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Title: HIGH-FRAME-RATE INTENSIFIED FAST OPTICALLY SHUTTERED
TV CAMERAS WITH SELECTED IMAGING APPLICATIONS

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MASTER

High-frame-rate intensified fast optically shuttered TV cameras with selected imaging applications

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ABSTRACT

This invited paper focuses on high speed electronic/electro-optic camera development by the Applied Physics Experiments and Imaging Measurements Group (P-15) of Los Alamos National Laboratory's Physics Division over the last two decades. The evolution of TV and image intensifier sensors and fast readout fast shuttered cameras are discussed. Their use in nuclear, military, and medical imaging applications are presented. Several salient characteristics and anomalies associated with single-pulse and high repetition rate performance of the cameras/sensors are included from earlier studies to emphasize their effects on radiometric accuracy of electronic framing cameras. The Group's test and evaluation capabilities for characterization of imaging type electro-optic sensors and sensor components including Focal Plane Arrays, gated Image Intensifiers, microchannel plates, and phosphors are discussed. Two new unique facilities, the High Speed Solid State Imager Test Station (HSTS) and the Electron Gun Vacuum Test Chamber (EGTC) are described. A summary of the Group's current and developmental camera designs and R&D initiatives are included.

Keywords: High Speed Imager Test Station (HSTS), Focal Plane Arrays, Electron Gun Vacuum Test Chamber (EGTC), Gated Image Intensifiers, High Frame Rate FPS and CCD cameras.

INTRODUCTION

Los Alamos National Laboratory historically has been tasked to design, develop, and test nuclear weapons devices for the nation's defense arsenal. Originally, this was to develop strategic weaponry, today it is stewardship. To carry out this mission the laboratory has developed dual core competencies in super computer-based device design/modeling and sophisticated field test instrumentation to provide theorists with essential feedback from experiments designed to measure key device parameters. The Laboratory's computing capabilities are among the most advanced and powerful in the free world, and their field/test capabilities are unequaled.

One key parameter which provides weapons designers with crucial information needed to evaluate new designs is the spatial and temporal evolution of neutron production following nuclear device detonation. To perform this measurement required development of neutron pinholes and radiation-to-light converters to convert neutron images to visible images. The physical phenomenon of interest occur in the nanosecond regime and shock wave arrival at instrumentation locations is typically in the millisecond regime. Taken together, these two factors required development of high speed optical shuttering coupled with fast readout TV cameras for telemetry of video images to recording stations at remote locations. The system was fielded in a hostile environment accompanied by high levels of radiation and EMP which the cameras had to withstand and recover in time to generate relevant video images of nuclear phenomena before they were eventually destroyed by shock wave associated with device explosion. This diagnostic became known as electronic "PINEX", for Pinhole Neutron Experiment. The state of either optical shuttering or TV technologies available from industry was not sufficiently advanced to provide nanosecond exposures or millisecond scans. Recognition of the need for in-house expertise in high speed imaging technology led to the early formation of a high speed camera/intensifier design and characterization capability at Los Alamos for improving the existing technologies and fostering development of new improved technologies in both imaging sensors and image intensifiers. Our earliest work on sensors was with magnetic deflection image orthicons and vidicons which were modified to reduce read-out times from ~33 ms to 8 ms. Later with joint Laboratory/Industrial R&D we pioneered improvements to Focus Projection and Scan (FPS) high speed electrostatic deflection vidicon technology resulting in 1-3 ms readout capability. Simultaneously, we carried out similar Industrial R&D to improve proximity-focused microchannel-plate image intensifiers (MCPII), increasing their shuttering speeds from microsecond regime to nanosecond regime. Most recently, we have concentrated our efforts in solid state imager R&D, including multiport imagers with sub-millisecond readout.

YATES

APPLICATIONS

1. UNDERGROUND NUCLEAR TESTS

The Underground Nuclear Test (UGT) program required a high speed single-field readout TV camera coupled to a single-exposure fast shuttered image intensifier. A simplified example of indirect imaging of radiation from a UGT experiment is shown in Fig. 1. Neutrons produced from a nuclear chain reaction are imaged through a special pinhole, forming a two dimensional image on a radiation-to-light converter. The TV camera is located outside of the direct path of the radiation flux. The incident radiation image is absorbed in a fluorescent or phosphorescent converter which transforms the radiation image to a visible image. The optical image is relayed to the TV camera via mirror/lens or fiber-optic coupling. Scattered components of the incident flux also inevitably strike the camera producing spurious charge that interferes with the imaged flux, compromising its integrity. For example, the video signal from the converter (the imaged flux) has both intensity and spatial calibration whereas the signals from the scattered flux have neither.

Figure 1. Simplified diagram of indirect imaging of neutron flux with PINEX intensified/shuttered TV cameras.

Figure 2 shows an image from a solid state TV camera from a Xenon strobe and radiation induced "stars" or charge centers from direct irradiation with a burst of neutrons. This demonstrates the composite image from the "imaged" and "scattered" components of flux. Both sources were pulsed simultaneously to illustrate the unwanted interference from scattered flux which is present during UGT experiments. We have developed charge dumping circuitry¹ to eliminate the scattered component while retaining the imaged component by using long persistence phosphors as radiation-to-light converters. Although both images are created nearly simultaneously, the charge dumping exercise requires only $\sim 1\mu\text{s}$ while the converter's light persists for $>1\text{ ms}$, which essentially rewrites the image after the background "stars" are removed. For intensified cameras, long persistence phosphor (i.e. P-20) in the MCPs are used.

