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PHOTOGRAPHIC MEASUREMENTS OF THE ENERGY DISTRIBUTION IN THE BEAM OF A RUBY LASER[1]

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26252

Abstract. The beam of a Q-switched ruby laser was directed toward a diffusely reflecting target at a distance of about 1/2 mile. The image on the target was photographed with a hand camera and the resulting films were measured with a microdensitometer. Two stop-openings were used for the photographs. The films exposed with the smaller stop-opening showed concentrations of energy with intensities up to 700 times the background energy. These concentrations are probably representative of the actual laser beam but they could be diffraction effects caused by irregularities in the surface of the diffuse target. The films exposed with the larger stop-opening were used to measure this background energy. Its average value was about half the nominal value of the energy determined from calorimetric measurements. This factor of one-half may be the combined effect of several losses that were neglected in the photometric measurements. The angular divergence of the beam was also measured.

1. Introduction

An experimental optical radar system is in operation at the Smithsonian astrophysical observing station, Organ Pass, New Mexico. This system uses a Q-switched ruby laser to generate a narrow light beam that can be reflected from the BE-B, BE-C, and GEOS Satellites.

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[1] This work was supported by grant NsG 87-60 from the National Aeronautics and Space Administration.

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The laser was built by the Reentry Systems Department, General Electric Company, Philadelphia, Pennsylvania. From a number of measurements they determined that the nominal values of its energy and beamwidth are 0.5 j and 1 mrad. They measured the energy with a calorimeter and determined the beam divergence from the size of a hole burned by the focused beam.

We measured the energy and the divergence of the laser beam photographically. These measurements were made for the following reasons:

1. The large size of the photographed image facilitated an accurate determination of the divergence of the beam.
2. The photographed image gave a visual presentation of inhomogeneities in the energy distribution of the laser beam.
3. The film used in photographing the beam was the same as that used in the Baker-Nunn camera. Thus the energy transmitted toward and received from the satellite could be measured with the same emulsion.

The photographs of the laser beam were obtained from a diffusely reflecting surface at a distance of about 1/2 mile from the laser. The camera was 14 to 16 ft from the surface.

2. Method

If E is the energy in the laser beam, and A is the area of its image on a diffuse reflector, the brightness (Strong, 1958) of the reflection is

$$B = \frac{E}{\pi A} \quad , \tag{1}$$

if the reflecting surface absorbs none of the light directed toward it. The image at the film of a camera photographing this reflection will have the same brightness (Jenkins and White, 1957). Consequently, the energy in the image is

$$E' = B \omega A' \ , \tag{2}$$

where A' is the area of the image on the film, and ω is the solid angle of the camera's aperture at the image. The value of ω is determined by the following relation:

$$\omega = \frac{\pi d^2/4}{f^2} = \frac{\pi}{4F^2} \ , \tag{3}$$

where d is the aperture of the camera, f is the focal length of the camera, and F is the f-number of the camera. The camera is assumed to be near the axis of the laser beam.* Equations (1), (2), and (3) in combination give the following relation between the energy in the beam and the energy incident on the film:

$$E = \frac{4A\,F^2}{A'}\,E' \ . \tag{4}$$

Let us now estimate what f-number is required of the camera. From the characteristic curves of Kodak-2475 recording film (used in the Baker-Nunn camera) we obtain a sensitivity of 1.6 at a wavelength of 6943 Å. This value is equivalent to 2.5×10^{-5} j/m^2. The energy

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*In practice, the camera was 20° to 30° off axis.

of the Q-switched laser has a nominal value of 0.5 j. The area of the image on the diffuse reflector at 741 m from the laser should be about 0.5 m^2 for a beamwidth of 1 mrad. With these values, equation (4) shows that the f-number of the camera should be about

$$F = \frac{1}{2}\left(\frac{E}{A} \cdot \frac{A'}{E'}\right)^{1/2} = \frac{1}{2}\left(\frac{0.5}{0.5} \cdot \frac{1}{2.5 \times 10^{-5}}\right)^{1/2} = 100$$

for a detectable image. This value is based on a uniform cross-sectional energy distribution.

In practice, a smaller f-number (f/9) was used to obtain a well-exposed image for measuring the shape and divergence of the beam, and a larger f-number (f/225) was used to show high-density concentrations of energy within the image. The camera was a Tower[*] Model 8 box camera. Its aperture is 0.5 inch and its focal length, 4.5 inches. A diaphragm with a 0.020-inch diameter hole was used to obtain the f/225 opening.

The target was made of plywood and painted a flat white. Such a surface should be effectively diffuse (Hurlbut, 1966). The target was square--6 × 6 ft. Its distance from the laser, as measured with a geodimeter, was 741.06 m.

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[*] Manufactured by Sears Roebuck and Company.

3. Measurements

Figure 1 shows two photographs of the laser's image on the diffuse reflector. Each image corresponds to a single Q-switched pulse of the ruby laser. Six other similar photographs were obtained. We measured the major and minor axes for each image, using the 6-ft side of the reflector to determine the scale. The results of the six measurements were the following:

major axis: 0.85 ± 0.02 m ,

minor axis: 0.75 ± 0.03 m .

