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High Frame Rate CCD Camera With Fast Optical Shutter

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KEY WORDS

Range-gated LADAR, 200pS optical shutter, 1-5KHz sustained frame rate, 5GHz "burst" frame rate, optical correlation

ABSTRACT

A high frame rate CCD camera coupled with a fast optical shutter has been designed for high repetition rate imaging applications. The design uses state-of-the-art microchannel plate image intensifier (MCPII) technology fostered/developed by Los Alamos National Laboratory to support nuclear, military, and medical research requiring high-speed imagery. Key design features include asynchronous resetting of the camera to acquire random transient images, patented real-time analog signal processing with 10-bit digitization at 40-75 MHz pixel rates, synchronized shutter exposures as short as 200pS, sustained continuous readout of 512x512 pixels per frame at 1-5KHz rates via parallel multiport (16-port CCD) data transfer. Salient characterization/performance test data for the prototype camera are presented, temporally and spatially resolved images obtained from range-gated LADAR field testing are included, an alternative system configuration using several cameras sequenced to deliver discrete numbers of consecutive frames at effective "burst" rates up to 5GHz (accomplished by time-phasing of consecutive MCPII shutter gates without overlap) is discussed. Potential applications including dynamic radiography and optical correlation will be presented.

BACKGROUND

Los Alamos National Laboratory (LANL) has developed a variety of high-speed intensified/shuttered TV-based cameras for diagnostics on nuclear weapons tests in support of the nation's underground test program over the last three decades. With the suspension of nuclear testing, LANL is now tasked to develop new diagnostics for Science

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Based Stockpile Stewardship (SBSS) of the nation's nuclear arsenal. It is from this technical base that the current camera described in this paper evolved. It is designated GY-11, Joint Use Camera, for the 11th discrete design in a series of high speed CCD cameras designed around a variety of new and developmental Interline Transfer, Frame Transfer and Full Frame CCD imagers designed for high frame rates. The camera will be used jointly by the Department of Energy (DOE) and The Department of Defense (DoD) in their respective programs. The principal DoD application is range gated imaging for target identification. The DOE applications include recording of time-resolved images associated with dynamic radiography of strategic materials. The optical shutter component is a LANL design stripline geometry microchannel plate image intensifier (MCPII) driven by tapered microstrip impedance matching gate drivers. Shuttering on is accomplished by forward biasing the photocathode-to-microchannel plate gap with an electrical gate pulse.

The extension of LANL cameras to address non-nuclear weaponry imaging applications has resulted in several range-gated laboratory studies and field experiments, which exploit the camera's capabilities to generate temporally and spatially resolved imagery of time-varying optical phenomena. The cameras are designed to be instantaneously reset for synchronization with random events to be recorded. Our earlier works (references 1,2,3,) on the current camera describe basic camera design and performance goals, circuit descriptions, some initial test data on individual camera components, as well as performance in preliminary range-gated field experiments.

CAMERA DESIGN

The two key components of the camera, the CCD and the MCPII, are shown in figure 1. The CCD is a Reticon HS0512J, which is a Frame Transfer CCD with 512x512 pixels with segmented multiport readout as illustrated in figure 2. The MCPII is a stripline geometry version generation-II device specially built to LANL specifications by Philips Components. The salient characteristics of both are found in Table 1.

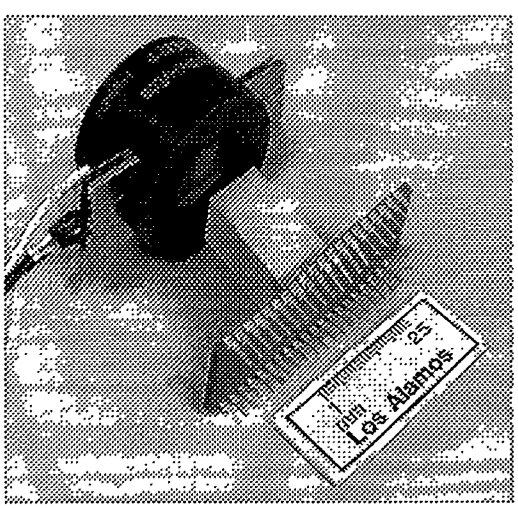
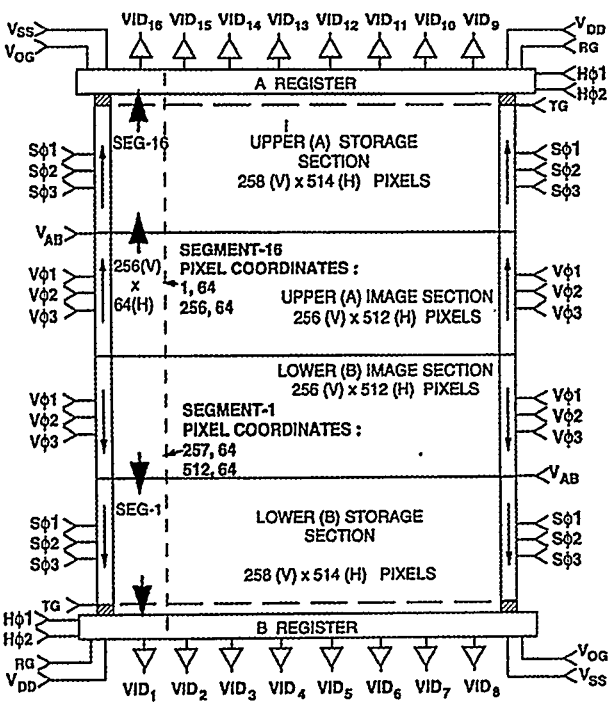


Figure 1. The Reticon HS0512J multiport CCD with 12x12mm-to-8.2x8.2mm fiber optic coupler bonded (bottom) and the Philips XX1412MH/E04 stripline MCPII (top).



The camera features real time precision (10-bit dynamic range with 1-bit time and amplitude resolution) control, measurement, and recording of MCPII gate width (shutter duration) and gain variables. Gate widths are controlled to 1nS out of 1024nS and gain voltage is controlled to 1V out of 1024V.

These data are recorded along with the video image captured by the camera, on a frame by frame basis, to provide radiometric calibration data for each individual image. The camera provides three methods of readout of analog images from the individual CCD output ports which are readout simultaneously in parallel via a 16-channel 50-ohm stripline transmission buss in the camera's motherboard.

Figure 2. The segmented architecture of the Reticon HS0512J CCD.

These are (1) buffered "raw" CCD unprocessed analog video, (2) digitized 10-bit data from on-board 50-MHz ADCs, (3) multiplexed analog video from high speed on-board analog processing, raster positioning, and mux circuitry. Block diagram level real-time analog signal processing flow (proprietary designs patented for LANL) for a single video channel is illustrated in figures 3 and 4. The blocks labeled with numbers in both figures are identified and described in U.S. patent 5,467,128, S-78,300-High Speed Imager Test Station.

