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Open-Path Transmissometry for Measurement of Visibility Impairment by Fugitive Emissions from Livestock Facilities

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Abstract. *We are adapting the long-path visibility transmissometer (model LPV-2/3, Optec, Inc., Lowell, MI) as a line-integrating, surrogate measurement for agricultural particulate matter where the source of the particulate matter, and therefore its "extinction behavior" as a function of mass concentration, is known with confidence. We report herein on our introductory field work to calibrate time-averaged measurements of total atmospheric extinction (L^{-1}) against time-averaged mass concentrations ($M L^{-3}$) of total suspended particulate (TSP) and PM_{10} as measured using standard gravimetric methods. Both measurements are to be taken along the downwind boundary of a cattle feedyard, open-lot dairy or other open-lot livestock facility wherein the fugitive dust is predominantly derived from dried, pulverized manure suspended in air by hoof action.*

Keywords. Visibility, feedyard, open-lot dairy, fugitive dust, transmissometry, atmospheric exinction.

Introduction: Atmospheric Extinction

The open-path transmissometer (Optec, 2002) is an active, visibility-monitoring device used to measure atmospheric extinction coefficients over distances up to 15 km. It consists of a constant-output, modulated light source (wavelength ~550 nm) at one end of the open path and a photometer at the other end. The photometer receives the modulated radiation that remains after the source irradiation is attenuated by distance (according to the inverse square of the distance between source and receiver) and the scattering and absorption effects of the intervening, atmospheric gases and aerosols. The detector circuitry permits an extinction measurement over an averaging time as short as 60 seconds, which is essentially a continuous measurement as contrasted with standard, filter-based gravimetry.

The extinction coefficient is defined in terms of the equation (Malm et al., 1986),

$$H = \frac{kI_0}{r^2} e^{-\alpha_t r} \quad [1]$$

in which H is the irradiance detected at a given location, I_0 is the radiant intensity of the source, r is the linear distance (km) between the source and detector, k is a geometrical parameter related to the solid angle subtended by the beam and α_t is the total atmospheric extinction coefficient (km^{-1}). (H and I_0 can be expressed in any consistent units, such as W km^{-2} and W, respectively.) The transmissometer installation fixes k, I_0 and r; we then measure H at the detector and infer α_t from Equation [1]. The extinction coefficient, α_t, is the sum of the absorption and scattering extinctions for both gases and suspended particles in the path:

$$\alpha_t = \alpha_{abs,g} + \alpha_{abs,p} + \alpha_R + \alpha_{sc,p} \quad [2]$$

In Equation [2], the subscripts abs and sc refer to absorption and scattering, respectively; g and p refer to gases and particles, respectively; and R refers to so-called Rayleigh scattering, which is a frequency-dependent refraction attributable to the gases in the earth's atmosphere. The Rayleigh extinction coefficient is zero in the limit as barometric pressure tends to zero; its value in clear air at sea level is approximately 0.010-0.012 km^{-1} (Malm et al., 1986).

Experimental Approach

Safety Emphasis

Safety as a motivation for the research. One of the practical motivations of this research is traffic safety. The evening dust peak that commonly occurs downwind of open-lot livestock facilities in the semi-arid West sometimes reduces local visibility along the adjacent, major highways. In some cases, high-speed rail lines parallel those major highways, raising visibility's importance further. (To date, we have no evidence that these low-visibility events have contributed to collisions, injury or death.)

Safety as a component of the research. Because our technical objectives require us to work repeatedly in the core of the evening dust peak, all employees involved in sampling and monitoring activities associated with this and related projects have access to passive, canister-style respirators, goggles, gloves and hard hats and are encouraged to use them as needed.

Experimental Objectives

Objective #1 is to determine the optimum path length for the LPV-3 transmissometer when deployed to measure visibility along the downwind boundary of a cattle feedyard under worstcase conditions. By inspection of Equation [1] and its differential forms, it is clear that the greater the path length, L [m], between source and photometer, the greater the resolution of small changes in α_t along that path. On the other hand, increasing the path length at high extinction values (i. e., under ultra-low visibility conditions) decreases the magnitude of the signal measured at the photometer, reducing measurement accuracy. Optimizing the path length, then, is a matter of balancing the need for short path lengths under low-visibility conditions and the need for longer path lengths under near-Rayleigh conditions. During preliminary tests in January 2004 in clear air (see Figure 1), we successfully calibrated our older transmissometer and verified that a path length of 300 m was too short to measure the low extinction values, even with the lamp at low power.

