APPENDIX A

Theory of Visibility

This discussion is limited to those aspects of visibility addressed in this study. More complete treatments can be found in Middleton (1952) and McCartney (1976). The discussion covers the optics of visibility, and the contributing role of specific gaseous and aerosol pollutants and the modeling of visibility.

1) Optics of Visibility

A person sees by the light reaching his eyes from objects. Light is electromagnetic radiation with wavelengths capable of stimulating the receptors in human eyes, covering the range of approximately 0.38 to 0.77 µm. The amount of light energy per unit time received per unit area of detector, per unit solid angle field of view of the detector and per unit wavelength interval at a specific wavelength (see Figure A1) is called spectral radiance, N. This spectral radiance is called inherent radiance, N_o, if the detector is located at distance, r, from the object. The contrast of a target against its background, usually the sky. As with radiance, contrast can be described as inherent or apparent, depending on the distance between the observer and the target. Inherent spectral contrast Co, is defined as:

$$C_o = \frac{{}_tN_o - {}_sN_o}{{}_sN_o} \tag{A1}$$

and apparent spectral contrast, C_r, is defined as:

$$C_r = \frac{{}_tN_r - {}_sN_r}{{}_sN_r} \tag{A2}$$

where ${}_tN_o$ = inherent spectral radiance of the target at zero distance (watt/m^2 steradian µm)

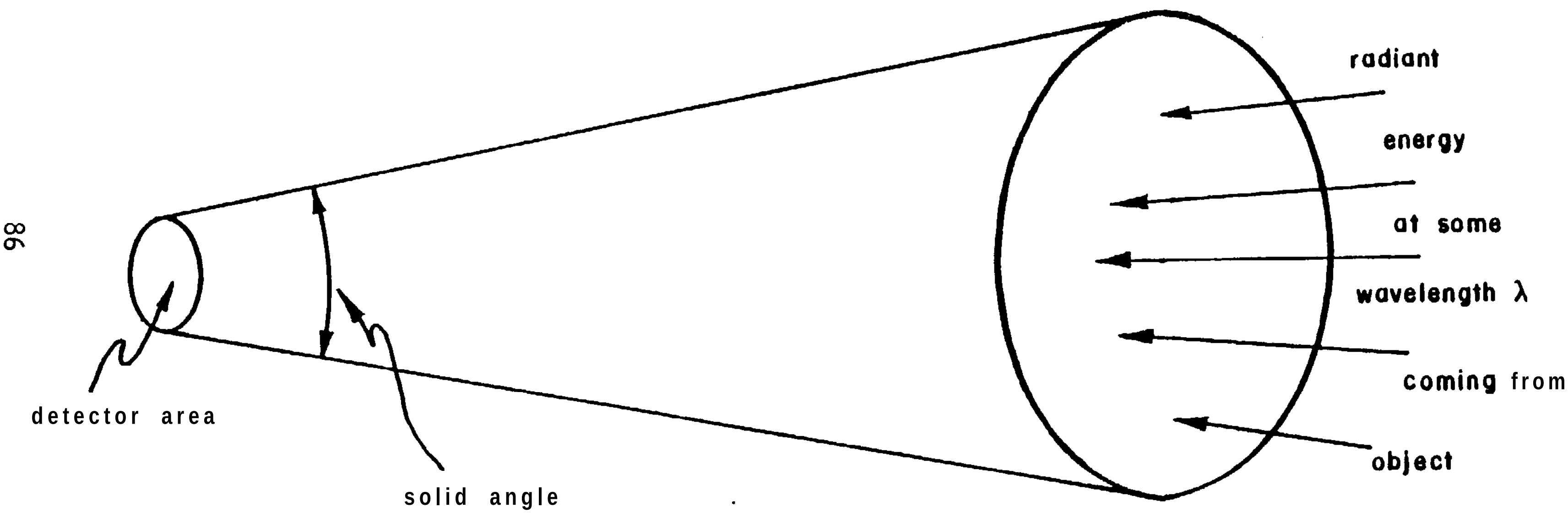
${}_sN_o$ = inherent spectral radiance of the sky at the target (watt/m^2 steradian µm)

${}_tN_r$ = apparent spectral radiance of the target at distance r, and (watt/m^2 steradian µm)

${}_sN_r$ = apparent spectral radiance of the sky at distance r from the target (watt/m^2 steradian pm)

Figure Al

Spectral Radiance



Contrast is dimensionless because it is a ratio of radiances. The light coming from a target is attenuated by scattering and absorption (see Figure A2 and A3). Gas molecules and particulate matter scatter some of the inherent radiance out of the sight path and absorb another portion. Skylight and light reflected from the ground is scattered by particulate and gas molecules into the sight path towards the observer (see Figure A4). The result of these processes is illustrated in Figure A5. A bright object loses radiance as the distance between it and the observer increases, approaching the limiting value of the adjacent horizon sky radiance. A perfectly black object has no inherent radiance. It acquires radiance as the path between it and the observer increases, again approaching the horizon sky radiance as the limiting value. A dark object is an intermediate case. The apparent radiance reaching the observer from a target has two parts, the attenuated inherent radiance and the path radiance added by scattering from the surrounding air. In equation form,

$$ {}_tN_r = {}_tN_o T_r + N_r^* \tag{A3} $$

where T_r = transmittance of light from the target to the observer at distance r (dimensionless)

N_r^* = spectral path radiance over distance r(watt/m^2 steradian µm).

Similarly, for the apparent background sky radiance,

$$ {}_sN_r = {}_sN_o T_r + N^*_r \tag{A4} $$

If Equation A4 is subtracted from Equation A3, then

$$ {}_tN_r - {}_sN_r = ({}_tN_o - {}_sN_o) T_r \tag{A5} $$

Equation AS expresses the fact that the difference in radiance between the target and sky is transmitted to the observer with the same attenuation as each image-forming ray of light. If we divide both sides of Equation A5 by the background sky apparent radiance and multiply the right side of the equation by ${}_sN_o/{}_sN_o$, then

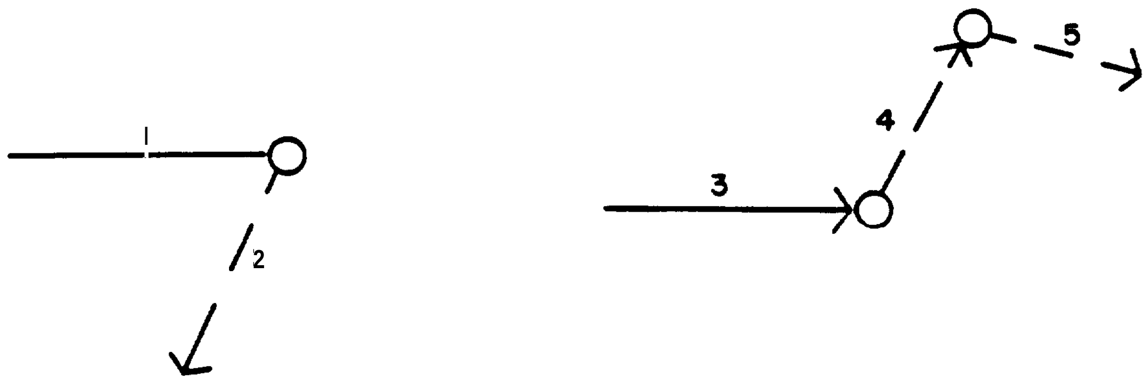
$$ \frac{{}_tN_r - {}_sN_r}{{}_sN_r} = \frac{({}_tN_o - {}_sN_o)}{{}_sN_o} \frac{{}_sN_o}{{}_sN_r} T_r \tag{A6} $$

Combining Equations Al, A2, and A6, we get the following relation for the apparent contrast of a target:

$$ C_r = C_o \frac{{}_sN_o}{{}_sN_r} T_r \tag{A7} $$

Apparent contrast depends on the inherent contrast of the target, which depends on the type and amount of vegetation on the target, the illumination of the

Figure A2



Scattering

Scattering: Photon on path I is backscattered along path 2. Photon on path 3 is forward scattering along paths 4 and 5.

Figure A3

Absorption

Absorption: Photon on path 1 is absorbed by the gas molecule or particle.

