Low-Light-Level 640×480-pixel CCD Camera for Night Vision Applications

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ABSTRACT

We report progress made over the past two years on a visible low-light-level 640×480-pixel CCD imager and the camera electronics developed for night vision applications. The CCD camera, operating at 30 frames per second, has demonstrated good performance to below starlight illuminance (<1 mLux) conditions. The high sensitivity of the CCD imager is the result of back-illumination and low-noise readout amplifiers. To improve the CCD bright-light-source performance, antiblooming drains have been integrated into the CCD architecture that inhibit pixel blooming for signal levels up to at least 10^5 times pixel full well. Sample CCD imagery under controlled and field illumination conditions, extending from full moon to overcast starlight, is shown.

1. INTRODUCTION

Nighttime imaging in the visible band of scenes illuminated by both natural and cultural light sources creates demanding requirements for detector performance. Besides the high camera sensitivity required for the low-light-level conditions expected at night, the detector system must also be able to perform over the wide dynamic ranges that commonly occur within an image. A single nighttime scene can have illumination levels ranging from less than 0.1 mLux up to greater than several hundred Lux [1]. To perform well over the varying nighttime conditions, the camera must also have flexible operating modes and provide a video output that can be post-processed.

Two years ago at this conference a visible 640×480-pixel CCD imager was described as a future development for a night vision imaging system. The CCD imager and camera electronics that have been under development have features that address the needs for seeing under the demanding nighttime lighting conditions. Besides high sensitivity of the CCD provided by back-illumination and low noise readout circuitry, the CCD camera has a high pixel full well, two-dimensional pixel binning, antiblooming control and 12-bit digital output.

This paper reports progress on the development of the 640×480-pixel CCD imager and camera electronics as well as the testing of the CCD camera under various low-light-level conditions. Section 2 describes the CCD imager including the detector architecture, device back-illumination, low-noise readout amplifiers and antiblooming control. In Section 3, the CCD camera electronics that operate the CCD imager at 30 frames per second (fps) are reported. Section 4 shows CCD imagery taken under various controlled and field (natural and cultural) lighting conditions that extend below starlight illuminance to several orders of magnitude beyond the CCD imager pixel full well. Also shown in this section are CCD images that have been processed through a real-time locally-adaptive compression algorithm [2] that essentially extends the dynamic range of the viewed image. The algorithm compresses the camera 12-bit digital data into 8-bits for proper display. Section 5 discusses future directions for improving the CCD camera.

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2. VISIBLE CCD IMAGER

Figure 1 shows a schematic and photograph of the 640×480-pixel CCD imager. The CCDs are fabricated on *p*-epitaxial silicon with a three-phase, triple-level-polysilicon, *n*-buried channel process. The CCD process sequence is described in detail elsewhere [3]. To reduce smear, the detector has a split frame-transfer architecture with two frame-store arrays located on opposite sides of the imaging array. The CCD has eight serial registers with four registers adjacent to each frame-store. Each output register has an on-chip two-stage source-follower that is responsible for the output of a 160×240-pixel section of the 640×480-pixel image. The multiple ports reduce the pixel frequency per port, for a given frame rate, thereby reducing the readout noise.

A back-illuminated process [4] has been developed using finished front-illuminated CCD wafers as starting material. In the process, the front-illuminated wafer is mounted circuit-side down to a supporting substrate using an adhesive. The wafer is thinned by a combination of lapping and polishing (which removes all but a few mils of the substrate) followed by a wet chemical etch that leaves a silicon membrane that is only a few tens of microns thick. A shallow p^+ layer is formed on the etched surface to pin the energy bands and provide an electric field that repels the photoelectrons towards the CCD wells at the front surface. This layer is formed by a shallow ion implantation which is then activated by a pulsed laser anneal. Figure 2 shows the quantum efficiency of a back-illuminated CCD imager along with front-illuminated performance for comparison. Back-illumination gives near-reflection-limited quantum efficiency in the visible (400-700 nm) by selecting the appropriate antireflection coating. Relatively high quantum efficiency is also obtained in the near infrared (700-950 nm) with the response decreasing as the photon energy approaches the silicon bandgap energy.

