Techniques for monitoring and maintaining the performance of Brewer MkIV spectrophotometers

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Abstract. We present data describing various techniques that operators of Brewer spectrophotometers can use to monitor and maintain the long-term performance of their instrument. The National Ultraviolet Monitoring Center (NUVMC) at the University of Georgia (UGA) operates, under contract from the U.S. Environmental Protection Agency (EPA), 21 Brewer spectrophotometer instruments. Due to the remote location of the instruments, constant monitoring of instrument performance is required to ensure that the instruments' performance does not deteriorate, hence impacting on data collection and quality. These techniques are illustrated with data from the Brewer instruments in the UGA/EPA network.
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1 Introduction

Ground based spectral ultraviolet (UV) radiation measurements and monitoring are necessary to help understand the UV environment at the surface of the earth to which humans and other forms of life are exposed. To understand the complex interactions between terrestrial solar UV, clouds, ozone, aerosols, solar zenith angle, and variation in the sun-earth distance, it is important to have as many sites as possible with calibrated, high resolution, UV measuring equipment.[1] Such spectral UV instrumentation is operational at a series of Northern Hemisphere (NH) and Southern Hemisphere (SH) sites, with the majority located[1–3] in the NH.

The National Ultraviolet Monitoring Center (NUVMC), located at the University of Georgia (UGA) in Athens, Georgia is contracted by the U.S. Environmental Protection Agency (US EPA) to operate and maintain a network of Brewer MkIV spectrophotometers for monitoring spectrally resolved UV throughout the United States. The UGA/EPA Brewer UV monitoring network consists of 21 MkIV Brewers deployed in 14 National Parks and 7 urban sites throughout the United States. The network covers the largest range of latitudes and longitudes of any Brewer network currently in operation in the world. The instruments are located in a variety of environments, ranging from the tundra of Denali National Park, Alaska; the Chihuahua desert of Big Bend National Park, Texas; the Caribbean Island of St John, Virgin Islands; as well as in urban environments of some major U.S. cities.

Understanding and characterizing the long-term performance of instrumentation is an important aspect of any environmental monitoring program. Due to the broad expanse and isolation of the sites in the US EPA/UGA Brewer network, it is critical for NUVMC staff to have a method for determining the long-term performance of the instruments remotely. An analysis procedure has been created to monitor each Brewer's diagnostic results on a monthly basis so that developing problems can be discovered and appropriate action taken before or during the annual site visit performed by NUVMC staff.

During the site visits upkeep is performed on the Brewer instruments by following written standard operating procedures (SOPs) developed at the NUVMC to maintain Brewer data at a high level of quality. This paper analyzes information from six critical diagnostic tests on six selected instruments and highlights corrections to diagnostic drifts as a result of performing the NUVMC maintenance procedures. This work focuses primarily on diagnostics as they relate to the spectrally resolved UV measuring capabilities of the instrument. The EPA network was established solely for UV monitoring and the NUVMC is, therefore, contracted to perform only spectral response calibrations and not ozone intercomparisons on the instruments.

Although this paper is by no means exhaustive in terms of a complete description of maintenance necessary to adequately maintain Brewer MkIV spectrophotometers, it is hoped that Brewer users in the worldwide community will be able to use the information to better understand and maintain the instrument(s) in their networks. Specific SOPs, available from the NUVMC, will be invaluable references for performing the actual checks and adjustments that are referred to in this paper. Furthermore the reader is referred to the Sci-Tec Operator's, acceptance and maintenance or final test record manuals that came with each instrument from the factory.[4] Although for the MkIV instruments these manuals are useful references, they have been found to be quite vague in some aspects and certainly do not contain complete descriptions of techniques and procedures required to fully maintain a Brewer.

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2 Methods

Various diagnostic checks are performed daily by the Brewers and the data is logged to a file corresponding to the specific diagnostic. These files are termed ''average'' or ''avg'' files and are appended to on a daily basis as the instrument collects data in the field. The diagnostics that are addressed in this paper are the standard lamp intensity values (SL), the shutter motor timing values (SH), the spectrometer shutter run/stop ratios (RS), the photomultiplier tube dead times (DT), the ozone calculating ratios (R6), and the micrometer position (MI). Due to an interdependency of some of the diagnostics, the order in which they are analyzed is critical. Specifically the SH should be optimized before the RS or DT can be properly diagnosed. Adjustments made to the instrument to correct the SH, RS, or DT diagnostics will likely cause changes to the SL and R6 values. If the micrometer system is not working properly, as evidenced by the MI results, there will be adverse affects to all of the diagnostics.

The instruments analyzed in this paper were chosen to reflect as many parameters that can affect the long-term performance of the instrument as possible. The primary consideration for long-term performance is the age of the instrument. One of the six instruments presented in this paper was manufactured in 1992 (92-087), one in 1993 (93-101), three in 1994 (94-105, 94-108, 94-109), and one in 1997 (97-147) by Sci-Tec Instruments in Saskatoon, Saskatchewan, Canada.

The second major factor affecting the long-term performance of a Brewer is the environment to which it is exposed. Humidity and temperature variability are the most critical concerns of instrument location. Brewer 92-087 has been located at Raleigh-Durham, North Carolina, in the southeastern region of the United States since October 1992. Brewer 93-101 was located in the southeastern United States until June 1996, at which time it was installed at Boulder, Colorado, at the foothills of the Rocky Mountain range in the central part of the United States. Brewer 94-105 has been located on the mid-Atlantic seaboard in Gaithersburg, Maryland, since July 1994. Brewer 94-108 has been running at the same site in Atlanta, Georgia, since 1996. Prior to 1996 it was in Atlanta but at a different location. Brewer 94-109 was stationed in Bozeman, Montana, before being moved to Albuquerque, New Mexico, in July 1998. Brewer 97-147 has been stationed at a U.S. Coast Guard base on the Strait of Juan de Fuca in Port Angeles, Washington, since June 1997.

Each of the six diagnostics analyzed in this paper are described next.

2.1 *Standard Lamp Intensity*

The Brewer instrument is equipped with an internal 20-W quartz halogen bulb, located in the foreoptics assembly. This bulb is powered via circuitry on an electronic card that is mounted on the card rack inside the instrument. The zenith prism, which focuses directly on the sun during ozone measurements and on the UV port during full-sky spectral scans, is rotated toward the lamp during an SL test routine. Measurements of the lamp intensity are made over several minutes and the data is recorded to the daily D-file. During the end-of-day routine the SL intensity values from each scan are averaged to produce one daily value that is written to the Sloavg file. Although the intensity values are not spectrally resolved, and the day-to-day deviations are too large to use for adjustments to the Brewer's spectral response, the SL data are a useful diagnostic tool for monitoring the relative change in the response of the instrument.

