LONG PATH TRANSMISSOMETER FOR MEASURING AMBIENT ATMOSPHERIC EXTINCTION

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Abstract

During the past eleven years, ambient atmospheric extinction has been monitored in national visibility programs primarily by measurements of apparent target contrast. While the ability of teleradiometer and photographic densitometry to accurately determine apparent target contrast is well proven, the calculation of extinction from contrast measurements is usually compromised by theoretical assumptions that are not met in practice. To address this problem, the National Park Service has supported the development, testing, and deployment of an instrument that accurately and reliably measures the transmission of an ambient atmospheric optical path. The average extinction of the path can be directly calculated from the transmission measurement. Twenty-one of these systems are currently in operation in federal visual air quality monitoring networks. In addition, several others have been and are being used in urban visibility studies and as a reference device for airport runway visual range measurements. A complete description of the instrument, the Optec LPV-2 long-range transmissometer, will be presented. Theoretical, atmospheric optical and turbulence considerations will be combined with design parameters and experimental data to confirm the ability of this instrument to make an accurate, precise, and reliable extinction measurement.

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Introduction

The Optec LPV-2 transmissometer was designed and is manufactured by Optec, Inc. of Lowell, Michigan. The development, testing, and deployment of this instrument has been supported by the National Park Service (NPS) Visibility Monitoring and Data Analysis Program and the Interagency Monitoring of Protected Visual Environments (IMPROVE) Committee. The system has been developed to improve the accuracy of atmospheric extinction measurements in remote pristine Class I areas. The transmissometer was designed to meet the following criteria:

- 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

Instrument Description

The Optec LPV-2 transmissometer consists of a constant output light source transmitter (Figure 1) and a computer controlled photometer receiver (Figure 2). The irradiance at 550 nm from the transmitter can be measured to a high degree of accuracy both day and night over a path length up to 30 km depending on the ambient extinction. The transmitter and receiver operate from 12-volt battery sources and use 34 and 5 watts respectively. The transmitter signal is processed at the receiver by an internal CMOS 8-bit computer with the output voltage made proportional to irradiance, extinction or visual range. The systems can operate for long periods of time unattended in a continuous or timed cycle mode. The transmitter control box and receiver computer have internal battery backup systems and self resetting circuits to ensure continued operation even after power blackouts or computer lockup due to local static electrical discharges. Both units can be synchronized, programmed and calibrated at a central facility and installed in the field ready for operation.

Transmitter

One of the major design requirements of the transmitter is that it produces a constant output, isotropic, modulated light beam and operates with low voltage (9 tO 14 volts DC) and limited power available from batteries with integrated solar cell recharging panels. Figure 3 shows a schematic of the transmitter function diagram.

Lamp and Lamp Regulation. The transmitter uses a 15-watt tungsten filament lamp with a nominal operating voltage of 5.8 VDC. It is critically prefocused, centered, and securely mounted in a special housing which allows easy removal and replacement in the field without the need to align the lamp with the optics after each servicing. To maintain the lamp output constant at better than 1%, an optical feedback method is used. Approximately 8% of the light in an area 0.17 degrees in diameter as referenced to the projected cone of light and centered around the optical axis is diverted 90 degrees to a silicon photodiode detector. A narrow band filter with a center wavelength of 550 nm and a bandwidth of 10 nm is mounted in front of the detector to ensure that the irradiance at 550 nm is held constant as the lamp ages and its spectral output changes. A pre-amplifier configured as a current-to-voltage amplifier converts the photocurrent from the detector to a voltage which is fed to the inverting input of a high gain (gain=200) difference amplifier. The non-inverting input is connected to an adjustable and highly-stable reference voltage which is initially adjusted to 5.80 VDC. As the lamp ages and output drops, the circuit will increase the voltage to the lamp until the voltage from the pre-amplifier is nearly equal to the reference. Thus, the irradiance at 550 nm from the transmitter is held constant as the lamp ages. At a lamp voltage of 6.8 VDC, an LED on the side of the control box will turn on indicating an abnormally high lamp voltage and the need for a lamp replacement. Since dust and evaporated films would effect the transmission of the feedback optics causing the lamp irradiance to increase unpredictably, the number of exposed optical surfaces are minimized by enclosing the feedback optics assembly and the projector condenser lens in a hermetically sealed block. The front surface of the condenser lens and both sides of the projector lens are the only surfaces which need to be cleaned on a regular basis.

Projection Optics. To increase the output of the 15-watt lamp to a level necessary to be measured accurately by the receiver over long sight paths, a Koehler projection system is used. This method increases the output of the lamp in a 1-degree diameter cone by a factor of approximately 100 while keeping the isotropy of the central 0.17 degree cone to within 1%. The condenser collects the light contained in a solid angle of 11 degrees as seen from the filament, concentrates it into a 1 degree cone. The 1 degree cone is set by a field aperture at the focus of the projector lens which is mounted close to the condenser. The beam isotropy is dependent on the uniform illumination of the field aperture by the lamp filament. Due to the shading within the coiled filament of the lamp (rear coils are shaded by the front coils), some non-uniformity is always present. Field and laboratory measurements of beam isotropy have indicated that the 1-degree cone is uniform to 5% with the central 0.17-degree cone viewed by the feedback circuit having less than 1% variation. To allow for precise alignment of the beam on the receiver, an eyepiece with a reticle indicating the 0.17-degree central cone is fitted to the transmitter.