Antiblooming drains [5] have been integrated into the CCD pixel architecture to limit the spread of charge into adjacent pixels. Without the antiblooming control, the photogenerated charge, created by a bright light source, would spread into other pixels after the charge has exceeded the pixel storage capacity. Figure 3 gives plan views of pixels with and without antiblooming drains and illustrates charge flow for the two arrangements. The pixel with blooming control has the drains integrated into the channel stop regions in between pixels. The antiblooming drains have been included in the CCD by adding two extra implantations and one extra masking step to the process fabrication sequence. The n^+ region of the antiblooming drain is surrounded by an undepleted p^+ layer. The undepleted p^+ layer repels photoelectrons away from the antiblooming drains and into the pixel collection wells. The pixel dimensions of the 640×480-pixel CCD imager are 24×24 μm square. The antiblooming structure occupies a 2×24 micron area in the pixel or about 10% of the pixel area. Figure 4 illustrates the performance of the antiblooming drains by showing images taken with and without antiblooming control. The bright LED in the photograph produces an optical overload of 1000× full well in the CCD. Laboratory measurements have shown that the antiblooming drains inhibit blooming for signal levels up to at least $10^5\times$ pixel full well. Placing the antiblooming structure in the pixel reduces the full well capacity by approximately 10% and the quantum efficiency by less than 2%.

Table 1 summarizes the operating performance of the 640×480-pixel CCD imager.

3. CCD CAMERA SYSTEM

Figure 5 is a photograph of the CCD camera system. The system is composed of the camera head, A/D multiplexer, power supply, and TE-cooler controller. The camera system, that operates the CCD imager at variable frame rates and in various modes, has a 12-bit digital dynamic range. Also shown in Fig. 5 is a photograph of the electronic board set that is located inside the camera head. The sensor board contains the CCD imager package and sixteen post-processing analog chains, eight of which are used for the 640×480-pixel CCD imager (one channel for each CCD readout amplifier). The analog chain consists of an amplifier for increasing the pixel signal above the noise of the following electronics, a correlated double sampler for removing reset noise of the readout circuit, and a 75 Ω buffer amplifier for driving the signal off of the board. The CCD imager is mounted on top of a two-stage TE-cooler that is inside a 68-pin package. The TE-cooler lowers the CCD temperature to approximately -35° C when the TE-cooler hot side is at room temperature (23° C). The cooling reduces the dark current to negligible levels at the nominal operating rate of 30 fps.

A digital timing board, not shown in the photograph of the electronic board set, contains a programmable logic device and set of EPROMs . These components comprise the state machine for operating the CCD imager in various modes. The camera has two imaging modes, full frame (640×480 pixels) or binned (320×240-pixels). The camera system requires three input signals, READ, BIN, and FLUSH. The READ signal determines the frame rate, the BIN signal selects binned or unbinned operation, and the FLUSH and READ signals set the integration or exposure time. A level shifter board translates the TTL signals received by the digital timing board into analog levels that are compatible with the CCD operation.

Two A/D multiplexer boards digitize and reformat the eight video signals received from the sensor board. Each multiplexer board has four A/D converters (one A/D for each CCD readout channel) that digitize the CCD pixel data to 12-bits. A row at a time of digitized data, coming from the upper and lower imaging array, is temporarily stored in FIFO memory. While in the FIFO, the pixel information is restructured into a pseudo video format before being sent to a frame grabber board located inside a computer. The multiplexer boards also generate the interface timing needed to communicate with a frame grabber.

When the camera is operated at 30 fps, the pixel rate per port is 1.33 MHz and the readout noise is approximately 4 e^- rms. Table 2 summarizes the operating performance of the CCD camera system.

