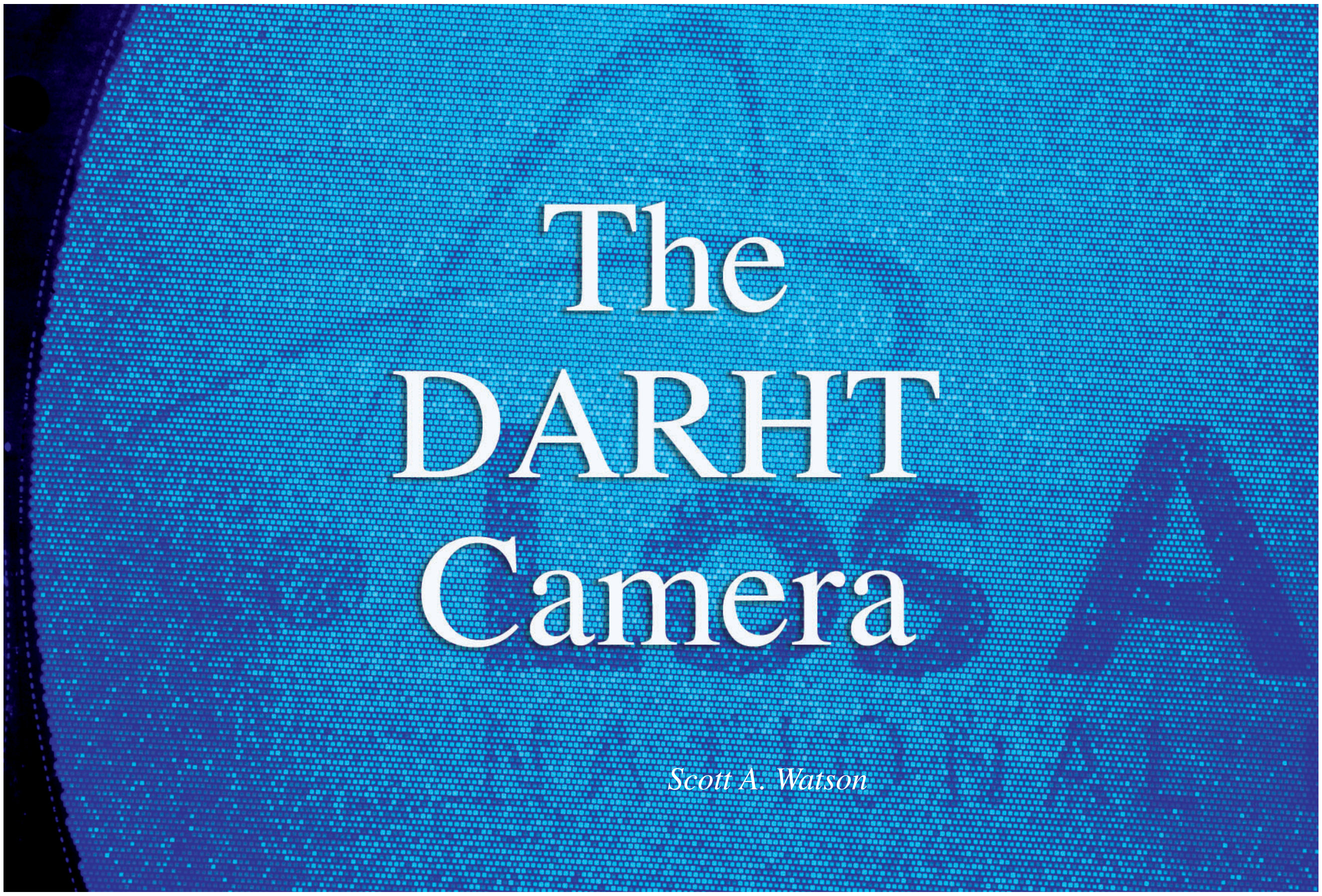


The DARHT Camera

Scott A. Watson

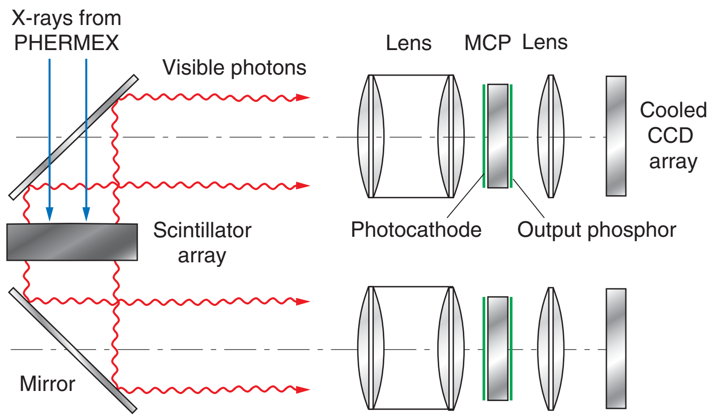
For almost 40 years, scientists in the weapons program at Los Alamos have x-rayed, or radiographed, implosions (hydrotests) using the giant PHERMEX (for pulsed high-energy radiographic machine emitting x-rays), which generated a single, brief flash of x-rays that were then recorded on film. Early on, they recognized that the design community really wanted an x-ray movie to better understand the implosion process. The value was obvious: One picture returns position; two pictures, velocity; three pictures, acceleration, and so on. Furthermore, because a movie records multiple images of a single hydrotest, the desired information could be gathered at a reduced cost. The limitation was the x-ray film.

Film has been used to record x-ray images since the discovery of the x-ray, but despite over a century of development, x-ray film still suffers from certain drawbacks. It is relatively transparent to x-ray photons—especially those at higher energies—that often pass right through without imprinting any information. In addition, film is essentially an analog recording medium with limited sensitivity; that is, it must be exposed to a minimum amount of light before an image can be recorded. Normally, for a movie, separate images are recorded on separate pieces of film. Because x-rays cannot be focused or reflected like visible light, no conventional technology existed to perform this task. Simply put, film cannot be advanced fast enough to capture the extremely rapid explosions.

