

APPLICATION OF A LONG RANGE TRANSMISSOMETER TO MEASURE THE AMBIENT ATMOSPHERIC EXTINCTION COEFFICIENT IN REMOTE PRISTINE ENVIRONMENTS

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Abstract

Measurement of the ambient atmospheric extinction coefficient is an essential component of any comprehensive visual air quality monitoring program. The ability to determine extinction in remote pristine Class I areas is difficult due to the need for systems that have low power consumption, require infrequent servicing, can operate at extreme ambient temperatures, have minimal environmental impact due to sheltering, and can accurately measure near Rayleigh extinctions. In the past extinction has been estimated from nephelometry or natural target contrast measurements with both techniques subject to severe limitations. These operational requirements and instrument limitations have recently been addressed in federal visibility monitoring programs by the implementation of a network of twenty-one Optec LPV-2 transmissometers. The performance of these instruments has been evaluated with a two-year pre-operational test period while the systems were procured and deployed. During this stage, siting requirements, shelter and power system design, data logging systems, installation, standard operating, calibration, maintenance and quality assurance procedures, and instrument reliability and performance characteristics have been thoroughly investigated. The quality and quantity of the collected data and observed operational characteristics illustrate the effectiveness of the measurement technique. The experience gained during the pre-operational test period has led to the full implementation of the operational network as of March 1, 1989.

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Introduction

A primary goal of visibility monitoring in remote pristine Class I regions is to quantify how well the image forming information of a scenic vista is transmitted through the atmosphere to an observer located some distance away. Determining this optical property of the atmosphere requires an understanding of the ambient atmospheric extinction (b_{ext}) coefficient. B_{ext} is the sum of the scattering and absorbing properties of the aerosols and gases, which directly influences the modulation transfer function of the atmosphere. However, an accurate determination of extinction in pristine atmospheres and under all meteorological conditions has proven to be a very difficult task. Until recently, the two methods routinely employed for estimating b_{ext} have been integrating nephelometry¹ and natural target/horizon sky contrast measurements². The integrating nephelometer measures only the scattering properties of an enclosed air sample and not the absorption. The enclosed sample volume usually modifies the ambient aerosol, significantly changing the scattering coefficient, in addition, the geometry of the sampling train and optical chamber results in an underestimation of the scattering by coarse particles. Determining atmospheric extinction from measurements of natural target contrast accounts for both scattering and absorption and incorporates, without modification, the effects of all ambient aerosols in the sight path. However, the extinction calculation from a contrast measurement is highly sensitive to variations in inherent contrast and non-uniform illumination conditions, neither of which can be readily accounted for in normal monitoring.³

To address the limitations of these past visibility monitoring techniques, the National Park Service (NPS) has supported the development and testing of new electro-optical instrumentation for the measurement of ambient atmospheric extinction in remote Class I areas.⁴ The mandatory design criteria to be met or exceeded were:

- Measure atmospheric extinction at 550 nm
- Measure extinction both day and night
- Provide a variety of sampling and averaging options
- Operate unattended for extended periods
- Operate at low power to accommodate remote solar applications
- Operate at a wide range of ambient temperatures
- Be capable of self recovery in the event of power interruptions
- Provide analog voltage outputs and panel displays of selected visual air quality measurements
- Be modular, lightweight, and easily transported to accommodate remote installations or field replacement of components
- Require minimal sheltering to limit visual impacts in scenic areas
- Be easily serviced by trained, non-technical personnel

This program has led to the development and deployment of a network of twenty-one transmissometers in Class I areas around the United States. Table I lists the locations of these monitoring sites. Nineteen of the sites operate year round. Crater Lake and Voyageurs monitor only in the summer due to their extreme winter conditions. From January 1987 through March 1989, these systems have been procured, installed, and tested; with procedures developed for siting, installation, operation, maintenance and calibration.^{5,6,7} Extinction and performance data collected during this two-year pre-operational period⁸ have proven the robustness of the instrument and applicability of the technique to monitoring ambient atmospheric extinction in remote pristine environments.

OPTEC LPV-2 Transmissometer

The Optec LPV-2 transmissometer has been developed to meet the specific requirements for measuring the ambient atmospheric extinction coefficient in Class I areas. The system consists of two primary components: a transmitter (light source) and a receiver (detector).

The transmitter emits a uniform, modulated light beam of constant intensity at regular intervals for a programmed duration. The transmitter has two components: a light source with associated optics and an electronic control box. The transmitter optics perform two functions: 1) concentrate light from a 15-watt tungsten filament lamp into a narrow, well-defined uniform cone, magnifying the beam to the equivalent of a bare 1500-watt lamp; and 2) allow the operator to accurately aim the light beam at the receiver. The intensity of the light emitted from the transmitter is precisely controlled by an optical feedback system which continuously samples the center 0.17 degree portion of the outgoing beam and makes fine adjustments to keep the irradiance of the transmitter constant to within 1%. The transmitted light is modulated (chopped) at precisely 78.125 hertz by a mechanical spinning disk located between the lamp and projection optics. This modulated signal can be differentiated from background illumination by the receiver computer, allowing the system to operate day and night. The transmitter can be programmed to run continuously or operated in a timed cycle mode to conserve power.