Light Beam Modulation. A four-bladed chopper mounted near the condenser modulates the beam at exactly 78.125 hertz. The chopper is rotated at the exact speed of 19.5315 revolutions per second by a low voltage synchronous timing motor. Pulses from a crystal oscillator are power amplified and shaped by a bridge driver to run the motor. To ensure reliable startup of the motor, the drive pulses are slowly ramped up to frequency before locking onto the crystal.

Timed Cycle Mode. The transmitter can be operated continuously if power is of no concern. However, in remote solar application, the transmitter can be operated in a timed cycle mode to conserve power. When operating in this mode and a new cycle starts, the lamp is turned on first and the motor second. The voltage to the lamp is increased gradually over a period of about four seconds to reduce the inrush current surge and thermal shock to the lamp filament. The chopper motor is started 3 seconds after the cycle begins. This eliminates the possibility of the remaining small inrush current reducing power to the chopper motor during the critical start-up period. From the start of the cycle time, it takes 10 seconds for both the lamp and chopper to reach stable operating levels. The possible cycle times (period between transmitter turn on) are 20 minutes, 1, 2, and 4 hours. The length of the time the transmitter is on (integration time) is selectable between 2, 16, 32, and 64 minutes. By setting the integration time equal or greater than the cycle time the transmitter will run continuously. In case of power failure or insufficient battery voltage, the cycle and integration timer continue to operate from internal AA alkaline backup batteries. When the external power returns, the transmitter will begin normal operation automatically.

Receiver

The LPV-2 receiver uses a very sophisticated and accurate method to collect the transmitter signal and retrieve it from amplifier and background noise, measure the irradiance, and calculate ambient atmospheric extinction. The modulated signal of the transmitter is locked onto by the computer. The signal difference between transmitter on and off is sampled and integrated over many thousands of cycles. This allows for an accurate determination of the strength of the received signal and the calculation of extinction. Figure 4 shows a schematic of the receiver function diagram.

Signal Acquisition. A 125mm anti-reflection coated, cemented achromat refractor lens with a focal length of 629mm is used to optically amplify the light from the transmitter and provide some smoothing of the signal noise caused by atmospheric optical turbulence. The collected light, which includes both background illumination and the transmitter signal, is focused through an identical filter as on the feedback optics of the transmitter, to a silicon photodiode operating in the photovoltaic mode with a very low bias current-to-voltage amplifier. The 1mm square detector surface is masked with a 0.75mm diameter aperture which defines a 0.07-degree solid angle for the detector field of view. The detector-electrometer unit is rigidly mounted on a X-Y adjustable bracket centered in the photometer head. The bracket is precisely positioned while on an optical bench so that it coincides exactly with an etched ring visible in the reticle of the eyepiece used to align the receiver telescope on the transmitter. Thus, when the transmitter and receiver are correctly aligned, the detector views a small area of the uniform central cone of the transmitted beam. Any beam wander due to turbulence will still allow the receiver to view a uniform portion of the transmitted signal.

Signal Pre-processing. Before the output of the detector-electrometer is processed by the computer, the signal is divided into two parts for amplification, wave shaping, and filtering. The first part is scaled by a 10-turn potentiometer attenuator and amplified by a low-noise fixed gain amplifier. The potentiometer is located on the front panel of the computer and is set such that under severe optical turbulence the signal is scaled to achieve maximum values without over-voltaging the A/D converter input or over-ranging the D/A converter output. A LED on the front panel will flash if the gain is set to high such that any peak signal would exceed the upper limit of the A/D converter. If the background illumination is sufficiently intense due to sun reflecting from snow or bright terrain in the field of view, the detector pre-amplifier will saturate and the signal will be lost. The second part of the signal is used to find the time when the transmitter chopper is open (signal on) or closed (signal off). A bandpass amplifier with a Q of 32 and center frequency of 78.125 Hz allows the fundamental frequency of the chopped signal to pass the zero cross detector. The positive half of the bandpass output (on) results in the zero cross detector going positive and the negative half (off) causes the bandpass to go negative with a very fast transition at the zero voltage points (Figure 5).

