video gain, brightness level, and vidicon target voltage.

Five Basic Modes

The system is intended to operate in five basic modes, the first of which is the generation of an analog TV signal essentially identical to that produced by conventional slow-scan cameras. The second mode of operation involves conversion of the slow-scan video signal to digital form at a serial pulse output rate of 90, 45, 15, 5, or $2\frac{1}{2}$ kilobits/sec. Quantization may be varied between 2 to 256 gray scale levels and fixed-bit errors inserted by means of front panel toggle switches on the A/D converter which allows any picture bit to be sent continuously in the 1 or 0 mode.

A third mode of operation allows tape recording of the slow-scan video data either in analog or digital form for later use. This makes the setup adjustments associated with the TV camera unnecessary and provides a relatively stable video reference source for experiments which are to be conducted over an appreciable length of time.

A fourth type of operation uses sampling in both the camera and kinescope recorder in order to simulate unconventional scanning patterns by modulation of the timing of the sample pulse generator. This technique increases the versatility of the system and has the additional advantage that changes in apparent scan velocity do not result in variations in reproduced image brightness and contrast as would occur with conventional TV systems.

In the fifth mode, the TV camera is useful as a form of densitometer or reflectometer with dynamic readout. The ability to repeat continually one line of video information allows convenient investigation of modulation parameters and analysis of picture information is practical on both vertical and horizontal axes due to the 90° axis rotation of the sampling process. Figure 10 shows the real-time monitor with both vertical and horizontal test markers superimposed and the accompanying waveforms generated, the horizontal being real-time video and the vertical being slow-scan video.

It was considered that all design objectives were met or exceeded in the final equipment, and some examples of performance are shown in the following illustrations. Figure 11 shows the typical quality achieved by the system at a 35-sec frame time with a picture being composed of 500 × 1024 elements. Signal-to-noise ratio is approximately 33 db with a flat noise spectrum and bandwidth is 8 kc. Figure 12 is the same input signal but this time digitally encoded to 6-bit precision with a serial bit output rate of 90 kilobits. Figure 13 is a 1500 × 1536-element picture with 150-sec frame time and 8-kc bandwidth. Figure 14 represents the opposite extreme, in this case a 110 × 128-element picture, 1-sec frame time, again 8-kc bandwidth, and a 30 db signal-to-noise ratio. Note that spot wobble is used to minimize the line structure in the reproduction. Figure 15 shows a resampled picture with the sweeps of both the camera and the slow-scan transcriber modulated at a 120-cycle rate. Figure 16 shows the resampling technique again, this time used with a vertical sawtooth added to the input of the sampling generator, thus producing the equivalent of a diagonal scan of the video information.

Acknowledgments

The development of this system was largely accomplished under Contract 950454 with the Jet Propulsion Laboratory of Pasadena, Calif. The author would particularly like to note the many significant suggestions of Gary Fultz of that organization.

Precision Range-Gated Imaging Technique

By DON B. NEUMANN

A giant-pulsed laser is used to actively illuminate a distant target with a light pulse of about 60 × 10^{-9}-sec duration. The 50 × 10^{-9}-sec exposure of an image-converter camera is delayed the proper amount with respect to the laser to allow only the return from the target to enter the camera. It is shown that backscatter from atmospheric particles (such as snow) can be greatly reduced by this technique-

Introduction

In general, this paper is concerned with the formation of an image which shows only those objects which fall between a certain minimum distance and a certain maximum distance from the imaging device. This is accomplished by illuminating the objects within the field of view with a very short pulse of light and then opening a shutter in the imaging device at precisely the proper time to allow the light returning from objects at the desired range to pass and form an image. Light returned from objects at too small a range arrives before the shutter opens and is therefore rejected while light from objects at too large a range is likewise rejected since the shutter is reclosed before it arrives.

Since light travels about one foot in one nanosecond, it is necessary to have submicrosecond illuminating pulses if range resolutions of tens or hundreds of feet are desired. In order to obtain an image in such a short time, it is necessary to have the object illuminated to a very high brightness. Both the short time duration (tens of nanoseconds) and the high brightness (more than 10^{12} w/steradian) may be obtained by using a Q-switched laser as the illuminating light source.

The experiment described below indicates the feasibility of two rather interesting applications of this technique. The data obtained are of a qualitative nature only, but serve to indicate the effectiveness of the technique and to lay the foundation for further experiments to yield more quantitative results and estimates of system parameters.

The first application concerns the reduction of the low visibility effects which occur when attempting to view objects under active illumination through atmospheric conditions which contain many light scattering particles. (A common example is the backscattering of headlight illumination into the eyes of a motorist driving in fog or a heavy snow.) In these cases, the "noise" light backscattered from the particles may completely swamp out the "signal" light returning from the desired object and the resulting image does not convey the information desired. By range gating, one may eliminate a very large percentage of this "noise" light and thus retain the desired image.