The receiver has three components: 1) a long focal length telescope; 2) a photodetector eyepiece assembly; and 3) a low power CMOS computer. The telescope views the transmitter, collects the ambient and signal irradiance, and focuses it on a photodiode that converts all the light gathered into an electronic signal. The receiver computer "locks-on" to the chopped frequency of the transmitter and separates the signal from ambient illumination. The received signal can be described as an AC waveform (chopped transmitter light) carried on a DC voltage (background illumination). The computer compares the measured transmitter light intensity with the calibrated transmitter output intensity to directly calculate the transmission of the intervening atmosphere. The effect of atmospheric optical turbulence is minimized by using 62,500 samples of the signal to calculate each one-minute average value. By knowing the exact distance to the transmitter, the computer can determine the path's average extinction coefficient.

Siting Criteria

The fundamental requirement for operation of the LPV-2 transmissometer is a clear, unobstructed line-of-sight between the transmitter and receiver. The basic operating assumption of the system is that in the absence of atmospheric extinction, the irradiance from the source decreases inversely as the square of the distance from the transmitter. This premise will be invalid if the transmitted beam is distorted by refraction due to temperature discontinuities or by surface reflections. To eliminate these effects, the transmitted light should not intercept or pass near any surface visible in the detector field of view. If possible, the sight path should be elevated above the terrain with both the transmitter and receiver located at the edge of a drop-off. Figure 1 depicts acceptable and unacceptable sight paths.

System Installation, Power Requirements, and Operation

A LPV-2 transmissometer configured for remote, unattended operation requires a stable mounting platform, adequate sheltering, and a reliable power supply. A diagram of a typical transmissometer installation is presented in Figure 2.

Transmitter and receiver telescope alignment is critical for proper operation of the system. The small angle of the transmitted cone of light (0.17°), and the very small angle of acceptance of the receiver detector (0.07°) require mounting platforms that are not susceptible to movement due to differential thermal expansion, slippage, or vibration. Receiver mounting is more critical than transmitter mounting. A massive concrete pier, or rock, should be used to support the mounting posts. Soil stability and frost depth should be considered when locating the pier. Alti-azimuth bases must be used to allow precise positioning of the transmitter and receiver telescopes.

The system can successfully operate at a wide range of ambient temperatures from -20°C to 50°C .; however, sheltering is required to protect the optics and electronics from dirt and moisture, to house support equipment, and in severe climates to shelter the operator during servicing. The type of shelters used in remote areas depends on the local weather conditions and site logistics. Shelters can range from small environmental enclosures to full-size instrument shelters. Two instrument-related requirements must be accommodated: 1) The mounting post should be isolated from the shelter vibrations and movement, and 2) transmittance at 550 nm for all windows must be known to within $\pm 0.1\%$.

Both the transmitter and receiver operate from 12 volts DC, requiring 34 and 5 watts respectively. Any well-filtered, stable power supply may be used. The transmissometer operates best from an array of deep-cycle batteries that are maintained by a surge-protected automatic charger connected to either AC line power or an adequate size system of solar cells. This allows the system to operate during intermittent power outages and to be located in remote areas. The transmitter and receiver circuitry contain internal battery backed timing circuits to maintain correct system timing in the event of a complete power failure. The system will restore itself to operation when power returns.

Servicing Requirements

Routine servicing requirements of the LPV-2 transmissometer system are minimal and can be performed by trained, non-technical personnel. Calibration and major system maintenance require the transmissometer to be returned to the central laboratory. Servicing tasks can be separated into four classifications:

WEEKLY

- Transmissometer and receiver telescope alignment check
- Cleaning of transmitter and receiver optical surfaces, general inspection

MONTHLY

- Transmitter and receiver system timing check and reset if necessary
- Transmitter lamp status check

EVERY FOUR MONTHS

- Transmitter lamp change

YEARLY

- Field technician site visit and factory servicing of system
- Operator training
- Post-calibration of old lamps
- Pre-calibration of new lamps

Instrument Calibration

Calibration determines the irradiance of the transmitter lamp that would be measured by the receiver if the optical sight path between the two units allowed 100% transmission. The LPV-2 transmissometer must be calibrated as a unit. Each lamp will have its own calibration number for use with a specific transmissometer system. No component of the system, including lamps, may be interchanged with another transmissometer without re-calibration.

