MEMORANDUM

Apr. 3, 1964

To:
From:

Subject: Prototype enlarger exposure requirements

The following notes relate to exposure times and illumination requirements to be expected with the laser and with the alternate source.

Laser Source

The lateral energy distribution over the unaltered laser beam is very non-uniform, (probably Gaussian - Ref.1). If a diffuser, wobble plate or other means of reducing coherence is used, the evenness of illumination generally improves over the collimated area, but generally at the expense of intensity at the film gate. In either case it is necessary to considerably overfill the film gate in order to obtain sufficient uniformity of illumination.

We can set up a constant, C_A (dimension cm^{-2}) which collects the area coverage factor, transmission of the diffuser (if used), and the minor factor of condenser and collimator transmission, the definition being implied from:

$$H_o = P \times C_A$$

where H_o is the irradiance at the object plane in $watts/cm^2$
P is total power output from one end of the laser.

The value of C_A will vary with the type of diffuser used, and possibly with laser mode in the absence of a diffuser, but in other respects will remain fixed for any given equipment and will provide a figure for film gate irradiance from a bolometer measurement of the laser output.

The numerical value of C_A can be determined experimentally in the equipment by substituting an aperture mask of known area at the film gate (object plane, Fig. 1). This aperture should represent the area over which the illumination can be considered to be uniform, and might for example be the inscribed circle of the square gate area. The light flux concentrated at the plane of the spatial filter is then compared to the total flux out of the laser by any convenient photo-cell means, providing a ratio R (less than unity), the value of C_A being found from:

$$C_A = R/T_1 A$$

T_1 being the measured transmission (see below) of the projector lens, L_1, and
A the measuring aperture area in cm^2.

Measurements made on the breadboard produced values of C_A of .0476 cm^{-2} for the laser source without any diffuser, and .0127 cm^{-2} with the combination of the sandwiched rotating diffuser and clear plastic film which provided suitable freedom from image noise at about 5% loss of coherence. The mask used at the time had an aperture diameter of 1.50 inches, and thus an area of 11.4 cm^2 which was perhaps too large to be representative of the one inch square breadboard gate. The values will be somewhat lower on the prototype due to the greater gate area, but some improvement in efficiency of the diffuser can be expected.

An alternate method of obtaining object plane irradiance is to make a bolometer measurement at the spatial filter position, using the aforementioned test aperture in place of the film gate. It may be mentioned here that the laser beam makes transmission measurements of any optical component or combination extremely easy by comparative photo-cell measurements at convenient points on the axis, particularly when the condenser and collimator are removed.

Knowing the irradiance H_0 at the object plane (without film gate glass) the corresponding irradiance at the camera back is:

$$H_f = \frac{H_0 T_s T_0}{M^2}$$

where T_s is the transmission of the system including lenses L_1 and L_2, film gate glass and filter plane glass if any.
T_0 is the transmission of the areas of interest of the object film.
M is system magnification.

The ratio T_s/M^2 will be fixed for a given system and can be called K_s, thus:

$$H_f = K_s T_0 H_0 \quad (1,a \qquad \text{or} \qquad H_f = K_s T_0 P C_A \quad (1,b$$

The above expressions can be used in determining the required exposure times when film sensitivity data is known. Since the laser and any other source usable with the enlarger is essentially monochromatic, the data can be taken directly from the spectral sensitivity curve for the film used. This curve provides data in terms of the reciprocal of the flux density times exposure, in ergs, or energy density required to produce a film density of 1.0 above gross fog at the wavelength selected. By conversion from ergs to watt seconds:

$$H_f S t = 10^{-7}$$

where t = exposure time in seconds.
S = film sensitivity at selected wavelength

Then from 1,a and 1,b

$$\frac{1}{t} = K_s T_0 H_0 S \times 10^7 \quad (2,a \qquad \text{or} \qquad \frac{1}{t} = K_s T_0 P C_A S \times 10^7 \quad (2,b$$

Much of the breadboard experimental work was done using Eastman Aerial Film type No. 4404, selected for suitable response at the laser wavelength, very high resolution and availability in standard 35 mm size. The sensitivity of this film at 6328 A° as derived from the published curve is 0.2 reciprocal ergs/cm². The best available figures as measured from breadboard work or estimated, for substitution in the above are:

$K_s = T_s/M^2 = 0.9/16 = .056 \qquad T_0 = 0.5$

$P = 0.5 \times 10^{-3}$ watts $\qquad C_A \cong .05\ \text{cm}^{-2}$ (full coherence)

$\log S = \bar{1}.3 \qquad S = 0.2\ \text{cm}^2/\text{erg}$

Whence, from (2,b

$$1/t = .056 \times 0.5 \times 0.5 \times 10^{-3} \times .05 \times 0.2 \times 10^7 = 1.4$$

and $t = 0.71$ seconds

This figure is compatible with experimental results obtained on the breadboard, where many satisfactory exposures under conditions as described were made at an exposure time of one second. Probably the greatest uncertainty at present is the actual power output of the laser, and arrangements should be made to procure a bolometer or calibrated cell to resolve this.

Alternate Source Considerations

The photometry of the more conventional types of lamps which might be considered for the alternate source differs basically from that applicable to the laser. The laser affords its maximum energy for film exposure when used at full coherence, and any means used to reduce coherence will in general increase the required exposure time. A conventional source, on the contrary, if arranged to produce a coherence approaching unity, results in impractically long exposure times (Ref. 2). The exposure time is reduced as the square of the relaxation from full coherence.

Incandescent Lamp Source

A possible source of this type may consist of a projection lamp, arranged for reimaging of the filament at a variable iris aperture, which is then considered as the secondary (reimaged) source (see Fig. 2.). The spectral band width of the radiation is finite, but due to the lack of chromatic correction in the optical system as well as for coherency considerations this band width must be limited by a "spike" filter to a 50% width of 100 A° or less.

However, the filtered lamp can be considered to be monochromatic from the standpoint of obtaining radiance conversion data without the necessity for integration, and the total radiance can be considered to be a linear function of the limited band width, i.e. : $N' \equiv N(\Delta\lambda) \quad \left(\frac{\text{watts}}{\text{cm}^2 \text{ steradian micron}}\right)$

If the source is a typical projection type lamp with interlaced filaments and a reflector is provided, the filament packing factor may be about 0.8 From the radiation curve or tables for tungsten (Ref.3, for example) it is found that the emittance at an operating temperature of 3000 degrees K in the region of 6328 A° is: $W(\Delta\lambda) = 80$ watts/cm² micron
and the radiance is then $N' = \frac{0.8 \times 80}{\pi} = 20.4 \frac{\text{watts}}{\text{cm}^2 \text{ micron ster.}}$

Using coated reimaging optics (L_r in Fig. 2) of adequate numerical aperture, radiance from the iris is substantially that of the lamp, (and independent of the magnification of the reimaging optics). The iris is at the focus of a collimator lens system of focal length F_c, and represents a small but finite source of area A_i at an effective distance of F_c from the object plane (film gate), where the irradiance is then:

$$H_o = \frac{A_i N' \Delta\lambda}{F_c^2} \qquad (3,a$$

and also

$$H_o = \frac{A_t N' \Delta\lambda}{F_p^2} \qquad (3,b$$

where A_t = area of the iris image formed at the spatial filter plane
F_p = focal length of projector lens L_1
$\Delta\lambda$ = spectral band width

In the design of the prototype alternate source system, in order to obtain 25 % coherence reduction without excessive iris size it was necessary to add an auxiliary collimator element (Fig. 2) not used with the laser source to reduce the composite collimator focal length to 34 cm, the resulting maximum iris diameter then being 2.36 cm and the area 4.38 cm². (Ref.4)

Examination of the spectrophotometer trace of a 6328 A° spike filter previously used on the breadboard shows that this filter has an effective band width as adjusted to 100 % transmission of probably about 30 A° (.003 microns) and we might use this figure for typical exposure calculations.

Substituting the above values in equation (3,a :

$$H_0 = \frac{4.38 \times 20.4 \times .003}{1115} = 0.238 \ \frac{watts}{cm^2}$$

Transmission through the object film is essentially specular, with the amount of diffraction in terms of energy at angles greater than the angular aperture of lens L_1 being negligible. Then, repeating equation (2,a above:

$$\frac{1}{t} = K_S T_0 H_0 S \times 10^7$$

and if as before $K_s = .056$ $T_0 = 0.5$ $S = 0.2\ cm^2/erg$

then $1/t = .056 \times 0.5 \times 0.238 \times 10^{-3} \times 0.2 \times 10^7\ sec.^{-1}$ $1/t = 13.3\ sec.^{-1}$
and the exposure time $t = .075$ seconds.

