THE ABSORPTION OF LIGHT BY FOG*

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(Received March 27, 1929)

ABSTRACT

Measurements between two stations 0.4 km apart with a thermocouple and galvanometer and with spectrograms, properly calibrated, of the absorption of light by fog for wave-lengths from 0.4 to 3μ showed that the absorption increased slightly with decrease in wave-length, but hardly enough to indicate that red light is appreciably better than blue light for the purpose of penetrating fog. For a fairly dense fog, such that in daylight dark colored objects at about 0.6 km could barely be be seen, the distances necessary to reduce the light to 10^{-2} of its original value were about 710, 843, 910, 970, 980 and 980 meters for wave-lengths 0.4, 0.5, 0.6, 1.0, 2.0 and 3.0μ, respectively.

NO QUANTITATIVE data appear to be available for the absorption of various wave-lengths of light by fog. In the present experiments the absorption by fog was measured for light in the region of the spectrum from 0.4 to 3.0μ and was found to increase slightly with decrease of wave-length, but hardly enough to indicate that red light is appreciably better than blue light for the purpose of penetrating fog.

The apparatus consisted of a transmitter and a receiver, 0.4 km apart with a fairly open field between them, situated on the banks of the Potomac River about five miles below the city of Washington. Although taken on land the measurements are considered to apply to fogs at sea, for it is thought, although it is not known with certainty, that the fogs, mists and vapors of the valley of the Potomac River near Washington have roughly the same optical characteristics as the fogs at sea and along the coast, Washington and its surroundings being less smoky than some localities. The transmitter was in a small shed about 3 meters above the level of the river and the receiver was on the top of a building about 15 meters high. A small Nichrome heating coil operated at a temperature of 940°K and placed at the focus of a 24 inch metal mirror served as a transmitter of infra-red rays in a band around 3μ. The calculated spectral energy distribution curve of a black body at 940°K is given in curve 3, Fig. 1; the dots along curve 3 are the relative spectral energies of the Nichrome coil measured with a calibrated infra-red spectrograph. To obtain a transmitter of spectrum bands around 1.4μ and around 0.6μ the Nichrome coil was replaced by a 2 kw tungsten lamp with a heat transmitting screen of black glass and a heat absorbing screen of pale bluish green glass, respectively. The observed spectral energy curves of the tungsten lamp through the two screens are given in curves 2 and 1, Fig. 1, respectively. The bluish green glass was slightly transparent from 2.0 to 2.4μ but the amount of energy transmitted in these wave-lengths was too small to affect the present measurements and to be percepti-

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ble on the scale of the drawing of curve 1. The transmitter was turned on and off by means of a shutter.

The receiver for measuring the 3μ, 1.4μ and 0.6μ bands was a 24 inch metal mirror at the focus of which was rigidly mounted a thermopile enclosed in a small metal box with a fluorite window transparent to about 8μ. The thermopile was connected to a galvanometer of moderate sensitivity with

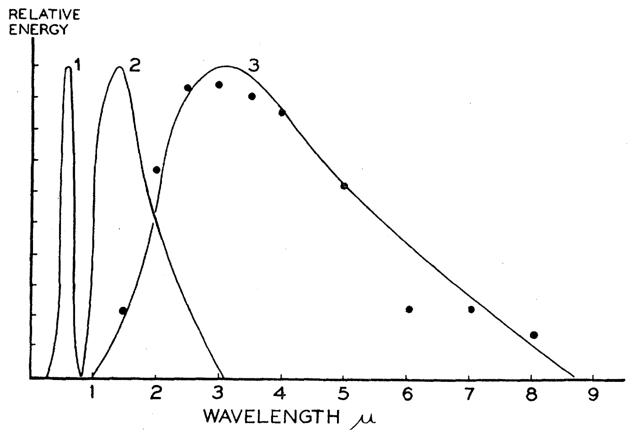


Fig. 1. Abscissas, wave-lenghts in μ; ordinates, relative energies in arbitrary units. Curve 1, tungsten lamp through bluish green heat absorbing glass; curve 2, tungsten lamp through black heat transmitting glass; curve 3, dots, Nichrome heating coil at 940°K, smooth curve, calculated black-body curve at 940°K.

a shunting resistance which could be varied to keep the deflections on the scale. For observing the intensities of wave-lengths in the visible spectrum a spectrograph was used. The transmitter and receiver were carefully focused at each other and the deflections for the 3, 1.4 and 0.6μ wave-length bands were observed on clear days, on days of fog and on clear days again.

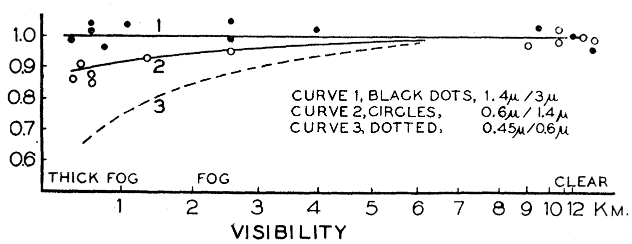


Fig. 2. Abscissas, the visibility defined as the maximum distance in km at which a dark object could be seen in the daytime; ordinates, the ratios of the intensity of one wave-length to another after transmission through 0.4 km of the atmosphere.

