Investigating the Causes of and Possible Remedies for Sensor Damage in Digital Cameras Used on the OMEGA Laser Systems

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Abstract

When a target is imploded using the OMEGA laser system, various types of radiation, including neutron radiation, are produced. Cameras using charge-coupled devices (CCDs) are used to record these implosions. However, the CCDs are vulnerable to neutron irradiation. The CCD used on the Neutron Temporal Diagnostic (NTD) shows significant increases in dead pixels in conjunction with high neutron yield shots. The high energy neutrons collide with the sensitive structure of the CCD, causing physical damage to the device. These physical defects are reflected in the images produced by the CCD in a Nikon D100 digital camera as noise, stuck pixels, and hot pixels that lead to line defects and in the images from the CCD in the NTD as dead pixels. The CCD soon becomes unable to function. Research into solutions for this problem has shown that little can be done to prevent or reverse the damage. While a polyethylene shield decreases the damage by a factor of two, a significant amount of radiation is still able to reach the CCD. Scientists must learn to work with the damage and develop a system to determine when the CCDs should be replaced.

1. Introduction

At the University of Rochester’s Laboratory for Laser Energetics (LLE), research on inertial confinement fusion is conducted through the implosion of cryogenic targets. Images of these implosions are recorded by a Nikon D100 digital camera located on the outside of the target chamber, approximately 1.8 meters from target chamber center. These images, such as those shown in figure 1.1, allow LLE scientists to record valuable information about what occurs in the target chamber during an implosion. However, the CCD becomes damaged after being exposed to numerous implosions over an extended period of time. The damage is obvious in the images taken by the device and lessens the amount of information scientists are able to gather from the image.

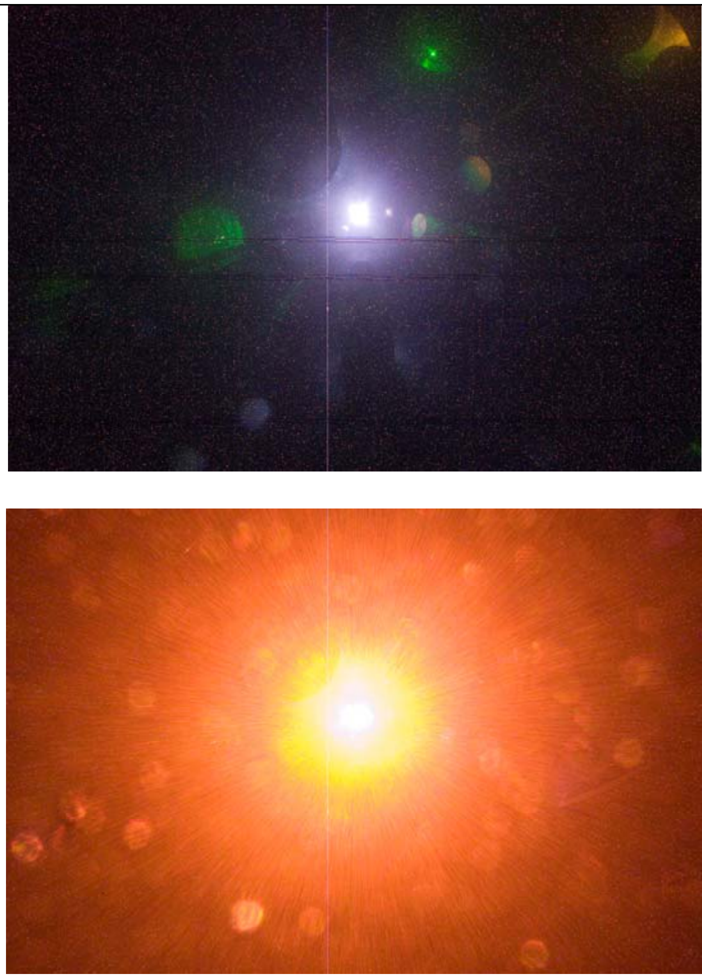

Figure 1.1: Examples of images taken by the damaged CCD in the Nikon D100 digital camera.

A CCD works by converting photons to voltage. When a camera takes a picture, it gathers the information in terms of photons. In each individual pixel on the CCD, this charge is converted to electrons and sent to an output node, where the electrons are converted to voltage and sent to the camera circuit board as an analog signal. At the circuit board, the analog signal is converted to a digital signal. The information is now in a form that a computer can read and convert to an image. Damage to the CCD occurs when this process is interrupted or otherwise malfunctioning.

