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Interim Guidance for Visibility Monitoring

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Interim Guidance for Visibility Monitoring

Environmental Monitoring Systems Laboratory

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

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1. INTRODUCTION

Section 169A of the Clean Air Act requires the Environmental Protection Agency (EPA) to promulgate regulations to assure reasonable progress towards the congressionally declared goal of "The prevention of any future, and the remedying of any existing, impairment of visibility in mandatory Class I Federal areas, which impairment results from man-made air pollution." Visibility analysis is also required under EPA's prevention of significant deterioration (PSD) regulations. EPA has proposed regulations which would require certain states to develop and implement programs to address the congressionally declared national goal (FRL 1487-2, Docket No. A-79-40). These regulations require the consideration of visibility monitoring and data in three aspects:

1. Identification of visibility impact from existing sources.
2. Visibility assessment for New Source Review.
3. Evaluation of long term strategy for making reasonable progress toward achieving the national goal.

In July 1978, EPA sponsored a Visibility Monitoring Workshop to address technical and programmatic visibility monitoring needs[1]. This workshop was attended by representatives of the EPA, Departments of Interior and Agriculture, Electric Power Research Institute, industry consulting firms, and other scientific and government organizations. The recommendations of this workshop served to provide a focus for EPA's visibility monitoring methods development program. EPA recognizes that continuing research is required in support of visibility monitoring both in the area of instrumentation and in the use and interpretation of data obtained. Although the Agency has not yet promulgated reference methods, there is substantial information available regarding visibility monitoring methods presently in use. This document is intended to summarize that information in terms of interim monitoring recommendations.

The first section of the document covers the general concept of visibility and principles of measurement. A more thorough discussion is found in "Protecting Visibility, An EPA Report to Congress"[2]. The remaining sections discuss technical considerations involving the design of visibility monitoring programs, selection of instrumentation, quality assurance and data processing.

A more detailed visibility monitoring procedures manual will be available in the near future which will detail procedures on operation and maintenance, data handling, calibration, and quality assurance for visibility monitoring. Over a longer time frame, EPA intends to develop a standardized reference method (or methods) for visibility monitoring.

2. GENERAL DISCUSSION

2.1 Visibility Definition

Visibility can be broadly defined as the degree or extent to which something is visible. The study of visibility and its relationship to meteorology and atmospheric aerosol content is a complex and, in many cases, a semi-quantitative science. Traditionally, visibility has been defined in terms of visual range; the distance from an object that corresponds to a minimum or threshold contrast between that object and some appropriate background. Threshold contrast refers to the smallest difference between two stimuli that the human eye can distinguish. The measurement of these quantities depends on the nature of the observer, his or her physical health, and mental attitudes of attention or distraction such as effects of boredom and fatigue.

Although visibility defined in terms of visual range is a reasonably precise definition, visibility is really more than being able to see a black target, or any target, at a distance for which the contrast is reduced to the threshold value. Visibility also includes seeing vistas at shorter distances and being able to appreciate the details of line, texture, color, and form. Since at this time it is not reasonable or even possible to define visibility in terms of one physical variable, the recommended alternative is to measure a set of variables that effectively characterize visibility, that is characterize the perception of such things as color, line, texture and form.

Characterization of visibility and its impairment involves the measurement of variables that: 1) relate directly to what the eye-brain system sees, 2) can be monitored directly, and 3) can be related to the atmospheric constituents controlling visibility. Apparent target contrast is a variable which meets the first two criteria and serves as the fundamental measure of visibility impairment. Color change also meets the first two criteria. However, current knowledge does not allow for a definition of the best way to express vista color and color change and thus they will not be addressed in this document. The measurements of fine particulate concentration and scattering coefficient go a long way towards achieving the second and third criteria and must be considered as an integral part of any visibility monitoring program. Visual range cannot be directly measured by any instrument. However, when site intercomparisons are required (such as for establishing regional trends) it will be necessary to use visual range as a normalizing parameter. Also, because of its historical popularity, it remains a useful concept to indicate atmospheric "clarity" to the lay person.

A visibility monitoring program should utilize a combination of these measures depending on the specific objectives of the program.

2.2 Visibility Theory

In order to deal quantitatively with visibility impairment, it is necessary to define the physical basis for light absorption and scattering.

The importance of air quality impact on visibility, "the seeing" of distant objects, is based on the ability of aerosol to scatter and absorb image forming light as it passes through the atmosphere (Figure 1). The loss of image forming light is proportional to b_s and b_{abs}, the atmospheric scattering and absorption coefficient. The combined effects of scattering and absorption will be referred to as extinction, and b_{ext} will be used to represent the extinction coefficient.

Radiance, N, is a measure of the amount of monochromatic radiant energy present at some point in space. Thus ${}_tN_r$, the apparent target radiance incident at an observation point located a distance r from some target, is a measure of radiant energy reaching an observer who is viewing a target in some specific direction. ${}_tN_r$ is then the sum of the attenuated inherent radiance of the target, ${}_tN_o$, and radiant energy scattered by the intervening atmosphere. The radiant energy scattered by the intervening atmosphere is a result of air molecules or aerosols scattering direct sun, diffuse, or ground reflected light into the sight path. The volume scattering function determines how much of the radiant energy incident on the sight path is scattered toward the eye. It is a minimum for radiant energy incident perpendicular to the sight path and a maximum for radiant energy incident on the sight path from in front of or behind the observer (forward and back scattering). The relative amount of forward and back scattered radiation necessarily depends on the relationship between the wavelength of incident radiation and particle size.

Apparent target contrast, C_r, is defined as the difference between target radiance, ${}_tN_r$, and some background radiance, ${}_bN_r$ (when the background is the sky, ${}_bN_r$ becomes ${}_sN_r$) divided by the background radiance.

$$C_r = \frac{{}_tN_r - {}_sN_r}{{}_sN_r} \qquad 1.)$$

In a similar manner, inherent contrast, C_o, is defined to be the contrast of a target viewed at a distance r = 0, against a background sky:

$$C_o = \frac{{}_tN_o - {}_sN_o}{{}_sN_o} \qquad 2.)$$

Apparent and inherent contrast of a coherent plume (or horizontally constrained layer) of aerosol as seen against a sky or vista background can be expressed in a similar way:

$$C_{r,p} = \frac{{}_pN_r - {}_bN_r}{{}_bN_r} \qquad 3.)$$

and

$$C_{o,p} = \frac{{}_pN_o - {}_bN_o}{{}_bN_o} \qquad 4.)$$

where $C_{o,p}$ and $C_{r,p}$ are the inherent and apparent plume (layer) contrast while ${}_pN_o$ and ${}_bN_o$ are the inherent plume (layer) and background radiance values respectively. ${}_pN_r$ and ${}_bN_r$ are the respective radiance values of the plume (layer) and background at a distance r. The background radiance, ${}_bN_r$, may be for either the sky or a selected vista. It should be noted that contrast is a unitless parameter.

The ratio of the apparent to inherent contrast (C_r/C_o) is contrast transmittance, a measure of the ability of an intervening atmosphere to transmit contrast. The equation that describes the reduction of contrast over a path of length r is given by:

$$C_r = C_o \frac{{}_sN_o}{{}_sN_r} e^{-\overline{b}_{ext} r} \qquad 5.)$$

where $\overline{b}_{ext}$ is the average extinction coefficient over the distance r. Change in apparent vista contrast, ΔC_r, the physical parameter that relates directly to human perception of visual air quality, is calculated by comparing apparent target contrast, C_r, to the apparent contrast for the same target when the atmosphere is free of any air pollution (Rayleigh atmosphere), $C_{r,ray}$:

$$\Delta C_r = C_r - C_{r,ray} \qquad 6.)$$

In most cases $C_{r,ray}$ will have to be calculated using equation 5 with ${}_sN_o/{}_sN_r = 1$ and assumming $\bar{b}_{ext}$ is equal to Rayleigh scattering at the altitude of the observation point.

The quantity ${}_sN_o/{}_sN_r$ is equal to 1 if the earth is assumed to be flat, the atmospheric aerosol and gas concentrations are assumed to be evenly dispersed both in the vertical and horizontal, and the observation angle is equal to zero (horizontal sight path). With these assumptions, equation 5 can be transformed to an equation for the extinction coefficient b_{ext}

$$b_{ext} = -\frac{1}{r} \ln C_r/C_o \qquad 7.)$$

In addition, if the above assumptions are met, visual range can be calculated from the extinction coefficient by:

$$V_r = 3.912/b_{ext} \qquad 8.)$$

If it is further assumed that the absorption coefficient is zero ($b_{abs} = 0$) then $b_{ext} = b_s$ and equation 8 becomes:

$$V_r = 3.912/b_s, \qquad 9.)$$

where b_s is the scattering coefficient. While radiance values, extinction and scattering coefficients can be measured at many different wavelengths (colors), it is usually desirable to make one measurement at 550 nm since the human eye response curve peaks near this wavelength. More detailed discussion of visibility theory is available elsewhere[2,3,4,5,6,7].

2.3 Instrumentation

Visibility, the seeing of distant objects, depends on properties of the object, its background, the quality of the air along the sight path, the length and illumination of the path, and the observation angle with respect to the horizontal.

As indicated previously there are three basic criteria to be used when evaluating candidate parameters to characterize visibility impairment.

1. Measured parameters should relate directly to what an observer perceives.
2. These parameters should be directly measurable.
3. Measured parameters should relate to pollutants causing visibility impairment.

Instrumental measures that relate to visibility are generally of two types: instruments that measure the optical properties of the atmosphere and those instruments that measure physical characteristics of atmospheric constituents.

2.3.1 Optical Measurements

Optical visibility-related instruments are divided into three major classes: contrast, scattering, and transmission type measurement.

2.3.1.1 Contrast Measurements: Contrast type instruments measure the amount of radiant energy reaching a detector from selected targets and their surrounding background. These instruments are called telephotometers and directly measure the apparent spectral radiance of the sky, target or a plume and thus allow for a calculation of target or plume contrast and its change. The apparent contrast of targets or plumes can be easily calculated from the measurements using equation 1 or 3. Visual range can also be calculated after making a series of assumptions about the inherent contrast of the target, uniformity of the atmosphere along the sight path and angle of observation.

Telephotometers make measurements in a way that is very similar to observations made by the human eye. In Figure 1, the eye could be replaced by a telephotometer (shown in Figure 2). Properties of the target, air quality (homogeneity and concentration of visibility reducing aerosols), distance to the target, illumination of the sight path, humidity, and observation angle all affect the measurement. A disadvantage of making such measurements with telephotometers is that it is difficult to separate the different effects. The separation of effects is important if the goal is to isolate the effect of anthropogenic air pollutants on visibility.

Currently telephotometer instrumentation can be broken into three classes: 1) telephotometers which measure radiance at one point in the sky and one point in the vista (two-point telephotometer). The resulting radiance values can

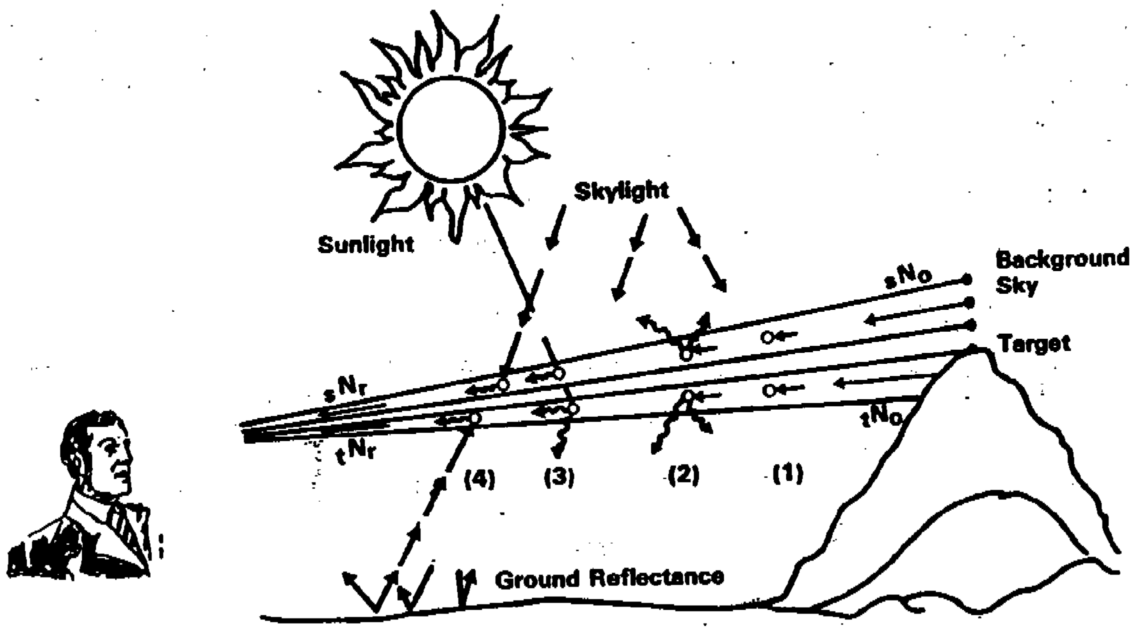

Figure 1. Elements of visibility.
The observer is at a distance r from the target; the inherent background and target radiance are represented by $_bN_o$ and $_tN_o$ respectively while $_bN_r$ and $_tN_r$ are the apparent background and target radiances. Point (1) represents the reduction of sky and target radiance resulting from absorption; point (2) shows the reduction in sky and target radiance resulting from scattering; point (3) represents the increase in target and sky radiance resulting from sunlight scattered into the sight path while point (4) represents increase in target and sky radiance due to scattering of sky light and ground reflected light.