Figure 2. Image from a CCD camera illustrating a composite image from strobe light and scattered neutrons, without charge dumping (a) and with (b) to eliminate the neutron-generated "stars", while retaining the strobe pattern. The neutron-generated signals are the bright spots visible in (b) but not in (a). In (b) the neutrons have been dumped and compressed to the single bright bar at top of frame.

Referring again to fig 1, we have the capability to perform either time-integrated PINEX (TIP) records or time-resolved PINEX (TRP) records, depending primarily on where the radiation-to-light conversion occurs and on the gate widths used for the image intensifier shutters. This is further illustrated in fig. 3. The device produces 14 MeV neutrons from fusion reactions which occur in a time interval $\sim 20\text{ ns}$. The time history is measured by locating several radiation-to-light converters at staggered strategic distances from the device. This establishes times of interest in the nuclear reaction that will produce images at the various converter planes by time-of-flight physics. The image intensifier shutters are then gated at proper times (fig. 3a.) to record the images from the various converters. In this fashion, the spatial evolution of the neutron image is recorded as a function of time as illustrated in fig. 3b. Such diagnostics have been deployed on scores of underground nuclear tests at the nation's Nevada Test Site. The chronological evolution of our PINEX camera/intensifier designs and their use in the UGT program are summarized in Table 1.

Real data from underground nuclear test is classified information which precludes its use in public forums. To demonstrate high speed optical shuttering in the nanosecond range, refer to fig. 4., where one of our advanced MCPs is fully illuminated with a single pulse of light which is sequentially time-phased ((a)→(c)) with respect to the electrical gate to generate the shutter sequence. In (a), the sequence shows the shutter partially-on in the area where the gate pulse is injected. In (b), the shutter is fully-on, and in (c) only partially-on again, but now in the area where the gate pulse exits.

Figure 3. Illustration of Time-Resolved PINEX recording scheme. The shuttered cameras are sequentially-gated time-phased across the integral corresponding to time of interest in a nuclear reaction (a) and map out the spatial/temporal neutron production (b).

Table 1. Chronology of PINEX camera evolution and usage in UGT program.

1968	•First underground Electronic PINEX, 16 ms Image Orthicon.
1969	•First use of 8 ms vidicon, replaced 16 ms orthicon.
1970	•First use of gated MCPiIs.
1975	•Energy flow in pipes significantly reduced, allowing use of shorter racks, and fast scan FPS & CCD cameras. •First use LANL-designed 18 mm Sb_2S_3 FPS Camera, 256 scan lines, 2.8 ms readout, 15 MHz. •First use of LANL-designed fast-readout CCD camera, (failed after 2 μ s of operation).
1977	•Technology Transfer of 18 mm FPS camera to industry resulting in XEDAR model XS501.
1979	•First use of commercial 18 mm FPS camera Xedar XS501.
1980	•First use of improved FPS cameras, Xedar XS502 & 503, 512 scan lines 3.2 ms readout, 30 MHz.
1982	•First use of LANL/GE grid-gated Silicon-Intensified-Target (SIT) FPS vidicon.
1985	•Completion of study of wide range of imagers for radiation sensitivity, light sensitivity, photoconductive lag, dynamic range based upon beam apertures and target capacitances, and readout capabilities. •First use of LANL/ITT microstrip/stripline gated MCPiIs.
1986	•First use of LANL designed 40 mm PbO FPS vidicon camera, 256-1024 lines, 1.6 ms readout, 50 MHz. •Technology Transfer of 40 mm FPS camera to Industry resulting in Xedar model XS504.
1988	•First use of commercial 40 mm FPS camera model Xedar XS504. •First use of LANL/LBL CCD camera, 488 x 380 pixels, 3.6 ms readout, 50 MHz.

Figure 4. Fast shutter sequence from advanced stripline/microstrip gated MCPiI gated at 1.1 ns.

2. REACTOR FUEL MOTION DIAGNOSTIC

An adaptation of the neutron TV PINEX was used to image fuel motion in fuel pins undergoing planned failure at the Transient Reactor Test (TREAT) Facility at Idaho National Engineering Laboratory. Two aspects of the TREAT experiments placed extra requirements on the cameras. First, the signal-to-noise was poor because the fuel pins emitted relatively few neutrons and the background radiation was high. Second, continuous variable-rate framing rather than single-field imaging was desired. In the early stages of an experiment, data could be taken relatively slowly because changes in the fuel pin happened slowly. Near the failure time, however, it was desired to take many frames at very rapid rates to gain time resolution. Several doubly intensified magnetic deflection vidicons were used to track the entire transient fuel-pin-failure sequence. The intensified configuration was a Gen I coupled to a Gen II MCP. These had constant frame rates of ~ 8 ms, so their integration period was constant throughout the sequence, producing continuously varying video signal amplitudes.

One doubly intensified FPS camera was configured to provide variable integration period under computer control. The computer was programmed to change the integration time as the reactor power-pulse amplitude changed. The camera's field period was held constant at 4 ms, while the integration period between successive field readouts was varied among 4, 8, 16, and 32 ms. In this way, the integrated signal amplitude was kept approximately constant even though the incident power varied by a factor of 15 during the transient. This is illustrated in fig. 5. In (a) Transient's power and energy are plotted, and the computer strobe pulses, and the FPS variable integration periods are identified across the transient. The neutron fuel motion images are shown in fig. 6. (a) and (b) as TV monitor pictures (at left) and as video scan line profiles (at right) depicting neutron intensity variation throughout the Transient. The arrow in top monitor photo of (a) shows neutrons in fuel pin (bright column in photos). The intensity profiles measured correspond to integration periods of 32 ms prior to pulse peak (a), 16 ms during rising edge (b), 8 ms during peak (c), and 16 ms during falling edge (d).