The deflections on clear days were reproducible within 10 percent for weeks at a time, and the ratios of the intensities $1.4\mu/3\mu$, $0.6\mu/1.4\mu$ were reproducible within ± 3 percent. Thus the change in the ratios with fog could be observed quite accurately. The ratios for atmospheric conditions during daylight of the past few months varying from clear to dense fog are given in curves 1 and 2, Fig. 2. It is seen that the ratio of the intensities $1.4\mu/3\mu$, shown by the dots and curve 1, remained constant when the atmosphere changed from clear to thick fog. The ratio $0.6\mu/1.4\mu$, shown by the circles and curve 2, decreased slightly with decreasing visibility. During several different periods of fog the ratios were the same, within experimental error, for the same conditions of visibility. This experimental result was hardly expected, for there was no reason *a priori* to suppose that all fogs were alike; they did seem to be alike as far as the foregoing ratios were concerned. However, as described later, the intensity ratios for wave-lengths in the visible spectrum differed a little for the various fogs. The fractions of the transmitted energy in the 3, 1.4 and 0.6μ bands arriving at the receiver through a fairly dense fog are shown by the three circles of Fig. 3. The scale of the abscissas below 1μ is spread out.

The intensities of the wave-lengths in the visible spectrum were determined by photographing with a spectrograph the spectrum of the unscreened tungsten lamp search-light. By means of a 90° quartz prism, which could

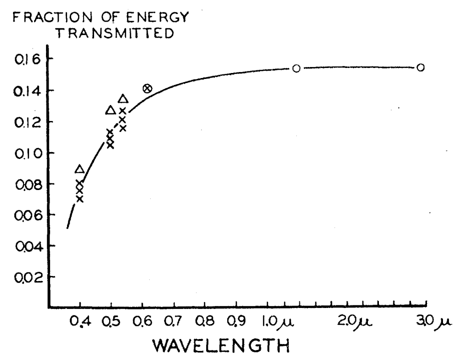


Fig. 3. Abscissas, wave-lengths in μ; ordinates, the fraction of the energy of a given wave-length transmitted through 0.4 km of the foggy atmosphere when the fog was so thick that in the daylight dark colored objects at 0.6 km could barely be seen. Crosses, triangles and circles are observed points, the smooth curve is a theoretical curve.

be swung into position in front of the slit, comparison spectra were photographed of a tungsten lamp 1 meter away through wire gauze screens. The transmission percentages of the screens were found to be independent of the wave-length of the light in the spectrum region under investigation and were 100 (i.e. no screen), 58, 32 and 15 percent. The procedure was to photograph on the same plate with the same time of exposure six spectra, namely, the spectrum of the search-light plus daylight, the spectrum of daylight alone, and spectra of the comparison lamp through the four screens. The intensity of the comparison lamp was adjusted so that its strongest spectrum was stronger and its weakest weaker than the spectrum of the search light. Curves with the recording densitometer were taken of these spectra, an example is shown in Fig. 4. Curves 1, 2, 3, 4, 5 and 6 are, respectively, from the spectrum of the search light plus the daylight, the spectrum of daylight alone, and the spectra of the comparison lamp through the 15, 32, 58 and 100 percent screens. In curve 2 it is interesting to note the *G*, *H* and *K* absorption lines at 4308, 3968 and 3934A, respectively, of the solar spectrum. The large maxima and minima in the tungsten lamp curves at the longer wave-lengths were due to the wave-length sensitivity characteristics of the panchromatic plate; the spectral energy curve of the tungsten lamp is of course smooth in this region. In justice to the densitometer it should be pointed out that the curves of Fig. 4 were purposely made broad for reproduction, the curves made for measurement were very narrow and sharply defined.

Curves similar to those of Fig. 4 were made from spectra taken on clear days, and, omitting obvious and tedious details, the relative intensities of the various wave-lengths of the spectrum through fog, corrected for daylight, were derived from measurements of the heights of all the curves. The results for four different days of fog are given by the crosses and triangles of Fig. 3; these points were all relative to the cross at 0.6μ, the absolute value at 0.6μ being given by the galvanometer deflection with the 0.6μ transmitter observed at the same time that the spectra were photographed.

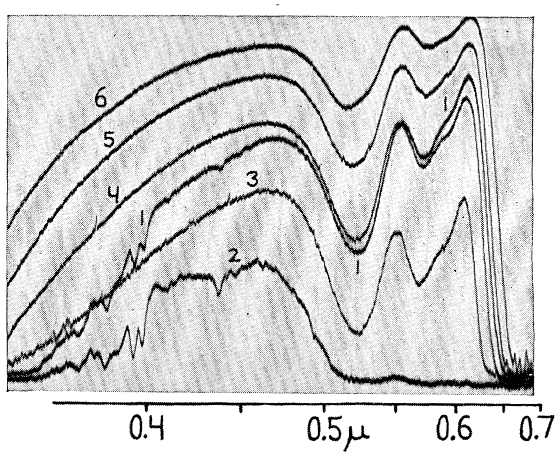


Fig. 4. Densitometer curves of spectra, Curve 1, tungsten search light (plus daylight) through 0.4 km of fog, visibility 0.6 km; curve 2, daylight spectrum; curves 3, 4, 5 and 6, the comparison lamp through 15, 32, 58 and 100 percent screens, respectively.