Signal Processing. In the absence of noise, the difference between the signal level at the top of the wave when the lamp is on and the bottom of the wave when the lamp is off would give an accurate measurement of the transmitter irradiance. Since noise due to atmospheric optical turbulence and receiver electronics is always present and usually several orders of magnitude greater than the signal, the average difference must be calculated over many thousands of cycles. To extract the signal from the background noise, the computer must be able to determine precisely the phase of the incoming signal with respect to the receiver phase pulse generator running at the same frequency. At the start of a measurement period, the computer compares the zero cross detector's positive transitions with the output of the phase pulse generator for a period of 1 second and computes the average phase difference (Figure 5). After the phase difference is measured, the center of the time intervals when the lamp is on and off can be determined. For each cycle during the next five seconds, 8 samples are taken of the signal during the lamp on interval and 8 more during the lamp off interval. A total of 6259 samples are taken during each 5-second measuring period, after which the computer again finds the phase difference and begins sampling the next 5-second interval. At the end of 60 seconds (ten measuring intervals), the average difference is computed and stored for further calculations or sent to the desired analog output.

Computer Output. Like the transmitter, the receiver computer has a cycle and integration timer with its own battery backup. In operation the transmitter and receiver timers are synchronized by manually resetting them simultaneously. The cycle times are the same as the transmitter; however, the integration times are set shorter to prevent differential drifting of the separate crystal clocks. The receiver integration times are 1, 10, 30, and 60 minutes. By dialing in the calibration value for the transmitter lamp and the path distance between the transmitter and receiver, the computer can calculate the average extinction of the sight path and corresponding visual range. In the continuous mode, the computer will output the one-minute average raw transmitter irradiance values and corresponding extinction and visual range. When operating in the timed cycle mode, the computer has the capability of outputting the average irradiance, extinction, or visual range for the integration interval along with the standard deviation of the population of one-minute raw irradiance values measured during the interval. In the event of power failure or computer lockup, the hard-wired reset circuit will attempt to restart the computer and program until proper operation begins again.

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:

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

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 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:

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

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. Figure 6 shows the results of a test of the ability to remove and replace a lamp and maintain a constant calibration number. Trials 1 - 15 indicate that the calibration was held constant to within 0.5% while the lamp was removed and re-inserted between calibrations. This compares favorably to repeated calibrations without lamp removal, trials 16-21, where the calibration was held constant to within 0.4%.

Post calibration has indicated a lamp calibration drift with hours of operation. This drift is plotted in Figure 7. The drift is a constant increase in the brightness of the lamp at the rate of 2% per 500 hours of use. This rate has been seen in every lamp used during the past two years.