The damage appears in the image as hot pixels, stuck pixels, and noise, as can be seen in figure 1.2(b). Hot pixels are permanently lit pixels that appear white and can lead to line defects, such as the vertical white line seen in figure 1.2(b). In a CCD, the charge from each pixel travels down a vertical line of pixels in order to reach the output node. If one of the pixels in this line has a defect, it can not correctly transfer the electrons to the output node, leading to a line defect. Stuck pixels occur when one or more sub pixels are permanently either lit or unlit, causing the pixels to always appear red, blue, or green. This can explain the many red and blue spots in the blank shot from figure 1.2(b). Noise is a statistical variation that can appear as monochromatic grain or colored waves. Figure 1.3 gives histograms of the red, green, and blue pixels in the image in figure 1.2(b) and indicates the presence of dark current, which occurs when a pixel is charged even though there is no incident light to produce a charge in that pixel. A histogram of a blank shot should show that the red, green, and blue color values for all the pixels are 0. However, the histogram of figure 1.2(b) shows that these color values vary between 0 and 255, indicating that the pixels are producing a charge when there is none.

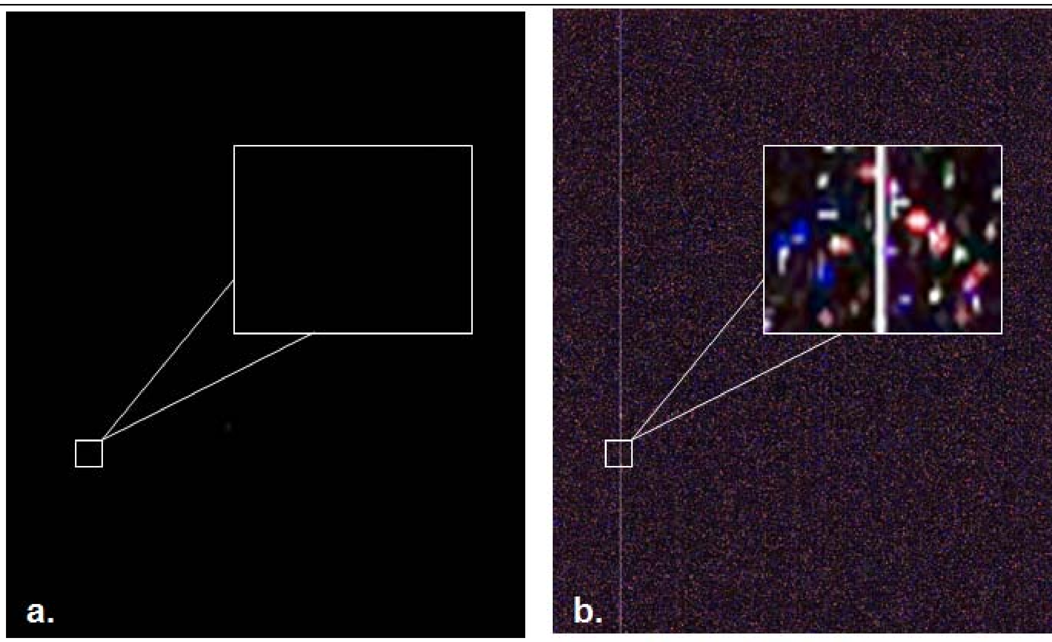

Figure 1.2: (a.) A blank shot taken with the D100 before being placed outside the target chamber
(b.) A blank shot taken with the D100 after 13 months outside the target chamber

