CHAPTER 3

OPTICAL DATA ANALYSIS

3.1 NEPHELOMETER MEASUREMENT UNCERTAINTY

The relative error of nephelometer scattering measurement due to drift of the slope of the calibration line was evaluated based on the instrument specific zero and span checks performed.

The desired scattering coefficient (b_{sp}) values for Freon used are those at standard atmospheric temperature and pressure (STP). The difference in the uncertainty values obtained when using STP values versus actual values for pressure and temperature has historically been found to be less than 5.0%.[1]

The following statistical analysis was applied to calculate potential error:

Let $V(t)$ = voltage reading at time t

$V_o(t)$ = voltage corresponding to zero air at time t

$V_f(t)$ = voltage corresponding to Freon at time t

$b_{sp,o}$ = b_{sp} scattering coefficient for zero air

$b_{sp,f}$ = b_{sp} scattering coefficient for Freon

V_o = desired voltage for zero air

V_f = desired voltage for Freon

$b_{sp}(t)$ = theoretical scattering coefficient at time t

m = slope of the calibration line used to calculate the theoretical scattering coefficient $b_{sp}(t)$

$$m = \frac{b_{sp,f} - b_{sp,o}}{V_f - V_o} \qquad \textbf{(3-1)}$$

Given a voltage reading *V(t)*, the theoretical b_{sp} at time *t* is:

$$b_{sp}(t) = b_{sp,o} + m(V(t) - V_o(t)) \qquad \textbf{(3-2)}$$

assuming that $V_o(t)$ and $V(t)$ are known without error. This is reasonable because these values are usually calculated by interpolating between automatic zero readings.

The slope of the calibration line is not constant as is defined above but changes (drifts) with time. Figure 3-1 illustrates the drift in the zero air and span voltages with time. Figure 3-2 illustrates how these drifting voltages cause the slope of the calibration line to drift.

The actual slope of the calibration line at time *t* is:

$$m(t) = \frac{(b_{sp,f} - b_{sp,o})}{(V_f(t) - V_o(t)} \qquad \textbf{(3-3)}$$

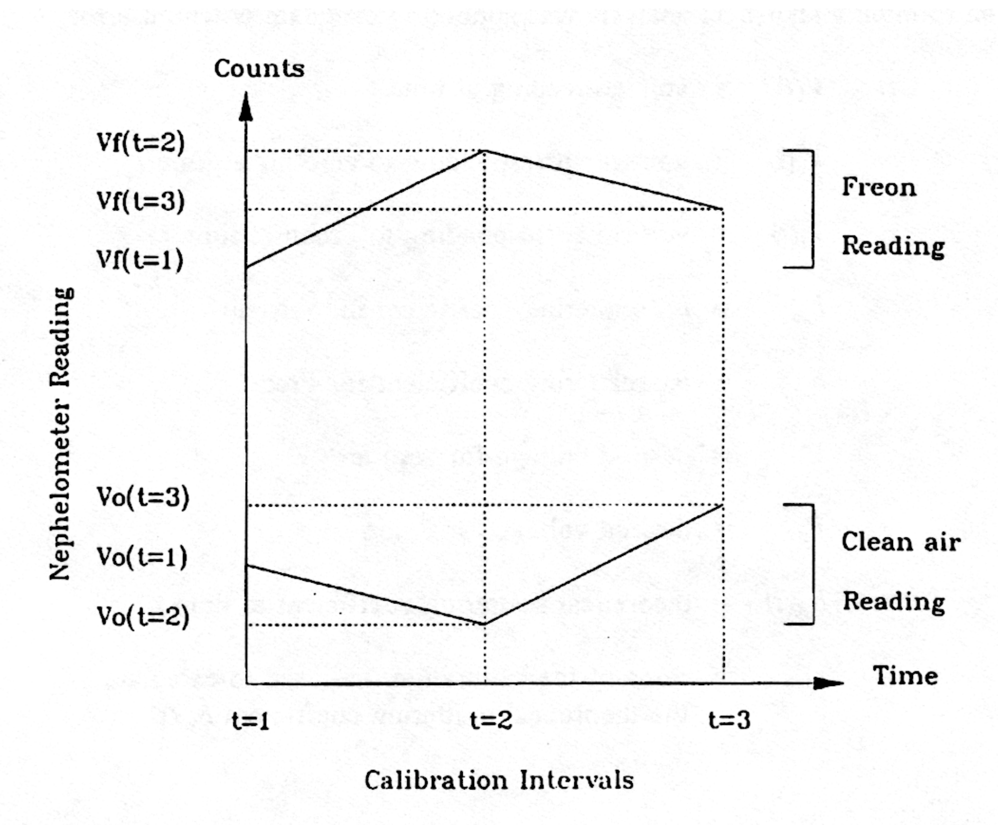


Figure 3-1. Drift in the zero air and Freon voltages with time.

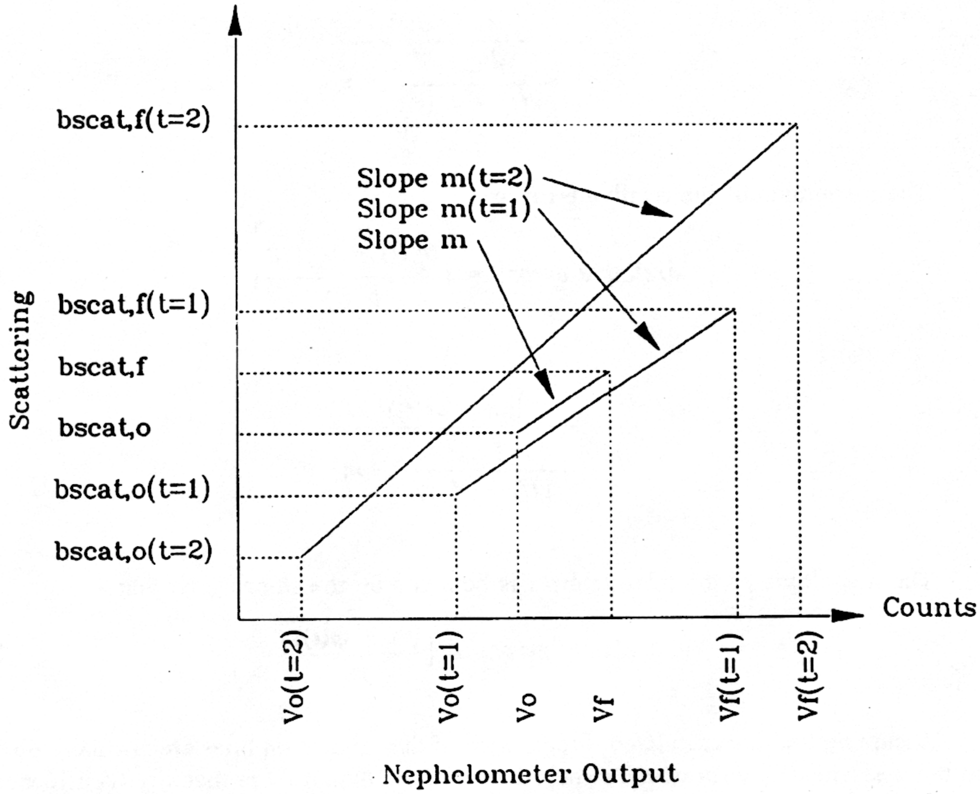


Figure 3-2. Drift in slope of calibration line due to drift of calibration voltages.