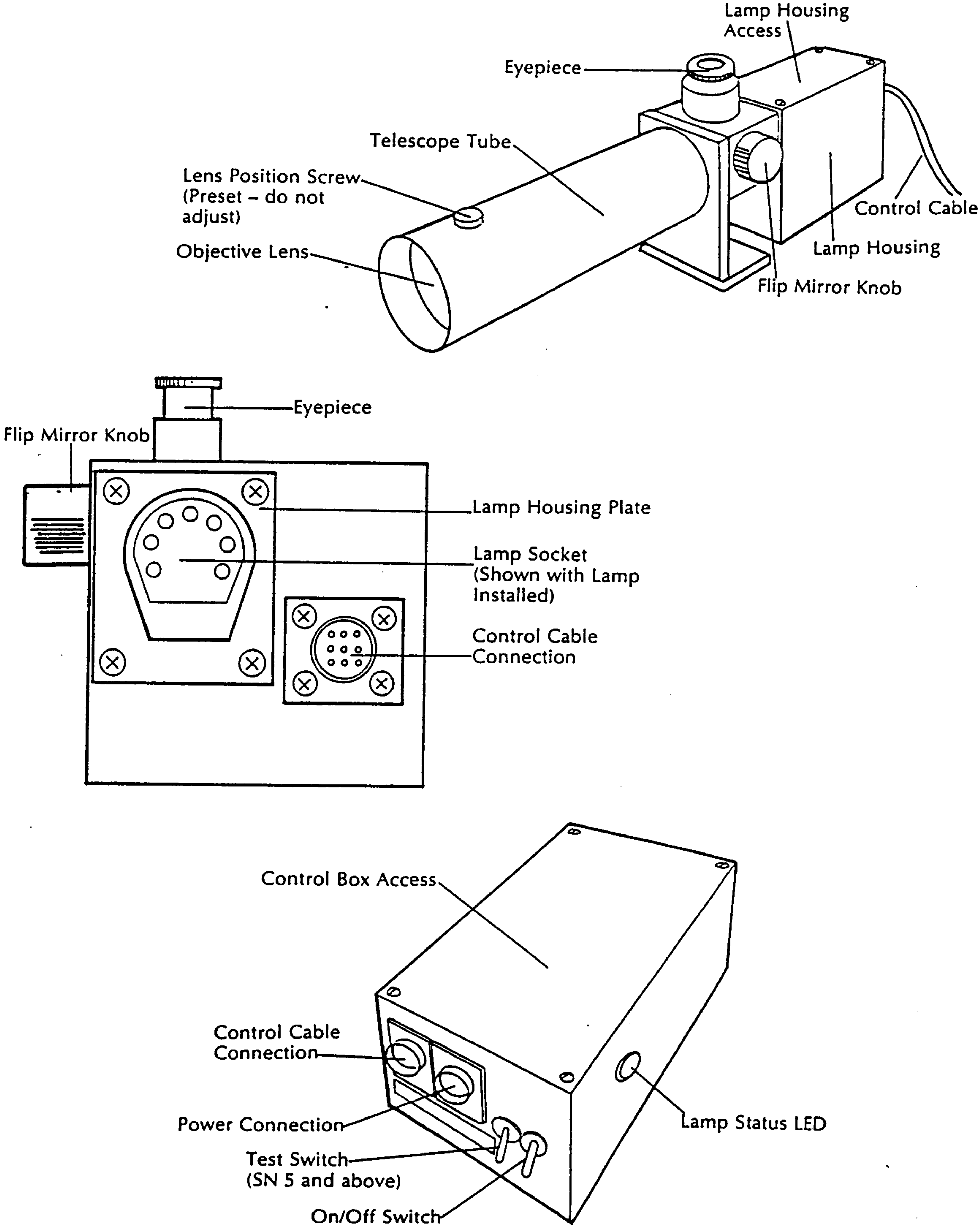

Figure 1. Transmissometer Transmitter Components

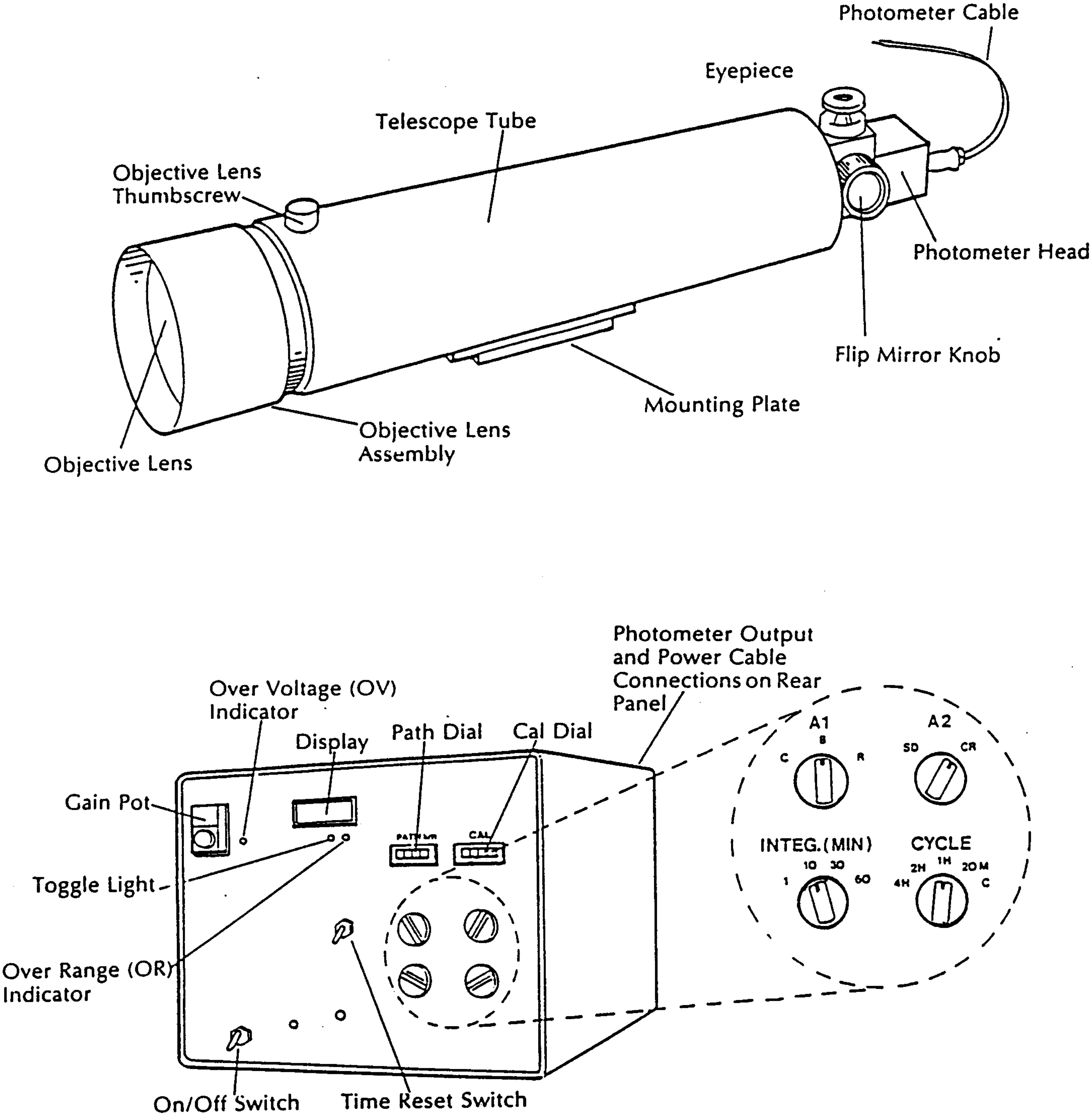