Figure A4

Sc representation of vision through the

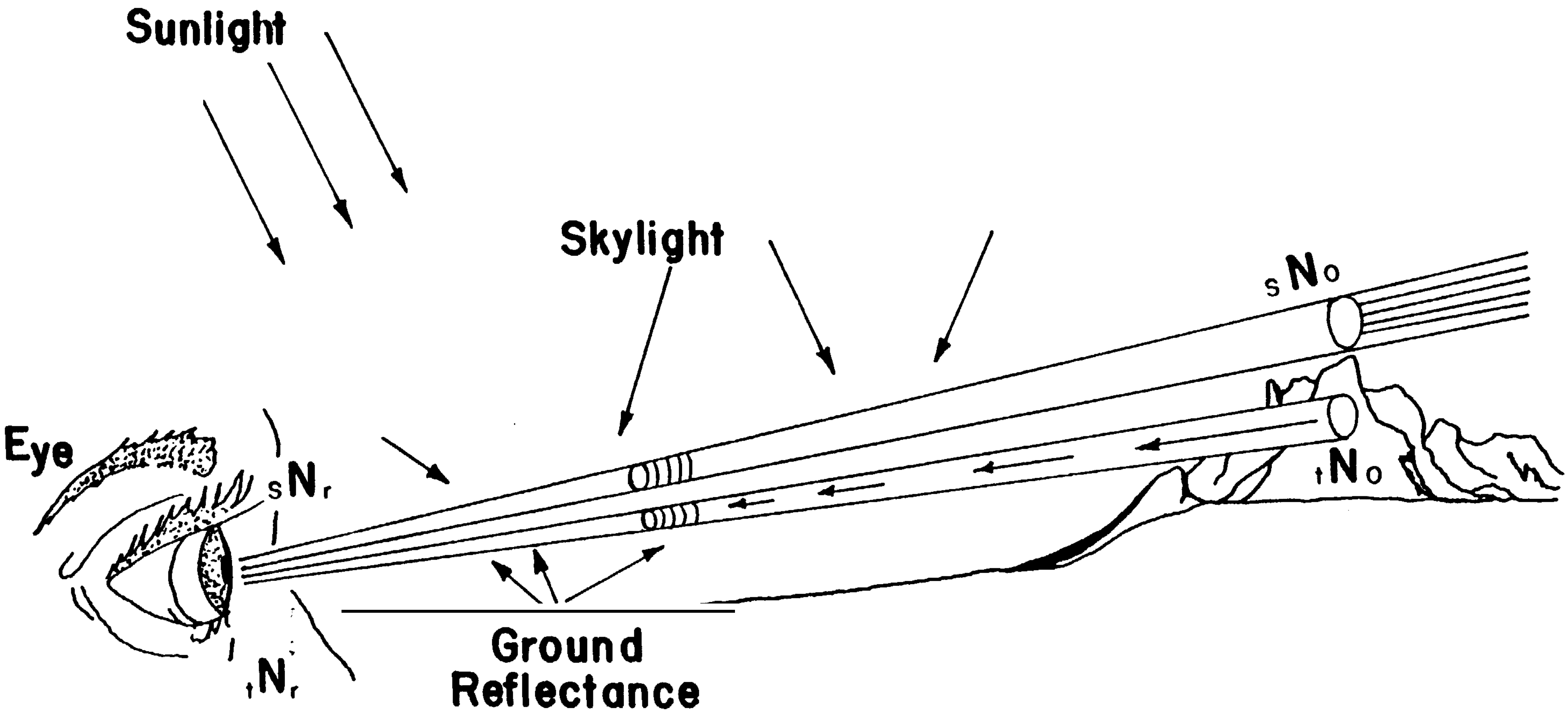
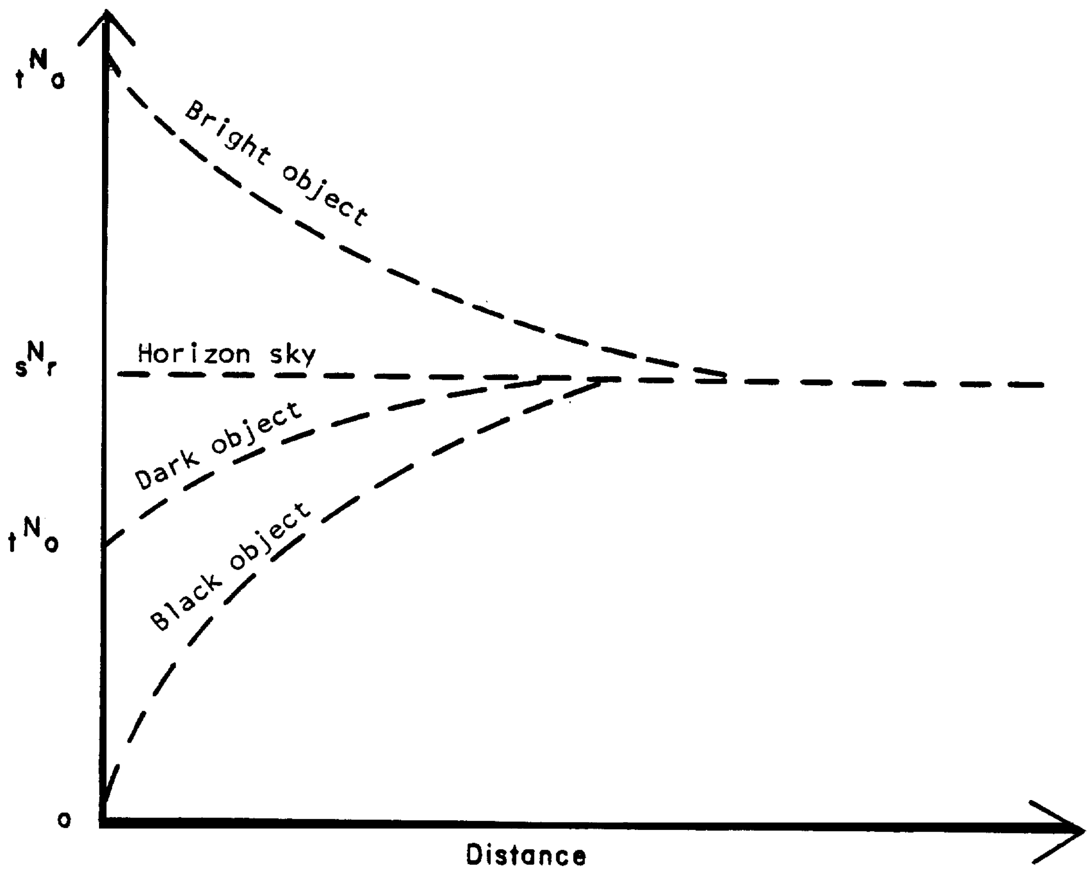


Figure As

The Dependence of Target Radiance on Distance



target as a function of time of day, latitude, longitude, azimuth of the sight path, azimuth of the normal to the face of the target, and the slope angle of the target. The ratio of sky radiances at the target and at the observer is equal to unity for the theoretical assumption of a uniform atmosphere and a horizontal sight path.

If the atmosphere is homogeneous in composition along the entire sight path, then the transmission, T_r, can be expressed as a function of the extinction coefficient, b_{ext}:

$$T_r = e^{-b_{ext} r} \qquad \text{(A8)}$$

Combining Equations A7 and A8:

$$C_r = C_o e^{-b_{ext} r} ({}_sN_o / {}_sN_r) \qquad \text{(A9)}$$

If C_r and Co are measured with a teleradiometer and r is known, then Equation A9 can be solved for the average extinction coefficient:

$$\bar{b}_{ext} = \frac{1}{r} \ln \left(\frac{C_o}{C_r} \frac{{}_sN_o}{{}_sN_r}\right)$$

The ratio ${}_sN_o / {}_sN_r$ is unity for a horizontal sight path through homogeneous air under uniform illumination on a flat earth.

Under these same conditions visual range is defined as the distance at which the apparent contrast of a black target is reduced to 2 percent ($C_r = -.02$). Equation A9 can then be solved for visual range, VR:

$$VR = \frac{3.912}{\bar{b}_{ext}} = \frac{3.912}{\frac{1}{r} \ln \frac{C_o}{C_r}} \qquad \text{(A10)}$$

The choice of 2 percent as the threshold contrast is easily adjusted to values as high as 5 percent. Middleton (1952) discusses the experiments conducted by others to-derive the threshold contrast. It is important to not interpret visual range too literally as the distance at which large black targets disappear. Hence the choice of threshold contrast is not critical but needs to be consistent for comparing different data sets.

This definition of visual range attempts to account for different distances between the observer and targets, and different inherent contrasts. It does not account for targets viewed at different altitudes, for which the atmosphere has a different clean air (Rayleigh) extinction coefficient. Measurements of the apparent contrast of targets at different altitudes are standardized by correcting the total extinction for the Rayleigh component. This correction is made by subtracting the average Rayleigh extinction coefficient of the actual sight path from the measured total extinction and coefficient and then adding back the reference Rayleigh extinction coefficient. This reference is set at .01 km^{-1} corresponding to an altitude of 1550m (Elterman, 1968). Hence standard visual range SVR, is defined by:

$$SVR = \frac{3.912}{\frac{1}{r}\ln\frac{C_o}{C_r} - \bar{b}_{ext,R} + .01} \qquad (A11)$$

where $\bar{b}_{ext,R}$ = average extinction coefficient of the sight path.