Using 0.80 m for the average diameter of the beam and 741 meters as the distance between the laser and the target, we obtained the following value of the beam divergence,

$$\theta = \frac{0.8}{741} \doteq 1.1 \text{ mrad.}$$

The density distributions of the images on the film were measured with a Joyce Loebl double-beam recording microdensitometer. The results are shown in Figure 2 for the photographs corresponding to Figure 1. A square aperture 50 μ on a side was used to scan the major and minor axes of the beam's cross section. Exposure levels are shown in the figure. The microdensitometer was used to measure a piece of the same film, which was exposed with a Kodak sensitometer. The lamp in the sensitometer gave an exposure of 170 m-c-s or 0.825 j/m. The microdensitometer measurements, the known densities of the various strips on the sensitometer wedge, and the exposure of the lamp gave the information for calculating the exposure levels.

We obtained the total energy in the beam by integrating in the following approximate manner. We used the exposure levels corresponding to known points on the sensitometer wedge to construct stepped outlines like the ones shown in Figure 3. If the beam is assumed to have a circular cross section, these outlines divide it into rings of constant energy density. The total energy is obtained by addition of the contributions from each ring; the results are then averaged from the measurements along the major and minor axes. The results from six photographs give the following value for the beam's average energy:

$$E = 0.22 \pm 0.04 \text{ j} \quad ,$$

where the error is the average deviation in the six measurements. To calculate the energy, the film's sensitivity to white light is assumed to be equal to its sensitivity to light at 6943 Å. We then made the conversion between visual and physical units by equating 206 m-candle-sec to 1 j/m^2.

The value of the measured energy is about half the nominal value of 0.5 j. This result may represent an accumulation of errors, or an explanation may be found in the small, high-intensity spots that are dispersed throughout the beam. These regions are shown in Figure 4, where the photographs were obtained with a stop opening of f/225. They do not show up in the other photographs because the latitude of the film is not sufficient to reveal them. Figure 5 shows measurements that were made with the microdensitometer on several of the brightest spots. Additional measurements were made on six other similar photographs.

The brightest spots had 100 to 700 times the average energy density obtained from photographs with the f/9 stop opening. These spots may result from inhomogeneities in the ruby crystal, from the mode structure of the laser's Fabry-Perot reflecting cavity, from atmospheric turbulence, or from diffraction effects associated with irregularities in the surface of the diffuse target. They may account for the difference between the nominal value of the energy and the photographic value obtained with the f/9 opening.

It may be concluded that the photographic measurements confirm the nominal values of the laser's energy and beamwidth within the error that may be expected from the present experiment.

