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QUALITY ASSURANCE/QUALITY CONTROL DOCUMENTATION SERIES	
TITLE	**TRANSMISSOMETER DATA REDUCTION AND VALIDATION (IMPROVE PROTOCOL)**
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AUTHORIZATIONS

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REVISION HISTORY

REVISION NO.	CHANGE DESCRIPTION	DATE	AUTHORIZATIONS
1.0	Add discussion regarding Olympus lamps	March 1995	

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1.0 PURPOSE AND APPLICABILITY

The purpose of this technical instruction (TI) is to describe the steps of transmissometer data reduction and validation, to assure quality data, and ensures that data are placed in a format consistent with IMPROVE protocol. This TI is referenced in SOP 4400, Optical Monitoring Data Reduction and Validation (IMPROVE Protocol).

A transmissometer directly measures the irradiance of a light source after the light has traveled over a finite atmospheric path. The transmittance of the path is calculated by dividing the measured irradiance at the end of the path with the calibrated initial intensity of the light source. The average extinction of the path is calculated using Bouger's law from the transmittance and length of the path. It is attributed to the average concentration of all atmospheric gases and ambient aerosols along the path.

This TI presents the detailed steps used to ensure high quality data reduction and validation from transmissometer stations operated according to IMPROVE Protocol:

- Processing data daily to convert the raw data to Level-A validation format
- Reviewing data visually and examining any error files for details on monitoring system performance
- Processing data through Level-0 validation to search for questionable or physically unrealizable data
- Processing data through Level-1 validation to calculate uncertainty values and identify values affected by weather or optical interferences

Because most stations are remote, daily data review is critical to the identification and resolution of problems.

2.0 RESPONSIBILITIES

2.1 PROGRAM MANAGER

The program manager shall:

- Review finalized data with the project manager to ensure quality and accurate data reduction.
- Coordinate with the Contracting Officer's Technical Representative (COTR) for desired method of data reduction required of the IMPROVE program.

2.2 PROJECT MANAGER

The project manager shall:

- Review and verify calibration results for each instrument.
- Review and finalize data with data analysts and field specialists.

2.3 DATA ANALYSTS

The data analysts shall:

- Run all processing programs required to generate preliminary seasonal summary plots.
- Review data with the project manager and field specialists.

2.4 FIELD SPECIALISTS

The field specialists shall:

- Review data with the project manager and data analysts.
- Provide input as to the cause of instrument problems and specific siting characteristics.

3.0 REQUIRED EQUIPMENT AND MATERIALS

All data reduction and validation occurs on IBM-PC compatible systems. The required computer system components are as follows:

- IBM compatible 386/486 computer system with VGA and 80 megabyte hard disk
- Software for processing raw transmissometer data:
    - Microsoft Windows 3.0/3.1
    - WordStar 5.1 or any ASCII editor
    - File viewing utility
    - ARS plotting and seasonal processing software
- Hewlett-Packard HP LaserJet II or 4 printer

4.0 METHODS

This section includes three (3) subsections:

4.1 Daily Reduction and Validation Procedures
4.2 Monthly Reduction and Validation Procedures
4.3 Seasonal Reduction and Validation Procedures

These subsections describe the processing procedures applied to transmissometer data to obtain extinction, SVR, and deciview data in IMPROVE Protocol format.

4.1 DAILY REDUCTION AND VALIDATION PROCEDURES

Data collected at each monitoring site are recovered daily from satellite data collection platforms (DCPs). Along with extinction, ambient temperature and relative humidity are also monitored. The data represent one ten-minute average value for each hour. The measurement interval begins three minutes after the hour and ends at thirteen minutes after the hour.

For times when the transmissometer system operated but DCP transmissions were not received, strip charts are available as backup. Data for missing DCP periods are manually reduced from the strip charts and added to the raw transmissometer files. (See TI 4300-4025, Transmissometer Data Collection via Strip Chart Recorder).

Once the data are appended into site-specific Level-A files (see TI 4300-4023, Transmissometer Daily Compilation and Review of DCP-Collected Data (IMPROVE Protocol)), the data analysts review each Level-A file (XXXX_T where XXXX is the four letter site abbreviation) using the file viewing utility "DR" (directory read). The Level-A files are located in the F:/USERS/TRANS directory of the ARS computer network. Each XXXX_T file is reviewed to determine if the transmissometer is functioning properly. Corrective action is taken when an instrument malfunction or data problem is detected. Data analysts contact the site operator by telephone and initiate troubleshooting procedures (see TI 4110-3300, Troubleshooting and Emergency Maintenance Procedures for Optec LPV-2 Transmissometer Systems (IMPROVE Protocol)).

4.2 MONTHLY REDUCTION AND VALIDATION PROCEDURES

Raw data plots are generated bi-monthly from the XXXX_T files. Data from operator log sheets are checked against data collected via data collection platform (DCP) to identify inconsistencies and errors. Information from the log sheets and comments from the bi-monthly plots are entered into the Quality Assurance (QA) Database. All hard copy log sheets are chronologically filed by site.

4.2.1 Bi-Monthly Data Plots

Level-A transmissometer data are plotted bi-monthly using ARS plotting software. The plots are displayed on the large corkboard outside the data collection center (DCC) and are reviewed by the project manager, data analysts, and field specialists on a monthly basis. Inconsistent or suspicious data are identified and troubleshooting procedures are initiated (see TI 4110-3300, Troubleshooting and Emergency Maintenance Procedures for Optec LPV-2 Transmissometer Systems (IMPROVE Protocol)).

4.2.2 Comments on Plots

As completed log sheets from transmissometer sites are received, the pertinent information (visibility conditions, alignment, system timing, instrument problems, etc.) is manually transferred to the bi-monthly plots. Figure 4-1 is an example bi-monthly data plot with comments. This procedure helps to identify the exact time of lamp changes, alignment corrections, and other actions done by the site operator affecting instrument operation. The data analysts can then use this information to correctly update the lamp and code files for Level-A verification (see Section 4.3.1).