Figure 2. Transmissometer Receiver Components

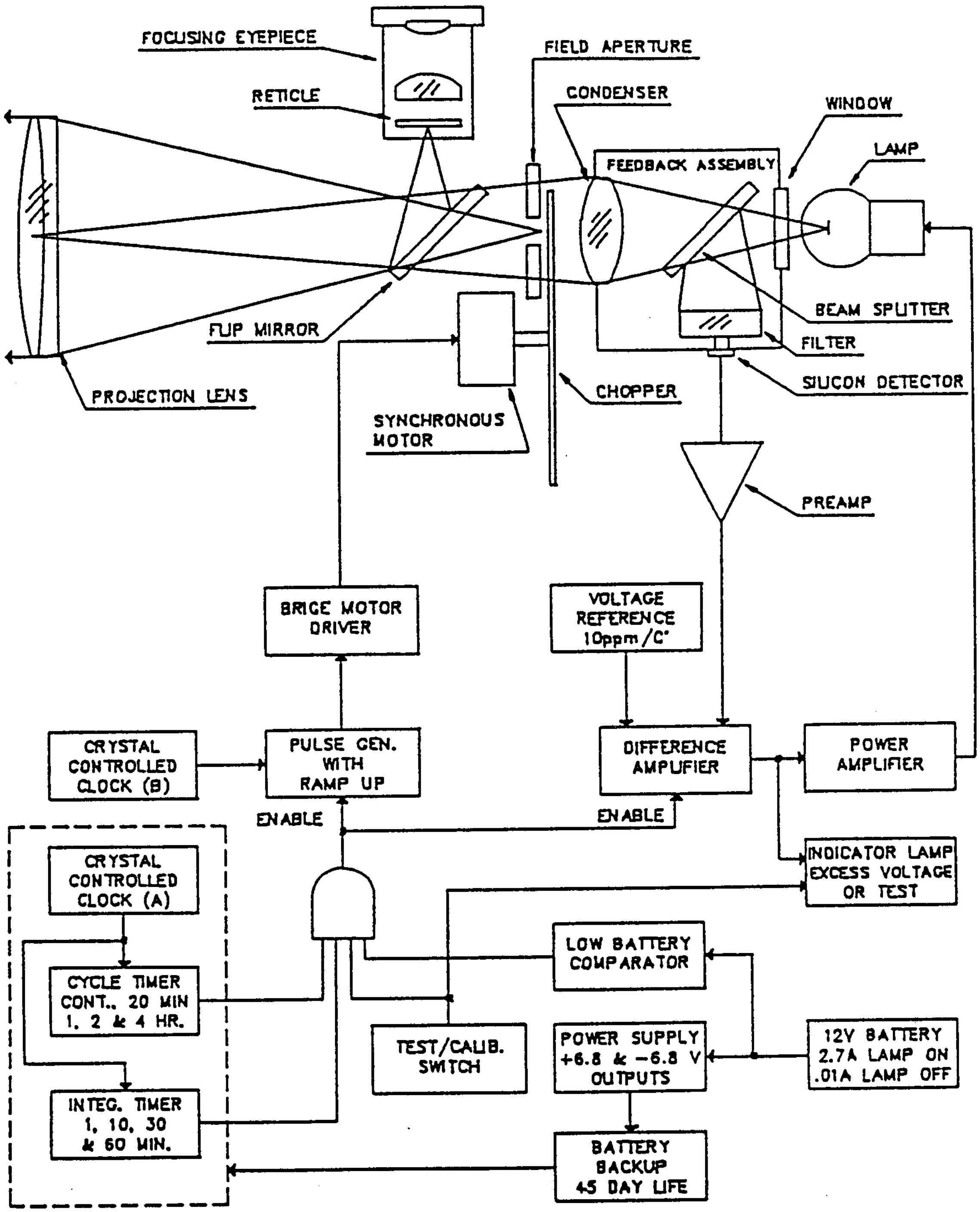

Figure 3. Transmitter