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AN AUTOMATED OPTICAL WEDGE CALIBRATOR FOR DOBSON OZONE SPECTROPHOTOMETERS

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ABSTRACT

The Dobson Ozone Spectrophotometer measures the difference of intensity between selected wavelengths in the ultraviolet. The method uses an optical attenuator (the "Wedge") in this measurement. The knowledge of the relationship of the wedge position to the attenuation is critical to the correct calculation of ozone from the measurement. The procedure to determine this relationship is time-consuming, and requires a highly skilled person to perform it correctly. The relationship has been found to change with time. For reliable ozone values, the procedure should be done on a Dobson instrument at regular intervals. Due to the skill and time necessary to perform this procedure, many instruments have gone as long as 15 years between procedures. This article describes an apparatus that performs the procedure under computer control, and is adaptable to the majority of existing Dobson instruments. Part of the apparatus is usable for normal operation of the Dobson instrument, and would allow computer collection of the data and real-time ozone measurements.

1. INTRODUCTION

The most important instrument used for ground observations of total ozone is the Dobson Ozone Spectrophotometer (Dobson, 1957). Originally designed in the 1920's, more than 100 of the instruments are in use today. The instrument measures the difference between the intensity of light at wavelength pairs in the 300-340 NM region of the solar spectrum. The pairs (called A, C or D) are chosen so light of one wavelength is significantly absorbed by ozone. In the instrument, the light of the other wavelength passes through a variable optical attenuator (the wedge). The wedge is adjusted so the light of each wavelength is seen as equal at a photomultiplier tube. The wedge position gives the intensity difference. This measured difference at a specific time, combined with the extraterrestrial difference and the ozone absorption spectrum indicates the total ozone amount. Normal observations of total ozone are made on two wavelength pairs to largely cancel atmospheric effects other than absorption by ozone. The knowledge of the wedge position to the difference of intensity (the calibration) is critical for the accurate determination of ozone. This paper documents an automated and a semi-automated method to determine this calibration.

2. MANUAL CALIBRATION

The optical wedge consists of two overlapping quartz plates, normally coated with chromel, deposited in a gradient. A graduated dial (the R-dial) controls the relative overlap through a shaft and taut-band arrangement. The R-dial is scribed in degrees, 0 to 300, 300 being the maximum attenuation. Readings of the dial can be made to a tenth of a degree. The calibration of the wedge is measured by the two-lamp method (Komhyr, 1980). Two-lamp refers to the external lamp unit. A third lamp (the S4 bulb) is fitted in the instrument illuminating a slit (S4). The instrument's internal masks are set so the PMT sees only the wedge slit (S3) and the S4 bulb. The external two-lamp unit (the X and Y bulbs) is fitted over the inlet window with the ground quartz plate in place. The unit normally has shutters so one or the other or both lamps can be seen by the instrument. The X and Y bulbs are adjusted so the R-dial readings on the individual bulbs are equal; this is the measurement of the difference between the bulb and the S4 lamp. When the instrument is simultaneously exposed to both bulbs, this doubled intensity produces another, higher reading. The difference (Delta R) between the original X and Y readings and the higher X plus Y reading is defined as being equal to the base ten logarithm of two (0.3010). This number is chosen because the calculation of ozone is made with base ten absorption coefficients. By varying the S4 lamp voltage (thus it's intensity), the Delta R value can be found for any point (R) on the R-dial. The calibration procedure is to determine the Delta R for many points on the R-dial for each wavelength. A representative plot of R versus Delta R is shown in Graph 1.

The calibration procedure is quite time-consuming. A skilled operator may take several days to produce enough points to cover the entire range with confidence that the true shape of the R versus Delta R curve has been found. One common method of doing this procedure uses a smoked disk and clock-stylus to record the position of the R-dial during each measurement. After many points have been taken, the R-dial is read against a hairline pointer. The data is hand plotted, and inspected for segments of noisy results, or places where more points are required to define fully the curve. The process is repeated if needed until the operator is satisfied there are enough points. A line is drawn by hand through the data, and points are picked off this curve at intervals of five degrees.

This R versus Delta R relationship over range of the R-dial is then used to form the G-table for the instrument at a particular wavelength pair. Table 1 is the A wavelength G-table derived from the R versus Delta R in Graph 1. This table converts an R-dial reading to a logarithmic difference of intensity. When the extraterrestrial difference for that instrument and wavelength is applied to the table, the result is the N-table, used in the calculation of ozone from observations.