Table 1. Salient characteristics of Reticon HS0512J CCD and Philips XX1412MH/E04 Stripline MCPII.

CCD:	MCPII:
Pixels: 512x512	Photocathode: S-20
Pixel Area: 16x16 microns	Phosphor: P48
Image Area: 8.2x8.2 mm	Image Area: 12x18 mm
Qsat: 120K electrons	Gain: 1-5K
Vsat: 200mV	Gate: 200ps
Trans: 1.8 microvolt/electron	Resolution: 28-36 lp/mm

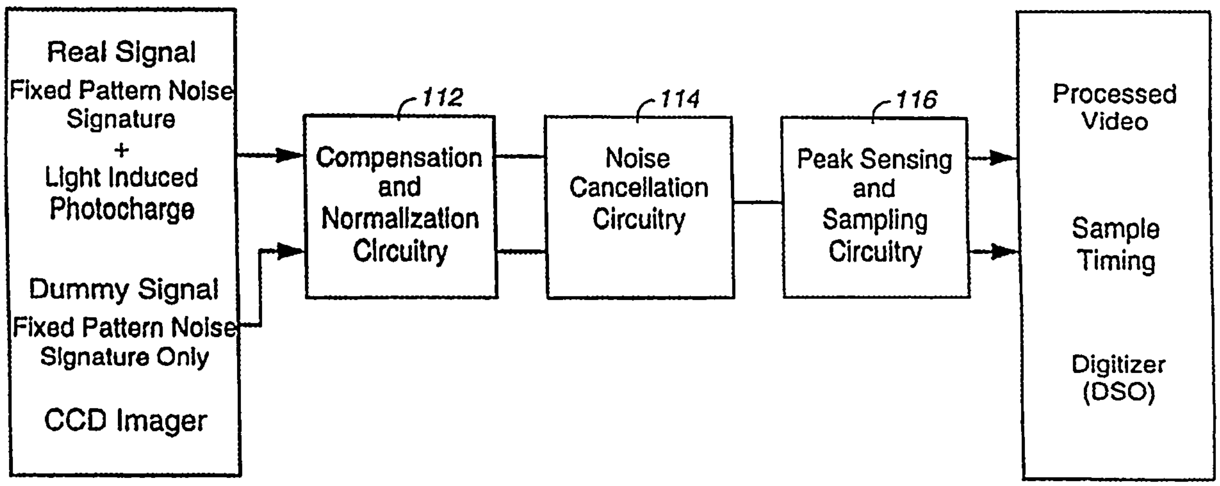


Figure 3. Analog signal processing diagram depicting key functions.

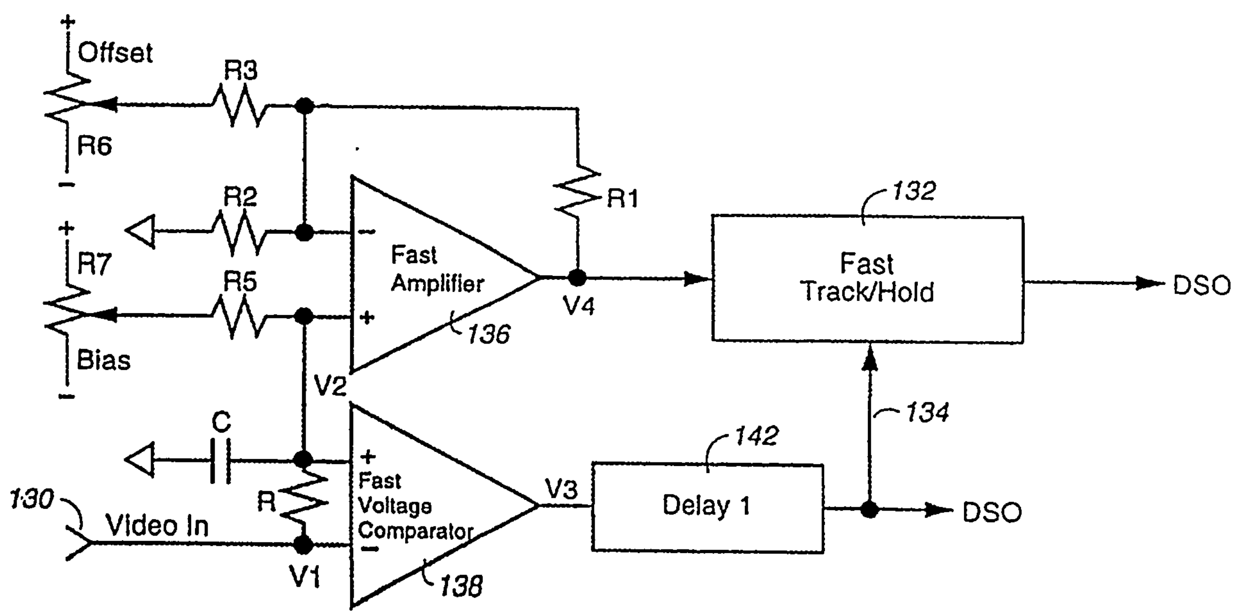


Figure 4. Schematic of an individual video analog channel showing video buffer and peak sensing comparator for properly time-phased generation of Sample and Hold clocks for peak stretching of individual CCD pixel transient signals prior to strobing data into the ADC or DSO.

In the design of the GY-11 camera, in addition to high performance digital logic and high bandwidth amplifier and analog processing circuitry, the CCD's charge-transfer-efficiency (CTE) rate issues were considered. The fundamental limit in charge transfer rate in CCDs is governed by mobilities of charge carriers in Si (ref 4).

Recent studies (ref 5) indicate CTE dependency on the quantity or magnitude of charge to be transferred, due to the effective E-fields in the Si that are generated by the CCD clock waveforms. For small magnitude charge, the charge transfer is drift-assisted due to effective E-fields, where as for large magnitude charge, only diffusion moves the charge due to collapsed potential wells in the CCD. This slows the movement of charge and restricts the rate at which the CCD can be read out.

In addition to the fundamental rate limits imposed by the carrier mobility arguments above, further restrictions arise from the reset settling time required by the on-chip output amplifiers and the CCD clock waveform degradation due to the resistivity of the polysilicon associated with clock electrodes.

Based upon the above considerations, our best estimate of readout speed limitations (with reasonable CTE) for the Reticon HS0512J are at pixel rates of 75MHz and line transfer rates of 5MHz. The resulting frame rates for various configurations using these pixel and line rates as well as slower rates for both are summarized in Table 2. The analog amplifier and processing bandwidth is approximately 100MHz. The CCD sync and clock circuitry operates in excess of 100MHz. The MCPII circuitry operates in the 1-2GHz range to provide the timing required for control and measurement of sub-nanosecond electrical/optical gates for shuttering.

Table 2. Reticon HS0512J readout calculations.