The actual b_{sp} (denoted b_{sp}'), given a voltage reading $V(t)$, is:

$$b_{s'p}(t) = b_{sp,o} + m(t)(V(t) - V_o(t)) \quad \textbf{(3-4)}$$

The relative error between the theoretical (b_{sp}) and actual (b_{sp}') is:

$$relative\ error = \frac{(b_{sp}(t) - b_{s'p}(t))}{b_{sp}(t)} \quad \textbf{(3-5)}$$

$$= \frac{(m - m(t))(V(t) - V_o(t))}{b_{sp,o} + m(V(t) - V_o(t))} \quad \textbf{(3-6)}$$

$$= \frac{m - m(t))}{\frac{b_{sp,o}}{(V(t) - V_o(t))} + m} \quad \textbf{(3-7)}$$

The magnitude of the relative error is:

$$|\,relative\ error\,| = |\,\frac{b_{sp}(t) - b_{s'p}(t))}{b_{sp}(t)}\,| \quad \textbf{(3-8)}$$

$$= \frac{|\,(m - m(t))\,|}{|\,\frac{b_{sp,o}}{V(t) - V_o(t))} + m\,|} \quad \textbf{(3-9)}$$

The magnitude of the relative error is bounded by the slopes such that:

$$|\,relative\ error\,| \leq |\,\frac{(m - m(t))}{m}\,| \quad \textbf{(3-10)}$$

Assuming that the calculated slopes, *m(t)*, of the calibration lines are normally distributed about the theoretical slope *m* with a standard deviation *s*, then for a probability (confidence level) of 95%:

$$|\,m - m(t)\,| \leq 2s \quad \textbf{(3-11)}$$

so that:

$$|\frac{b_{sp}(t) - b_{s'p}(t)}{b_{sp}(t)}| \leq \frac{2s}{m} \quad \textbf{(3-12)}$$

Assuming that ***s*** is estimated by s_m with *k* degrees of freedom, based on *k+1* sample values of *m(t)*, and using the two-tailed *t* distribution:

$$|\,relative\ error\,| \leq t_{k,0.025} * s_m \,/\, m \quad \textbf{(3-13)}$$

at a 95% confidence level.

An error analysis was performed for all sites. The National Park Service (NPS) stations were equipped with barometric pressure sensors. The pressure, along with the chamber temperature during Freon calibration, was used to calculate the expected Freon scattering value. For each NPS station, an error analysis was performed with Freon values obtained by both the altitude method and the pressure/temperature method. Results of the error analysis for each site are summarized in Table 3-1.

Table 3-1. Summary of the error analysis for 1990 PREVENT study nephelometers.

Site Location	Relative Error Percent (%)	Method
Dog Mountain	14.3	Altitude
South Mountain	12.5	Altitude
Tahoma Woods	9.0	Pressure/Temperature
Tahoma Woods	9.0	Altitude
Paradise	34.5	Altitude
Carbon River	5.1	Pressure/Temperature
Carbon River	6.9	Altitude
Marblemount	32.0	Pressure/Temperature
Marblemount	30.7	Altitude
Newhalem	15.6	Altitude

3.1.1 Nephelometer Station Meteorological and Support Sensors

Meteorological and support sensors (nephelometer inlet and chamber thermocouples) were checked for correct operation prior to installation and during the take-down. All sensors performed well. No periodic checks of sensor operation were made throughout the PREVENT study.

3.1.2 Nephelometer Operating Temperature Considerations

The three NPS nephelometers (Tahoma, Carbon River, and Marblemount) operated with sample chamber temperatures that were kept as close as possible to the ambient temperature. This was accomplished by the following:

- Inlet canes were kept short and were covered with reflective (silver) tape.

- Nephelometers were housed in small (4'l x 4'w x 8'h) stand-alone shelters equipped with a high air flow fan (1500 cfm). The fan circulated ambient air through the shelter, after first passing through a moisture trap and a dust filter. The inside of the shelter was maintained at temperatures very close to ambient.

- Nephelometers were equipped with medium size muffin fans (150 cfm) mounted so as to draw heat, produced by the chamber illumination lamp, away from the sample chamber.

Inlet and chamber temperatures were measured with small diameter copper-constastan thermocouples. Reference junctions were incorporated within each Campbell Scientific 21X data logger (this is a standard feature).

The average increase in chamber temperature over ambient temperature for the NPS stations was 1.93°C (3.5°F).

The Washington Department of Ecology (WA-DOE) nephelometers, on the other hand, were housed in available shelters. These shelters varied in construction type, ventilation, collocated equipment, and free-air space. At a number of sites the shelter configuration or placement required the use of long inlet tubes. In addition, the nephelometers were not equipped with lamp heat ventilation fans.

The average increase in chamber temperature over ambient temperature for the WA-DOE stations was 11.68°C (21.0°F).

A composite hourly summary depicting the difference between inlet and chamber temperatures averaged for all data is summarized in Table 3-2, and presented graphically in Figure 3-3.

Table 3-2. Nephelometer chamber temperature increase over ambient temperature averaged for selected intervals (^{o}C).

Site Location	Average Increase During Hours			
	0-5	6-11	12-17	18-23
South Mountain	15.8	11.9	10.2	14.8
Dog Mountain	12.9	10.6	9.0	12.7
Tahoma Woods	2.2	2.0	2.5	2.4
Paradise	14.9	12.1	11.7	15.4
Carbon River	2.3	2.0	1.9	2.3
Marblemount	1.1	1.5	1.9	1.3
Newhalem	11.0	7.1	7.1	9.7

3.1.3 Meteorological Stations

Meteorological sensors on NPS surface stations were checked for correct operation prior to installation, during repairs, and during the take-down. All sensors performed well. No periodic checks of sensor operations were made throughout the PREVENT study.