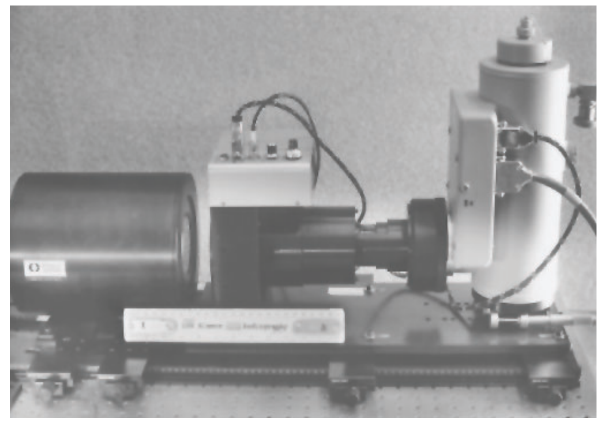
Interestingly, a filmless system was proposed during the design phase of PHERMEX by Doug Venable and Ralph Stevens: "The PHERMEX detection system will consist of a mosaic of scintillation detectors that will view pulses of . . . radiation through systems of interest . . ." (Stevens 1959). The scintillator would absorb the x-rays and convert them to visible light, which could record a limited number of channels electronically. Berlyn Brixner and the late Fred Doremire then expanded on the original concept with proposals for a high-speed electronic camera that had the potential of returning multiple radiographs for each experiment. Unfortunately, these ideas were ahead of their time; it took another 30 years for technology to catch up with this initial vision.

First used in 1996, the PHERMEX x-ray camera (Watson et al. 1995) takes just two pictures—hardly a movie. Still, it was a solid-state, all-electronic system with no film, which demonstrated higher sensitivity and absorbed more x-rays (that is, it had higher "quantum efficiency") than

(a)



(b)



(c)

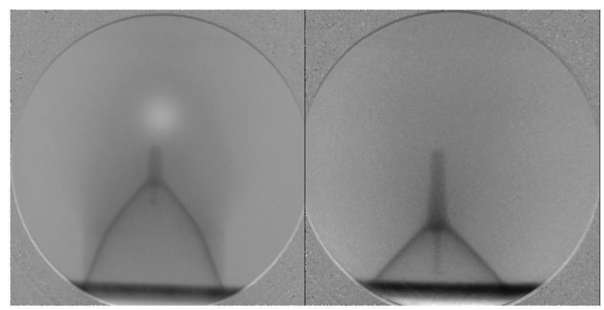
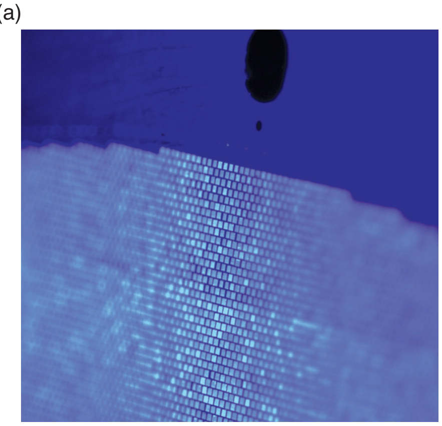