The second application concerns the addition of range information to the image. For example, an aerial photograph taken with the range-gating

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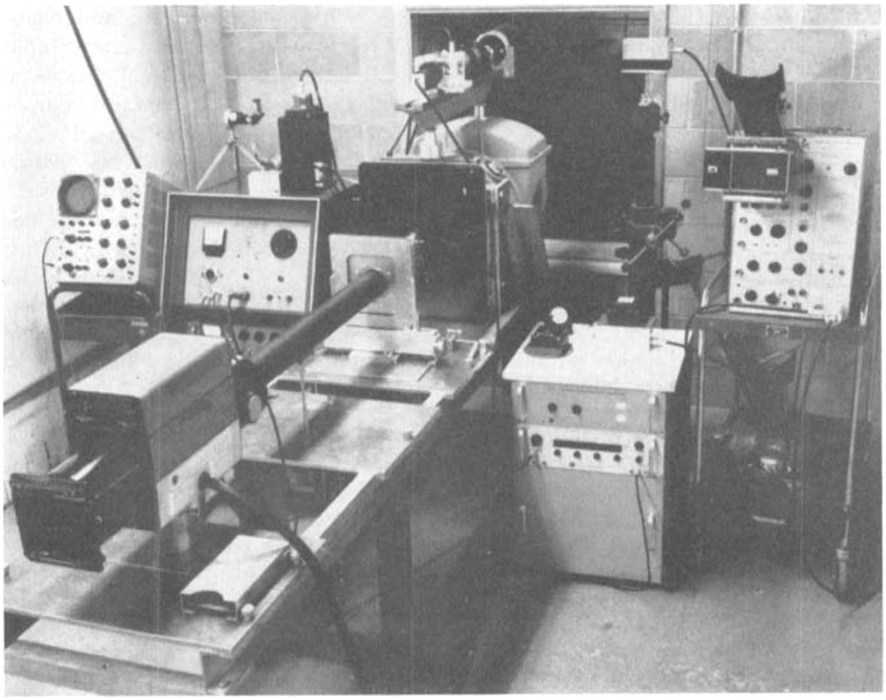
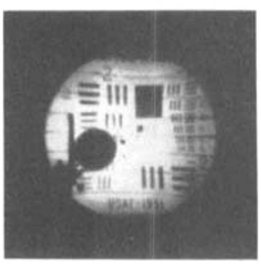


Fig. 1. Experimental apparatus.



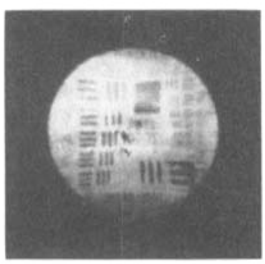


Fig. 2A. (Left) Camera system resolution: photoflood illumination.

Fig. 2B. (Right) Camera system resolution: laser illumination.

technique would show only those portions of the terrain which were at a certain distance from the aircraft. A series of such photographs, each taken with a different shutter delay, would provide the necessary information for the compilation of an elevation contour map of the area.

The Experimental Breadboard

The equipment as assembled for the initial experiment is shown in Fig. 1. Two rails, which extend from the port in the rear wall to the lower left corner of the picture, support the elements which make up the imaging device or camera. Nearest the port is an $f/4$, 36-in. focal-length aerial camera lens which serves as the collecting optics for the system. The plate at the end of the black tube holds a 5-in. focal-length lens which magnifies the original image, making the system have an effective focal length of about 20 ft. The second image is formed on the S-1 photocathode of the STL image-converter camera at the left. When a shutter pulse is applied to the camera tube, photoelectrons are accelerated to the P-11 photoanode which is imaged onto the film plane of the Graflok back by a rear lens system. Polaroid Type 57 4 × 5 film having an ASA speed of 3,200 was used for most of the tests. The film back may be removed and replaced by an eyepiece for visual observations.

A resolution chart which is used as a target object for the experiments is located 290 ft downrange through the port in the rear wall.

The laser elements are mounted on a small optical bench over the aerial camera lens. The laser power supply and Q-switching electronics are located in the console immediately to the left of the aerial camera lens.

The laser used in these experiments is of the Q-switched ruby type and emits at 6943 A. The laser is operated to give about 0.3-j output with a pulse width of approximately 60 nanosec. The Q-switch is of the Kerr cell and Wollaston prism type. The Q-switch electronics are such that the switch is open for about 200 μsec. This results in the first giant pulse being followed by a number of relaxation oscillations. Since the first of these does not occur for at least a microsecond after the giant pulse, they may be neglected in this experiment. However, the effect of these later pulsations will be noticed in some of the open shutter shots shown later in the paper. Lasers which do not have