Figure 5. TREAT neutron fuel pin Transient experiment. From left to right, the cross-hairs on the Power curve correspond to integration periods of 32 ms, 16 ms, 8 ms, and 16 ms, labels (a), (b), (c), and (d) respectively in fig. 6.

Figure 6. Neutron image data from FPS camera during the TREAT Transient, (a) early and peak, (b) later phases.

3. ANOMALIES ASSOCIATED WITH SINGLE PULSE IMAGING

Several anomalies were observed during characterization of the camera/intensifier components as single-pulse recorders. Four are described, one each for the FPS, CCD, and two for the MCPPII, which could contribute to erroneous interpretation of data collection. For the FPS vidicons, when exposed to single-field transient illumination, their transfer curve is superlinear², resulting in shortened dynamic range and actual loss of signals at low light levels. This is shown in fig. 7. The effect is attributed to a combination of the loss of light-induced signal charge to trapping centers in their photoconductive targets and poor electron beam acceptance. Both effects are dominant at weak surface charge levels on the FPS target. The use of bias light accomplishes the filling of target traps as well as establishing a higher positive quiescent charge on the target resulting in improved acceptance or "beam landing" characteristic. The inset line scan photographs of fig. 7. show the effect of adding various amounts of light bias while keeping the strobe light at fixed intensity. The strobe amplitude increases with increasing bias light, as indicated in (a) → (e). Percentages next to data points (b), (c), and (d) refer to percent of maximum bias light (e). Note, without bias light (a), no signal is recovered, resulting in truncation of dynamic range by over a decade. This has effect of infinite error in low level signal recording, since no signal is recovered. For the MCPPII, one particularly bothersome anomaly was that of poor correlation between electrical and optical gate widths shown in fig. 8. (a). We first reported this in the open literature³ in the early 1980's. Prior to this, it was generally assumed that the optical gate would track the electrical shutter gate. Our earliest solutions were to calibrate the gate widths. Later we modified standard MCPPII geometry (stripline tabs for gate interface and Ni undercoating for increased Photocathode conductivity) and developed microstrip transmission line pulse injection techniques^{4,5} which produced better fidelity between the two gates. Most recently, we measure the electrical gate in real time and provide digital 10-bit words (LSB~1 ns) corresponding to the gate width sample. A second problem with MCPPII shutters is that they "iris", fig. 8. (b), during turn-on with loss of information, in areas not shuttered, i.e. within the iris.

Figure 7. Superlinear transfer curve for low dark-current FPS targets when exposed to a single pulse of light. This curve, for the Hiemann CdSe target, is also typical for PbO and Saticon targets.

Figure 8. MCP-II electrical and optical gate widths, (a) illustrating possible poor correlation between the two. The optical gate is shown as longer-than, shorter-than, and approximately equal-to the electrical gate, by varying reverse bias (which in principal shouldn't affect width). Typical MCP-II shutter sequence illustrating iris turn-on characteristics is shown in (b) in nanoseconds into the optical gate. The shutter is "fully-on" with no iris at 1.6 ns. At 2.0 ns, the iris again opens, signifying start of turn-off.

For the CCD, dynamic smearing characteristics⁶ occur from transient light exposures falling outside of the photosite transfer interval. Because of the architecture of the Interline Transfer (ILT) CCD, the pixel is composed of three components---even and odd photosite, and a storage/transport vertical register which is adjacent to the photosites. Although the data sheets for the Fairchild CCD-222 used in this study refer to the aluminum shields that cover the vertical shift registers as "opaque", our data indicate that they actually may be semi-transmissive, or subject to optical crosstalk between the photosites and vertical registers. Whichever mechanism is the real cause for observation of ghost signal charge from the vertical register, the net result is that artificial images are created. When the light is asynchronous with the photosite transfer command, a "ghost" image from the vertical register component of the pixel signal becomes "spatially and time-separated" from the photosite component because it immediately is moved thru the vertical register but the photosite signal remains fixed until the next photosite transfer command when it begins to move thru the vertical registers. The illustrations and photos in fig. 9(a). show the photosite and ghost images partially merged left, and separated right. Intensity levels (in arbitrary units) of (83) to the left and (99) to the right of the bottommost circle of the photosite (top image) were measured. Similarly, intensity levels of (66) and (56) were measured for left and right areas adjacent to the center circle of the ghost (bottom image). When the two images are partially merged, the corresponding intensity levels to the left (130) and right (140) are in good agreement with expected values (149) and (155) from linear addition of the individual unmerged values. The experimental accuracy or repeatability for these experiments is $\pm 10\%$, so the measured and expected intensity levels of the merged images are indicative of simple linear addition, as expected. The same data are presented in isometric form in (b) and (c). Again, the addition of the two waveforms is illustrated as highlighted by the labels. This ghost image, especially for large area images occupying most of the CCD array, can be nearly merged but yet displaced from the real image. The result can be a "mixed" image, destroying the integrity of the "real" image. It is important to stress that the out-of-phase merging results in destructive interference and consequent distortion of the real photosite image. For scenes of unknown structure (as in many field applications, where recording of spatial intensity variations itself is the experiment), this interference can be difficult or impossible to unfold.