2.2 *Shutter Timing*

The MkIV Brewer is equipped with a movable shutter that enables wavelength selection at the spectrometer exit slits. There are eight shutter positions, five of which correspond to the ozone calculating wavelengths: 306.2, 310.0, 313.5, 316.8, and 320.0 nm. There are also shutter positions for counts at the mercury (Hg) spectral lines during wavelength calibrations and for the dark counts and dead-time tests.

A stepper motor is used to drive the shutter among the various positions. It is important to have the shutter stepper motor timed so that the dark count is minimized while at the same time the signal count is maximized. The shutter timing test is used to find the optimum motor delay by measuring counts from the internal standard lamp at the dark count, the Hg calibration, and the 306.2-nm shutter position in a sequential order of motor timing delays. Unlike the other diagnostic parameters discussed in this paper, the SH test is not performed in the automated Brewer schedule, it is undertaken once per year during the annual UV calibration. The user must give the SH command at the Home screen command line and enter some input parameters. The output results are stored in the daily D-file.

2.3 *Run/Stop Ratios*

The run stop test monitors the operation of the shutter position and the alignment of the spectrometer mirror by taking measurements while the shutter is still and again while it is in motion. The instrument's internal lamp is used as a source. The ratios of the ''run'' to the ''stop'' results for each slit are calculated and the results are written each day to the D-file and to the Rsoavg file during the end-of-day routine.

The ratios for positions 0 and 2 through 6 should fall in the range 1.003 to 0.997, as stated in the Brewer's acceptance manual. It is to be expected that the optical alignment of an instrument will worsen during the time between adjustments due to slight shifts in the mechanical geometry of components. This loss of alignment will be reflected in the run/stop results as the values at one or more of the shutter positions begin to fall outside of the tolerance range.

2.4 *Photomultiplier Dead Times*

The dead-time test measures the minimum time interval between two photon events that can be resolved as individual events by the Brewer's photomultiplier tube (PMT). It is determined from a comparison of the sum of the count rates when two slits are opened individually to the count rate when the two slits are opened simultaneously. If the dead time were zero, these would be the same. However, because the PMT cannot resolve two closely timed events (within the dead time), the count rate with both slits opened will be slightly less. An algorithm is then used to obtain the dead-time value from the difference between these two measurements. This value is a property of the PMT and should be independent of count rate unless there has been some change in the response time of the PMT or counting electronic circuitry. However, as the sensitivity of the PMT decreases, or optical misalignments cause a reduction in the count rate for a given light input signal, the standard deviation in the dead-time measurement will increase. As a result, the average value of the dead time that is calculated may also change, especially as negative dead times are obtained for some individual determinations due to the poor statistics resulting from the low count rates. A complete description of the DT calculation can be found in the *Brewer Operator's Manual*.[5]

During a single DT test the dead time is measured five times with a high transmission neutral density filter (high intensity). The mean and standard deviation of the five counts are calculated. The DT is then measured 10 times with a low transmission neutral density filter (low-intensity DT) and the mean and standard deviation of the 10 counts are calculated. These values are written into the daily D-file produced at the end of the day. For each scan recorded for a day, the average high intensity value and the average low intensity value are written to the Dtoavg file. The Sci-Tec manual indicates that the PMT dead-time values should fall approximately in the range 28 to 40 ns and high- and low-intensity DT means should be within two standard deviations of the low intensity mean.

2.5 *R Ratios*

To calculate the total column ozone, the Brewer measures photon counts at five distinct wavelengths in the UV-B region of the sun spectra once per day. Four different ratios (R-1 through R-4) are calculated using these five ozone wavelength counts and then two higher order ratios (R-5 and R-6) are determined for use in the ozone-calculating algorithm. Although the Brewer's sensitivity may decay over time, the ratio of counts at the five wavelengths should remain constant if there is no wavelength dependent change in the instrument's optics. The 20-W standard lamp is the source used for these tests and is itself subject to wavelength dependent changes as the lamp filament ages. Drifts in the R-5 and R-6 value should remain below 1.5% according to the manufacturers' *Brewer Operator's Manual* (Sci-Tec Operator Manual).

A $NiSO_4$ filter is placed in the optical path during ozone and spectrally resolved UV scans in the wavelength range 286.5 to 325 nm. The filter is sandwiched between two Schott UG-11 filters that are coated with magnesium fluoride. The filter package is mounted on a filter wheel that is housed inside a sealed compartment. The $NiSO_4$ filters are known to be hygroscopic, and if the instrument is not properly sealed from the ambient environment, or if the humidity desiccant packs are not changed regularly, humidity will eventually find its way into the filter. The filter will absorb the humidity and its optical properties will be compromised. Any changes in the filter transmission will directly affect both the ozone measurements and the spectral responsivity of the Brewer in regards to its UV measurements. Most of the wavelength-dependent changes observed via changing R-6 ratios are believed to be manifested in clouding $NiSO_4$ filters due to humidity absorption.

2.6 *Micrometer Position*

The wavelength selection of a Brewer MkIV spectrometer is determined by the position of the shutter and the angle of the diffraction grating that is moved via an automated micrometer. The micrometer is driven by a set of gears that are powered by a stepper motor. As the micrometer rotates, it acts on a lever arm attached to the diffraction grating that enables the instrument to select a particular wavelength incident on the appropriate spectrometer exit slit. The manufacturer's specifications indicate a wavelength precision of 0.005 nm with a stability of 0.01 nm over the operating temperature range for a Brewer MkIV.

To determine the starting position of a UV scan, the Brewer must first successfully complete a mercury line calibration (HG scan). The dispersion constants of the diffraction grating that are stored in the dispersion constants file (DCF) are then used to calculate the position corresponding to the first wavelength in the UV scan, i.e., 286.5 nm. During the UV scan, the instrument rotates the diffraction grating via the micrometer assembly while the shutter is set at position 2, slit 1 (306.2 nm) for the spectral region 286.5 to 325 nm. Shutter position 6, slit 5 (320.0 nm) is used for the spectral region 325.5 to 363 nm, and the micrometer is reset to near the original start position to begin the second half of the scan. The micrometer rotates in incremental steps, causing the diffraction grating to swivel in its mount, allowing for wavelength selection.

