TRANSMISSOMETER EXTINCTION MEASUREMENTS IN AN URBAN ENVIRONMENT

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Abstract

Continuous monitoring of the atmospheric extinction coefficient is an important component in the characterization of urban hazes. The Optec LPV-2 transmissometer was applied to measure extinction (at 550 nm) throughout the 1987-1988 Metro Denver Brown Cloud Study. The extinction was continuously monitored along a 2.67 km sight path, 75 m above street level in downtown Denver. Extinction measurements were compared with co-located independent measurements of the scattering and absorption components of the total extinction. The results of the measurement program illustrate how a transmissometer can effectively document the dynamics of an urban haze.

The paper specifically details the design, implementation, and operational application of the system, presents the results of comparisons with colocated measurements, and discusses the dynamics and diurnal cycles of the extinction and optically observed visual air quality.

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Introduction

The visibility in many urban areas is reduced by airborne pollutants. Public perception of the severity of air pollution is often affected by characteristics of the visible urban haze, including its color, contrast, extent and density. In many western cities where the public is more accustomed to unobstructed views of distant vistas, these hazes are particularly apparent. The urban haze, often referred to as a brown cloud, is becoming an unwelcomed trademark of many western cities.

To better understand the optical characteristics and dynamics of urban hazes, the light extinction properties of the atmosphere can be measured. By making point measurements of the particles and gases that scatter and absorb light, a point estimate of total extinction can be made. However, until recently, an effective way to directly measure total light extinction was not available. An effective tool to measure extinction over a sight path of several kilometers is now available with the Optec, Inc., LPV-2 long-range transmissometer.

A sight path extinction measurement over several kilometers accounts for the combined effect of the light scattering and absorbing components of the atmosphere along the sight path. Although many views in urban areas are farther than several kilometers, the sight path extinction measurement can provide quantitative information about the visual characteristics and dynamics of the urban air mass.

The first urban application of the Optec LPV-2 transmissometer occurred during the 1987-88 Metro Denver Brown Cloud Study. This paper details the implementation and operational application, and illustrates how the measurements can effectively document the dynamics of urban haze.

Instrumentation

During the 1987-88 Metro Denver Brown Cloud Study,[1,2,3] the Optec LPV-2 long-range transmissometer was used to make a path measurement of atmospheric extinction. The transmissometer directly measures the ability of the atmosphere to transmit light of a specific wavelength (550 nm, green) by measuring the loss in light received from a light source of known intensity as the light beam travels a known distance.

The LPV-2 transmissometer has two primary components: a light source (transmitter), and light detector (receiver) as displayed in Figure 1. Depending on the average visual air quality, the components are generally placed from .5 to 10 kilometers apart. The system can make measurements day and night because the light emitted from the transmitter is "chopped" at 78 pulses a second to allow the receiver to differentiate the lamp signal from background, ambient lighting. The receiver-measured transmitter light intensity is compared to the known (calibrated) transmitter light output to calculate the percent transmission of the atmosphere. For a known path distance, the receiver computer can calculate and express visibility measurements in terms of the extinction coefficient (light loss per unit distance) in units of inverse kilometers (km^{-1}) or as visual range in kilometers (km). As the air gets dirtier, the transmission of light through the atmosphere decreases, the extinction increases, and the visual range decreases. Technical and operational specifications of the Optec LPV-2 have been prepared by Optec, Inc. and Air Resource Specialists, Inc.[4,5,6]

During the Denver study, the transmitter and receiver were located on the roofs of downtown buildings. The transmissometer receiver was located atop the Federal Building at Champa and 20th Streets. The transmitter was located to the southeast on a condominium complex in Cheezman Park. The sight path distance was 2.67 km, and the path elevation was approximately 75 m above ground level. This elevated sight path was chosen for several reasons:

- During daylight hours this elevation was at approximately mid-level of the haze layer.

- This portion of the brown cloud is visible from a distance, and represents a layer of the cloud often viewed when approaching Denver.

- An elevated path reduced the potential optical interference from surface turbulence.

- The selected buildings were well spaced, easily accessed, and the owners were cooperative.