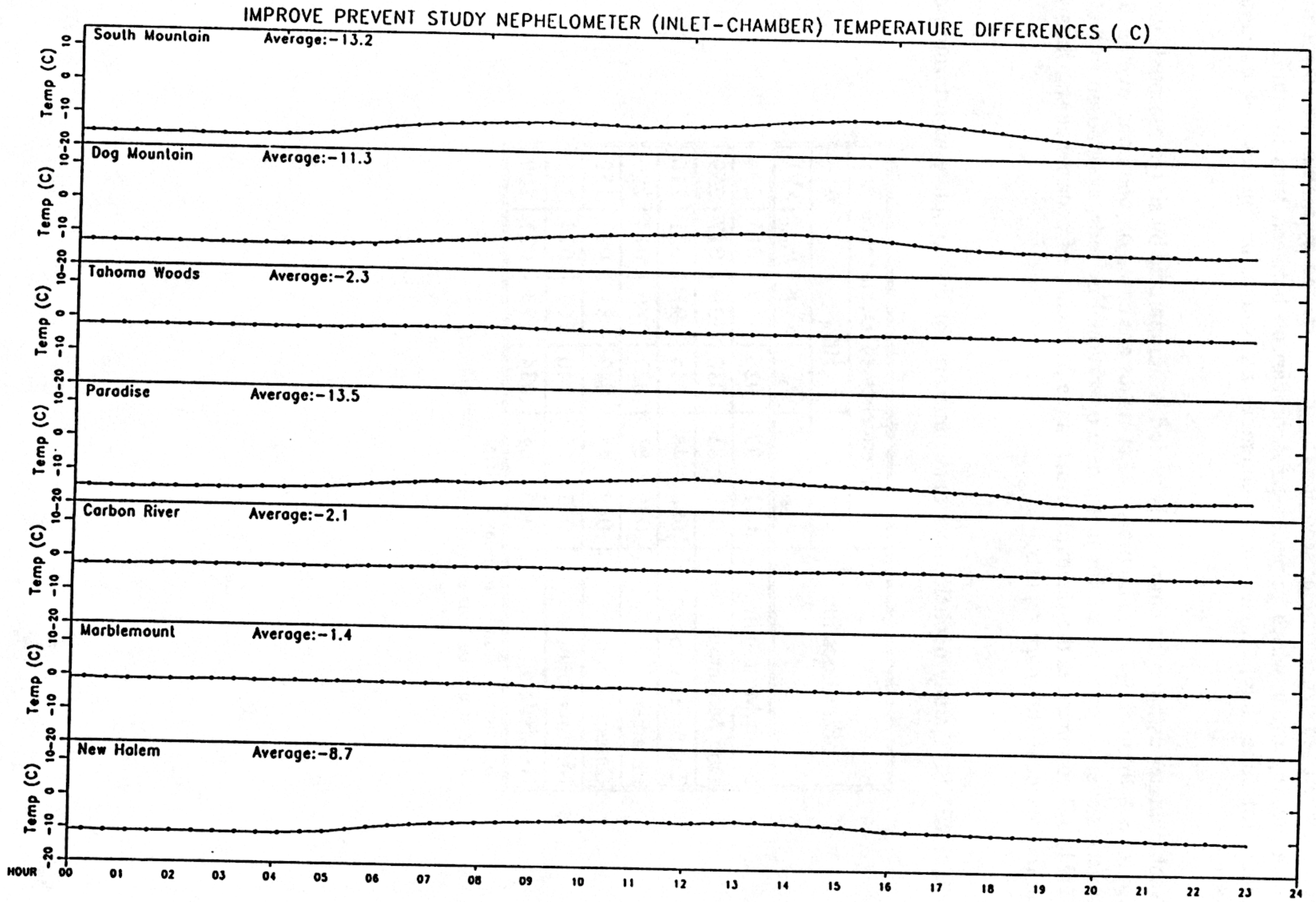


Figure 3-3. Composite hourly summary, (inlet-chamber) temperature.

3.2 DESCRIPTIONS OF DATA PRESENTATIONS - NEPHELOMETER

Hourly averaged nephelometer readings (b_{scat}) are depicted by month for all monitoring stations in a plotting order which provides easy comparison between sites in similar regions. "Stack plots" for June, July, August and September are shown in Figures 3-4 through 3-7, respectively.

Nephelometer data for the entire study period is summarized by site in seasonal summary plots (Figures 3-8 through 3-14). The plots and statistics are based on one-hour, averaged data. Data recovery statistics reported are for instrument operational periods, as opposed to the study period. Table 3-3 summarizes the standard visual range frequency of occurrence statistics which appear on the seasonal summary reports.

Table 3-3. PREVENT study nephelometer data summary for the complete monitoring period.

Site Location	Frequency of Occurrence					
	10%		50%		90%	
	b_{scat}	SVR	b_{scat}	SVR	b_{scat}	SVR
South Mountain	.041	99	.026	160	.015	294
Dog Mountain	.049	83	.030	139	.017	259
Tahoma Woods	.084	48	.045	91	.021	210
Paradise	.049	81	.027	149	.014	296
Carbon River	.089	45	.049	83	.027	158
Marblemount	.073	56	.040	105	.024	185
Newhalem	.066	61	.034	123	.021	209

b_{scat} units = (km^{-1}), includes Rayleigh
SVR = standard visual range (km) (2% contrast