Figure 9. Photosite and ghost images from our ILT CCD camera from asynchronous excitation with pulsed light. In (a) the two images are illustrated merged (left) and separated (right). The actual CCD video shows the images merged (b) and separated (c).

4. MINE DETECTION USING OPTICAL IMAGING

We are investigating ways to integrate our high speed camera technology with laser technology to give the military a fast-response detection and imaging capability. Underwater mines, for instance are often difficult to locate and identify because of their obscure location over wide and deep, areas of the ocean surf and beach. "Antipersonnel" mine fields, which are placed in the sandy areas and the shallow waters of a beach to counter amphibious landings, are hard to locate and identify. Referring to fig. 10., a pulsed laser mounted along with a fast-imaging camera system in a high speed jet aircraft can image large areas via reflected laser light without jeopardizing the pilot's safety. Within a matter of seconds, these

images are transmitted from the electronics aboard the aircraft to a waiting ship or other remote location where the image can be analyzed for possible mine fields. This real time mine-detection system would allow military commanders to make timely decisions. The initial goals for such a system (provided by our sponsor, then Naval Coastal Sea Command (NCSC)) were to be able to identify 6-in. diameter targets in a 500 ft. x 1000 ft field of view (FOV) at water depths up to 10 ft with turbidity of 0.5. This would be accomplished by using 4000 frame/sec cameras with 8 ns shutters imaging reflected laser light from an AV-8B Harrier Jet flying at ~300 Knots at 500 ft to 1000 ft altitude, covering 15 km of beach.

We have prototyped such a TV camera system, and field tested it for the Marine Corps in an outdoor laboratory (referred to as "Tank") at EG&G Energy Measurements, Santa Barbara, California simulating ocean water conditions such as purity, K-factor, etc. These tests, referred to as "Tank Tests", were carried out in conjunction with our sponsor, the Navy's Coastal Systems Station (CSS) Panama City, Florida. A simplified diagram of this experiment is shown in fig. 11.(a). Typical photographs, taken with a LANL CCD shuttered camera, of a submerged target at several depths with water quality conditions held constant are shown in fig. 11.(b). The target was a black glossy disk on dark background. Images were first taken dry (in air) (1) and then wet (in the Tank at several depths (2), (3), (4)). The specular component of the disk's reflectance caused the disk to appear lighter-than-background in air as shown in (1). In the water, the specular reflectance causes the disk's appearance to vary from lighter-than-background (2), to darker-than-background (3) and (4) based upon depth and water quality. The black disk was predicted to be darker than the background, based upon the assumption that diffuse components of reflectance would be the dominant source of total light reflected from the dark disk. However, as observed, the specular components dominated in air and shallow water whereas the diffuse components dominated only in deeper (or more turbid) water.

These tests revealed important information for mine detection analysts in mine recognition and identification studies. They also illustrate the depth measuring capability of the system from strategic timing between image shutter gates and the reflected laser beam. A 532 nm laser was used for these experiments, and our high frame rate camera was reconfigured for RS-170 rate readout for convenience in recording. This camera system is easily upgraded to few KHz framing rates.

Another potential application which LANL is investigating is similar to the Marine Corps shallow water mine detection application, but it involves deeper laser ranging for deep water mine detection or submarine detection for the Navy. For this application, a helicopter replaces the high-speed jet aircraft, with reduced framing speed requirements.

Figure 10. Artist's illustration of airborne laser/high speed shutter-based mine detection scheme. In a real scenario a LANL high speed CCD camera aboard the Jet opens its MCPH shutters at strategic times to provide images at various locations of beach area. Each blocked segment on the beach corresponds to one image captured by the camera. The area of beach/image is $\approx 500,000$ sq. ft. The data files are transmitted in real time for analysis.

Figure 11. Simplified experiment diagram for depth profile imaging for Mine Detection Studies is shown in (a). Images obtained using LANL gated image intensifier shutters to image reflected laser images from submerged pattern (black glossy disk) in the EG&G/SBO Tank are in (b) for the disk imaged in air (1) and at depths 1.4 meters (2), 5.6 meters (3), 7.0 meters (4) in the Tank under constant water turbidity (not quantified here).

5. BIOMEDICAL IMAGING

In the biomedical arena, we are investigating ways of using our high-speed camera systems to image and measure human motion, such as a runner's or walker's gait. This unique application, depicted in fig. 12., will help medical practitioners better assess and evaluate disorders of both muscles and bone joints. We are developing a high-speed "x-ray" camera for use with a specialized x-ray imaging system to take real-time images of knee-joint kinetics. This is a collaborative effort with medical researchers at the Bone & Joint Center Motion Analysis Laboratory of Henry Ford Hospital, Detroit Michigan.

Figure 12. Artist's illustration of a source of x-rays, passing through a patient's knee. In a real experiment, the knee will be photographed by LANL high-speed camera to provide time resolved images of knee joint motion. The camera video is transmitted to a television monitor for viewing by medical personnel.

Two LANL gated intensified cameras were modified to record images from an x-ray Image Converter tube to demonstrate the potential of high frame-rate radiographic videography in the analysis of bone and joint dynamics. Preliminary experiments were done at Los Alamos to test both cameras initially unintensified. The setup is shown in fig.