Calibration requires moving the transmitter and receiver close enough together to negate the effects of the atmosphere on the transmission of the light. A recommended calibration path length is 300m. A precisely-machined calibration aperture is placed on the receiver telescope to avoid detector saturation. The calibration number of each lamp is calculated by:

$$\text{Calib. \#} = (\text{CP/WP})^2 \times (\text{WG/CG}) \times (\text{WA/CA})^2 \times \text{WT} \times (1/\text{T}) \times \text{CR}$$

where: (suggested values)

CP = calibration path length (.300 km)
 WP = working path length (0.50 to 10.00 km)
 CG = calibration gain setting (800 to 900)
 WG = working gain setting (200 to 400)
 CA = calibration aperture (11.00 mm)
 WA = working aperture (110.00 mm)
 WT = total shelter(s) window transmittance at 550 nm
 If windows are used on both ends, multiply their
 transmittances together. Typical value for two
 windows is 0.846
 T = estimated or measured transmittance for the
 calibration path
 CR = average of 15 one minute readings of lamp
 irradiance over calibration path

The calibration number represents the reading in counts that would be measured if the atmosphere between the transmitter and receiver allowed 100% transmission over the length of the working path. With the calibration number dialed-in on the computer front panel, the transmission (T) of the sight path is directly calculated by the receiver computer by dividing the measured reading with the calibration number. With the working path length (r) dialed-in on the computer front panel, the average extinction of the sight path can be calculated:

$$b_{\text{ext}} = (1/r) \times \ln(1/T)$$

A precisely machined lamp housing positions the lamp filament in the correct optical position. This allows the system to be pre-calibrated with a number of lamps at a central facility, transported to the monitoring location, operated for an extended period of time with regular lamp changes, and then returned to the central facility for regularly scheduled maintenance, system upgrades, and post-calibration.

Data Collection

Figure 3 depicts the complete monitoring system that has been developed to maintain a high quality data collection efficiency for the twenty-one-station network of remote transmissometers. Handar 570 data collection platforms (DCP) are used to collect extinction, temperature, relative humidity, and operating parameters of the complete system. The DCP transmits the data through a geostationary satellite to a collection facility (Wallops Island) where it is available by telephone modem access. A strip chart recorder provides data collection backup as well as on-site visual record of instrument performance for the field operator.

Data are retrieved daily from the Wallops Island downlink, reviewed to monitor the operation of the entire network, and archived for validation and reporting. Any operational problems encountered result in an immediate call to the field operator for diagnosis and repair. If the instrument cannot be returned to nominal status, a complete pre-calibrated system is sent to the site for installation by the field operator. The complete faulty system is returned to the central facility for maintenance and calibration.

In remote areas, transmissometers operate in a timed cycle mode. This procedure conserves power by having the transmitter on for 16 minutes of every hour and the receiver computer on for 10 minutes. The cycle is as follows:

- 1) At the beginning of the hour the transmitter control box turns the lamp on, spins the chopping motor up to frequency, and stabilizes the transmitter irradiance at its calibrated value;
- 2) Three minutes past the hour the receiver computer turns on and begins a ten-minute average extinction measurement;
- 3) Thirteen minutes past the hour receiver computer finishes measurement, updates panel display, and outputs to data logger; and
- 4) Sixteen minutes past the hour the transmitter control box turns the lamp and chopping motor off.

Each ten-minute extinction calculation uses the average value of ten one-minute measurements of lamp irradiance. To minimize the effect of atmospheric optical turbulence, every one-minute value is the mean of 62,500 samples of the chopped signal. Along with mean extinction, the receiver computer calculates and outputs the standard deviation of the ten one-minute irradiance counts. Under normal conditions, the standard deviation of the ten values is less than 2% of the signal. High standard deviations typically occur when an interference with the transmitted beam such as precipitation or extreme background illumination appears. The hourly standard deviations are monitored daily to review the performance of the system.

Data Reduction

After collection, the data are edited by flagging measurements when the system was known to be inoperative or delivering questionable measurements. These conditions include optical misalignment, unknown window transmission due to exceptionally dirty, broken, or missing glass, inadequate power supply, or questionable data logging, transmission, or retrieval. These conditions are retrieved from on-site operator log sheets and operational parameters monitored by the DCP.

The data are then reduced to six-hour average values of extinction. The time periods of the four daily six-hour averages are:

- 1 - 0000 to 0559 hrs
- 2 - 0600 to 1159 hrs
- 3 - 1200 to 1759 hrs
- 4 - 1800 to 2359 hrs

Transmissometer data are reported in quarterly reports and archived in the NPS visibility database. Data summaries are available in single page format. Figure 4 is an example of the Summer 1989 seasonal summary report for Grand Canyon National Park (June 1, 1989, through August 31, 1989). Table II lists the mean extinction measured and data collection efficiency at the twenty-one locations during the Summer 1989 season.