4. EXPERIMENTAL RESULTS

In laboratory experiments, the CCD camera system has demonstrated sensitivity below starlight illuminance conditions (< 1 mLux). Figure 6 shows contrast resolution charts for illumination conditions ranging from full moon (33.3 mLux) to half starlight (1 mLux). All images were taken at 30 fps in full frame mode with an f/1.4, 25 mm lens (approximately 40° diagonal field of view). The three resolution charts shown for the different lighting conditions have contrasts of 20%, 50% and 100%. The center bar pattern of each 3×3 resolution chart array has the highest spatial frequency at 21 line pairs per mm (lp/mm) at the CCD focal plane, which is the CCD Nyquist limit. Even at starlight illumination conditions, the 20% contrast bar pattern with 21 lp/mm was visible.

The Lincoln low-light CCD system (LLCCD) was also tested in nighttime driving field experiments (vehicle driven without headlights) with natural and cultural lighting conditions. Figures 7 and 8 show typical images taken during the driving demonstration. Besides the night vision LLCCD camera system, an intensified CCD (IICCD) camera and an uncooled long wavelength infrared camera (LWIR) were viewing the same scenes for comparison. The scene illumination consists of background sky illumination at several mLux and cultural lighting. The IICCD is an early version of a third generation (GEN III) tube coupled to a CCD camera. Both LLCCD system and IICCD camera were operated at 30 fps, used a f/1.4, 25 mm lens, and had approximately a 40° field of view. The images shown for the LLCCD have been processed through a real-time adaptive compression algorithm [2] before being displayed. The algorithm locally adapts the camera 12-bit words into an 8-bit dynamic range for image display. The compression uses information from the full 12-bit range extending the usable information that is displayed in a single scene.

The visible and LWIR cameras give complementary information. In Fig. 7, the visible cameras show the utility wires and foliage detail clearly, while in the LWIR image the wires are not seen and the foliage is much less distinct. In the same scene, the LWIR camera shows the road/shoulder boundary distinctly while the same boundary is not clearly distinguished by the visible cameras. Figure 8 shows more of the complementary information between the LWIR and visible data. The LWIR image displays strong contrast between the people and background while the visible image gives more tree detail. A separate paper [6] describes in detail the work being done to fuse the images from the two spectral bands into a single color image.

Three differences between the LLCCD and IICCD cameras are apparent in the nighttime driving demonstration images. The LLCCD camera has a wider dynamic range, improved contrast, and also less blooming than the IICCD camera . In the images taken using the LLCCD camera system, the CCD antiblooming drains limit the blooming within the scene. As an example of the performance difference, the images in Fig. 7 show that the region around the street light has saturated in the IICCD image while most of the detail is still displayed in the LLCCD picture. Also within the same scene, the GEN III tube's limited dynamic range and reduced gain due to the bright street lights causes regions of low-light illumination to lose detail (i.e. the trees along the roadside begin to disappear).

5. FUTURE DIRECTIONS

Over the next year, the effective dynamic range and sensitivity of the night vision CCD camera will be increased. The 640×480-pixel CCD imager has a dynamic range that is greater than 16-bits but the camera electronics only uses 12 bits of that range. The analog chain will be redesigned to better utilize the wide CCD dynamic range while still retaining the 12-bit word size. To increase sensitivity, the noise will be lowered by redesign of the readout amplifiers. The goal is to reduce the noise to 1 to 2 e^- rms. The sensitivity will also be increased by improving the quantum efficiency in the near infrared. This will be done by increasing the silicon membrane detection region from 10 µm to 45 µm.