Functional Diagram

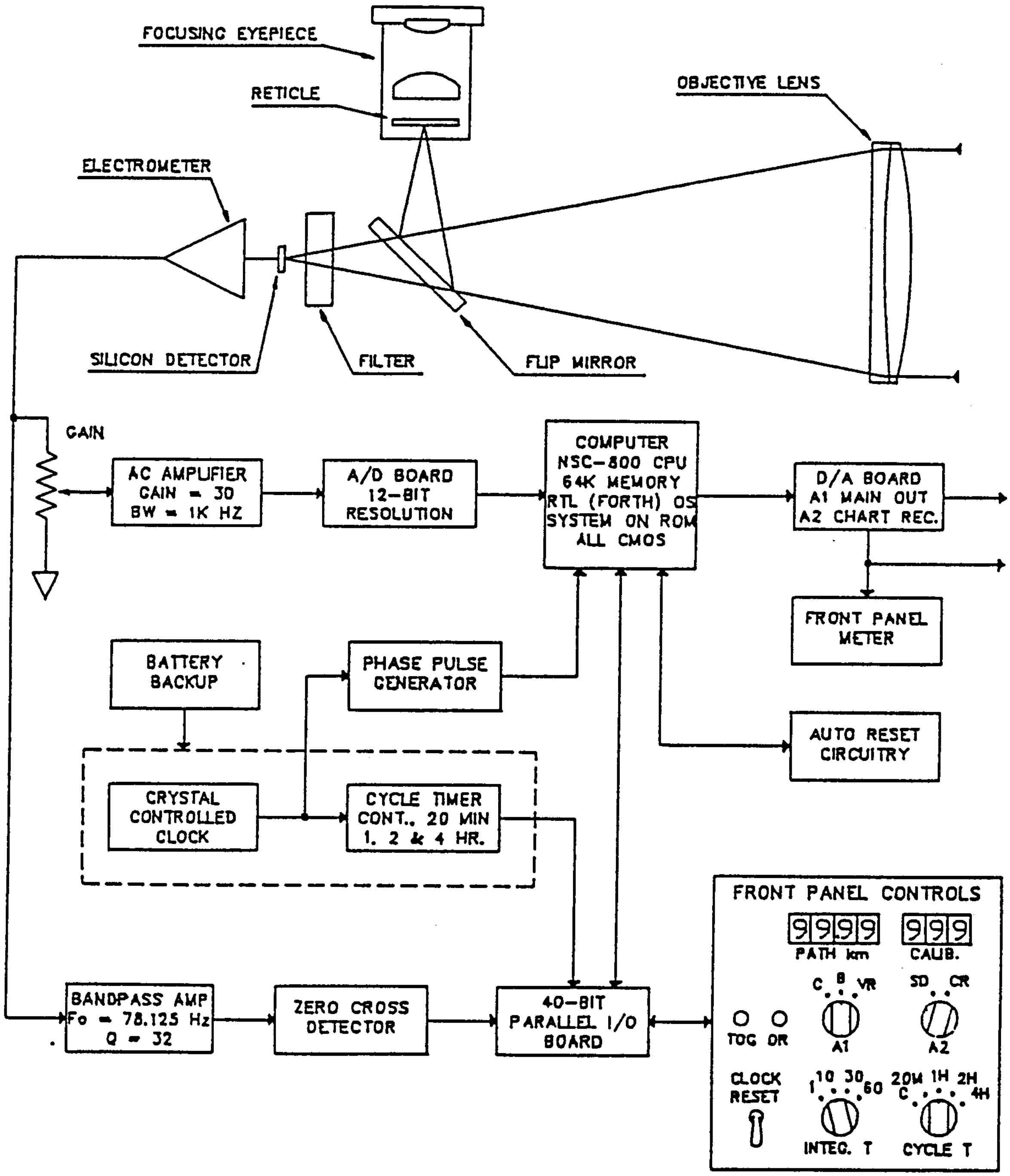

Figure 4. Receiver Functional Diagram

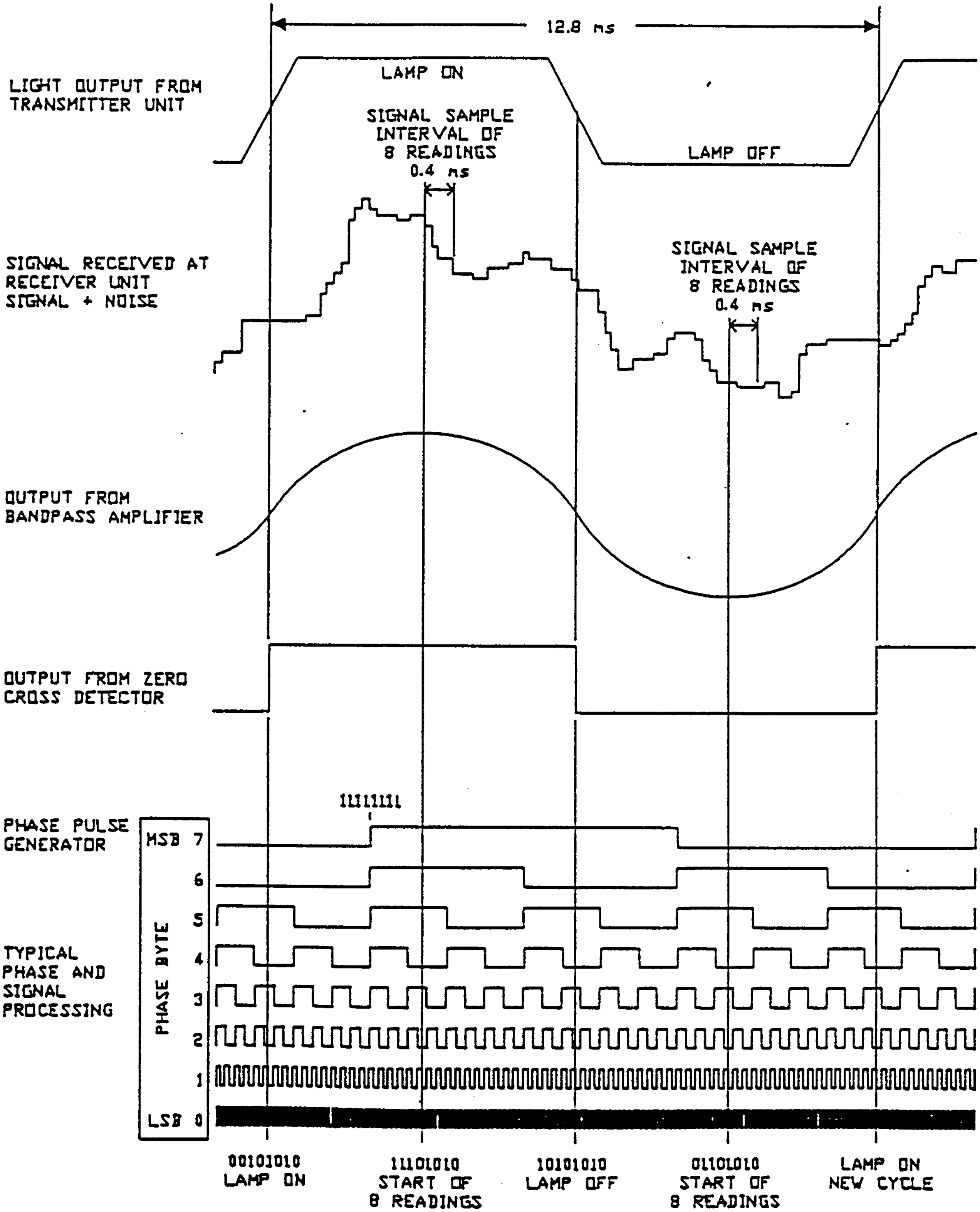