13. Our 28 mm target FPS camera was configured to generate a 200 line raster $\sim 7 \times 10$ mm at 1000 frames per second. Our GY5 ILT CCD was configured to readout 244×380 pixel array 8×11 mm at 500 frames per second. The x-ray intensifier, Precise Optics P500/P600 series 16-in. diameter CsI target was irradiated with 50-100 KeV flux from Sperry pulsed x-ray source, operating at 900 Hz, with pulse width of 10 ns. A swinging Pb pendulum was placed at the intensifier focal plane to measure time smear and an x-ray spatial bar pattern from Optics Precise was used to measure resolution. The bar spacing is $\sim$ in. Either camera was alternatively lens coupled to the x-ray intensifier phosphor and digitized with LeCroy 9314 digital sampling oscilloscope (DSO). The data were then downloaded to a PC and analyzed using IDL software. Two 1-ms frames separated by 9 ms (frames 1 and 10) of FPS camera data are shown in fig. 13. (a) and (b). Also in fig. 13. (c) and (d) are two 1.5 ms frames separated by 12 ms (frames 1 and 9) from CCD camera.

Figure 13. Calibration of 1-ms readout LANL 28-mm FPS and 1.5-ms readout GY5 ILT CCD cameras using pulsed x-rays. Time resolution is measured by pendulum velocity and displacement between consecutive camera frames. The stationary resolution pattern serves as background and shows the moving pendulum's travel.

The systems were then evaluated at the Motion Analysis Laboratory at Henry Ford Hospital. The fast scan cameras alone were insufficient to record the x-ray intensifier's output without blurring because its P-20 phosphor retains images for longer than 1 ms. To minimize this, a 100 μ s-shuttered MCP-II was coupled to the 28 mm FPS camera and the camera frame rate was reduced to 500 frames per second. Although not ideal, these two modifications reduced image blurring between frames to an acceptable level for these experiments. Imaging of a 9 inch diameter acrylic disk with embedded Pb markers rotating at $\sim$ 1000 RPM demonstrated the system response to a high velocity/high contrast target⁷. This setup is shown in fig. 14. with four consecutive frames of data illustrating the framing capability of the system.. Tangential velocity of the Pb markers was $\sim$ 8.5 meter/second indicated by axial displacement of markers between frames. The velocity of knee joint motion requires $\sim$ 1 ms time resolution over $\sim$ 30 ms, which can be achieved by the LANL high speed cameras.

Figure 14. Simplified diagram of x-ray imaging records obtained at Henry Ford Hospital from LANL 28-mm FPS PbO vidicon camera viewing rotating Pb markers in x-ray flux. The velocity resolution provided by the camera was 0.35 in/ms. The bar patterns at the top and left of each frame are due to noise in the camera's 'scanning/blanking' circuitry. The after image in the data is due to combination of incomplete removal of FPS target charge between frames, (typical of vidicons) and MCP-II's P-20 phosphor persistence. The notation t_0 refers to a particular frame used as time reference. Each frame, t is incremented by 2ms, consistent with 500 frames/sec.

6. HIGH REPETITION RATE IMAGING PROBLEMS

These applications are similar to the UGT and Fuel Motion applications in terms of shutter and readout speeds, but with one major difference -- repetition rate required of the camera system. Mine detection involves collection of many

consecutive frames of data at frame rates in the 1-5 KHz range. The x-ray imaging requires similar speed. This requires the complete transfer of data from a current frame before a succeeding frame is illuminated, otherwise smearing from mixing and convolution of images will occur. Also, high speed automatic gain control (AGC) concepts need to be designed to adjust key camera/intensifier gain functions in between successive frames. For the CCD, contrast transfer efficiency must be enhanced and for the MCP, recharge time of the MCP and phosphor persistence decay times pose limits on repetition rates possible. The high pixel rates pose yet another problem -- that of proper sampling of slew-rate limited pixel signals as functions of both pixel rate and intensity of input light.

We characterized and reported^{8,9} the effects of operating MCPs at various rates in the range from 10 Hz to 10 KHz. Two MCPs were evaluated, one with a standard current ($\sim 1\text{-}2\mu\text{A}/\text{cm}^2$) MCP and one with a high strip current ($\sim 28\mu\text{A}/\text{cm}^2$) MCP. The plots of fig. 15. were obtained by strobing the two MCPs with fixed intensity $\sim 55\text{ pJ}/\text{cm}^2$ ($\sim 50\%$ of saturation) from a 200 ps FWHM laser diode pulse emitting at 820 nm. The diode was pulsed once per frame and the MCP phosphors readout with a CCD camera. The high strip current MCP appears to give constant gain out to 10 KHz whereas the standard MCP exhibited declining gain from 1 KHz to 10 KHz. Both MCPs had P-20 phosphors, which have persistences extending to milliseconds which contribute to blurring at high repetition rates. However, the on-set to loss in gain observed for the standard current MCP is attributed primarily to slow recovery time of the MCP since both MCPs were generically identical otherwise.

Figure 15. Plots of measured MCP gain for standard and high strip-current MCPs at various frame rates.

At high pixel rates, the CCD on-chip amplifiers can have insufficient bandwidth and slew rate to faithfully replicate the raw pixel voltage signals. The pixel data rate is dependent only on clocking rates which, being digital, can often operate faster than the analog amplifiers which must accept the pixel data. The slew rate problem at fixed pixel clock frequency and variable charge level is illustrated in bottom waveforms of fig. 16. The top waveforms show non-slew rate limited response from slower clocking rates where the amplifiers have sufficient bandwidth and rise time to handle varying amplitudes without distortions. We have developed high speed peak sensing and stretching circuitry to provide "flat-topped" waveforms similar to the non-slew rate limited waveforms. We also generate clock signals, properly time-phased for use as sampling commands for digitizers. The clocks are generated by sampling raw and integrated video with high speed ECL comparators as described in earlier work¹⁰.