Several constants are stored in the ICF pertaining to the operation of the micrometer system. As changes are made to the optical alignment of the instrument or as the components of the micrometer system age, it may be necessary to replace or repair micrometer components and to update some of the ICF constants to ensure the accuracy of the wavelength calibration. In this paper, we omitted the use of the internal mercury bulb as a long-term diagnostic tool, as changes in the lamp output are typically due to lamp aging, not necessarily instrument degradation, as the other diagnostics presented are typically more useful for long-term trends in instrument performance. However, low counts of the internal mercury lamp do not stop the Brewer from using this lamp to ensure wavelength accuracy.

3 Results

Each of the six instruments selected for analysis in this paper has experienced problems with one or more of the listed diagnostics during its history of field operation. In several cases, maintenance was performed either in the field during an annual site visit or in the NUVMC laboratory to bring the instrument back into operating tolerance. For cases where maintenance was performed, the plotted diagnostic results show a significant improvement in the instrument performance.

3.1 *Standard Lamp Intensity*

Analysis of the standard lamp intensity values indicates variability in the response stability of each instrument. There are a number of factors that can contribute to a change in the detected internal lamp intensities. These factors can be divided into random changes and operator changes.

Random changes to the Brewer include temperature-dependence issues, degradation of photon counting effi-

Table 1 Percent change in measured standard lamp intensity (January mean to December mean).

Brewer Number	1996	1997	1998	1999	2000	2001	2002
92-087	NA	−10.9	−6.9	−19.7	−21.5	+9.4	−9.5
93-101	NA	−6.2	−11.0	−10.1	+4.8	+3.9	+13.9
94-105	−2.2	−2.5	−10.4	−13.4	−5.1	+7.5	−25.0
94-108	−2.0	−24.3	−2.2	−8.0	+0.7	+4.5	+0.3
94-109	NA	NA	NA	−2.0	−4.4	−10.6	−13.6
97-147	NA	−0.8	−11.5	−4.9	+0.6	+2.0	+2.5

ciency, and degradation of optics. Each Brewer instrument has a unique wavelength-dependent spectral response on the order of −0.1 to −0.4% change in measured signal for a 1° change in PMT temperature. Also, the lamp controlling circuitry and bulb are not temperature stabilized so there may be drifts in the actual output of the lamp from one scan to the next. The temperature dependence of the instrument's spectral response in conjunction with the lack of temperature stability of the lamp circuitry yields cyclic drifts in the measured lamp intensity values throughout the year. A second random change to the standard lamp measured counts is due to a loss in the efficiency of the PMT and photon-counting circuitry. Another factor that can contribute to a change in measured lamp intensity values is degradation in the Brewer's optics over time. This includes the clouding of filters, accumulation of residue on the prisms and lenses, drifts in the spectrometer mirror alignment, as well as misalignments of the zenith prism.

Operator changes to the detected internal lamp intensities are normally due to maintenance work performed by NUVMC staff during a site visit. If the zenith prism has become misaligned due to operational problems with the instrument, a spectral response measurement is made and a realignment of the instrument's zenith prism is performed. Based on various diagnostic considerations, the PMT high voltage may be optimized during a site visit. Due to the decaying nature of the PMT efficiency, an optimization always corresponds to an increase in the high voltage, which leads to an increase in instrument response and, therefore, an increase in the internal lamp counts.

To quantify the change in the measured lamp intensities over the history of each instrument, the percentage change of the measured counts was calculated for each year using the average counts for all days in January and the average counts of all days in December for that year. In some cases, data did not exist for January or for December. In these cases, the first complete month's data were used as the initial reference and the last complete month's data were used as the end point reference and the result was adjusted for a 12-month period. Table 1 shows the results of this analysis, while Fig. 1 shows plots of the standard lamp counts for the history of each instrument used in this study.

A decrease in instrument sensitivity over time is to be expected as the instruments age. However, there are times when the lamp intensity decreases of the order of 20 to 50% from one day to the next. This is normally the result of a zenith prism misalignment that can occur due to power and communication failures between the Brewer and the controlling computer. The data in Fig. 2 indicates that this problem occurred on instrument 97-147 on July 11, 2001, at which time the lamp counts decreased by 5.7% compared to the counts on July 10. The zenith prism alignment procedure was performed by the local site operator under the direction of NUVMC staff on November 27, 2001, and the lamp count values increased by 8.3% compared to the counts on November 26. The counts have remained stable since the adjustment was performed, as seen in Fig. 2.

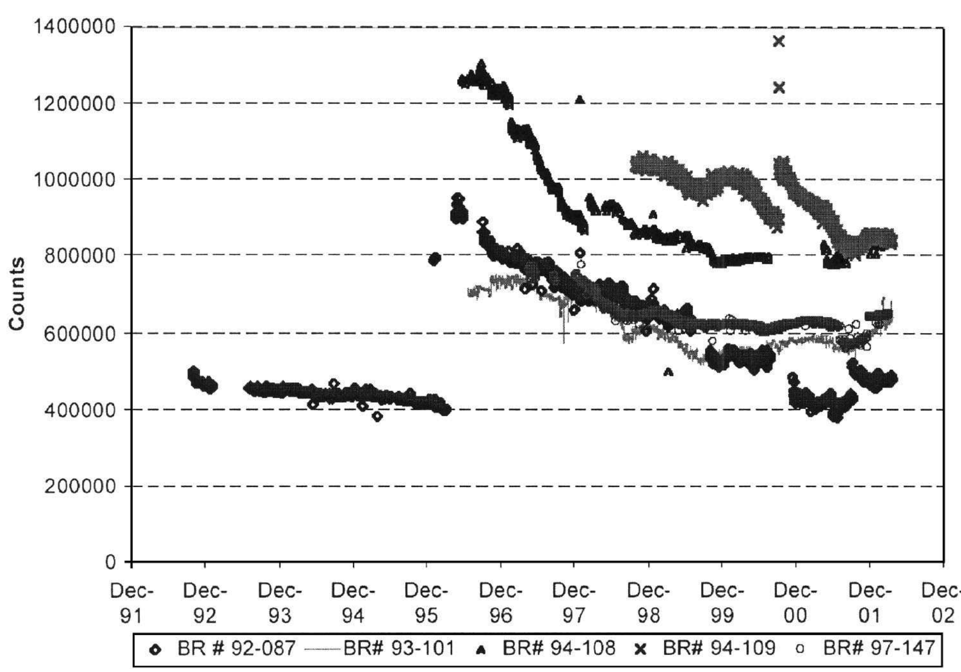

Fig. 1 Change of intensity of internal standard lamp counts for Brewer instruments 92-087, 94-105, 94-109, and 97-147.