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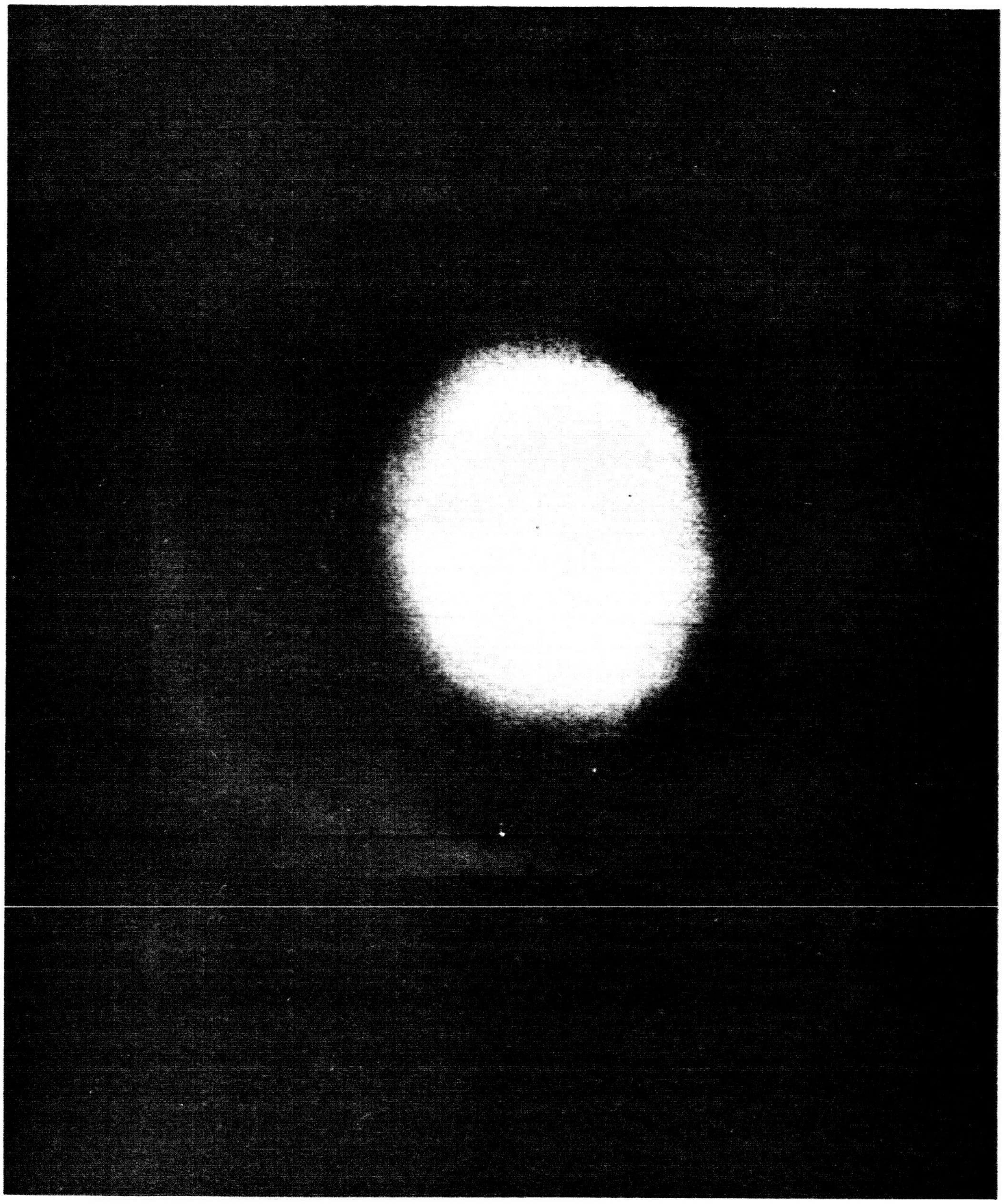
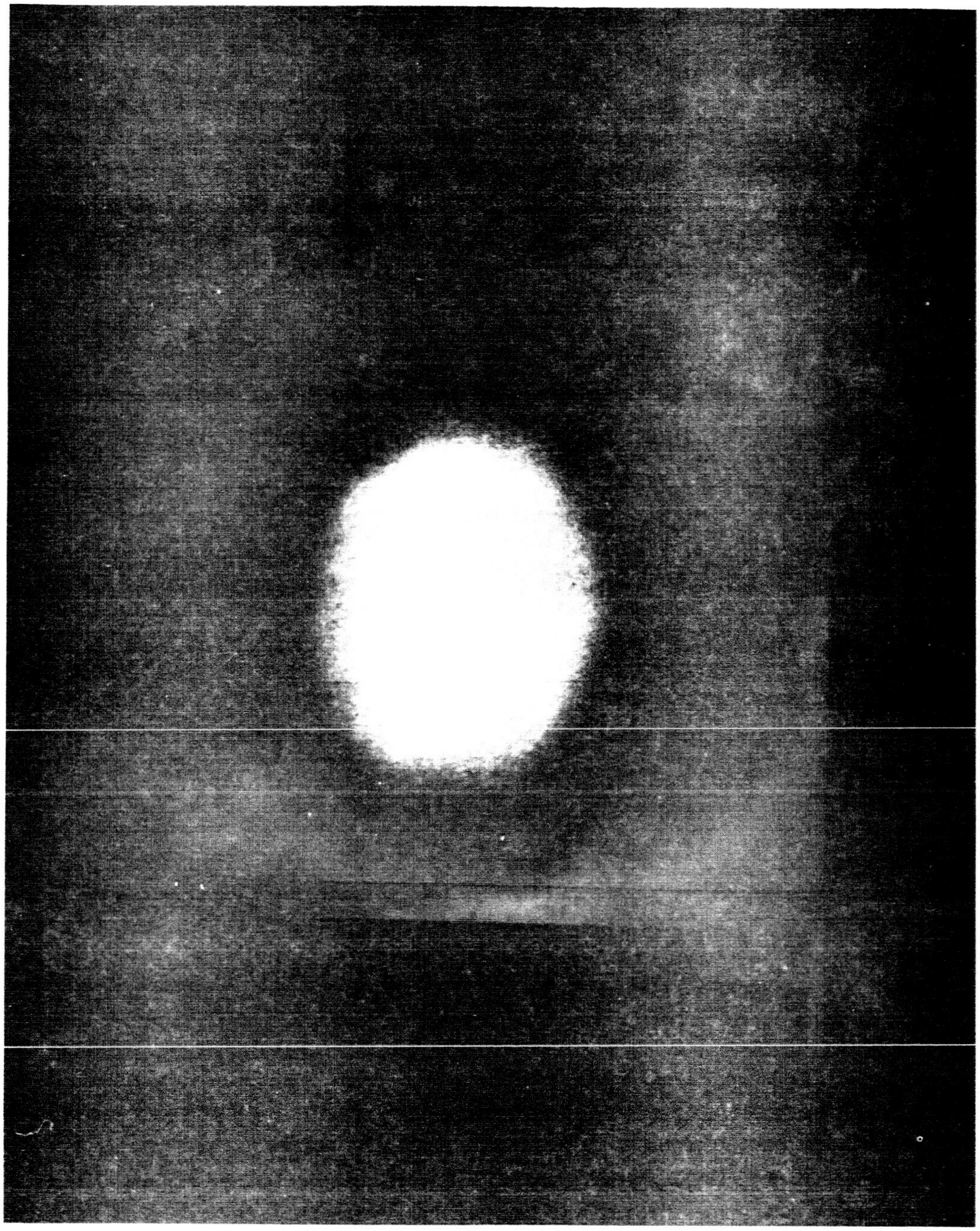