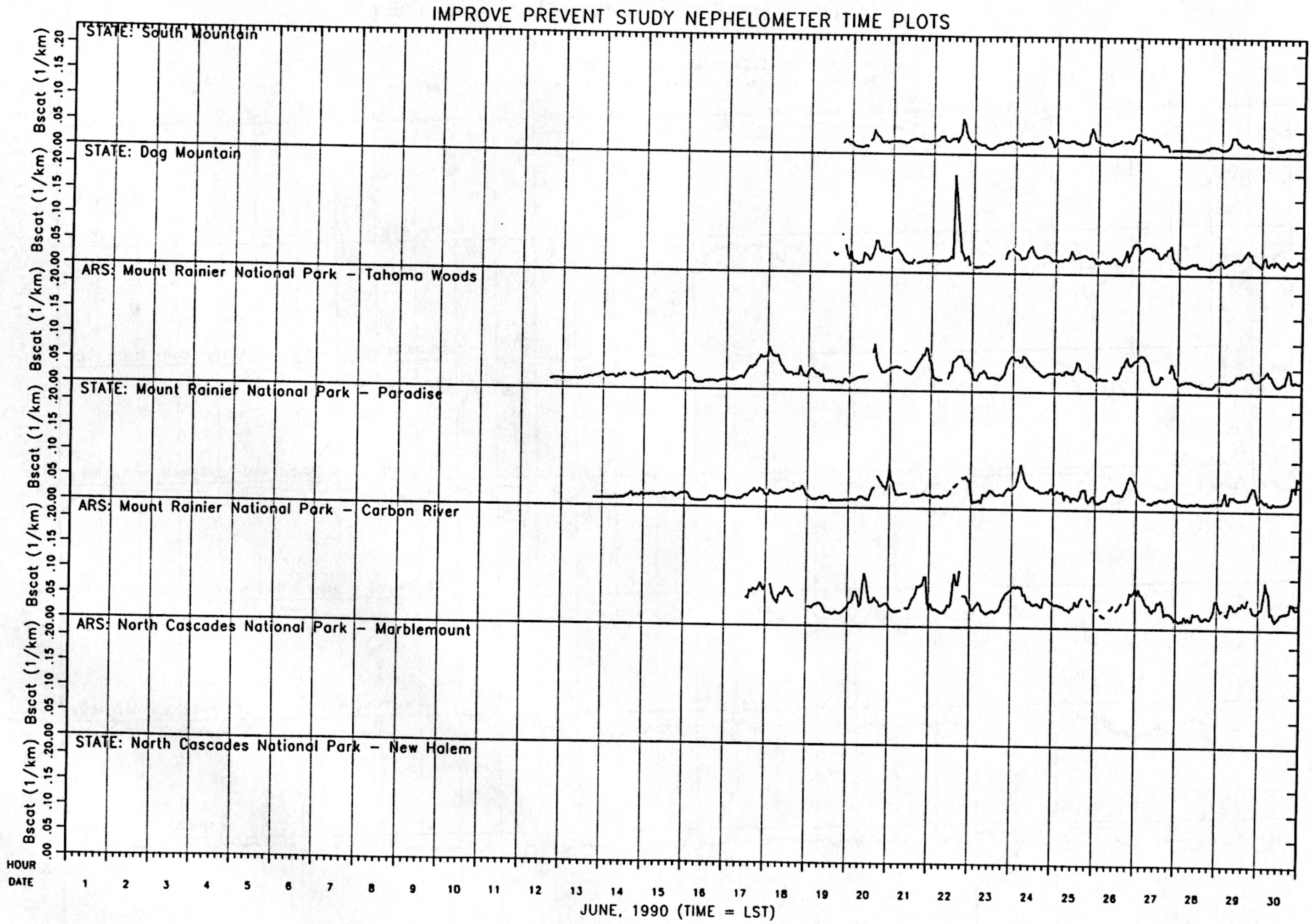


Figure 3-4. Nephelometer stack plots – June 1990

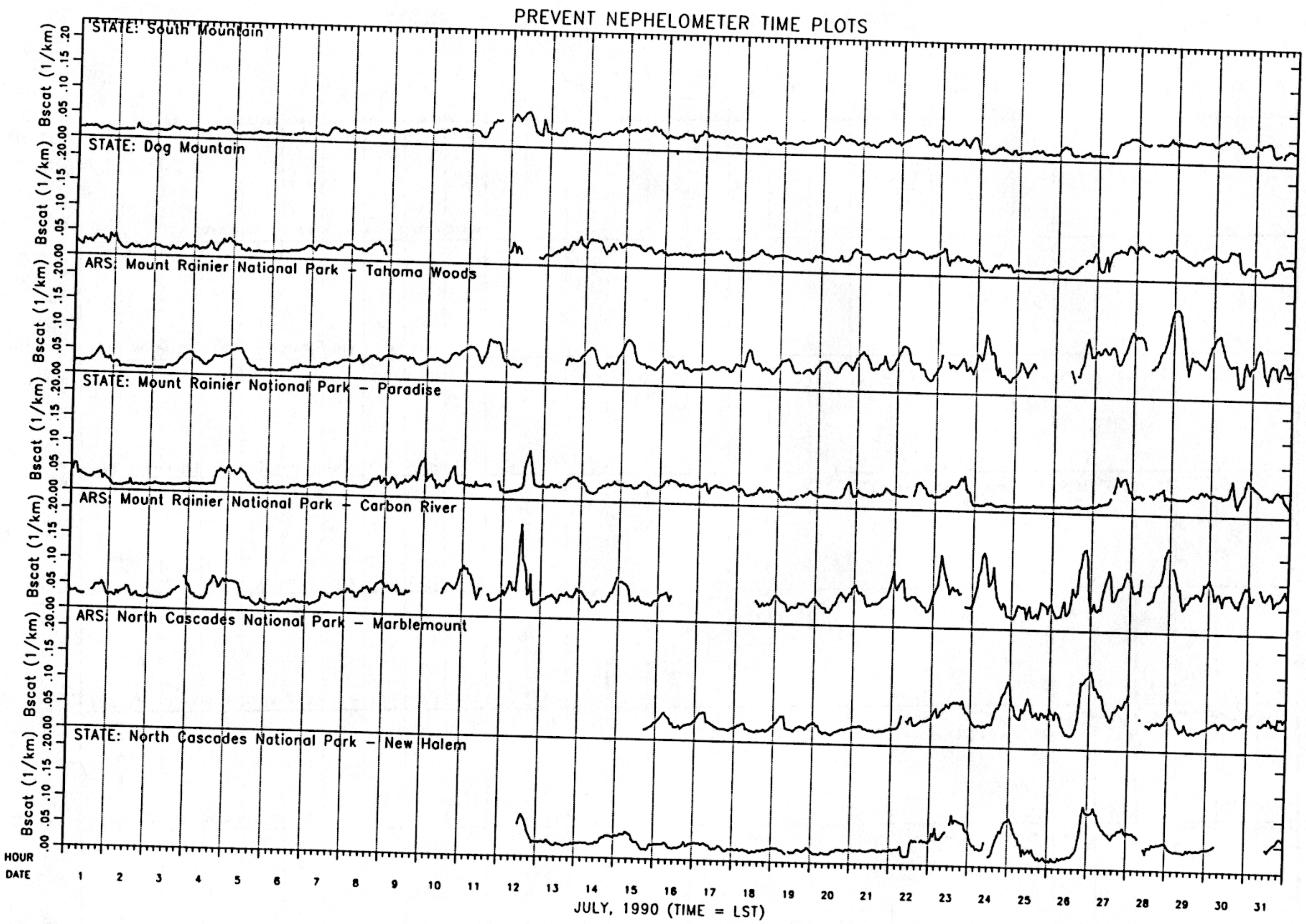


Figure 3-5. Nephelometer