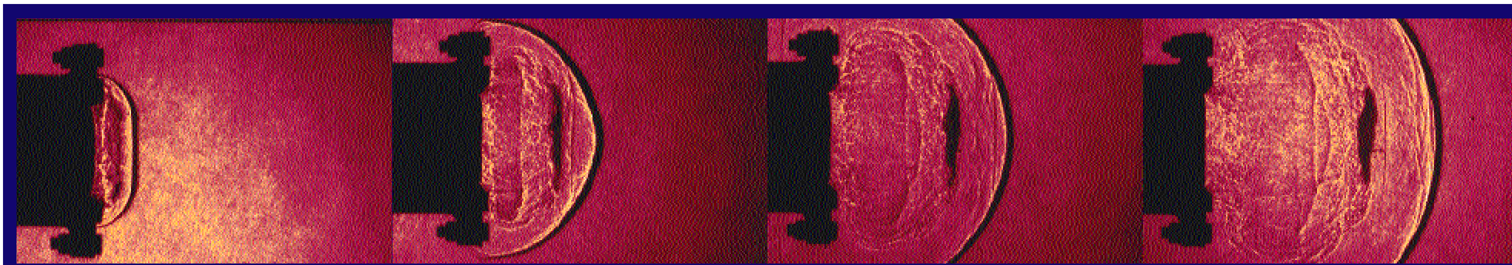
by David Bowley, Joseph Honour, and Brian Speyer

# Ultrahigh-Speed Electronic Imaging

During an 1852 demonstration to the Royal Society in London, Henry William Fox Talbot placed a page of *The Times* newspaper on a drum that turned at high speed. Using a single spark to illuminate the page surface, he astonished his audience by capturing the image of the fast moving print on a photographic plate and developing a clear image of the newspaper page. Since this first example of high-speed imaging, scientists and technologists have successfully applied the technique to the visualization and analysis of a range of real-world events that take place too fast for the eye to see, from golf swings to ballistic impacts.



Recent advances in electronic imaging technology have not only increased the capabilities of the high-speed systems available, but have also allowed the production of easy-to-use equipment that one can fully integrate with complementary methods of recording transient-event data, such as data recorders. The expanding breadth and power of these imaging techniques have created extraordinary new analytical tools for industrial physicists working on the cutting edge of product development and testing.

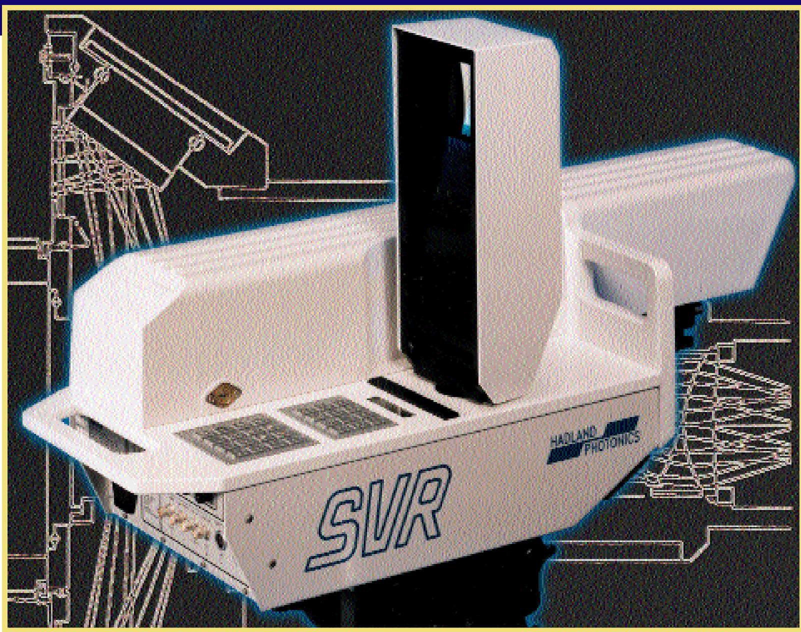



**Figure 1. This gated still-video camera produces photographic-quality electronic images with exposure durations of 100 ns.**

Modern ultrahigh-speed electronic image recording techniques may be divided into three principal categories: multiple-image-capture framing cameras capable of frame rates from 1,000 to 100 million pictures per second; gated still-video cameras providing single images with submicrosecond exposure durations; and smear or streak cameras that offer time resolutions of nanoseconds, picoseconds, and recently, femtoseconds. These techniques, each with its own advantages and limitations, can provide users with a better understanding and analysis of complex physical processes.