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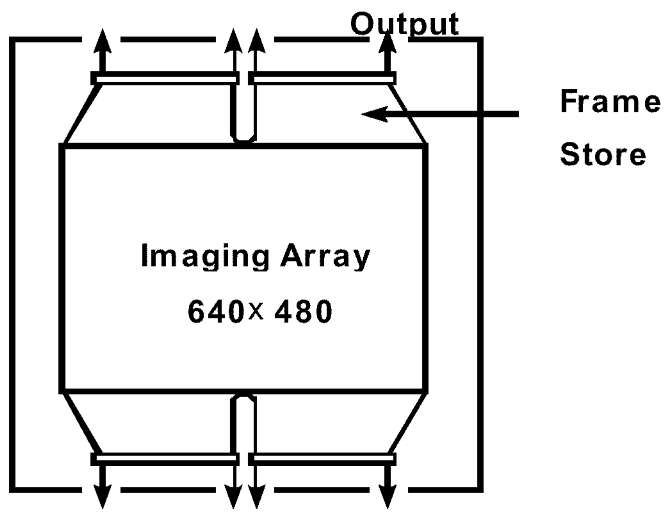
Resolution	640×480-pixels
Pixel Size	24 µm
Responsivity	17 µV/e
Full Well	>150,000 e
Charge Transfer Efficiency (parallel)	>0.99999
Dark Current (23° C)	2 nA/cm^2
Fill Factor	~100%

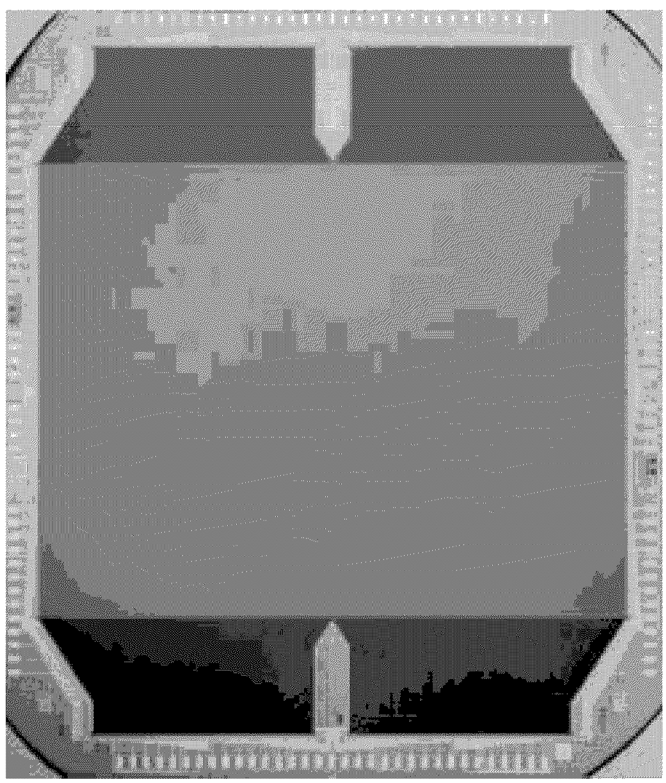
Table 1. CCD imager performance

Maximum Frame Rate	90 fps
Noise at 30 fps	4 e^- rms
Dynamic Range	72 db
TE-Cooler Temperature	$-35^{\circ}C$

Table 2. CCD camera performance



Device Schematic



Device Photograph

Figure 1. Schematic and photograph of the 640×480-pixel night vision CCD imager.