(a) CCD pixel signal with adequate bandwidth

(b) CCD pixel signal with slew rate limited response

Figure. 16. Video signals from individual CCD pixels, illustrating (b) the slew rate limited peak amplitudes of raw unprocessed pixel data as function of input light intensity. The times t , t_1 , t_2 , are marked on the waveforms to illustrate possible variable periods between consecutive peaks at two amplitudes, and possible digitizing errors from improper and/or fixed period phasing. The dotted lines on the two amplitudes illustrate our pulse stretching technique to allow less stringent phasing. In (a), the pixel rate is slow enough, and amplifier bandwidth sufficient to allow adequate settling time at two amplitudes. For this case fixed sampling period, t , is allowed for input intensities from CCD noise to saturation. For both (a) and (b), " t " is used for nominal periods for the two cases, but they are not equal.

VIDEO TEST FACILITIES & CAMERA SYSTEMS

1. TEST FACILITIES

Los Alamos has developed state of the art test equipment/systems to facilitate characterization of image intensifiers and solid state focal plane arrays (FPAs). Our unique High Speed Solid State Imager Test Station (HSTS) is designed to operate imagers at up to 100 MHz pixel rates. The HSTS described in earlier work^{11,12} is a PC-based clock generation and data acquisition system. It continues to evolve as new equipment is added or upgraded, and is currently in patent status, DOE Docket No. 5-78-3000, submitted January 1994. The system is shown in fig. 17. There are seven major components that comprise the station. These are (1) a programmable pattern generator and logic recorder for clock waveform generation and monitoring; (2) an imager header board that serves as a chip carrier mounting interface with clock level shifters to drive the FPA and video buffers/amplifiers to sample the FPA video outputs; (3) a multi-channel high-speed digitizer for CCD video acquisition and storing video images from the FPA with subsequent downloading to PC/workstation using general purpose interface bus (GPIB) interface; (4) real-time display capability using a video multiplexer and x-y display for observation of one FPA video port at a time; (5) software for array reformatting and manipulation including translation, rotation, and analysis; (6) optical/electro-optic apparatus including PC-based precision

mounts with 1" travel in X, Y, & Z planes and with submicron resolution, various wavelength continuous wave (cw) and pulsed light sources, special pinhole arrays and conventional resolution patterns for optical stimulus to the FPA; and (7) high-power TV microscope for chip inspection and for precise monitoring of location and positioning of pinhole illumination on strategic FPA pixel structures, and for analysis of light source spatial linearity and uniformity.

Figure 17. LANL's High Speed Solid State Imager Test Station (HSTS). Major blocks are identified in (a) for the console and in (b) for the optical platform. The station is used to characterize imagers at variable pixel rates, from 1 KHz to 100 MHz.

The HSTS is comprised of Tektronix DAS 9200 PC and several IBM and Macintosh personal computers which are interconnected to a Sun PC2X workstation thru ETHERNET as shown in Fig. 18. This network allows all computers to be centrally controlled from one console with single keyboard and monitor using Windows environment, while still allowing each to be operated locally. This arrangement allows the use of PCs with wide variety of hardware and software options for control, acquisition, analysis, processing, and display.

Several imagers have been or are currently being characterized using the HSTS. These include CID TECHNOLOGIES CID-HSA35, English Electric Valve (EEV) CCD-13, Reticon HSO512J, Sarnoff HDL512ZIF002 and some "proprietary" Tektronix designs. All are new recently developed multiport imagers intended for high frame rate applications. The identified imagers are summarized in Table 2. and their readout characteristics and potential frame and pixel rates are identified later in fig. 23. The EEV and Reticon data are reported¹³ separately. All of these CCDs are 512x512 pixel arrays and have some form of antiblooming. The Reticon and Sarnoff CCDs have 1024x1024 pixel versions. The Sarnoff imager is back-thinned and has on-chip double correlated sampling. All CCDs readout contiguous segments of the array to single port. The CID reads every fifth row or line to the same port.

Table 2. Multiport Imagers recently tested in HSTS.

Imager	Architecture	Pixel count	Pixel size	Video ports
Proprietary Tektronix	FT	256 x 512		2
CID TE/CID-	CID	512 x 512	$16\mu^2$	4
HSA35				
EEV CCD-13	FF	512 x 512	$21\mu^2$	8
Reticon HS0512J	FT	512 x 512	$16\mu^2$	16
Sarnoff 1512ZIF002	FT	512 x 512	$18\mu^2$	16

Figure 18. The HSTS utilizes several personal computers which are networked as shown using Ethernet and Sun workstation. Plans for expanding to Internet are underway, to allow exporting of files.

Recent upgrades to the HSTS include the addition of the Sun workstation controller upgrade, addition of a new high energy, multiple output, multiple wavelength pulsed solid state laser Orion model SB2-2R (fig. 19 and Table 3), acquisition of NIH IMAGE data processing/acquisition public domain software (from National Institute of Health) to compliment our original IDL version 2.2 software package, incorporation of a new three axis tracking platform, Polytec PI model M-353. The Orion laser compliments our Spectra Physics Laser (fig. 19., top).