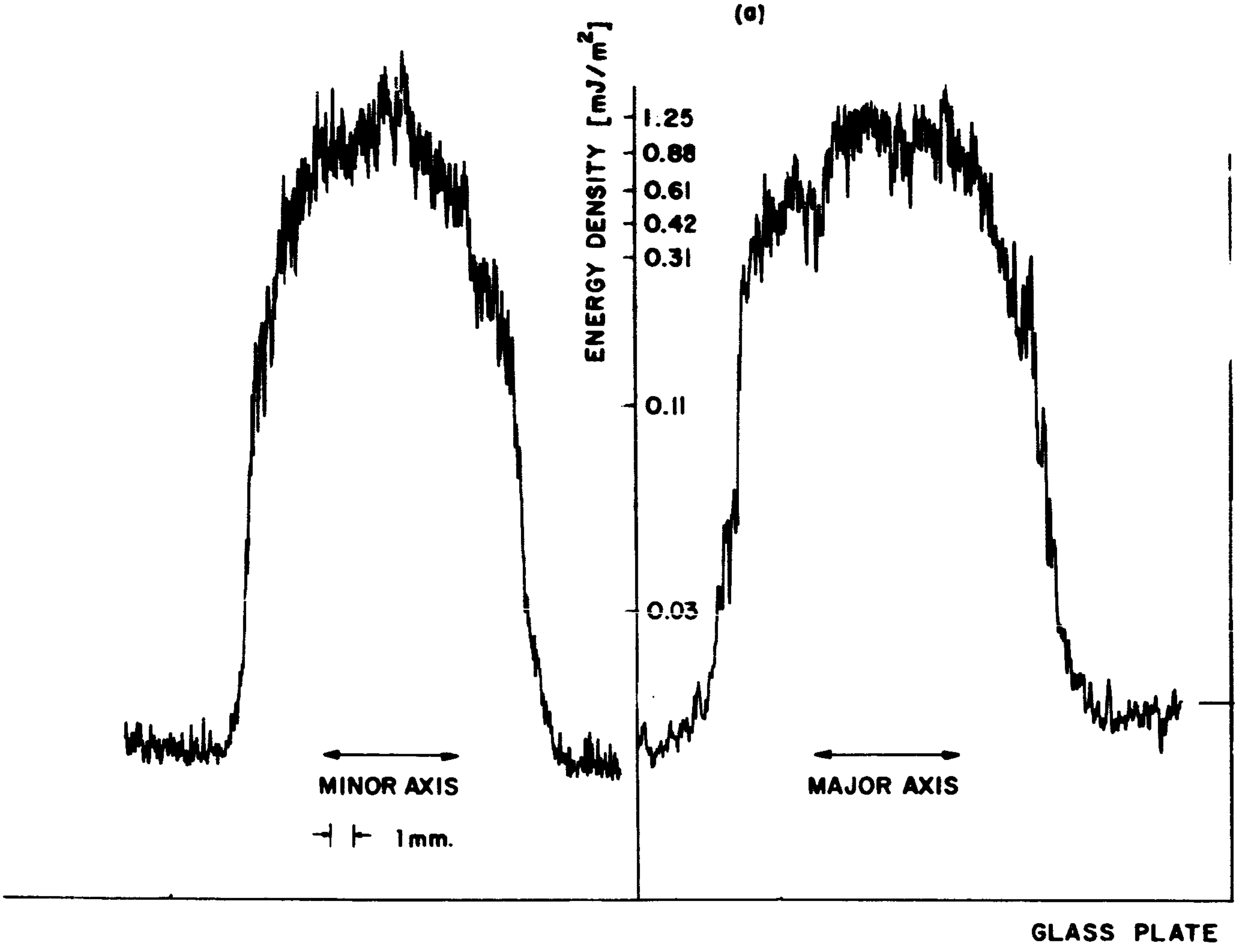
(a)

Figure 1. Two photographs of the laser's image on the diffuse reflector. (The stop opening was f/9. The 6- × 6-ft target was illuminated with a flashlight. The film is enlarged about 5 times.)



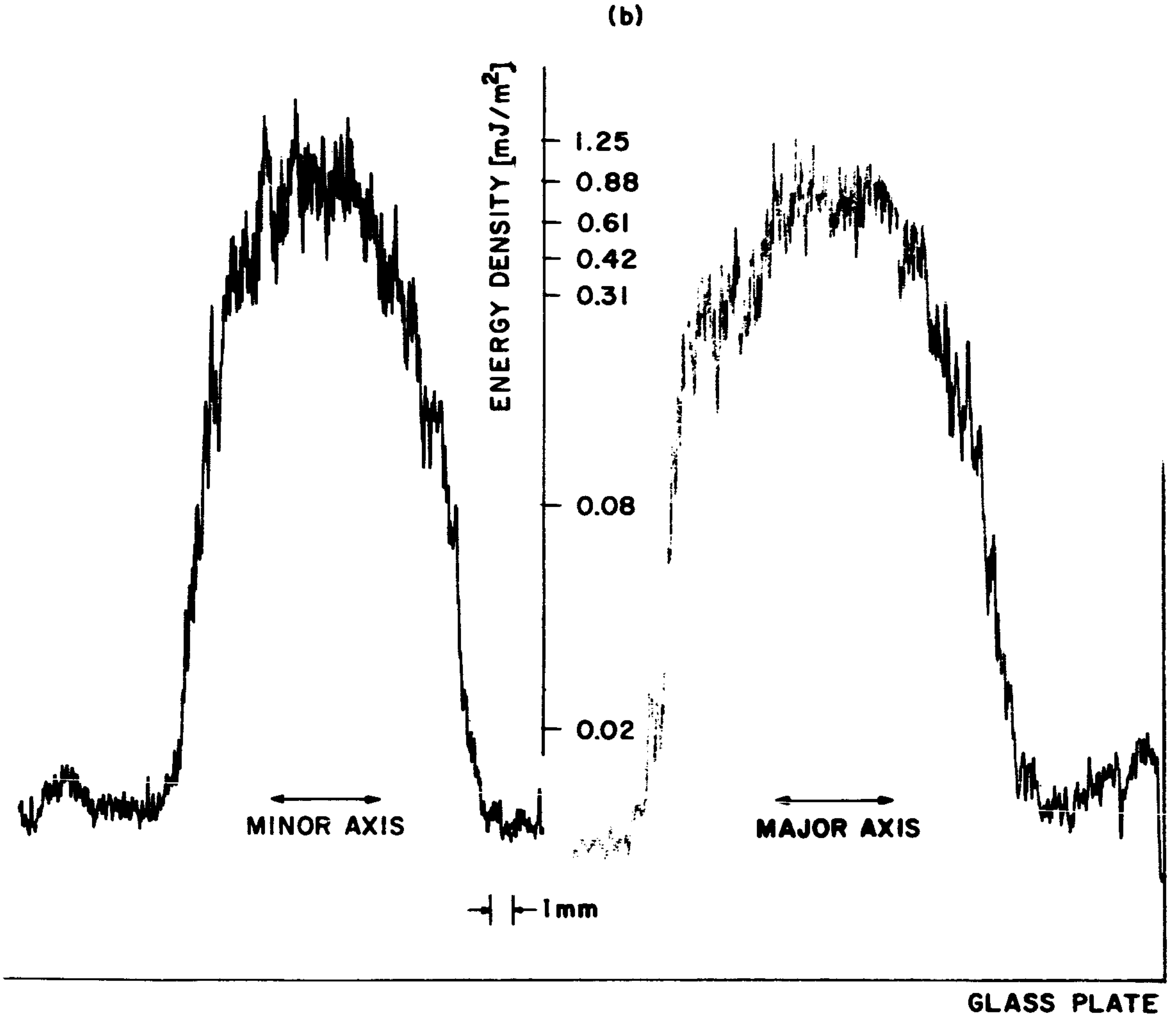
(b)