The top graph on the seasonal summary plot is a time line of all the collected six-hour average extinction values. The left axis of the plot is labeled as standard visual range (SVR) and the right as b_{ext} . A Rayleigh atmosphere is defined as having a SVR of 391 km and a b_{ext} of 0.01 km^{-1} . The middle graph presents a time line of six-hour average relative humidity measurements. This allows convenient interpretation of the effect of increasing relative humidity on measured b_{ext} . The bottom graph is a rank-ordered cumulative frequency plot of the data. The 10% to 90% values are plotted in 10% increments. The 10%, 50%, and 90% cumulative frequency values are listed to the right of the plot. The listing at the bottom of the seasonal summary plot contains the data recovery statistics for the season. The total possible number of six-hour average values are compared to the number of valid, usable six-hour average values.

Summary

A complete monitoring system that can make accurate measurements of atmospheric extinction in remote pristine areas has been developed, tested, and implemented. The system is based on the Optec LPV-2 transmissometer and meets the stringent requirements for operation in Class I areas. Complete installation, data logging, operating, calibration, and reporting procedures have been developed. Twenty-one transmissometers have been deployed in a nationwide visibility monitoring network that became operational in the Spring 1989.

References

1. Charlson, R.J., H.Horvath, and R.F.Pueschel, "The Direct Measurement of Atmospheric Light Scattering Coefficient for Studies of Visibility and Pollution," Atmospheric Environment 1:469 (1967).
2. Malm, W.C. and J.V.Molenaar, "Visibility Measurements in National Parks in the Western United States," APCA Journal 34 (9):(1984).
3. Malm, W.C., "Review of Techniques for Measuring Atmospheric Extinction," Paper 86-17.2, presented at the 79th Annual Meeting and Exhibition of the Air Pollution Control Association, June 22-27, 1986, Minneapolis, Minnesota.
4. Malm, W.C., G.Persha, R.Tree, R.Stocker, I.Tombach, and H.Iyer, "Comparison of Atmospheric Extinction Measurements Made By A Transmissometer, Integrating Nephelometer, and Teleradiometer With Natural And Artificial Black Target," in Transactions: Visibility Protection Research And Policy Aspects, P.S. Bhardwaja, Editor (1987).
5. Air Resource Specialists, Inc., "LPV-2 Transmissometer Standard Operating Procedures Manual," May 1988.
6. Air Resource Specialists, Inc., "Transmissometer System Field Operator's Manual," September 1988.
7. Air Resource Specialists, Inc., "Transmissometer Operator Training Guide," March 1989.
8. Air Resource Specialists, Inc., "Summary of Transmissometer-Based Visual Air Quality Data Collected During The Pre-operational Test Period (Winter 1987 Through Winter 1989 Seasons)," June 1989.