PARAMETER	RATE 1	RATE 2
pixels/line:	64	64
pixel period:	13.5ns	25ns
line readout:	865ns	1600ns
line transfer:	200ns	300ns
Total line readout:	1065ns	1900ns
lines/segment:	256	256
segment readout:	273 microsec	487 microsec
frame transfer time:	51.2 microsec	76.8 microsec
total frame readout:	324.2 microsec	563.8 microsec
continuous line xfrs:	273 microsec	487 microsec

For the fastest conditions calculated in Table 2, total frame rate is 3.1KHz for conventional readout with time allocated between image and storage phases, or 3.7KHz for continuous line transfer readout mode. The design goal of 5KHz readout can be achieved with increased pixel and line transfer rates, but with reduced performance.

Figure 5 shows layout of the camera motherboard. The distribution of signals in the multilayer (12 layers) motherboard are shown in figure 6, and photographs of the camera components and the complete camera package are found in figures 7,8,9, and 10.

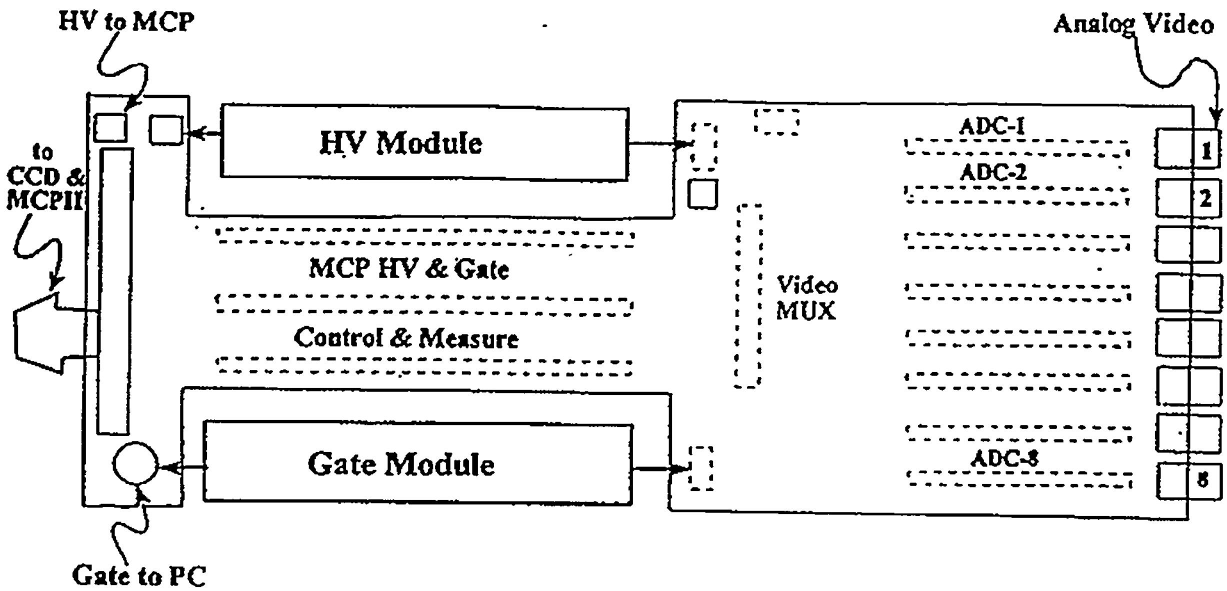


Figure 5. Camera motherboard layout, showing location of MCPII control circuit boards with their gate and gain modules, and location of eight ADC circuit boards and corresponding analog outputs. The bottom side of the motherboard is similar, and contains the remaining eight ADC circuit boards and the CCD logic/clock generator modules.

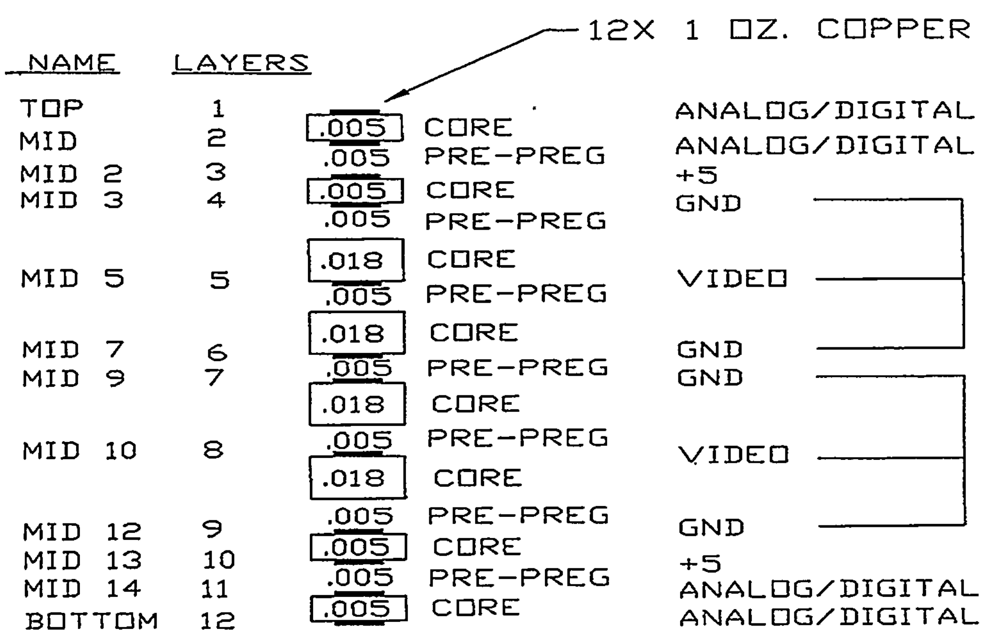


Figure 6. The 12-layer motherboard showing stripline design of the video channels in the inner layers with embedded power and ground buses. The outer layers are used to channel CCD logic and MCPII control signals bi-directionally.