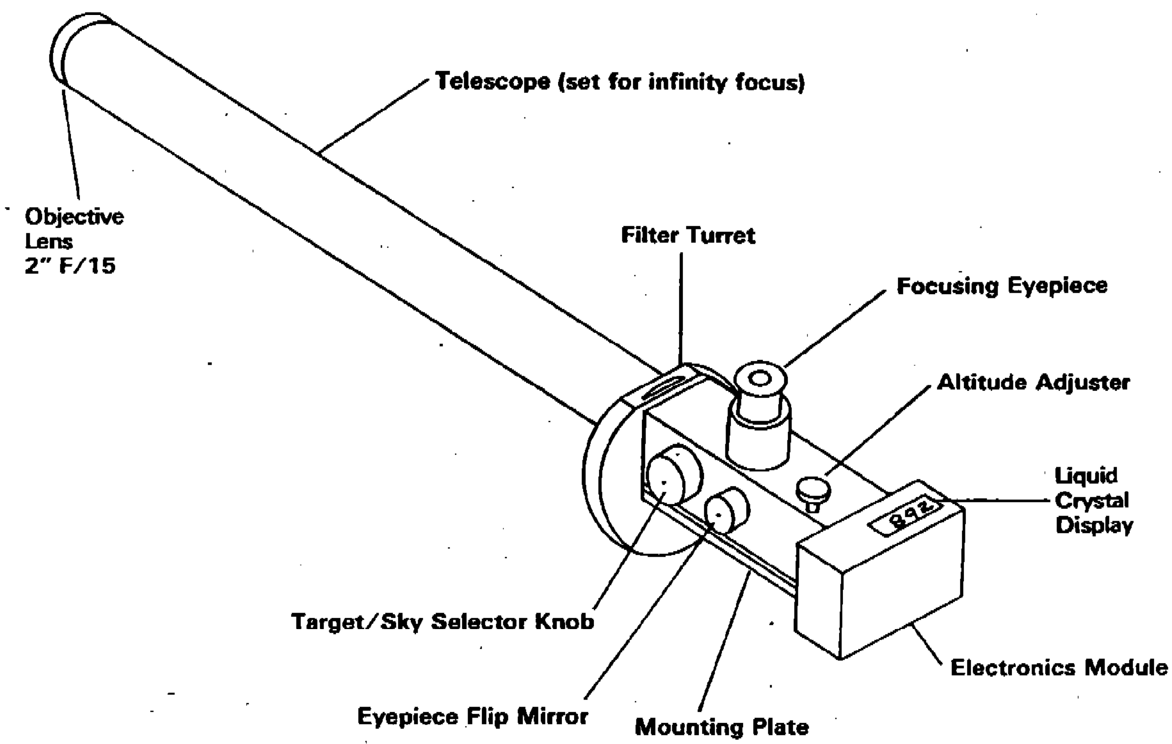

Figure 2. Telephotometer Diagram.
This diagram shows the typical configuration of the electronic and optical components for a telephotometer. This instrument measures sky and target radiance at a number of different wavelengths.

then be used to calculate the apparent target contrast between these two points in the vista. 2) Scanning telephotometers which measure the radiance of a number of points (40 or more) within a vertical scan of the vista. This type of measurement will allow for a calculation of plume or layered haze contrast as well as the contrast reducing capability of the layered haze. Calculation of vista apparent contrast using only radiance values measured from two points in the vista might miss the visual effect of a layered haze, while a measure of radiance values at each point within a vertical scan would not. 3) Cameras; telephotometers which use photographic film as the detector. Photographic documentation can be utilized to "reasonably attribute" visibility impairment to existing stationary sources as required under "Phase I" of the proposed visibility regulation. It also provides a means of documenting the effect of light absorption by NO_2 on plume color (the brown cloud effect). Photographic data serves as a valuable supplement to other measurement techniques. For example, cloud cover, snow cover, and vertical stratification as documented through photography can be used to interpret telephotometer contrast data.

Human eye observation is another important contrast type approach to measuring visibility. Human eye observations are useful in establishing whether visibility impairment is "reasonably attributed" to an existing stationary source. Also, these observations presented as visual range form the largest source of historical visibility data[8]. By knowing distances to spatially distributed vistas or targets, trained observers are able to approximate the furthest distance they can see, that is, determine the visual range. However, the natural targets available for viewing at different locations are not uniform in directions and distances from the observation sites, making the comparison of sites difficult. The availability of targets at long distances

(>100 km) has usually set an arbitrary upper bound on the visual range reported for each location.

In summary, it is recommended that, when doing routine visibility monitoring, contrast measurements should be made with a two-point multi-wavelength telephotometer that has a capability of measuring apparent target and sky radiance. Color photography should also be employed to document vista appearance.

2.3.1.2 Scattering Measurements: The second major class of visibility-related instruments measures the light scattered from a relatively small volume of air in specified directions and at one point in space. Scattering instruments measure a basic optical property of the air sample, the volume-scattering function, which is independent of target properties, natural illumination of the atmosphere, and distance between the observer and the target. Many scattering instruments enclose the air sample, allowing continuous day and night operation by eliminating any need to use natural illumination. Enclosed instruments also allow control of ambient air conditions in order to study the influence of relative humidity, for example. Some unenclosed scattering instruments modulate (vary) the intensity of the light source in order to allow operation during daylight hours.

Scattering instruments measure the light scattered at various angles from the air sample. The choice of scattering angle allows a classification of the instruments into integrating nephelometers, backscatter meters, forward scatter meters and polar nephelometers.

Integrating nephelometers (schematically shown in Figure 3) measure the

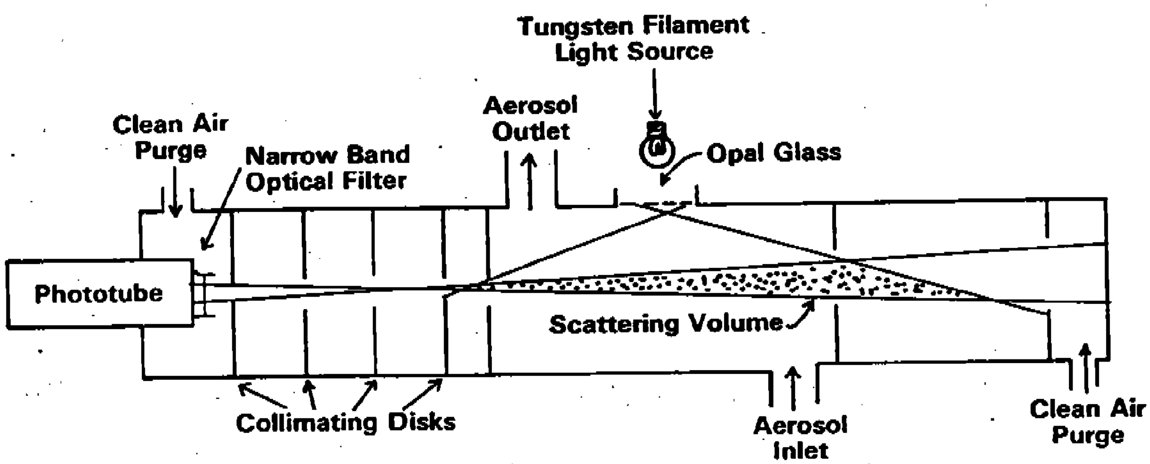

Figure 3. Integrating Nephelometer Diagram.

Schematic shows a typical configuration of the electronic and optical components of an integrating nephelometer. Notice how the relative location of the phototube and light source allow this instrument to detect radiant energy that has been scattered in the forward and back directions. As a consequence, this instrument measures the total scattering coefficient.

light scattered over an angular range covering nearly 0° to 180°, hence, these instruments approximate the total scattering coefficient b_s. The air sample is enclosed, allowing automated, continuous day and night operation. The instrument is calibrated to read out the total scattering coefficient of the air sample. This variable can be translated into the visual range of a black target if the atmosphere is uniform over a distance as long as the visual range and if the target is viewed horizontally. Otherwise instrumental output interpreted in terms of visual range is not valid.

Backscatter meters measure the amount of light scattered backwards from a volume of air (scattering angle between 90° and 180°). The instruments that use a laser for the light source are usually called lidars. Several other backscatter instruments use incandescent or spark lamps. Lidars have been most commonly used to measure the elevation of aerosol layers in the atmosphere by probing from the ground or aircraft with an upward or downward directed beam. Except for the problem of eye safety, lidar could be used in a horizontal orientation to measure the distance of plumes and other inhomogeneities. No backscatter instrument is suitable for measuring scattering coefficients less than the 0.03 km^{-1} (130 km visual range) found in many Western Class I areas.

Forward scatter meters similarly limited to measuring scattering coefficients greater than 0.2 km^{-1} are much too insensitive for use in most Class I areas. These instruments measure the amount of light scattered from a collimated beam in a forward direction (scattering angle between 0° and 90°). They are most commonly used for measuring visibility at airports and along stretches of highway where fog is a danger.

The polar nephelometer is a scattering instrument that measures the light scattered from a collimated source in any specified direction, that is, the volume scattering function. The volume-scattering function is usually measured at a number of scattering angles between 10° and 120°. The polar nephelometer is a powerful research instrument but it is not yet appropriate for routine monitoring use.

It is important to note that the transfer of light through the atmosphere depends on two aspects of air quality: scattering and the absorption of light by gas molecules and aerosol. The total attenuation (loss) of light being transferred through the atmosphere is equal to the sum of scattering and absorption. Typically, since scattering dominates absorption, especially in clean air, it is acceptable to neglect absorption. However, it is not acceptable for urban air or for plumes of rurally located large point sources like coal-fired power plants.

The final type of scattering instruments measure sky radiation. Some of these instruments are used just like a telephotometer, measuring the amount of light (the apparent spectral radiance) reaching the detector from a small portion of the sky. The measurement of sky radiation is important to a rigorous calculation of the visual range of mountains and other natural targets viewed against a sky background. Other sky radiation instruments (pyranometers) measure the total amount of light coming from the sun and sky (the downwelling irradiance). The total sky radiation (sky irradiance) can be measured without the sun irradiance if the instrument is used with an occulting disk to block the direct solar radiation.

The integrating nephelometer is the only instrument recommended for routine monitoring of scattering coefficient.

2.3.1.3 Transmission Measurements: Transmission instruments, shown schematically in Figure 4, measure the amount of light transmitted from a specified source to a receiver, allowing the direct calculation of the average attenuation coefficient of the air along the instrument path. These instruments are independent of the effects of target properties and the natural illumination of the sight path.

One class of transmission instruments called transmissometers uses artificial light sources, including incandescent lamps, xenon spark lamps and lasers. Transmissometers require the placement of either the receiver or reflectors at one end of a baseline and the transmitter at the other end. This fixed baseline does not allow the instrument to easily measure visibility-related variables in different directions. The path for transmission instruments is long compared to the small volume measured by scattering instruments and short when compared to a typical 50 to 90 km path used by a telephotometer.