Figure 1. (Continued)



(a)

Figure 2. Energy distributions within the images shown in Figure 1.



(b)
Figure 2. (Continued)

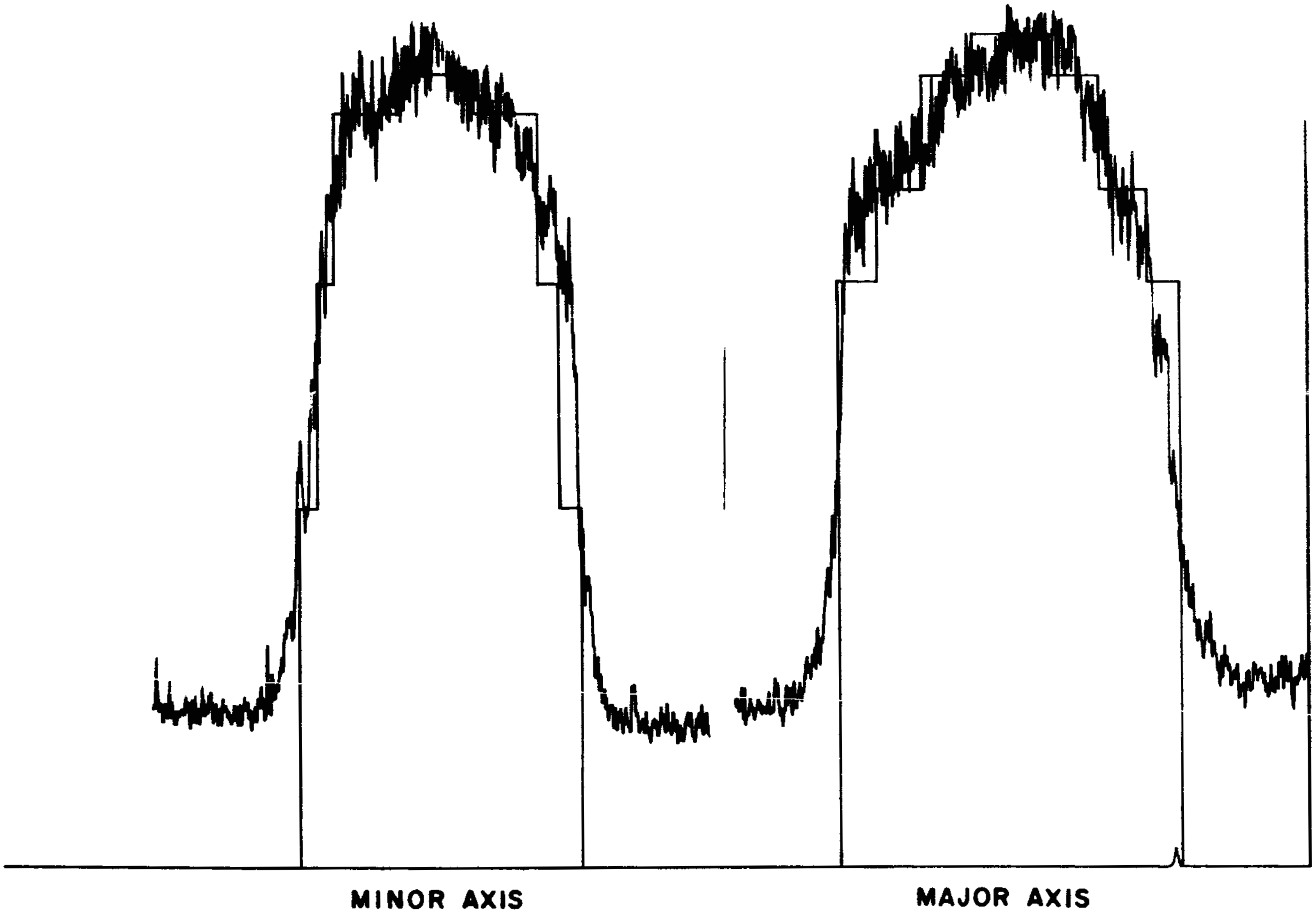
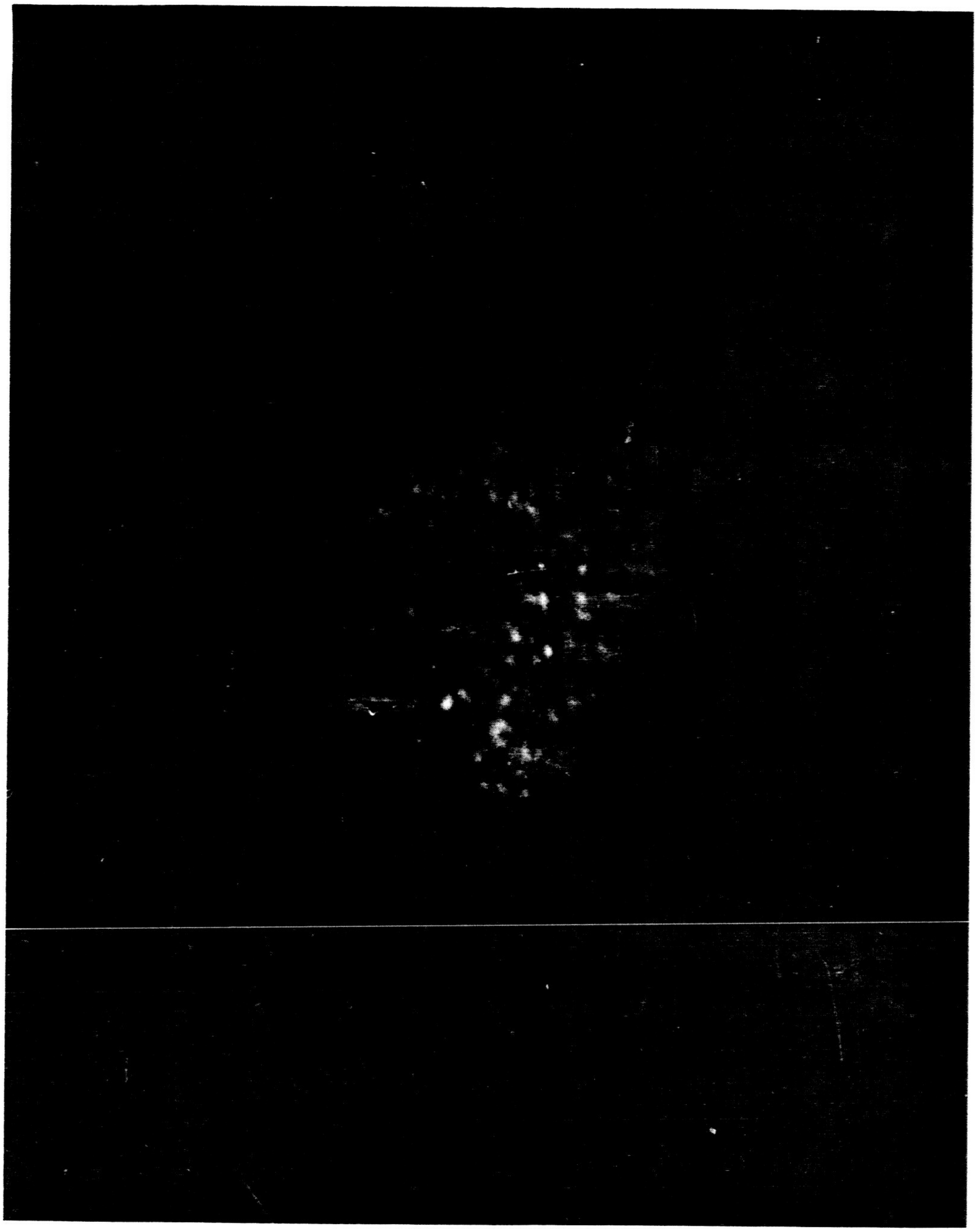
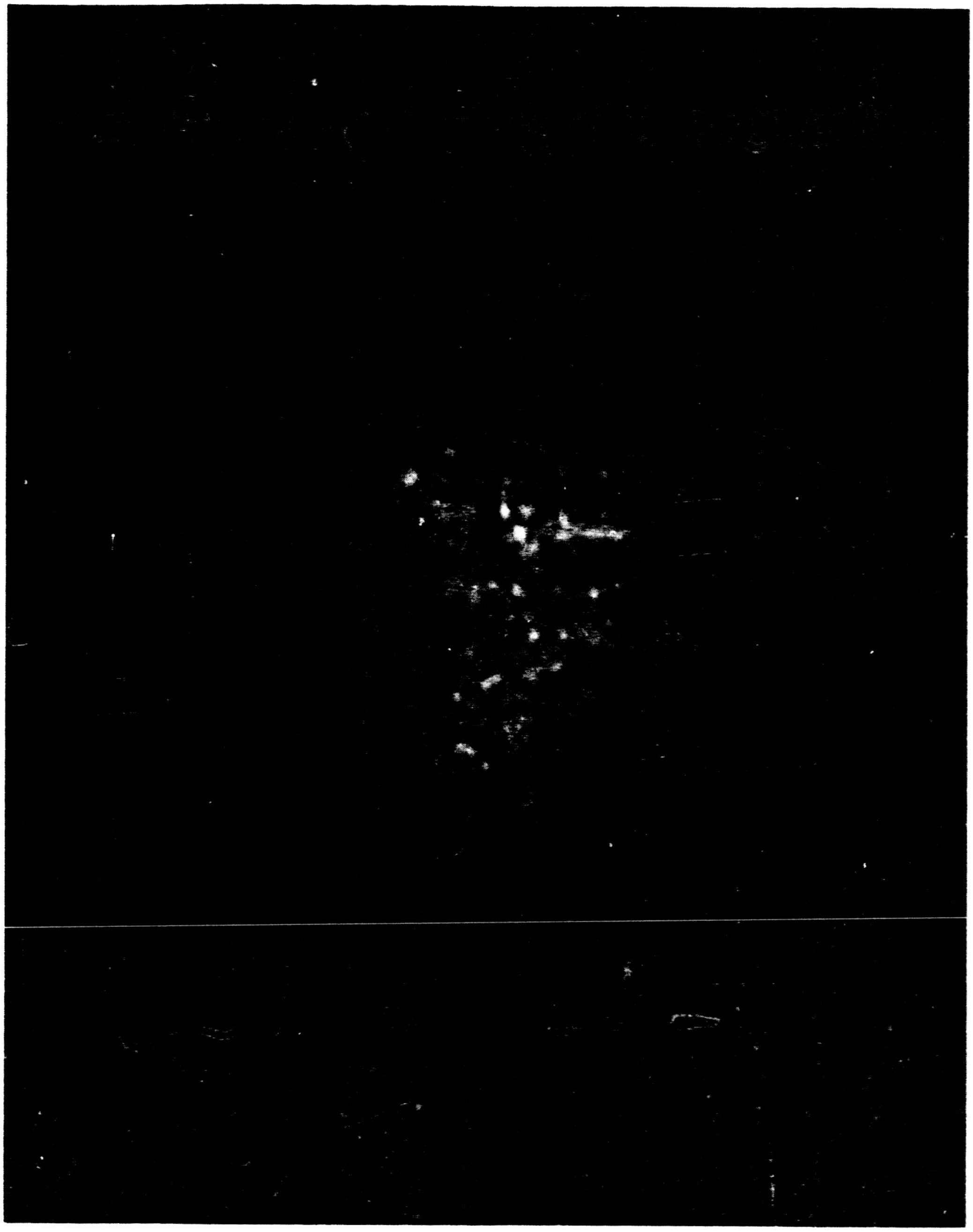