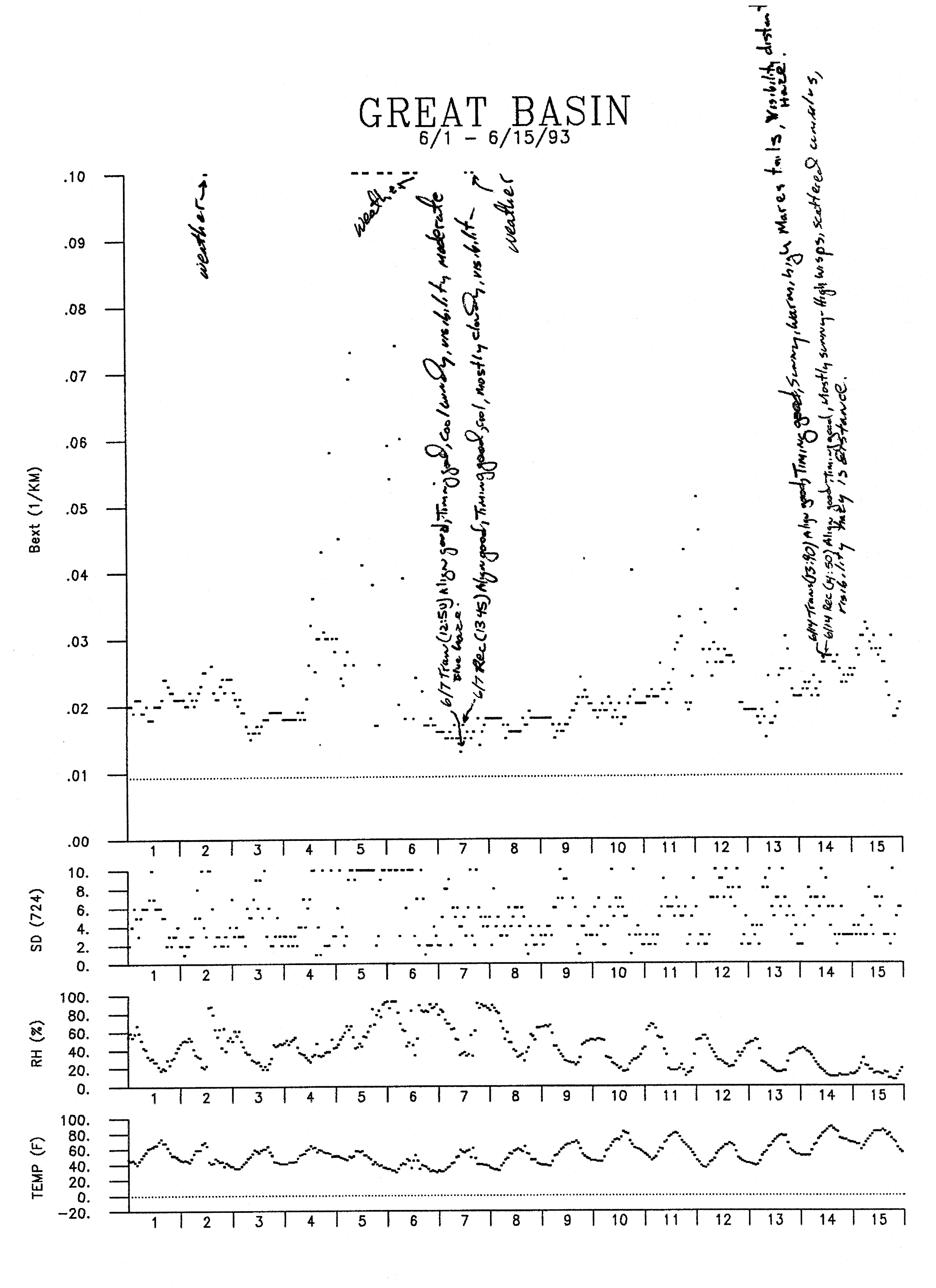

Figure 4-1. Example Bi-Monthly Data Plot With Comments.

4.3 SEASONAL REDUCTION AND VALIDATION PROCEDURES

Data analysts create a seasonal data file for each site. Standard meteorological seasons are defined as:

Winter	(December, January, and February)
Spring	(March, April, and May)
Summer	(June, July, and August)
Fall	(September, October, and November)

Processing begins with the raw transmissometer files and consists of three levels of data verification: Level-A, Level-0, and Level-1. Processing that defines each level is presented in Figure 4-2, Transmissometer Data Processing Flow Chart, and described in the following subsections.

4.3.1 Level-A Verification

Raw files are converted to Level-A verification format. Reduction at this level includes updating constants files:

- Lamp files (XXXX_L) where XXXX is the site abbreviation
- Code files (XXXX_C) where XXXX is the site abbreviation
- Processing file (TPROCESS.CON)

Refer to TI 4300-4023, Transmissometer Daily Compilation and Review of DCP Collected Data (IMPROVE Protocol), for a description of the procedures to be followed when updating the site-specific lamp files and the processing file (XXXX_L and TPROCESS.CON).

UPDATING THE SITE-SPECIFIC CODE FILES

The site-specific code files include the following information:

- Beginning and ending dates and times that identify invalid data
- Codes indicating reason for invalid data
- Comments describing specific reason for invalid data

The information in the code files is required to identify known periods of invalid data. The block of data that is coded invalid will not be used in the seasonal or annual report(s). The code files must be edited with the most current information available regarding instrument and support equipment operation. Each site has its own code file with the file name XXXX_C, where XXXX is the site abbreviation.

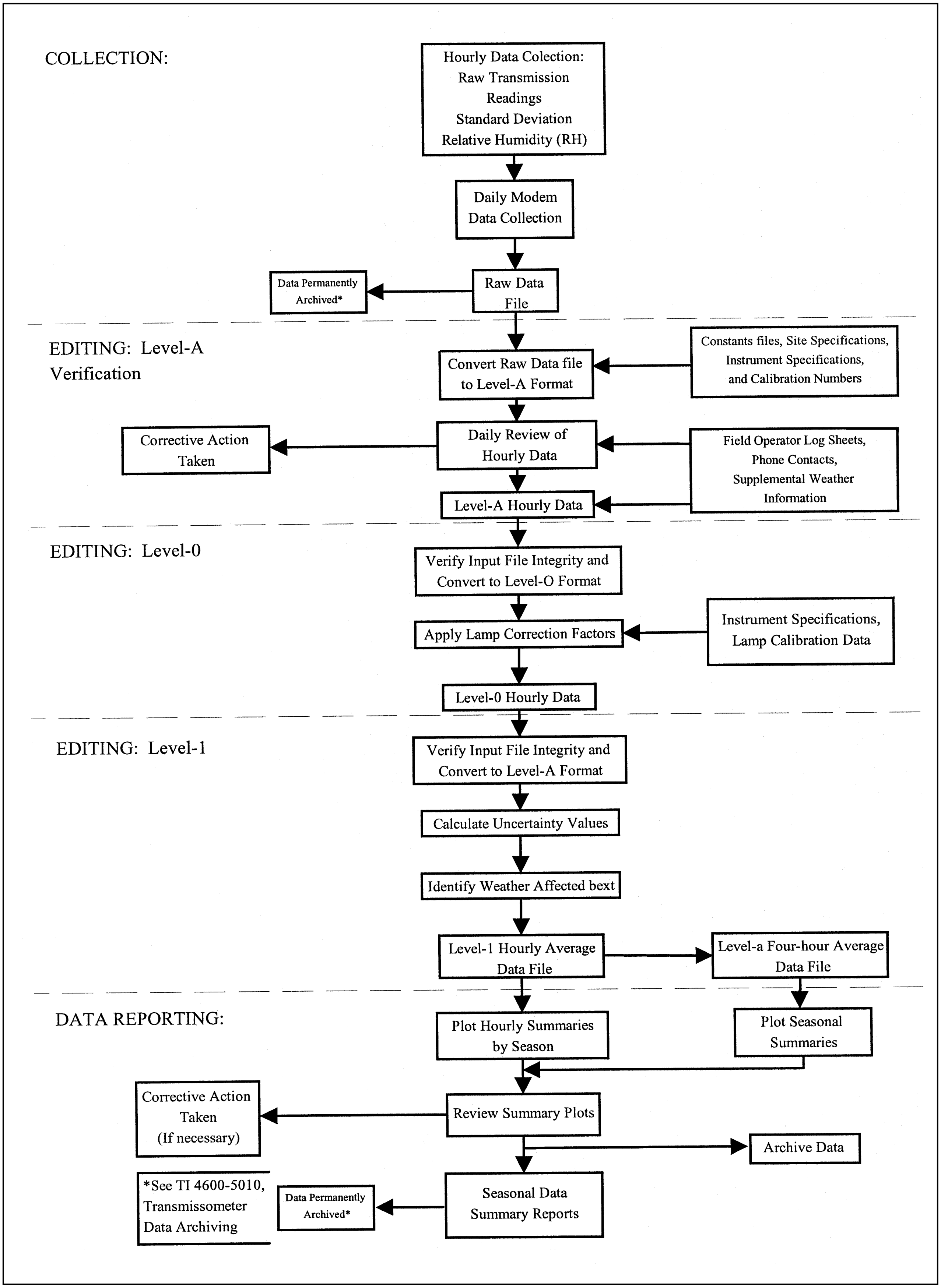

Figure 4-2. Transmissometer Data Processing Flow Chart.

The following procedures detail the steps for editing individual code files:

- Locate code files which are on the computer network in the F:\USERS\SITE.CON directory.

- Edit an individual code file using any plain ASCII editor. The WordStar command is: **WS F:\USERS\SITE.CON\XXXX_C**, where XXXX is the site abbreviation. The file format for code files is detailed in Figure 4-3.

- Edit the fields in the code file to reflect current information regarding the instrument and support equipment operation. Commas must be included between fields.

- Save the code file; the WordStar command is: **Alt-F S**.

Once the site-specific lamp files, code files, and the processing file are all updated with the most current information available regarding lamps, instrument and support equipment operation, and calibration parameters, seasonal processing can be initiated.

Level-A processing software performs the following functions for each site:

- Generates Level-A formatted seasonal data files which include only the data records for the season to be processed.

- Recalculates b_{ext} from the raw readings, using calibration information in the lamp files.

- Removes periods in the raw file when the b_{ext} exceeds a number of consecutive times specified. In effect, this removes periods of constant b_{ext}.

- Adds codes specified in the code files to the raw files. This saves time from entering long strings of codes manually.