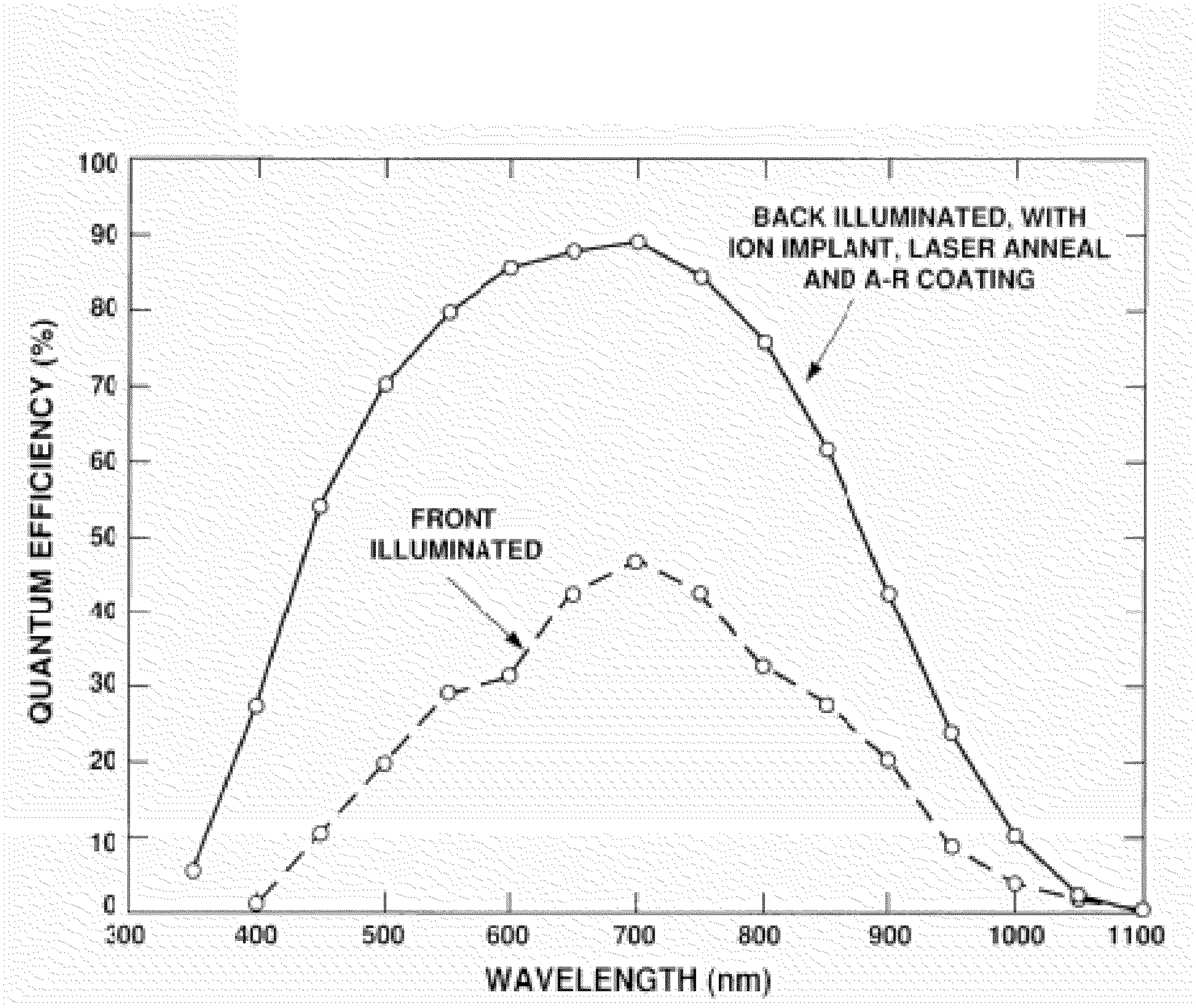


Figure 2. Quantum efficiency versus wavelength of a back-illuminated 640×480-pixel CCD imager compared to a front-illuminated imager.