Figure 1. PHERMEX Two-Frame Camera System
(a) X-rays coming from the target are converted into visible photons by the scintillator. Photons emerging from the front of the scintillator follow one optical path and create one radiograph, while those emerging from the back create the second radiograph. The microchannel plate (MCP) in each pathway is the crucial electronic "shutter." The MCP photocathode converts the photons into electrons (which are then converted back into photons by the output phosphor). By changing the voltage on the MCP, we can rapidly stop the flow of electrons and thus prevent any light from reaching the cooled CCD detector. Appropriate timing of the two MCP voltages allows us to take consecutive radiographs. (b) This photo is of the camera system. (c) The two radiographs of H-1970, a VIPER shape-charge munition, were taken 17 µs (left) and 21 µs (right) after detonation. These are the first Los Alamos radiographs showing an explosive event at different times.

film (see Figure 1). The large image format allowed us to see the entire imploding pit, and the increased sensitivity allowed us to see through dense materials for the first time. This revolutionary system changed forever the way we think about hydrotesting and, indeed, stockpile stewardship.

As modern hydrotesting facilities such as the Dual-Axis Radiographic Hydrotest (DARHT) come online, x-ray camera technology continues to advance significantly with highly optimized components. In particular, the "scintillator" has evolved into a large mosaic of inlaid crystals—much akin to Zuni jewelry, but with up to 350,000 pieces. Long (more than 40 millimeters) square rods of very dense (greater than 7 grams per cubic centimeter) scintillator crystals are used to facilitate the x-ray absorption process. Exotic manmade crystals such as Lu_2SiO_5:Ce (LSO) are also used because they exhibit a rapid (50 nanoseconds) phosphorescent decay between x-ray flashes so that light from one image does not corrupt its neighbors in the movie sequence. These crystals are then assembled into the mosaic by means of stack lamination constructed from hundreds of layers of photochemically etched stainless steel (see Figure 2).

(a)



(b)

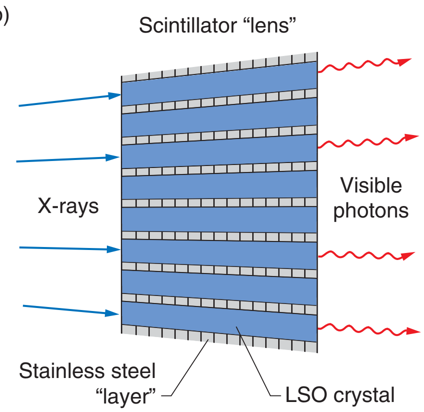


Figure 2. The DARHT Scintillator Lens
(a) The LSO inlaid scintillator shown here has more than 135,000 focused pixel elements. The blue color is a result of the natural emission spectrum of LSO, which peaks around 420 nm. (b) This schematic shows how the pixels are held in place to form the mosaic. The pixel pitch is 1.1 mm (1.0 mm LSO and 0.1 mm stainless steel).

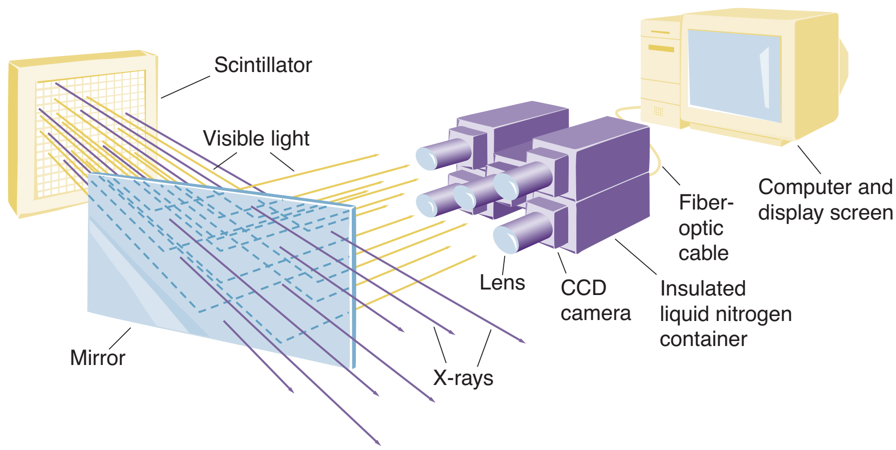


Figure 3. The DARHT First-Axis Camera
The camera consists of the scintillator, lens, and five optical lens/CCD systems for capturing the scintillator light. The multiple cameras, with overlapping fields of view, allow us to image the entire scintillator with less than 1% geometric distortion.