Transmissometer validity codes reflecting instrument operation are manually added to the raw files. These can be obtained from operator log sheets or other operator communications. Transmissometer validity codes used at this level include:

0 = Valid
1 = Invalid: Site operator error
2 = Invalid: System malfunction or removed
3 = Valid: Data reduced from an alternate logger
6 = Valid: b_{ext} data exceeds maximum (overrange)
8 = Missing: Data acquisition error
9 = Valid: b_{ext} data below Rayleigh (underrange)
A = Invalid: Misalignment
L = Invalid: Defective lamp
S = Invalid: Suspect data
W = Invalid: Unclean optics

<u>Line Number</u> <u>Contents of XXXX_C File</u>

```
1             GRAND CANYON NATIONAL PARK (SOUTH RIM, GRCA)   UPDATE:  9/08/93
2             CODE DESCRIPTION FILE
3
4
5             START START START  START  START END   END   END    END
6             YEAR  MONTH  DAY  JULIAN  TIME  MONTH DAY  JULIAN  TIME
7                                 DATE                     DATE        CODE COMMENT
8             -----------------------------------------------------------------
9             86,    12,    1,   335,    0,   12,   17,  351,    0,   8,
10            86,    12,   18,   352,   21,   12,   21,  355,   16,   1,   FLIP MIRROR
11            86,    12,   28,   362,    2,   12,   31,  365,    6,   1,
12            86,    12,   31,   365,    7,   12,   31,  365,   23,   8,
13            87,     1,    1,     1,    0,    1,    3,    3,   12,   8,
14            87,     1,    6,     6,   19,    1,    9,    9,   15,   1,
15            87,     1,   23,    23,   13,    1,   24,   24,   12,   2,   POWER OUTAGE
16            87,     2,   18,    49,   22,    2,   19,   50,    0,   8,
```

Line Number	Description
1	Site name - Date this file was last updated
2	Information
3	Blank
4	Blank
5-8	Headers
9-xx	Data code information

Field	Description
START YEAR	Year containing data to be coded out
START MONTH	Beginning month containing data to be coded out
START DAY	Beginning day for data to be coded out
START JULIAN DATE	Beginning julian date for data to be coded out
START TIME	Beginning hour (24-hour format) of data to be coded out
END MONTH	Ending month for data to be coded out
END DAY	Ending day for data to be coded out
END JULIAN DATE	Ending julian date for data to be coded out
END TIME	Ending hour (24-hour format) of data to be coded out
CODE	Code indicating reason for data to be coded out *
COMMENT	Comment concerning this line in the file

Important: The fields must be separated by a comma! (No commas in the comment field).

* Refer to description of Transmissometer validity codes (page 7)

Figure 4-3. Example Code File (XXXX_C).

A -99 in any data field indicates missing or invalid data.

The maximum $b_{\mathrm{ext,max}}$ occurs when the transmittance falls below 5%. The $b_{\mathrm{ext,max}}$ is calculated when data are appended using:

$$b_{ext,\max} = \frac{-\ln(0.05)}{r} \qquad (1)$$

where ***r*** = path distance.

4.3.2 Level-0 Verification

Data and validity codes are checked for inconsistencies using a screening program. The same validity codes used at Level-A apply at Level-0.

All b_{ext} data are corrected for lamp drift. This value is based on the calculated average drift of a number of lamps. The algorithm for calculating the drift-related offset applied to each b_{ext} value is:

Let t_1 = 16 number of minutes per hour the lamp is on.
t_2 = 60 number of minutes in an hour.
t_3 = number of lamp-on hours for current lamp.
L = number of hours the lamp resides in the transmitter.
r = path length.

The lamp-on time (t_3) for the current lamp is:

$$t_3 = L \times t_1 / t_2 \qquad (2)$$

The lamp drift correction factor (F_{drift}) is a function of the lamp-on hours (t_3) defined by the following curve for Olympus lamps operating at a nominal voltage of 5.9 VDC:

$$F_{drift}(\%) = 0.270 \times t_3^{0.4405} \qquad (3)$$

The lamp drift corrected transmittance (T_{corr}) is:

$$t_{corr} = [1 + (F_{drift}/100)] \times T \qquad (4)$$

where ***T*** is the measured transmittance. The drift corrected b_{ext} is:

$$b_{ext,\,corr} = -\ln\left(\frac{1}{T_{corr}}\right)/\,r \qquad (5)$$

where ***r*** = path distance.

Level-0 data files are kept active on hard disk, backed up on cassette tape daily, and archived on cassette tape seasonally.

4.3.3 Level-1 Verification

Level-1 verification includes two processing steps:

- Calculation of uncertainty values for all data
- Identification of b_{ext} values affected by weather or optical interferences

A key to the Level-1 data file, including validity codes for b_{ext} data, is presented as Figure 4-4.

A screening program is used to again check all data and validity codes for inconsistencies. The data are then reduced to four-hour average values of extinction (b_{ext}), standard visual range (SVR), and haziness (dv). The time periods of the four-hour average values are:

03:00	0000 - 0359 hours
07:00	0400 - 0759 hours
11:00	0800 - 1159 hours
15:00	1200 - 1559 hours
19:00	1600 - 1959 hours
23:00	2000 - 2359 hours

The four-hour average b_{ext} and average dv, along with the average relative humidity, average temperature, and the transmissometer validity code are recorded and kept in the database.

4.3.3.1 Calculation of Uncertainties

Transmissometer Uncertainties

Operationally the basic equation used to calculate path transmittance in the network is:

$$T = I_r / (F_{lamp} \times I_{cal}) \tag{6}$$

where:

$\boldsymbol{T}$ = Transmittance of atmosphere of path $\boldsymbol{r}$
$\boldsymbol{I_r}$ = Intensity of light measured at $\boldsymbol{r}$
$\boldsymbol{I_{cal}}$ = Calibration value of transmissometer
$\boldsymbol{F_{lamp}}$ = Variability function of lamp output

The relative uncertainty ($\boldsymbol{U_x}$) of any measured parameter $\boldsymbol{x}$ is defined as:

$$U_x = \sigma_x / \bar{x} \tag{7}$$

Field Number

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
GRCA	900702	183	700	28	1	4	0	18	10	300	0	17	1	0	38	3	0	134
GRCA	900702	183	800	-99	-99	0	4	18	10	300	4H	-99	-99	0	-99	-99	0	-99

Field	**Description**
1	Site abbreviation
2	Date in year/month/day format
3	Julian Date
4	Time using a 24-hour clock in hour/minute format
5	b_{ext} x 1000 (km^{-1})
6	b_{ext} uncertainty x 1000 (km^{-1})
7	Number of readings in average
8	Number of readings not in average due to weather
9	Uncertainty threshold x 1000 (km^{-1})
10	Δ threshold x 1000 (km^{-1})
11	Maximum threshold x 1000 (km^{-1})
12	b_{ext} validity code [1]
13	Temperature (°C)
14	Temperature uncertainty (°C)
15	Temperature validity code [2]
16	Relative humidity (%)
17	Relative humidity uncertainty (%)
18	Relative humidity validity code [2]
19	Haziness (dv x 10)

[1] b_{ext} validity codes:

0 = Valid
1 = Invalid: Site operator error
2 = Invalid: System malfunction or removed
3 = Valid: Data reduced from alternate logger
4x = Weather: a letter code representing specific conditions as noted below:

Condition	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
RH > 90%	x		x		x		x		x		x		x		x
b_{ext} > maximum threshold		x	x			x	x			x	x			x	x
b_{ext} uncertainty > threshold				x	x	x	x					x	x	x	x
Δ b_{ext} > delta threshold								x	x	x	x	x	x	x	x

(Letter Code)

Z Weather observation between 2 other weather observations.

Threshold values may be different for each site. See Appendix A.

8 = Missing: Data acquisition error
9 = Invalid: b_{ext} below Rayleigh
A = Invalid: Mis-alignment
L = Invalid: Defective Lamp
S = Invalid: Suspect Data
W = Invalid: Unclean optics

[2] Meteorology validity codes:

0 = Valid
1 = Invalid: Site operator error
2 = Invalid: System malfunction or removed
3 = Valid: Data reduced from alternate logger
5 = Invalid: Data > maximum or < minimum
8 = Missing: Data acquisition error

A -99 in any data field indicates missing or invalid data.