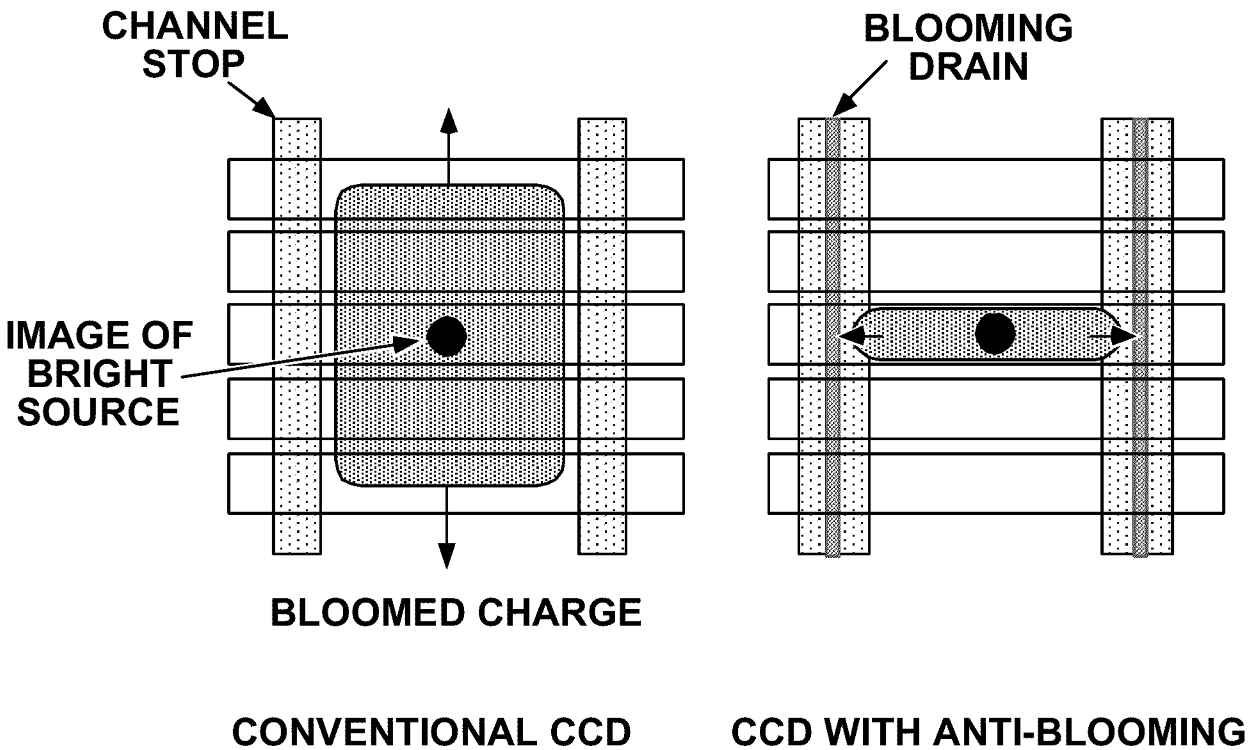


Figure 3. Schematic top view of pixels with and without antiblooming drains. The pixel without blooming control has charge spilling down the column while the pixel with antiblooming drains confines the charge to a single pixel.