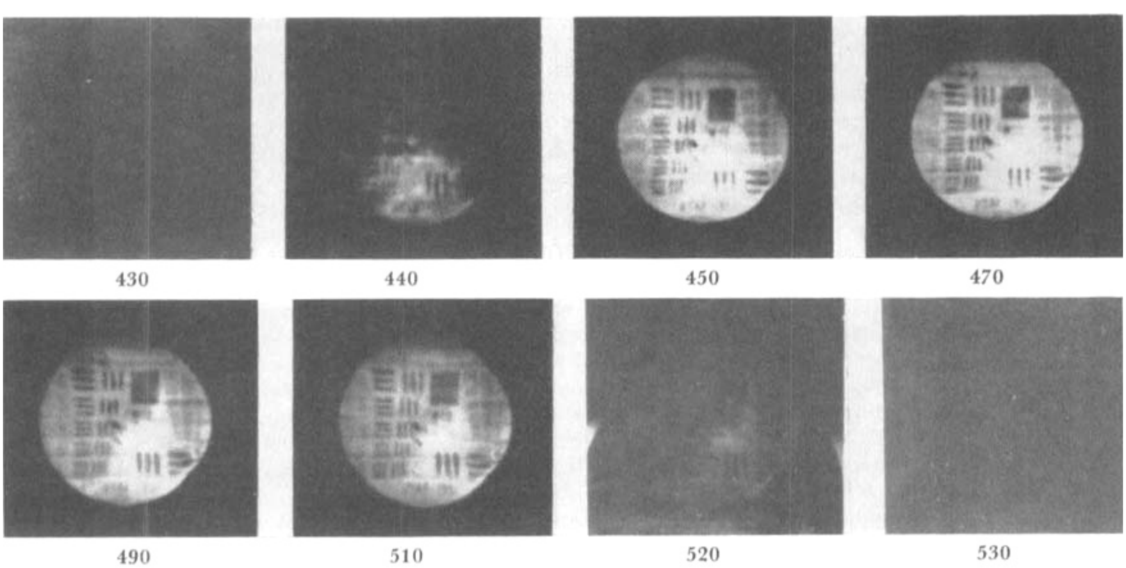


Fig. 3. Exposure variation with delay; all exposures, 20 nanosec.

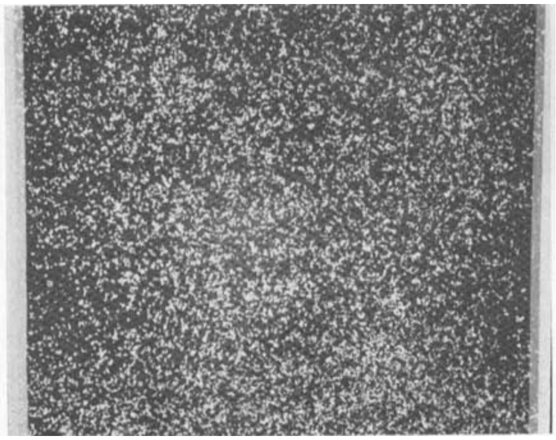


Fig. 4. Snow screen.

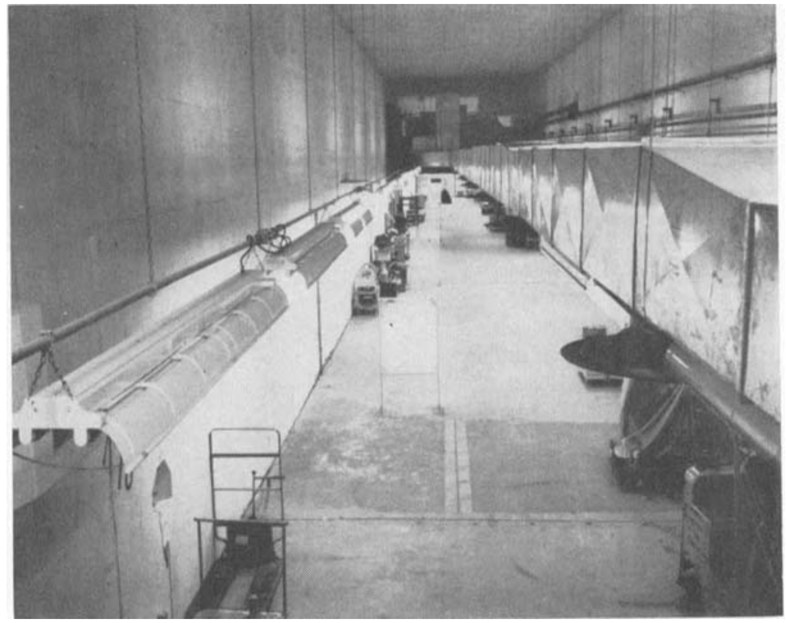


Fig. 5. Test range with snow screens.

these trailing pulsations may be constructed and should probably be used in future experiments and applications.

A pair of lenses has been added to the output end of the laser to increase the $\frac{1}{4}$-in. beam to about 3 in., thereby eliminating the possibility that a single particle could nearly block the beam in the backscatter experiments.

The shutter time delay is provided by the STL trigger delay generator mounted in the camera power supply console to the right of the aerial camera lens. This delay generator allows delays to be inserted in steps of 10 nanosec. Light "leaking" through the rear reflector of the laser is carried by a fiber-optic bundle to a photodiode in the delay electronics input circuit. This provides the reference time to synchronize the camera shutter with the light pulse. The light is passed through a 10 A red filter before it enters the fiber-optic bundle to prevent triggering on the laser flashtube illumination. The variable attenuation provided at the optic input to the delay generator allows the trigger threshold to be adjusted to trigger on the giant pulse, but not on the relaxation oscillations mentioned previously.

An alternate scheme of triggering using the Kerr cell trigger voltage as a time reference was tried and found to be unacceptable due to the various time jitters which are introduced.

The length of the fiber-optic bundle and the coaxial cables and the various electronic delays combined to give a fixed minimum delay of approximately 110 nanosec.