Figure 4-4. Key to the Level-1 Transmissometer Data File.

where

$\bar{x}$ = arithmetic mean of all ***x*** measurements
δ_x = precision of measurements ***x*** defined as

$$\sigma_x = \left[\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right]^{1/2} \tag{8}$$

Using propagation of error analysis the relative uncertainty of the path transmittance can be calculated from the relative uncertainties of the measured variables as:

$$U_T = (U_{Ir}^2 + U_{Ical}^2 + U_{lamp}^2)^{1/2} \tag{9}$$

where

U_{T} = relative uncertainty of T
U_{Ir} = relative uncertainty of I_{r}
U_{Ical} = relative uncertainty of I_{cal}
U_{lamp} = relative uncertainty of F_{lamp}

To understand the uncertainty of a transmittance measurement requires a thorough investigation of the precision of each of the following:

- Precision in calibration to determine I_{cal}
- Precision in the measurement of I_{r}
- Precision in the measurement of F_{lamp}

Relative Uncertainty of I_{cal} - The precision in calibration value I_{cal} can be determined by investigating the calibration equation. I_{cal} is the value that would be measured by the transmissometer detector if the atmospheric path was a vacuum. I_{cal} incorporates the path distance ***r***, transmittance of all windows in the path, and size of working aperture used. I_{cal} is determined from:

$$I_{cal} = (CP/WP)^2 \times (WG/CG) \times (WA/CA)^2 \times WT \times (1/FT) \times (1/T) \times CR \tag{10}$$

Using propagation of uncertainty analysis the relative uncertainty in I_{cal} can be shown to be:

$$U_{cal} = (2U_{CP}^2 + 2U_{WP}^2 + U_{CG}^2 + 2U_{WA}^2 + 2U_{CA}^2 + U_{WT}^2 + U_{FTt}^2 + U_{CR}^2)^{1/2} \tag{11}$$

Path distances are measured using a laser range finder. Calibration apertures are measured with a precision micrometer. Gain settings are measured with a precision voltmeter. Window and neutral density filter (NDF) transmittances are measured with a reference transmissometer by differencing techniques, thus they do not require absolute calibration. The standard deviation of the raw readings (CR) are calculated at each calibration. The typical working values, measurement precision, and relative uncertainties of these values are:

Parameter		Value	Precision	Relative Uncertainty
CP	Calibration Path	0.3 km	1 x 10-6 km	3.3 x 10-6
WP	Working Path	5.0 km	1 x 10-6 km	2.0 x 10-7
CG	Calibration Gain	100	1 x 10-2	1.0 x 10-4
WG	Working Gain	500	1 x 10-2	2.0 x 10-5
CA	Calibration Aperture	100 mm	1 x 10-2 mm	1.0 x 10-4
WA	Working Aperture	110 mm	1 x 10-2 mm	9.1 x 10-5
WT	Window Transmittance	0.810	0.001	1.2 x 10-3
FT	NDF Transmittance	0.274	-0.001	3.6 x 10-3
T	CP Transmittance	0.975	0.003	3.1 x 10-3
CR	Raw Readings	900	2.0	2.2 x 10-3

Combining the above values into the uncertainty equation leads to a typical relative uncertainty for I_{cal}: $U_{Ical} = 0.005$.

Relative Uncertainty of I_r - Under ambient operating conditions the irradiance measured by the transmissometer receiver will fluctuate due to:

- Atmospheric optical turbulence causing scintillation
- Atmospheric optical aberrations causing beam wander
- Varying meteorological conditions along the path: rain, snow, fog
- Insect swarms causing beam interference

The precision of each ten-minute irradiance measurement is calculated by the receiver computer as the standard deviation of the ten one-minute average irradiance measurements. The measured standard deviation is a direct estimation of atmospheric optical interference. Typical values of I_r and various operational precision estimates that have been observed in the monitoring network are listed below.

Ambient Extinction (km^{-1})	I_r Value	No Optical Interferences		Optical Interference	
		Precision	Relative Uncertainty	Precision	Relative Uncertainty
0.010	200	1	0.0050	20	0.100
0.020	190	1	0.0053	20	0.105
0.030	180	1	0.0056	20	0.111
0.050	163	1	0.0061	20	0.123
0.100	127	1	0.0079	20	0.158
0.500	17	1	0.0580	20	1.117

Working Path = 5.0 km, I_{cal} = 210

As can be seen the relative uncertainty of the measured intensity is a function of the extinction of the path. For typical extinction measurements free from optical interference in the network, the average relative uncertainty in I_r is approximately: $U_{Ir} = 0.0055$

Relative Uncertainty of F_{lamp} - The major source of uncertainty in the transmissometer data is lamp drift correction. The transmitter employs an optical feedback loop designed to maintain constant irradiance within the 10nm bandwidth of the receiver filter/detector module. However, comparison of pre and post lamp calibrations show that the transmitter lamp output increases (brightens) with increased hours of lamp use. Tests have shown that the brightening is definitely a function of the lamp rather than the feedback circuit or filter. It is important to note that a 1% increase in irradiance over a path length of approximately five kilometers (the Grand Canyon sight path for example) results in the apparent extinction being decreased by 0.002 km^{-1} (20% of Rayleigh!!); i.e., the instrument measurement indicates the air to be cleaner than it actually is.

The method initially used to handle this bias was to compare the pre and post lamp calibrations and generate a lamp brightening factor that would be applied to the raw irradiance prior to calculating path transmittance. Early results from 1987 suggested a fairly stable 2% per 500 hour brightening rate through the first 500 hours of lamp use. Site operator lamp changes were scheduled at three month intervals (approximately 575 hours of lamp "on" time). The systems were returned to Fort Collins annually for routine servicing. Prior to servicing the instrument, lamp brightening would be verified by post-calibrating all lamps. This method resulted in delays of over a year before final data were available. Additionally, due to instrument failure, instrument damage, or lamp breakage, it is not always possible to post-calibrate all lamps used operationally. Therefore, a constant 2% per 500 hours correction factor was applied to all lamps to facilitate data collection, processing, and reporting. This lamp drift correction factor was based on post-calibrations of the first 10 lamps from the three systems used in the WHITEX study.

During 1992, a re-examination of all available post-calibration data showed that the lamp brightening factors were not as well-behaved as early post-calibrations had indicated. In January 1993, development of revised processing procedures that more accurately estimate transmissometer lamp drift correction was completed. Lamp brightening percentages and lamp "on" hours for all systems and lamps post-calibrated at the Fort Collins, Colorado transmissometer calibration facility are entered into a lamp brightening database. The data in this database are used to create statistics on lamp brightening. Lamp brightening percentages for post-calibrated lamps are sorted into time bins based on lamp operational hours. The mean and standard deviation of operational hours and percent lamp brightening were calculated for each bin. Power law functions are fitted to these data to define a statistically based mean lamp brightening and the one sigma upper and lower bounds. Applying the mean function to the raw transmissometer irradiance readings corrects for lamp brightening. The precision of the correction is calculated from the upper and lower bounds for the number of hours on the lamp at the time of the reading.

If, upon post-calibration, a system exhibits abnormally high or low lamp brightening, previously reported extinction data are flagged for further review. The lamp brightening database is continually updated as additional lamps are post-calibrated. Periodically, the lamp brightening statistics are reanalyzed to provide a more accurate description of the lamp drift correction and the precision associated with this correction.

Variations in lamp brightening characteristics for a given lamp design may occur due to variations in manufacturing processes between manufacturers. All lamps used with the LPV-2 transmissometer are purchased from the transmissometer manufacturer, Optec, Inc. Optec purchases standard lamps from the lamp manufacturer and precisely aligns the filament of each lamp prior to delivering the lamps for operational use. From 1986 through March 1993, all lamps supplied by Optec were purchased from Micro-Optics, Inc. Beginning in April 1993, lamps supplied by Optec have been purchased through a new distributor, Lamp Technology, Inc. These lamps are manufactured by Olympus and are considered to be of higher quality than the Micro-Optics lamps. A second factor that influences lamp brightening is the lamp operating voltage. Prior to 1990, IMPROVE operating procedures specified a nominal lamp operating voltage of 5.6 VDC. In 1990, the nominal lamp operating voltages was increased to 5.9 VDC. As a result of these changes, all operational lamps were placed in one of the following three categories:

- Low voltage Micro-Optic lamps, 5.6 VDC (1986 - 1989)
- High voltage Micro-Optic lamps, 5.9 VDC (1990 - March 1993)
- High voltage Olympus lamps, 5.9 VDC (April 1993 - present)

Using the revised processing procedures described above, statistically based lamp brightening functions were derived from post-calibration data for lamps in each of these three operational categories.