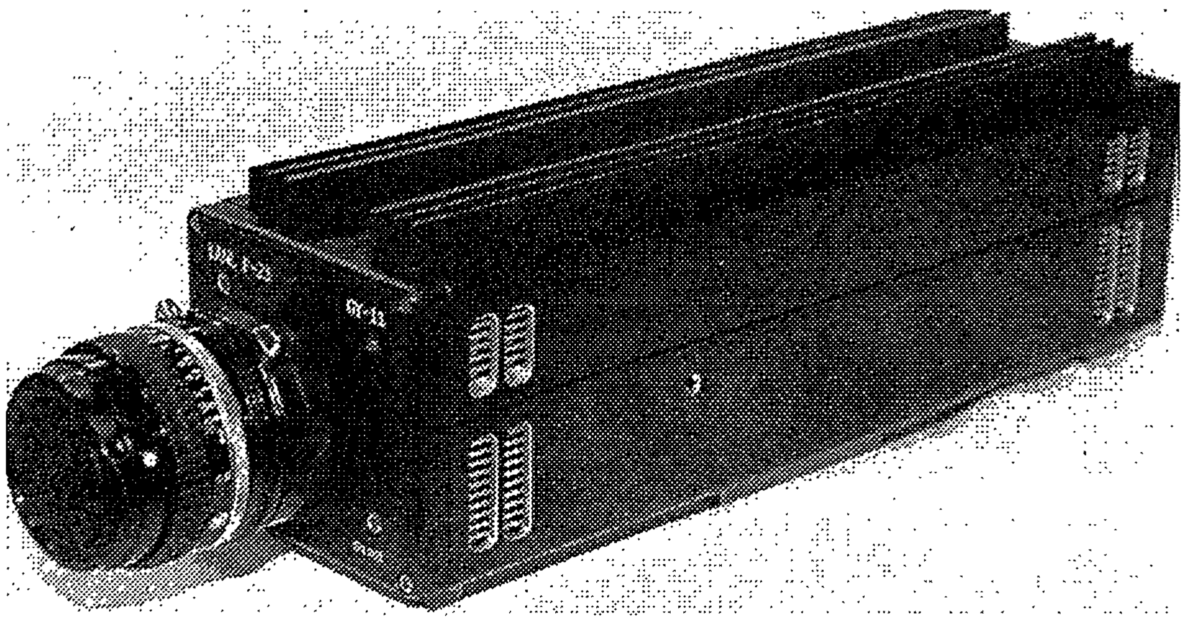


Figure 7. Photograph of GY-11 camera with covers on and with lens attached.

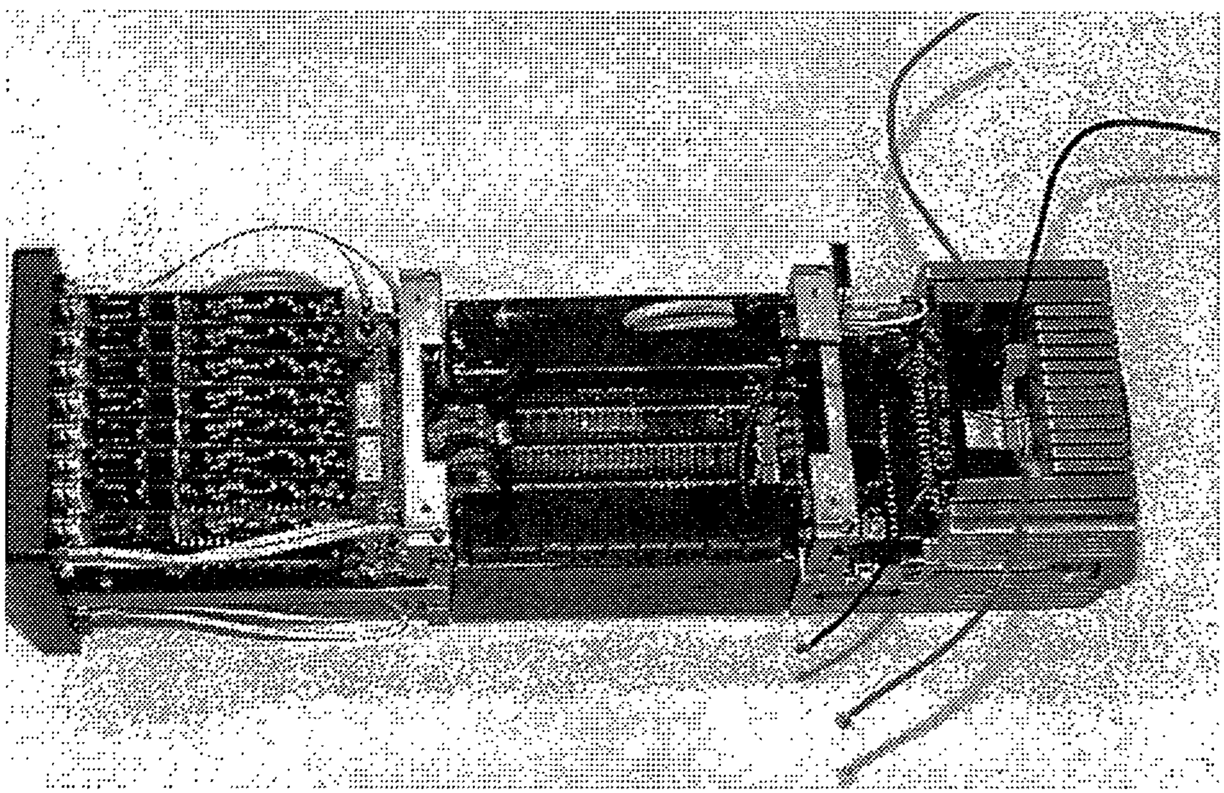


Figure 8. Photograph of the GY-11 camera with covers off, showing the location of logic(center)and ADC circuit boards(rear)on the motherboard and the MCPII/CCD module(front), which is coupled, normal to the motherboard via 56-pin surface mount connector. The flying leads are for controlling the Peltier Coolers.

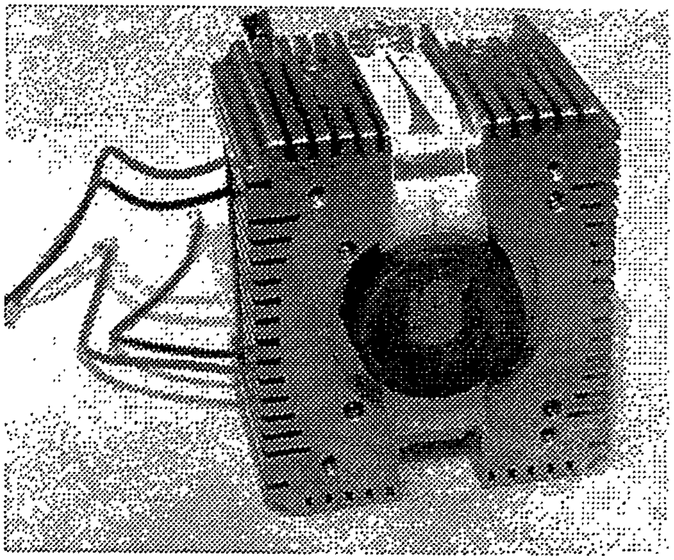


Figure 9. Photograph of camera head, i.e. the MCPII/CCD module, decoupled from the motherboard.