The calibration should be measured:

> whenever optical adjustments are made to the instrument.
> when comparison with a standard instrument shows the need.
> when repeated ozone observations series on clear half days show a pattern in the measurements related to R-dial position.
> before and after cleaning of the wedges (recommended).
> at regular intervals, no longer than four years.

3. APPARATUS

The two-lamp unit has two 250 watt quartz halogen bulbs. Each bulb is powered by a separate DC supply, which in turn is controlled by an input voltage. Two fans cool the unit. Shutters below the lamps are opened and closed by lead-screw type stepper motors. The unit can be adjusted side to side for centering. The S4 lamp mounted inside the instrument is also powered by its own voltage controlled DC power supply.

The Dobson instrument under test has its internal high voltage power supply disconnected and the voltage supplied by an external voltage controlled power supply. The output from the instrument is connected to a circuit that converts the analog current signal to a digital and a voltage signal, if the unit is used in a semi-automated mode, this step is omitted.

Graph 1. Example R versus Delta R from two-lamp wedge calibration.

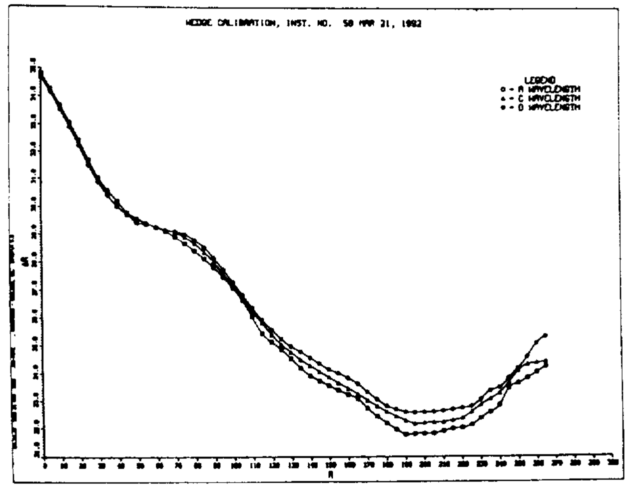

Table 1. G-table derived from A-wavelength data in Graph 1.

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GA TABLE

R	0	1	2	3	4	5	6	7	8	9
0						.0	.8	1.7	2.5	3.3
10	4.2	5.0	5.9	6.7	7.5	8.3	9.2	10.0	10.8	11.7
20	12.5	13.4	14.3	15.1	16.0	16.8	17.7	18.6	19.5	20.5
30	21.4	22.3	23.2	24.1	25.1	26.0	27.0	28.0	28.9	29.9
40	30.8	31.8	32.7	33.6	34.6	35.5	36.5	37.4	38.4	39.3
50	40.3	41.2	42.2	43.2	44.2	45.2	46.2	47.2	48.3	49.3
60	50.3	51.4	52.4	53.4	54.5	55.5	56.6	57.6	58.6	59.7
70	60.7	61.7	62.8	63.8	64.8	65.9	66.9	67.9	68.9	69.9
80	70.9	71.9	72.9	74.0	75.0	76.0	77.0	78.1	79.1	80.2
90	81.2	82.3	83.4	84.4	85.5	86.6	87.7	88.7	89.8	90.9
100	92.0	93.1	94.2	95.2	96.3	97.4	98.5	99.5	100.6	101.7
110	102.7	103.8	104.9	106.0	107.1	108.2	109.3	110.4	111.6	112.7
120	113.8	115.0	116.2	117.3	118.5	119.6	120.8	122.0	123.2	124.4
130	125.6	126.8	128.0	129.2	130.4	131.6	132.8	134.0	135.2	136.5
140	137.7	138.9	140.1	141.3	142.6	143.8	145.0	146.2	147.5	148.7
150	149.9	151.2	152.4	153.7	155.0	156.2	157.5	158.8	160.1	161.4
160	162.7	164.0	165.3	166.6	167.9	169.2	170.4	171.7	172.9	174.2
170	175.5	176.8	178.0	179.3	180.6	181.9	183.2	184.5	185.8	187.2
180	188.5	189.8	191.1	192.5	193.8	195.2	196.5	197.8	199.2	200.5
190	201.9	203.2	204.6	205.9	207.3	208.6	210.0	211.4	212.8	214.1
200	215.5	216.9	218.3	219.7	221.1	222.5	223.9	225.3	226.7	228.1
210	229.5	230.9	232.2	233.6	235.0	236.3	237.7	239.0	240.4	241.8
220	243.1	244.5	245.9	247.3	248.7	250.1	251.5	252.9	254.2	255.6
230	257.0	258.4	259.7	261.1	262.4	263.8	265.1	266.5	267.8	269.2
240	270.5	271.8	273.2	274.6	275.9	277.3	278.6	280.0	281.3	282.7
250	284.0	285.3	286.6	287.9	289.2	290.5	291.8	293.1	294.4	295.7
260	296.9	298.2	299.5	300.8	302.0	303.2	304.4	305.6	306.9	308.1
270	309.4	310.7	312.0	313.3	314.5	315.8	317.1	318.3	319.6	320.8
280	322.1	323.3	324.6	325.8	327.0	328.2	329.4	330.7		