(b)

(a)

Figure 19. Orion (a) and Spectra Physics (b) lasers. The Orion SB2-2R laser provides up to 5 simultaneous output beams with a variety of wavelengths from 355 nm to 1064 nm, and pulse widths of 8 ns, 400 ps, and 15 ps from using various Brillouin and Raman cells for time compression and wavelength shifting. The repetition rate limit is 10-15 Hz. More information on possible modes currently available is found in Table 3. The laser is visible in the background. In the foreground at left is a TV microscope sampling the spatial uniformity of the laser beam as it exits a fiber optic cable; at right the FPA under test is shown in the tracking platform viewing a second fiber optic cable. This laser is an integral part of the HSTS. The Spectra Physics model 2030 laser (b) is located at EG&G Energy Measurements facility at Goleta, California. It is a mode-locked Argon ion synchronously pumped dye laser. The mode locker is driven at rates up to 40 MHz and provides visible and rear IR wavelengths with 30 ps pulse width and 10-100 nano joules of energy per pulse. The system also has a cavity dumper and Pockells cell.

Table 3. Orion laser modes of operation.

Port	Wavelength	Pulse width	Energy	Stability
First mode of operation				
Output port #1	$\lambda = 1.064 \mu\text{m}$	$\tau = 8 \text{ ns}$	$E = 3 \text{ mJ}$	1.5%
Output port #2	$\lambda = 559 \text{ nm}$	$\tau = 17 \text{ ps}$	$E = 2.5 \text{ mJ}$	10%
Output port #3	$\lambda = 772 \text{ nm}$	$\tau = 17 \text{ ps}$	$E = 2.5 \text{ mJ}$	10%
Output port #4	$\lambda = 532 \text{ nm}$	$\tau = 400 \text{ ps}$	$E = 0.7 \text{ mJ}$	5%
Second mode of operation				
Output port #1	$\lambda = 1.064 \mu\text{m}$	$\tau = 8 \text{ ns}$	$E = 3 \text{ mJ}$	1.5%
Output port #3	$\lambda = 772 \text{ nm}$	$\tau = 17 \text{ ps}$	$E = 2.5 \text{ mJ}$	10%
Output port #5	$\lambda = 416 \text{ nm}$	$\tau = 17 \text{ ps}$	$E = 1.5 \text{ mJ}$	8%
or				
Output port #5	$\lambda = 355 \text{ nm}$	$\tau = 400 \text{ ps}$	$E = 2 \text{ mJ}$	6%
Third mode of operation				
Output port #1	$\lambda = 1.064 \mu\text{m}$	$\tau = 8 \text{ ns}$	$E = 3 \text{ mJ}$	1.5%
Output port #4	$\lambda = 532 \text{ nm}$	$\tau = 400 \text{ ps}$	$E = 12 \text{ mJ}$	6%
Fourth mode of operation				
Output port #4	$\lambda = 532 \text{ nm}$	$\tau = 8 \text{ ns}$	$E = 8 \text{ mJ}$	3%

Figure 20. Schematic of LANL's Electron Gun Test Chamber (EGTC).

Figure 21. LANL's EGTC showing the Faraday Cup and Electrical I/O ports in rear of the photo.

LANL has also developed an electron beam source referred to as Electron Gun Test Chamber (EGTC), for insitu characterization of microchannel plates (MCPs), phosphors, electron-bombarded CCDs, and various GaAs and silicon detectors. This system, diagrammed in fig. 20, can provide beam currents in the microamp to milliamp range with pulse widths as short as hundreds of picoseconds, and with control of kinetic energy of the electrons in the few KeV range. The system is shown in fig. 21 and 22. Figure 21. is a view of the EGTC showing sample insertion mechanism. Figure 22. is another view, enlarged to show details. Several sample holders have been designed for a variety of phosphor and MCP samples. The system is currently operational but sample testing has not started because diagnostics for the beam as well as for the sample evaluation are now being incorporated.

Figure 22. Side view of the LANL Electron Gun Test Chamber (EGTC), with major components identified.

2. CAMERA SYSTEMS

A variety of framing camera systems have been designed. Some address high resolution, others address high speed. Rotating mirror and photo-emissive shuttered electrostatic deflected image tube cameras generate high data rates in the 10^{10} -to- 10^{13} Hz range with low to moderate pixel density providing frame rates in the 10^7 -to- 10^9 Hz range. Slow-scanned cooled large area CCDs have data rates in the kilohertz range with high pixel density and sub-second readout. Intermediate to these two extremes are most video cameras with 30 Hz to a few KHz frame rates which provide data rates in the 10^6 -to- 10^8 range. The wide spread in video frame rates is due in part to the use of simultaneous readout of segments of a frame by multiporting.

Los Alamos has designed cameras of medium resolution and high speed readout by increasing inherent pixel rates as well as multiporting. Our current cameras have continuous data rates in the 10^7 -to- 10^9 range as shown in fig. 23. Our advanced camera design goals target the range of 50,000-to-500,000 pixels, with single port-to-sixteen port readout architecture, and readout rates of 500-to-5000 frames/sec. This range is highlighted in fig. 23., with some of our newest designs noted. This range is driven by the fact that most of our cameras are MCP-II shuttered with current repetition rate limits in the few kilohertz range. The resolution provided by the cameras is adequate for the resolution provided by the MCP-II shutters at short gate times in the 5-15 ns range.