Figure 2 shows the resolution of the camera system and film. The pincushion distortion and the horizontal lines are inherent in the image-converter tube. Also, the series of small black spots near the center of the picture is the result of damage to the photocathode of the tube in previous laser experiments. Figure 2A is taken with the resolution chart illuminated by a photoflood, which can be seen silhouetted in the picture. Figure 2B is taken using laser illumination. It should be noticed that the contrast is considerably reduced. This is apparently due to the fact that the resolution chart, while made of mat photographic paper, still has a fairly high coefficient of specular reflection. In the laser case, the angle of incidence is nearly normal to the chart with the result that some light returned by specular reflection enters the camera and reduces the contrast of the image. The photoflood having a much larger angle

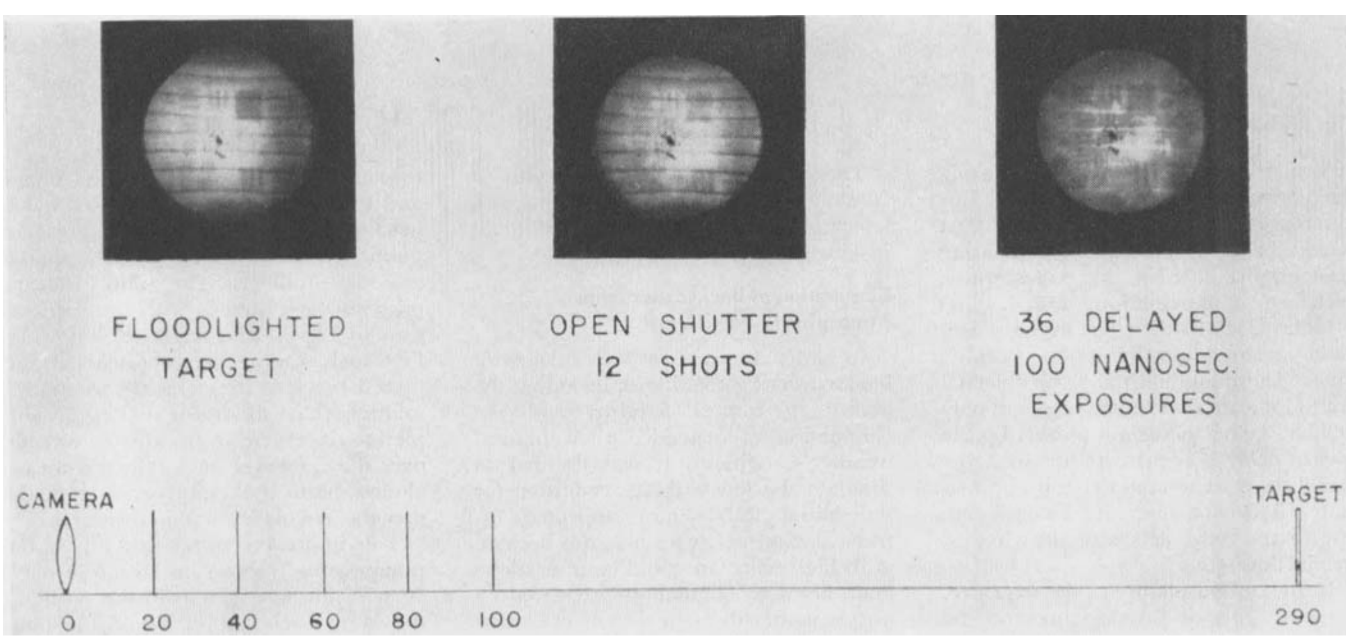


Fig. 6. Range gate effect (20 ft).

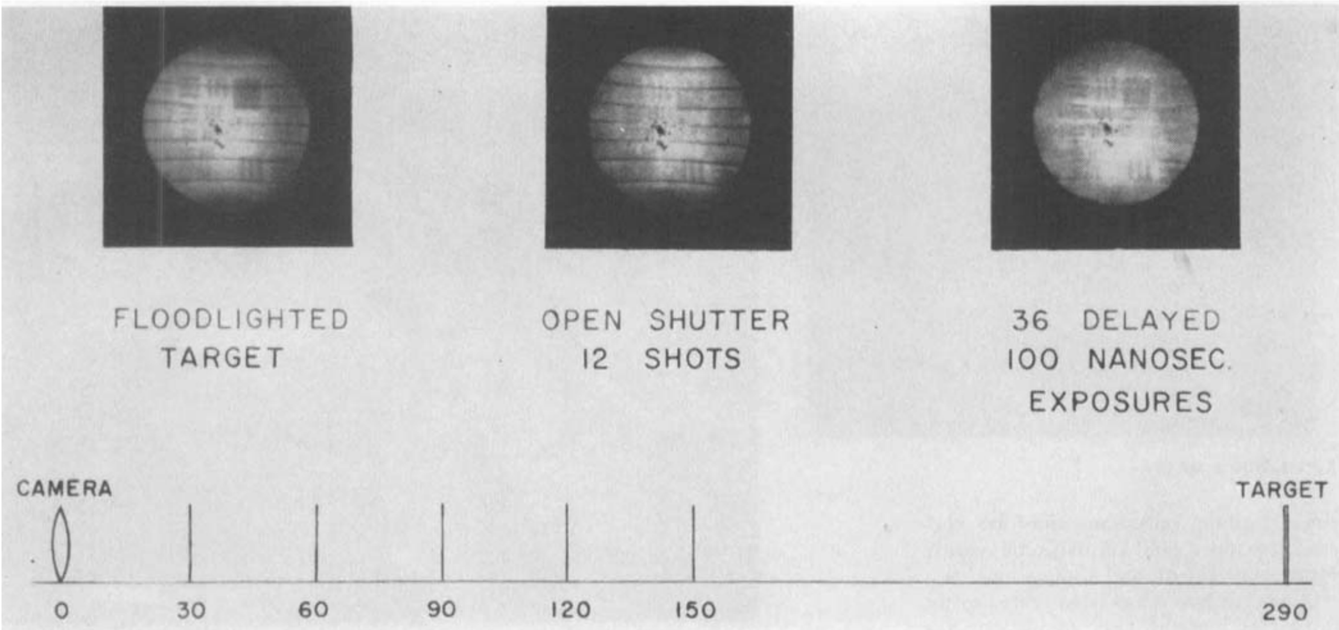


Fig. 7. Range gate effect (30 ft).