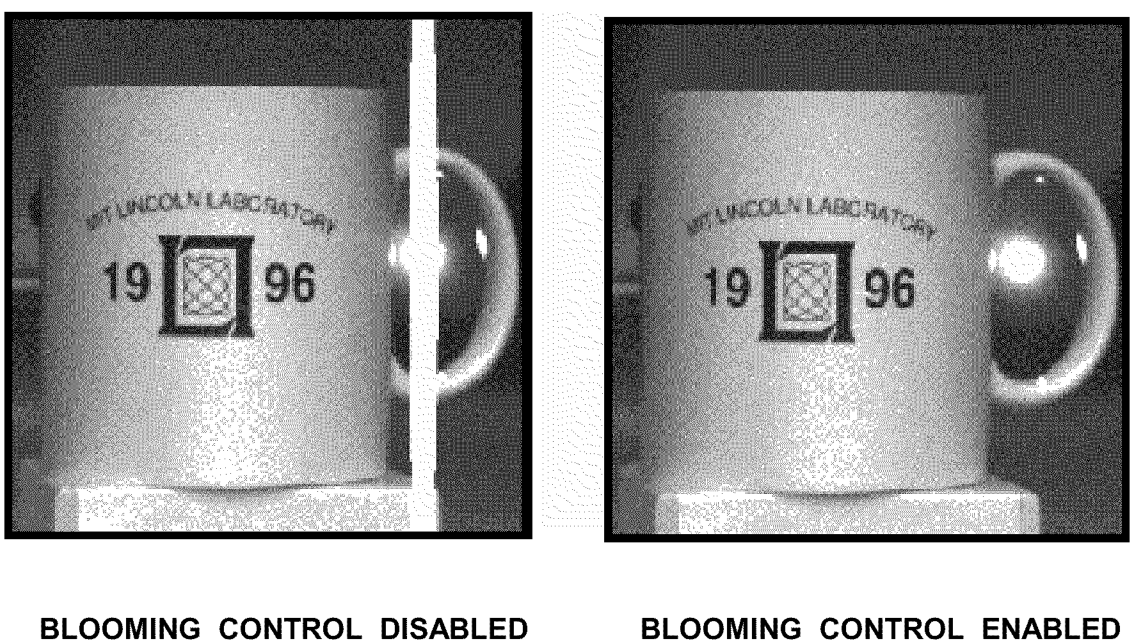


Figure 4. Photographs showing images with and without the antiblooming control enabled. A bright LED in the scene causes blooming in the absence of antiblooming control.

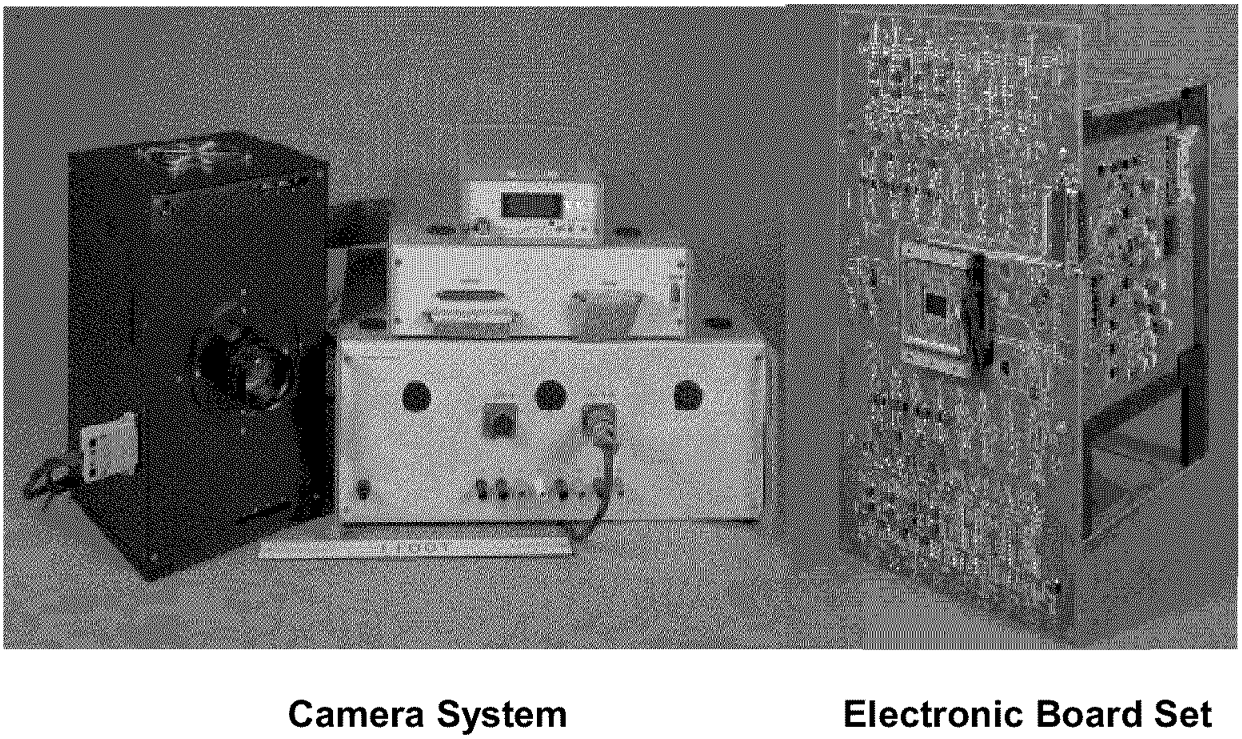


Figure 5. Camera system used to operate the 640x480-pixel CCD Imager. Also shown is the electronic board set that is inside the camera head.