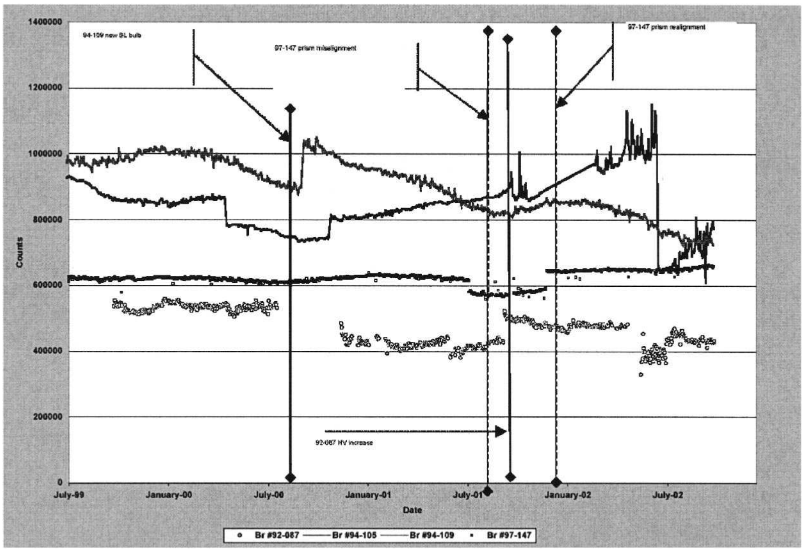

Fig. 2 Standard lamp counts of four Brewers highlighting changes to the instruments.

Another factor that can cause a decrease in the measured lamp intensity is a change to the lamp circuitry that yields a change to the voltage on the lamp. This problem occurred on instrument 94-105 in June 2002, at which time the lamp counts fell by 36.7% from June 15 to June 17. The daily D-files corresponding to those days show that the voltage to the standard lamp fell from 11.83 to 10.86 V. The normal daily fluctuation in the standard lamp voltage is less than one tenth of a volt. In this particular case, the SL bulb was replaced in September 2002, but the lamp voltage remained at approximately 10.8 V. It is assumed that the effect was caused by a change in the lamp circuitry, and it is believed that there are no side effects to the performance of the instrument.

The standard lamp counts may experience a change when an aging lamp bulb is replaced. The data in Fig. 2 for instrument 94-109 show that there was an approximate increase of 16% in the lamp counts from September 10 to September 15, 2000, due to replacement of the bulb by the site operator. When the NUVMC staff increases the high voltage of the PMT during instrument maintenance, a step increase in the measured lamp intensity occurs. This type of behavior is exemplified in the instrument 92-087 data in Fig. 2 in year 2001. The standard lamp counts increased by 22% from September 10 to September 12 due to an increase in the PMT high voltage from 1600 to 1632 V.

3.2 *Shutter Timing*

The shutter-timing test was performed for each instrument at the factory and the optimal timing constant was set in the ICF file. As count rates and various other parameters change within the instrument it is possible for the optimal timing of the shutter motor to drift. The SH test can be performed and new results updated to the ICF before any other adjustments are made to the instrument. The NUVMC performs SH tests as part of the standard site visit procedure. The results of Table 2, which also show timing delays measured several years after the factory calibrations, indicate that there is usually not much drift in the optimum value. Of the six instruments studied only Brewer 92-087 experienced a change to the SH value.

Figure 3 shows plots of motor timing results from the instruments used in this study. Generally the ratio of counts to dark counts is relatively small when the motor timing constant is less than about 60 units or greater than about 100 units. The timing constant is normally selected as the number close to the middle of the plateau and typically is between 70 and 80 units. There is generally a large deviation in the ratio in the range of the plateau due to division of a large signal count by a small dark count value. The plots show that the motor timing constant for Brewer 92-087 changed from its factory setting of 76 to a new value of

Table 2 Instrument run/stop values before and after spectrometer mirror or shutter alignment.

Instrument Number	Julian Date	Shutter Position 0	Shutter Position 1 (dark ratio)	Shutter Position 2	Shutter Position 3	Shutter Position 4	Shutter Position 5	Shutter Position 6	Shutter Position 7
92-087	21000	1.000	1.3	0.9995	0.9980	1.0000	0.9958	0.9977	0.9978
92-087	04101	0.9997	2.1	0.9973	0.9984	1.0001	0.9992	0.9992	0.9991
93-101	18000	1.0000	2.2	0.9980	0.9960	0.9984	0.9935	0.9951	0.9976
93-101	20700	0.9994	3.0	1.0000	0.9990	1.0004	1.0008	0.9997	0.9997
94-108	20500	0.9985	4.5	0.9934	0.9902	0.9927	0.9902	0.9937	0.9931
94-108	20001	1.0001	1.1	0.9997	0.9997	0.9999	0.9996	0.9984	0.9992

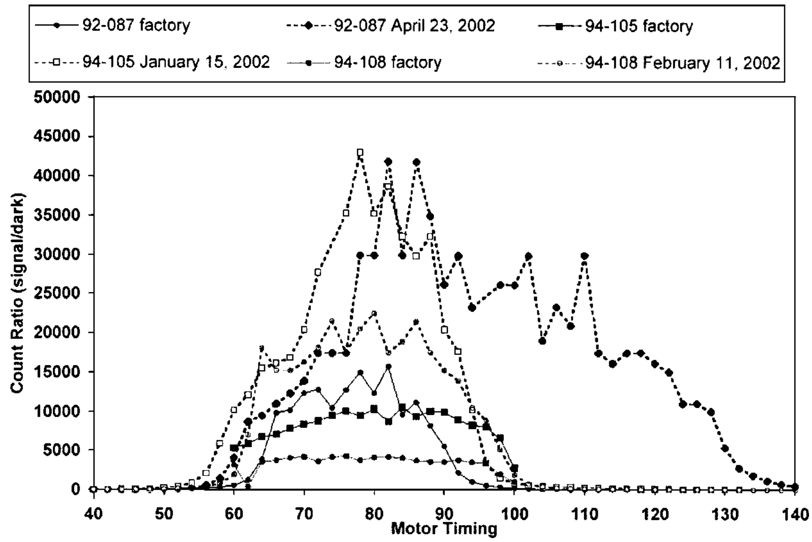

Fig. 3 Shutter timing for Brewers 92-087, 94-105, and 94-108 for factory and postfactory settings.