The variables discussed so far describe visibility without reference to what it would be in a Rayleigh atmosphere, completely unpolluted by natural or anthropogenic sources. The change in the apparent contrast of a target from its best possible value in a Rayleigh atmosphere is called delta contrast, ΔC, and is defined by:

$$\Delta C = C_r - C_o e^{-\bar{b}_{ext,R}(z_m)r}$$

where $z_m = \frac{z_o + z_t}{2}$

z_m = altitude of sight path midpoint (m).

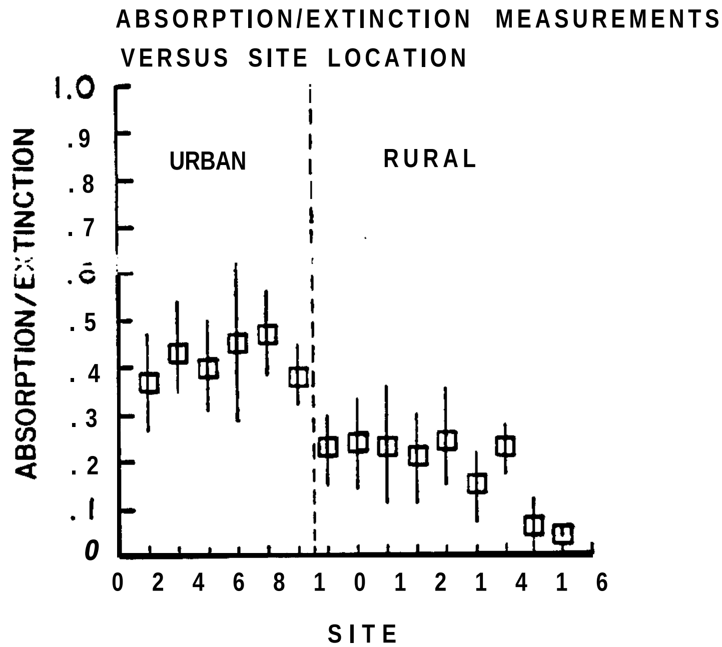
The second term is the apparent contrast of the target computed as if it were viewed through a Rayleigh atmosphere.

Now that several variables describing visibility have been covered, we are ready to discuss the physical processes by which particles and gas molecules affect the transfer of light through the atmosphere.

2) Relating Optics to Pollutants

Particulate and gaseous pollutants attenuate light by scattering and absorption as a function of the gaseous molecular structure, the size and composition of the particles, and the wavelength of light. Most absorption is caused by NO_2 and carbon particles, while most scattering is caused by particles. Any changes in source emissions and meteorology that cause higher concentrations of light scattering or absorbing pollutants will result in increased visibility impairment. Scattering usually dominates absorption, especially in clean air, where 78-95% of the total attenuation is caused by scattering. Scattering is closer to 55-63% of the total attenuation in highly polluted urban areas (Weiss, et al., 1979). The proportional contribution of absorption to total extinction (attenuation) can be seen in Fig. A6.

Figure A6



1. Industrial Seattle, WA.
2. Downtown Portland, OR.
3. Industrial St. Louis, MO.
4. Denver, CO. (fairgrounds)
5. Denver, CO. (trout farm)
6. Central Phoenix, AZ.
7. Residential Seattle, WA.
8; Residential St. Louis, MO.
9. Tyson, MO. (1973)
10, Tyson, MO. (1975)
11, Milford, MI.
12. Hall Mt. AR.
13. Puget Island, WA.
14. Flagstaff, AZ
15. Mauna Loa Observatory, HI

(After Weiss, et al, 1979)

2-1) Gaseous Scattering

Scattering of gases is treated separately from scattering by particles because of important differences. Gaseous scattering has an inverse fourth power dependence on wavelength, which accounts for the blue color of skylight. In Rayleigh unpolluted air, scattering is the dominant process because the nitrogen, oxygen, and other gases absorb a negligible amount of visible light. The Rayleigh scattering by gases depends somewhat on the direction of observation as shown in Fig. A7. Maximum forward and backward scattering is at observation angles of O and 180, and minimum scattering is at 90°.

More detail on the scattering by an individual gas molecule can be found in McCartney (1976). If the scattering by air molecules in a specific direction is summed over all possible directions, the total scattering can be found. Expressing total scattering as a coefficient, the effect of air with a molecular density appropriate to sea level is about 10^{-2} km^{-1}. Hence, Rayleigh scattering removes about 1% of the incident light per kilometer of horizontal path. Using Eq. AlO, this Rayleigh scattering coefficient translates into a visual range of 391 km, assuming no abosrption nor particulate scattering. Do not expect to see real objects over such distances. Mountains are not black objects and they are not tall enough to be seen at such distances.

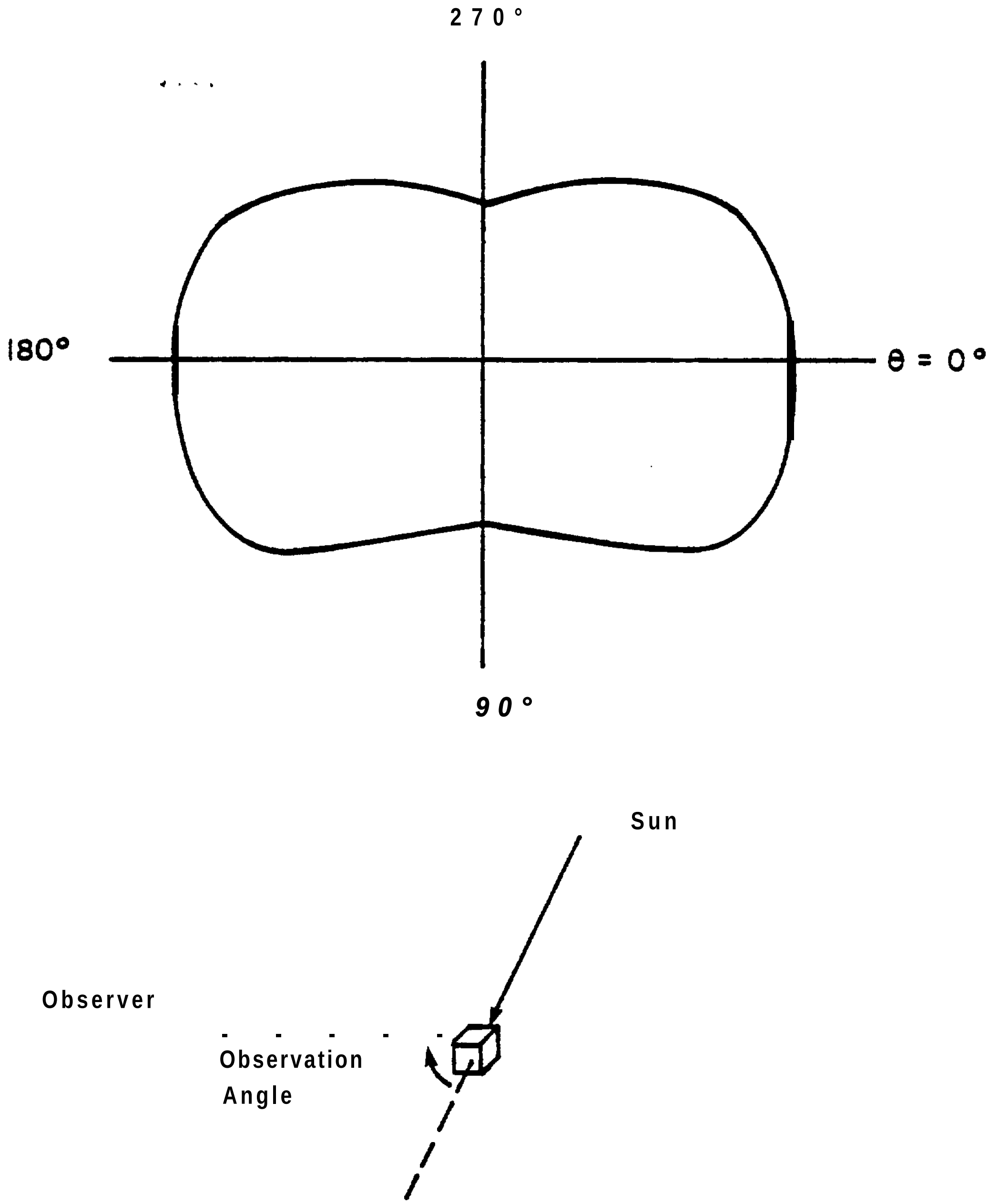
2-2) Particulate Scattering

Scattering by particles is more complex in its angular dependence, which itself depends on the size of the particle. Particulate scattering is often called Mie scattering, after the scientist who developed the first successful theory (Mie, 1980). As particle size decreases, the Mie theory of scattering approaches the Rayleigh theory, appropriate to particles or gas molecules smaller than 1/10 the wavelength of light (McCartney, 1976).