stack plots – July 1990

Figure 3.6. Nephelometer stack plots – August 1990

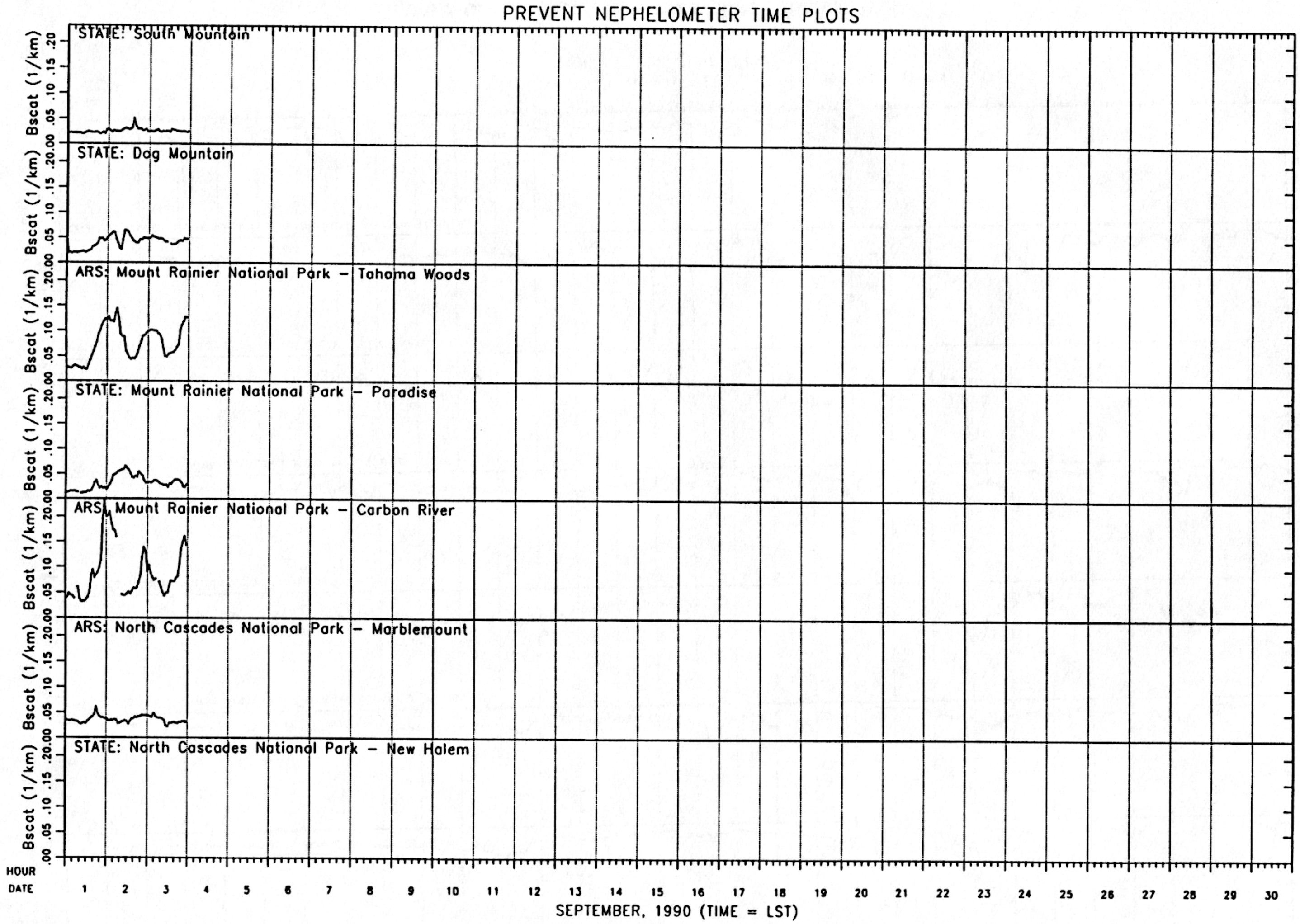
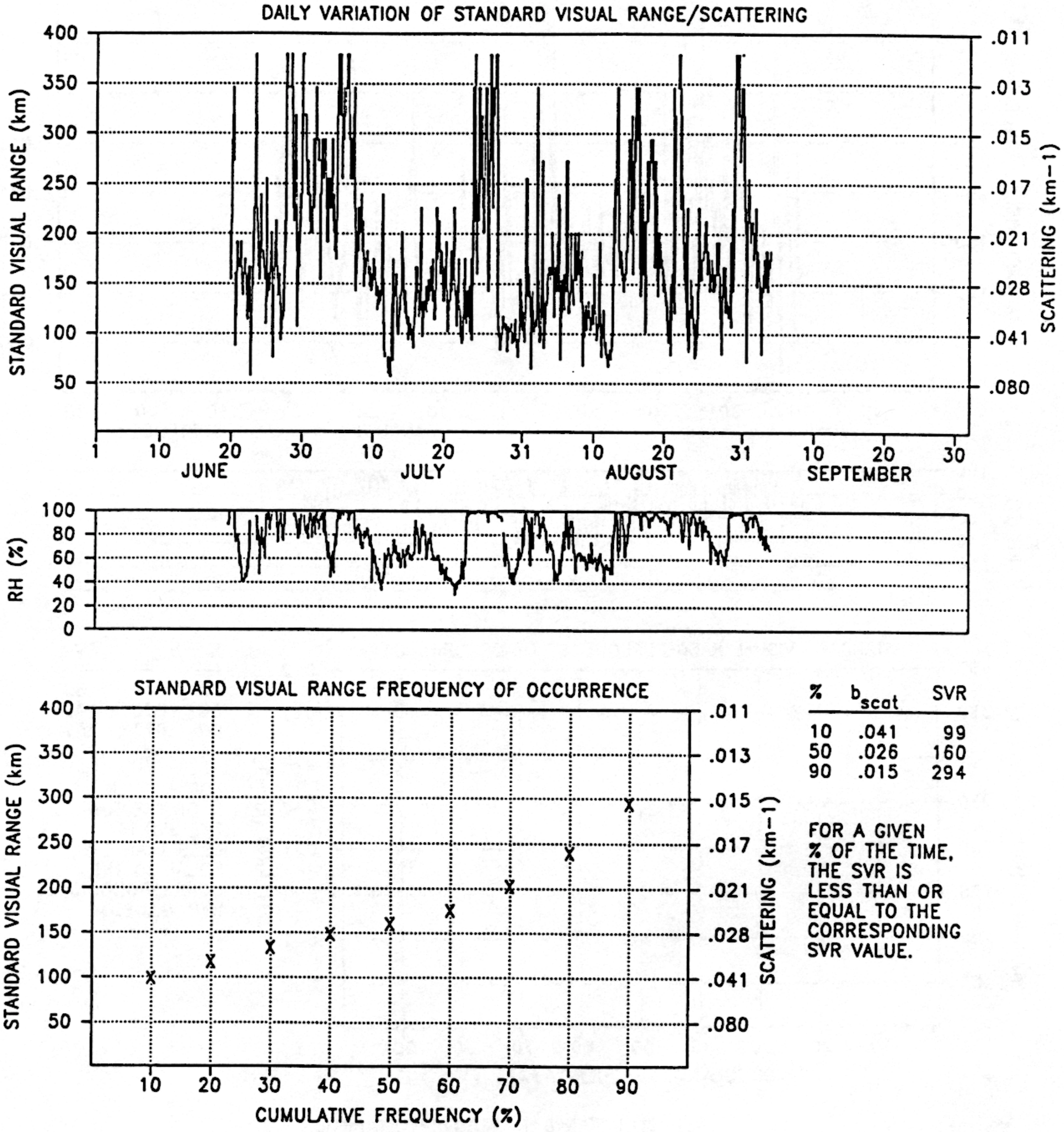