Laser transmissometers are faced with a critical sensitivity to atmospheric turbulence, which is a problem when attempting to measure transmission through the very clean air characteristic of Western Class I areas. Additionally, a laser transmissometer is limited to one wavelength and, in the case of a He-Ne laser (663 nm), to a wavelength that is unrepresentative of the peak sensitivity of the human eye (550 nm).

Another class of transmission instruments called pyrheliometers measures the apparent sun radiance. These measurements allow the calculation of the optical thickness of the total atmosphere along the path between the observer

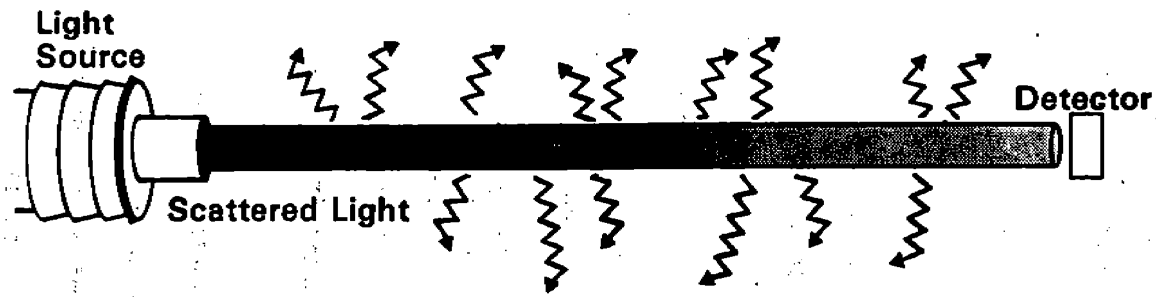

Figure 4. Laser Transmissometer.

Diagram shows the operating principle of a laser transmissometer. As light passes through the atmosphere, it is removed through scattering and absorption processes (extinction). By knowing the amount of radiant energy at the transmitter (laser) and measuring how much of that energy is left after passing a certain distance through the atmosphere, extinction is measured.

and the sun. Corrections for Rayleigh scattering and ozone absorption allow a calculation of the optical thickness due to just aerosol scattering and absorption.

Transmission type measurements are not recommended for routine visibility monitoring.

2.3.2 Additional Measurements

2.3.2.1 Particulate Measurement: There are several instrumental methods that measure the size distribution, mass concentration, or number concentration of the aerosol that usually dominates the scattering and absorption of light in air. Given the aerosol size distribution, the Mie theory of aerosol scattering can be used to calculate the scattering coefficient and thus allow an approximate determination of contrast reduction, visual range, and color change. More importantly, aerosol characterization (composition and morphology) may allow the identification of aerosol sources so that the relative contribution of these sources to visibility degradation can be evaluated and in turn the visibility degradation resulting from anthropogenic activities can be determined.

Generally speaking, the mass distribution of atmospheric aerosol is bimodal in nature (see Figure 5). The coarse mode is defined as containing particles greater in size than about 2 m while smaller particles are said to be in the fine mode. For the most part, the coarse particles are mechanically produced and the fine particles result from condensation and coagulation processes. Traditionally particle sampling has been performed with filters collecting particles over the the entire range from about 100 to 0.1 micrometers in diameter. Ideally for visibility monitoring, particles should be size-

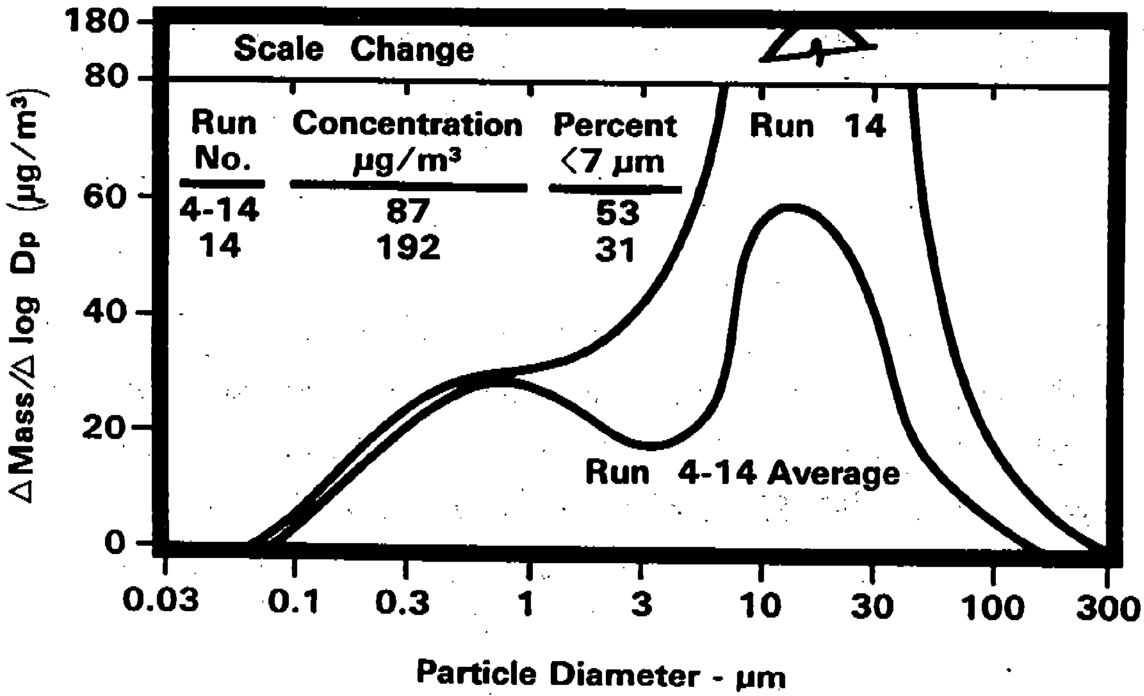

Figure 5. An Example of a Bimodal Mass Distribution of Atmospheric Particles. Bimodal mass distributions measured with a set of special impactors and a cascade impactor are shown in this plot of change in mass concentration for a certain change in diameter versus particle diameter. Run 14 contains many more coarse particles than the average because of construction activity upwind. Note the negligible effect of this increased concentration of coarse particles on the fine particle mode[10].

segregated into many samples (e.g., ten size ranges less than 20 µm) since their efficiency for light scattering is size dependent. However, since airborne particles between 1 and 0.1 micrometers in diameter dominate other particles in their efficiency to scatter light, it is possible to sample in fewer size ranges. As a minimum, particles should be collected in two size ranges corresponding to the two ambient aerosol modes. The size ranges selected by EPA for the Inhalable Particluate Monitoring Network (15 to 2.5 µm and less than 2.5 µm) can be used for this purpose[9].

There are a number of size-segregating particle samplers available. These include physical and virtual impactors, cyclones, and series filtration samplers. In selecting a sampler several things must be considered. The sample configuration and collection medium or substrate must be compatible with the anticipated analysis. Sample duration and flow rate plus estimated concentration within each size range can be used to estimate collected sample mass. Collected sample mass must also be compatible with the analysis techniques. Most manufacturers of sampling equipment include with their specifications a list of compatible analysis techniques.

There are potential problems associated with various types of size segregating samplers which can result in erroneous capture of large particles on smaller particle stages. The use of some types of sample substrates can promote the conversion of gaseous pollutants to particles on the substrate. Detailed discussion of these problems and methods to avoid or minimize them are beyond the scope of this document. A review of literatue pertaining to particle sampling and analysis methodology is a prudent step to take before selection of a sampling technique.

2.3.2.2 Meteorological Measurements: Meteorological information is essential for the thorough interpretation/evaluation of the physio-optical and supplementary particulate data and for use with tools like models to ascertain the effectiveness of proposed control strategies. For instance, information on the speed and direction of the wind can help in the identification of sources of pollutants contributing to visibility degradation. Also, relative humidity, obtainable from measurements of a temperature and dewpoint temperature, can assist in the understanding of local aerosol growth.

Ideally, detailed spatial and temporal information on the dynamic structure (e.g., wind speed and direction and mixing layer thickness) and attendant turbulent properties of the atmospheric boundary layer should be collected. For some monitoring sites, data collected at nearby locations by governmental agencies such as the National Weather Service or by private agencies may be sufficient. For other sites, especially in remote regions in complex terrain or near large bodies of water, such data may not exist or may not be representative. The necessary meteorological monitoring thus should be determined on a case-by-case basis and include consideration of existing data collection.

Guidance for meteorological measurements with regard to monitoring is found in "Ambient Monitoring Guidelines for Prevention of Significant Deterioration"[11] and in "Guidance for NAQTS: Review of Meteorological Data Sources"[12] while that with regard to modeling is found in "Guideline on Air Quality Models"[13].

3. PROGRAM DESIGN CONSIDERATIONS

3.1 General

Three broad objectives of routine visibility monitoring are considered in this guideline. One is to determine the impact of existing emission sources on visibility in mandatory Class I areas. Another is to document and evaluate progress towards achieving the national goal in preventing and remedying visibility impairment. Monitoring to achieve these two objectives is the responsibility of the State and the appropriate Federal Land Manager (FLM). An existing emitting facility may also monitor to document its impact on a Class I area. The third objective is to develop a visibility data base as might be required as part of new source review procedures for PSD permit approval. This monitoring is conducted by the Prevention of Significant Deterioration (PSD) applicant, at the discretion of the State or permit granting authority. Although these objectives are different, the visibility monitoring program developed to meet them must address two needs in each case.

1. Document visual air quality.

2. Ascertain a cause-effect relationship for the observed impairment.

As a result, several different measurements must be made for a given vista. Documenting visibility impairment requires contrast measurements using a telephotometer, with supporting photographs. Supplemental measurements include fine-particulate collection and analysis, measurement of scattering coefficient by an integrating nephelometer, and measurement of meteorological parameters. These measurements are important for interpreting visibility data and establishing the cause of visibility impairment.

3.2 Monitoring Duration

Regulatory language suggests that visibility assessment for new or existing major point sources be done on a seasonal basis. Seasons are defined as:

Winter,	December to February
Spring,	March to May
Summer,	June to August
Fall,	September to November

It is recommended that a minimum of one full year of monitoring be conducted for visibility analysis of major point sources. Because of climatological variability, it is recommended that five years of data be obtained to document ambient conditions and to perform trend analysis. Selected monitoring stations will be needed to monitor over a longer term (10 to 15 years) in order to document progress towards achieving the national goal.

3.3 Monitoring Instrumentation

The minimum recommended sampling configuration for routine visibility monitoring is shown in Table 1. Detailed guidance concerning instrumentation, siting, measurement frequency, and operation is presented below.

TABLE 1. RECOMMENDED MINIMUM VISIBILITY MONITORING PROGRAM

Instrument	Parameter	Frequency
Electro-optical Measurements Manual or Continuous multi-wavelength telephotometer	Target and sky radiance	Manual: 3 measurements/day Continuous: daylight hourly averages
Camera (color photography)	Vista appearance	3 photographs/day
Integrating nephelometer	Scattering coefficient	Continuous (hourly average)
Supplemental measurements Particulate monitor	Mass concentration of particulates, elemental constituents, in 2 size ranges	2 samples/week
Meteorological sensors	See Section 2.3.2.2	

3.3.1 Contrast Measurement

Target contrast provides a basic measure of visibility impairment. It is directly measurable and relates directly to what people perceive in terms of visual air quality[14].

3.3.1.1 Instrumentation: The multi-wavelength telephotometer is the fundamental instrument for contrast measurement. The telephotometer should have the capability of recording sky and target spectral apparent radiance at wavelengths of 400 nm, 450 nm, 550 nm, and 630 nm. The 550 nm wavelength corresponds to the peak response of the human eye and is used as a measure of contrast and to calculate visual range. The other wavelengths will be needed to evaluate vista color. The full width at half maximum (FWHM) of each "color band" should not exceed 30 nm. The sensitivity of the instrument should be such that it is capable of measuring a radiance of 2 μwatts/cm^2, steradian, nanometer. Depending on operating requirements, either a manual or continuous telephotometer may be used. If a coherent plume can typically be seen, or if levels of layered haze are observable, a scanning telephotometer should be considered. A two-point telephotometer might look over or under the layered haze or plume.

