Remarks on Visibility in Fog[1]

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Within the past few months, fog caused the fatal crash of a commercial jet aircraft at Logan Airport in Boston and, on 24 October 1973, the collision of 65 ground vehicles over a many-mile stretch of the New Jersey Turnpike. These are but two examples of the periodic catastrophes caused by visibility degradation in fog. The problem has attracted considerable interest over the years, with recent attention focusing on numerical models to simulate fog and/or to test modification concepts (Zdunkowski and Nielsen, 1969; Pilié *et al.*, 1972; Silverman, 1972; Mandel *et al.*, 1974).

Ironically, despite the growing elaboration of numerical models, the basic equation for expressing visibility is subject to interpretation and used incorrectly at times. Accepting the customary but simplified visual contrast assumptions, the well-known Koschmieder (1924) expression relating visibility and the extinction coefficient σ can be used to define the "standard visual range" V as

$$V=\frac{3.912}{\sigma}. \tag{1}$$

In most cases it is also permissible to assume that droplet scattering β dominates adsorption so that

$$V=\frac{3.912}{\beta}=\frac{3.912}{\sum_i N_i k_s \pi r_i^2}, \tag{2}$$

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where k_s is the Mie scattering area coefficient, N_i the number of droplets per size interval i, and r_i the respective drop radius.

The scattering area function, as theoretically predicted by Mie theory and experimentally verified by Stratton and Houghton (1931) and several others since, varies with the scatterer's size and the illumination wavelength. For water drops larger than a few microns and visible light, k_s is customarily taken as 2. Thus, the total scattering by a sizable drop approximates twice its geometric cross section; or as Houghton and Chalker (1949) and Johnson (1954) observed, from Babinet's principle, total scattering is due to diffraction and defocusing (i.e., refraction and reflection) of light in roughly equal amounts. (A large drop acts as a lens of short focal length so that light is widely spread or defocused.) As these investigators and several others such as Hodkinson (1966) have since indicated, the effective k_s varies from 1 to 2 for large drops depending on (i) the detection angle considered and (ii) the distance between detector and scatterers.

Item (ii) reflects the fact that less diffracted light is received from a scatterer as a detector is moved away from it. In practice this does not greatly influence k_s or V (at least in horizontally homogeneous fog) because visibility detectors are generally in immediate contact with fog droplets. It does imply that proportionally more light is scattered into the receiver by nearby droplets.

Of considerable importance, and a factor sometimes overlooked, is the observing method or the effect of the detection angle. The diffracted light is transmitted in the forward direction within a narrow cone whose half-angle decreases as drop size increases. One can readily show that the half-angle for a 10-μm diameter drop and light of wavelength 0.555 μm (maximum eye sensitivity) to the first diffraction ring minimum is 3.9°, containing more than 80% of the diffracted light, and to the fifth ring containing virtually all the diffracted light, 16.8°; for a 30-μm drop, the respective half-angles are 1.3° and 5.5°. Thus, most of the diffracted light from larger drops is received by the typical transmissometer with separated illuminator and detector, and only the defocused light is lost. Therefore, Johnson concludes that for drops $>10\ \mu$m (perhaps somewhat small) and typical field configurations, k_s is approximately 1 ($\beta = \sum n_i \pi r_i^2$); Brillouin (1944) and Sinclair (1947) experimentally confirmed this result for scatterers of 26 and 30 μm diameter, respectively. Note that the *total* scattering cross section obtained by integrating over all angles is 2, in complete agreement with Mie theory, but the light diffracted by large drops in the forward direction essentially is not "lost" with the typical detector. An exception might be created by multiple scattering in fogs, where k_s presumably would tend to increase.

TABLE 1. Representative fog values.

Surface fog variables	Radiation fog	Advection fog
Average drop diameter	10 μm	20 μm
Typical drop range*	5–35 μm	7–65 μm
Liquid water content	110 mg m^{-3}	170 mg m^{-3}
Droplet concentration	200 cm^{-3}	40 cm^{-3}
Vertical fog depth		
a. typical	100 m	200 m
b. severe	300 m	600 m
Horizontal visibility	100 m	300 m

* Lower size limit influenced by sampling techinque.

Some time ago, an attempt was made to assess representative visibility and microphysics characteristics in radiation (inland) and advection (coastal or sea) fogs (Jiusto, 1964). Averaging the results of all the measurements that could be found in the literature at the time, the following table was constructed.

Clearly the above simplified numbers represent only typical values that will vary considerably in individual cases and with local conditions. While perhaps fortuitous in view of the diverse measurements involved, it is interesting to note that the average visibilities, drop sizes and concentrations observed suggest a k_s value of 2 for small-drop radiation fogs and of 1 for the larger drop advection fogs. However, no great faith can be placed in this deduced result, nor were the data intended to be used in such a fashion.

Recently Weinstein and Silverman (1973), using some of the above values in their fog model, stated that the advection fog numbers were not internally consistent. Such is not necessarily the case. They overlooked the fact that the effective k_s for large drops can depart from 2. Hence the visibilities they calculated, using Eq. (2), for four types of advection fog considered could be as much as half the actual values measured in the field.

A re-examination of droplet scattering coefficients, light attenuation and visibilities in a variety of fogs possessing different droplet spectra would appear worthwhile. In this context, the visual determination of meteorological range by an observer is even more uncertain and worthy of investigation.

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