Low Voltage Micro-Optic Lamps (1986 - 1989)

Figure 4-5 is an analysis of lamp brightening data for Micro-Optic lamps pre-calibrated prior to 1990. These lamps were calibrated for a nominal operating voltage of 5.6 VDC. For low voltage lamps, the lamp drift correction applied for the first 500 hours of accumulated lamp time is a linear approximation to the mean brightening curve of Figure 4-5 (3.08% per 500 hours). Beyond 500 hours, the lamp drift correction is a constant offset equal to the correction at 500 hours (3.08%). The precision of the brightening measurements for the low voltage lamps has been approximately 3.1%. The relative uncertainty in $\boldsymbol{F_{lamp}}$ for a low voltage lamp at 500 hours is: $\boldsymbol{U_{lamp}}$ = 0.030.

High Voltage Micro-Optic Lamps (1990 - March 1993)

In early 1990, the nominal lamp operating voltage was increased to 5.9 VDC. An analysis of the lamp brightening data for Micro-Optics lamps calibrated at this higher operating voltage is presented in Figure 4-6. For these lamps, the lamp drift correction applied during the first 700 hours of accumulated lamp time follows the mean brightening curve of Figure 4-6. The equation for calculating lamp brightening using this curve is:

$$Lamp\ \ Brightening\,(\%) = a_o \times t^{a_1} \qquad (12)$$

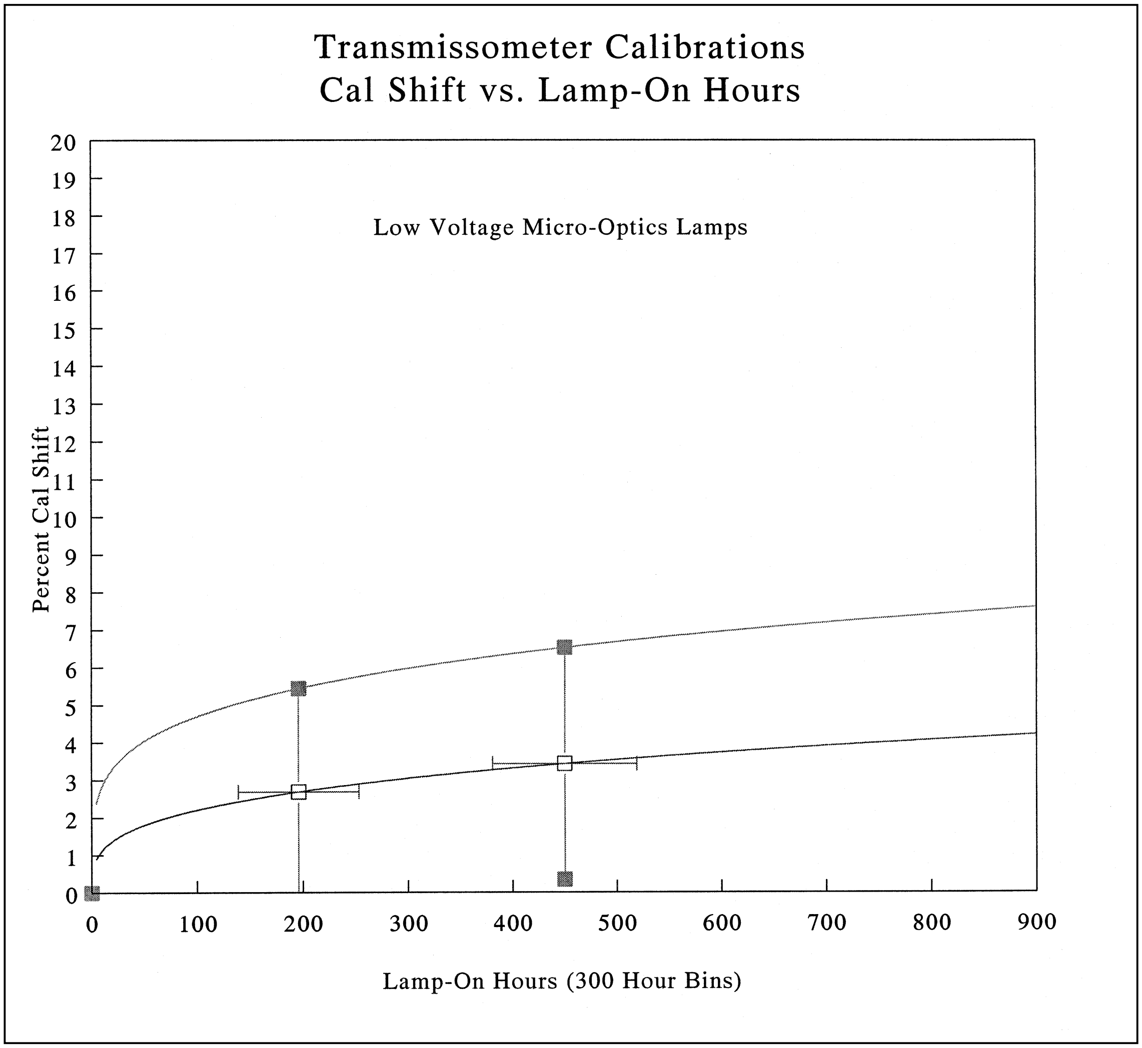

Figure 4-5. Lamp Brightening Curve - Low Voltage Micro-Optics Lamps.

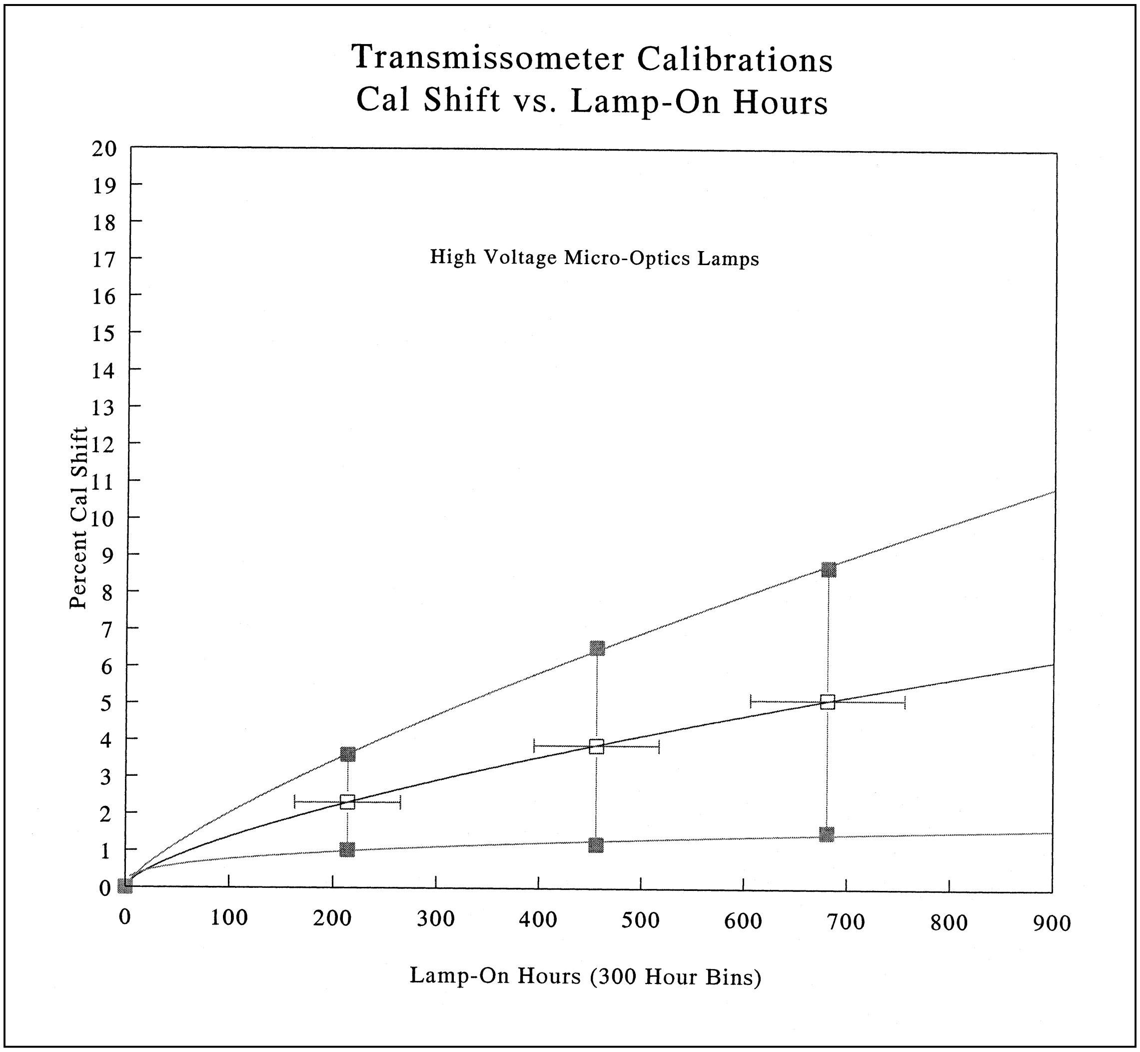

Figure 4-6. Lamp Brightening Curve - High Voltage Micro-Optics Lamps.