A stepper motor is mounted to drive the R-dial through a pulley clamped to the R-dial. One step produces 0.05 degree movement to the R-dial. An optical switch to define the zero is mounted under and to the side of the R-dial. Gear lash is taken up by a spring. In operation under computer control, the position of the R-dial is recorded by counting the number of steps sent to the stepper motor and summing with the sign of the direction.

Again, if the unit is used in a semi-automated mode, this step is omitted.

A Keithley 556 Measurement and Control Processor (K556) controls the power supplies for the lamps in the two lamp unit, and for the S4 lamp and the shutter stepper motors. It also controls the PMT voltage, and reads the output voltage and digital state in the fully automated mode. A computer directs the K556 through a IEEE-488 interface. A Compaq Model II computer was used in this system.

An operator of a manual instrument makes a reading by turning the R-dial until an external meter reads zero (the balance point). The electronics of the instrument are designed so at this reading the wavelengths are seen as equal at the PMT. The operator adjusts the PMT voltage until the meter reading is slightly unsteady, which indicates the sensitivity is correct. The actual reading is made after setting the PMT voltage by moving the R-dial back and forth so the needle moves from one side of zero to the other, for about 20 seconds. A clockwork scribe scratches a trace on a waxed chart or smoked disk during the reading. The operator then moves the R-dial back until the scribe is in the center of the trace, and reads the R-dial position against a hairline.

In the automated mode, the system attempted to imitate the human operator. The position of the R-dial relative to the zero on the meter was determined from the digital output from the instrument, and the R-dial was moved in the direction of the zero until the output changed state. The system repeated this until the R-dial was very close to the balance point. While the system monitors the noise level of the output signal, the PMT is adjusted for a certain noise level. The R-dial is then moved slowly back and forth so the output signal moves through zero. At each change of state the position of the R-dial is recorded. After a set number of reversals, the average of the positions is taken as the reading.

4. AUTOMATED OPERATION

In the fully automated mode, the system and operator followed these steps to find a R versus Delta R curve:

1. The lamp unit was centered on the instrument by the operator under the direction of the computer program.

2. The zero position was found and entered into the computer by the operator.

3. By turning the R-dial to various positions, and varying the S4 voltage until the output signal from Dobson was zero, the relationship of R-dial position versus S4 lamp voltage was determined. This was done also under the control of the operator. The X and Y lamps are also adjusted mechanically, and their individual power supplies adjusted, so each lamp has separately equal R-dial readings.

4. The operator would give the computer program a starting and ending point on the R-dial, as well as an increment. The program would drive the system through the measurement, opening and closing shutters, adjusting voltages, moving the R-dial, and making readings. A first guess for the S4 voltage at an R-dial reading on a single lamp was made from the data obtained in step 3, then R-dial was turned to the R-reading. The actual reading for the X lamp would be found as described above. The reading for both (X+Y), and for the Y alone, was found next. If the readings for the X and the Y differed by 0.5 degree or more, the system adjusted the voltage on the bulbs, and repeated the readings and adjustment until they did agree.

The data was displayed and saved on disk. After a run, the operator would view the data plotted on the computer screen, and decide if more points were required to fully define the curve, or if the data was acceptable.

5. DISCUSSION OF RESULTS WITH THE AUTOMATED VERSION

This unit was tried on several instruments with varying degrees of success. The wedge calibration on these instruments had been measured by a highly skilled operator shortly before the automated unit was tried. In each case, the automated unit produced curves similar to the human operator, but each instrument produced new problems. The first version of the unit had lamp power supplies that were adjustable only over a short range of output voltage, moreover were poorly regulated in this application. The results were still encouraging, and new power supplies were bought for further development. After testing on several more Dobson instruments, these problems were evident:

1. The heavy R-dial combined with uneven friction characteristics of the wedge slides made it difficult for the stepper motor always to start and stop without error. The data points produced by the system were not always repeatable. This could be minimized by resetting the R-dial drive to zero more often, but increased the time to obtain a curve. The data was less reliable; requiring more points for a useful curve.