The transmissometer was only one component of this comprehensive urban air quality study. A variety of instruments were spatially distributed throughout Denver and the surrounding area[1,2,3]. Instrumentation colocated with the transmissometer receiver on the Federal Building included:

- Integrating nephelometer
- Sequential filter samples
- Nitrogen oxides monitor
- Micro orifice uniform deposit impactor
- Optical cross wind sensor[7]
- Conventional meteorological measurements.

Measurements from these instruments were used to quantify the scattering and absorption components of extinction and to document mid-haze air flow. 35mm still-frame and 8mm time-lapse cameras were colocated with the transmissometer transmitter. These cameras visually documented the conditions along the transmissometer sight path during daylight hours.

Operational Considerations

The transmissometer is designed for operational field applications and is a rugged, low-power, low-maintenance instrument. A schematic of the Denver installation is provided as Figure 1 and specific operational considerations are listed below:

Requirements

Continuous day-night operation was required over a three-month study period: November 1987, December 1987, and January 1988.

Sheltering

The instrument operates at ambient temperatures and only requires sheltering from precipitation, wind, and dust. Simple shelters were constructed for the Denver study. During the study, the instrument operated in temperatures that ranged from -18^{o}C to 27^{o}C.

Mounting

The transmissometer is an optical instrument that requires stable mounting. Both the transmitter and receiver alti-azimuth bases were attached to steel piers mounted on concrete pads. The pads (2'x 2'x 4") were placed on the flat gravel roofs of the buildings.

Power

Both transmitter and receiver operate on 12 volts DC, requiring 34 and 5 watts respectively. Both components were powered by line power converted through a 12-volt battery charger and battery. The system would run on battery power for extended periods if power failure occurred.

Service

Exterior optics were cleaned and optical alignment was checked weekly. The calibrated transmitter light bulbs were replaced monthly.

Data Logging

The primary data logger was a Campbell Scientific 21X micrologger. This system collected one-minute and 10-minute average data. Data were retrieved, reduced, and archived weekly. A strip chart recorder provided backup data collection and permitted for convenient on-site data review by service personnel. A satellite data collection platform also logged and transmitted ten-minute and hourly average data to Air Resource Specialists, Inc. Fort Collins' office for near-real-time data interpretation.

Data Collection and Reduction

The data collection and reduction procedures used for the Denver study are summarize below.

Sampling

One-minute readings of atmosphere extinction were collected. Each one-minute reading represents an integration of 62,500 instantaneous samples. One-minute readings were combined into 10-minute, hourly, 7-hour daytime (0900-1600 MST) and 17-hour nighttime (1700-0800 MST) averages.

Data Validation

Station logs and photography taken along the sight path were used to assign validity codes to each one-minute reading. Codes defined good, missing, or bad data due to: system down time, precipitation events, and overrange values. Ten-minute averages of atmospheric extinction were calculated if 5 or more one-minute readings were present. Hourly averages were calculated if 3 or more ten-minute averages were present.

All data were adjusted for changes in lamp brightness due to lamp aging. A lamp-aging offset of 3.0×10^{-7} km^{-1} per minute (0.3×10^{-5} km^{-1} per 10 minutes or 1.8×10^{-5} km^{-1} per hour) were applied to each valid average from the time a new bulb was installed to the time it was placed. This value was calculated from absolute measurements of pre- and post-operational lamp radiance.

Precision

A method for operational performance testing of transmissometer precision had not been developed at the time of the Denver study. In lieu of a precision test, a nominal precision value of $\pm$ 10% was assigned for extinction values greater than 0.1 km^{-1}. Data from side-by-side comparisons of Optec systems performed since the study are currently being compiled that will provide a precision value.

Accuracy

No operational audit technique had been developed for the LPV-2 at the time of the Denver study. Pre and post calibrations of each transmissometer bulb were performed with the study instrument.

During the study, instrument alignment was periodically checked and exterior optics were cleaned at least weekly. Absolute accuracy determination is difficult. Malm[8] reported transmissometer-based extinction error for 6 to 15 km sight paths may be on the order of 10%. The estimate applied to the Denver data was on the order of 6% to 10%,depending in extinction value.[2,3]

Data Collection Statistics

Table I summarizes the data collection statistics by month based on 10-minute average averages. November statistics include the preliminary 2-week shake-down period which included initial receiver alignment problems that were alleviated by a redesigned mounting. The instrument ran without incident during December and January. Data collection for the three-month period was excellent. The system did not operate or was down for scheduled maintenance less than 1% of the total time. Transmissometer data invalidated by natural phenomenon, such as snow storms or sun flares (that occasionally occurred when low-lying clouds were brightly illuminated near sunrise), accounted for approximately 12% of the total hours.