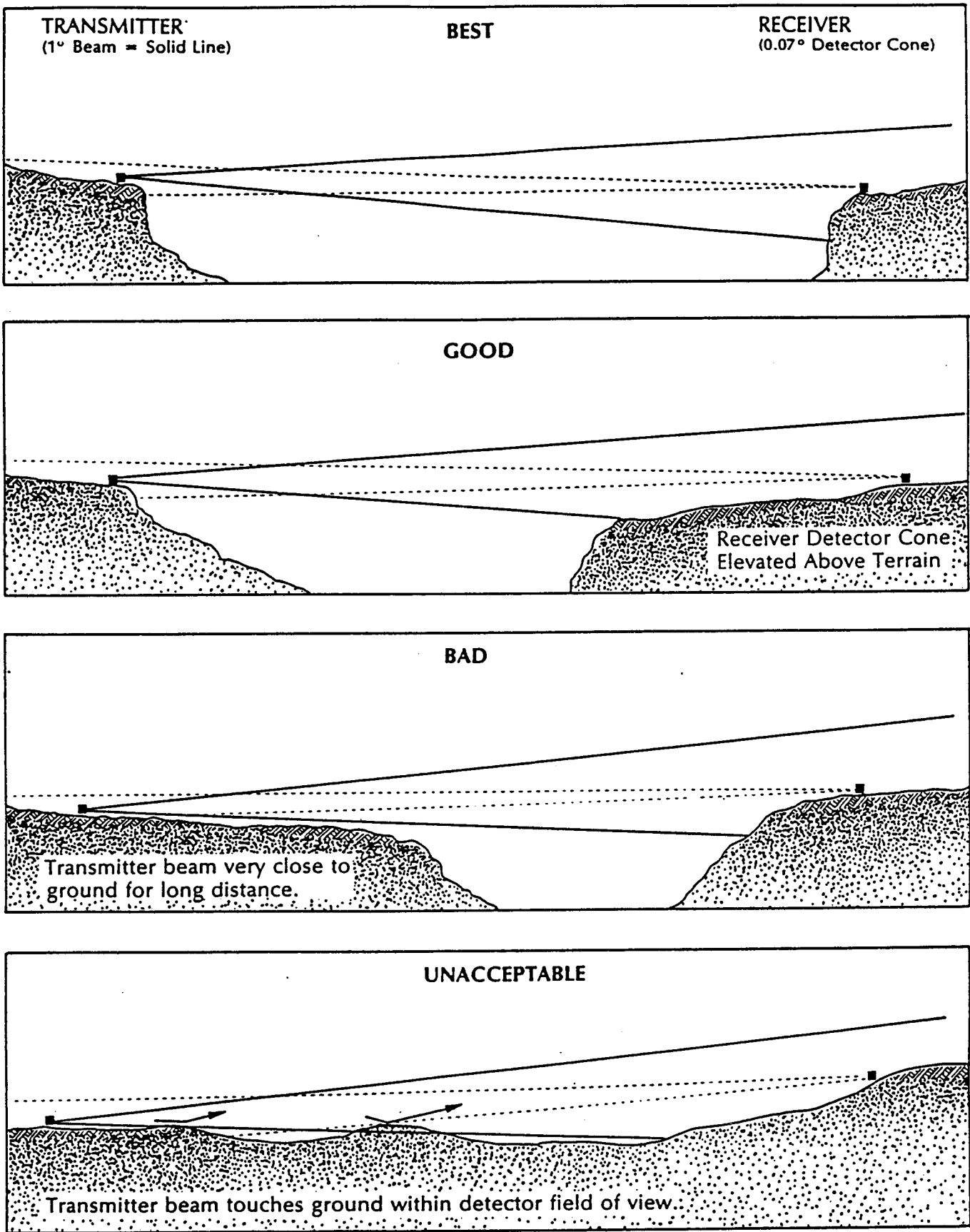
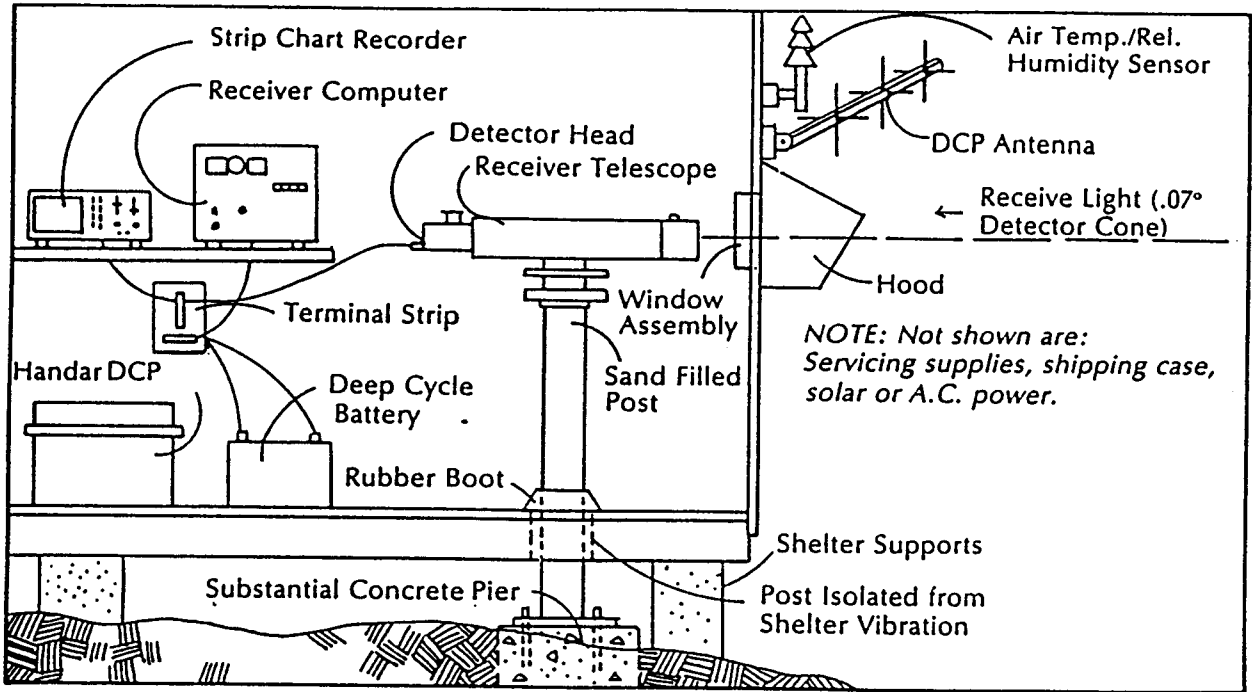


Figure 1. Transmissometer Sight Path Examples

Receiver Station

(6'x 6'x 8')



Transmitter Station

(3'x3'x4'6")