Figure 1. Calibrating the open-path transmissometer at Nance Ranch, Randall County, TX. Transmitter unit is on the tripod in the foreground; also note three pairs of federal reference method PM monitors (PM_{10} and TSP) along the open path. Receiver unit is barely visible on a white pedestal between the most distant PM_{10} monitor and the end of the maroon-and-white barn. Calibration path length was 300 m.

As can be seen in Figure 2, severe feedyard dust events can reduce the apparent visible range to 100 m or less (the corrals in the photo are about 60 m deep from feed apron to the back of the pen). On the other hand, visual air quality in the southern High Plains is usually quite good. In most Class I areas (e. g., national parks) where visibility standards are enforced, changes in visibility are more subtle than the diurnal phenomenon in which we are interested. The Wyoming Visibility Monitoring Network, for example, has selected path lengths closer to 10 km, a path length that would make the device useless for fugitive dust events like that in Figure 2.

To overcome this device limitation, we have devised a two-transmissometer approach to be tested in the feedyard environment during the summer of 2004. (Update: As of the date of distributing this paper, above-average rainfall in the Texas Panhandle during June and July has

Figure 2. Severe feedyard dust event in late September 2000. Photo was taken about 30 minutes before dusk.

virtually eliminated feedyard dust events for weeks at a time, preventing us from testing our two-transmissometer method.) In this approach, we will deploy two transmissometers side-by-side, one with a long open path (~1-2 km) and one with a short path (300-500 m), as in Figure 3. Approaching Rayleigh conditions (visible range > 300 km), the short-path photometer is expected to saturate and will return garbage values (Optec, 2002), but the long-path photometer signal should be within the measurable range. Under low-visibility conditions like those in Figure 2, the short-path photometer is expected to return measurable extinction values while the magnitude of the signal at the long-path unit is likely to be below the photometer's detection threshold.

The two-transmissometer approach is subject to several limitations of its own. First, at nearly every moment one of the transmissometers is either over-ranging (short path, clear air) or under-ranging (long path, low visibility), so the cost per measurement is at least twice that of the typical, single-transmissometer deployment. A transmitter with a wider range of source intensity and an auto-adjusting feedback system between photometer and transmitter would make it possible to use one unit instead of two. One key element of Objective 1, then, is to determine how to ensure that the measurement ranges of the two transmissometers overlap adequately so that there is a period of time every day during which both transmissometers are measuring the same value accurately. If that can be achieved, control software can be written to turn the transmitters OFF and ON to conserve power and lamp life, and we can automate the transfer of measurement control from one unit to the other as visibility changes throughout the day.

Theoretical considerations based on Equation [1] and the operating specifications of the units suggest to us that the region of overlap between the two units is governed by the *optical depths* of the air along the LOS for each unit. (The optical depth of the LOS is the absolute value of the exponent on the right-hand side of Equation [1] and is defined as the product of the total extinction coefficient, α_t, and the path length, which is denoted by r_S and r_L for the short- and long-path units, respectively.) At present, although we have not been able to verify this in the field because of chronically wet weather, we estimate the range of overlap between the two

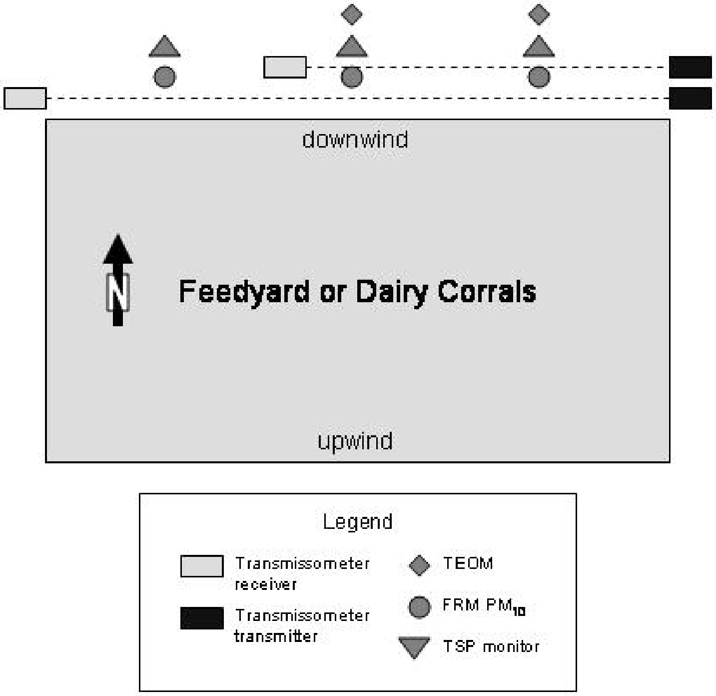

Figure 3. Schematic plan view of typical two-transmissometer deployment along the downwind edge of an open-lot animal feeding operation. Also shown are ambient monitors to measure mass concentrations of PM fractions at points along the line of sight. (TEOM=tapered-element oscillating microbalance; FRM=federal reference method)