Discussion

Haze Dynamics

The continuous transmissometer data taken during the Denver study details the dynamics of haze events. Figure 2 is a data summary based on hourly extinction for the entire 3-month period. The median extinction for the period was .081 km^{-1} (visual range of 48 km). However, hourly and daily extinction varied over a wide range of values. As an example, a plot of the ten-minute average extinctions for a haze episode that occurred between December 15 and 21, 1987, is presented in Figure 3. A December 14 snowstorm was followed by a classic winter haze event. The December 15 to 20 period was characterized by relatively stable conditions. Local inversion conditions enhanced by snow cover persisted throughout most of the day. Light winds allowed pollutants to accumulate over Denver and be gradually transported to the southeast down the Platte River Valley. During the afternoon, the down-valley drainage flows weakened and were often overridden by up-valley return flows driven by a low pressure gradient along the foothills[3]. These up-valley flows can rather quickly return aged pollutants into the urban area to mix with the continuing urban emissions. By early morning, the drainage flow again dominates the area, transporting the polluted air mass down valley. This series of events can occur for several days until stronger synoptic disturbances such as snowstorms or high winds move into the area. On December 21, high winds and unstable conditions that preceded a snowstorm cleared the Denver area. Emissions, particularly the ground-based emissions associated with the working day, induce varying levels of pollutants into the stagnant air mass.

On many days, cleanest air (low extinction) occurs during the early morning (4 to 6 a.m.). A peak in extinction occurs around 8 a.m. as the city comes to life. Relatively low values again occur around noon. The highest extinction values occur in the late afternoon and evening as the return flows move aged pollutants back into the urban area to mix with the continuing emissions in urban air mass. These high levels persist until drainage flows become re-established and move the pollutants from the city. This occurs after midnight and coincides with the time when local sources are at a minimum. During this 5-day episode, extinction ranged from approximately .05 to .70 km^{-1} (visual ranges of 78 to 6 km).

As a point of comparison, a plot of hourly average extinction taken at Rocky Mountain National Park during the December 15 to 20, 1987, period is presented in Figure 4. The extinction values in this pristine, mountain setting 80 km northwest of Denver consistently remained at near .02 km^{-1} (visual ranges of 195 km) except during snow showers.

During periods when pollutants did not accumulate in Denver, such as the December 6 to 12 period shown in Figure 5, extinction values generally ranged between .025 and .10 km^{-1} (visual range of 150 to 39 km). During these relatively clean periods, the daily variation in extinction is small compared to haze episodes; however, daily peak values often occur near 8 a.m. and 8 p.m. Relative minimum values occur at approximately 4 a.m. and noon.

These measured variations in sight path extinction are verified by time-lapse and still-frame photographic records taken during daylight hours and by coincident measurements of the scattering and absorption components of extinction measured by instruments colocated at the Federal Building. Figure 6 includes photographs that document the visual conditions. A photograph of Denver taken from Thornton (10 km north of Denver) during the late afternoon on December 20 shows much poorer visual air quality than a photograph taken early the next morning. Denver was often not visible from Thornton during the most severe haze episodes.

Watson[9] illustrated that the measured components of atmospheric extinction could effectively be combined to estimate and verify measured extinction. Component calculations (for the sum of 7 and 17-hour day and night averaging periods) were done using two methods to estimate.

- light absorption by particles
- light absorption by gases
- light scattering by gases
- light scattering by course particles
- light scattering by fine particles

Method 1 used point-based measurements to estimate total extinction from its components as follows:

- nephelometer particle scattering
- Rayleigh light scattering by gases
- Teflon filter light absorption by particles
- nitrogen dioxide light-absorption by gases

Method 2 estimated total extinction by considering the physical properties of measured chemical constituents as follows:

- elemental carbon light absorption by particles
- nitrogen dioxide light absorption by gases
- fine particle sulfate light scattering
- fine particle nitrate light scattering
- fine particle organic carbon light scattering
- fine particle remaining mass light scattering
- course particle light scattering
- Rayleigh light scattering by gases

Both methods compared well with the transmissometer extinction measurements with correlations of approximately 0.9 for a variety of data set comparisons[9].