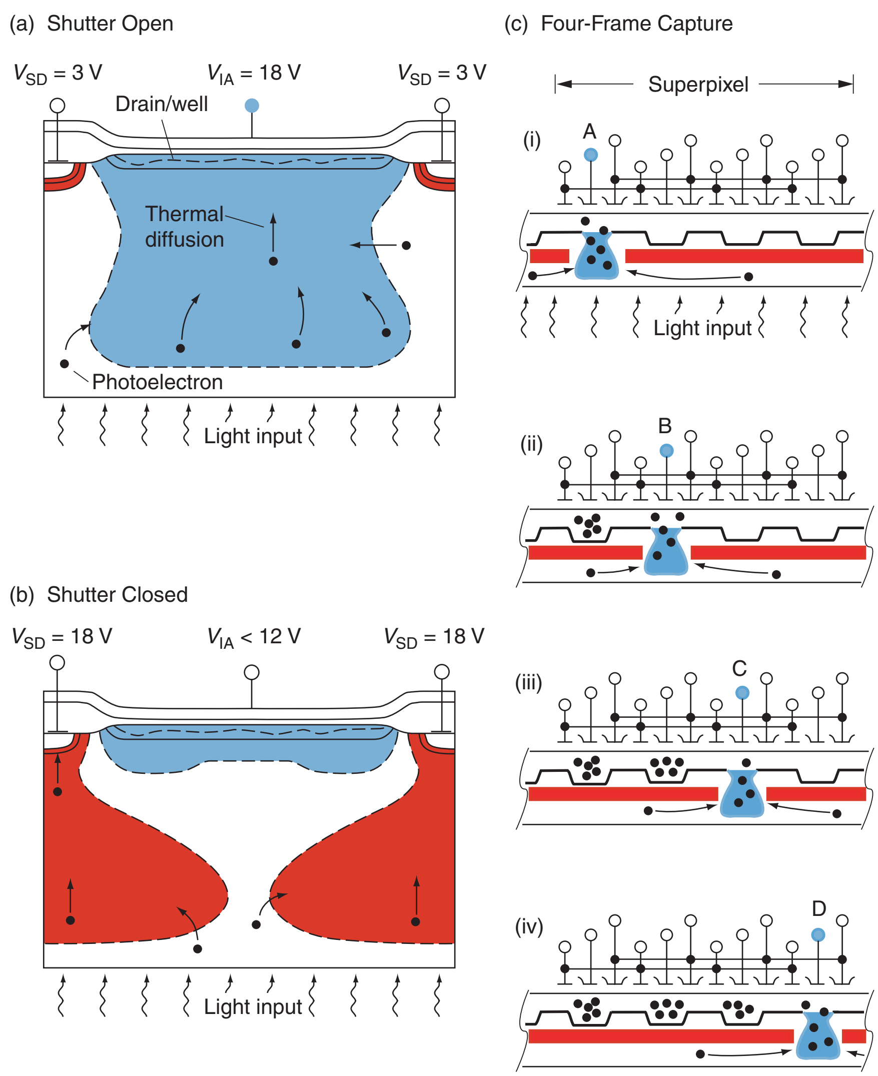


Figure 4. Multistage CCD Pixel
A CCD pixel can be thought of as a bathtub, complete with a faucet (DARHT) and drain, that collects the photoelectrons produced when light strikes the surface of the silicon pixel. (a) Thermal diffusion guides the photoelectrons to a "drain" region, where a local electric field captures the photoelectrons in a potential well that is ultimately connected to the readout electronics. The number of photoelectrons produced is proportional to the number of photons striking the pixel. (b) Reversing the bias on the electrodes prevents the photoelectrons from reaching the collection drain. Thus, we can shutter the pixel and control the light signal collected from that drain. (c) For the DARHT second-axis camera, each pixel is actually a superpixel with four separate drains and four storage wells. Each drain region has its own electrodes, which allow us to open a "hole" in the bathtub over any selected well region. To capture the first frame (i), drain A is opened whereas the other drains are closed. All the photoelectrons generated in the entire superpixel region are collected by well A. Thus, the device exhibits a 100% fill factor, giving increased sensitivity. After the first image is stored, we close drain A and open drain B to collect charge in region B for the second image (ii). This procedure is continued until all four frames are collected. The charge from each region is then read out slowly (to minimize noise in the charge amplifier), bucket-brigade fashion from pixel to pixel as in a conventional CCD.