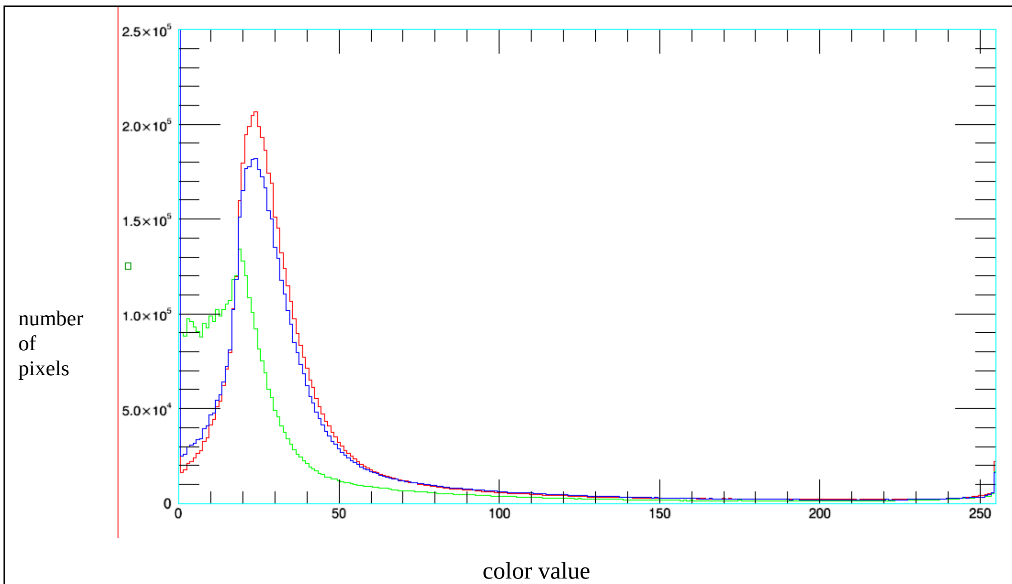

Figure 1.3: Histograms of red, green, and blue pixels corresponding to the image in figure 1.2(b)

2. Causes of the Damage

The damage to the CCD is caused mainly by neutron irradiation of the device. A CCD is composed of several layers of silicon, each layer including a different form of silicon. These layers can be seen in figure 2.1. Previous research has shown that neutrons with energy of 190 eV or greater can displace the silicon atoms from their lattice positions, creating trapping sites in the signal channel. This causes bulk damage, making it difficult for the information from the pixels to correctly reach the output node and resulting in low charge transfer efficiency.[1] Other research has yielded similar results.[2,3]

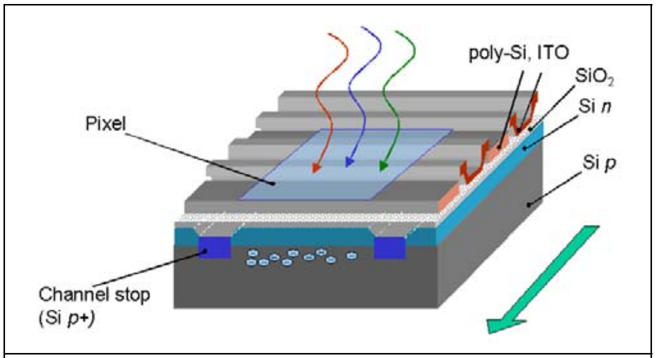

Figure 2.1: A cross-section of a CCD

The damage can be seen not only on the images but also on the CCD sensor. When the imager was examined under a stereo microscope, many small white spots could be seen around the surface of the device, as can be seen in figure 2.2. These spots could be the result of the device being pelted with high energy particles, such as neutrons.


Figure 2.2: A 12.1 mm long and 15.6 mm wide (1536 by 2000 pixels) section of the damaged CCD taken from the Nikon D100

Further evidence for neutrons being the cause of damage to CCD sensors used on the OMEGA laser systems is provided by data from the Neutron Temporal Diagnostic (NTD). The

NTD includes a streak camera that utilizes a CCD and gathers information about the neutron burn history.[4] The CCD sensor used on the NTD showed significant damage, mainly in the form of dead pixels, or pixels that are permanently unlit and appear black. Analysis of images from the streak camera includes the implementation of an algorithm that calculates the number of dead pixels in that image, among other calculations. The graph in figure 2.3 shows the progression of the amount of dead pixels over a time period of 6 months. The graph contains 157 data points, beginning at shot 46068, when the current CCD was first used, and ending at shot 47970. In this time period, the two most noticeable spikes include a rise from 13 dead pixels in the image from shot 46825 to 36 dead pixels from shot 46827 and an increase from 13 dead pixels in the data from shot 47485 to 77 dead pixels from shot 47575. Both spikes correspond to shots with high neutron yields. The graph shows some decrease in dead pixels over time, as it is possible for dead pixels to resurrect.