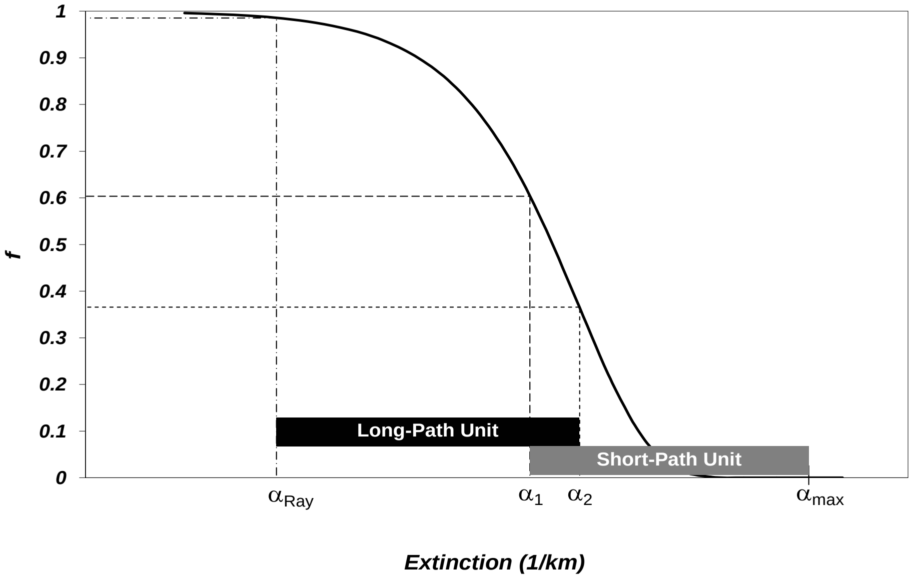

Figure 4. Overlapping ranges of atmospheric extinction between the long-path unit, used for measuring in the near-Rayleigh range, and the short-path unit, which will used to quantify the low-visibility conditions that typically occur in the evening near cattle feedyards. (Horizontal axis is logarithmic; function on vertical axis is derived by solving Equation [1] for exp[-α_t].)

units as being $8.0 < \alpha_t < 9.9$ (9.0 +/- 10%) for the path lengths that are implied by typical feedyard dimensions. Experiments by Molenar et al. (1992) suggest that the accuracy of the Optec transmissometer is better than 10%; therefore, the range of overlap appears just wide enough to be resolved.

The second limitation pertains to topography. To ensure reliable measurements, the photometer telescope must be precisely aimed at the center of the 1-degree cone of green light generated by the transmitter, and the cone of light must not impinge upon any fixed surfaces (e. g., the ground) before it reaches the telescope to prevent reflected radiation from entering the photometer. In many Class I areas, native topographical relief is such that the source cone does not hit the ground between transmitter and receiver, but in the flat Texas Panhandle, either transmitter or receiver or both must be elevated in proportion to the path length. (As a practical matter, because the transmitter is simply turned "ON" and left alone during the measurements, it makes more sense to leave the receiver/photometer near the ground where access to the central processing unit (CPU) and its controls is convenient and continuous.) Assuming that the slope of the ground is uniform between transmitter and receiver, the difference in elevation between the receiver and the elevated transmitter must be a minimum of 0.873 m for every 100 m of path length (~46 ft per mile). For the short-path transmissometer (L=300 m), it is sufficient to put both transmitter and receiver on pedestals such that the telescope centerlines are 1.31 m (4.3 ft) above ground level, a convenient working height for access to the telescope "peep sights," scope adjustments and electronic diagnostics. The long-path unit, however, requires an instrument tower to be used on at least one end (Figure 5).