3.3.1.2 Sensitivity: On-going studies are establishing the functional relationship between physical variables (apparent target contrast) and human perception. There is strong evidence that the functional relationship between perceived visual air quality and contrast is linear; furthermore, that an observer can perceive differences between vista apparent contrast as small as 0.04[14,15]. Ideally then, an instrument should have a sensitivity such that its output is capable of predicting vista apparent contrast changes of approximately 10 percent of the smallest perceptible value or a contrast change of 0.004. For most commercially available telephotometers the actual uncertainty in measured contrast is less than 0.01[16], which is satisfactory for routine monitoring.

3.3.1.3 Site Selection: A number of criteria must be considered when selecting a site for contrast monitoring.

a) Appropriate vistas: The visibility regulation requires the identification by Federal Land Managers of vistas to be afforded visibility protection. Such vistas become priority candidates for visibility monitoring sites.

b) Logistics: In the design, deployment, and operation of a monitoring station, the accessibility of the site and the availability of power are prime considerations. Security and aesthetic impact are other practicalities which must be considered.

c) Local Impact: Telephotometer measurements tend to be quite independent of local sources if the vista of concern extends well beyond the immediate vicinity of those sources. However, local sources should be avoided.

d) Target Diversity: If possible, it is recommended that multiple targets be monitored from a single site. A minimum of three targets is recommended.

3.3.1.4 Target Selection: The four primary considerations for target selection are:

a. the distance from the observation point
b. size of target
c. the inherent color of the target
d. the observation angle.

a) Target Distance: The optimum target distance to minimize measurement error and maximize sensitivity is directly dependent on the visual air quality. The optimum distance between observer and vista should be between 10 percent and 75 percent of the average visual range; the ideal distance being 25 percent of the average visual range. Figure 6 graphically displays acceptable observer target distances as a function of the average visual range and extinction coefficient.

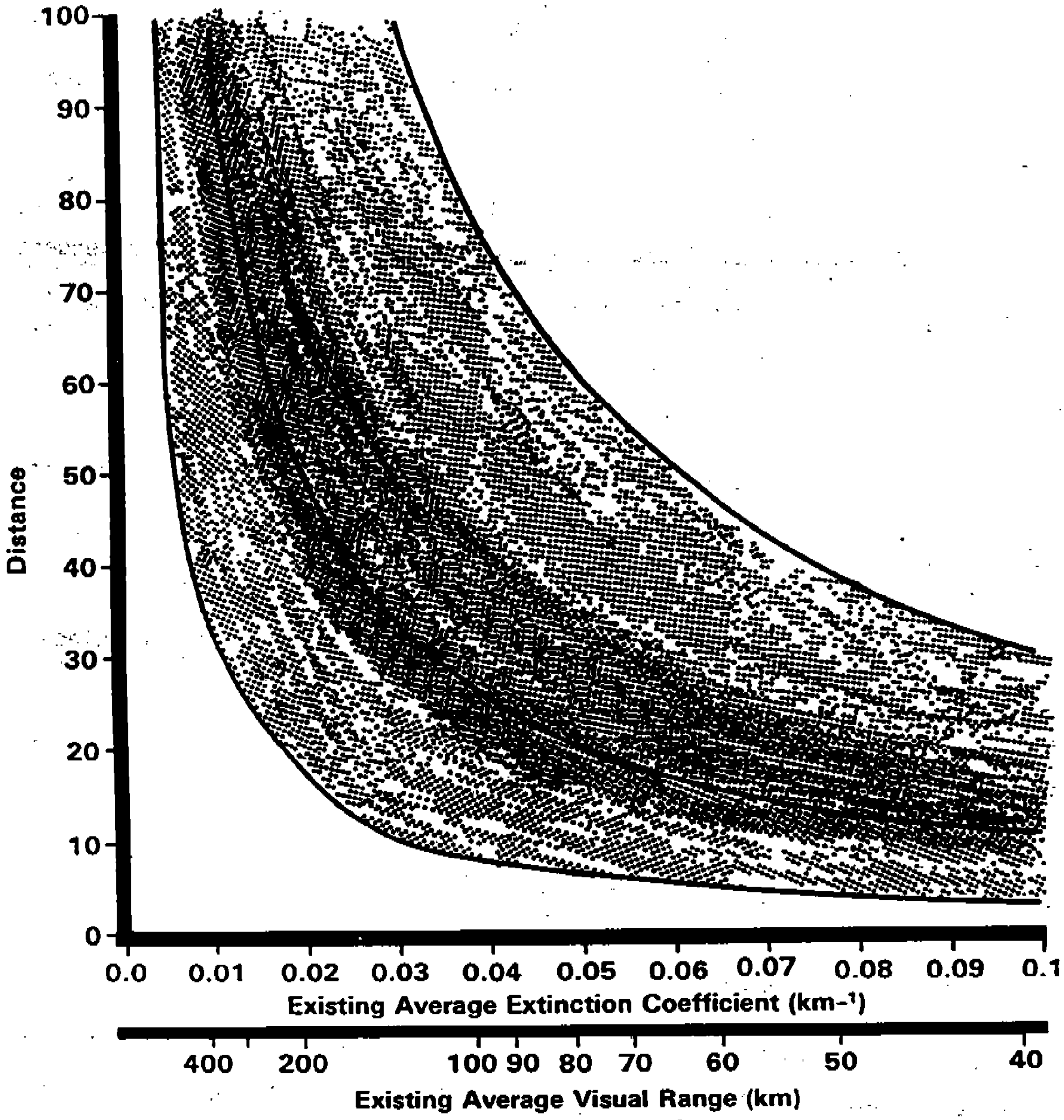

Figure 6. Telephotometer Target Distance as a Function of Average Extinction Coefficient.

This graph shows the acceptable telephotometer observer-target distance as a function of the average existing visual range or extinction coefficient. The solid center line is the ideal distance while the shaded area represents acceptable telephotometer target distances.

For example, for a condition typical of a Western Class I area, one can assume an average visual range of 130 km (extinction coefficient = $0.03\ km^{-1}$). For this average condition (from Figure 6), targets between 13 and 98 km would be acceptable, with 33 km being optimum. In an Eastern situation with an average visual range of 40 km (extinction coefficient = $0.1\ km^{-1}$), the optimum target distance would be 10 km.

b) Target Color: The ideal (black) target normally does not occur in the real world. However, targets of uniform dark color (conifer tree-covered mountain or hill) are often available. Target color and inherent contrast must be corrected for especially if the data are to be used for calculating visual range[17].

Figure 7 shows the effect that an erroneous assumption for inherent contrast, C_0, will have on calculated visual range or extinction coefficient as a function of the ratio of target distance (r) to visual range (V_r). This figure also points out the extreme importance of choosing a target that is greater than 10 percent of the average visual range.

For example, tree covered mountains have an inherent contrast, C_0, at 550 nm, of -0.87 in shade and -0.72 in sunlight. Assuming this type of target to be black ($C_0 = -1.0$) would result in an error in C_0 of 15 percent and 39 percent respectively. Fo- a short target-observer distance ($r/V_r < 0.2$) the resulting error in calculated visual range or extinction coefficient is greater than 25 percent. This error drops to less than 10 percent for $r/V_r > 0.6$. Thus when visual range is calculated, it is important to know the appropriate C_0 values; targets cannot be assumed to be black. The development of C_0 values specific for individual targets under varying light conditions is an area of active

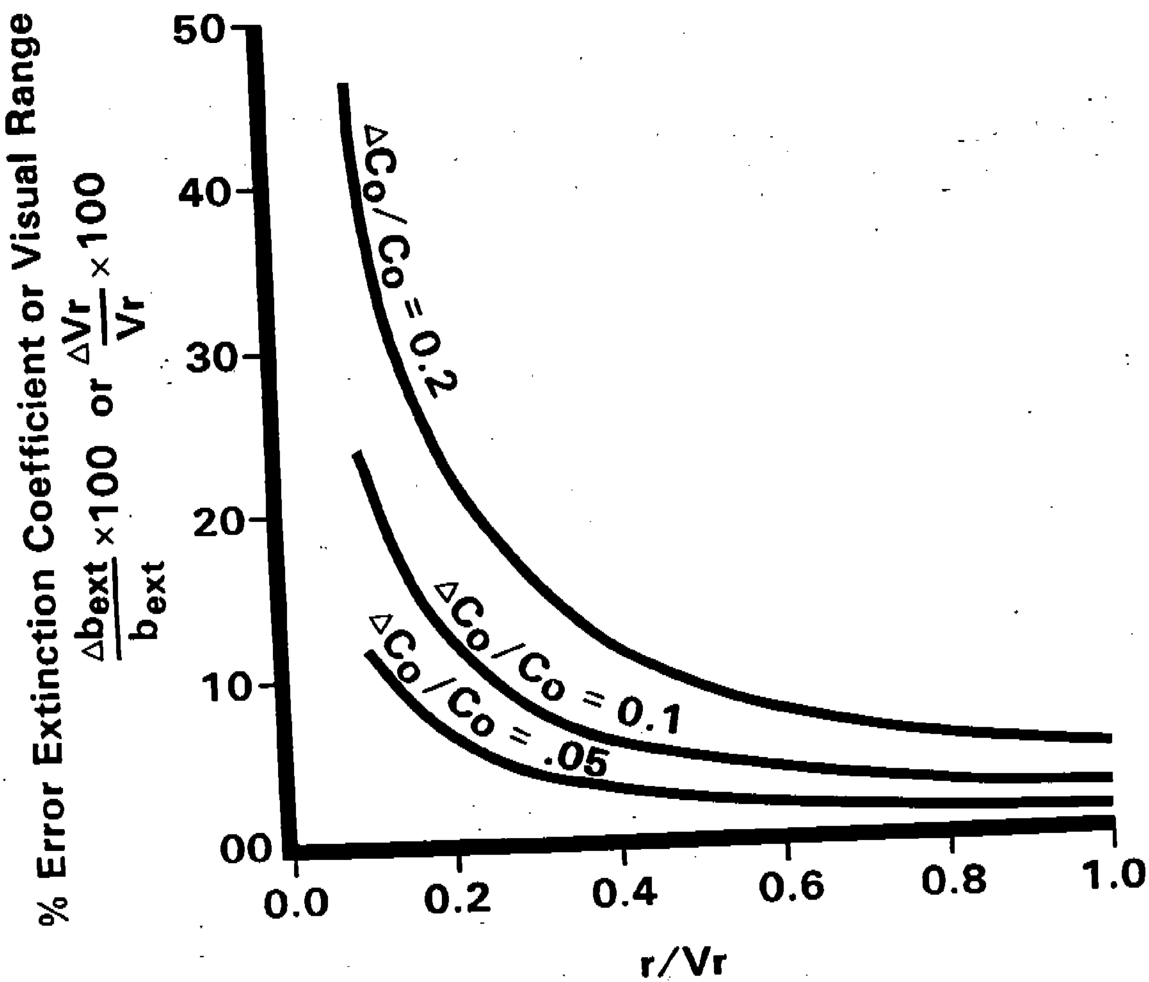

Figure 7. Visual Range Error Resulting from Inherent Contrast Assumptions. This graph shows the error in extinction or visual range as a function of the target distance divided by existing visual range (r/V_r) for different inherent contrast errors. It should be evident that it is important to keep the target distance greater than 10 percent of the average visual range. Typically for tree-covered targets under even illumination, the error in inherent contrast is less than a few percent.

research. The previously stated values of inherent contrast for tree-covered mountains, -0.87 for shade and -0.72 in direct sun, have been shown to be reasonable estimates[18].

c) <u>Target Observation Angle</u>: Target observation angle becomes important if telephotometer data are to be used to derive visual range[4]. This derivation assumes that the sky radiance at the target and observation point are equal and the average attenuation coefficient between the observer and target is the same as that between the observer and a distance equal to the visual range. Because scattering coefficient generally decreases with elevation, viewing an object at some observation angle greater than 0° induces an error in the calculation of visual range. Although it is recognized that all targets will not be able to be viewed horizontally, it is recommended that viewing angles be kept less than 3° from the horizontal plane.

3.3.1.5 <u>Measurement Frequency</u>: When siting permits, continuous instrumentation should be used. Telephotometer measurements of contrast and spectral apparent target radiance should be made at the four different wavelengths continuously during daylight hours. Hourly averages should be computed. When using a manual telephotometer, measurements of contrast and color should be made at least three times a day: 9:00 a.m., 12:00 noon, 3:00 p.m. local time. However, more measurements are desirable. At the time the measurements are made, a color photograph should be taken of each vista that is being used as a telephotometer target. Additionally, a record of time of day the measurement was made, cloud cover and target condition (snow cover, sun illumination, etc.) must be kept. Measurements should be made daily, irrespective of weather conditions, as long as the targets are visible.