94 when it was tested in April 2002. The plots for Brewers 94-105 and 94-108 show examples of timing constants that have remained relatively stable.

If the SH constant is updated in the ICF, it could lead to changes in some of the other instrument diagnostics such as the run/stop and dead-time values. Whenever an update to the shutter timing value is required, a reference spectral response calibration is performed by NUVMC staff to be used for data prior to the adjustment, followed by a study of the other diagnostics and instrument adjustments that may be required in response to the change. A final response calibration is always performed after any adjustments are made as a reference for new data after the adjustment.

3.3 *Run/Stop Ratios*

Figure 4 shows plots of the RS values for shutter position 7, slit 5, over the history of instruments 94-105 and 94-108. The horizontal dashed lines indicate the accepted tolerance range of 1.003 to 0.997 units. It is clear that instrument 94-105 has been operating within tolerance range throughout its history, although there has been a slight increase in the deviation of the values in recent years. The data for instrument 94-108 indicates that the RS values were falling below factory tolerance levels in the spring of 1998 through the summer of 2000. At this time, the instrument was moved to UGA, where the standard operating procedure to correct the alignment of the spectrometer mirror and the shutter was performed by NUVMC staff. When the instrument was reinstalled at the site in the summer of 2001, the RS values were within tolerance levels and have remained there up to the fall of 2002 with very little deviation.

The RS values as measured at the factory fall within tolerance levels for all six instruments. Table 2 lists the RS values for instruments 92-087, 93-101, and 94-108 before and after the NUVMC staff performed alignment to the mirror and/or shutter. An initial (before adjustment) and final (after adjustment) spectral response calibration following the NUVMC's standard procedure is always performed

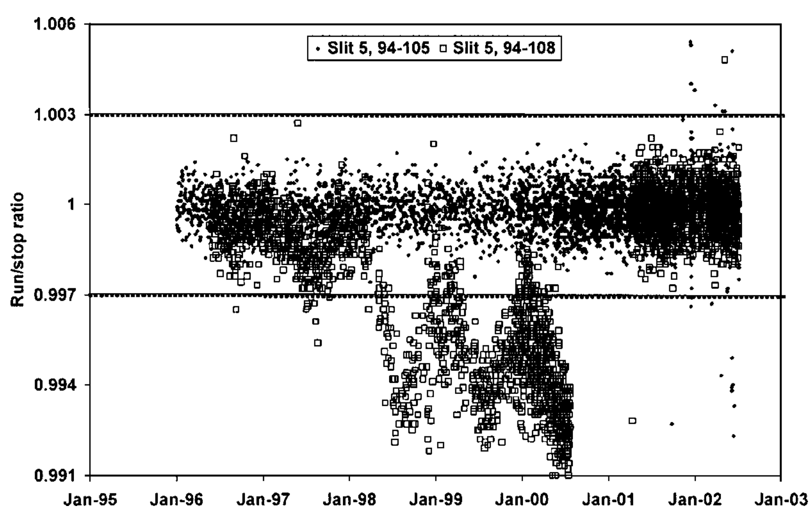

Fig. 4 Run/stop ratios for Brewers 94-105 and 94-108 indicating the maximum acceptable tolerance for these ratios.

Table 3 Dead-time values for annual percentage change.

Brewer Number (Intensity)	1996 Slope	1996 Stdev.	1997 Slope	1997 Stdev.	1998 Slope	1998 Stdev.	1999 Slope	1999 Stdev.	2000 Slope	2000 Stdev.	2001 Slope	2001 Stdev.	2002 Slope	2002 Stdev.
087 (H)	−1.6	0.080	0.1	0.0117	−0.2	0.094	−0.5	0.0117	−1.0	0.0326	1.0	0.0269	0.1	0.0160
087 (L)	−1.2	0.0149	0.16	0.0182	−0.3	0.0226	−0.5	0.0267	−1.8	0.0538	1.1	0.0558	−0.8	0.0454
101 (H)	NA	NA	−0.4	0.0410	−0.2	0.0107	−0.4	0.0150	1.1	0.0195	0.2	0.0086	0.2	0.0111
101 (L)	NA	NA	0.2	0.0582	−0.7	0.0416	−0.8	0.0458	3.4	0.0616	0.2	0.012	0.1	0.0231
105 (H)	−0.5	0.067	0.0	0.0048	−0.1	0.0084	−0.2	0.0055	−0.000	0.0063	0.1	0.093	0.5	0.0086
105 (L)	−0.4	0.0109	−0.0	0.0106	−0.1	0.0300	−0.1	0.0163	0.000	0.0179	0.2	0.0158	0.2	0.0195
108 (H)	−1.3	0.0111	−0.2	0.0074	−0.6	0.0121	−0.6	0.0127	1.0	0.0108	0.000	0.086	0.7	0.0085
108 (L)	−1.6	0.0176	−0.5	0.0172	−0.24	0.0364	−1.2	0.0279	0.1	0.0231	−0.4	0.0214	0.6	0.0195
109 (H)	NA	NA	NA	NA	−3.0	0.0091	−0.3	0.0092	−0.2	0.0115	−0.2	0.0132	0.8	0.0138
109 (L)	NA	NA	NA	NA	−3.5	0.0165	−0.4	0.0183	−0.2	0.0223	−0.3	0.0350	0.8	0.0406
147 (H)	NA	NA	NA	NA	−1.7	0.0234	−0.6	0.0129	−0.1	0.0097	−0.2	0.0101	−0.8	0.0110
147 (L)	NA	NA	NA	NA	−3.1	0.1014	−3.0	0.0871	−0.6	0.0759	−2.1	0.0829	−7.7	0.0835

when adjusting any optical components within the Brewer. Changes in the optical alignment may also have effects on the R ratios as discussed in that section of the paper.

3.4 *Photomultiplier Dead Time*

In general, the dead-time values for all of the instruments show decline in the mean of both the high- and low-intensity values in addition to an increase in the standard deviation of these values. In most cases, the high- and low-intensity values exhibit similar behavior patterns, while in some cases there are distinct differences in the behavior patterns.