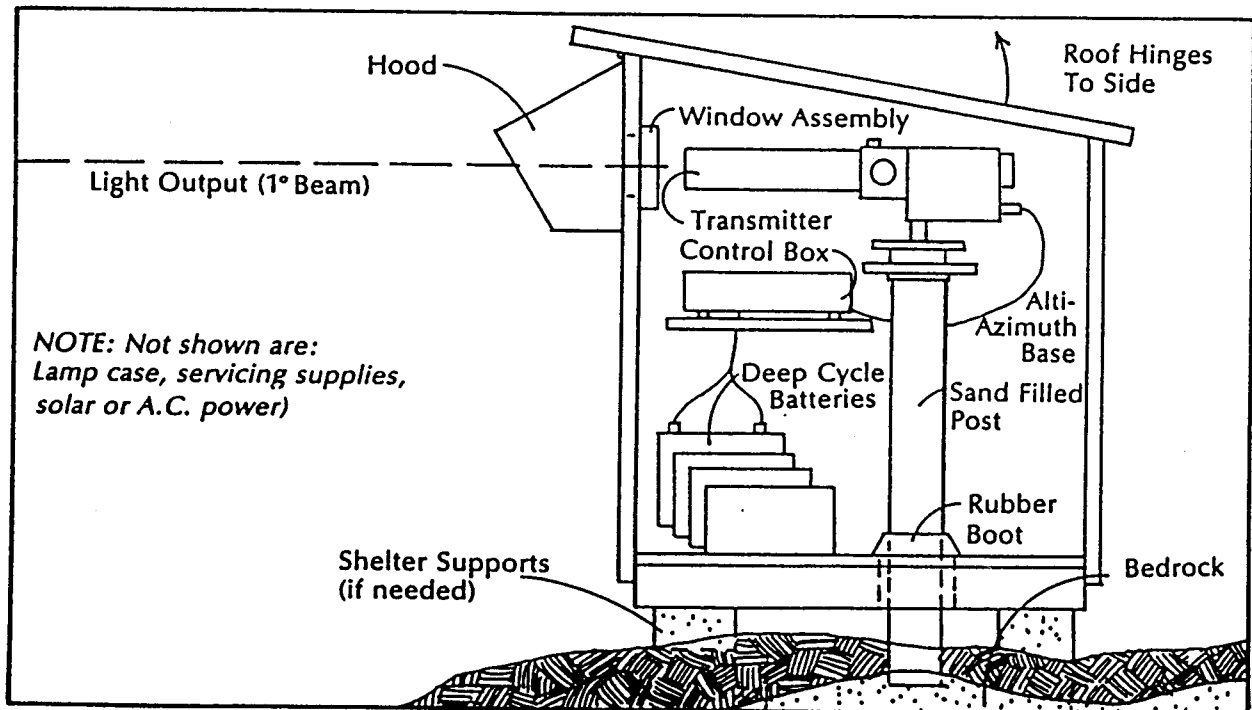


Figure 2. Transmissometer System Component Placement