3.3.2 Scattering Measurements

Scattering coefficient provides a measure that is directly related to the primary cause (particulate scattering) of visibility impairment.

3.3.2.1 Instrumentation: The fundamental instrument for scattering measurement is the integrating nephelometer. The integrating nephelometer should be a single wavelength instrument with peak response at 550 nm, with a FWHM of 100 nm.

3.3.2.2 Sensitivity: As presented in section 3.3.1.2, the instrument should be sufficiently sensitive to predict a contrast change of 0.004. Figure 8 shows the uncertainty in C_r as a function of scattering coefficient error ($\Delta b/b$) or visual range error ($\Delta V_r/V_r$) for various atmospheric fine particulate concentrations (FPC) and for a black target ($C_0 = -1$) located 50 km from an observation point. The horizontal dashed line represents the acceptable error in the measured scattering coefficient to yield the sought after uncertainty of apparent contrast of 0.004 or less. Currently available integrating nephelometers claim an overall accuracy of ± 10 percent of reading, over an operating range 0 to 0.25 km^{-1}. For the case shown in Figure 8, this would not be within the required accuracy to predict an apparent vista contrast change as small as 0.004 in a pristine atmosphere (FPC < 8 $\mu g/m^3$). An error in the measured scattering coefficient of 10 percent would correspond to an uncertainty of 0.03 in predicted target contrast under Rayleigh scattering conditions. The same error corresponds to a contrast uncertainty of only 0.005 under conditions equivalent to a FPC of 16 $\mu g/m^3$ [19]. It is important to recognize these limitations when interpreting nephelometer data. An additional problem with currently available nephelometers is zero drift. Corrective action for zero drift is discussed in section 3.3.2.4.

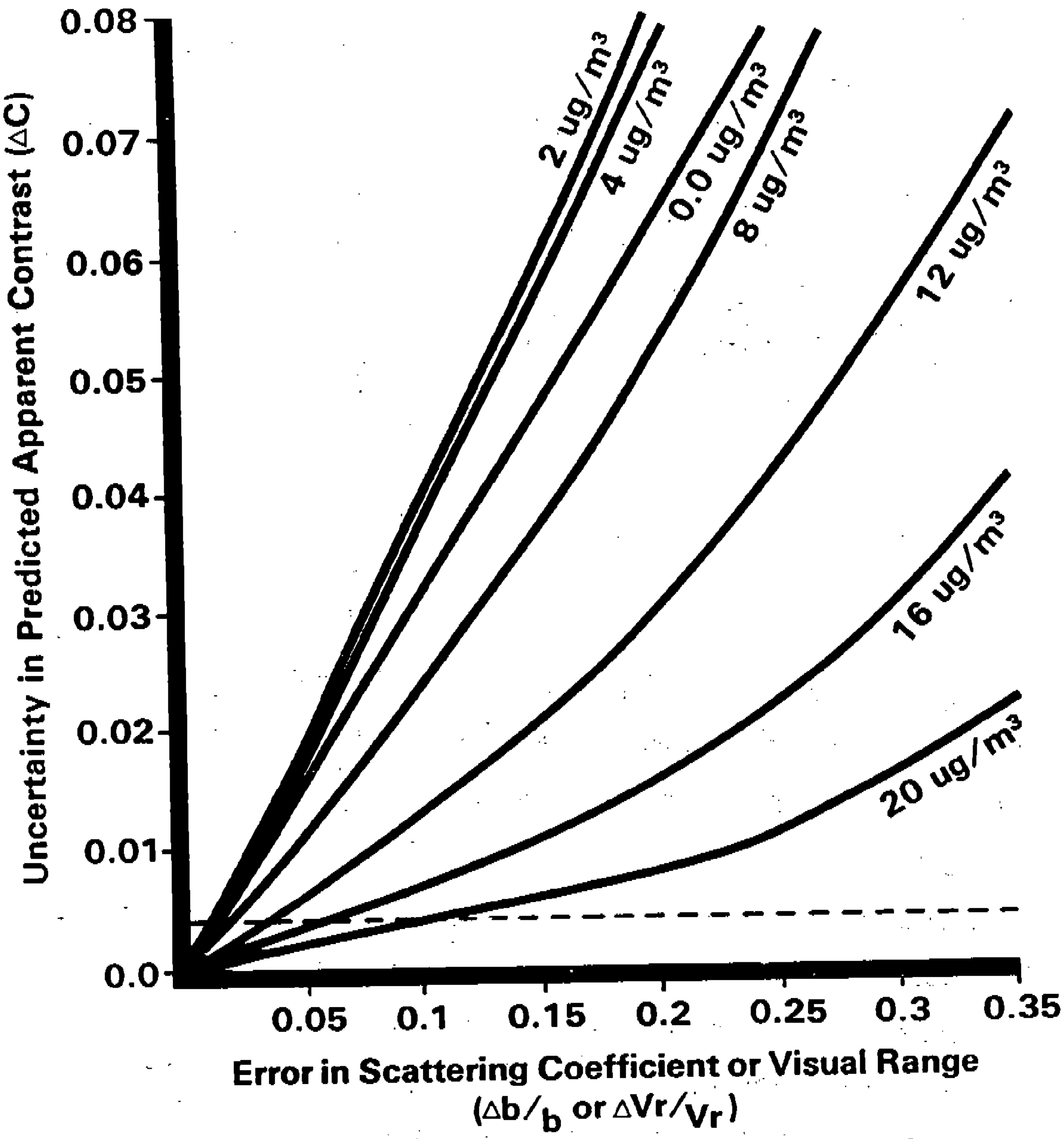

Figure 8. Uncertainty in Predicted Apparent Contrast Resulting from Extinction Coefficient Frror.

Plot of uncertainty in predicted apparent contrast resulting from error in measured scattering coefficient for various atmospheric fine particlate concentrations. The horizontal dashed line corresponds to the acceptable error in scattering coefficient that would yield a contrast change of 0.004 or less.

3.3.2.3 Site Selection: Site selection for the nephelometer is critical. The nephelometer, being a point measurement, will be insensitive to horizontal pollutant gradients or inhomogeneities. If the monitoring objective is to document regional haze, the site may be collocated with the telephotometer. If, however, the objective is to measure a distinct or channeled plume then a site or sites must be selected to be representative of plume impact. For Western Class I areas this is a difficult task. The nephelometer is also very sensitive to local sources, i.e., automobiles, space heaters, generators, etc.[19]. Consequently, it must be located in an area free from local traffic or population impact.

3.3.2.4 Probe Siting: Probe siting criteria should follow that specified for particulate non-criteria pollutants under "Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD)[11].

3.3.2.5 Operations: When operating a nephelometer in an area of high relative humidity (greater than 60 percent), care must be taken not to modify the aerosol as it passes through the inlet sampling tube (see Figure 9)[20]. Specifically, the optional heater/dryer should not be used. Experience has shown that the sensitivity of the instrument can be increased by : 1) controlling the temperature at which the nephelometer operates and 2) monitoring the zero point drift. Temperature can be maintained by housing the nephelometer in an insulated, temperature controlled shelter. Zero drift can be monitored by routinely recording the nephelometer output when its sample chamber has been purged with clean air. The clean air reference system (Figure 10) consists of a blower (brushless motor) with preceding and following glass fiber filters. A clock timer interrupts the nephelometer sampling pump and engages the external blower, which is connected to the sample inlet through a tee fixture[21].

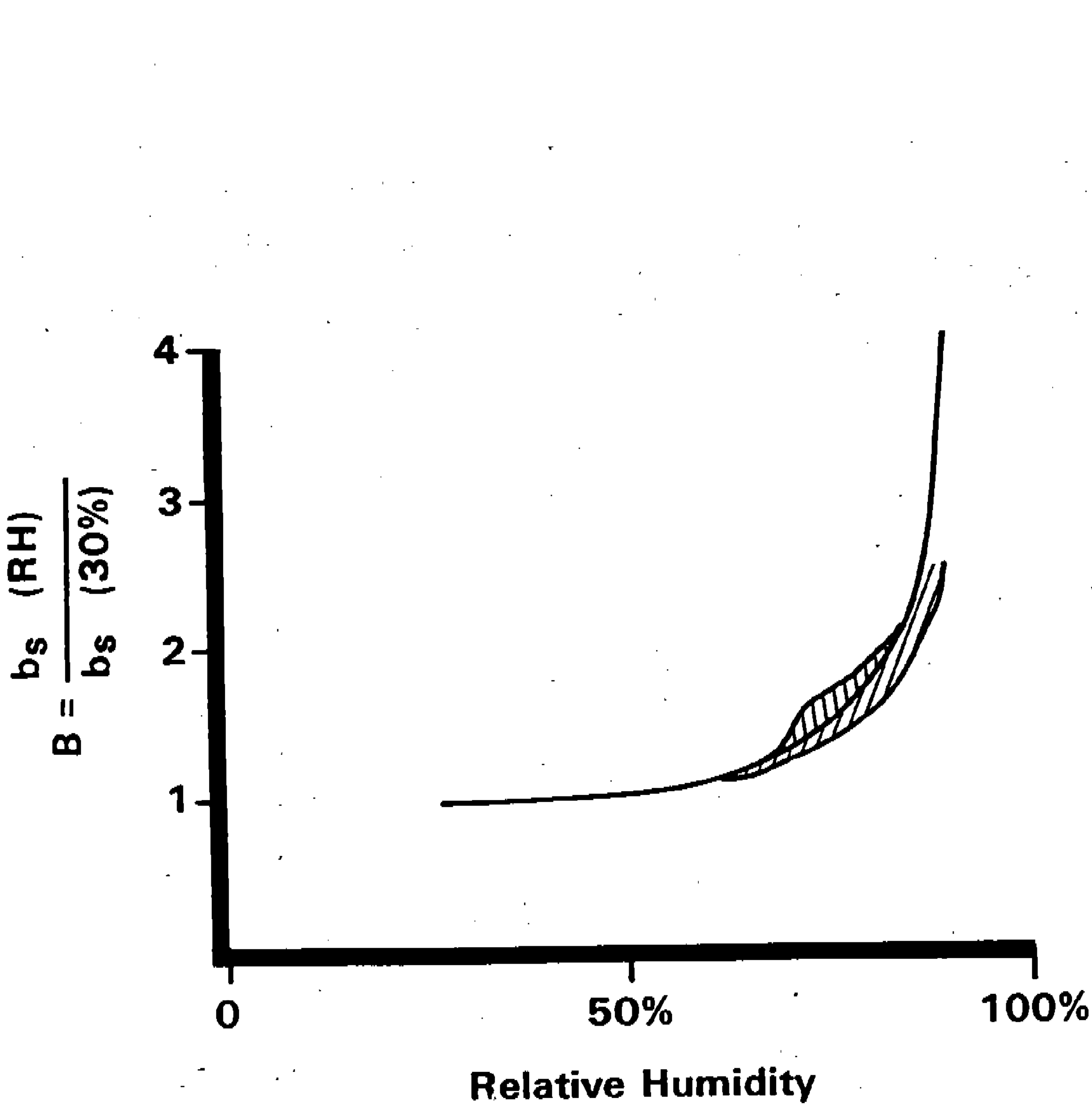

Figure 9. Effect of Relative Humidity on Scattering Coefficient. This figure shows the response of scattering coefficient to relative humidity obtained for a number of locations in the West and Midwest. The cross hatched area includes the entire range of observations[11].