The triangles are a little higher than the crosses. It is thought that this represented a real difference between the fogs on the respective days because of the consistency of the measurements throughout the investigation. The variation of the ratio $0.45\mu/0.6\mu$ with the visibility is given in the dotted curve 3 of Fig. 2.

During days of clear weather and good visibility the intensity ratios for all the wave-lengths investigated did not vary appreciably with changes in the water vapor content and the temperature of the atmosphere. The data on the absorption coefficients of water vapor for wave-lengths from 0.5 to 5μ, which surprisingly enough are uncertain and incomplete,[1] indicate that the ratio of the intensities $1.4\mu/3\mu$ should have increased with the increase of water vapor content of the atmosphere. That this was not observed may have been due to the rather wide spectral regions, embraced in the transmitted bands, see Fig. 1, and to the relative narrowness of the water vapor

[1] Smithsonian Physical Tables, page 308 (1923); also see references in Lecompte, "Le Spectre Infrarouge," page 347 (1928).

bands. The question deserves a further investigation which will require a complete determination of the light absorption coefficients of water vapor from 0.4 to 5μ.

Discussions of the passage of light through a medium containing particles are usually based on Rayleigh's λ^{-4} scattering formula, where λ is the wave-length of the light. For example, King[2] has pointed out that the intensity of light passing through fog or smoke might be represented by the equation

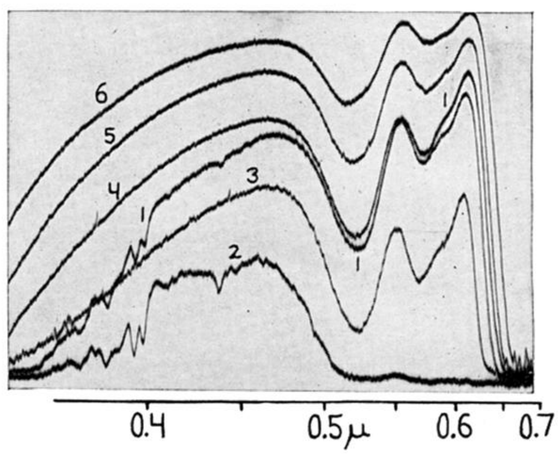
$$I = I_0 e^{-(a+b/\lambda^{-4})x}, \tag{1}$$

where I_o is the original intensity of the light, I the intensity after passage through a distance x in the medium, and a and b are constants. The formula neglects scattering back into the beam, probably a negligible effect in the present experiments. The a term represents an absorption or a blocking out of the energy which is independent of the wave-length. The b/λ^{-4} term was derived for scattering by particles small compared to the wave-length. Although fog probably contains many particles which are large compared with λ as well as small particles, we may never-the-less suppose that (1) represents the passage of light through fog, on the idea that the edge of a large particle is in effect a small particle as far as diffraction is concerned. The curve of Fig. 3 is plotted from Eq. (1) and was made to pass through the points at $\lambda 0.4$ and 3.0μ; a and b were 4.70 and 0.0459, respectively, for λ in μ and x in km. Although the theoretical curve fits the observations fairly well, we can hardly regard the theory as complete, for many equations with two arbitrary constants will fit equally well.

The present measurements indicate that a red light is practically no better than a blue light for fog penetration purposes. For example, from the data of Fig. 3 the distances through a fairly thick fog necessary to reduce the light to 10^{-3} of its original value were 1.40 and 1.20 km for red light $\lambda 0.65\mu$ and for blue light $\lambda 0.45\mu$, respectively, and the distances to reduce the light to 10^{-2} were 925 and 800 meters, respectively. It should be clearly understood, however, that the present measurements, which were concerned only with light intensity, do not in themselves yield a complete answer to the question whether a red light is better than a blue light in a fog. A complete answer about the visibility or recognizability of a particular light should probably consider in addition to light intensity such matters as the visibility curve of the eye, the contrast with the background, etc. In conclusion, it should be emphasized very strongly that the measurements of this paper on thick fogs over short distances can not be safely extrapolated to give information about mists, or haze due to moisture, smoke, dust, etc., over long distances. The facts that the sun is sometimes red at sunset, that distant lights are sometimes reddened, and that photography with light of the longer wave-lengths often gives pictures free from the veiling effects of haze[3] indicate that in haze the selective absorption, probably due to Rayleigh scattering, in the blue is often more pronounced than in the case of fog.

[2] King, Proc. Roy. Soc. **A88**, 83 (1913).

[3] Eastman Kodak Company, Monograph No. 4, "Aerial Haze and its Effect on Photography from the Air," page 15 (1923).



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