where:

t = accumulated lamp "on" time (hours)
a_0 = 0.0585
a_1 = 0.6849

Beyond 700 hours, the lamp drift correction is constant at the 700 hour value (5.19%). The precision of the brightening measurements for the high voltage Micro-Optics lamps has been approximately 2.7%. The relative uncertainty in F_{lamp} for a high voltage lamp at 500 hours is: U_{lamp} = 0.026

High Voltage Olympus Lamps (April 1993 - Present)

Beginning in April 1993, all replacement lamps calibrated for use in the IMPROVE network have been Olympus lamps with a nominal operating voltage of 5.9 VDC. Figure 4-7 is an analysis of lamp brightening data for the post-calibrated Olympus lamps. The lamp drift correction for the Olympus lamps follows the mean brightening curve of Figure 4-7. The equation for calculating lamp brightening is of the same form as the equation given for the high voltage Micro-Optic lamp (Equation 12) with:

t = accumulated lamp "on" time (hours)
a_0 = 0.2700
a_1 = 0.4405

Current IMPROVE network operations procedures specify that eight (8) pre-calibrated lamps be provided with each replacement transmissometer installed during an annual site servicing visit. This permits lamp changeouts at two-month intervals, ensuring that operational lamps will generally accumulate less than 500 hours of "on" time. Therefore, a separate high-hours lamp drift correction is not required.

Until additional Olympus lamps have been post-calibrated, the relative uncertainty in F_{lamp} calculated for the high voltage Micro-Optics lamps will also be used with the high voltage Olympus lamps (U_{lamp} = 0.026).

Relative Uncertainty in Path Transmittance

From the above analysis, the relative uncertainty in path transmittance can be calculated for each ten-minute transmittance measurement by the transmissometer. The typical values are:

Condition	**Relative Uncertainty (U_T)**
No Optical Interference	0.02
Optical Interference	0.20

Precision of Extinction Estimates From Transmittance Measurements

The average extinction b_{ext} of the transmissometer optical path (r) is calculated from the transmittance measurement (T) by:

$$b_{ext} = -\ln(T)/r \tag{13}$$

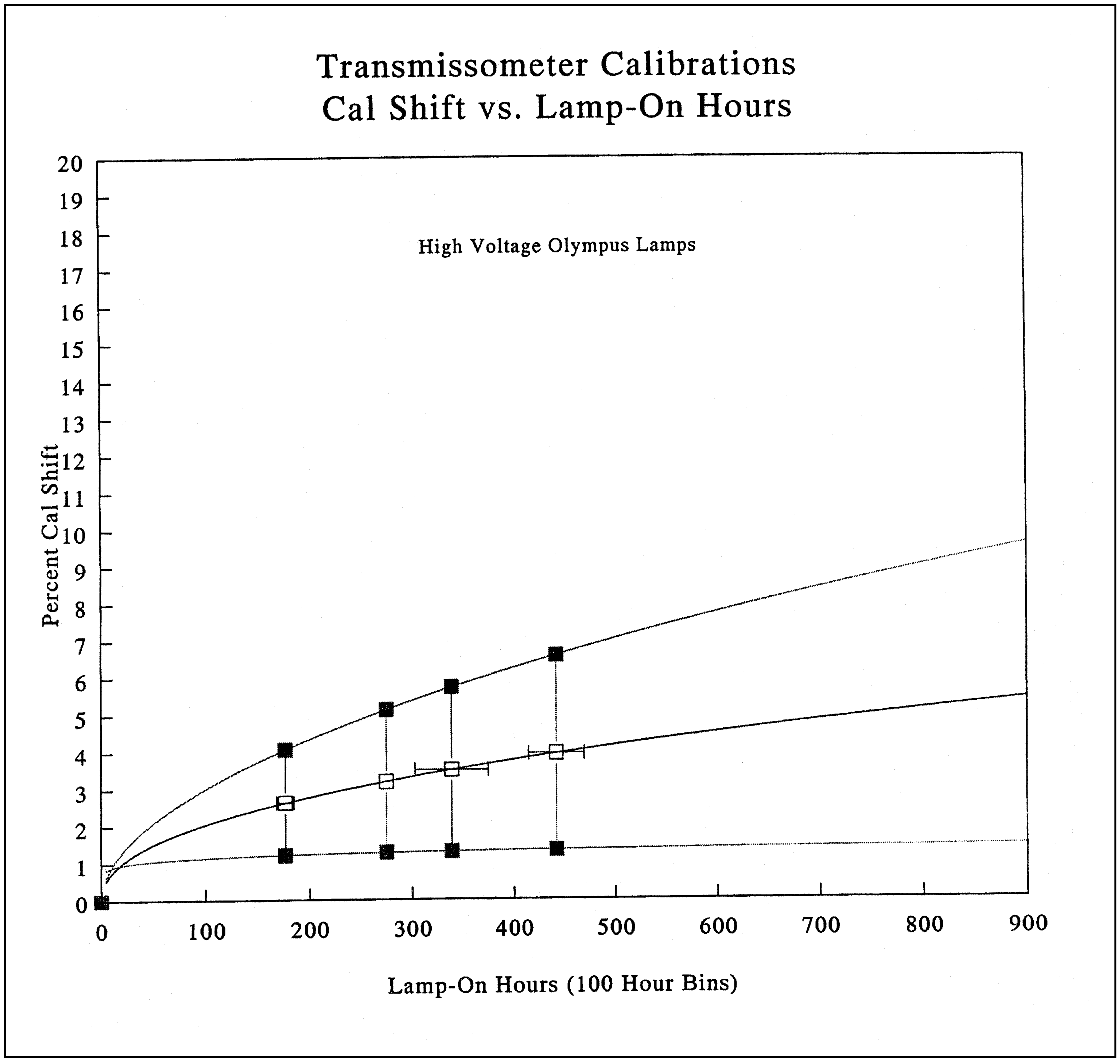

Figure 4-7. Lamp Brightening Curve - High Voltage Olympus Lamps.

Since the path length $\boldsymbol{r}$ is measured to an extremely high precision, the precision in $\boldsymbol{b_{ext}}$ can be approximated from propagation of error analysis as:

$$\sigma_{bext} = \pm U_T / r \tag{14}$$

The relative uncertainty in transmittance leads to an additive uncertainty in extinction that depends on the path length of the transmittance measurement. Table 4-1 lists the average uncertainty of b_{ext} estimates for typical sight paths in the monitoring network when no optical interferences are present along the path.

Table 4-1

Typical Uncertainty in b_{ext} for
Selected Monitoring Locations

Location	Path (km)	Precision (km^{-1})
Tonto	7.20	0.004
Grand Canyon	5.79	0.005
Acadia	3.67	0.007
Yosemite	2.71	0.100
Shenandoah	0.68	0.398

Bias In Extinction Calculations

The calibration equation assumes clean glass surfaces of constant transmittance. Any change in the window transmittance results in a bias added to the calculated extinction. If the window transmittance decreases the calculated extinction will increase, if it increases the calculated extinction will decrease. As with the precision, the bias is a function of the relative change in window transmittance and path distance:

$$\textbf{\textit{Bias = (relative change in window transmittance)/r}} \tag{15}$$

The possibility exists for errors to arise from changes in the transmittance of the windows due to:

- Pitting of the windows by wind blown dirt
- Staining of the windows by pollution
- Dirt collecting on the window surface due to dust, rain, snow
- Fogging of the windows at high humidities
- Improper servicing resulting in smudging of the windows
- Removal of the windows due to breakage

National Park Service (NPS) transmissometer data collected during 1991 was used to investigate the bias associated with varying window transmittance. Field operators are instructed to visit both the receiver and transmitter weekly. One of their duties is to observe the windows carefully and clean them regularly. These actions are noted on field log sheets. The NPS data base was scanned to locate the indicated times when the windows of the transmissometer systems were cleaned. The previous three hours and the following three hours of data were extracted for each cleaning. Servicing periods when the measured irradiance was constant before the windows were cleaned and also remained constant (independent of the previous three hours) after cleaning were identified. Three hundred thirty-five (335) servicings were selected that met these requirements. The average change in window transmittance was calculated from the difference between the mean irradiance values before and after servicing from this data set. The mean change was found to be 0.1%. This is misleading due to the fact that the servicing of the windows can have three possible effects:

- No change in window transmittance - the windows were perfectly clean before and after servicing.
- The window transmittance increased - the windows were dirty and servicing cleaned them.
- The window transmittance decreased - the windows were clean and servicing made them dirty.