## Framing cameras

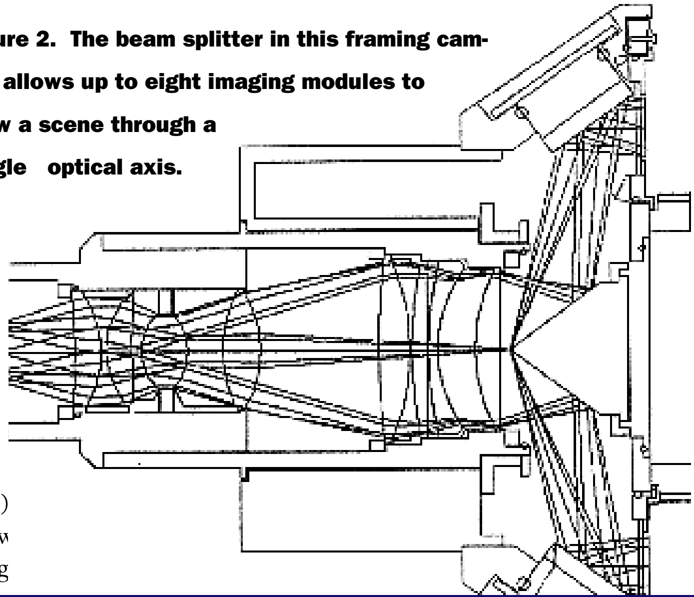
The high-speed recording of a sequence of discrete images traditionally has been restricted by the mechanical limitations of film, the materials from which cameras are constructed, and the principles on which cameras work. Difficulties associated with the synchronization of mechanical cameras to short-duration events further compounded these weaknesses.

During the 1950s a concept was developed that overcame many limitations of mechanical cameras. The image-converter camera relied on the assumption that a beam of electrons could be manipulated more rapidly than camera components. The principle of the image-converter camera centers around vacuum-tube technology. An evacuated envelope has a photocathode material deposited on the input window and a phosphor screen at the output window. Photoelectrons emitted by the photocathode when it is irradiated by light are accelerated to the phosphor screen by applying a high voltage between cathode and screen, where the image produced on the cathode is visually replicated. In order to obtain multiframe sequences, the camera uses complex internal electrode assemblies that enable the electron beam to be moved progressively over the phosphor to create a series of discrete images.

Developments in microelectronics and electro-optical imaging devices have offered designers the opportunity to improve upon the image-converter camera. The current generation of ultrahigh-speed framing cameras operates at high frame rates, with both high image resolution and dimensional stability, to allow accurate measurements from images.

Multisensor, ultrahigh-speed electronic imaging systems (such as that shown in Figure 1) are capable of recording sequences of

Figure 2. The beam splitter in this framing camera allows up to eight imaging modules to view a scene through a single optical axis.



discrete images at frame rates of up to 100 million pictures per second. They incorporate compact, intensified charge coupled device (CCD) modules that exhibit virtually no geometric distortion or intensity variation and provide the user with digital images that can be analyzed using a personal computer (PC). Measurements of experimental parameters can be established rapidly within seconds of being recorded, thus providing the researcher with accurate, almost immediate data from the recorded event. Interfacing a number of these devices to specifically designed optical beam splitters (Figure 2) has made it possible to manufacture a versatile imaging system controlled by a PC. This system can capture a sequence of up to eight images, time separated by increments of 10 ns, and can be used with most types of conventional image recording techniques.

Ultrahigh-speed framing cameras are increasingly providing an important tool for measuring ultrafast transient events. Materials scientists developing protective systems for a range of applications—from shielding communications satellites against high-energy particles and space debris to personal body armor—have used framing cameras to verify computer models and prove design specifications. In electrical discharge research and plasma physics investigations, sequences of ultrahigh-speed images have helped researchers understand and quantify the critical early stages of breakdown and discharge phenomena. Using specially modified "optical test engines," which allow engineers to look through the pistons and crankcase, automotive engineers have studied flame-front propagation within the combustion chambers of gasoline and diesel engines to help optimize their performance (Figure 3).