Reducing the iris diameter to the point where a 5 % loss of coherence is obtained increases the exposure time to 1.87 seconds.

Vapor Lamp Source

STAT An [redacted] sodium vapor lamp was finally chosen for the prototype alternate source, as this provides a monochromatic light of sufficient intensity, and the wave length of 5890 A° is sufficiently close to the laser wavelength so that the optical corrections in lenses 1 and 2 are not violated.

STAT Catalog information on [redacted] lamps gives the luminous output in photometric units, i.e. brightness, but here again the conversion is facilitated by the monochromatic nature of the output. The brightness of the sodium lamp is given as 12 candles/cm^2 (12 lumens/steradian/cm^2). This energy is nearly all at the double line 5890–5896 A° which is isolated by an interference type filter, whose transmission is given by the manufacturer [redacted] as 65 %. STAT

From a curve of the standard visibility function (Ref. 5, for example), one obtains a visibility coefficient of 0.8690 at 5890 A°. Then, using values given above, the lamp (and iris aperture) radiance is:

$$N = \frac{12 \times 0.65}{680 \times 0.869} = .0132 \ \frac{watts}{cm^2\ steradian}$$

ILLEGIB In this case, [redacted] we have essentially monochromatic radiation and consider total irradiance:

$$H_0 = \frac{A_i N}{F_c^2}$$

where $A_i = 4.38\ cm^2$ (for 25 % coherence loss)
$F_c = 34$ cm (as above)

thus

$$H_0 = \frac{4.38 \times .0132}{1155} = .050 \times 10^{-3}\ watts/cm^2$$

Sensitivity of the Type 4404 film at 5890 A° is about 0.32 (somewhat higher than the sensitivity at 6328 A°) Then, from equation (2,a, using values as given above:

$1/t = .056 \times 0.5 \times .050 \times 10^{-3} \times 0.32 \times 10^7$ $1/t = 4.5\ sec.^{-1}$

and the exposure time $t = 0.33$ seconds (for 25 % coherence loss).

Coherence and Spatial Filtering

It might be of some possible interest to relate the exposure time directly to the degree of permissible departure from coherence and source emittance (for estended sources of the types considered in the last two sections. From equation (3,a :

$$H_0 = \frac{\pi r_i^2 N}{F_p^2}$$

where N = total radiance
r_i = radius of the iris image at the filter plane
F_p = focal length of the lens No.1

and for a Lambertian source:

$$N = \frac{W}{\pi}$$

$$\frac{r_i}{F_c} = \sin(K_i\lambda) \cong (K_i\lambda)$$

K_i a frequency in inverse of same units as λ

$$\frac{1}{t} = (K_i\lambda)^2 W K_s T_0 \; 5 \times 10^7$$

which can be expressed in terms of $E = r_i/R_i$ if desired where R_i = radius of filter plane aperture

the quantity E is the departure from coherence as used in the above.

It will be observed that nothing is mentioned in these notes with regard to expected exposures when spatial filtering is used. These will in general be much greater than the figures given, and of course dependent on the type of filtering and also on frequency content of the object, and should be considered in detail.

References:

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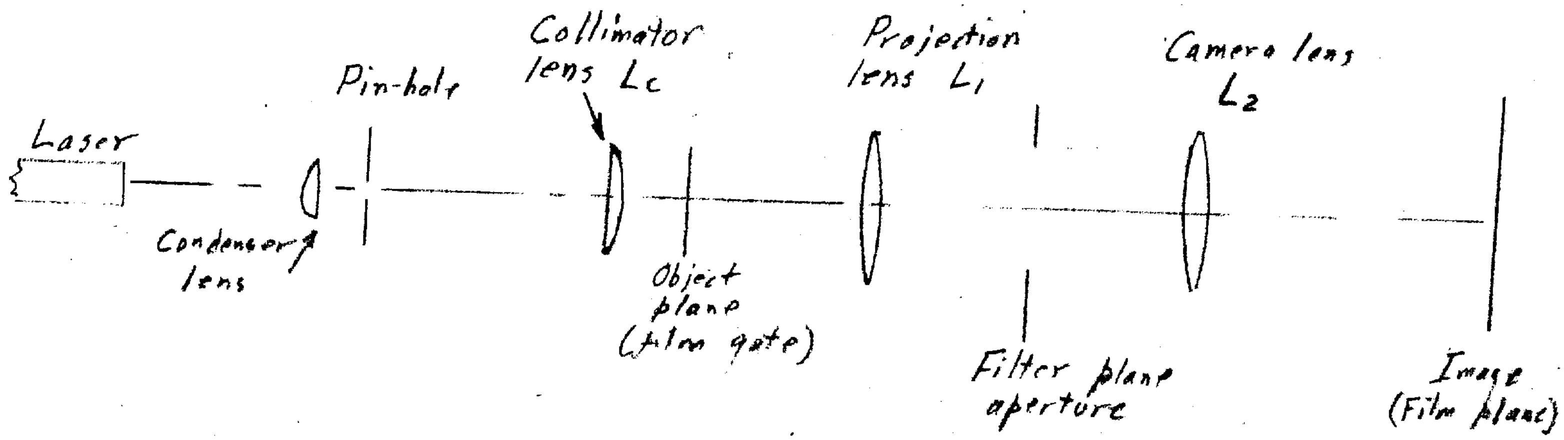

FIG. 1

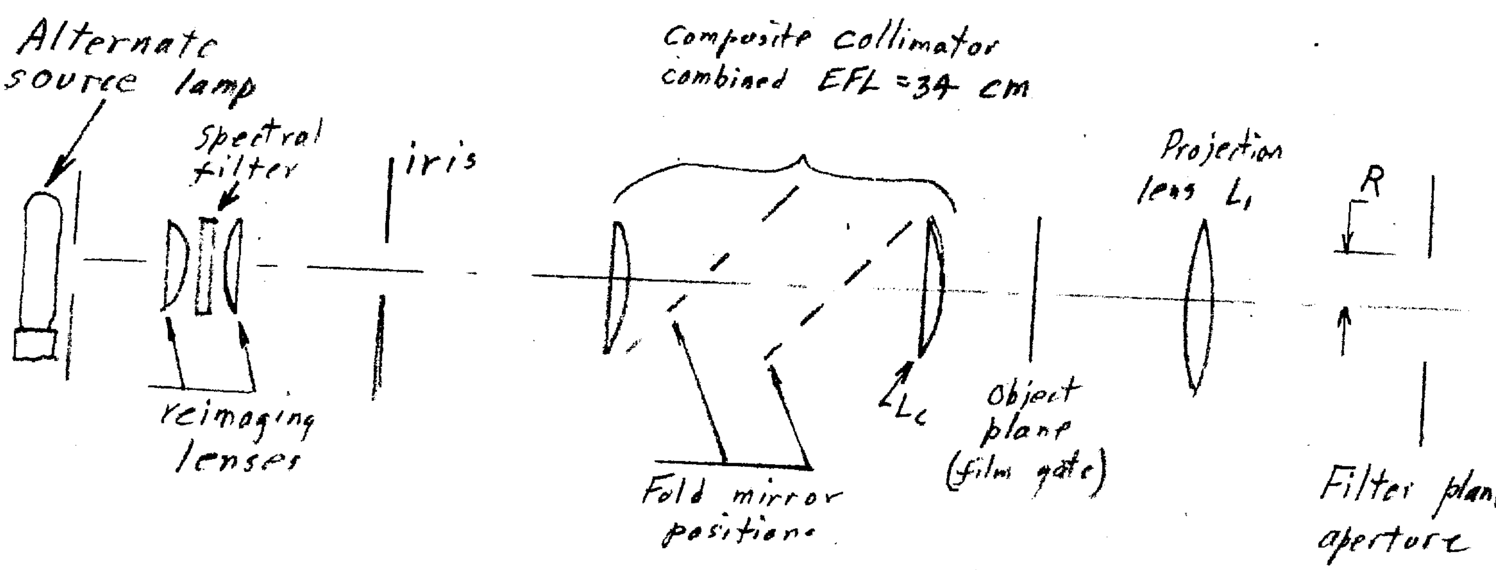

FIG. 2

(Lens L_2 & Film plane not shown)