The third limitation of the two-transmissometer approach pertains to the cross-sectional uniformity of the dust plume along the LOS between transmitter and receiver. Transmissometer theory (Malm et al., 1986) assumes that the extinction coefficient is uniform along the LOS. We have observed that the dust plume within the source area, especially as it builds during the early evening, does vary spatially. Even so, that does not obviate the need for a line-integrating measurement; it is easily conceivable that placing point monitors along the downwind boundary might result in artificially low measurements at one location and artificially high measurements at another. By adopting transmissometry as a measurement technique, we are presupposing that atmospheric extinction coefficients exhibit a sort of ergodicity, that is, that the spatially averaged measurements and time-averaged measurements eventually coincide. To justify that presupposition, we must ensure that both the short-path and long-path units (including both transmitter and receiver) remain strictly within the dust plume throughout the measurements. The deployment of point, gravimetric monitors along the LOS will help to verify the quasi-ergodicity of the plume, which is an implied element of Objective #2.

Objective #2 is to calibrate the transmissometer data against two kinds of simultaneous measurements that provide comparability between visibility and ambient PM concentrations. The first is an array of single-point, gravimetric PM monitors deployed along and slightly downwind of the transmissometer line-of-sight (LOS). Gravimetric procedures for determining time-averaged, mass concentrations of PM are adapted from Federal Reference Methods (USEPA, 2002) including provisions for pre- and post-exposure filter conditioning, repeated weighing of each filter and laboratory and field blanks. In general, these single-point monitors may be configured with size-selective inlets for TSP, PM_{10}, $PM_{2.5}$ or any other size fraction. We integrate the time-varying trace of extinction coefficient numerically over the sampling duration (nominally 3, 6, 12 or 24 hours, depending on wind stability and other weather conditions) to obtain the time-averaged extinction coefficient,

$$\alpha_{\Delta t} = \tfrac{1}{\Delta t}\int_0^{\Delta t} \alpha_t(\tau)\,d\tau \quad \text{..........} \quad [3]$$

Figure 5. Ten-meter tower to be used to elevate transmitter for long-path (>1 km) transmissometer deployment.

in which $\alpha_t(\tau)$ is the time-varying extinction coefficient (km^{-1}), $\alpha_{\Delta t}$ is the time-averaged extinction coefficient (km^{-1}), Δt is the gravimetric sampling interval (min) and τ is a dummy variable of integration representing sampling time (min). The value of $\alpha_{\Delta t}$ will be plotted against the arithmetic average of the gravimetric measurements along the LOS,

$$C_{\Delta t} = \tfrac{1}{n}\sum_{i=1}^{n}\left[\frac{W_{\Delta t,i} - W_{0,i}}{Q_i \bullet \Delta t}\right] \qquad [4]$$

in which $C_{\Delta t}$ is the time-averaged concentration ($\mu g\ m^{-3}$) of PM in the air averaged along the LOS, n is the number of gravimetric monitors deployed along the LOS, $W_{\Delta t,i}$ is the post-exposure mass (μg) of the filter in monitor i, $W_{0,i}$ is the pre-exposure mass (μg) of the filter in monitor i, Q_i is the volumetric flow rate of air ($m^3\ min^{-1}$) through monitor i, and Δt is the gravimetric sampling interval (min).

We do not yet know and can not reliably predict what the functional relationship will be between $C_{\Delta t}$ and $\alpha_{\Delta t}$, but we anticipate that $\alpha_{\Delta t}$ will increase monotonically with $C_{\Delta t}$. Malm (1999) published a value of 0.6 $m^2\ g^{-1}$ (or, more intuitively, $6x10^{-4}\ km^{-1}\ [\mu g\ m^{-3}]^{-1}$) for the *extinction efficiency* ε_e of coarse particles, as in Equation [5]:

$$\varepsilon_{e,j} = \frac{\partial \alpha_t}{\partial C_j} \quad \text{[5]}$$

In Equation [5], the subscript j refers to an arbitrarily selected fraction of total suspended particulate matter, such as TSP itself, PM_{10}, $PM_{2.5}$ or, more generally, particles between aerodynamic diameters x and y (PM_{x-y}). Note that Equation [5] can only be used to compute additive extinction efficiencies for two or more size fractions as long as their diameter ranges do not overlap; otherwise, the values of C_j are no longer independent. For example, we cannot use Equation [5] to compute independent extinction efficiencies for $PM_{2.5}$ and PM_{10} because $PM_{2.5}$ mass is included in any measured PM_{10} mass, and any change in $PM_{2.5}$ concentration will be reflected in the PM_{10} concentration. We may, however, speak of independent extinction efficiencies for $PM_{2.5}$ and $PM_{10-2.5}$.