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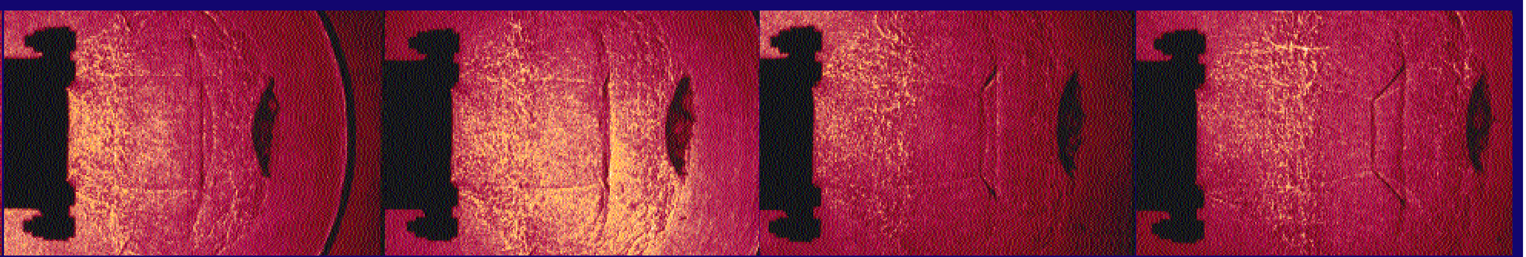

Figure 4. This framing sequence shows the "shock bottle effect" within helium on firing of a high-velocity two-stage gas gun. (Courtesy of GASL USA).

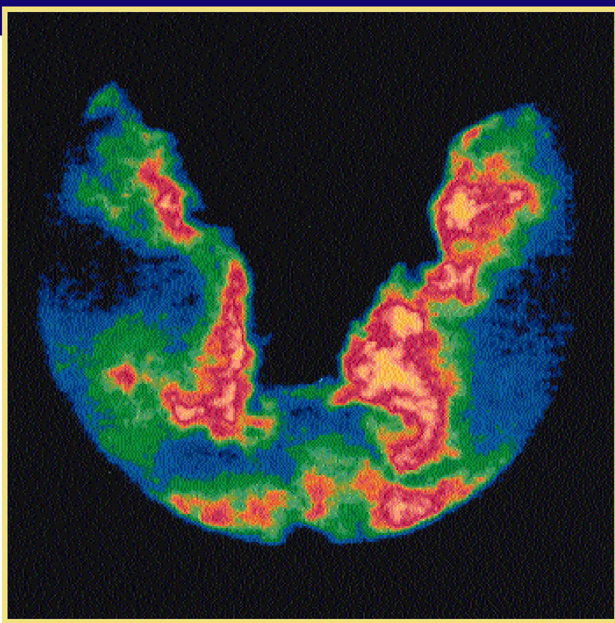

Figure 3. Pseudo-colored image from a framing sequence shows combustion within a diesel engine.

changes in air and other transparent materials, recordings from ultrahigh-speed framing cameras have provided valuable quantitative data in aerodynamics and fluid dynamics research (Figure 4). Coupled to conventional optical microscopes, framing cameras enable researchers to visualize and measure complex microprocesses associated with emerging nanotechnologies.

## Gated still-video

One of the primary high-speed imaging challenges of the military sector has been the need to record images of projectiles in flight. Although 16-mm high-speed film cameras have traditionally served to record these events, their limitations, particularly that associated with down time for the reloading of film, have led to the development of electronic alternatives. In the late 1980s the first gated still-video ballistic range camera systems were deployed by the U.S. Department of Defense. Such systems have proved to be highly successful alternatives to the traditional film-based camera systems for exterior ballistics photography.

In the gated still-video ballistic range camera, film is replaced with a high-resolution CCD sensor that views the image produced by a night-vision image intensifier. Normally, image intensifiers are left on to produce a continuous image. However, eliminating motion blur and recording a sharp image of a projectile in flight requires an exposure duration of 1 ms or less. This is achieved by gating on the intensifier for the period of the exposure, which turns the intensifier into a fast shuttering device. Gated still-video cameras allow shuttering times down to 200 ns. This is fast enough to record events such as explosively formed projectiles, whose velocities exceed 5 km/s. Such projectiles lie at the heart of many new types of antiarmor ammunition now coming into service.

There are many advantages of using a gated CCD electronic imaging system over film-based systems. These advantages include low running costs, the ability to remotely control the camera head in hazardous environments, fast set-up times, and the ability to take rapid test pictures to check set-up conditions prior to an expensive test. The immediate viewing of images after each test and the direct input of the electronic images into a PC for analysis and storage have proved that the CCD-based high-speed camera system is cost effective for today's testing needs.