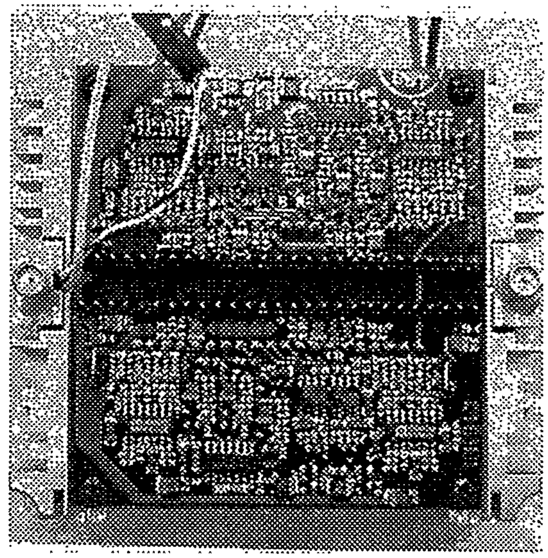
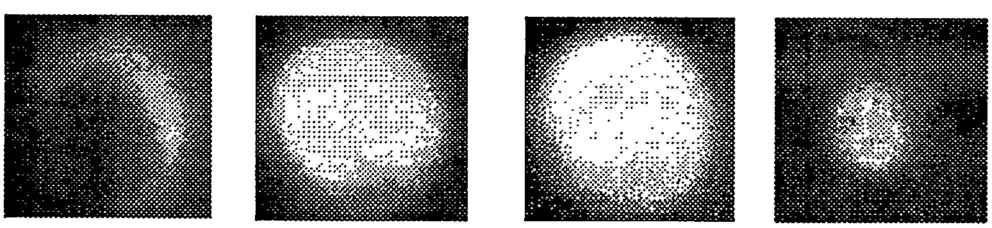


Figure 10. Photograph of the backside of the CCD header board showing connector which connects camera head to the motherboard.

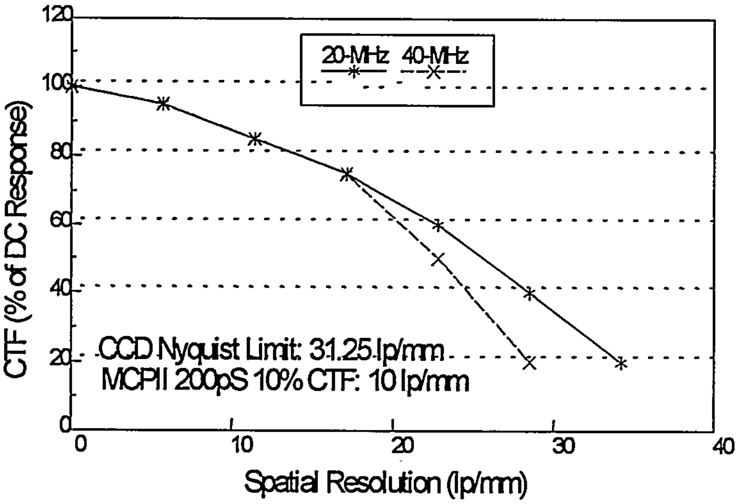
CAMERA TESTS

Preliminary shuttering performance studies for the MCPII in the sub-nanosecond range of exposures and extensive electrical/electro-optic tests were described earlier (references 1,3). Initial resolution measurements for the CCD operated at various pixel rates were also reported earlier (references 2,3). For completeness, typical examples of shutter and resolution are included in figures 11 and 12.



t= +50ps **t= +100ps** **t= +150ps** **t= +200ps**

Figure 11. Shutter sequence for the stripline MCPII when gated with a 250-pS FWHM pulse. The shutter is closed at t=0, fully on at t=150pS, and closed again at t=250pS. This MCPII design has been gated as short as 175pS.



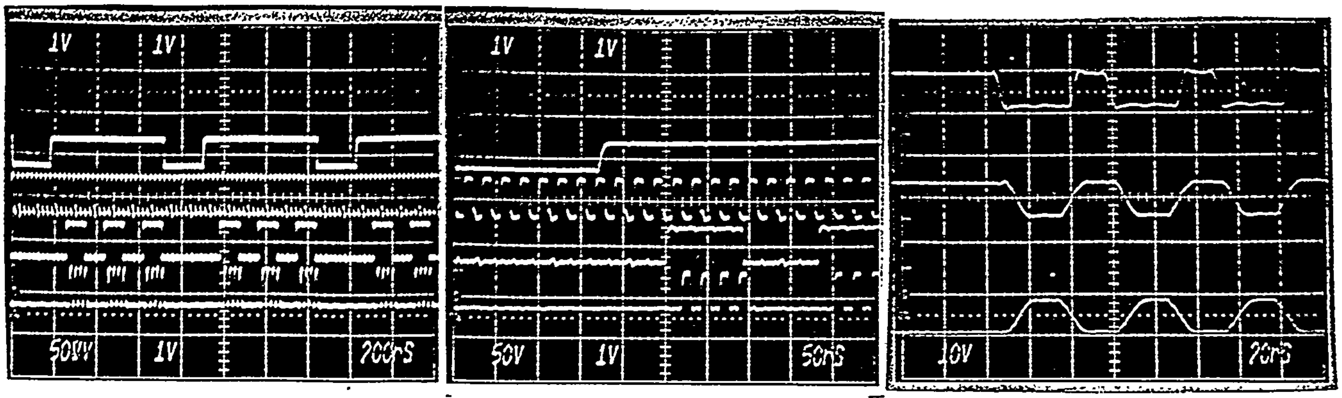
The camera's clock waveforms are shown in figure 13. The clock periods, phasing, overlap, etc. are digitally programmable by preloading counters in the sync logic. For the faster pixel clock waveforms, the rise and fall times of the waveforms are individually adjustable to allow optimum CTE. The reset signal resets the CCD logic and intiates a "smear free" light integration period and subsequent image transfer and readout cycles.

Figure 12. The CCD resolution measured at 20 and 40 MHz pixel rates.

For the dynamic range and crosstalk measurements described next, the MCPII was decoupled from the CCD and only the CCD response was characterized. The frame readout rate for these tests was arbitrarily set to approximately 600 microsec, for comparison with faster and slower rates, which are currently under study.

In the first of these series of tests on the camera, the entire CCD image area was illuminated with pulsed light from a Xenon strobe of approximately 5-microsecond FWHM. The broad band Xenon spectrum was narrowed to the 400-450nm range with a spectral filter to evaluate the CCD's response to blue light. The raw CCD video signals from individual analog video channels were recorded using multichannel digital sampling oscilloscopes (DSOs). Figure 14 shows the DSO data for the GY-11 vertical sync and video data from two (2) of the sixteen (16) channels. The remaining fourteen (14) channels were also confirmed to be operational with similar responsivity.

Next, only one segment, segment 5, was illuminated. The signal from this segment for both dark and illuminated cases is shown in figure 15. The signals obtained concurrently from unilluminated horizontally adjacent segments 4 and 6, and from vertically adjacent segment 12 indicated insignificant crosstalk. The unilluminated segments measured < 0.1% modulation. More comprehensive tests are currently being conducted to measure both optical and electrical crosstalk among segments.



a. b. c.