Figure 3. Stepped approximation used in integrating the energy distribution of the laser image.



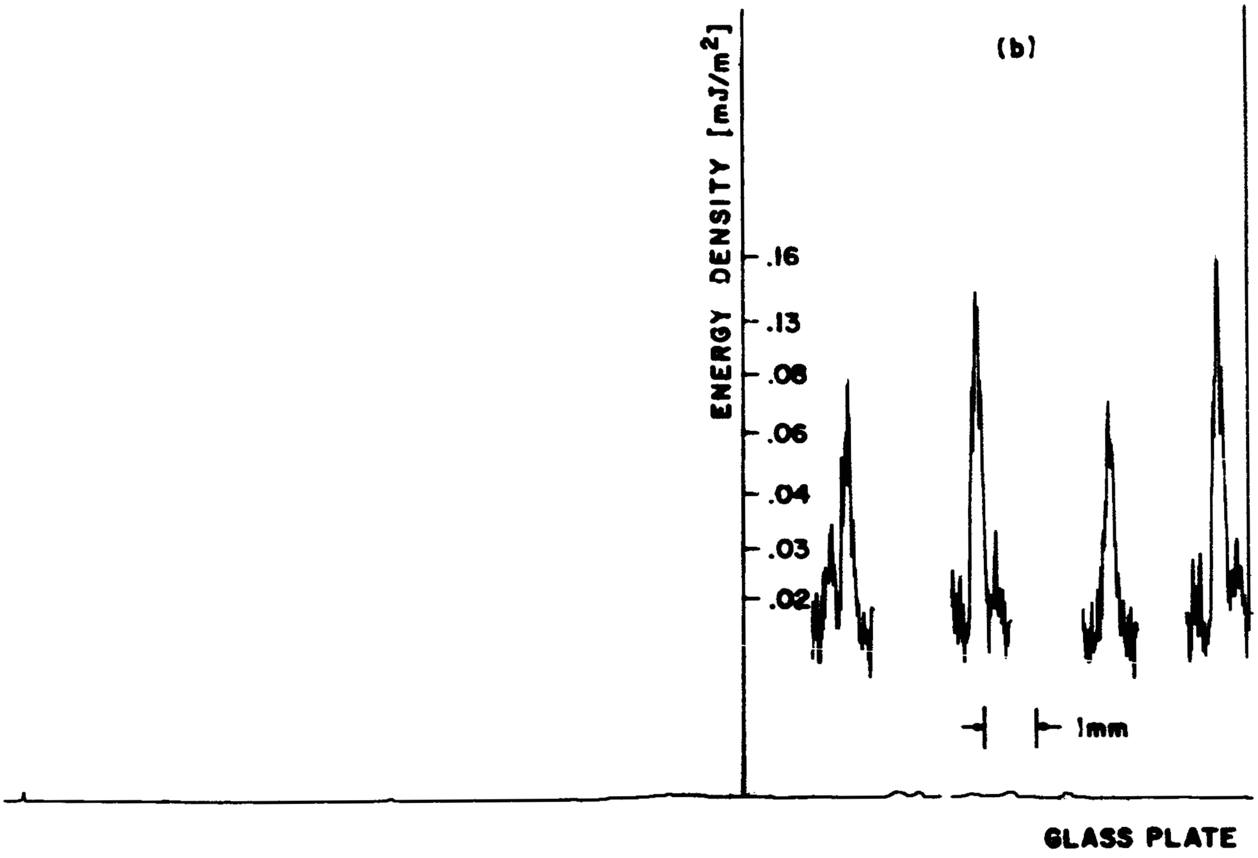
(a)