Figure 3-7. Nephelometer stack plots – September 1990.

SOUTH MOUNTAIN
Nephelometer Data Summary -- Hourly Averages
June 1, 1990 – September 3, 1990



%	b_{scat}	SVR
10	.041	99
50	.026	160
90	.015	294

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

NEPHELOMETER DATA RECOVERY STATISTICS

CATEGORY	NUM	%
TOTAL POSSIBLE 1-HOUR AVERAGES IN THE TIME PERIOD	1834	100
USABLE 1-HOUR AVERAGES IN THE TIME PERIOD	1787	97

DATE PREPARED: 2/ 4/91

Figure 3-8. Nephelometer seasonal summary – Tahoma Woods.

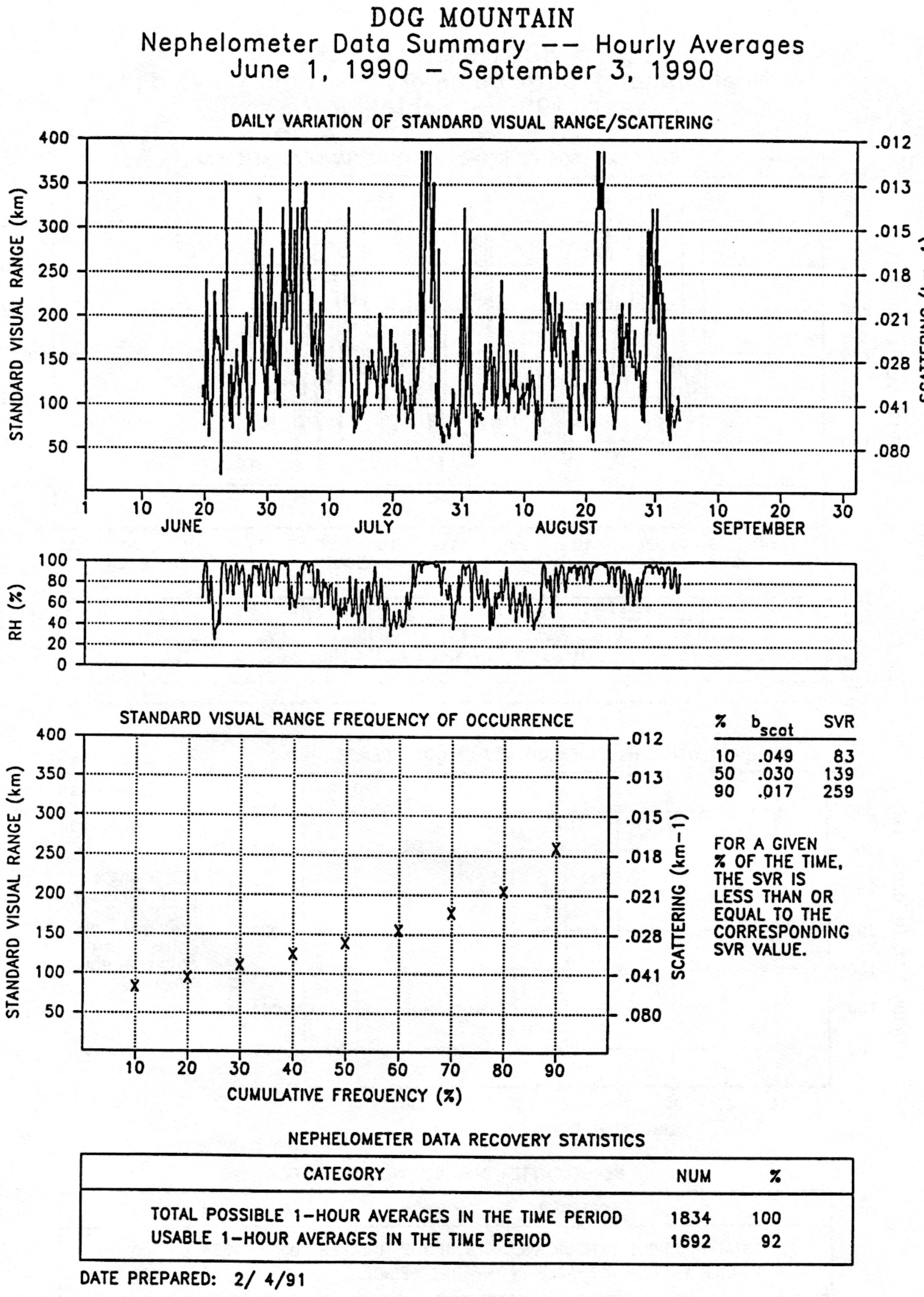
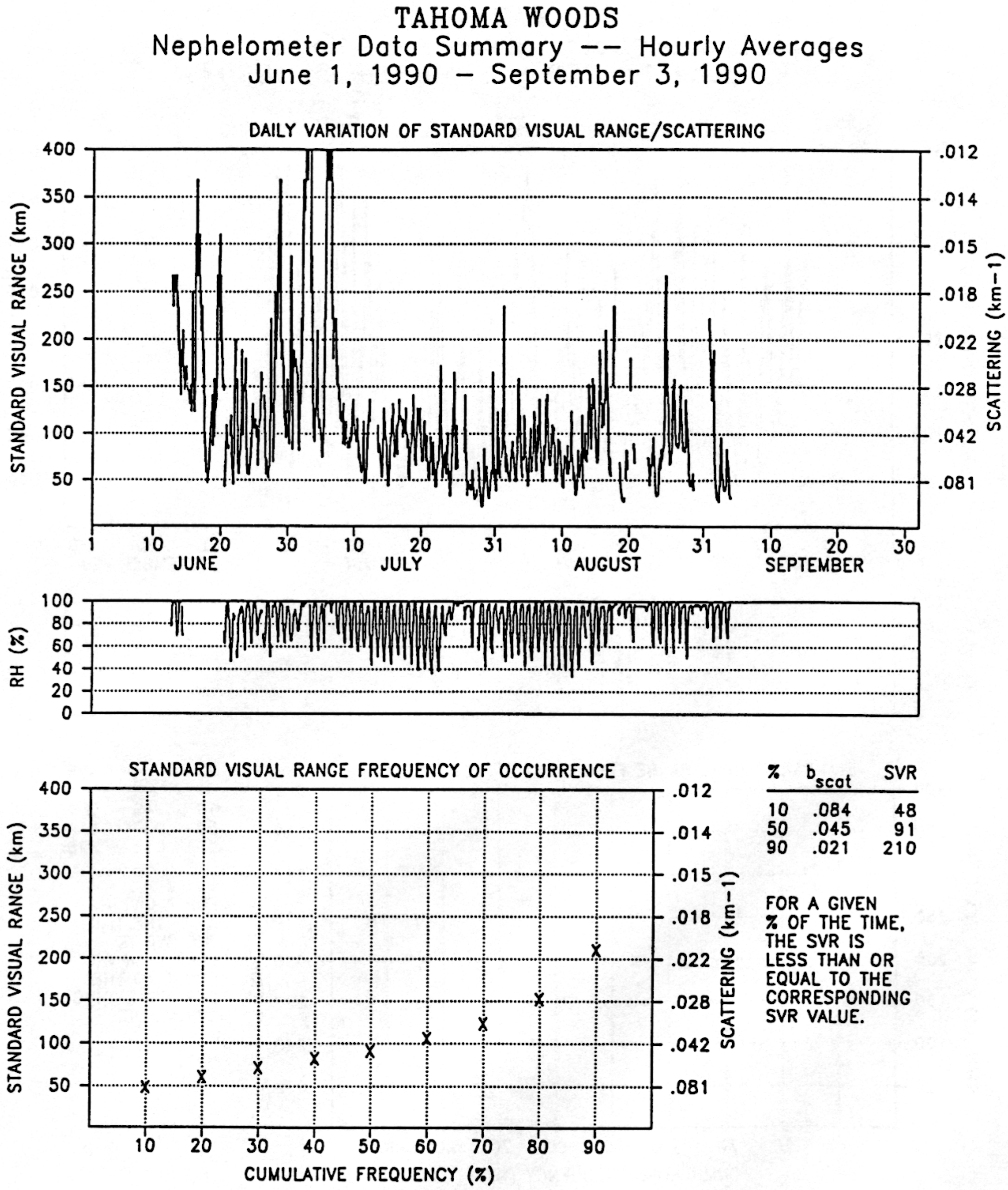


Figure 3-9. Nephelometer seasonal summary – Dog Mountain.



%	b_{scat}	SVR
10	.084	48
50	.045	91
90	.021	210

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

NEPHELOMETER DATA RECOVERY STATISTICS

CATEGORY	NUM	%
TOTAL POSSIBLE 1-HOUR AVERAGES IN THE TIME PERIOD	1999	100
USABLE 1-HOUR AVERAGES IN THE TIME PERIOD	1779	89

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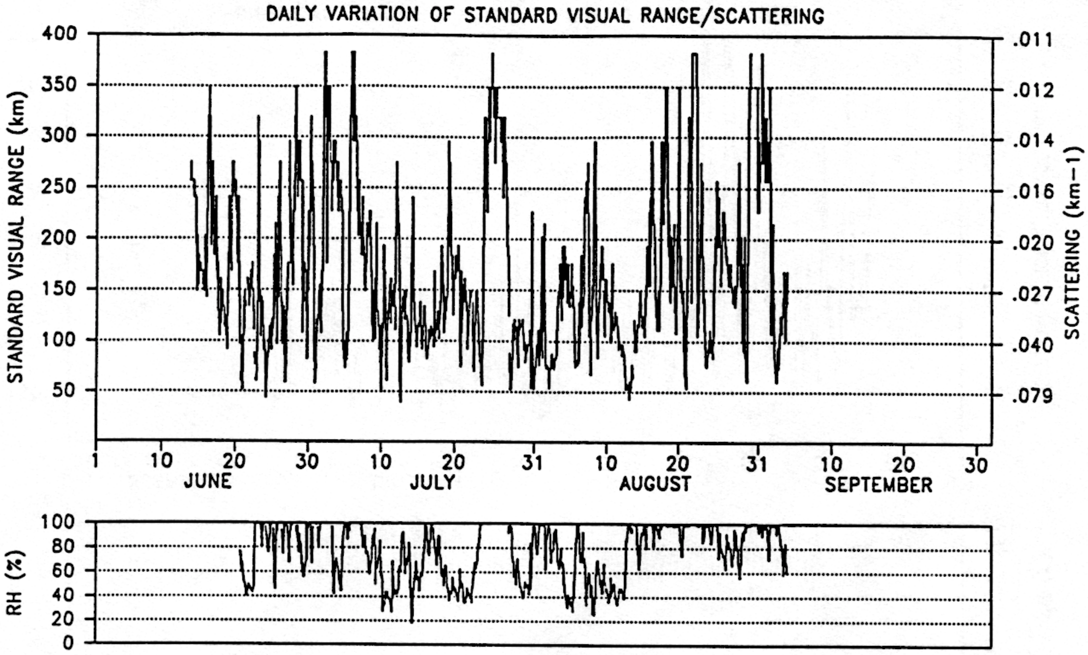
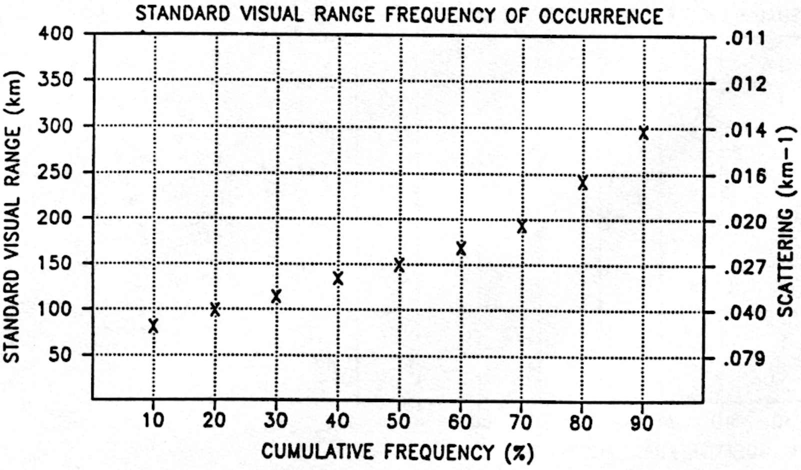
Figure 3-10. Nephelometer seasonal summary – Tahoma Woods.