LANL VIDEO CAMERA PERFORMANCE

Figure 23. Performance profile of LANL electronic framing cameras. The shaded area shows future design goals in terms of quantity of pixels, pixel rates, and frame speeds. Our current and developmental cameras' performance characteristics are noted.

Our FPS camera currently in use is shown in fig. 24. Its resolution and readout as noted in the figure are 65,536 pixels and 1.6 ms, for ~ 41 MHz pixel rate. The FPS tubes are either 18 mm (7803 or equivalent) or 21-28 mm diameters (XQ8705 and 88XQ respectively), and use either Sb_2S_3 , Saticon, or PbO photoconductors. Other targets are also available. For these cameras, the quantity of scan lines, line durations, raster dimensions, and amplifier bandwidth are all programmable, resulting in our most versatile camera platform. The older FPS vidicons of the generic G.E. 7803 type used triode electron guns whereas the newer Phillips 88XQ and Heimann XQ8705 are higher resolution diode gun designs.

Our basic ILT CCD GY series camera is shown in fig. 25. These cameras (GY2/3 in fig. 23.) use either Sony ICX-016 or Fairchild CCD-222 imagers. These have 92,720 pixels which are readout in 3.6 ms for ~ 26 MHz pixel rate, which includes inactive horizontal and vertical pixels. This camera evolved to GY5 (fig. 26.) which uses ECL logic to increase PIXEL rate, allowing 1 ms readout with some truncation of the array (244x256, for 62,464 pixels) as shown in fig. 23. Our highest frame rate of ~ 2.3 KHz was obtained by 50 MHz clocking of the CCD-222 in a masked configuration (fig. 27.) which allowed partial readout (16,560 pixels) of the array at ~ 38 MHz pixel rate which included $\sim 24\%$ "overhead" for minimum vertical and horizontal blanking intervals. This design was to be used with four imagers similarly masked in the Quad Head configuration shown in fig. 27. With the four masked imagers readout in parallel the effective pixel rate is quadrupled to ~ 152 MHz but with frame rate at 1 KHz. Using four full GY5 arrays in Quad Head camera gives 250K pixels in ~ 1 ms for parallel readout of the arrays. Alternatively for time-phased readout, the speed is ~ 4 KHz but with ~ 63 K pixels. The Quad Head camera details are reported¹⁴ separately. All GY5 configurations are shown in fig. 23.

Figure 24. LANL's 1.6 ms FPS camera head showing the GE 7803 and Philips 88XQ vidicons currently used in this camera.

Figure 25. LANL's model GY2/3 ILT CCD 3.6 ms camera which uses Loral Fairchild CCD-222 Interline Transfer CCD.

Figure 26. Higher speed GY5 ILT camera featuring 100 MHz clocking and 75 MHz data processing circuitry.

Figure 27. Schematic of masked GY5 to increase readout speed by minimizing charge transfers required to move an image through the array.

Figure 28. Quad head camera (a) for various parallel/serial/phased readout modes of four CCD-222 imagers utilizing GY5 electronics.

Figure 29. Miniature camera head for 8-port EEV CCD-13. The head is ~2"x2"x2" and is laid out in surface mount for high speed operation. The view shows the CCD carrier with CCD-13 in place.

The GY series represents a continually evolving, high speed single-port design. As new improved circuitry is developed, it is incorporated in later model cameras. The GY single-port cameras feature the highest pixel readout rates that we are aware of. Serial pixel rates up to 75 MHz have been achieved with reasonable signal to noise ratios (100/1) employing extensive real-time signal processing.

A miniature camera head fig. 29. was designed for the 8-port EEV CCD 13. The head contains only CCD biases and level shifting electronics and buffer amplifiers to minimize head dimensions, and to allow flexibility in image processing by remote circuitry. Design criteria obtained by testing of the EEV CCD-13 in the HSTS were used to extract optimum performance from the imager. The camera is capable of sub-millisecond frame rates, as shown in earlier fig. 23., and 20-40 MHz pixel rates. The camera was developed for dual-use DOE/DoD high frame rate imaging applications. DOE applications include laser and pulsed power plasma diagnostic imaging in LANL's Above Ground Experiments (AGEX). DoD applications include Binary Imaging for optical correlation processing in military pattern recognition applications and various surveillance applications. A similar camera head is in design phase for the 16-Port Reticon HS0512J.

Development of high frame rate (up to 4 KHz) camera with fast MCP-II shutter (as short as 5 ns) was accomplished using a high strip current MCP and our GY5 CCD camera. Special MCP-II circuitry was designed to control, sample digitize, and encode gain and gate parameters with 10-bit resolution. For gain, the MCP voltage is controlled from 0-to-1024 volts in 1V resolution. For shutter control, the gate width is controlled from 1 ns to 1024 ns with 1 ns resolution. The MCP-II printed circuit board for this is shown in fig. 30. and the camera/intensifier package is in fig. 31.

(a)

(b)

Figure 30. A new LANL design for image intensifier 10-bit gain and gate control for operating MCPiIs is the 5 ns to DC range, using Stanford Computer Optics gain and gate modules. Top view in (a), bottom view in (b).

(a)

(b)

Figure 31. LANL's GY5/MCPII intensified/shuttered high speed ILT CCD camera for Mine Detection deployment. The MCPII circuitry of fig. 30 is shown in (a) RF box housing attached to GY5 camera. The control chassis shown in (b) generates the MCPII gate and gain control words and decodes and annotates samples of both at camera field rates, in near real-time

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