either brighter or darker than the normal light levels, as shown in the left panel of Figure 7. Since hot and defective pixels have a sharp decline in performance from linearity, a routine flat-fielding process is unable to correct these pixels. In order to get rid of them efficiently, we make a mask map in the middle panel of Figure 7 by specifying positions of all hot and defective pixels. Apart from individual hot pixels, a super hot pixel located at (801, 262) deserves special attention. On a dark image, it appears as an individual hot pixel with a extremely high count level of 14859 ADUs. However, when the FPA is exposed to light, this individual pixel blooms into a cluster with $14 \times 14$ pixels or larger. The size of cluster depends on input light levels. In addition, four columns at 255, 511, 766, 1023 have abnormal count levels, as shown in Figure 7. After a routine dark- and flat-fielding processing, a majority of non-uniformity on the image could be removed except for hot and defective pixels. The mask map was applied to further eliminate these abnormal pixels, clusters, and lines. This processing was accomplished by replacing them with averaged count of surrounding normal pixels. The right panel in Figure 7 shows a clean image after a processing of dark-, flat-, and mask-fielding.
4. DISCUSSION AND CONCLUSIONS

RSC TCM8600 IR FPA camera has been repackaged to meet the special needs of the new scientific instruments of the NST. To ensure its proper use, the repackaged camera has been evaluated in BBSO Coudé Lab by characterizing the system performance. The main conclusions are summarized as follows,

1. RSC TCM8600 IR FPA and electronics have been successfully transferred into a new ND-5 dewar, which is functional in inverted operation. A low-background filter wheel has been installed in the dewar to accommodate cryogenic JHK filters, as well as a cold dark mask. The internal nitrogen vessel can hold up to 1.25 liters $LN_2$. The hold time of the new dewar is over 14 hours under an adequate guard vacuum.

2. Over an output range from 2500 ADU to 10000 ADU, the repackaged camera shows good linearity and the nonlinearity is less than 0.5%. The camera saturates around a level of input signal between 10000 and 11000 ADUs, which is much lower than 14-bit ADC saturation value $\sim 16384$ ADUs. The current factory default setting is not well-calibrated such that the maximum A/D output is achieved near full well.

3. The moveable dark patterns are a newly-found problem. As the integration time increases, two dark patterns sweep across FPA bi-directionally toward the detector center. The positions of the dark patterns depend strictly on the adopted integration time. This glitch is suspected to be caused by electronic interference. Currently, Teledyne Imaging Sensors is troubleshooting it. Fortunately, the two dark patterns are able to be corrected with flat fields. However, the flat fields must have exactly the same integration time as image exposures.

4. The total hot and defective pixels are less than 0.5 % of all available pixels. The hot pixel located at (801, 262) deserves special attention. It always blooms into a cluster with $14 \times 14$ pixels or larger with exposure to input light. For this reason, observational targets of interest should be kept far away from this region. In addition, the four columns at 255, 511, 766, 1023 have abnormal count levels. It is strongly suggested that one removes these hot and defective pixels with the mask map.

5. PTC approach is used to estimate the gain and readout noise. Aforementioned measurements were performed under a frame rate of 20 Hz, which is close to the real operating mode of routine observations. The averaged gain and readout noise over 8 domains are $24.3 \, e^-/ADU$ and $42.1 \, e^-$ under a frame rate of 20 Hz. The corresponding dynamic range should be better than 75 dB. The full well capacity is only $250,000 \, e^-$, much lower than the specification in Table 1 which the RSC claimed.

6. Due to the lack of a well-calibrated light source and an isotopic source, we failed to measure the quantum efficiency and charge transfer efficiency.

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REFERENCES