Assuming that the extinction efficiency from Malm (1999) is accurate, a 3-hour average concentration of 1000 $\mu g\ m^{-3}$ would yield a 3-hour average $\alpha_{\Delta t}=0.6\ km^{-1}$, but the extinction efficiency of Malm (1999) was associated with coarse-particle concentrations nearly three logarithms lower than 1000 $\mu g\ m^{-3}$, raising doubt as to whether his published value is accurate for organic, agricultural aerosols like feedyard dust. We will have to compute our own extinction efficiency for the range of concentrations we are likely to encounter.

Interim Results

As mentioned previously, persistently wet weather in the Texas Panhandle has reduced feedyard dust emissions considerably throughout the summer of 2004. However, prior to the onset of that weather pattern we were able to collect a small data set (April 23, 2004) downwind of a commercial feedyard. The objective of our field measurements at that time was to determine if an on-board jumper in the receiver's CPU would reduce the gain of the unit's internal amplifier enough to allow us to operate the transmissometer at its calibration distance of 300 m (i. e., instead of at a much longer distance, like 1+ km). Analysis of our data from that experiment revealed that as long as the user-selected gain, lamp power and calibration constants were properly selected, the extinction measurements were stable and qualitatively consistent with expected trends, as shown in Figure 6. We have not yet been able to determine precisely why the measured extinction coefficient increased smoothly over time, although there are at least three rational explanations:

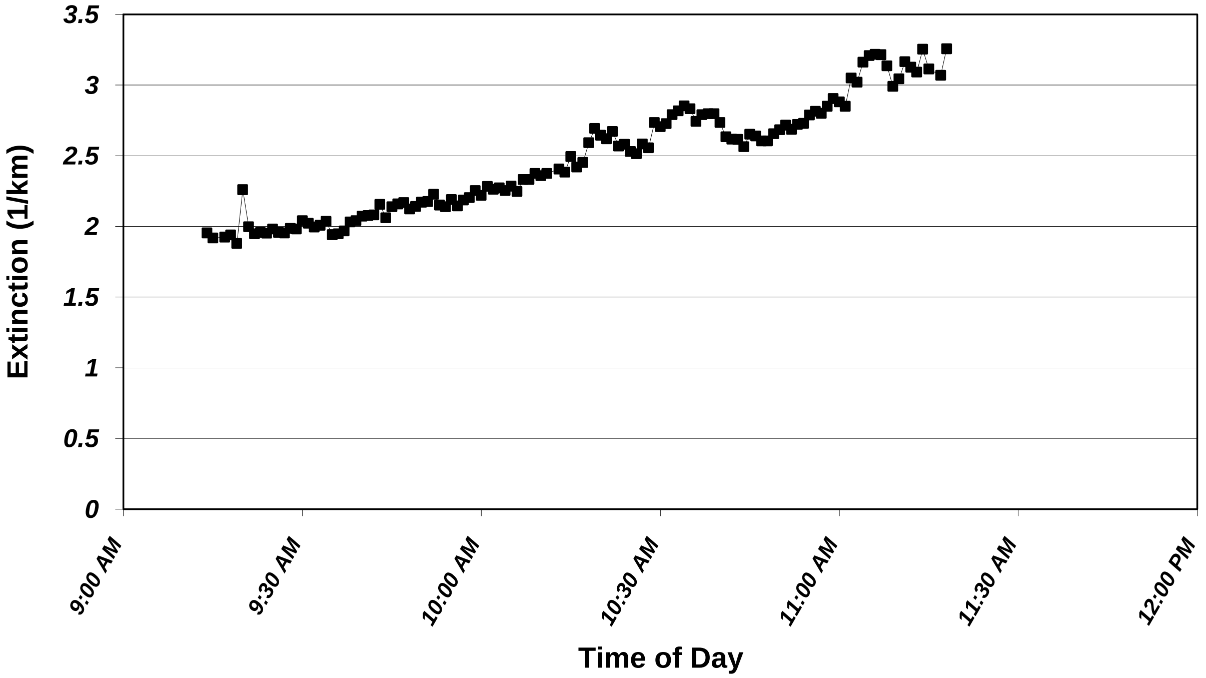

Figure 6. Sample extinction values measured by an LPV-3 transmissometer at a working path length of 300 m along the downwind boundary of a cattle feedyard in the Texas Panhandle. Working gain was 100; calibration constant was 277; filter transmissivity was 0.00998. On-board gain jumper was set so that internal amplifier gain was reduced from 30 to 2.