Figure 4. Two photographs of the high-intensity regions of the laser beam.



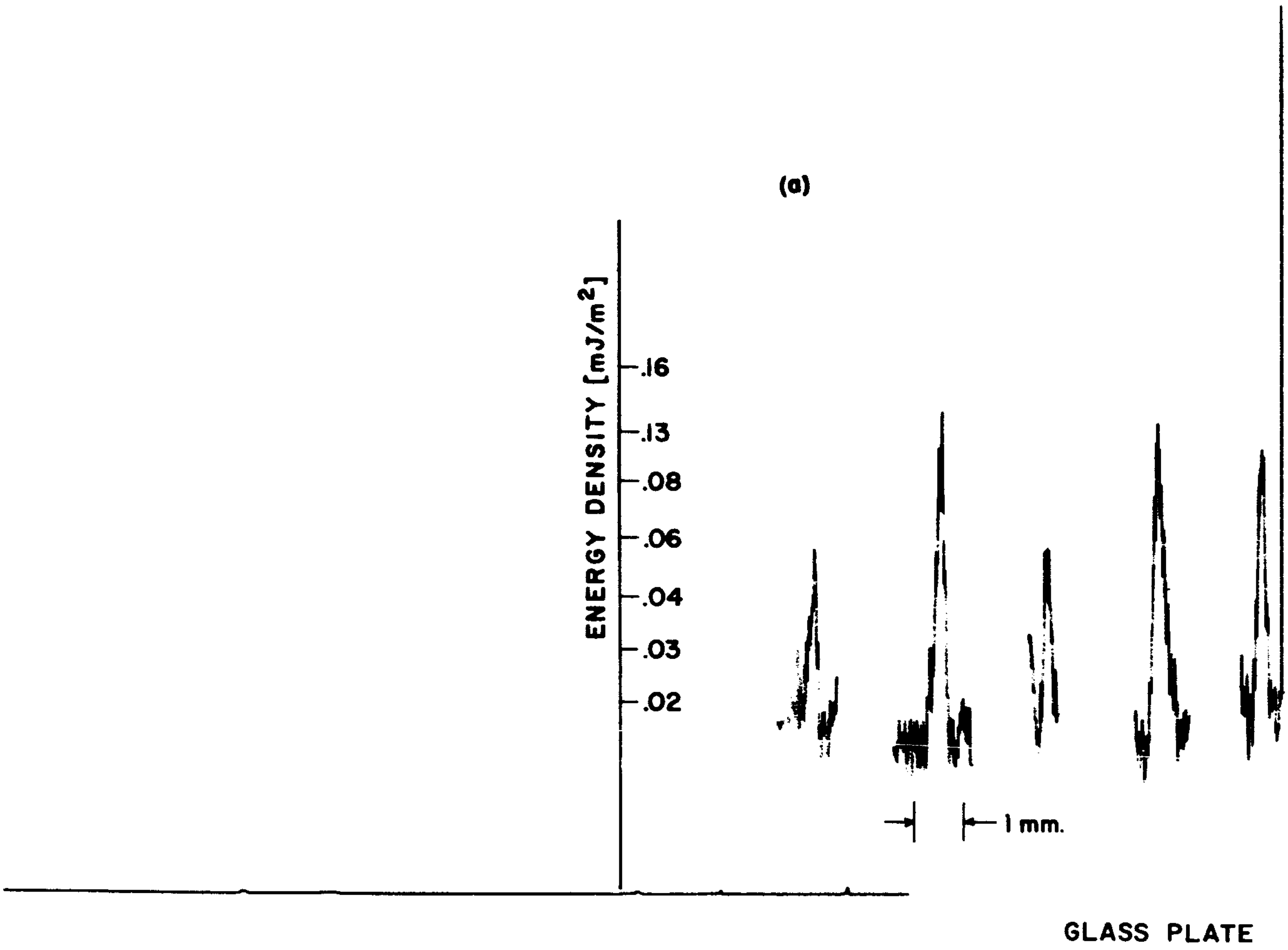
(b)

Figure 4. (Continued)



(a)

Figure 5. Microdensitometer measurements corresponding to a few of the brightest spots shown in Figure 4.



(b)

Figure 5. (Continued)

NOTICE

This series of Special Reports was instituted under the supervision of Dr. F. L. Whipple, Director of the Astrophysical Observatory of the Smithsonian Institution, shortly after the launching of the first artificial earth satellite on October 4, 1957. Contributions come from the Staff of the Observatory.

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