The first condition leads to no change in window transmittance thus no bias. The second condition would indicate that b_{ext} values measured before the servicing were biased too high. The third condition would result in b_{ext} values measured after window cleaning biased to high. Thus, in practice, unless the window is removed or a window with a higher transmittance is substituted, the bias due to a change in window transmittance is in one direction: increasing the calculated extinction either before or after the servicing. If second and third conditions have about the same magnitude and occur at about the same frequency, a simple comparison of mean radiance differences before and after servicing will come out as a zero percent change. Therefore, a better indication of this bias is a calculation using the absolute value of the difference in mean radiances measured before and after servicing. When this is done, the mean change in window transmittance for the NPS network was 1.5%.

Typical bias estimates in b_{ext} for a 1.5% change in window transmittance at selected monitoring locations are listed in Table 4-2.

Table 4-2

Typical Bias in b_{ext} for
Selected Monitoring Locations

Location	Path (km)	Bias (km^{-1})
Tonto	7.20	0.002
Grand Canyon	5.79	0.003
Acadia	3.67	0.004
Yosemite	2.71	0.006
Shenandoah	0.68	0.022

Air Temperature and Relative Humidity Uncertainty

The uncertainties and limits for meteorological data collected are obtained from the manufacturer's literature. The values used are listed below:

U_{temp} = 1°C

U_{RH} = 2% (Rotronics MP100F Sensor)

Maximum temperature = 60°C

Minimum temperature = -50°C

Maximum relative humidity = 100%

Minimum relative humidity = 0%

4.3.3.2 Identification of Meteorological and Optical Interferences That Affect the Calculation b_{ext} From Transmittance Measurements

The transmissometer directly measures the irradiance of a light source after the light has traveled over a finite atmospheric path. The average extinction coefficient of the sight path is calculated from this measurement and is attributed to the average concentration of atmospheric gases and ambient aerosols along the sight path. The intensity of the light, however, can be modified not only by intervening gases and aerosols, but also by:

- The presence of condensed water vapor in the form of fog, clouds, and precipitation along the sight path
- Condensation, frost, snow, or ice on the shelter windows
- Reduction in light intensity by insects, birds, animals, or vegetation along the sight path, or on the optical surfaces of the instrumentation or shelter windows
- Fluctuations in light intensity both positive and negative due to optical turbulence, beam wander, atmospheric lensing, and miraging caused by variations in the atmospheric optical index of refraction along the sight path

A major effort was undertaken to develop an algorithm to identify transmissometer extinction data that may be affected by the interferences described above. This algorithm contains five major tests:

1) Relative Humidity
2) Maximum Extinction
3) Uncertainty Threshold
4) Rate of Change of Extinction
5) Isolated Data Points

Due to the large volume of extinction data collected by transmissometers as compared to aerosol monitors, the algorithm has been designed to be a conservative filter on the extinction data. That is, if an hourly extinction measurement indicates the slightest possibility of meteorological or optical interference by failing any one of the above tests, it is flagged with identifier codes in the Level-1 data file. The following describes each of the five tests:

Relative Humidity

When the relative humidity measured at the transmissometer receiver is greater than 90%, the corresponding transmissometer measurement is flagged as having a possible interference. The 90% level has been chosen due to the following considerations:

- The relative humidity is only measured at the receiver location and not at any other position along the sight path.
- A 1.5°C change in dew point temperature results in a 10% change in relative humidity.
- The atmosphere is continuously undergoing both systematic and random variations in its spatial and temporal properties.
- The typical precision of relative humidity measurements is ±2%.

The above considerations all indicate that inferring a precise knowledge of the meteorological conditions along a sight path at high relative humidity from a single point measurement is very difficult. When the relative humidity is above 90% at one end of the path, small random temperature or absolute humidity fluctuations along the path can lead to condensation of water vapor causing meteorological interferences. Thus, in accordance with the conservative philosophy expressed above, the 90% relative humidity limit was selected for this test.

Maximum Threshold

For every transmissometer sight path, a maximum b_{ext} can be calculated that corresponds to a 5% transmittance for the path. All sight paths were selected, such that based on historical visibility data, this maximum b_{ext} occurs less than 1% of the time. When the measured b_{ext} is greater than this threshold value, it is assumed that meteorological or optical interferences, not ambient aerosols, are causing the high extinction. All measurements greater than the calculated site-specific maximum threshold are flagged in the data file.

Uncertainty Threshold

The normal operating procedure for the transmissometer is to take ten one-minute measurements of transmitter irradiance each hour, and report the average and standard deviation of the ten values. A mean hourly extinction and associated uncertainty is then calculated as described in Section 4.3 from these measurements. In remote, rural areas, the ambient aerosol concentration typically varies quite slowly with time constants on the order of a few hours rather than minutes. This leads to the expectation of relatively constant extinction during the ten minutes of receiver measurements and a low standard deviation of measured transmitter irradiance. If only one of the ten irradiance values varies more than 20% from the mean, the uncertainty in b_{ext} will increase dramatically. The presence of any meteorological or optical interferences along the sight path will lead to large standard deviations in lamp irradiance, thus large uncertainties in b_{ext}. With the conservative assumption of constant b_{ext} during any ten minute measurement period, any increase in the uncertainty of b_{ext} above a selected threshold flags the measurement as affected by one of these interferences. The uncertainty threshold is determined for each sight path and is included in each Level-1 data file for reference.

Rate Of Change Of Extinction (Delta Threshold)

Transmissometer data collected before September 1, 1990, did not include standard deviation of measured irradiance values. For data collected before this date, another test was developed to identify periods of interferences associated with rapidly fluctuating irradiance measurements. This test consists of comparing the hourly average extinction to the preceding and following hours, and calculating a rate of change in each direction. If the absolute value of this rate of change is greater than some assigned Delta threshold, the hourly b_{ext} value is flagged as being affected by interferences. Delta thresholds have been determined for each sight path by analyzing extinction data collected after September 1990, which have corresponding uncertainty thresholds to determine appropriate Delta thresholds for the sight path. The Delta threshold is typically not as low as the uncertainty threshold, due to the possibility of larger hourly variations in b_{ext} as compared to variations during ten minutes of measurements. Each sight path has its own Delta threshold and it is listed in the Level-1 data file for reference.

Isolated Data Points

This test is performed after the above four thresholds are applied to the hourly extinction data. It is used to identify data points that have passed the above thresholds, but are located between hourly b_{ext} data that have failed the above thresholds. The conservative assumption is, if data before and after the isolated hour indicates interferences, the hour in question probably is also affected by interferences. This data is also flagged as weather-affected.

4.3.4 Supplemental Visibility Indices

4.3.4.1 Standard Visual Range

Standard visual range (SVR) can be interpreted as the farthest distance that a large, black feature can be seen on the horizon. It is a useful visibility index that allows for comparison of data taken at various locations.

$$SVR = \frac{3.912}{(b_{ext} - b_{ray} + 0.01\,km^{-1})} \qquad (16)$$

SVR is calculated to normalize all visual ranges to a Rayleigh scattering coefficient of 0.01 km^{-1} or an altitude of 1.524 km (5000 ft.). The Rayleigh scattering coefficient, b_{ray}, for the mean sight path altitude is subtracted from the calculated extinction coefficient, b_{ext}, and the standard Rayleigh scattering coefficient of 0.01 km^{-1} is added back. The value 3.912 is the constant derived from assuming a 2% contrast detection threshold. The theoretical maximum SVR is 391 km.

4.3.4.2 Deciview

An easily understood visibility index has been recently developed to uniformly describe visibility impairment. The scale of this visibility index, expressed in deciview (dv), is linear with respect to perceived visual changes over its entire range, analogous to the decibel scale for sound.