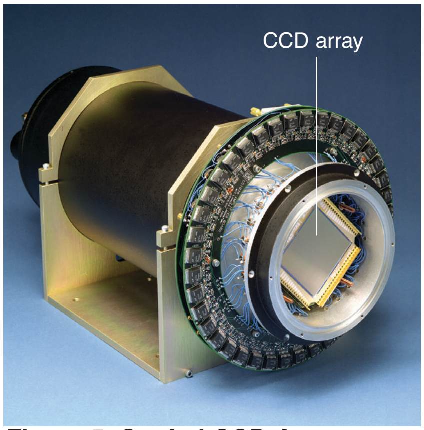


Figure 5. Cooled CCD Array System
This photo shows a CCD array of 512 by 512 pixels and its electronics collar, mounted on a liquid nitrogen Dewar (black cylinder).

Because this special inlay technique allows each rod to point directly to the x-ray source, the scintillator exhibits no parallax blur despite the long pixels used to construct it.

Converting the x-rays into a more useful visible light signal is only one challenge. In photography, the required sensitivity normally increases with higher frame rates, but unfortunately, the available sensitivity normally decreases with higher frame rates, and the net difference is made up with bright movie lights. In our case, the movie light is DARHT, which cannot be made much brighter, so we must construct an extremely sensitive detector.

To construct the detector, we employ a number of tricks. We use a custom f1.0 lens to collect as much of the scintillator light as possible and focus that light on the largest, most sensitive optical recording devices available, namely, astronomy-grade charge-coupled devices (CCDs), which are much like those on the Hubble Space Telescope. Even this combination is not sensitive enough, so we must use multiple cameras in a mosaic, as Figure 3 shows, and cool the CCDs with liquid nitrogen to reduce electronic noise to the level of a few electrons. At this point, we have a remarkable camera system, which is easily 100 times more sensitive than film and 40 times more efficient at absorbing x-rays. This system is now routinely used on the DARHT first axis (Watson et al. 2000).

To obtain multiple images, we employ a unique CCD architecture jointly developed by Los Alamos and Massachusetts Institute of Technology Lincoln Laboratories specifically for the DARHT second axis (Reich et al. 2003). This chip architecture retains the large format, low noise, and high sensitivity of astronomy-grade CCDs but also records four images at a rate of two million frames per second. Because there is insufficient time to transfer data off the chip at this high frame rate, the information for each frame must be stored locally on each pixel and then slowly read off when the explosive experiment is over (see Figures 4 and 5).

The next-generation camera (Watson et al. 2003) will employ a technology in which the scintillator light is collected by an avalanche photodiode, amplified, and then pipelined into a dedicated high-speed digitizer for every pixel. Although this approach requires a larger, more complex electronics package, the enhanced performance should be astounding. Whereas the PHERMEX camera can take two radiographs at 500 kilohertz and the DARHT camera can take four radiographs at 2 megahertz, the next-generation camera will take thousands of pictures at 20 megahertz. We hope that the advanced camera will generate useful results for the weapons community in a timely manner. ■

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Further Reading

Reich, R. K., D. D. Rathman, D. M. O'Mara, D. J. Young, A. H. Loomis, E. J. Kohler et. al. 2003. High-Speed, Electronically Shuttered Solid-State Imager Technology. *Rev. Sci. Instrum.* **74** (3): 2027.

Stevens, R. R. 1959. "An Investigation of the Statistics Inherent in the Detection of Small Numbers of X-Ray Quanta in the PHERMEX System." Los Alamos National Laboratory memorandum GMX-11-TM-141.

Watson, S. A., T. J. Kauppila, K. H. Mueller, and R. C. Haight. 1995. "Multiframe, High-Energy, Radiographic Cameras for Submicrosecond Imaging." Los Alamos National Laboratory document LA-UR-95-3570.

Watson, S. A., C. A. Ekdahl Jr., S. J. Balzer, H. A. Bender, and A. Daiz. 2003. "Reliable, Low-Current, Continuous Cavity Imaging at DARHT." Los Alamos National Laboratory document LA-UR-03-0908.

Watson, S. A., J. M. Gonzales, C. Gossein, M. Hoverson, and M. Ulibarri. 2000. "Quantum Efficiency, Noise Power Spectrum, Linearity and Sensitivity of the DARHT g-Ray Camera." Los Alamos National Laboratory document LA-UR-00-0653.

Scott A. Watson came to Los Alamos National Laboratory as a summer student in 1986. He holds a master's degree in electrical engineering from the University of New Mexico. He has spent his entire career improving hydrotest radiography—at PHERMEX first and at DARHT more recently. He enjoys still photography in his spare time.