To determine the magnitude of change to the photon count rate with a change in the dead time, the DT correction was carried out on typical data [day 21,902 in Athens, Georgia, at ~14:00 Eastern daylight time (EDT), count rate at 360 nm=973,665 counts/s]. When the data were processed using a 40-ns dead time, the percentage change in the measured count rate to the true count rate was 4%. When the data were processed using a 20-ns dead time, the change in the measured count rate to the true count rate was 2%. When the data were processed using a 10-ns dead time, the change in the measured count rate to the true count rate was 1%. The percentage change of the correction will be greater, the greater the count rate. To correct photon count rates for any particular day's UV data, the NUVMC uses the daily average of the high and low intensity DT values for that same day obtained from the Dtoavg file.

To quantify the changes in the PMT dead times, a linear regression was fit to both the high and low values for individual years for each instrument and the standard deviation of the values for each year were calculated. Note that this standard deviation of daily values is different from the standard deviation of the counts for any single dead-time measurement. Both are important checks on the dead-time stability. Table 3 shows the slope of the linear regression fits and the standard deviations of the daily dead-time values for each year for each of the instruments used in this study.

If the dead-time values of an instrument show significant decay after SH and RS adjustments are made, it is normal operating procedure for NUVMC staff to perform a high-voltage check during a site visit to find the optimum operating voltage for the PMT. The results are analyzed and adjustments to the HV are made if it is deemed necessary. This procedure is outlined in the Sci-Tec acceptance manual but a more complete description of the procedure was written by NUVMC staff and it is available as an SOP. Normally when the DT values have decreased by a significant amount it is found, via an HV test, that the PMT is operating below the optimum high voltage setting. When the HV is adjusted upward to the optimum operating value, the DT values normally increase to within tolerance values or near the initial values.

If an adjustment was made to the PMT high voltage during the year, it usually causes a step increase in the dead-time values as well as a decrease in the standard deviation of the mean values. Figure 5 shows the dead-time values for Brewer 92-087 for 2001. During the site visit in September, the PMT voltage was increased from 1600 to 1632 V that increased the high and low dead-time means and significantly reduced the standard deviation of the means. In this particular case, the instrument's spectral response increased by 20% at all wavelengths due to the increase in high voltage.

If it is found from analysis of the run/stop ratios that the Brewer required an optical alignment to the spectrometer mirror or shutter, the procedure is performed by NUVMC staff as discussed in the previous section. The optical alignment generally causes an increase in the dead-time mean values as well as a reduction in the standard deviation of the means. During July 2000 the spectrometer mirror was adjusted to optimize the run/stop diagnostic results on Brewer 93-101 in Boulder. Figure 6 shows the step change in the dead-time values and the decrease in the spread of the values due to this maintenance. In this particular case, the instrument's spectral response increased in a wavelength dependent manner. The average increase in the spectral range 286.5 to 325 nm was 10%, while in the spectral range 325 to 363 nm the response increased by an average of 4% due to the realignment of the shutter and mirror.

Brewer 97-147 has experienced a type of dead-time behavior not seen in any other instruments in the U.S. EPA/

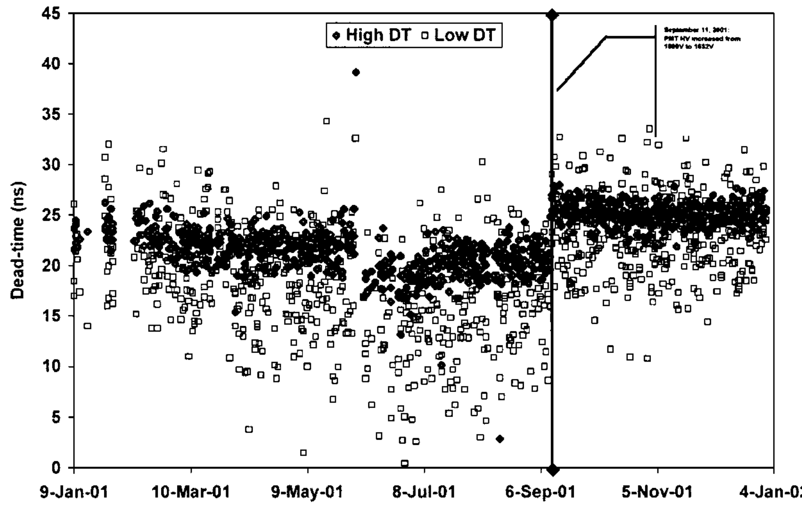

Fig. 5 Low and high dead-time values for Brewer 92-087 during 2001, showing the result of a PMT high-voltage change.

UGA network. This is highlighted in Fig. 7, which shows the DT data for 1998 through July 2002 for that instrument. The low-intensity dead-time values during the cold months exhibit a notable increase as well as a significant increase in their standard deviations. This is thought to result from a temperature dependence or humidity issue within the instrument. However, the spectral response temperature dependence coefficients as calculated by staff at the National Oceanic and Atmospheric Administration (NOAA) are of average magnitude relative to other Brewers in the EPA/UGA network.[6] There has been no significant decay in the transmission of the $NiSO_4$ filter, so it would seem that the humidity has been kept low inside the instrument.

All other diagnostics for instrument 97-147 indicate that the instrument is operating properly, so it is assumed that the unusual dead-time behavior is not necessarily a problem. Note, however, that the dead-time value stored in the ICF will be biased during the time of the year at which the actual dead time is much different from that which is stored in the ICF file. This can lead to errors in the calculated photon counts of the order of several percent under certain circumstances, as discussed earlier in this paper. This error is avoided by the NUVMC by using the daily DT values from the Dtoavg data file during data correction.

3.5 *R Ratios*

The instruments used in this study show much larger drifts in the R-6 values than the ±1.5% suggested by the manufacturer, as evidenced in the data in Fig. 8. The R6 values for instruments 93-108 and 97-147 deviate by ±5% relative to the first 30 days average. For instruments 92-087 and 93-105 the R-6 deviates by ±10% relative to the first 30 days average value, while the deviation for instrument 94-108 is ±20%.