Figure 13. The GY-11 CCD clock waveforms as setup for initial checkout of timing and phasing among vertical, horizontal, and pixel clock components. Part (a) shows the frame sync (top trace) set for 2.5 frames, the continuous pixel clock (2nd trace), the line sync (3rd trace) set for 3 lines/frame, and the gated pixel clock (bottom trace). Part 9b) is expanded version of (a). Part (c) shows the pixel clocks, reset (top trace), bi-polar phases 1 and 2 (center trace) and (bottom trace) respectively.

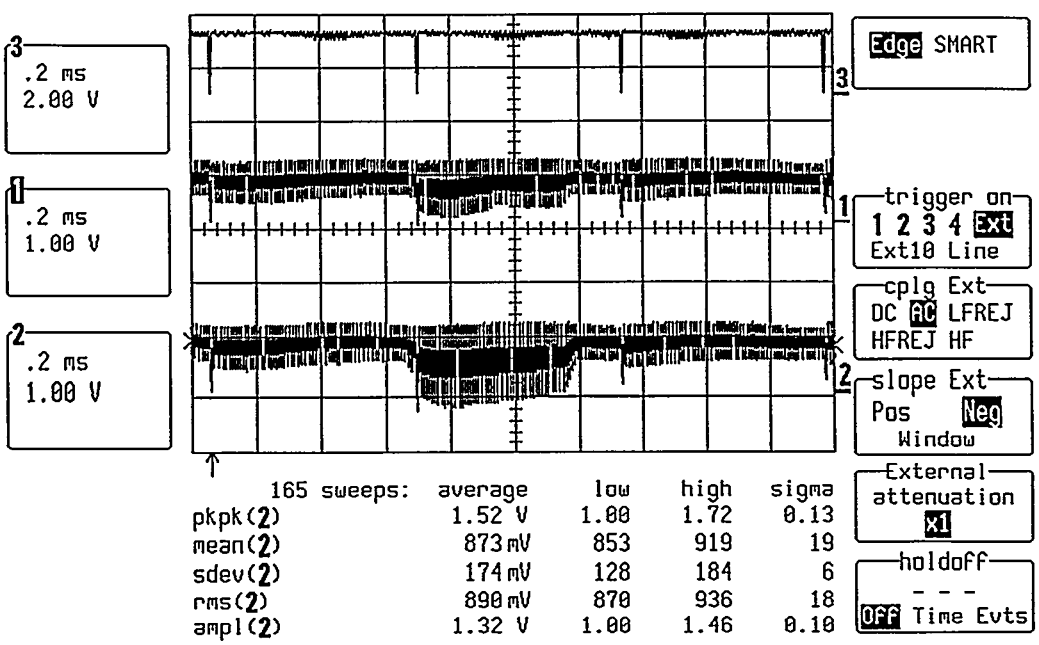
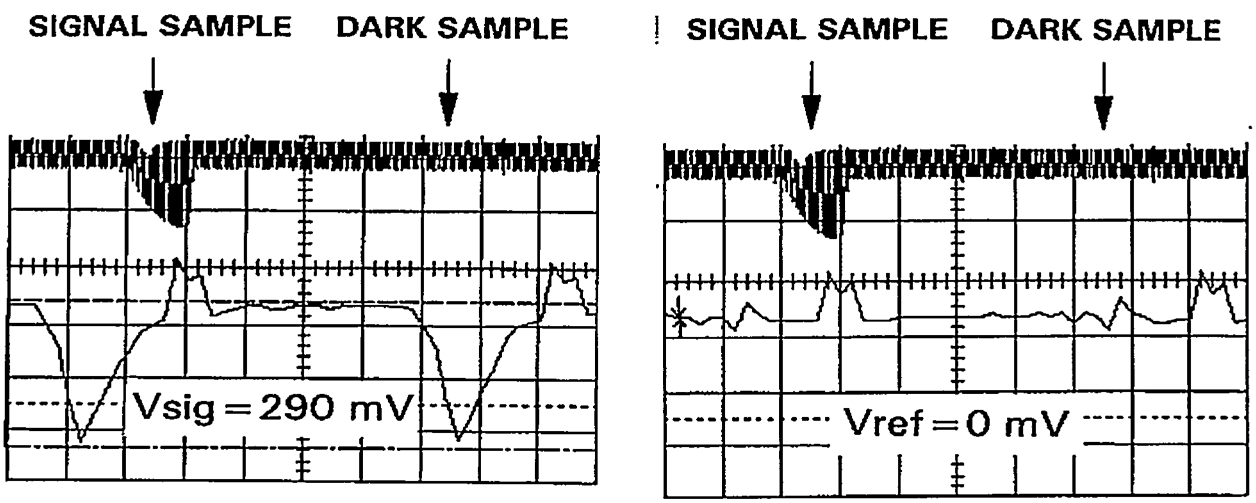


Figure 14. DSO plots of GY-11 frame timing and CCD video signals from two typical channels when flood-illuminated with unfocused pulsed light.

The dynamic range for segment 5 was measured by attenuating the input illumination from the Xenon strobe with neutral density (ND) filters to generate the transfer curve shown in figure 16. These are preliminary results only and do not reflect the benefits expected of the camera's analog processing circuitry. The DSO data were taken using the CCD's pixel clock to assure properly timed sampling by the DSO ADCs. The data were taken with LeCroy 9314L DSOs.



a. Signal Sample

b. Dark Sample

Figure 15. GY-11 video from single segment illumination of segment 5 of the HS0512J CCD with remaining segments masked dark. This setup was used to look for optical crosstalk among illuminated and dark segments and also to generate dynamic range data for a single channel. The top traces show the field data (image) and the bottom traces shows the line data (row of the image) expanded from the field data, to give signal levels both at the signal peak (a) and outside the peak (b). The DSO cursors used to measure magnitude of the two components.

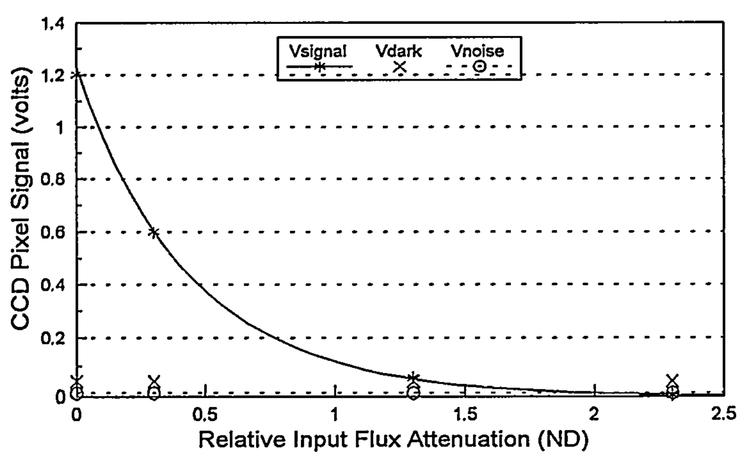


Figure 16. The GY-11 transfer curve obtained from a single video channel (segment 5) of the CCD without the MCPII coupled.