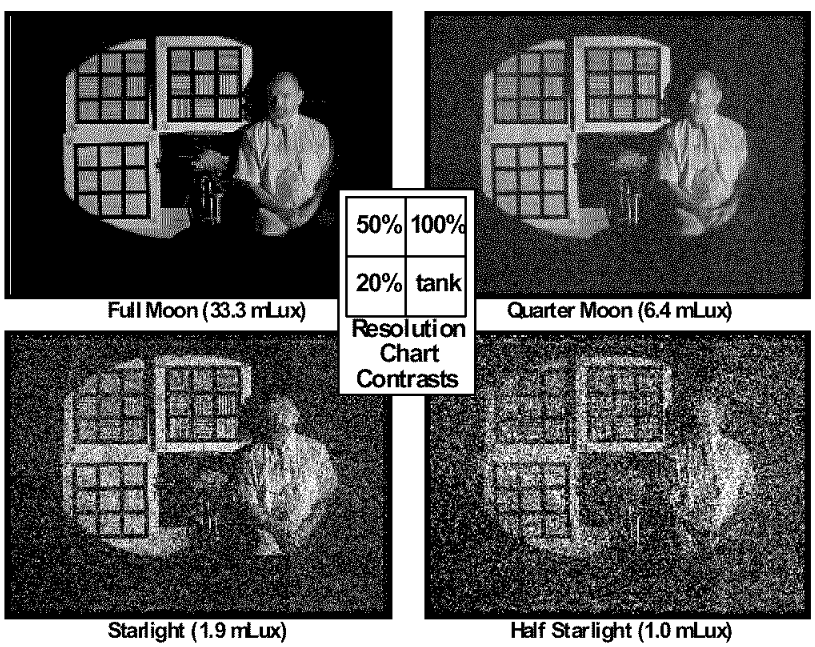


Figure 6 Contrast resolution charts for varying low-light-level conditions ranging from full moon down to below starlight.

Lincoln Low-Light CCD

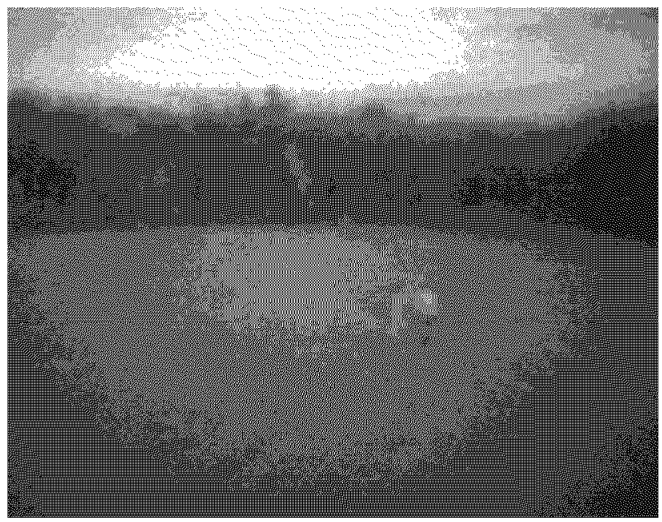
Gen III Intensified CCD

RTIS Uncooled LWIR

Figure 7. Nighttime driving images (vehicle headlights off) taken using the night vision LLCCD, an IICCD and an LWIR camera. The lighting in the scene is a combination of sky illumination and cultural lighting.

Lincoln Low-Light CCD

Gen III Intensified CCD



RTIS Uncooled LWIR

Figure 8. Images taken using the LLCCD, an IICCD and an LWIR camera, of people

walking in a field at night. The measured scene illumination of 15 mLux is a combination of sky background and cultural lighting.