Current and Future Urban Applications of the Transmissometer

Optec transmissometers are now, or soon will be, documenting the visibility of several urban areas. In Denver, state legislation (Senate Bill 77) requires that the Colorado Department of Health establish an urban visibility standard. A standard has been proposed and will undergo a public hearing process during the end of 1989. The proposed standard is an extinction value which was determined by correlating human judgment of photographic slides with measured extinction. Extinction data and photographs from the 1987-88 Metro Denver Brown Cloud study provided the framework for development of the proposed standard. An Optec transmissometer will be installed in Denver during the Winter 1989-90 to serve as an operational method of measuring extinction relative to the standard.

Other urban applications of the Optec transmissometer include:

Phoenix, Arizona	As part of the Phoenix and Tucson Urban Haze study, a transmissometer will operate in downtown Phoenix from October 1989 to January 1990.
Dallas, Texas	A system will operate in downtown Dallas during winter 1989-90 as part of an urban haze study.
Lake Tahoe Regional Planning Agency	Operational monitoring of the south Lake Tahoe area is scheduled to begin during the Fall 1989.
Clark County, Nevada	Clark County is considering the application of a transmissometer for monitoring urban visibility in Las Vegas.

Conclusions

The Optec LPV-2 transmissometer proved be an effective method of documenting and quantifying the light extinction dynamics of urban haze during the 1987-88 Metro Denver Brown Cloud study. The system was easily installed and maintained, and yielded quality data under a wide range of weather conditions. The transmissometer sight path extinction measurements and point measurements of the scattering and absorption components of extinction compared well in the Denver study.

During the Winter 1988-89, the LPV-2 transmissometer will become an important operational monitoring tool in Denver. In addition, an LPV-2 transmissometer is now operating in the Phoenix Urban Haze study, and will soon be applied in several other western cities.