- The uncompacted manure layer on the feedyard surface was drying out in the late morning (see an accompanying paper by Marek et al. in this conference), increasing the manure's intrinsic dustiness; AND/OR
- The amount of hoof energy being generated by the livestock was increasing, likewise increasing the amount of fugitive dust being emitted; AND/OR
- Airborne dust was settling on the transmissometer optics, increasing the apparent extinction coefficient and biasing the data upward over time.

Conditions permitting, field tests planned for late summer 2004 will allow us to rule out one or more of those explanations.

Conclusions

We are still well short of validating the use of the open-path transmissometer as a surrogate measurement of airborne PM immediately downwind of open-lot animal feeding operations like cattle feedyards and dairies. Thus far, we have determined that the most recent model of the LPV can be configured to measure extinction values at the short path length that is required when visibility is severely limited and that the measurements appear to be stable and repeatable at that path length. When weather conditions permit, we will validate the two-transmissometer approach outlined herein to allow us to measure extinction values from the Rayleigh limit (0.012 km^{-1}) to the dramatic occlusion associated with the evening dust peak at cattle feedyards (est. 40 km^{-1}).

References

Auvermann, B. W. 2000. Lesson 42: Controlling dust and odor from open lots. In: Koelsch et al. 2000. Livestock and poultry environmental stewardship (LPES) national curriculum. Ames, IA: Midwest Plan Service.

Auvermann, B. W. 2003. Objective 1 work plan: open-path transmissometry. In: Sweeten, J. M. et al. 2003. Year 2 work plan: Air quality: odor, dust, and gaseous emissions from concentrated animal feeding operations in the southern Great Plains. Year 2 work plan, Special Research Grant No. 2003-34466-13146, USDA-CSREES, Washington, D. C.

Auvermann, B. W. and T. H. Marek. 2003. Estimating water demand for feedyard dust control using small weighing lysimeters. Final report to the Texas Water Resources Institute, College Station, TX.

Auvermann, B. W. and A. Romanillos. 2000.   Effect of Stocking Density Manipulation on Fugitive PM_{10} Emissions from Cattle Feedyards. Salt Lake City, UT.

Auvermann, B. W., D. B. Parker and J. M. Sweeten. 2000. Manure Harvesting Frequency: The Feedyard Manager's #1 Tool for Dust Control in a Summer Drought. Texas Cooperative Extension, College Station, TX. Bulletin E-52.

Grelinger, M. A. and T. Lapp. 1996. An evaluation of published emission factors for cattle feedlots. Proceedings of the First International Conference on Air Pollution from Agricultural Operations, Kansas City, MO, February 7-9.

Holmén, B.A., T. A. James, L. L. Ashbaugh and R.G. Flocchini. 2001. Lidar-assisted measurement of PM_{10} emissions from agricultural tilling in California's San Joaquin Valley II: Emission factors. *Atmospheric Environment* 35(19):3265-3277.

Malm, W. C. et al. 1986. Comparison of atmospheric extinction measurements made by a transmissometer, integrating nephelometer and teleradiometer with natural and artificial black target. Presented at the Air Pollution Control Association International Specialty Conference, "Visibility Protection: Research and Policy Aspects," Grand Teton National Park, WY, Sept. 7-10.

Malm, W. C. 1999. *Introduction to Visibility*. Ft. Collins, CO: National Park Service.

Molenar, J. V., D. S. Cismoski and R. M. Tree. 1992. Intercomparison of ambient optical monitoring techniques. Technical Report 92-60.09, Air Resource Specialists, Inc., Ft. Collins, CO.

National Research Council. 2003. *Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs*. Washington, DC: National Academy Press.

Optec, Inc. 2002. Operator's manual for the LPV-2/LPV-3 long-path visibility transmissometer. Lowell, MI.

Sweeten, J. M. et al. 2003. Air quality: odor, dust, and gaseous emissions from concentrated animal feeding operations in the southern Great Plains. Year 2 work plan, Special Research Grant No. 2003-34466-13146, USDA-CSREES, Washington, D. C.

USEPA. 2002. Reference method for the determination of particulate matter as PM_{10} in the atmosphere. 40 CFR Part 50 Appendix J.

Figure 7a, b. Identical digital images of Ft. Collins, CO, modified in WinHaze software (Air Resource Specialists, Inc., Ft. Collins, CO) to simulate total extinction coefficients of α_t=0.025 (top) and 0.626 (bottom) km^{-1}, respectively.