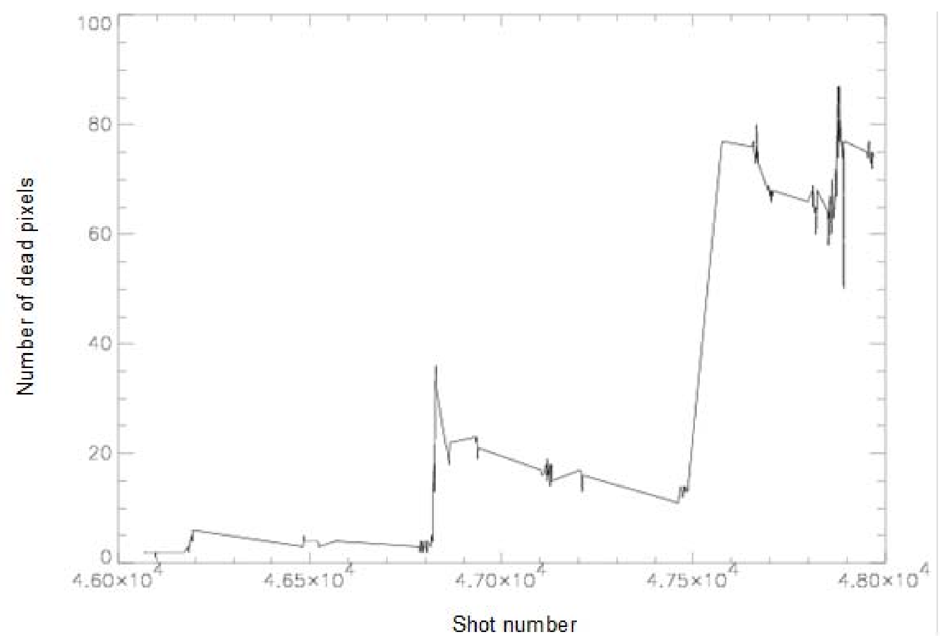

Figure 2.3: A graph representing the progression of damage to the CCD in
the Neutron Temporal Diagnostic. Noticeable spikes correspond to high neutron yield shots

Further research is needed to confirm the conclusion that neutron irradiation causes the CCD to become damaged, as there are other possible causes. Proton and gamma ray irradiation can cause damage similar to that of neutron irradiation.[1] Direct hits by lasers can also damage CCD sensors,[5] though neither the Nikon D100 nor the streak camera in the NTD is exposed to direct hits by the laser beams.

3. Possible Remedies

With current technology, it is difficult to find an effective method of protecting CCD sensors from radiation damage. However, shielding can increase the life of the device. For example, when 1 meter of polyethylene shielding was placed in front of the NTD, the damage was decreased by a factor of two.[6] Other types of shielding, such as paraffin wax, concrete, water, and boron have been found to be somewhat effective.[7] Future research may reveal other means to extend the period of time in which the CCD can be utilized.

One possible solution for the problem is to use a different, more radiation-tolerant camera sensor. An example of such a sensor is the charge injection device (CID), which has several inherent features that make it more able to withstand radiation than the CCD. Such features include a single transfer sense, meaning that the charge from the photon is sensed at the pixel site. Therefore the sensing of the charge is not destructive to the device and a good charge transfer efficiency is not as essential as in a CCD. A CID can accommodate a large full well, using up to 90% of the pixel area for charge storage. The sensor is anti-blooming, as the charge never leaves the pixel. Any excess charge is transferred to a reverse biased substrate, which acts as a buried collector and eliminates any path that would allow the signal to cause blooming. CID sensors also have improved design and improved process that minimize dark current, radiation damage, and threshold shift as a result of ionizing radiation.[8] Unfortunately, CID imagers are not readily available in the applications needed on the OMEGA laser systems. A special camera would most likely have to be built by LLE scientists in order to utilize a CID.

4. Conclusions

Further research is needed to confirm that damage to CCD sensors in cameras used on the OMEGA laser systems is caused mainly by neutron interaction with the devices. Currently, there is no known method to prevent or reverse this damage to the CCD sensors. Scientists must learn to work with the damage, by developing a system to determine when the sensors should be replaced or by using a camera with a sensor that is more tolerant to radiation exposure.

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6. References

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