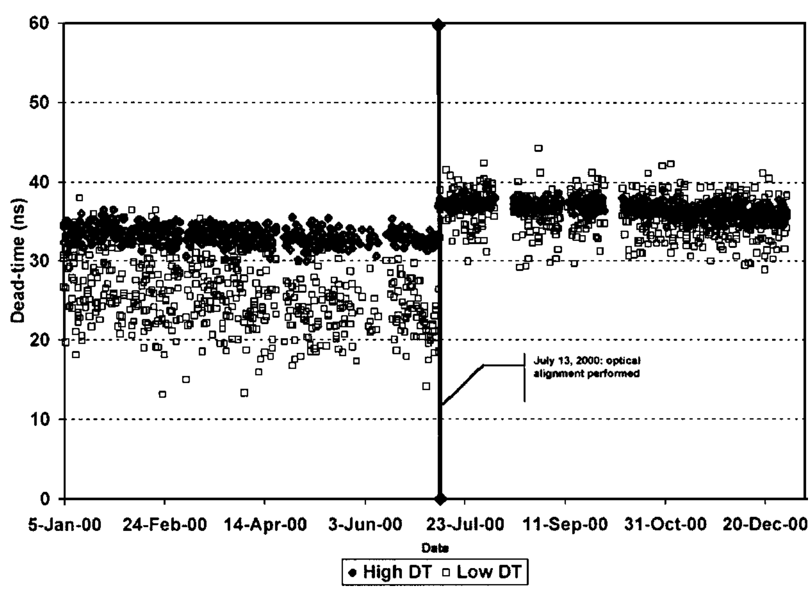

Fig. 6 Low and high dead-time values of Brewer 93-101 for 2000 indicating the impact of an optical realignment.

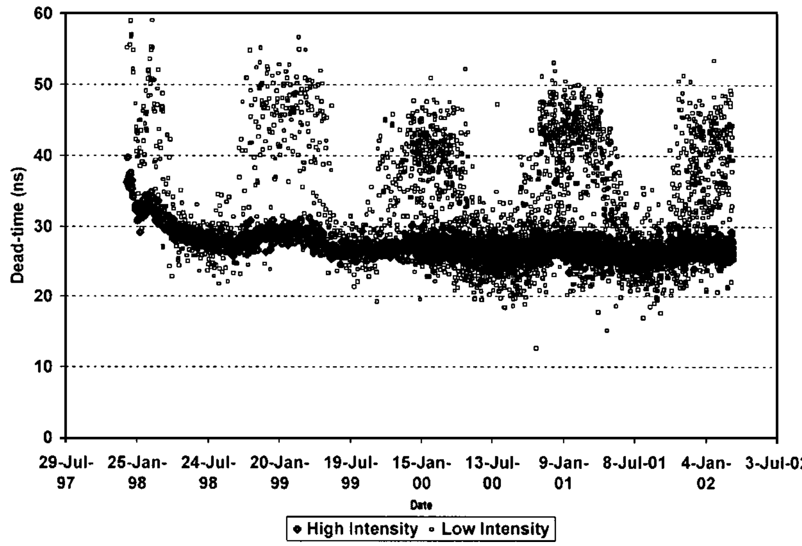

Fig. 7 Low and high dead-time values of Brewer 97-147.

As mentioned previously, changing the alignment of the spectrometer mirror has an effect on the R-6 ratios. A clear example of this effect is seen in Fig. 8 in the data for instrument 93-101 during July 2000 when the spectrometer mirror was adjusted on site by NUVMC staff. The R-6 ratio decreased from 1725 on July 9 to 1396 on July 13.

Figure 9 shows the R-6 values for instrument 94-109. As of July 2002, there has been decay in the values of 250% relative to the 30-day average from September 1998. It seems that the $NiSO_4$ filter has had a wavelength-dependent decay in its transmittance during this time, as evidenced in the spectral response calibrations performed on this instrument over this time period. From May 1998 until March of 2001, there was an average decay of 10% in the filter transmission between 2900A and 3250A (update with new RES info from calibration visit). As the wavelength channels used to calculate the R-6 values change in sensitivity relative to one another, it is to be expected that these changes translate into drifts in the R-6 values.

From the factory the Brewers are equipped with an internal desiccant tube that allows for drying of the air as the air within the instrument contracts and expands due to diurnal temperature fluctuations. The desiccant tube is ported through a hole in the bottom case of the instrument via a flexible rubber hose. Bags of desiccant are kept within the instrument to absorb moisture that collects inside the case. If the tube and bags are not changed as necessary to keep the humidity level below approximately 30% inside the instrument, the $NiSO_4$ filter assembly will absorb the humidity from within the instrument due to its hygroscopic nature. The filter assembly then begins to experience a wavelength-dependent decay in transmission that affects the spectral response and possibly the temperature dependence of the instrument.

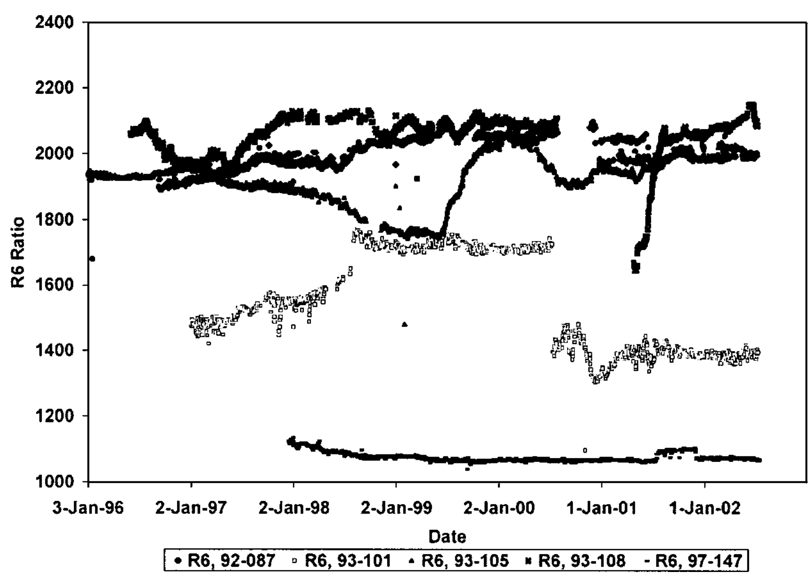

Fig. 8 Long-term R-6 ratios for Brewers 92-087, 93-101, 93-105, 93-108, and 97-147.