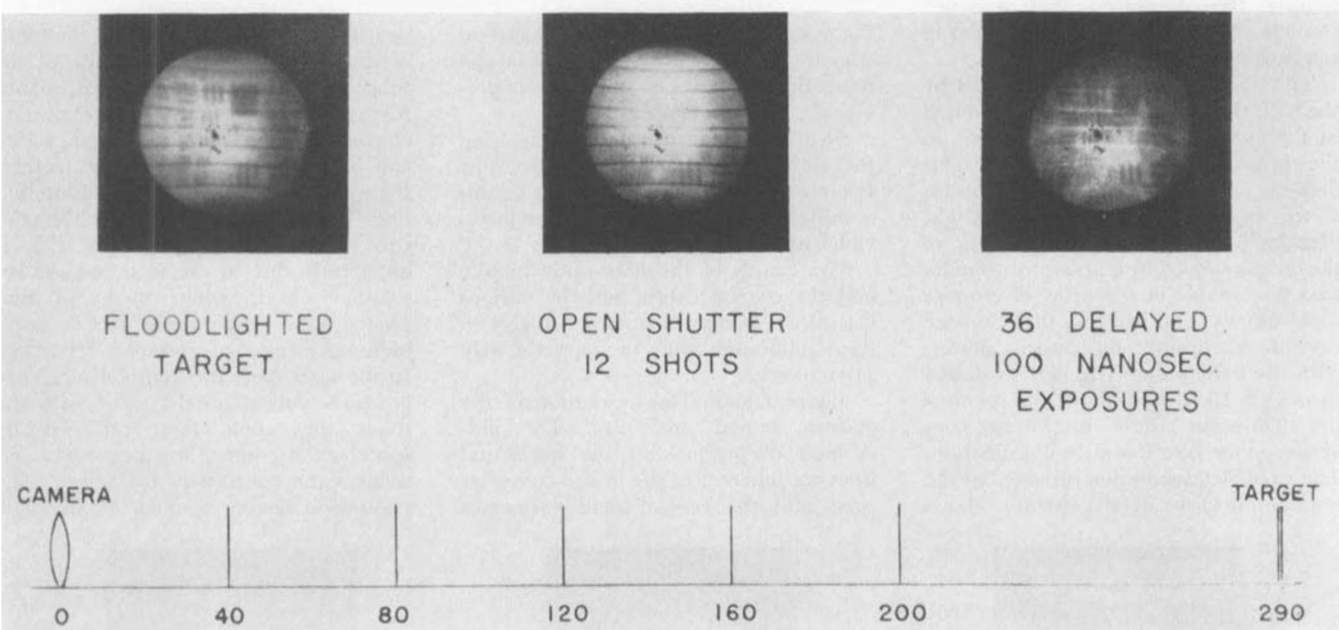


Fig. 8. Range gate effect (40 ft).

of incidence results in pictures showing the normal contrast of the chart. This difference in apparent object contrast should be considered when comparing photographs later in the paper where both forms of illumination are used.

Figure 3 shows the effect of the range-gating technique with various "delay" times. The quotation marks on "delay" are to indicate that these values are only relative, being the delays formed by the trigger delay generator rather than the actual delay. The total delay is approximately 110 nanosec greater in each case due to the fixed delays of the circuits, coaxial lines, etc.

In the second picture of the sequence, the laser pulse is just forming and the radiation does not yet cover the entire face.

These pictures are taken with a 20-nanosec exposure and a 60-nanosec laser pulse. The time jitter is very small, making the results easily repeatable.

Elimination of Backscatter from Atmospheric Particles

In order to gain the advantages of indoor working conditions, including the ability to control lighting, and the elimination of dependence on natural weather conditions, it was decided to simulate the low-visibility condition for the initial tests. Snow appeared attractive as a scattering medium because of its high reflectance and large particles and because simulation appeared a simple matter through the use of Christmas spray snow applied to Plexiglas panels. The Plexiglas panels were found to cause severe distortion of the image and were replaced by screens of nylon net which, while periodic, are not positioned where they cause any spatial filtering problems. The snow was applied to these screens with the result as seen in Fig 4. The screen is 3 ft wide. Five such screens were constructed and placed between the camera and the resolution chart as shown in Fig. 5. This picture is taken from almost directly over the camera system. The screens included both the laser beam and the camera field of view within their area.

The improvement in visibility using range gating is shown in Figs. 6 through 10 with the five screens in the positions shown in each figure. While the positions may seem a bit odd, they resulted from the manner in which the experi-