The Mie theory was developed for spherical particles of uniform composition and hence, uniform index of refraction. Ambient aerosol, though, comprises spherical, irregular, plate-like, and rod-like particles. In order to utilize the Mie theory for nonspherical particles, a compromise is made. Size distributions are measured by some instruments in terms of the aerodynamic behavior of the particles, from which an equivalent spherical diameter is computed. This diameter is then used in the Mie theory to predict the approximate scattering of complex shaped aerosol. The angular dependence favors the forward direction, as shown in Fig. A8, with greater complexity as the particle size increases.

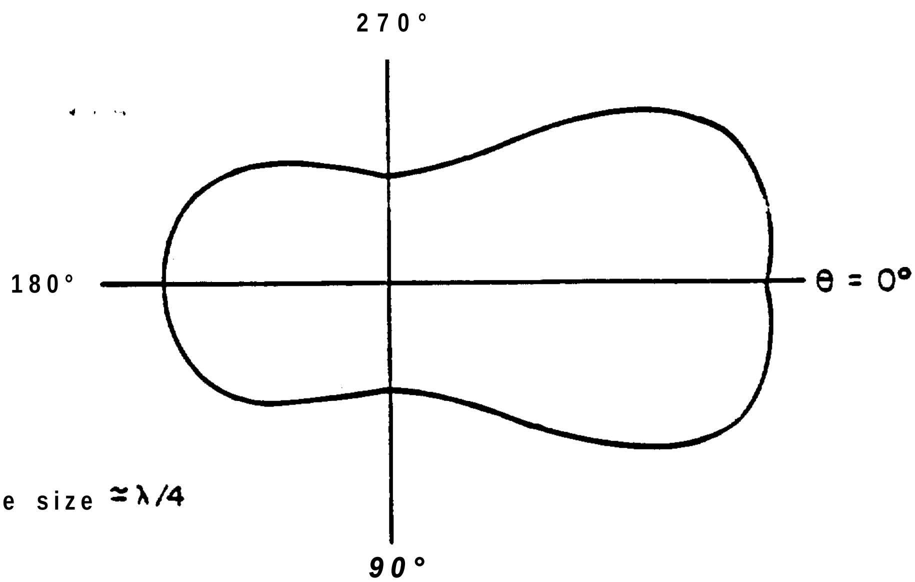
An important aspect of scattering is the efficiency with which particles of different size scatter incident light in all directions. The scattering efficiency factor is defined as the ratio of the total scattering cross-section and the geometric cross-section. For a spherical particle, the geometric cross-section is πr^2, where r is the radius of the particle. The total scattering cross-section is "that cross-section of an incident wave, acted on by the particle, having an area such that the power flowing across it is equal to the total power scattered in all directions" (McCartney, 1976). The dependence of the scattering efficiency factor on the size parameter, $\alpha = 2\pi/\lambda$, is shown in Fig. A9. The relative size of the particle with respect to the

Figure A7

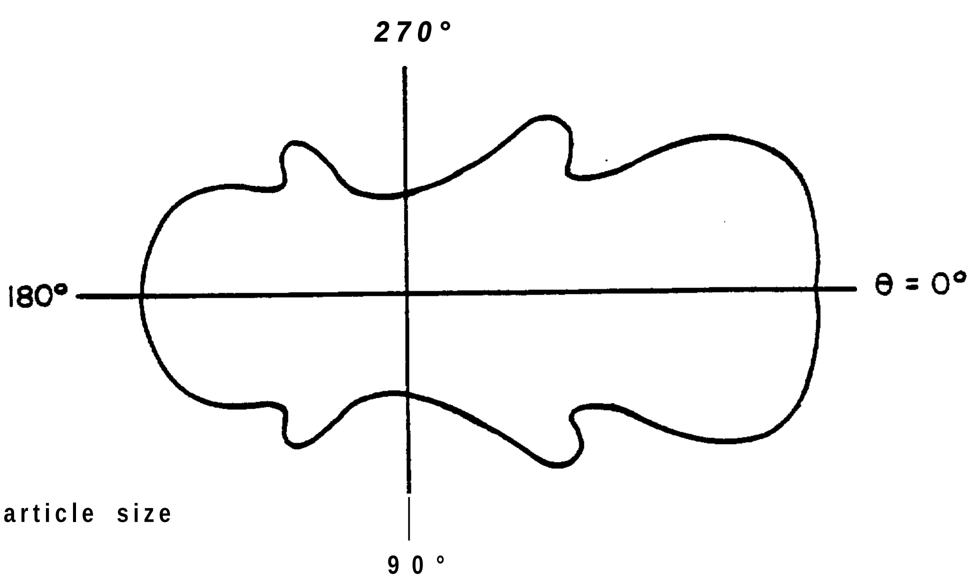


Rayleigh Scattering Dependence on Observation Angle

Figure A8



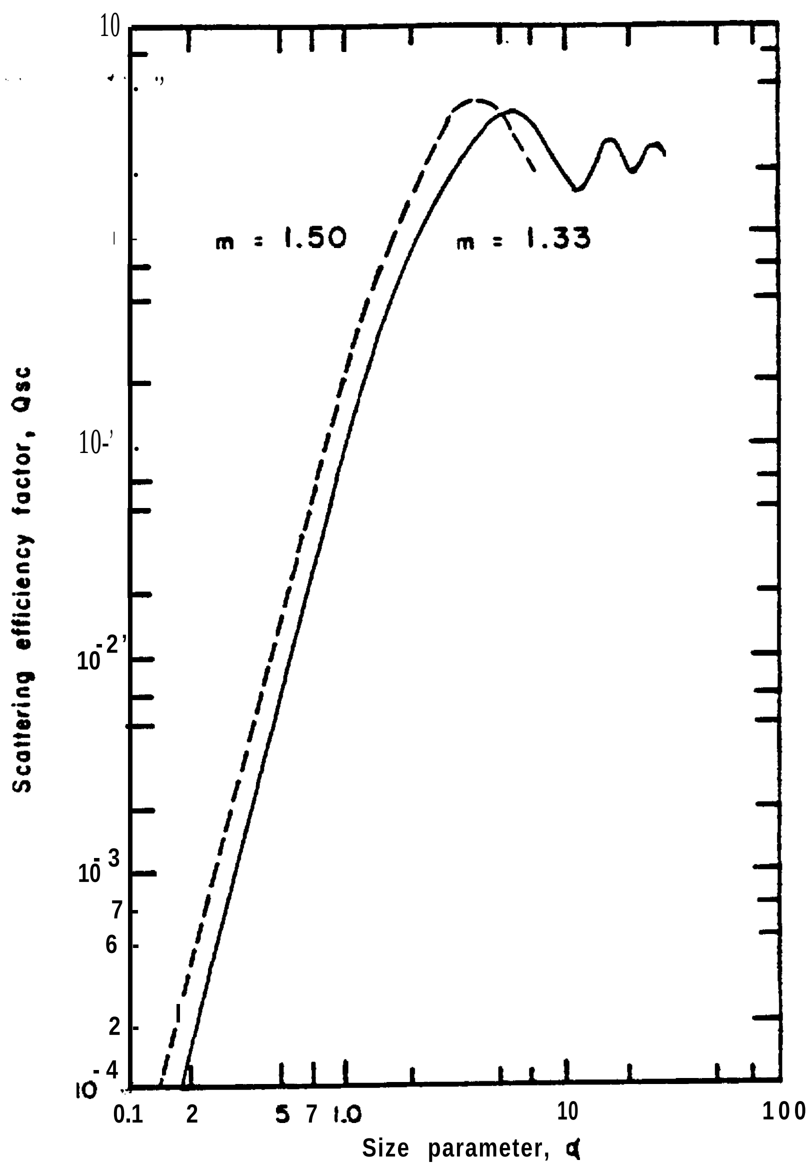
a) Particle size ≃ λ/4



b) λ < Particle size

Observation Angle Scattering Dependence for Particles
(Adapted from McCartney, 1976)

Figure A9



Scattering Efficiency Factor as a function
of Size Parameter, a, and Refractive Index. m
(After McCartney. 1976)

wavelength of incident light, not its absolute size, is the important independent variable, as implied by the use of the size parameter, a. The curve with index of refraction m = 1.33 represents particles of water, while the m = 1.5 curve approximates silica or ammonium sulfate, two critical components related to soil and coal combustion sources respectively. In Fig. A9 the scattering efficiency factor oscillates less and less around a value of 2 as relative size becomes very large. At this value a particle refracts, reflects and diffracts twice the radiant power incident on the geometric cross-section (McCartney, 1976) . White and Roberts (1977) found that sulfates and nitrates in the Los Angeles air basin scattered light more efficiently per unit mass concentration than other chemical fractions of the ambient aerosol. The high scattering efficiency of sulfates and the large stationary source emissions of sulfates led these authors to suggest that this source was comparable with the automobile in reducing visibility there.