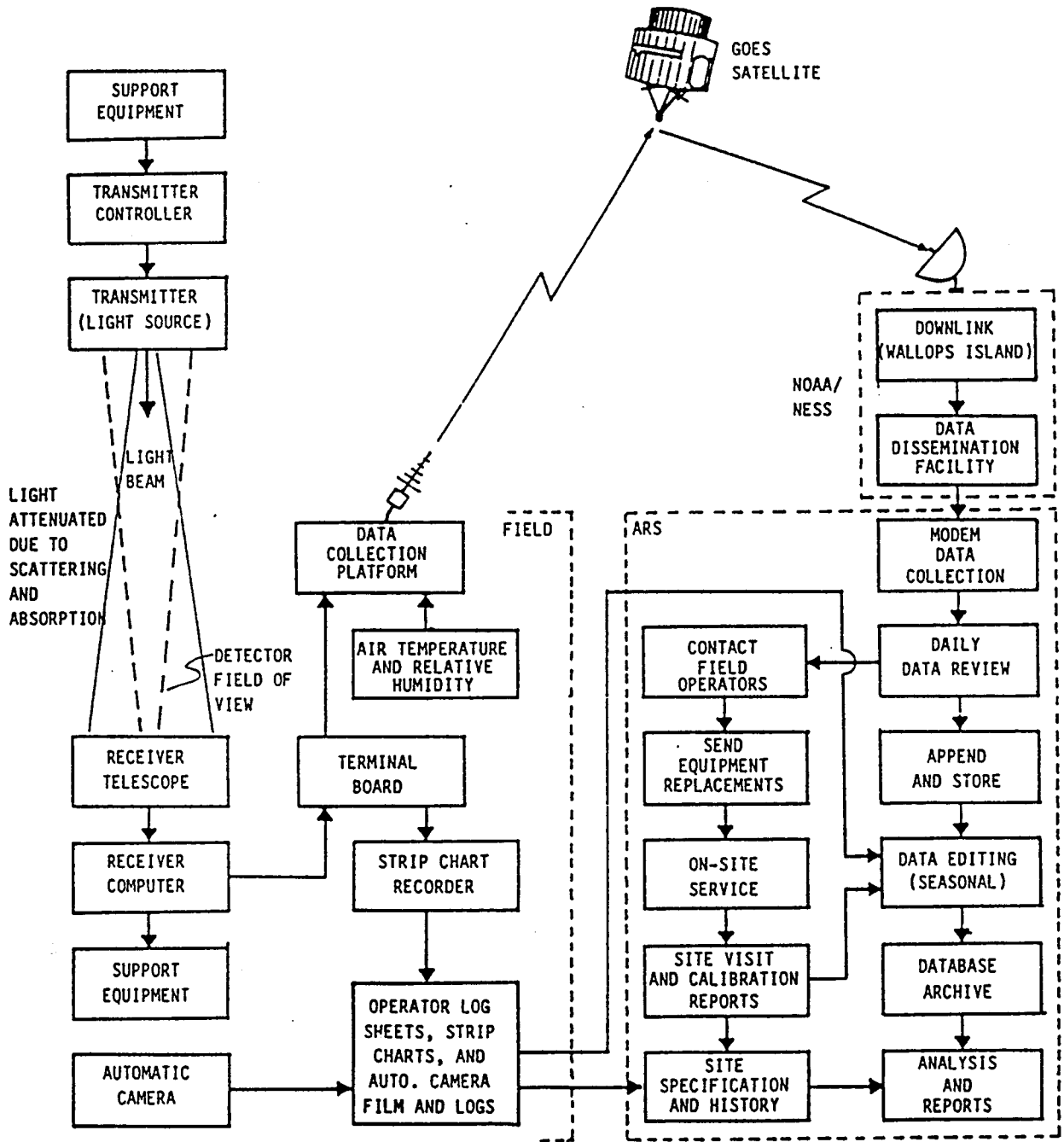
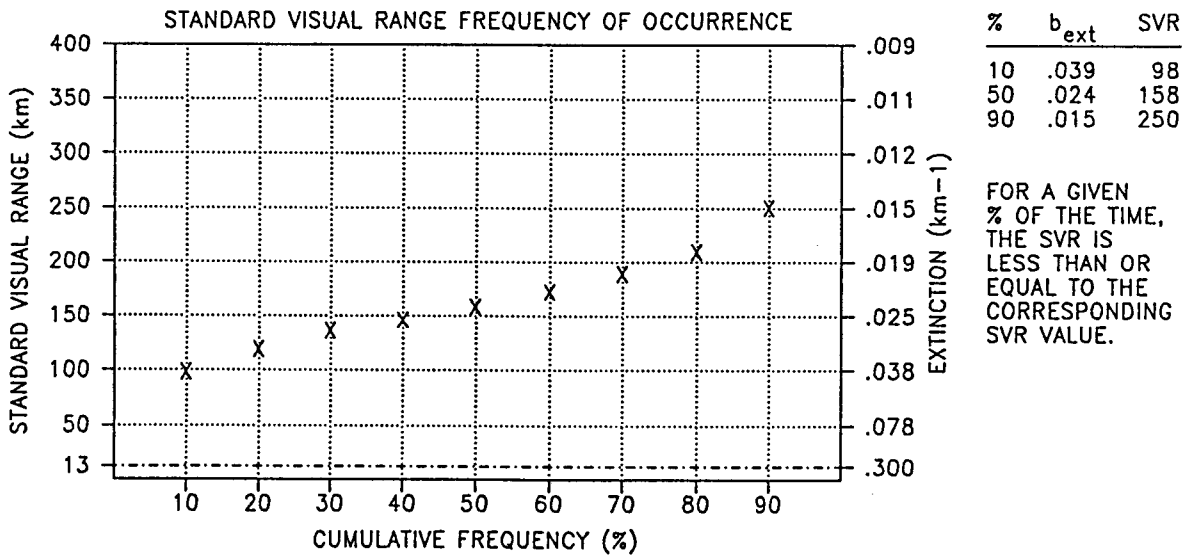
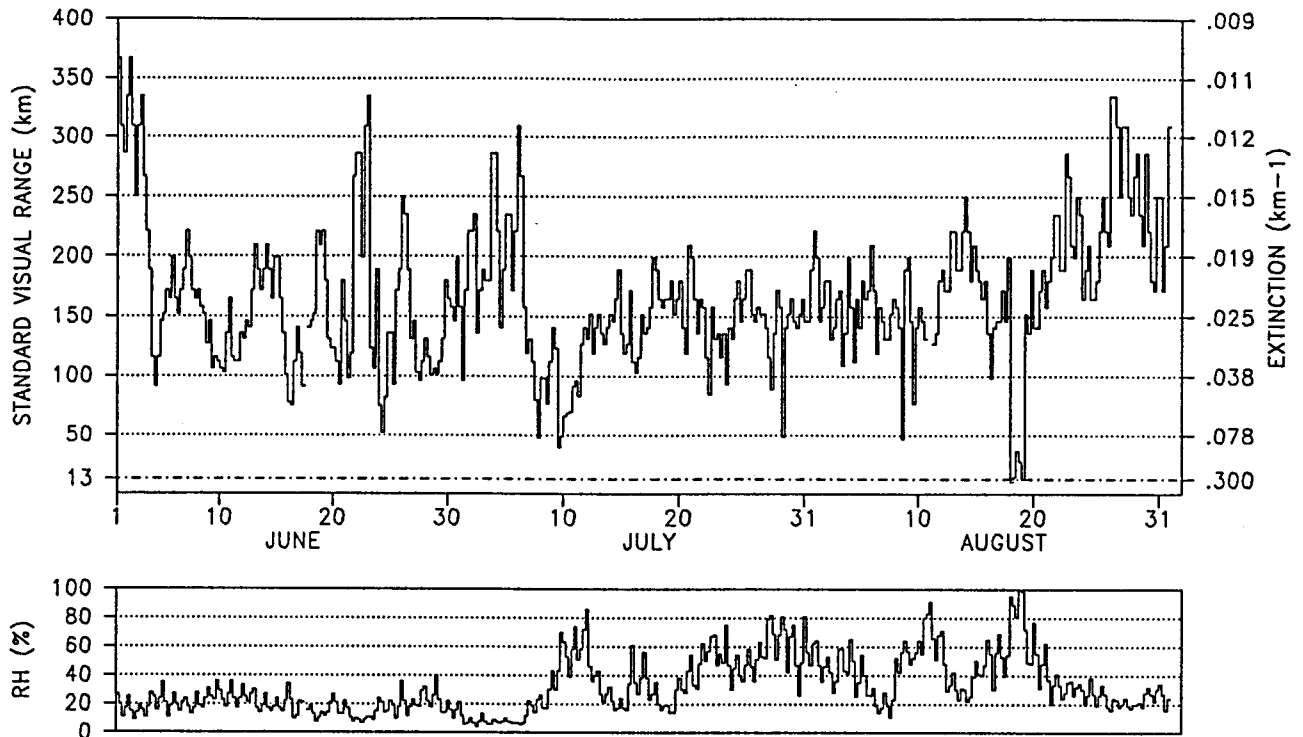