References

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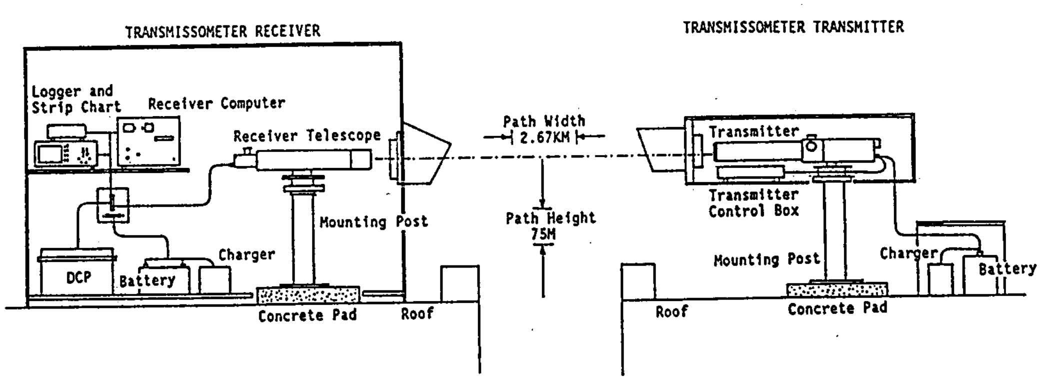
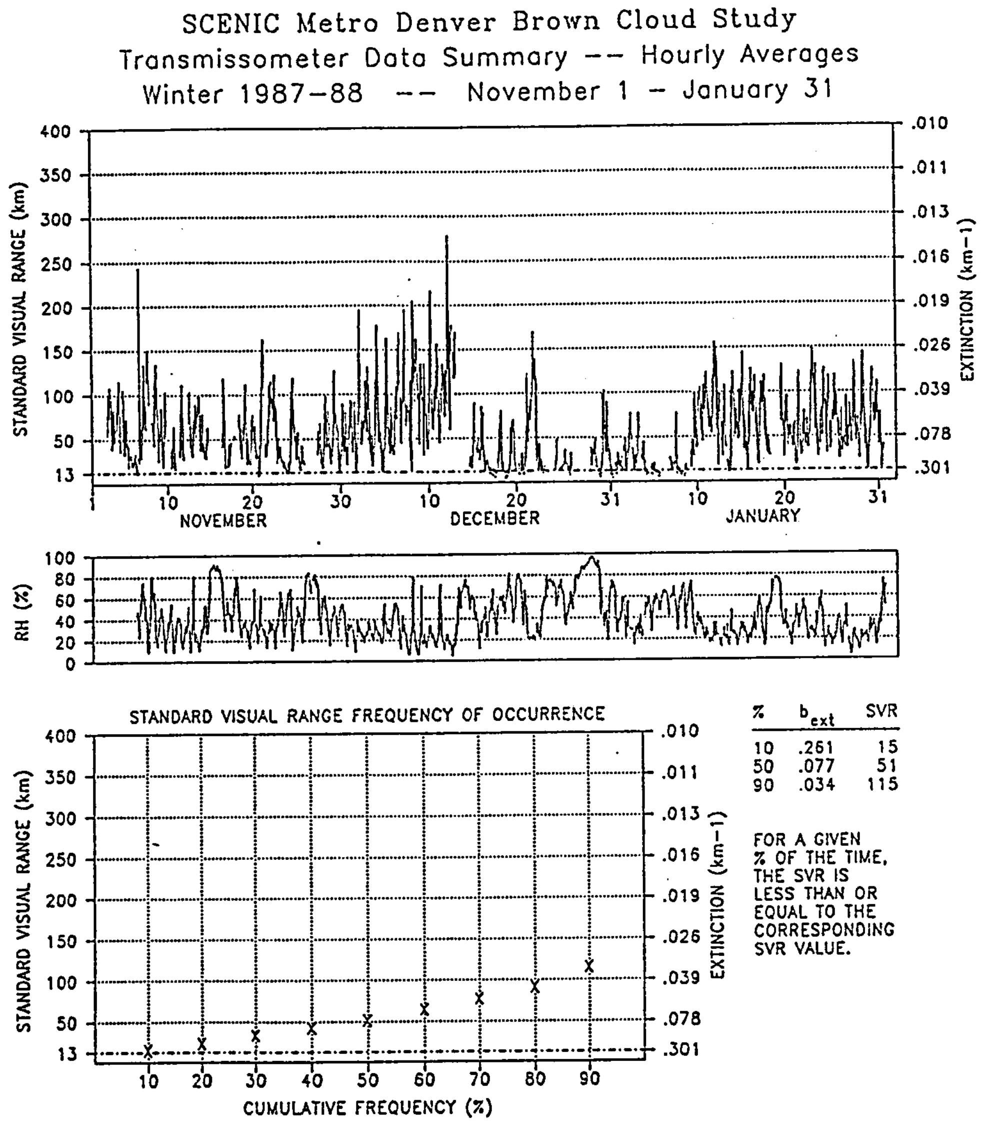


Figure 1. Schematic of Optec LPV-2 Transmissometer Installation During the 1987-88 Metro Denver Brown Cloud Study.



%	b_{ext}	SVR
10	.261	15
50	.077	51
90	.034	115

FOR A GIVEN % OF THE TIME, THE SVR IS LESS THAN OR EQUAL TO THE CORRESPONDING SVR VALUE.

TRANSMISSOMETER DATA RECOVERY STATISTICS

CATEGORY	NUM	%
TOTAL POSSIBLE 1-HOUR AVERAGES IN THE TIME PERIOD	2208	100
USABLE 1-HOUR AVERAGES IN THE TIME PERIOD	1760	79

Figure 2. Downtown Denver Transmissometer Data Summary Based on 1-Hour Average Data for the 3-Month Study Period (November 1987, December 1988, and January 1989).