The size of particles and the resulting light scattering is sensitive to the relative humidity of the air. When the relative humidity rises above 70% water condenses on particles and makes them bigger (Charlson, Waggoner and Thielke, *1978).* The composition of the particle affects the threshold relative humidity, above which water vapor condenses on the particle. The ratio of scattering coefficient at any relative humidity to that at *30%* is plotted in Fig. A1O.

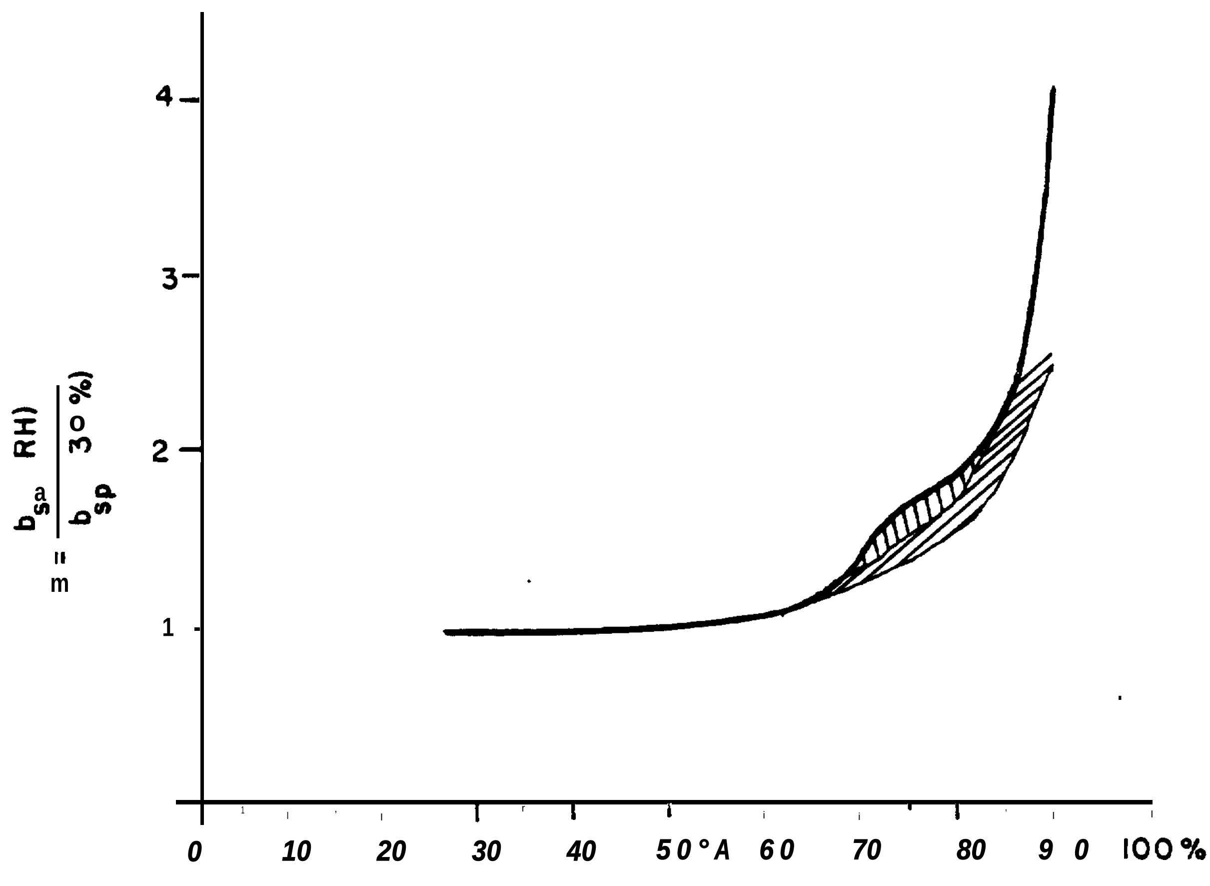
2-3) Absorption

Absorption of light is the process by which the incident light at specific wavelengths is converted to internal energy of molecules (rotation, vibration, and electronic arrangement). A quantum of energy is absorbed for each discrete change in any of these forms of internal energy. The energy of a quantum is inversely proportional to the wavelength of the light or other electromagnetic radiation.

The only absorption of enough consequence in the gaseous air pollutants from power production is that of nitrogen dioxide, NO_2 . The absorptivity is the relative loss of incident light per unit length of absorbing path per unit concentration of pollutant. The absorptivity of NO_2 as a function of wavelength is shown in Fig. All taken from Hall and Blacet (1952). The absorptivity is strongest in the blue. Also, there are many detailed absorption peaks in the overall curve, whose wavelengths correlate with specific changes in the internal energy of the NO_2 molecule. The strong NO_2 absorption of blue light causes plumes and urban hazes to appear brown. Simultaneous scattering of all wavelengths by particles and scattering of blue by air leads to a variety of brown, gray, and white colors, depending on the relative contribution of these processes.

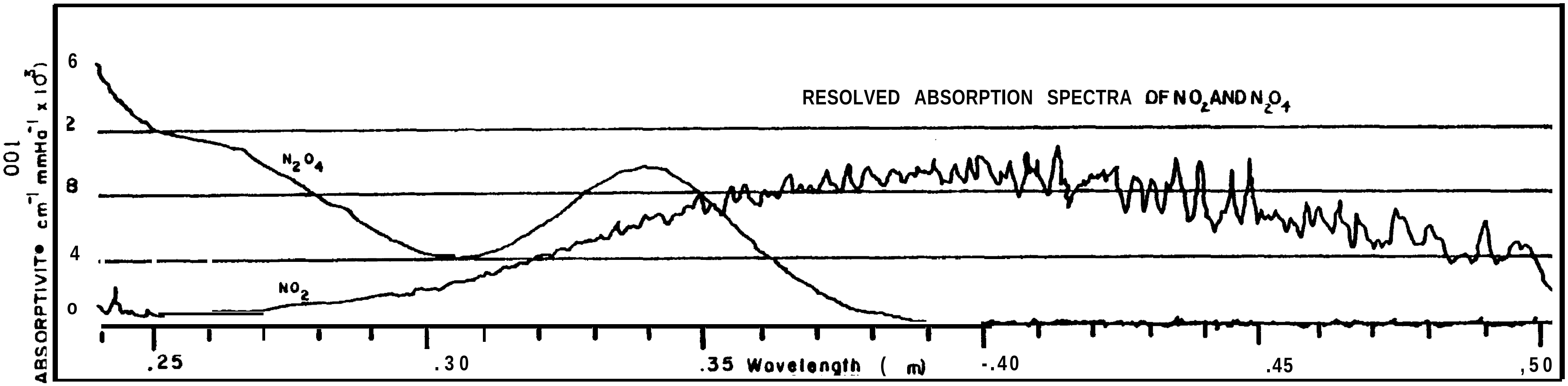
Absorption of light by particles is attributed to their graphitic "soot" content (Rosen, et al., 1979; Weiss, et al., 1979). Faxvog and Roessler (1978) found that carbon particles were mcst effective in reducing visibility if their diameters were 15-50% of the wavelength of light. Roessler and Faxvog (1980) found that 85% of the acetylene smoke particle attenuation of 514 nm light was caused by absorption and 15% caused by scattering. Roessler and Faxvog *(1981)* found that absorbing aerosols increase the visual range com-

Figure AIO



Range of variability in Humidogram data averaged by site; vertically hatched area includes strongly deliquescent aerosol at Pr. Reyes and Tyson. (Adapted from Charlson, Waggoner and Thielke, 1980)

Figure All



Absorptivity of NO_2 and N_2O_4 vs. wavelength measure at 25 °C

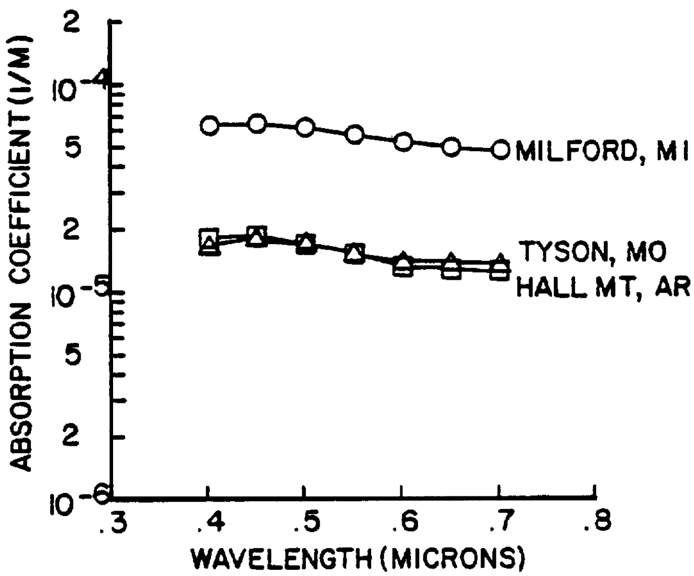
Absorptivity of NO_2 as a function of Wavelength of Incident Light
(After Hall and Blacet, 1952)

puted for light objects viewed against the horizon sky. The dependence of absorption on the wavelength of incident visible light is quite weak as shown by the curves in Fig. All (Weiss, et al., 1979). The effect of absorption in optical computations can be expressed in terms of an absorption coefficient, as plotted in Fig. A12.