PARADISE
Nephelometer Data Summary -- Hourly Averages
June 1, 1990 - September 3, 1990





%	b_{scat}	SVR
10	.049	81
50	.027	149
90	.014	296

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

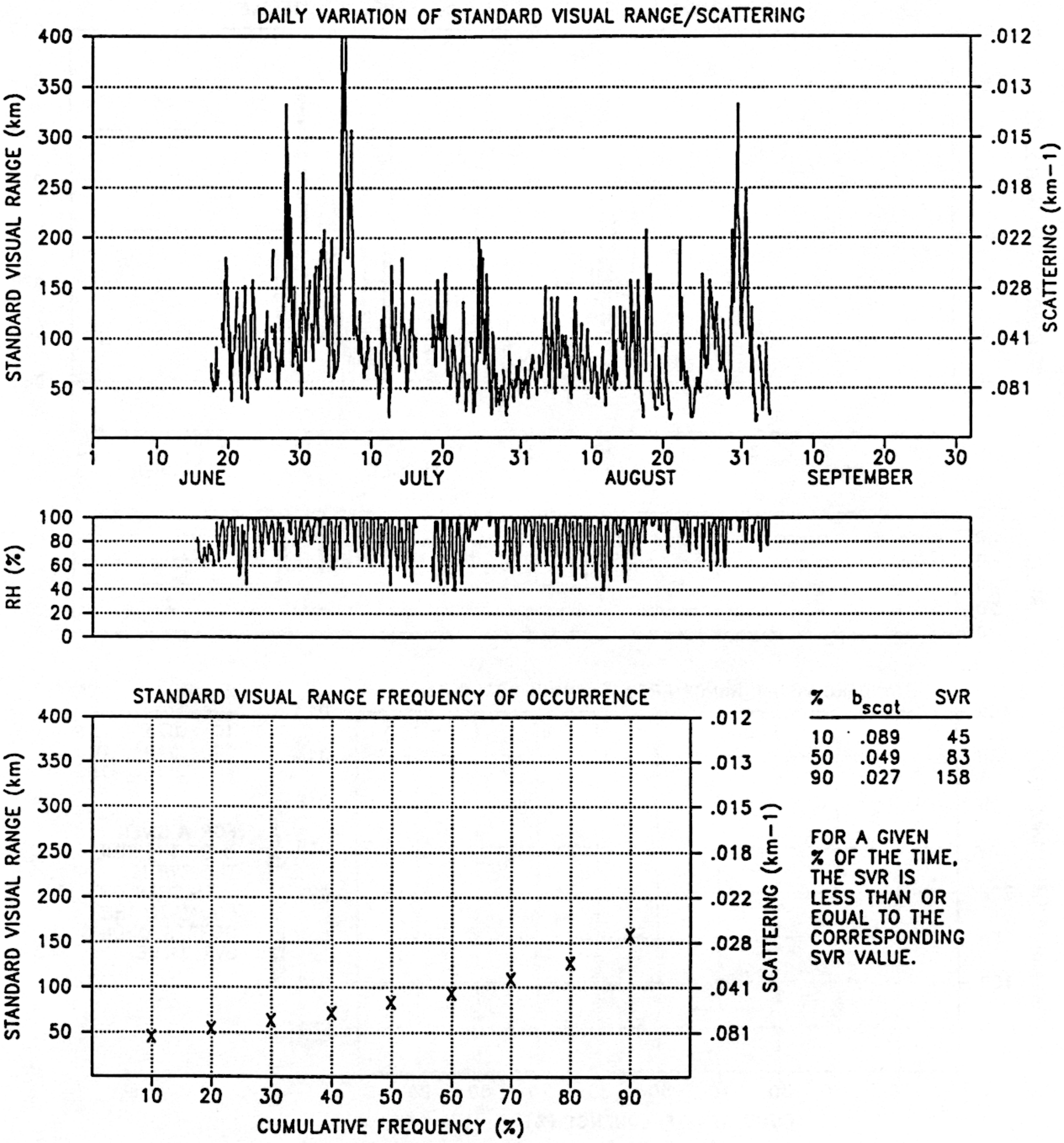
NEPHELOMETER DATA RECOVERY STATISTICS

CATEGORY	NUM	%
TOTAL POSSIBLE 1-HOUR AVERAGES IN THE TIME PERIOD	1973	100
USABLE 1-HOUR AVERAGES IN THE TIME PERIOD	1922	97

DATE PREPARED: 2/ 4/91

Figure 3-11. Nephelometer seasonal summary – Paradise.

CARBON RIVER
Nephelometer Data Summary -- Hourly Averages
June 1, 1990 - September 3, 1990



NEPHELOMETER DATA RECOVERY STATISTICS

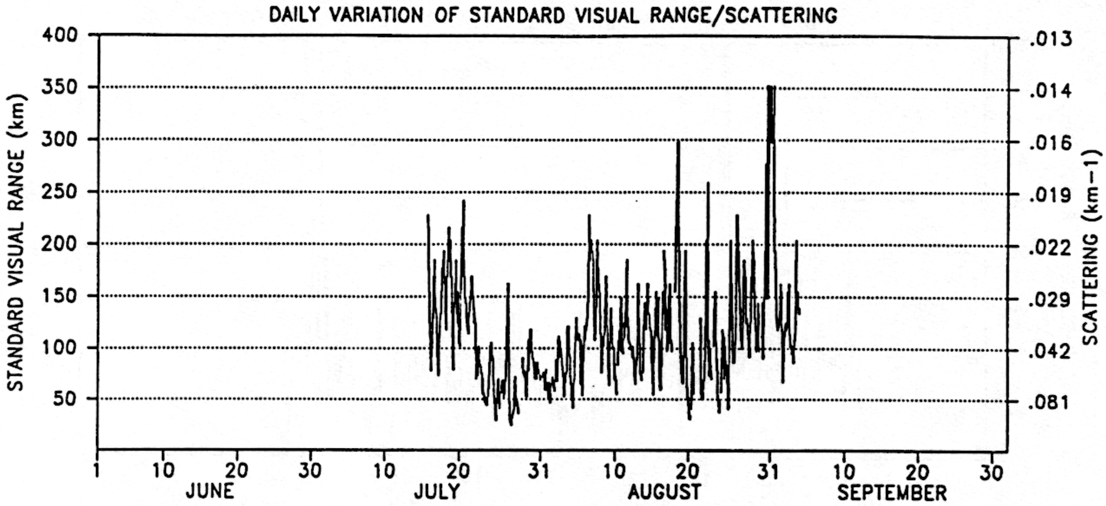
CATEGORY	NUM	%
TOTAL POSSIBLE 1-HOUR AVERAGES IN THE TIME PERIOD	1883	100
USABLE 1-HOUR AVERAGES IN THE TIME PERIOD	1713	91

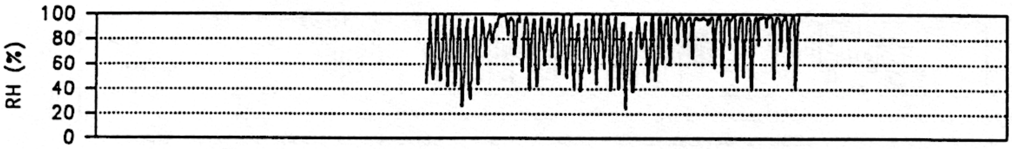
DATE PREPARED: 2/ 4/91

Figure 3-12. Nephelometer seasonal summary – Carbon River.