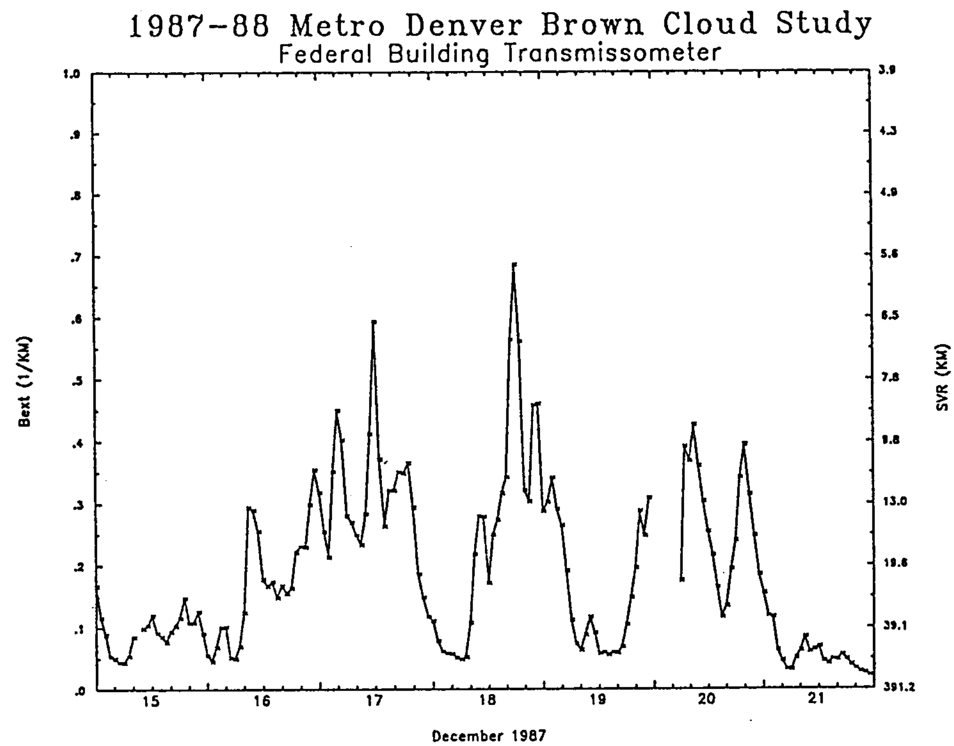


Figure 3. Downtown Denver Transmissometer Data Plot (1-hour averages) for December 15 to 21, 1987, Haze Episode.

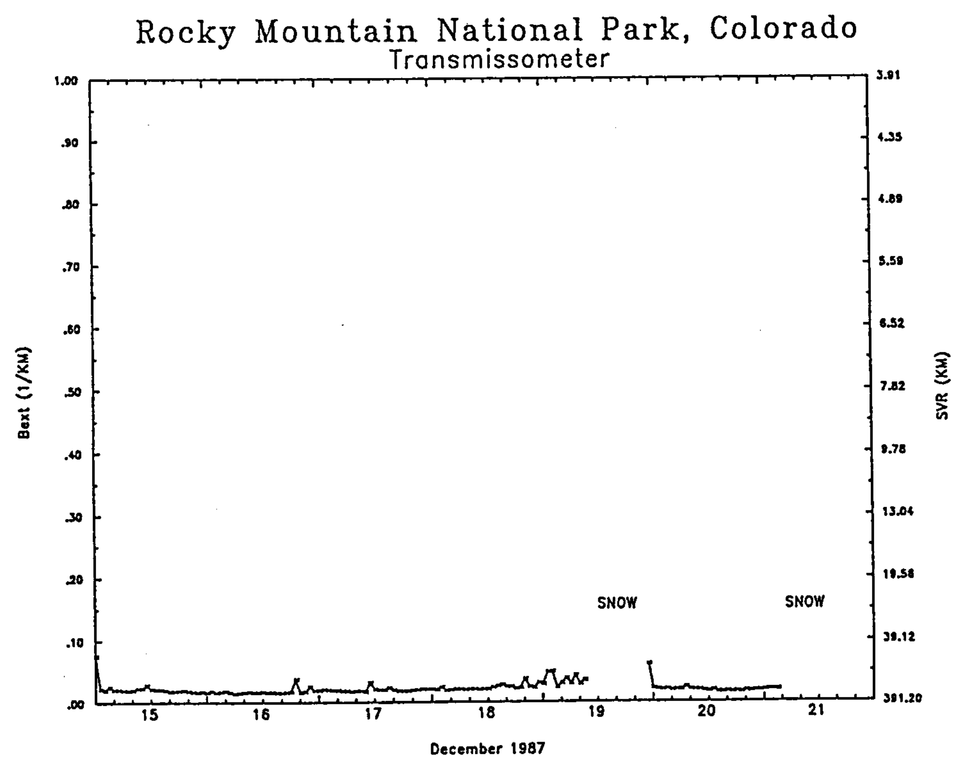


Figure 4. Rocky Mountain National Park Transmissometer Data Plot for December 15 to 21, 1987.