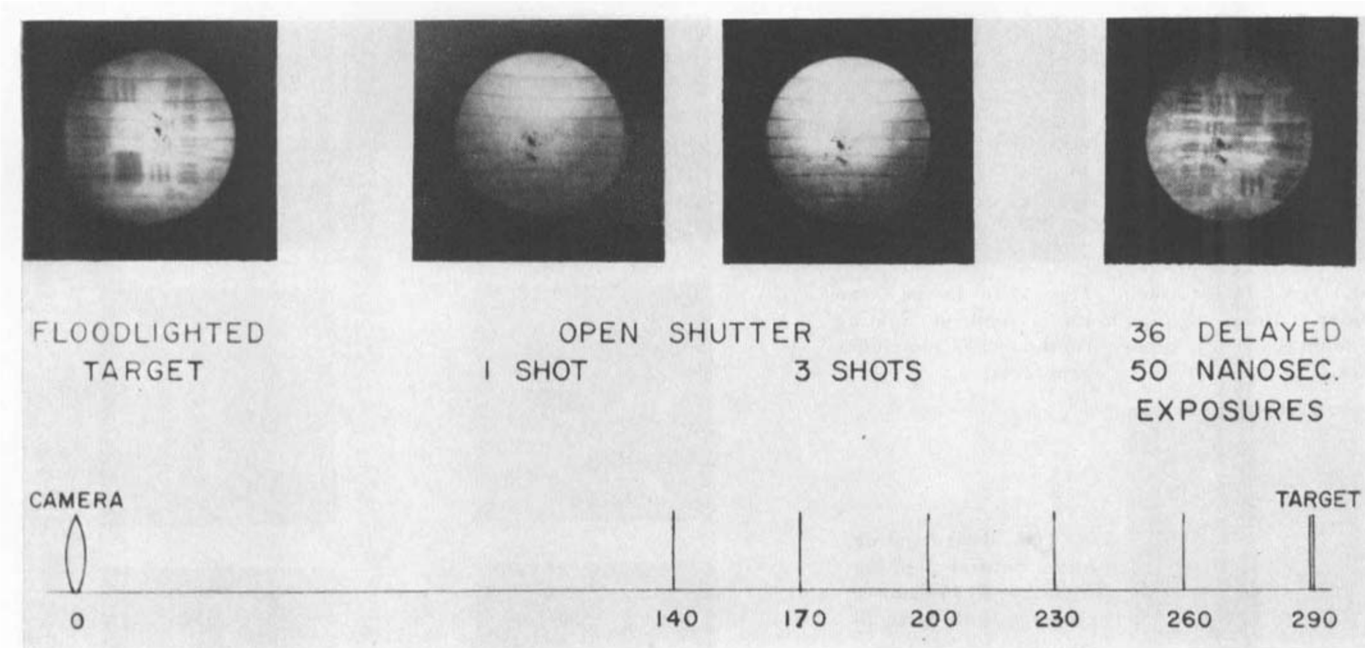


Fig. 9. Range gate effect (−30 ft).

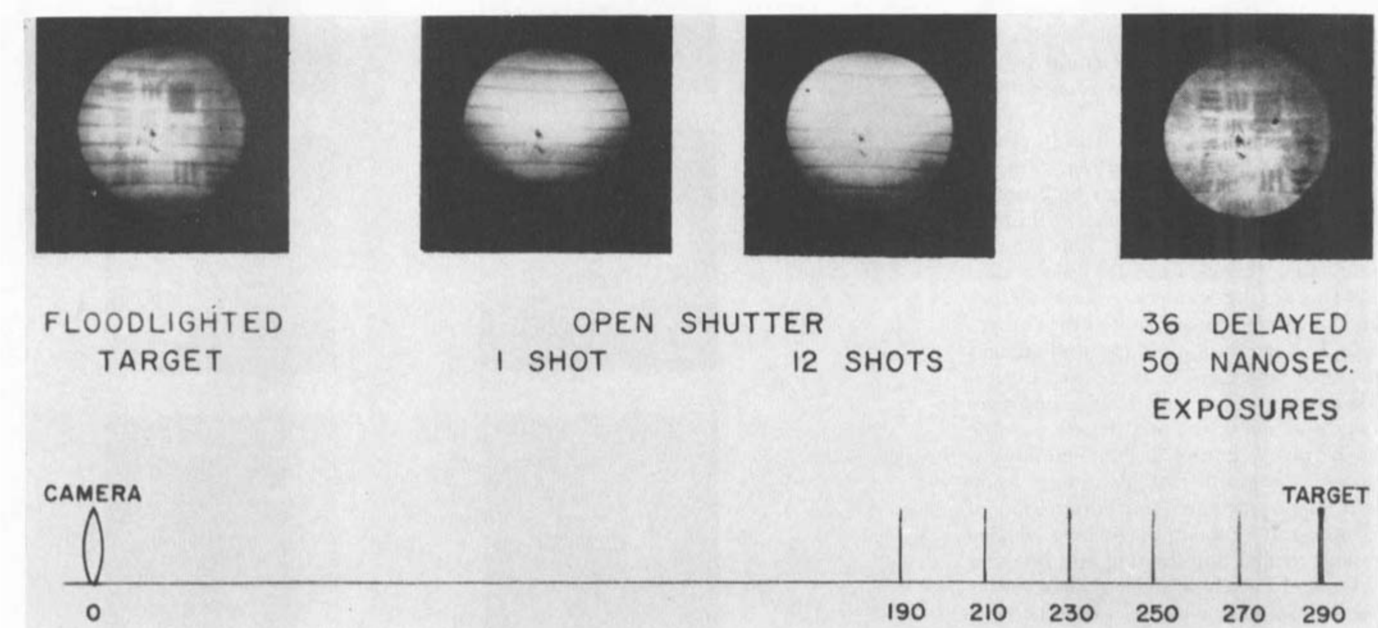


Fig. 10. Range gate effect (−20 ft).

ment developed and do suffice to show the important qualitative results.