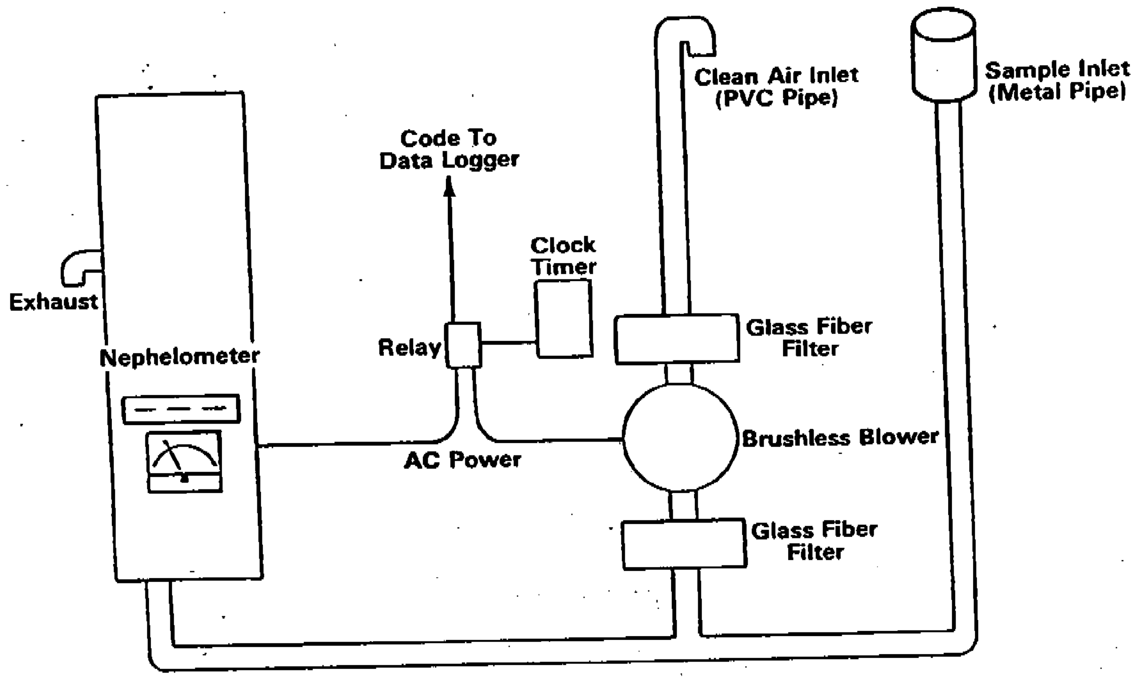

Figure 10. Nephelometer Clean Air Reference System.
The clean air reference system consists of a timer, relay, two glass fiber filters, and a brushless blower. The blower must create a sufficient air flow to purge the integrating nephelometer with clean air despite the fact that the nephelometer is still open to its own sample inlet.

3.3.2.6 Frequency: The nephelometer is a continuous monitoring instrument. Data should be reduced to hourly average values.

3.3.3 Photographic Measurements:

Photography provides a means for documenting overall vista appearance, and the effect of NO_2 on plume color.

3.3.3.1 Instrumentation: The camera system should be equipped with a 135 mm lens with a UV filter. Kodachrome 25 film is appropriate for use. The camera must have an automatic exposure feature and be operated in the automatic mode.

3.3.3.2 Site and Target: The site and target selection criteria are the same as for the telephotometer.

3.3.3.3 Frequency: In conjunction with continuous telephotometers, a photograph should be obtained of each vista a minimum of three times per day (morning, noon, and afternoon). At manual telephotometer sites, photographs should be obtained concurrent with contrast measurements.

3.3.4 Particulate Measurement

The value of collecting particulate samples in conjunction with visibility monitoring comes from the development of statistical relationships between particle characteristics and visibility.

3.3.4.1 Instrumentation: As a minimum, particles should be collected in two size ranges corresponding to the two ambient aerosol modes (Figure 5). The size ranges selected by EPA for the Inhalable Particulate Monitoring Network[8] (15 to 2.5 μm and less than 2.5 μm) can be used for this purpose. There are a number of size-segregating particle samplers available. These include physical and virtual impactors, cyclones, and series filtration samplers. In selecting a sampler, a number of things must be considered: 1) sample configuration and collection medium or substrate must be compatible with the anticipated analysis 2) collected sample mass must also be compatible with the analysis techniques of choice. Most manufacturers of sampling equipment include with their specifications a list of compatible analysis techniques.

3.3.4.2 Site Selection: The same criteria should be used for particulate sampling site selection as for the nephelometer site.

3.3.4.3 Probe Siting: Probe siting criteria should follow that specified for particulate non-criteria pollutants under "Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD)[11].

3.3.4.4 Frequency: Ideally sampling would be performed continuously for the entire period of visibility data gathering, with sample durations of twenty-four hours or less. The low concentrations in many visibility protected areas coupled with the modest flow characteristics of most size-segregating samplers and the sensitivities of many analytical techniques may dictate sample periods of two or three days. Beyond a three-day sample duration many interesting fine features of the aerosol temporal distribution are lost. Sampling should at least be conducted twice weekly.

3.3.4.5 Analysis: The mass concentration of aerosols in various size ranges can be used to estimate visibility levels, however, this use is not suggested since it is not nearly as reliable as direct optical measurements. More important is the use of particulate data to establish statistical relationships between particle characteristics and visibility. Often the composition and morphology of particles can be used to identify their sources. In other words, particle characterization data is used to form a bridge between ambient visibility and pollution emission sources.

The characterization of the particle samples is the key to relating visibility to sources. The more completely the samples are characterized, the better the chance of defining the relationship. There are a variety of analytical techniques suitable for aerosol samples. X-ray fluorescence, neutron activation and atomic absorption techniques are available for elemental analysis. There are many chemical and instrumental techniques to analyze for individual chemical compounds and ions. X-ray diffraction can be used to identify the crystalline nature of samples. Optical and electron microscopy plus individual particle elemental analysis by electron and ion microprobe can be powerful tools for source identification. Because of its relatively low cost, high information yield and non-destructive nature, a multi-element X-ray fluorescence type of analysis is recommended. When applied to all samples collected, it provides a large data set for statistical and other interpretive schemes. It also can be employed as a screening tool to identify samples for subsequent, more complete, analysis. When the influence of a specific source (or sources) is suspected the analysis scheme should be tailored to characteristics of the particles emitted.

3.3.5 Meteorological Measurement

Guidance for meteorological measurements is found in "Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD)"[11].

4. NON-ROUTINE MONITORING

Phase I of the proposed visibility regulation deals specifically with the requirement to control visibility impairment that can be traced to a single major source or small group of sources. It specifies that simple monitoring techniques, such as visual observation or other methods, should be utilized to "reasonably attribute" visibility impairment to a source. Several monitoring methods are available to accomplish this. The objectives of such monitoring would be to 1) demonstrate visibility impairment and, 2) establish the source of the impairment.

The most straightforward method is human observation, where a plume and its source are visible from the protected area. A minimum documentation for each such sighting would include: time and date, observation location, direction and estimated distance to the plume, and a description of plume apparent size, shape and color. Color photography is another method to document impairment as reasonably attributable to a source. The time, date, observation location, and sighting direction would have to accompany each observation.

If visual impairment of a protected vista is evident but the source of the impact is not, other means to demonstrate that a specific source is reasonably attributable can be employed. These would include; 1) concurrent visual observations made from other view points, 2) the use of aircraft observations or aerial photography, or, 3) the application of airborne instrumental techniques such as lidar, correlation spectrometers, or in situ sensors to establish plume source and continuity. These data should be used to augment conventional, ground based visibility monitoring data.

5. QUALITY ASSURANCE FOR VISIBILITY MONITORING DATA

5.1 Introduction

The objective of the quality assurance program discussed here is to control and assess characteristics of the visibility data collected. Unfortunately, many assessment techniques, such as would be used to determine precision and accuracy, are still in the research or testing stage of development. Thus, many of the procedures described here are control oriented and documentary in nature. As such they represent the minimum quality assurance program for an organization operating a visibility monitoring station or network to produce acceptable monitoring data. (In this discussion, "organization" is defined as a source owner/operator, a government agency, or a contractor who operates a routine visibility monitoring network.) If an organization has or wants to develop a quality assurance program more extensive than the one described here, EPA encourages them to do so.

A more comprehensive discussion on quality assurance is available in Volume I of the EPA Quality Assurance Handbook[22]. Several aspects of quality assurance unique to visibility monitoring, such as the criteria for choosing monitoring locations and targets and specifications of instruments, have already been discussed in this guideline. Additional aspects of both internal and external quality assurance programs will be discussed in this section.

5.2 Internal Quality Assurance Procedures

Internal quality assurance is the responsibility of the organization performing the monitoring. It consists basically of using standardized and documented procedures when carrying out essential activities such as:

- Installation and testing of equipment
- Calibrations
- Zero/span checks (as appropriate)
- Control checks (as appropriate)
- Corrective actions resulting from out-of-control conditions (as appropriate)
- Preventive and remedial maintenance
- Recording and validating data
- Documentation of quality control information.

Each visibility monitoring project should develop a project-specific operation manual which details procedures for each of the activities listed above. This manual should be based on manufacturer's instrument manuals and the detailed information on span checks, calibrations, etc., discussed in Section 5.4. Similarly, each project should also have a monitoring project description. In the case of PSD monitoring, this description will be suitable for review by the permit granting authority and the FLM prior to collection of data. In other types of monitoring, it will serve as a summary of project information provided by the monitoring organization when its data are released to other users. The minimum contents of this description, listed in Table 2, generally follow those required for a PSD ambient air monitoring plan, but with one key difference. Target specifications, in addition to monitoring site specifications, are necessary. Project review and data use will be facilitated by the information provided by the monitoring description.

TABLE 2. MINIMUM CONTENTS OF VISIBILITY MONITORING PROGRAM DESCRIPTION

I. NETWORK DESCRIPTION

- Topographical description
- Land-use description
- Climatological description
- Wind roses (if available)
- Topographical map of area showing proposed and existing sources and environs as appropriate with monitoring sites and targets marked
- Rationale for visibility monitoring equipment locations

II. MONITORING SITE DESCRIPTION (Sites with fine particulate monitor, or nephelometer, or meteorological instruments)

- Universal Transverse Mercator (UTM) coordinates and elevation above sea level
- Height of probe(s) above ground
- Distances from obstructions
- Distances from pollutant sources such as generators or roadways
- Photographs of each site, of each cardinal direction looking out from probe, of the nephelometer intake, and of the temperature-humidity sensor

III. OBSERVATION POINT AND TARGET DESCRIPTION

- Universal Transverse Mercator (UTM) coordinates and elevation above sea level for each observation point and target
- Photographs of each vista, with telephotometer targets identified
- Description of target surface features such as vegetation, rock color, etc.
- Elevation angle from horizontal, azimuth angle from true north, and distance from observation point to target

IV. INSTRUMENT DESCRIPTION

- Manufacturer make and model number, principle of operation
- Age of instrument
- Description of calibration system

V. SAMPLING PROGRAM DESCRIPTION

- Time periods for which measurements will be made
- Discussion of the use of existing data or model results in lieu of and/or in addition to collecting ambient data

VI. QUALITY ASSURANCE PROGRAM

- Internal quality control procedures
- Calibration frequency; precision and accuracy calculation procedures
- External audit program

5.3 External Quality Assurance Procedures

External quality assurance for a project generally consists of two parts: a systems audit for the total project, and performance audits for the individual instruments.

The system audit includes a variety of activities designed primarily to identify solutions to problems inherent in the entire data gathering/reporting system. The key activity associated with the systems audit is a critical review of the operational procedures employed. This review should be performed by a person who is intimately familiar with proper visibility monitoring procedures yet is not associated with the design or operation of the project in question. Performance of this review requires monitoring site and laboratory evaluations, interviews with the station operators, laboratory technicians, and managerial personnel, and an inspection of log books, the procedures manual, and other pertinent documentation. Another activity associated with the systems audit should be the submission of test data into the data handling system to insure that proper procedures are followed throughout the entire data system. The systems audit should be performed on an annual basis, or at the beginning and end of the project. The systems audit report and the organization's response to it should be provided to the permitting authority along with the PSD monitoring data, or if the monitoring is for other purposes, the report and response should be made available to data users.

Instrument performance audits should be conducted for telephotometer, nephelometer, and particulate measurements. The specific auditing procedures are described in section 5.4. Performance audits should be conducted annually, or at the beginning and end of the project, whichever is more frequent.

Results of the performance audits should accompany the corresponding data report.

5.4 Data Assessment Techniques

Each visibility monitoring instrument requires specific data quality control and evaluation procedures. Table 3 lists the recommended assessment techniques, their frequency and the information that is obtained. The evaluation techniques listed in the table for external audits and internal procedures are the same in some cases. However, external audits are to be conducted annually, by someone not involved in routine operations, using standards different from those normally used in the project. Internal procedures are to be conducted by regular project personnel. External audits should also be performed at the beginning and end of a project. It is recognized that these procedures are not as comprehensive as the precision and accuracy determinations required by 40CFR58 and the PSD regulations and guidelines for ambient air monitoring. However, these interim guidelines may be revised as instrument evaluations continue.