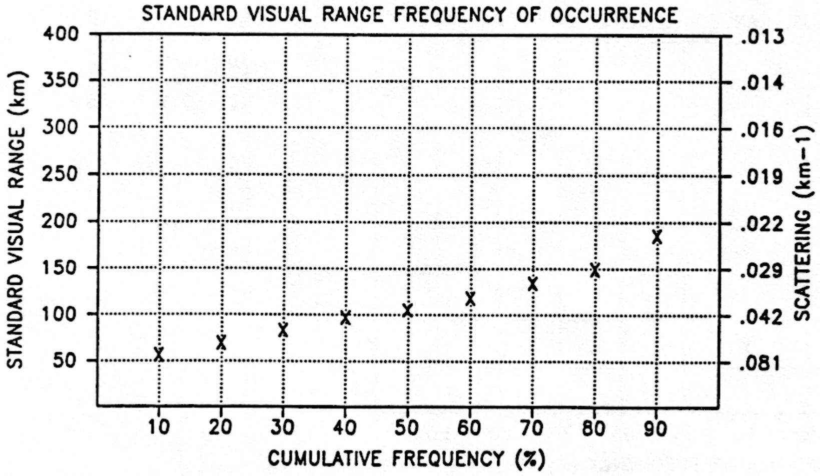
MARBLEMOUNT
Nephelometer Data Summary -- Hourly Averages
June 1, 1990 – September 3, 1990

DAILY VARIATION OF STANDARD VISUAL RANGE/SCATTERING





STANDARD VISUAL RANGE FREQUENCY OF OCCURRENCE



%	b_{scat}	SVR
10	.073	56
50	.040	105
90	.024	185

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

NEPHELOMETER DATA RECOVERY STATISTICS

CATEGORY	NUM	%
TOTAL POSSIBLE 1-HOUR AVERAGES IN THE TIME PERIOD	1207	100
USABLE 1-HOUR AVERAGES IN THE TIME PERIOD	1142	95

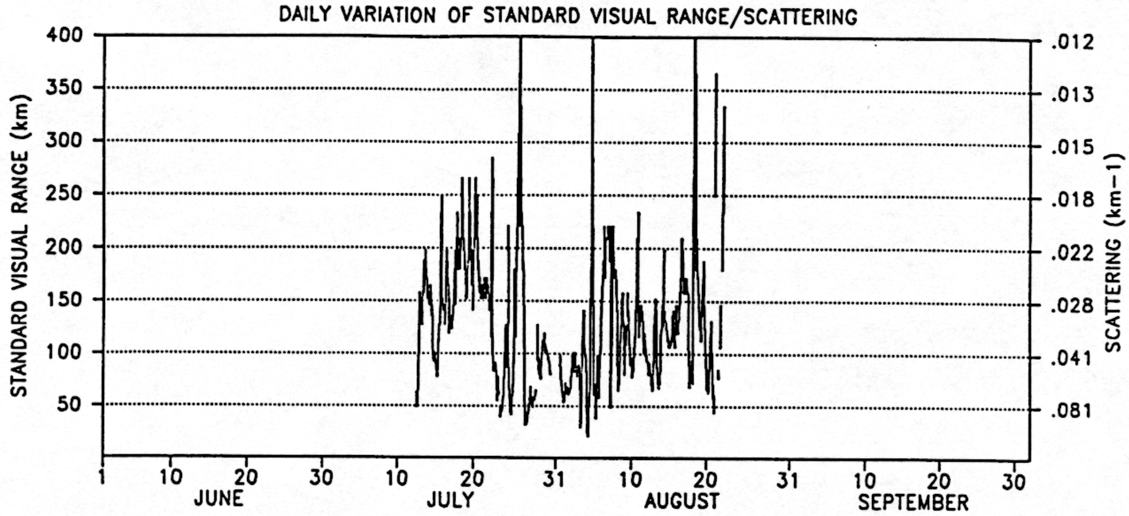
DATE PREPARED: 2/ 4/91

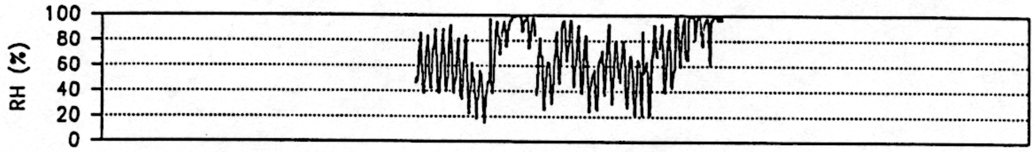
Figure 3-13. Nephelometer seasonal summary – Marblemount.

NEWHALEM

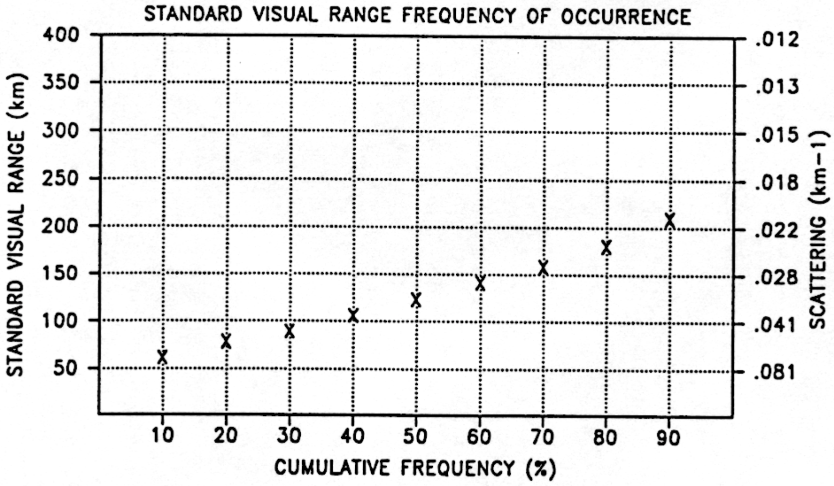
Nephelometer Data Summary -- Hourly Averages
June 1, 1990 - September 3, 1990

DAILY VARIATION OF STANDARD VISUAL RANGE/SCATTERING





STANDARD VISUAL RANGE FREQUENCY OF OCCURRENCE



%	b_{scat}	SVR
10	.066	61
50	.034	123
90	.021	209

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

NEPHELOMETER DATA RECOVERY STATISTICS

CATEGORY	NUM	%
TOTAL POSSIBLE 1-HOUR AVERAGES IN THE TIME PERIOD	1283	100
USABLE 1-HOUR AVERAGES IN THE TIME PERIOD	908	71

DATE PREPARED: 2/ 4/91

Figure 3-14. Nephelometer seasonal summary – Newhalem

REFERENCES

1. Molenar, J.V., D.S. Cismoski, and R.M. Tree, 1992. Intercomparison of ambient optical monitoring techniques. Presented at the *85th Annual Meeting and Exhibition, Air and Waste Management.* Kansas City, MO, Paper No. 92-60.09, June 21-26.