The processes by which light is attenuated as it moves through air have been described to help understand the physical measurement of visibility variables. The discussion now moves on to the way we construct complete models of visibility as a function of air pollution.

Figure A12

CHARACTERISTIC ABSORPTION WAVELENGTH DEPENDENCE MEASUREMENTS



Absorption wavelength dependence measurements.

(After Weiss et al, 1979)

APPENDIX B

VALUING PUBLIC GOODS: A COMPARISON OF SURVEY AND HEDONIC APPROACHES'

INTRODUCTION

Although the theory of public goods has progressed rapidly since Samuelson's seminal article (1954), the empirical measurement of the value of (demand for) public goods only recently has received increased attention. Perhaps the best known and most widely accepted empirical approach has been the use of hedonic prices wherein, for example, it is assumed that either wages or housing values reflect spatial variation in public good characteristics of different communities. This indirect approach, based on theoretical work of Tiebout (1956), Lancaster (1966), Rosen (1974) and others has proven quite successful. Among public goods or bads which have been valued using the hedonic approach are climate [Hoch (1974)], air pollution [Anderson and Crocker (1971) and Harrison and Rubinfeld (1978)], social infrastructure [Cummings, et al. (1978)] and other community characteristics such as noise level [Nelson (1979)] and ethnic composition [Schnare (1976)].

An alternative approach is to directly ask households or individuals to state their willingness to pay for public goods using survey techniques. Despite arguments that strategic bias will invalidate survey results, there exists the need for an alternative to the hedonic approach. As an example, consider the case of a remote and unique scenic vista, valuable to recreators, which is threatened by air pollution from a proposed coal fired plant--a typical situation in the Western United States. Although it is possible, in principle, to impute the value of clean air and visibility from the relative decline in local visitation which might follow construction of a power plant, information on the value of visibility at the site is needed prior to construction for socially optimal decisionmaking on plant location and pollution control equipment. The hedonic approach is unavailable both because the scarcity of local population--as opposed to recreators--makes use of wage or property value data impossible and because scenic vistas may themselves be unique. For these 'reasons, Randall et al. (1974) first applied survey methods for valuing visibility and other environmental effects of large coal fired power plants in the Four Corners region of New Mexico. Since this initial application, the survey approach has been widely used to value environmental commodities where market data for hedonic analysis is difficult to acquire [see, for example, Brookshire, Ives and Schulze (1976), Rowe, et al. (1980), and Brookshire, et al. ([1980]). Other early attempts to value public goods using the survey approach include Davis (1963), Bohm (1972) and Hammack and Brown (1 974).

Although results of using the survey approach for estimating the value of public goods appear to be internally consistent, replicable and consistent with demand theory [see Schulze et al. (forthcoming)], no external validation has been reported (i.e., a comparative analysis using another approach independent of the survey has not been conducted). Thus, the purpose of this paper is to report on an experiment designed to validate the survey approach by direct comparison to a hedonic property value study.

The Los Angeles 'metropolitan area was chosen for the experiment because of the well defined air pollution problem and because of the existence of detailed property value data. Twelve census tracts were chosen for sampling wherein 290 household interviews were conducted during March, 1978. Respondents were asked to provide their willingness to pay for an improvement in air quality at their current location. Air quality was defined as poor, fair, or good based both on maps of the region (the pollution gradient across the Los Angeles Metropolitan Area is both well defined and well understood by local residents) and on photographs of a distant vista representative of the differing air quality levels. Households in poor air quality areas were asked to value an improvement to fair air quality while those in fair areas were asked to value an improvement to good air quality. Households in good air quality areas were asked their willingness to pay for a region-wide improvement in air quality. The region-wide responses are reported elsewhere [Brookshire, et al. (1980)].

For comparison to the survey responses, data was obtained on *634* single family home sales which occurred between January, 1977 and March, 1978 exclusively in the twelve communities used for the survey analysis. As we show in the next section, households, in theory, will choose to locate along a pollution-rent gradient, paying more for homes in clean air areas based on income and tastes. However, ceteris paribus, we show that the annualized cost difference between homes in two different air quality areas (the rent differential for pollution) will in theory exceed the annual willingness to pay for an equivalent improvement in air quality for a household in the lower air quality area. Thus, the rent differential associated with air quality improvement from hedonic analysis of the property value data must exceed estimates of household willingness to pay for the survey responses, if the survey responses are a valid measure of the value of air quality improvements. Section *3* describes the data analysis and experimental design in more detail.

We also conjecture that the willingness to pay for air quality improvements is greater than zero for residents in our sample communities based on statewide political' support for air quality regulation. The State of California, principally in response to the air pollution problem in the Los Angeles Metropolitan area, has led the nation in imposing automobile emissions standards. The automobile industry, under pressure from the California Legislature, installed the first pollution control devises on California cars in 1961. This initial step was followed nationally in 1963. Again, California imposed the first exhaust-emission control regulations in 1966, leading the nation by two years. Over the decade of the 1970's, California has had more stringent automotive emission standards than Federal levels, resulting in higher initial costs and sacrifices in both performance and fuel economy.

In spite of these difficulties, political support, as reflected both in the State Legislature and in several administrations, has remained strong for auto emission controls.

In Section 4 the results of the hypotheses tests are presented. As Table 2 illustrates, results of the experiment can be summarized as follows: In the nine census tracts where air quality improvements are possible (poor and fair communities), we cannot reject our dual hypotheses that, in each census tract, household willingness to pay for air quality improvements, as estimated by surveying households, falls below equivalent property value rent differentials and lies above zero. We view these results as a qualified verification of the survey approach for estimating the value of public goods. Further interpretation of the results is contained in the concluding remarks offered in Section 5.

A THEORETICAL BASIS

The property value and the survey approaches for valuing public goods have received considerable theoretical scrutiny. Property value studies are conceptually based on hedonic price theory as developed by Rosen (1974) and recently summarized by Freeman (1979). The survey approach has been modeled using standard concepts of consumer surplus by Randall et al. (1974), Bohm (1972), and Brookshireet al. (1976) where the latter two analyses also focus on the possibility of strategic behavior. The considerable empirical evidence now available suggests that strategic bias may be of little consequence both in survey work [See Brookshire et al. (1980) and Rowe et al. (1980)] and in experimental economics [See Grether and Plott (1979), Scherr and Babb (1975) and Smith (1977)]. However, other types of bias may still invalidate a survey approach for valuing public goods. It has even been suggested that the survey approach produces "noise" since responses are purely hypothetical and have no necessary connection to actual budgetary decisions.

In this section, a simple theoretical model is developed for comparison of survey responses to a property value study for valuing air quality improvements in the Los Angeles region in order to determine if valid public good measures can be obtained from survey data.

We use the following notation:

Let P = the level of air pollution

X = consumption of a composite commodity excluding housing

c = unit cost or price of the composite commodity X

R = rent or periodic cost of housing

Y = household income

and $U(P,X)$ = household utility, a decreasing function of pollution $U_P < 0$ an increasing function of consumption $U_X < 0$.[2]

Each household maximizes utility, $U(P,X)$, subject to the budget constraint:

$$Y - CX - R(P) = 0$$

where we assume the existence of a continuous differentiable rent gradient R(P). [See Rosen (1974)] for a complete discussion of the generation and existence of rent gradients. Our model is a simple adaptation of Rosen's, so we will not elaborate here.) Two distinct choices are modeled: consumption of the composite commodity, X, and that of housing location by pollution level, P. Presumably, lower rents will be paid for homes in more polluted areas, so $R'(P)<0$.[3] The first order conditions for choice of P and X imply that

$$c\frac{U_P}{U_X} = R'(P)$$

or that the marginal rate of substitution between pollution, P, and the composite commodity, X, valued at the cost of the composite commodity, C, equals the slope of the rent gradient R' (P) at equilibrium location and consumption levels.