Figure 3. Transmissometer Data Collection System

GRAND CANYON NATIONAL PARK, ARIZONA
 Transmissometer Data Summary -- 6 Hour Averages
 June 1, 1989 - August 31, 1989



TRANSMISSOMETER DATA RECOVERY STATISTICS

CATEGORY	NUM	%
TOTAL POSSIBLE 6-HOUR AVERAGES IN THE TIME PERIOD	368	100
USABLE 6-HOUR AVERAGES IN THE TIME PERIOD	362	98

Figure 4. Transmissometer Seasonal Summary Plot

TABLE I

OPERATIONAL TRANSMISSOMETER NETWORK

1. Acadia National Park, Maine
2. Badlands National Monument, South Dakota
3. Bandelier National Monument, New Mexico
4. Big Bend National Park, Texas
5. Bridger Wilderness, Wyoming
6. Canyonlands National Park, Utah
7. Chiricahua National Monument, Arizona
8. Crater Lake National Park, Oregon
9. Glacier National Park, Montana
10. Grand Canyon National Park, Arizona
11. Guadalupe Mountains National Park, Texas
12. Mesa Verde National Park, Colorado
13. Petrified Forest National Park, Arizona
14. Pinnacles National Monument, California
15. Rocky Mountain National Park, Colorado
16. San Geronio Wilderness, California
17. Shenandoah National Park, Virginia
18. Tonto National Monument, Arizona
19. Voyageurs National Park, Minnesota
20. Yellowstone National Park, Wyoming
21. Yosemite National Park, California

TABLE II

MEAN TRANSMISSOMETER DERIVED EXTINCTION COEFFICIENT SUMMER 1989

Location	Mean b_{ext} (km^{-1})	Usable Data (%)
Acadia	0.116	55
Badlands	0.052	34
Bandelier	0.038	95
Big Bend	0.056	94
Bridger	0.031	70
Canyonlands	0.022	69
Chiricahua	0.041	96
Crater Lake	0.026	100
Glacier	0.050	93
Grand Canyon	0.024	98
Guadalupe	0.061	94
Mesa Verde	0.037	80
Petrified Forest	0.038	98
Pinnacles	0.062	93
Rocky Mountain	0.031	59
San Geronio	0.122	83
Shenandoah	0.392	25
Tonto	0.039	94
Voyageurs	0.067	14
Yellowstone	0.036	90
Yosemite	0.089	88