The military primarily uses gated still-video camera systems to visualize projectiles in flight soon after launch. Modern antitank ammunition consists of small-diameter "darts" encased in lightweight "petals" or "sabots," which fall away immediately after the shell leaves the gun. During development it is vital to record images of this process to determine whether the dart, or subprojectile, has suffered any damage that could dramatically affect its accuracy. Other uses of this type of system on military firing ranges include the measurement of spin rate, projectile attitude and position, as well as measurements of many different types of detonation phenomena.

As electronic imaging techniques continue to improve, gated still-video systems are finding wider application in nonmilitary applications. The three-chip camera (an intensified CCD module that bundles three individual chips and an optical assembly that splits light into red, green, and blue segments) provides full-color electronic imaging with submicrosecond exposure times. By multiple pulsing of the image intensifier, a sequence of superimposed images can be captured that records the dynamics of an event. Some examples include detailed analysis of the interaction between a golf club and ball, fluid dynamics studies to examine droplet formation in, for example, crop-spraying systems, and dynamic flame-front analysis.

## Streak cameras

A streak or smear camera presents a representation of movement or intensity change within one axis of a dynamic event, the image being graphically presented against a known time reference. For example, a camera flash is not instantly turned on and off. Its output rises over tens of microseconds from zero to a peak brightness, holds at its peak for hundreds of microseconds, then decays back to zero, again over tens of microseconds. A streak camera allows one to visualize and measure the time from trigger to peak brightness, the length of that peak, and the time from when the flash gun is turned off to when light stops being emitted. A streak camera may be considered as an optical oscilloscope, and the simplified image it yields can dramatically assist in the understanding and quantitative analysis of complex processes. Streak camera imaging offers the additional advantage of continuous recording throughout the entire event, overcoming “dead time” between images as in a framing sequence.

The combination of streak recording and simultaneous high-speed framing through a single optical axis is now achievable. These complementary techniques offer a unique analysis of transient processes. Using a combination of the two techniques, complex combustion and detonation events have been recorded that provide critical measurements of wavefront propagation velocities.

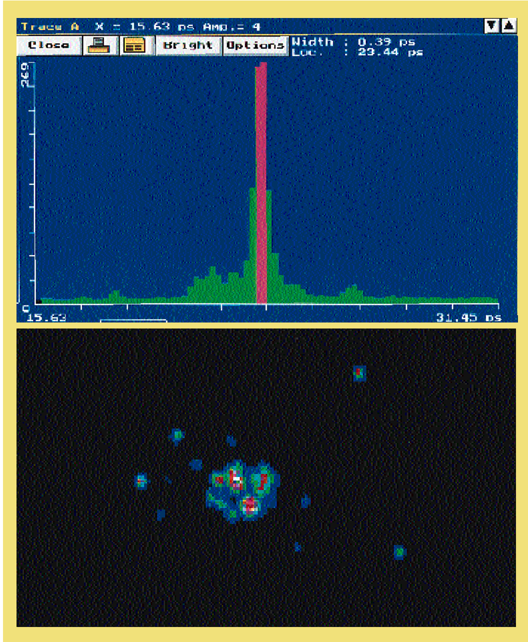


**Figure 5. Streak camera images of the time/intensity profile for a pulse width of 390 fs (top), and of a light pulse from a YAP laser with a width of 112 ps (bottom).**

Electronic streak cameras use a variant of the image converter tube described earlier in this article. For streak recording, a fine sheet of electrons generated from a slit mask on the photocathode is swept across the phosphor during the exposure period. Streak recording is a one-dimensional imaging technique that is possible only by isolating a single line through the image. Masking the cathode by using a slit produces the line, and the resulting line of electrons is swept across the phosphor at high speed to create the time axis of the image.

The latest generation of ultrahigh-speed streak camera systems provides time resolution of better than 300 fs (Figure 5). Here the characterization of rise time and structure within subpicosecond-duration light pulses generated by high-frequency solid state lasers is helping to improve the capacity of modern telecommunications systems. Ω

**B I O G R A P H Y**


David Bowley, Joseph Honour, and Brian Speyer are product managers at Hadland Photonics Ltd. in Tring, Herfordshire, England (post@hadland.co.uk).