Figure 1 illustrates the solution graphically and allows us to structure hypotheses for testing the validity of survey results in comparison to the property value approach. The vertical axis measures the quantity of the composite commodity, X, where we assume that the cost, C, of the composite commodity is unity; i.e., the vertical axis measures dollars as well. Pollution is on the horizontal axis. Given household income Y^o, the budget constraint, shown as $Y^o - R(P)$ in Figure 1, is obtained by vertically subtracting the rent gradient, R(P). Thus, household A with preferences shown by indifference curve I^o_A would maximize utility at point "a", choosing to locate at pollution level P^o, consume X^o and pay rent R^o. If household A's income were to increase to Y^1, the budget constraint would shift vertically to $Y^1 - R(P)$ and the same household would relocate, choosing point "b", at a lower pollution level P^1 with higher consumption, X^1, given tastes as represented by indifference curve I^1_A. Alternatively, another household, B, with, income Y^o, but tastes as shown by I^3_B would choose point "d", locating at P as well, but choosing lower consumption X^3. Thus, both tastes and income enter location decisions over pollution levels.

The survey approach used in the Los Angeles metropolitan area to obtain an estimate of the value of air quality asked households how much, at most, they would be willing to pay for an improvement in air quality at the site where they presently live. Thus, the household in equilibrium at point "a" in Figure 1 was asked how much X it would forego to experience P^1 rather than PO while maintaining the same utility level. Presumably, household A would be indifferent between points "a" and "c" and be willing to pay W^A dollars (or units of X) to achieve a reduction in air pollution of ΔP. Unfortunately, as is illustrated in Figure 1, the budget constraint, $Y^o - R(p)$, obtainable by estimating the rent gradient function, R(p), does not provide information on the bid for improved air quality, W^A. Rather, the change in rent between locations with air quality levels P^o and P', ΔR in Figure 1, must, for any household located at "a", equal or exceed the bid W^A, if the second order conditions for the household optimization problem are generally satisfied. Thus, we can establish an upper bound on the willingness to pay for air quality improvement by examining the rent gradient. For example, if household B had a lower income, Y, it would locate at point "e". Even though household B is now located at pollution level P^o like household A, its bid for an air quality improvement ΔP would be W^B, smaller than W^A yet still less than ΔR. Thus, if survey bids are a valid measure of willingness to pay for air quality improvements then $\Delta R > W$.

This hypothesis holds for each household even if we consider the case of multiple housing attributes. Including other attributes such as square footage of the home, bathrooms, fireplaces, neighborhood characteristics, etc., denoted by the vector $\vec{Z}$, the model is revised as follows:

$$\text{Max } U(\vec{Z}, P, x)$$

$$\text{St. } Y - Cx - R(\vec{Z}, P) = 0$$

with first order conditions [4]

$$c\frac{U_P}{U_x} = R_P(\vec{Z},P)$$

and $$C\frac{U_{\vec{Z}}}{U_x} = R_{\vec{Z}}(\vec{Z},P).$$

These first order conditions constitute, along with frequency distributions for housing characteristics and household preferences, a system of partial differential equations which solve for $R(\vec{Z},P)$.[5] Thus, a hedonic rent gradient is defined for pollution, P, and other household characteristics, $\vec{Z}$, as well.

As is illustrated in Figure 1, in which housing characteristics other than pollution are not incorporated, budget constraints for different households are obtained by vertically shifting the same rent gradient. Thus, all households face the same rent differential ΔR for a change in pollution level ΔP even though willingness to pay for that change may differ, i.e., $W^A \neq W^B$. However, turning to Figure 2, household A, located at P^o, may occupy a house with attributes $\vec{Z}^A$ while household B also located at P^o may occupy a house with a different set of attributes $\vec{Z}^B$. Household A, with income Y^A, would then face a rent gradient like that shown in Figure 2 defined by $R(\vec{Z}^A, P)$ and choose point "a", but household B with income Y^B, would now face a different rent gradient of $R(\vec{Z}^B, P)$ and choose to locate at point "b". Therefore, households with different housing characteristics may face different rent gradients over pollution when projected in the (X, P) plane. In general, ΔR, unlike the case shown in Figure 1, will no longer be constant across households at the same location. However, for each household i (i = A, B in Figure 2), it is still true that the rent differential, ΔR_i, for a change in pollution ΔP, calculated for the fixed vector of housing characteristics $\vec{Z}^i$, will exceed that household's willingness to pay, W^i, for the same change in pollution level at the same location. Note that households were asked their willingness to pay with the specific assumption that they remained in the same house and location. Thus, $\vec{Z}^i$, for a particular household was truly fixed --allowing the simple analysis in the (X,P) plane as shown in Figure 2.

The first hypothesis for testing the validity of the survey approach can be constructed as follows: for each household i in a community, $\Delta R^i \geq W^i$. It then follows that in each community the average rent differential across households, $\overline{\Delta R}$, must equal or exceed the average willingness to pay $\overline{W}$ for an improvement in air quality. In other words, if survey bids are a valid measure of willingness to pay, then for each community in our sample, $\overline{\Delta R} \geq \overline{W}$, i.e., average willingness to pay cannot exceed the average rent differential. Our second hypothesis is that, given the political history of air pollution control in the State of California as described in the introduction, mean bids in each community are non-negative, $\overline{W} > 0$.

Our dual test of the validity of survey measures must remain somewhat imprecise because hedonic rent gradients themselves only provide point estimates of the marginal rates of substitution (slopes of indifference curves) between pollution and other goods (money) for individuals with possible differing tastes and income. One does not have information necessary to estimate, for example, the shape of I^{*}_{A} in Figure 1 solely on the basis of the slope of the budget constraint, $R'_A(P^o)$, at point "a". Attempts to estimate individual willingness to pay (W^A in Figure 1) from hedonic rent gradients must thus introduce strong assumptions about the nature of preferences. (See, for an example of an hedonic approach which derives willingness to pay by making such assumptions, Harrison and Rubinfeld [1978].

SAMPLING AND DATA ANALYSIS

The previous section has presented a theoretical framework for a comparison between the survey technique and the property value approach for valuing public goods. In order to empirically implement the comparison, the two approaches require a consistent sampling procedure. This section describes the sampling procedure and results of the separate studies.

Sampling was restricted to households within the Los Angeles metropolitan area. The first concern was air pollution data. Air monitoring stations are located throughout the Los Angeles area providing readings on nitrogen dioxide (NO_2), total suspended particulate matter (TSP) and other pollutants. The objective was to relate as closely as possible the readings of two constituents of air pollution (NO_2 and TSP) to census tracts used both for the property value and survey studies. The air shed was divided into the following air quality regions: "good" (NO_2 < 9 pphm) (TSP < 90 $\mu g/m^3$); "fair" (NO_2 9-11 pphm) (TSP 9-110 $\mu g/m^3$); and "poor" (NO_2 > 11 pphm) (TSP > 110 $\mu g/m^3$). Improvements from poor to fair and fair to good across the region are each associated with about a 30% reduction in ambient pollution levels. Consideration was given to wind patterns and topography of the area in making these distinctions.

Many variables may affect the value households place on air quality. To control for as many of these as possible in advance of the actual experiment, the sample plan identified six community pairs where each pair was relatively homogeneous with respect to socioeconomic, housing and community characteristics, yet allowed for a significant variation in air quality.[6]

The property value analysis attempts to provide external validation for the survey approach. The absence of such validation explains in our view, the lack of general acceptance of survey techniques. The objective, then, is to estimate the hedonic rent gradient $R(Z, P)$ and calculate rent differentials associated with the poor-fair and fair-good air quality improvements for sample census tracts. These results are then utilized for comparison to the survey results.

A hedonic rent gradient was estimated in accordance with literature as recently summarized by Freeman (1979).[7] Housing sale price is assumed to be a function of housing structure variables (living area, bathrooms, fireplaces, etc.), neighborhood variables (crime rate, school quality, population density, etc.), accessibility variables (distance employment to centers and beach) and air quality as measured by total suspended particulate (TSP) or nitrogen dioxide (NO_2).[8] The primary assumption of the analysis is that variations in air pollution levels as well as other household, neighborhood and accessibility attributes are capitalized into home sale price. Implicit or hedonic prices for each attribute are then determined by examining housing prices and attribute levels.