BURST MODE CONFIGURATION OF FOUR FRAME CAMERA

By synchronizing the MCPII shutter sequences of four units so they are time-phased to gate in consecutive order, extremely high effective frame rates can be achieved. The CCD readout rate does not determine camera frame rate for this mode of operation. For our MCPIIs which can be gated in 200pS, this configuration results in a "burst" frequency frame rate of 5GHz, albiet for only four frames. This is illustrated in figure 17, and is to be contrasted with the GY-11 sustained readout rate of approximately 5KHz.

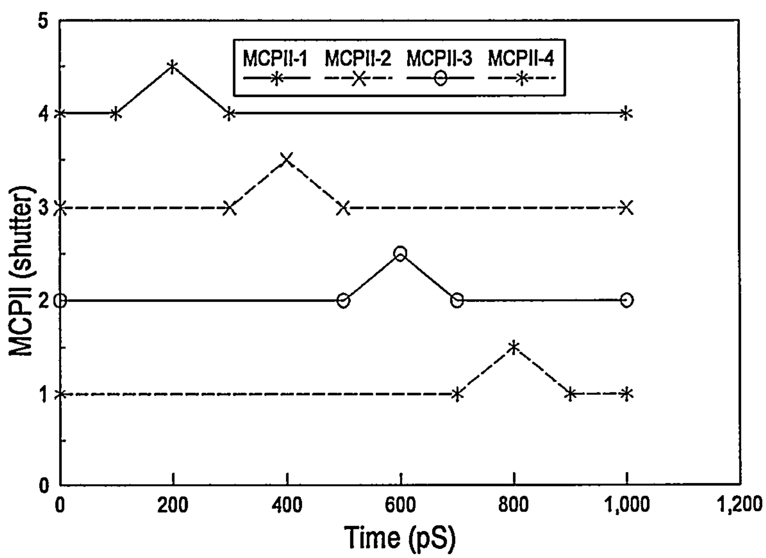


Figure 17. Time-phasing of four MCPII shutters to produce a "burst" mode four-frame 5GHz framing camera.

POTENTIAL OPTICAL CORRELATION APPLICATION

The high frame rate of the GY-11 camera could provide a basis for increased reading/scanning of Fourier domain templates used in optical and acousto-optical correlation systems. Conventional optics can provide two-dimensional Fourier transforms of an image, and by using templates (transparencies) in the Fourier plane, can do convolutions of images. Spatially resolved light modulators (SLMs) allow dynamic alterations of the transparencies used in the Fourier plane, thus blocking some spatial frequency components while transmitting others to the image plane. The two dimensional convolution of incoming images and calibrated templates (containing target recognition information) can be used effectively to generate spatial domain images in the optical systems image plane, where the CCD camera records what is essentially a comparison of the diffraction patterns of incoming image and the template.

The technique operates at extremely high rates because it is basically an optical system (ref.6), but times associated with switching templates slows the rate to 2-3KHz. Template scanning with existing CCD cameras (with readout times much longer than that for the GY-11 camera) further slows the system throughput rate. The use of a CCD camera in an optical correlation system is illustrated in figure 18.

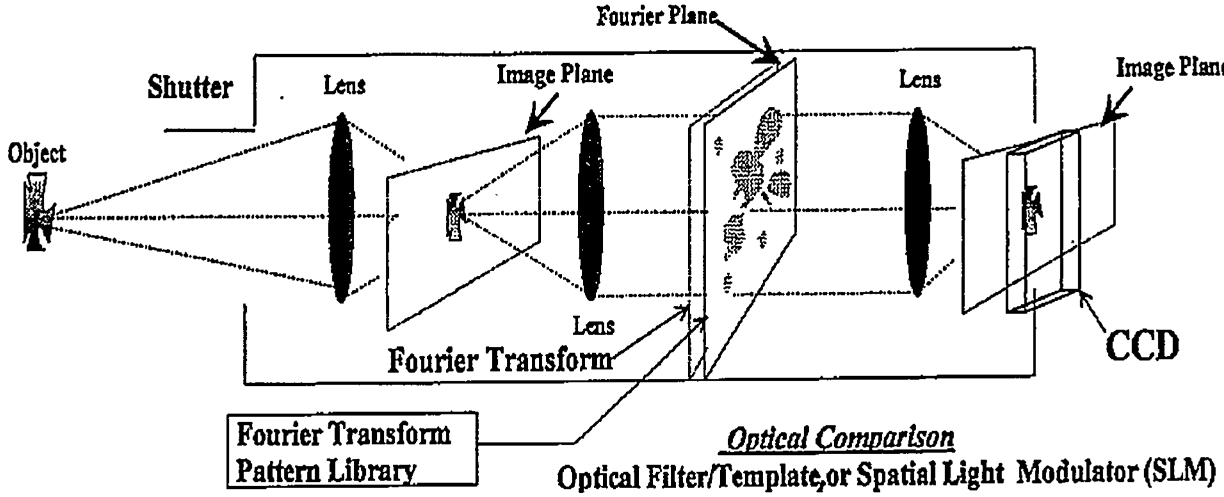


Figure 18. Optical correlation system illustrating the use of a CCD camera for image plane readout of convolution images produced in Fourier space.

RANGE-GATED EXPERIMENTS

Two range-gated experiments are described. The first is a medium range experiment involving target identification in atmospheric scattering mediums at kilometer ranges for the US Air Force. The second is a near-field target identification experiment involving identification at a few yards for potential use in turbid seawater imaging applications for the US Navy.

The medium range experiment was conducted at Eglin Air Force Base, using a high power pulsed laser to illuminate large resolution patterns at distance of about one half kilometer. The probe laser energy was about 50-100mJ with pulse duration of 12nS FWHM. The laser beam was expanded with a diverging lens to illuminate a large area of the LADAR range, including the surrounding forest and targets (military vehicles). The MCPII was programmed to gate for 6nS in coincidence with the arrival time of the reflected laser beam from the down range patterns. The gate times were adjusted to give time and space resolved images from the various patterns, which were spaced a few feet apart. These images are shown in figure 19. The ungated scene, top left, is a photograph of two resolution patterns; the top right image is for MCPII shutter timed to accept the reflected laser beam from the left hand pattern; the left bottom image is from the front surface of the right hand pattern and the right bottom image is from the back surface of the right hand pattern.