2. The relationship of the S4 voltage to the R-dial position varies with intensity of the Y and X lamps. The process of obtaining

equal X and Y readings changed this relationship. The solution again increased the time required for determining the R versus Delta R curve.

3. Individual Dobson instruments have individual response times (i.e., how quickly the output signal changes when the wedge is moved slightly in the region close to the balance point). This response time is also dependent on the PMT voltage, the intensity of the lamps, and rate of change of wedge density. This could be accounted for in the software, but required selection of parameters after some data had been taken.

4. The mechanical connection between the R-dial and the stepper motor was not perfect. The pulley clamped on to the R-dial would sometimes not be rotating on the axis as the R-dial. This also could be accounted for, but required time with each mounting of the pulley.

5. Measurements below five degrees on the R-dial were not possible due to mechanical constraints. These are important points on the curve; they were taken manually by the operator.

The solutions to these problems were time-consuming; the automated calibration was taking as much time as a manual calibration. The necessary teaching of the software for the individuality of the instrument was complex.

7. SEMI-AUTOMATED OPERATION

A shaft encoder with 0.1 resolution and a counter was added to the system described above. The computer reads the counter through an RS-232 interface. The encoder is mated to the R-dial by a replacement R-dial mounting bolt that passes through the axis of rotation.

The PMT high voltage is controlled by the operator, who makes the measurements manually. The computer controls the S4 lamp, the two lamp unit's shutters, reads the encoder and records the data.

The measurement of the R versus Delta R for a wavelength pair curve with the semi-automated system consists of these steps:

1. At ten degrees R-dial reading, the operator finds the S4 voltage for this position for a single lamp. The operator has control, through the computer, over the opening and closing of the shutters, and the S4 voltage. The two-lamp unit is adjusted mechanically and the voltage on the lamps adjusted until each single bulb produces the same R-dial position.

2. The S4 voltage is increased so the R-dial position for the X or Y bulb is zero. The operator then manually finds the X+Y position. The S4 voltage is then set back to that for the 10 degree R-dial reading.

3. Step one is repeated at R-dial positions 150 and 300. The X and Y readings are checked to verify they are equal.

4. The computer system is given the starting point, the ending point, and the increment on the R-dial.

5. The system sets the S4 voltage for a point, opens the X shutter, and then prompts the operator with an audio signal.

6. The operator starts the measurement. After a short period to allow the operator to find the correct PMT voltage and R-dial position and to start tracking the output signal on the microampmeter, the system reads the encoder ten times. The average is taken as the reading.

7. Step 6 is repeated for the Y and the X+Y reading.

8. The system displays the X, Y, X+Y, R and Delta R for the operator. The operator can inspect and if needed, adjust the two-lamp mechanically to keep the X and Y readings equal. The procedure for this particular S4 voltage can be repeated at the operator's option.

9. Steps 5 through 8 are repeated for the succession of S4 voltages to make the measurements through the interval selected at the increment selected.

After the data has been taken, the operator can display plots of the data on the computer screen to determine if more points are needed to define fully the curve. The data can be quickly edited, and smoothed. Points are rejected based on the X-Y difference, and inspection of the general shape of all three curves. Smoothing is done by inspection also. The edited and smoothed data is used to produce wedge density tables such as the one in Table 1.

8. DISCUSSION OF RESULTS FROM SEMI-AUTOMATED OPERATION

This semi-automated version of the apparatus is quicker than the automated version. Set-up is easier with the process of finding the correct parameters for the computer program minimized. The apparatus is installed on the instrument in about one hour. To find the curve for the three wavelengths subsequently took approximately three hours.

There are several places for improvement in the semi-automated operation. The apparatus is not very portable. The software is not user friendly. Newer computers and control devices would be cheaper and more compact. The two-lamp unit mechanical adjustment arrangement needs improvement. Adding the stepper motor to the encoder version could solve some of the problems with the fully automated version.

9. CONCLUDING REMARKS

The apparatus performs wedge calibrations semi-automatically much quicker than manually, with the result that calibrations can be made more often.

The encoder attachment to the Dobson instrument obviously can be used for normal observations. A computer can be used to prompt an observer through the observations, and collect and store the data for processing. The program could give a calculation of the ozone amount very soon after the observation. The result of this would be more consistent observations.

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