The property value analysis was conducted at the household level in order to provide an appropriate comparison to the survey instrument. Thus, the household data used were at the micro level of aggregation and include a large number of characteristics.[9] Data was obtained for 634 sales of single family homes which occurred between January, 1977 and March, 1978 in the communities used for the survey analysis. In addition to the immediate attributes of the household, variables which reflected the neighborhood and community were included to isolate the independent influence of air quality differentials on home sale price.

As indicated by Mäler (1977) even under the Presumption of correct model specification, estimation of a single equation hedonic rent gradient may be hindered by severe empirical difficulties, primarily multi-collinearity. With respect to this problem, in each of three data categories--household, neighborhood, and air quality--multi-collinearity forced the exclusion of variables and the usage of proxy variables. For instance, collinearity between number of rooms, number of bedrooms and living area as quantitative measures of house size allowed the use only one--living area which serves as a proxy for all. Further, since housing density and population density measure essentially the same phenomenon, only the former is used in the estimated equations. The estimation procedure was not able to separate out the independent influence of each air pollutant. Thus, only one pollution measure, either NO_2 or TSP, was utilized to describe the level of air quality. In order to provide information concerning the sensitivity of our analysis, results are presented for each of these pollutants. Finally, contrary to expectation a collinearity problem did not exist between distance from beach and air pollution. This can be attributed, in part, to the success of the sample plan in isolating the effects of air quality.

Two alternative nonlinear specifications are presented in Table 1 alternatively using NO_2 or TSP to represent pollution level.[10] A number of aspects of the equations are worth noting.

First, approximately 90% of the variation in home sale price is explained by the variation in the independent variable set. Second, with only a minor exception, all coefficients possess the expected relationship to the dependent variable and are statistically significant at the one percent level. The exception is the crime rate in both the NO_2 and TSP equations. Third, in their respective equations, the log form of the pollution variables have the expected negative influence on sale price and are highly significant. The estimated relationship between house sale price and pollution is therefore consistent with the graphical analysis of Section 2; that is, the rent gradient is convex from below in the pollution/dollars plane. Finally, the stability or relative insensitivity of the regression coefficients to the particular pollution variable indicates that individuals have an aversion to pollution in general rather than to any one pollutant.

Estimation of the rent gradient was also completed using other forms of the pollution variables (linear, squared, cubic). Whereas the squared and cubic terms did not demonstrate statistical significance, the first order terms performed only marginally worse than the log formulation. Rent differentials have also been calculated for these and other forms with results nearly identical to those presented here.

The next step was to estimate the rent differential ΔR. for each individual household for each census tract. The rent differential specifies the premium an individual household would have to pay to obtain an identical home in the next cleaner air region (poor to fair for six communities, fair to good for three communities). Due to the estimated functional form of the rent gradient, the calculated rent differential is dependent upon the value of all other variables.[11] The average home sale price change based on individual data in each census tract associated with an improvement in air quality, *ceteris paribus*, is shown in column two of Table 2 of the next section. Column one of Table 2 lists communities by air quality level. The table only shows for the log-linear NO_2 equation since, as noted above, other specifications give nearly identical results. The figures shown are derived by evaluating the hedonic housing expression, given the household's characteristics, for a pollution change from poor to fair or fair to good as the case may be. The resulting sale price differential is then converted to an equivalent monthly payment through the standard annualization procedure and division by twelve.[12] Since our hypothesis test is posed in terms of the average rent differential in the relevant communities, then a community mean and standard deviation are calculated. Column three of Table 2 shows the number of homes for which data was available to calculate average rent differentials and standard deviations for each community. Monthly rent differentials ranged from \$15.44 to \$45.92 for an improvement from poor to fair air quality and \$33.17 to \$128.46 for an improvement from fair to good air quality. The higher figures in each case are associated with higher income communities. Again, these average differentials should provide an upper bound for the survey results.

The survey approach followed the work of Davis (1963) and Bohm (1972) in gathering the information necessary for estimating a Bradford (1972) bid curve. The approach involves the establishment of a hypothetical market via a survey instrument. Through the work of Randall, et al., (1974) and Brookshire, et al., (1976), the necessary structure for constructing a hypothetical market for the direct determination of economic values within the Hicksian comsumer surplus framework has been developed. The survey reported here is consistent with this previous literature.

The hypothetical market was defined and described both in technical and institutional detail. The public good (air quality) was described by the survey instrument to the respondent in terms of easily perceived levels of provision such as visual range through photographs[13] and maps depicting good, fair and poor air quality levels over the region. Respondents had little difficulty understanding the levels of air quality represented to them because of the sharp pollution gradient across the region.

Payment mechanism:[4] were specified within the survey instrument and the respondent was asked to react to alternative price levels posited for different air quality levels. In every case the basis for the bid for better air quality was the existing pollution situation as determined by location of their home shown on a map of the Log Angeles metropolitan area which depicted regional air quality levels. Various starting points for the bidding prices and differing information structures were included in the survey format. Biases from alternative starting points and information structures were not present in the. results [See Brookshire, et al. (1980)].[15]

The survey was conducted over the period of March, 1978. A total of 290 completed surveys were obtained[16] for the above mentioned areas. Sampling was random within each paired area.

Table 2 in the next section presents the mean bids and standard deviations and number of observations in Columns four and five respectively for each community for an improvement in air quality. Two types of bids are presented: proposed improvements from poor to fair air quality and from fair to good air quality. In poor communities--El Monte, Montebello and La Canada--the mean bids ranged from $11.00 to $22.06 per month. For the fair communities--Canoga Park, Huntington Beach, Irvine, Culver City, Encino and Newport Beach communities--the mean monthly amounts range from $5.55 to ***$28.18*** to obtain good air quality.

TEST OF HYPOTHESES

The previous sections have described a theoretical structure and two different empirical estimation techniques for determining the value of urban air quality improvements in the Los Angeles metropolitan area. The theoretical relationship between the valuation procedures ($\overline{\Delta R} > \overline{W}$) and the hypothesis that survey bids are non-zero ($\overline{W} > 0$) are tested in this section.

Table 2 presents the community average survey bids (column four) and corresponding rent differentials (column two). As is indicated, in each community the sample survey bids are non-zero and less than the calculated rent differentials in absolute magnitude. This establishes that the survey bid bounds are consistent with our theoretical arguments but does not indicate statistical significance, which is provided below.

With respect to the test of equality of mean survey bids to zero, Table 2 (column six)" presents the experimental results. The calculated t-statistics indicate rejection of the null hypothesis (that the population mean, $\mu_{\overline{W}}$ equals zero at the one percent level in every community sampled.) These resuYts are in accordance with the political situation of the region and indicate that individual households are willing to pay amounts significantly greater than zero for an approximate 30% improvement in air quality.

The comparison of the survey bids to the estimated rent differentials is presented in Table 2 (column seven). In this instance the compound hypothesis that population average rent differential $(\mu_{\overline{\Delta R}})$ equals or exceeds the population average survey bid $(\mu_{\overline{W}})$ is again tested using the t-statistic. Rejection of the null hypothesis requires that the calculated t-statistics be negative and of sufficient magnitude.[17] The standard t-test calculations (column seven, Table 2) imply that the hypothesis $\mu_{\overline{\Delta R}} \geq \mu_{\overline{W}}$ cannot be rejected for the population means $\mu_{\overline{R}}$ and $\mu_{\overline{W}}$ even at the 10% critical level. Although we present only the results for the hedonic housing equation in which log (NO_2) is the pollution measure, these results remain essentially unchanged for all communities, for all estimated hedonic rent gradients, regardless of the variable (NO_2 or TSP) utilized as a proxy for the general state of air quality. The results then are quite insensitive to the particular hedonic model specification, providing a degree of generality to the results.

The hypotheses tests indicate that the empirical analysis is entirely consistent with the theoretical structure outlined above. This conclusion, when combined with the absence of any identified biases [see Brookshire, et al. (1980)] suggests that survey responses yield estimates of willingness to pay for environmental improvements in an urban context consistent with a hedonic-market analysis. A further implication is that individual households demonstrated a non-zero willingness to pay for air quality improvements rather than free riding. This conforms to the previous survey results of Brookshire, et al. (1976) and Rowe, et al. (1980) as well as the experimental work of Scherr and Babb (1975), Smith (1977) and Grether and Plott (1979) concerning the role of strategic behavior. This seems to indicate that the substantive effort to devise a payment mechanism free of strategic incentives for consumers [see Groves and Ledyard (1977)] has been directed towards solving a problem not yet empirically observed. However, the conclusions of this experiment are not without qualifications. In the next section possible limitations of survey analysis and conclusions concerning the efficacy of employing surveys to value a wide range of non-market commodities are discussed.