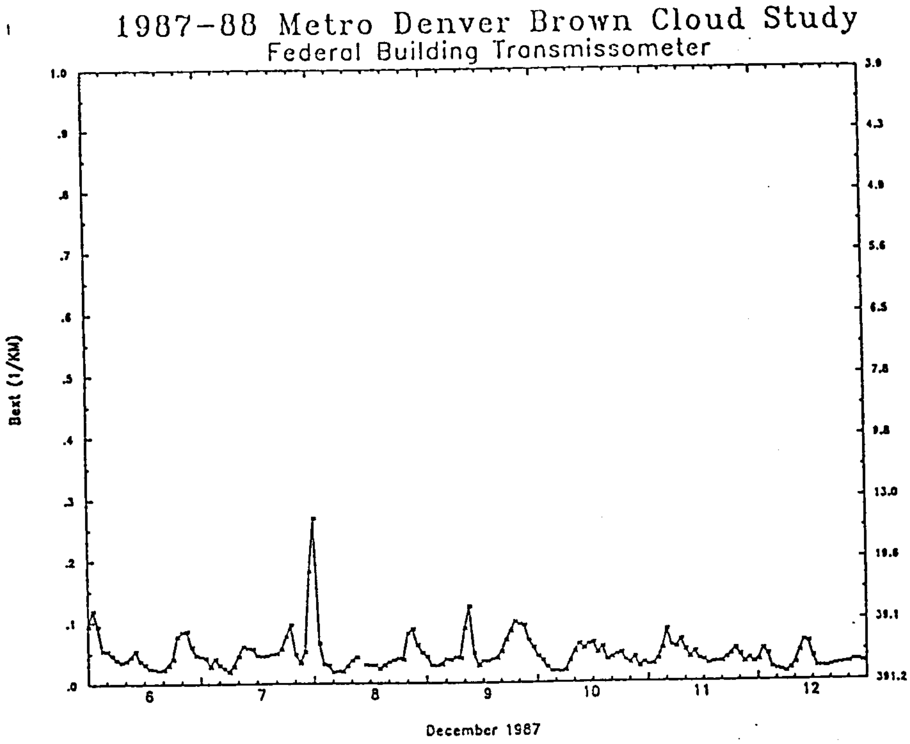
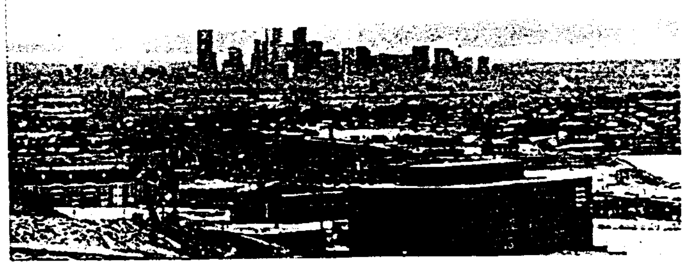


Figure 5. Downtown Denver Transmissometer Data Plot (1-hour averages) for December 6 to 12, 1987, Clean Period.

Late Afternoon on December 20



Early Morning on December 21

Figure 6. Photographs Illustrating the Effect of Urban Haze on Visual Air Quality in Denver Photographs taken from Thornton, Approximately 10 km North of Denver.

Table I

Transmissometer Data Collection Statistics
by Percent (%) of Total Month
(based on 10-minute averages)

	November	December	January	Total
Good Data	68.47	80.91	86.11	78.50
Insufficient Data for 10-Minute Average	6.30	0.02	0.07	2.13
Rain, Snow, or Fog	10.23	10.66	10.30	10.40
Maintenance	0.14	0.11	0.16	.14
System Down	1.67	0.00	0.00	.56
Overrange (unexplained)	1.69	6.90	0.11	2.90
Sun Flare Overrange	2.59	1.39	3.25	2.41
Alignment Error	8.91	0.00	0.00	2.97