Neither visual range nor extinction coefficient is linear to perceived visual scene changes caused by uniform haze. For example, a 5 km change in visual range or a 0.01 km^{-1} change in extinction coefficient can result in a scene change that is either imperceptible or very obvious, depending on the baseline visibility conditions.

The newly-developed visibility index's dv scale is linear to humanly-perceived changes in visual air quality. A one dv change is about a 10% change in extinction coefficient, which is a small but perceptible scenic change under many circumstances. Since the deciview scale is near zero for a pristine atmosphere (dv=0 for Rayleigh conditions at about 1.8 km elevation) and increases as visibility is degraded, it measures perceived haziness. Expressed in terms of extinction coefficient (b_{ext}) and visual range (vr):

$$haziness(dv) = 10\ln\left(\frac{b_{ext}}{0.01\,km^{-1}}\right) = 10\ln\left(\frac{391\,km}{vr}\right) \tag{17}$$

The name deciview was chosen because of the similarity of the decibel scale in acoustics. Both use 10 times the logarithm of a ratio of a measured physical quantity to a reference value to create scales that are approximately linear with respect to changes as perceived by human senses.

Ideally, a just noticeable change (JNC) in scene visibility should be approximately a one or two dv change in the deciview scale (i.e., a 10% to 20% fractional change in extinction coefficient) regardless of the baseline visibility level. Similarly, a change of any specific number of dv should appear to have approximately the same magnitude of visual change on any scene.

The dv scale provides a convenient, numerical method for presentation of visibility values. Any visibility monitoring data that are available in visual range or extinction coefficient are easily converted to the new visibility index expressed in deciview.

Use of the dv scale is an appropriate way to compare and combine data from different visibility perception and valuation studies. When results from multiple studies are presented in terms of a common perception index, the effects of survey approach and other factors influential to the results can be evaluated.

4.4 SEASONAL SUMMARY PLOTS

Seasonal summary plots are generated using the WIN_TSUM software. The following procedures describe the operation of the WIN_TSUM software:

EXECUTE WIN_TSUM SOFTWARE	Execute the WIN_TSUM software from the Windows Program Manager. The WIN_TSUM display will appear as shown in Figure 4-8.
EDIT THE SUBMIT FILE	The submit file defines the Level-1 validated data files and associated parameters used to generate the plots. Figure 4-9 details the format of the submit file. The following procedures are used to edit the submit file:

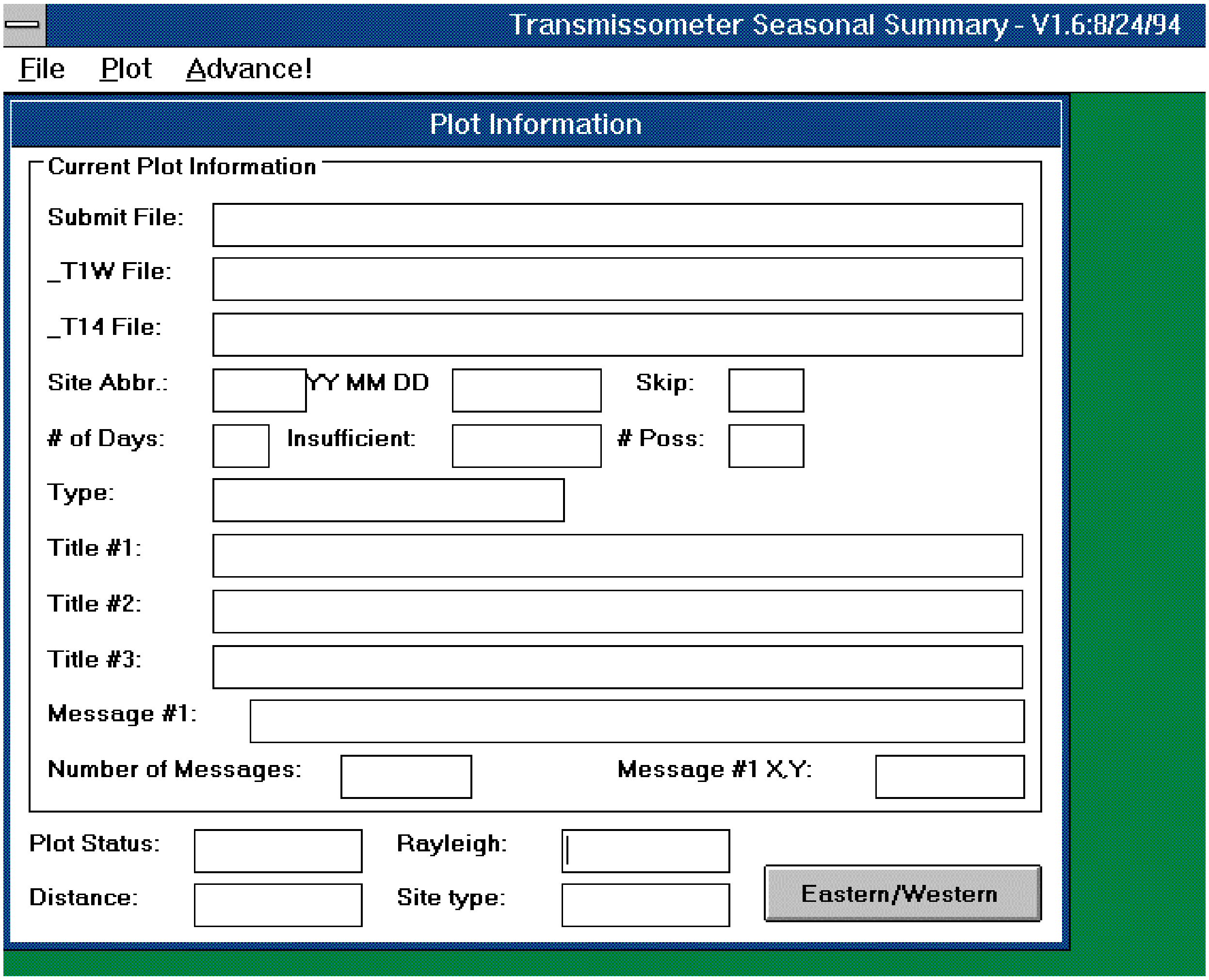

Figure 4-8. WIN_TSUM Software Display.

```
BADL_T1W.933                                 Level-1 validated file
BADL_T14.933                                 Level-1 validated file
BADL                                         Site code
93,6,1                                       Year, month, and day of start of plot
92                                           Number of days to read from file
0                                            Number possible hours, 0=all
0                                            Plot type, 0 = final, 2 = preliminary
BADLANDS NATIONAL PARK, SOUTH DAKOTA         Main title
Transmissometer Data Summary                  Second title
Summer Season:  June 1, 1993 - August 31, 1993  Third title
TIMING                                       Timeline plot comment
4.50,0.60                                    Location of comment ("from lower left")
BAND_T1W.933                                 Next site ...
BAND_T14.933
BAND
93,6,1
92
0
0
BANDELIER NATIONAL MONUMENT, NEW MEXICO
Transmissometer Data Summary
Summer Season:  June 1, 1993 - August 31, 1993

-99,-99
```

Figure 4-9. Example Submit File for WIN_TSUM Seasonal Summary Plot Software.

- Click on **File**. Click on **Edit Submit File**. The Windows Notepad program will be initiated.

- Open an existing submit file or create a new one in Notepad.

- Save the submit file and exit Notepad.

GENERATE PLOTS

The plots defined in the submit file can be plotted to the screen or to any Windows-compatible printer attached to the system. The following procedures are used to generate the plots:

- Choose the submit file to use by clicking **File** and then choose **Submit File**. Select the submit file to use from the file selection box.

- Generate the plots defined in the submit file by clicking **Plot** and then **Plot All Plots**.

4.4.1 Review of Level-1 Seasonal Summary Plots

Seasonal summary plots of Level-1 validated data are reviewed by the data analysts and project manager to identify the following:

- Data reduction and validation errors

- Instrument operational problems

- Lamp or calibration problems

Problems identified in the Level-1 seasonal summary plot review are resolved by editing the lamp, code, and/or constants files to identify additional valid or invalid data and performing the Level-0 and Level-1 validation procedures again.

When the Level-1 seasonal summary plots have passed the review process, the raw through Level-1 validated data and associated lamp, code, and constants files are archived. (Refer to TI 4600-5010, Transmissometer Data Archiving (IMPROVE Protocol)).