In each figure, the picture to the left shows the resolution chart image as seen when illuminated by a floodlight near the chart. These pictures were made to provide a measure of the image degradation due to the effect of the snow screens on the light as it passes from the chart to the camera. Thus, these shots are free from any backscattered noise light such as would occur if the illumination were furnished by a laser or conventional light source located near the camera; therefore, they provide an indication of the optimum image to be expected from that set. However, it should be recalled that the object for these lefthand pictures has a higher apparent contrast than the object for the other pictures in the figures and, therefore, is somewhat unfair to the range-gated pictures.

The center picture(s) in each figure are made by placing the entire range in darkness, opening the camera shutter and firing the laser. This procedure was then repeated the number of times shown beneath the picture.

The pictures to the right of each figure were made by delaying the camera shutter and thus providing the range gating described above.

It has been found that the attenuation resulting from the snow screens requires an increase from one shot to 36 shots to obtain an adequate exposure. Due to the relaxation oscillations following the giant pulse, the open shutter pictures require only one third as many shots for the same exposure. This one-third ratio is the same with or without the snow screens.

The particles which lie within the laser beam tend to throw shadows on the object to be photographed and result in a very spotted image. Therefore, the screens are randomly moved to three positions during each of the laser-illuminated exposures. That is, one third of the shots required for an exposure are made, the screens are shifted slightly, another third of the shots are fired, then after a second shift of the screens the final one third of the shots are made. This was done since such a particle motion would occur during the forma-

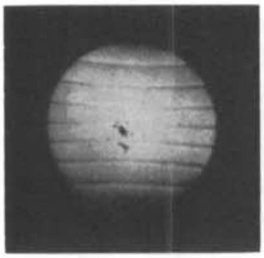


Fig. 11A. Image seen under natural lighting conditions: ½ sec exposure.

Fig. 11B. Image seen under natural lighting conditions: 36 50-nanosec exposures.

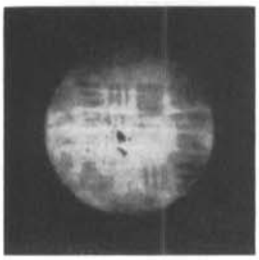
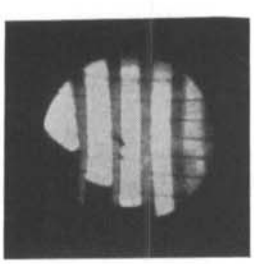


Fig. 11C. Range gating under natural lighting conditions: 36 50-nanosec exposures with laser illumination.

tion of an image with multiple laser pulses. If the image sampling rate is too great for sufficient particle motion to take place, similar results could be obtained by illuminating with multiple lasers.

Figures 6 and 7 show little improvement with the range gating. This is because the snow particles which are illuminated by the laser are not within the field of view of the camera. This is fortunate since backscatter for these particles near the camera suffers such a small r^2 loss before arriving at the camera lens. The separation of laser and camera entrance aperture is therefore an important technique for image improvement and should be used where possible when range gating is not employed. However, a number of advantages (such as a single aperture and elimination of parallax) may be gained in a device having coaxial illuminating and imaging systems. In such a device, backscatter effects from near particles would become severe and range gating would be even more effective in improving image quality.

In Fig. 8, the laser beam begins to intersect the last screen or two within the camera field of view and the noise light begins to become apparent. Notice that the effect comes in from above as one