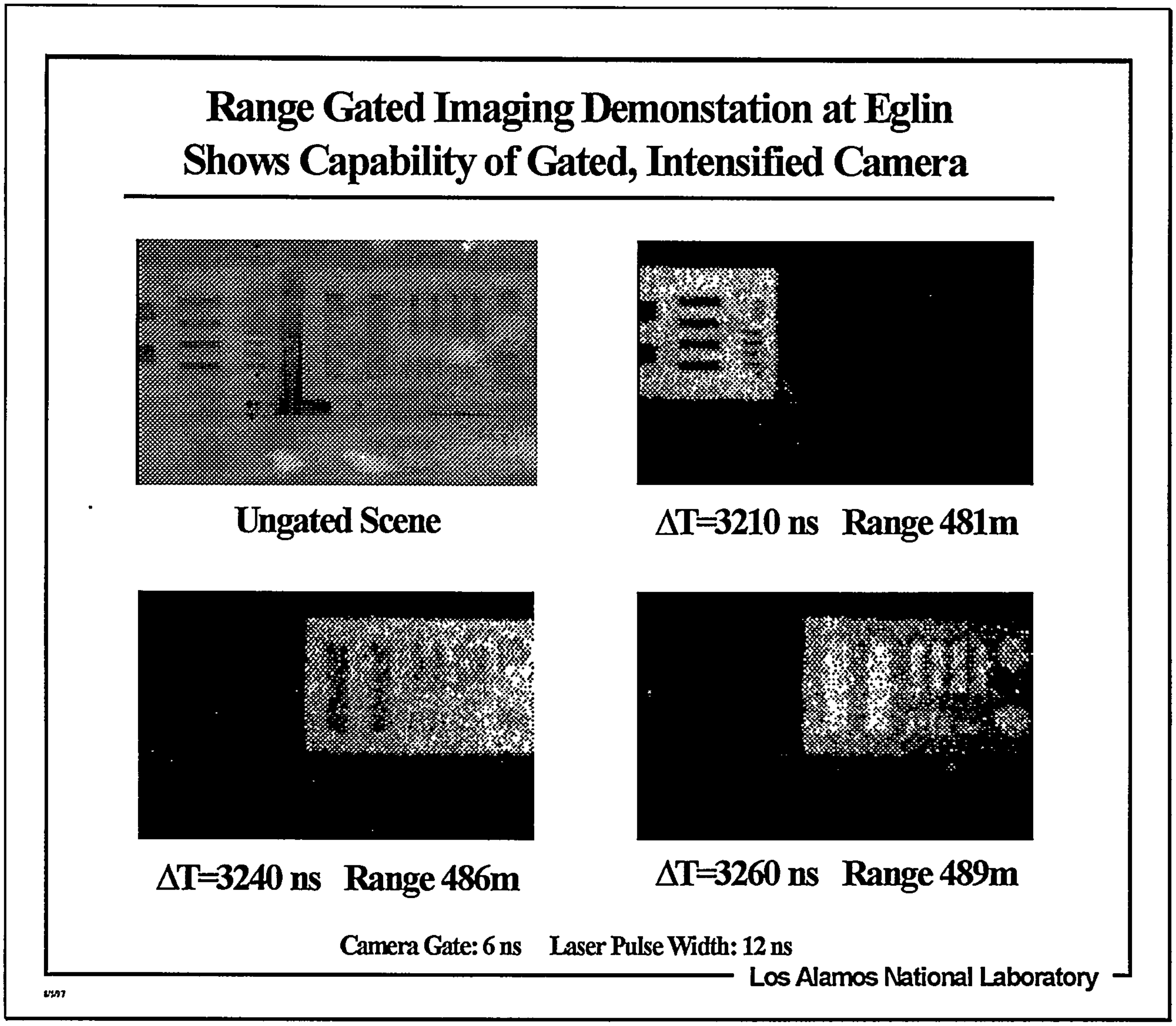
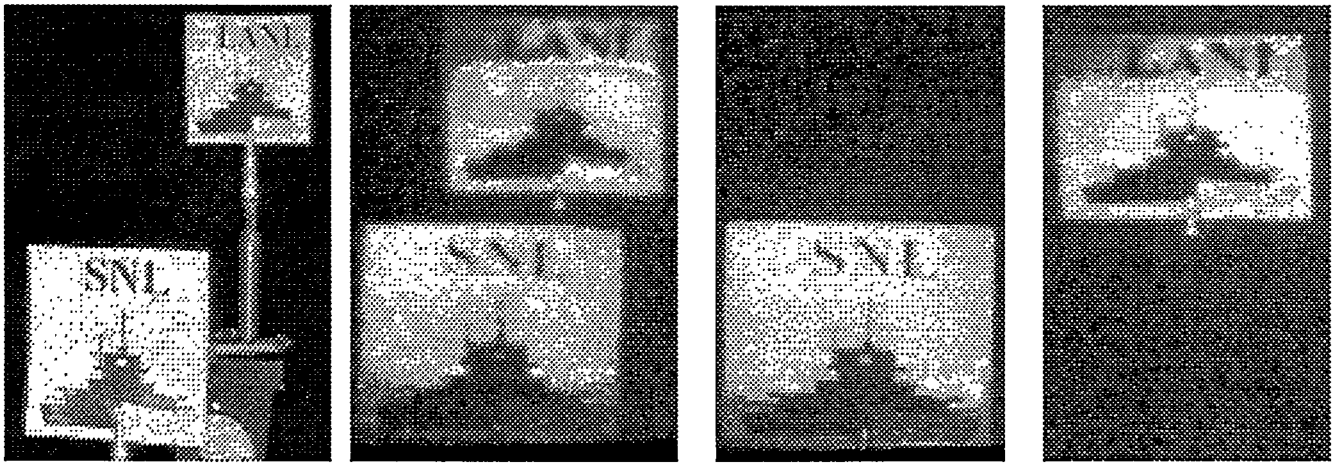


Figure 19. Range-gated images obtained at Eglin Air Force Base. The sequence shows the ungated, and range-gated images at indicated distances.

The near-field experiments were performed at Sandia National Laboratory, using their gain switched laser diode arrays (GaAs-based photoconductive semiconductor switch (PCSS) driving a laser diode array (LDA)) to provide a pulsed cone illumination source of a few feet diameter at distances of 10-20 feet. The projected laser diode energy was about 12 microjoules, pulse width was 3nS FWHM, and wavelength was 896-905nM. Two targets were placed at about three feet separation and illuminated with the laser diode. The MCPII was gated at 1nS FWHM and time-phased to image first one, then the other target, demonstrating the range-gated capability of the system to acquire images from different locations and distances in space. The images are shown in figure 20.



a. b. c. d.

Figure 20. Near-field range-gated images obtained at Sandia National Laboratories. The two images are from laser illuminated targets separated by three feet and labeled SNL and LANL (to highlight the collaboration and joint system design between the two National Laboratory's). The figure shows photograph of the two targets, (a) the two range-gated images of the individual target (c) and (d), and extended range-gated depth of field to capture both targets images with one shutter interval (b).

Results from our earlier experiments (references 7 and 8) discuss system performance in detail. Follow-on experiments are planned to establish system depth resolution limits and improvements in signal-to-noise in range-gated images in scattering environments.

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