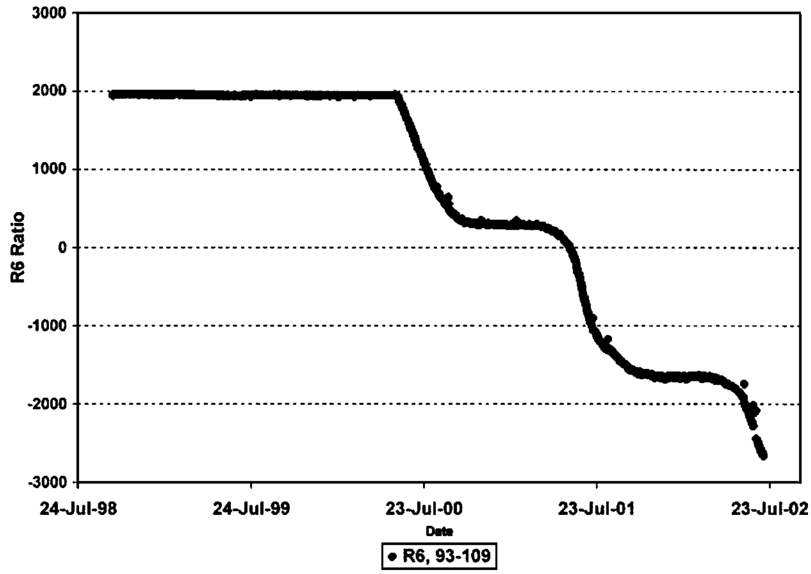

Fig. 9 R-6 ratio for Brewer 94-109.

Once degradation of the $NiSO_4$ filter begins, the only permanent solution is replacement of the filter. The NUVMC has written an SOP for this procedure that includes a before-and-after spectral response calibration. Furthermore, the filters have significant wavelength-dependent temperature dependence in the operating range of the instruments and, therefore, the temperature dependence of the instrument needs to be measured before and after replacement of the filter (reference NUVMC paper). If replacement of the filter is not a viable option, the spectral responsivity calibration can be measured more frequently and a regression line can be fit to the decay to provide a daily responsivity with which to correct the UV spectral data.

3.6 *Micrometer Position*

As the micrometer within an MkIV Brewer spectrophotometer ages, the grease coating on the internal threads begins to break down, causing friction to the micrometer rotation. This condition can eventually cause the micrometer to function erratically due to excessive wear. Erratic micrometer behavior is evidenced in failed Hg calibrations and is usually accompanied by a coating of fine, black dust on the micrometer barrel. A procedure for repairing and replacing the micrometer unit is available from the NUVMC.

The measured micrometer zero position and the corresponding ICF constant number are stored in the Mioavg file. The measured number is the number of stepper motor steps required to move the micrometer from the position at which it performs an HG calibration to the optical switch that is used as a zero reference. The measured value and the constant should match to within about 10 steps. If there is a larger discrepancy the micrometer zero position stored in the ICF should be updated with the new measured value. Figure 10 shows micrometer offset results for instrument 92-087. The constant for this instrument was updated in the ICF from 6684 to 6648 to match the measured offset results in June 2001.

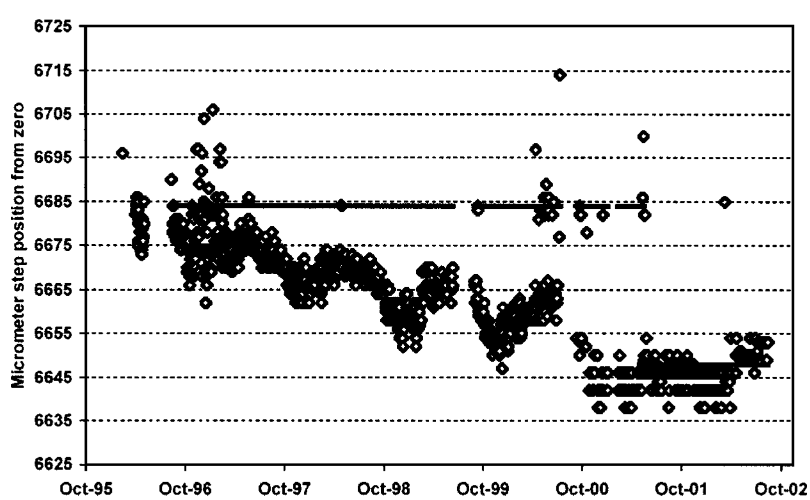

Fig. 10 Micrometer step positions of Brewer 92-087.

Table 4 Diagnostic troubleshooting guide for MkIV Brewer spectrophotometer.

Diagnostic Symptom	Cause of Problem	Adjustment Needed	Comment
Step decrease in SL counts	Misalignment of zenith prism	Zenith prism alignment	Step increase in SL New response calibration required
Step decrease in SL counts	Decrease in standard lamp output	Replacement of standard lamp and/or controlling circuitry	Step increase in SL
Drift in RS values; decay in DT values	Change in SH value	Adjust slit mask motor delay in ICF	May affect RS values May affect DT values
Drift in RS values	Misalignment of spectrometer shutter/mirror	Shutter/mirror alignment	RS within tolerance Increase in DT New response calibration required
Decay in DT values	Decrease in PMT count rate	HV adjustment	Step increase in SL DT within tolerance New response calibration required
Drift in R ratios	Clouding of $NiSO_4$ filter assembly	Replace $NiSO_4$ filter	Change in SL Change in R ratios New response calibration required New temperature-dependence measurement required

When an update is made to the micrometer zero position in the ICF it may be necessary to update the wavelength calibration step number used for the ozone scans. This number is determined by running an SC scan on a clear sky day. As mentioned previously, the U.S. EPA/UGA network is solely concerned with UV measurements, so details of Brewer ozone capabilities are not considered in this paper.

4 Conclusions

Although the Brewer MkIV spectrophotometer is a complicated instrument with many moving parts and sensitive optical equipment, the daily diagnostic results can be monitored to watch for changes that may adversely affect the instrument's performance. The NUVMC creates weekly plots of the diagnostics for each instrument and analyzes them to look for drifts from the manufacturer's suggested tolerance values. Many of the diagnostics are interrelated and they must therefore be looked at together to fully understand what may be occurring within the instrument.

When an instrument is found to have a diagnostic that is out of tolerance values, the appropriate adjustment to the instrument can be carried out. The NUVMC has developed an array of standard operating procedures for the major adjustments and tests that need to be performed in order to maintain a Brewer MkIV. It is important to follow a specific sequence for making adjustments to the instrument as one adjustment to correct a specific diagnostic may affect another diagnostic. Table 4 shows a list of diagnostic symptoms that may occur on a Brewer and the appropriate action that must be taken to correct the underlying cause of the problem. For many of the diagnostic adjustments, it is necessary to perform one before-and-after spectral response calibration. This is always done by NUVMC staff. If the $NiSO_4$ filter is replaced, a new set of temperature-dependence coefficients should be measured since most of the wavelength dependence of the instrument is caused by the filter and each filter has a unique wavelength-dependent temperature response.

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