Open shutter

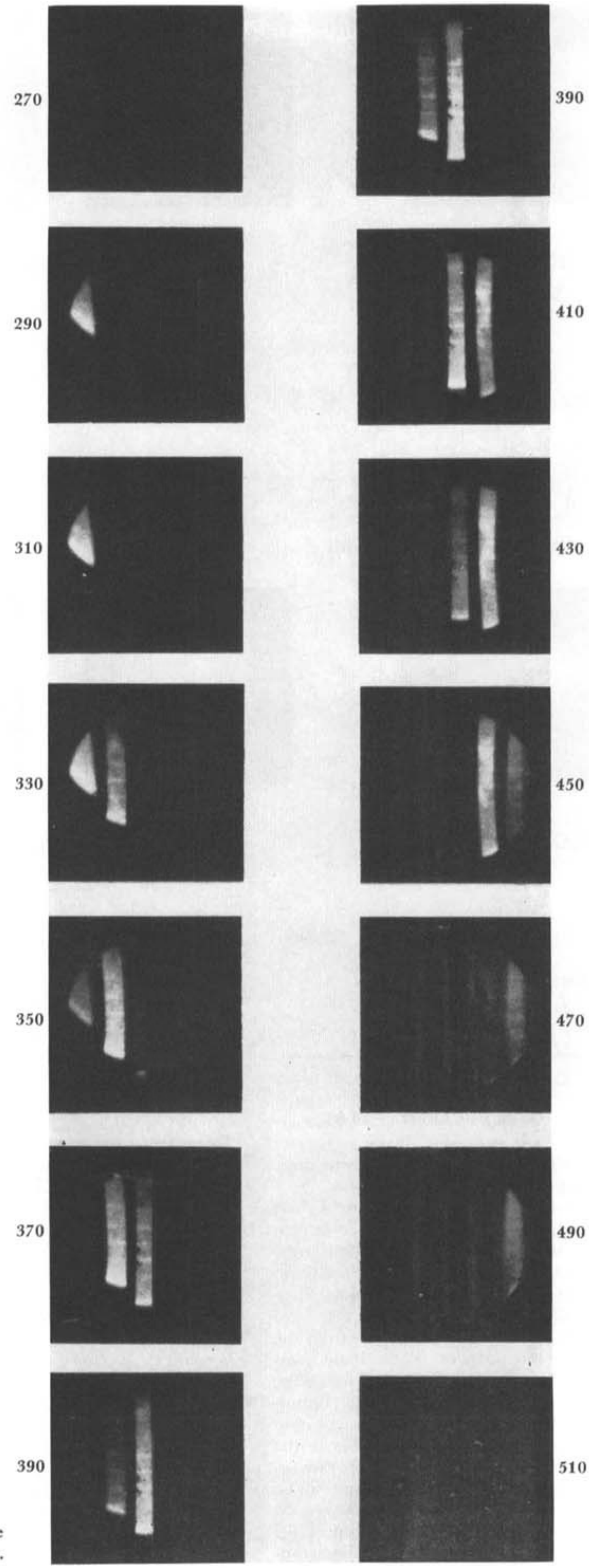


Fig. 12. The results of delay time variation; 50-nanosec exposures.

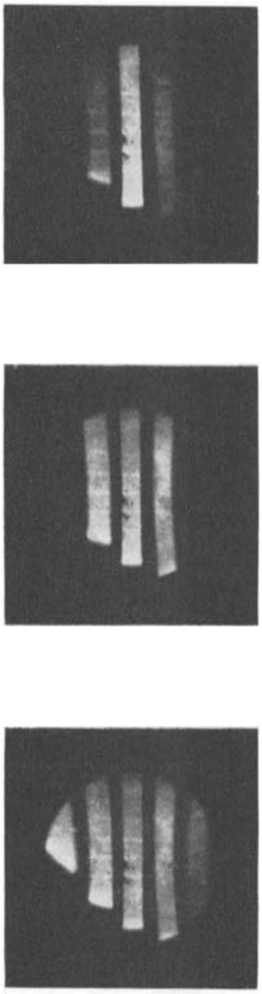


Fig. 13. The effect of exposure length: top, 50-nanosec exposure— 400-nanosec "delay"; center, 100-nanosec exposure— 370-nanosec "delay"; bottom, 200-nanosec exposure — 320-nanosec "delay."

would expect. This will be noticed more in some later illustrations.

In Figs. 9 and 10, the illuminated particles are nearly all within the camera field of view and the low signal-to-noise ratio now completely destroys the image. Twelve shots are still required to illuminate the target sufficiently for an open shutter exposure. However, since the noise resulting from twelve shots overexposes the film, fewer shots were tried to see if an image could be brought out. In these two illustrations, the value of the range gating becomes very obvious. Note that the noise light can be gated out even when the last screen is only 20 ft from the resolution chart.

Figure 11 shows the effect of natural lighting or daylight conditions. For these pictures the screens are placed at 50-ft intervals or approximately even spacings from the camera to the resolution chart. All the lights in the range were turned on, giving the snow and the chart approximately equal illumination levels. Figure 11A shows the normal image with nearly zero signal-to-noise ratio. Figure 11C shows a range-gated picture similar to those of Figs. 6 through 10. Figure 11B merely verifies that, during the 1.8 μsec the camera shutter is open, the range lights or natural lighting has a negligible effect in forming the range-gated picture in Fig. 11C. Therefore, the technique is equally valid in improving visibility under most natural lighting conditions.

Determination of Distance to Imaged Objects

In order to show that an application such as the contour mapping mentioned above is feasible, a target object with "depth" was devised. Five vertical white slats of sufficient height to intersect the laser beam were inserted in the camera field of view to give the image shown at the left of Fig. 12 when illuminated by a laser shot. The slat to the left is 210 ft from the camera and each successive slat is 20 ft more distant, the one at the right being 290 ft from the camera. The effect of the laser beam converging from above is quite apparent in this picture. Although the laser beam is symmetrical about a vertical axis in this picture, it appears shifted to the right since it strikes the first or left slat higher than the second, the second higher than the third or center slat, etc. All slats are not in sharp focus because the depth of field is not very great with this object distance. This effect would be reduced with the greater distances which would occur in a likely system.

The two columns of pictures in Fig. 12 show the change in the image as the delay time is altered. Again, the relative delay is shown rather than the total actual delay. The 390-nanosec picture is repeated to give continuity in the two columns. Each slat appears at least faintly in five frames of the original photographs. This is in accord with the fact that a 50-nanosec shutter pulse may be shifted 110 nanosec with respect to a 60-nanosec light pulse, while maintaining some transmission. This is reduced from a possible six exposures spaced at 20 nanosec to the five mentioned above when one considers that 20 to 30 nanosec of transmission are required to produce an image.

The last few pictures of the series appear somewhat different because the back wall at just over 290 ft falls within the acceptable range and begins to appear in the image.

Figure 13 shows the effect of increasing the shutter pulse width and thus spreading the "depth" of the image. The delay was adjusted to keep the center slat in the center of the acceptable ranges.

Summary

It has been shown that a Q-switched laser may be used to illuminate the field of view of a camera or other imaging device such that a shutter properly timed will admit only light reflected from objects in a certain range interval and thus limit the image to objects within this interval. The timing of present lasers and shutters allows the range interval or range resolution to be tens of feet. It is not inconceivable that resolutions or interval lengths of near-future systems could be reduced to the order of feet.

Two rather interesting applications of this technique are (1) the elimination of noise light backscattered from atmospheric particles such as rain or snow, and (2) the insertion of range information into an image such as the elevation contours in an aerial photograph. Both systems appear to be immediately feasible, being limited only in range and field of view by the output energy from the lasers presently available.