5.4.1 Telephotometer

Both external and internal methods to assess telephotometer data are listed in Table 3. The external telephotometer instrument audit involves side-by-side field performance comparisons between the routine monitoring instruments and a calibrated instrument of the same type operated by the person performing the audit. Target and sky radiance values and contrast values for all targets routinely observed should be obtained with both the field and audit instruments. The person operating the auditing instrument

TABLE 3. DATA ASSESSMENT TECHNIQUES FOR VISIBILITY MONITORING INSTRUMENTS

Instrument	Method	Frequency	Result
Telephotometer	Side by side, in-the-field comparison of field telephotometer with auditor's telephotometer External audit Internal procedure	 Annually Every 6 months	Percent differences of radiance and contrast values at 4 wavelengths
	External audit with NBS traceable standard light source	Annually	Accuracy as a percent difference of radiance values at 4 wavelengths
	Internal field test and calibration with NBS traceable light source	Every 6 months	Precision as a percent difference of radiance values at 4 wavelengths
	Internal procedure: check and align telephotometer optics check physical integrity of filters	Every 6 months	Properly aligned instrument, filter integrity verified
Nephelometer	External, 1 point audit with with Freon-12* or Freon-22*, according to instrument manufacturer's specification	Annually	Accuracy as a percent difference
	Internal procedure: sample clean, filtered air to determine zero drift	Every six hours or less	Correct data appropriately
	Internal field span check and calibration with Freon-12* or Freon-22*, according to instrument manufacturer's specifications	Every 2 weeks	Precision as a percent difference between known and measured scattering coefficient
Camera	Photograph color chart and gray scale under standard lighting conditions. Check for color uniformity for each roll of film.	At beginning of each roll of film	Qualitative comparison
Fine Particulate Sampler and Analyses	External audit with NBS-traceable weights	Three weights annually	Weighing accuracy as a percent difference
	External audit of flowrate with flowrate audit device	Annually	Accuracy as a percent difference in flowrates
	Internal/external evaluation: participate in interlaboratory comparisons of analytical results and audits when available	Annually	Report summarizing differences between laboratories
	Internal procedure: construct a control chart [illegible] initial flowrates for samplers; establish appropriate control limits	Use flowrate value for each sample collected (minimum of 2 per week)	Invalidate data outside control limits
	Internal procedure: construct a control chart for measurements of a known weight	Weigh sample after each set of 20 filters or before and after weighing session, whichever is more	Invalidate data outside control limits; reweigh filters
Meteorological Sensors	Calibrate sensors (same as PSD requirements)	Every 6 months or less as needed	New calibration factors to use if appropriate

should not be the station operator. For each filter, results of these comparisons are summarized as percent differences. Percent difference, d_i, is defined as

$$d_i = \frac{Y_{field} - X_{audit}}{X_{audit}} \times 100 \qquad 9.)$$

where Y_{field} and X_{audit} represent target contrast, and target and sky radiance values measured for each filter by the field and auditing instruments respectively. In addition, as part of the audit, a portable, standard National Bureau of Standards (NBS) traceable light source should be used to check the calibration of the telephotometer for each filter. The resulting accuracy data should be expressed as percent differences between calibrator radiance and telephotometer-measured radiance values.

Two of the three internal procedures for the telephotometer are similar to those for external audits. In the first procedure, the field telephotometer is calibrated at one point for each filter using an NBS traceable standard lamp; in the second, the field telephotometer is compared to another calibrated telephotometer as described previously. When the instrument is calibrated, the response to the standard lamp should be recorded for each filter before any instrument adjustments are made. Instrument precision for each wavelength can then be computed using equation 9 in the same manner as for accuracy. The results of this comparison are presented as percent differences. In the third procedure, the internal alignment of the telephotometer should be checked and adjusted every 6 months according to the manufacturer's instructions. At the same time, the filters should be examined for physical integrity. A record of these calibrations, instrument checks, and alignments should be maintained for each telephotometer. These three procedures should be conducted twice a year.

5.4.2 Nephelometer

Three data assessment procedures for the nephelometer are mentioned in Table 3. The first procedure, the external nephelometer instrument audit, involves introducing a test gas into the instrument to evaluate the response. Freon-12™ or Freon-22™, as specified by the instrument's manufacturer, should be used. The audit should be conducted by someone other than the station operator. A percent difference is calculated between the known scattering coefficient of the standard gas and the instrument-measured scattering coefficient using equation 9. The second, an internal assessment procedure, consists of sampling filtered air a minimum of every 6 hours so corrections for zero drift can be made. The last is a combination one point field span check similar to the external audit above, and a calibration according to the instrument manufacturer's specification. This is to be conducted once every 2 weeks. The span check values should be determined before the calibration adjustments are made, and a percent difference should be calculated using equation 9. This percent difference should be reported with the quarterly data.

5.4.3 Camera

One data assessment procedure for the camera is given in Table 3. It consists of photographing a standard color chart and gray scale under controlled lighting conditions at the beginning of each roll of film. A controlled lighting condition is achieved by photographing the color chart and gray scales indoors, using an electronic flash located approximately a meter to the side of the camera to minimize glare[23]. It is important to fill as much of the field of view as possible with the gray and color scales so densitometer readings of the slides may be taken at a later time (if desired). At present the technique involves only a visual review of the processed photographs of color charts. A second photograph should be taken to document the film roll number, site name, date, and time.

5.4.4 Particulate Measurement

Five techniques to assess different aspects of particulate measurement are described in Table 3. The external particulate sampling audits involve flowrate audits in the field and weighing audits for the laboratory. A "blind" flow audit device is provided to the station operator who tests the sampler and returns a sampler flowrate value and the associated flow audit device value. The flowrate accuracy results should be presented as percent differences between measured and known flowrates. In the weighing audit a set of three "blind" masses is provided to the laboratory where each mass is weighed. The result, the weighing accuracy, should be presented as percent differences between known and measured weight values.

Several internal procedures are recommended for particulate sampling. To document the status of the pump in the sampler, a control chart should be constructed using initial flowrate for each sample. Details on the construction of control charts and the setting of control limits are discussed in Appendix H of Reference 22. Data collected with flowrates outside the control limits should be invalidated. To document the status of the balance used to weigh the filters, a control chart based on measurements of a known mass should be used. The test mass should be weighed after each set of 20 filters is weighed, or before and after a weighing session, whichever is greater. Filter weights determined when the test mass weight is outside the control limits should be invalidated, and the filters reweighed.

Finally, to check the analytical results, the laboratory should participate in interlaboratory comparisons and external audits where available for the parameters of interest. Results of these comparisons should be summarized and reported annually.

5.4.5 Meteorological Measurement

Procedures for assessment of meteorological measurements are described in the PSD Ambient Monitoring Guidelines[11]. In general, the guidelines call for sensor calibrations every 6 months or more often as needed.

6. DATA REPORTING MANAGEMENT AND INTERPRETATION

As discussed previously, nephelometer data (scattering coefficient) and particulate data are most useful in ascertaining the cause of visibility impairment while telephotometer measurements (contrast) are most useful in quantifying the effect of visibility impairment. Visual range is a useful parameter for interrelating scattering and contrast and to indicate atmospheric clarity to the lay person.

Table 4 outlines, for either a telephotometer or nephelometer, the relationships necessary to calculate apparent target contrast, contrast change, visual range and scattering/extinction coefficient. Only radiance measured at 550 nm should be used in these calculations. Data gathered at other wavelengths will be used to assess vista color change when EPA has determined the most appropriate formulae.

Terms in Table 4 which weren't explicitly defined previously are:

$b_{s,a}$ = aerosol scattering coefficient

$b_{ext,a}$ = extinction coefficient (less Rayleigh)

$b_{ray,h}$ = Rayleigh scattering coefficient at altitude h of the observation point[24]

0.01 km^{-1} is defined as the standard Rayleigh atmosphere

Calculations of visual range are all standardized to the standard Rayleigh atmosphere.

TABLE 4. VISIBILITY RELATED VARIABLES

	Telephotometer (two point)		Nephelometer	
Measures	Apparent Sky Radiance (${}_{s}N_{r}$) Apparent target Radiance (${}_{t}N_{r}$)		Scattering coefficient ($b_{s,a}$)	
Apparent target contrast	$C_r = \frac{{}_{t}N_{r} - {}_{s}N_{r}}{{}_{s}N_{r}}$	(10)	$C_r = C_o\, e^{-(b_{ray,h} + b_{s,a})}$	(11)
Contrast change	$C = C_r - C_{r,ray}$ where $C_{r,ray} = C_o\, e^{-b_{ray,h}\, r}$	(12)	$C = C_r - C_{r,ray}$ where $C_{r,ray} = C_o\, e^{-b_{ray,h}\, r}$	(13)
Visual Range	$V_r = \frac{3.9}{(1/r)\ln(C_o/C_r) - b_{ray,h} + 0.01}$	(14)	$V_r = \frac{3.9}{b_{s,a} + 0.01}$	(15)
Extinction coefficient (less Rayleigh)	$b_{ext,a} = \frac{1}{r}\ln(C_o/C_r) - b_{ray,h}$	(16)	Not applicable	
Aerosol scattering coefficient	Not applicable		$b_{s,a}$ (measured)	(17)

An example calculation using these equations follows:

Assume measurements are made at 550 nm and that:

Site/target characteristics

target distance r = 50 km

$b_{ray,h} = 0.008\ km^{-1}$

$C_o = -0.87$ (shaded forest)

Telephotometer measurements yield

${}_tN_r$ = 7 units of radiance

${}_sN_r$ = 10 units of radiance

Nephelometer measurement yields

$b_{s,a} = 0.011\ km^{-1}$

Then for a telephotometer:

Apparent target contrast

$$C_r = \frac{7-10}{10} = -0.3$$

Contrast change

$$C_{r,ray} = -0.87e^{-(0.008\ km^{-1})(50\ km)} = -0.58$$

$\Delta C = -0.3 - (-0.58) = 0.28$ (Seven times perceptible limit)

Visual Range

$$V_r = \frac{3.9}{[(1/50\ km)\ ln\ (-0.87/-0.3)] - 0.008\ km^{-1} + 0.01\ km^{-1}} = 167\ km$$

Extinction Coefficient less Rayleigh

$$b_{ext,a} = [(1/50\ km)\ ln\ (-0.87/-0.3)] - 0.008\ km^{-1} = 0.013\ km^{-1}$$

While for a nephelometer:

Apparent Target Contrast

$$C_r = (-0.87)\ e^{-(0.008\ km^{-1} + 0.011\ km^{-1})\ 50\ km} = -0.34$$

Contrast Change

$$C_{r,ray} = -0.87\ e^{-(0.008\ km^{-1})(50\ km)} = -0.58$$

$$\Delta C = -0.34 - (-0.58) = 0.24 \text{ (six times perceptible limit)}$$

Visual Range

$$V_r = (3.9)/(0.011\ km^{-1} + 0.01\ km^{-1}) = 186\ km$$

Aerosol Scattering Coefficient

$$b_{s,a} = 0.011\ km^{-1}$$

Similar calculations can be carried out using data derived from a scanning telephotometer; however, in addition, the contrast of a plume or layered haze as seen against the sky or vista background can be calculated.

When extinction coefficient or apparent contrast are measured at a number of locations and are to be intercompared or intracompared, readings should be converted to visual range using the appropriate equations from Table 4. In doing this, however, it is important to recognize the significance of background radiance to the interpretation of apparent target contrast in terms of visual range. A target with a bright cumulus cloud behind it will indicate a higher contrast (larger visual range) than a clear sky situation. Therefore, such comparisons should be considered only for those scenes which are cloud free or have a cloud cover which results in uniform illumination (such as high cirrus clouds or uniform overcast).

The proposed visibility regulation suggests that the visibility analysis dealing with existing or new sources be done on a seasonal basis. Seasonal statistical analysis of visual range, apparent target contrast change, and layered haze contrast should include maximum, minimum, mean, geometric mean, and standard deviation values, and a cumulative frequency distribution. Visual range data should be plotted as a log normal probability plot while apparent contrast should be presented on a normal probability plot.