Figure 5. Transmissometer Signal Processing Waveforms

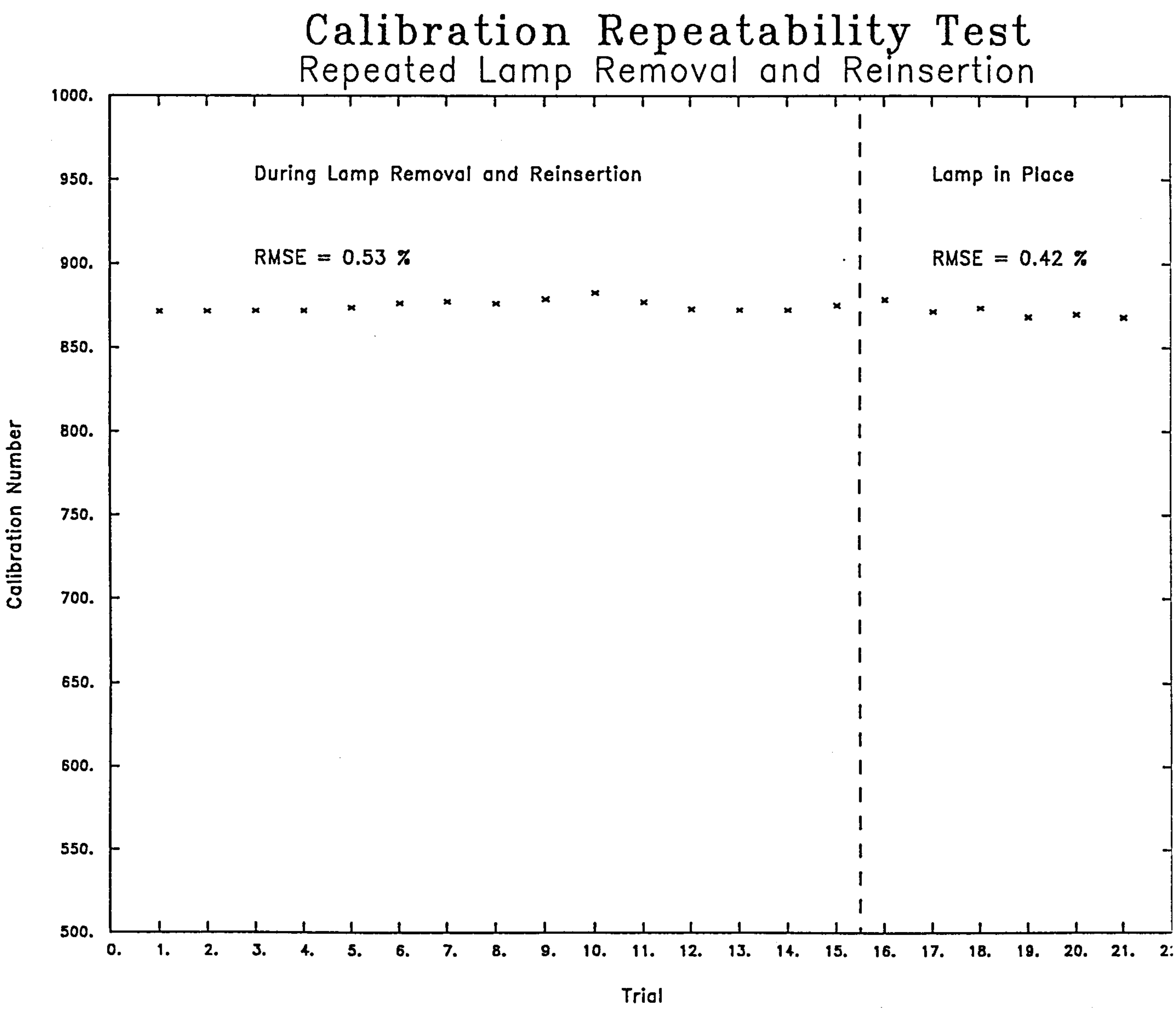