Examples of hypothetical cumulative frequency plots (see Figures 11, 12, and 13) for visual range, apparent target contrast change, and plume contrast are included for reference. The visual range and contrast plots were developed from telephotometer measurements of sky and target radiance for a target 103 km distant from the observation point.

There will be days when certain telephotometer targets are not visible and visual range and change in contrast cannot be calculated. However, if target distance is, for example, 60 km and the target is not visible, the visual range is evidently less than 60 km and the contrast change has reached a maximum. This observation then becomes a data point that can be integrated into the cumulative frequency distribution. Consequently, when a target has a high occurrence of not being visible, the approximate geometric or arithmetic mean derived from the probability plots is more meaningful than the mean calculated analytically.

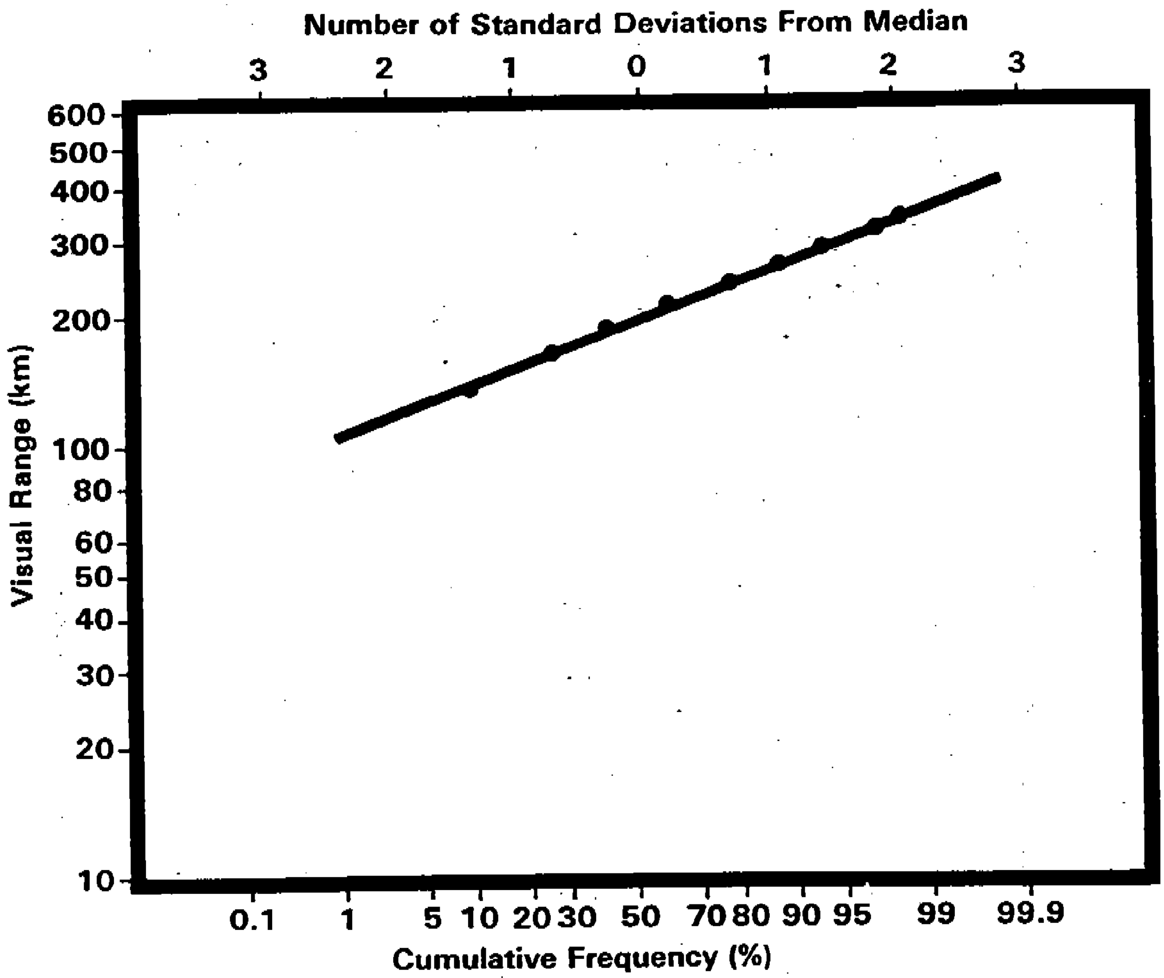

Figure 11. Log Probability Cumulative Frequency Distribution for Visual Range. This figure shows the percent occurrence of visual ranges equal to or less than the specified value. Visual ranges equal to or less than 200 km occur 50 percent of the time.

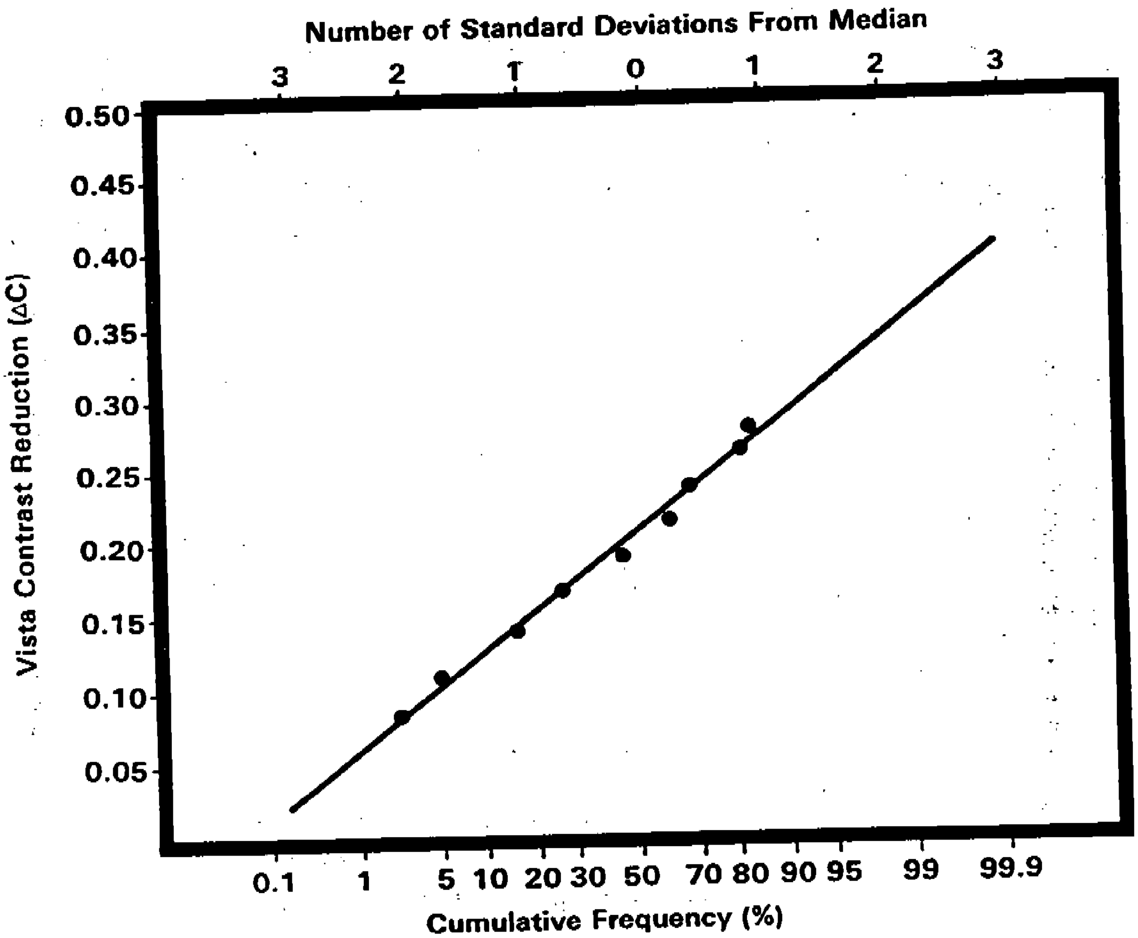

Figure 12. Normal Probability Cumulative Frequency Distribution for Apparent Vista Contrast.

This figure shows the percent occurrence of vista contrast equal to or less than the specified value. A vista contrast of equal to or less than 0.20 occurs 50 percent of the time. A vista contrast change of 0.04 may be perceptible.

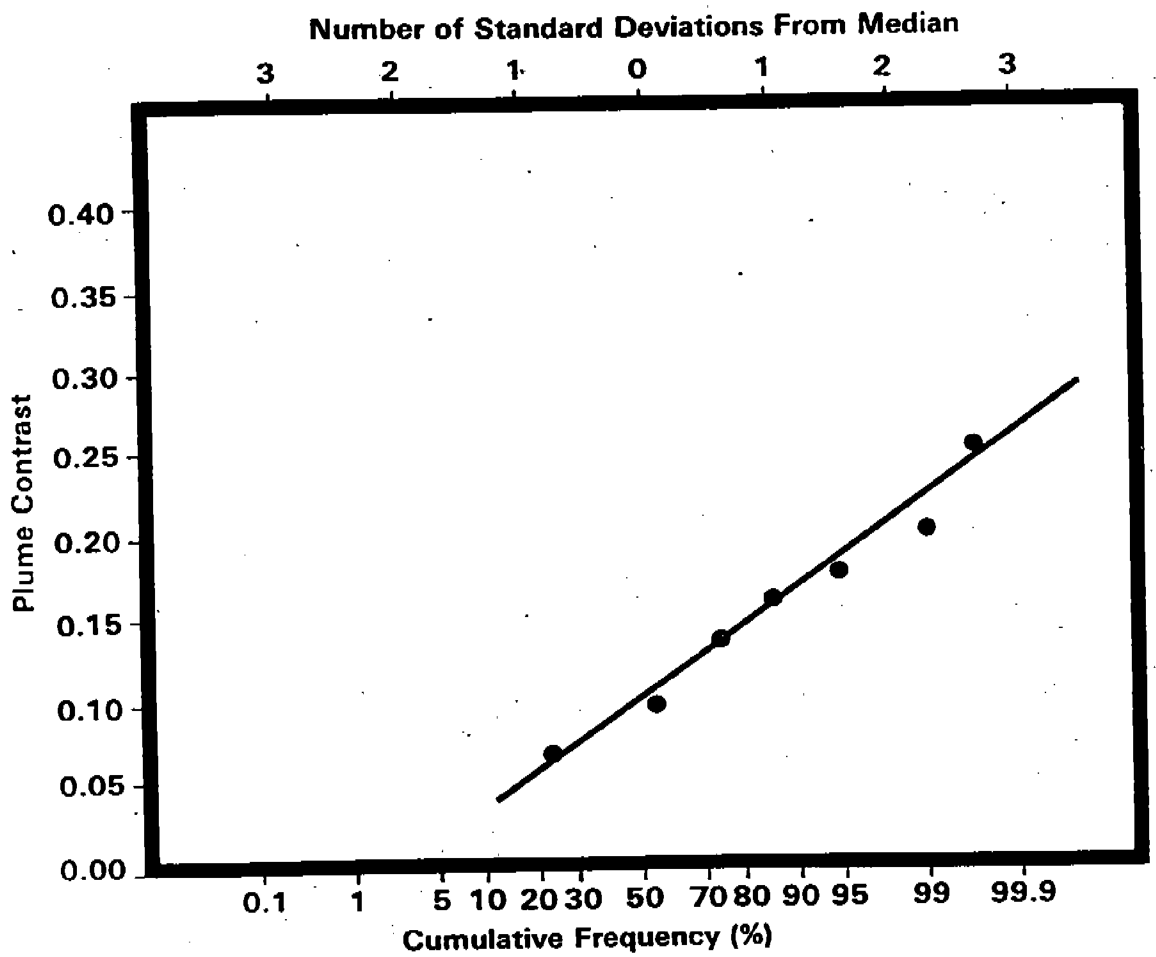

Figure 13. Normal Probability Cumulative Frequency Distribution for Plume Contrast.

This figure shows the percent occurrence of plume contrast equal to or less than a specified value. A plume contrast equal to or less than 0.10 occurs 50 percent of the time. A plume contrast as low as 0.02 may be perceptible.

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16. ABSTRACT

This report is designed to summarize the substantial information available regarding visibility monitoring methods presently in use. It does not specify a reference method, but recommends measures for interim visibility monitoring.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Aerosols Monitoring Nitrogen oxides Sulfur oxides Visibility	Class I Areas Monitoring	

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