Figure 6. Transmissometer Calibration Repeatability

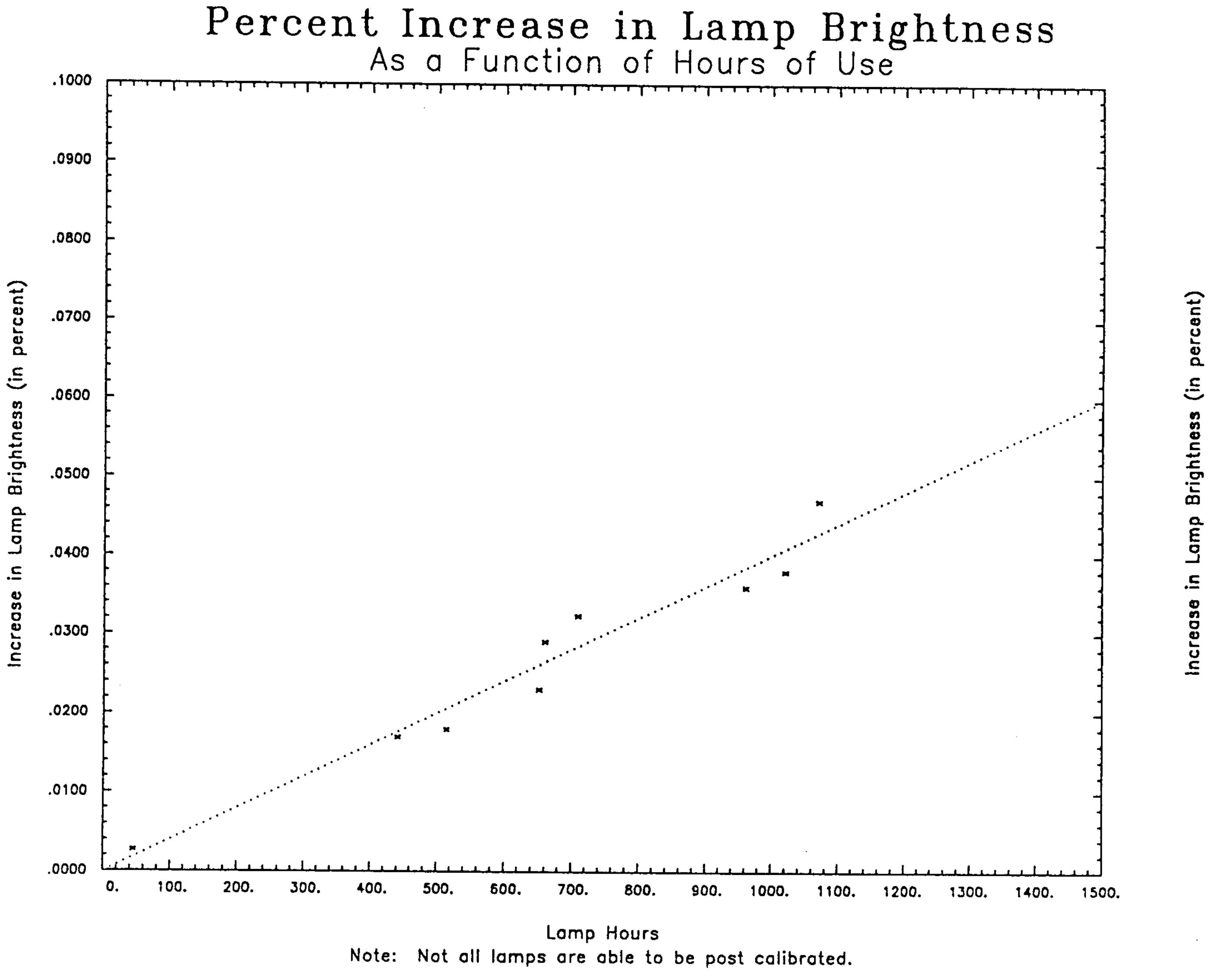

Figure 7. Transmissometer Lamp Drift