Novel use of a Bentham UV Double Monochromator for measurements of global and direct irradiance, ozone and aerosol

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Abstract. A novel ultraviolet spectrometer has been developed and tested over 10 years at Lauder, New Zealand. The system, UV2, makes alternating measurements of the global and direct UV irradiance and can therefore be used to measure ozone and aerosol optical depth. After an analysis of the stability of UV2, these measurements, along with UV irradiance are compared to relevant observations made by an additional UV spectrometer (UV4), a Dobson spectrophotometer (#72) and

10   two radiometers measuring aerosol optical depth, a Prede skyradiometer and a Middleton Solar radiometer (SP02). UV2 irradiance is shown to be lower than UV4 by between 2.5-3.5%, with a standard deviation of a similar magnitude. Total column ozone values are shown to agree with Dobson values with a mean bias of 2.57 Dobson units (DU) and standard deviation of 1.15 DU when using the direct sun measurements. Aerosol optical depth at 400-412nm and 500nm agrees to within 0.015 and is comparable to the difference between the reference radiometers. Further work is needed, particularly in

15   the radiometric calibration at longer wavelengths, in order to determine if this instrument can supersede or enhance measurements made by the Dobson or the aerosol radiometers.

1 Introduction

Soon after anthropogenically induced threats to the ozone layer first manifested themselves with the formation of the Antarctic ozone hole in the 1980s, a measurement programme was initiated at Lauder, New Zealand (45°S, 170°E, alt 370

20   m) to measure the spectral distribution of UV irradiance at the surface. The aims of the programme were to characterise and understand its variability, and to monitor changes due to ozone depletion. Double monochromator systems were developed to measure the global spectral irradiance incident on a horizontal surface over the wavelength range from 290 to 450 nm to an accuracy of +/-5%. An early use of the data showed the inverse relationship between ozone and UV (McKenzie et al., 1991). Shortly afterwards the data showed that peak irradiances were unexpectedly greater than at similar latitudes in Europe

25   (Seckmeyer & McKenzie, 1992). Before the end of the same decade, the time series showed the increases in peak summertime UV at Lauder over the 1990s due to ozone depletion (McKenzie et al., 1999). The measurement systems as developed met the demanding criteria of the Network for the Detection of Stratospheric Change (NDSC, later NDACC). With continued refinement including extended range (to 285 nm), better analog-to-digital conversion, custom diffuser, fibre-optic coupling, and containerisation with integrated calibration, instruments were deployed at several other clean air sites

30   around the world. These spectrometer systems have since been used to quantify the effects of volcanic aerosols (Zeng et al.,

1994), surface albedo (McKenzie et al., 1996; McKenzie et al., 1998), altitude (McKenzie et al., 2001) and air pollution (McKenzie et al., 1994; McKenzie et al., 2008) on surface UV irradiance. They've also been used to find the relationship between irradiance and actinic flux (Hofzumahaus et al., 2004; McKenzie et al., 2002) in validation of satellite data (Tanskanen et al., 2007) and studies of vitamin D exposure (McKenzie et al., 2009), though the input geometry is not well

35 suited to that task. A recent publication showed the effectiveness of the Montreal Protocol in curbing increases in UV due to ozone depletion at these sites and others since the turn of the century (McKenzie et al., 2019). Most recently, the decades of data from all the NDACC sites with these spectrometers have revisited the 1991 theme in closely characterising the relationship of UV irradiance to column ozone (McKenzie et al., 2022).

40 Over recent years, the focus of UV research at Lauder has broadened. Previously, it was to understand the effects of ozone depletion. Our new foci include understanding effects of other factors, in particular the effects of clouds and aerosols, which are likely subject to future changes, particularly in the event of possible climate interventions that would involve aerosol seeding of the upper atmosphere. We want to be able to quantify their effects on UV doses relevant to skin damage and to vitamin D production (i.e., both negative and positive health outcomes), and the effects on energy balance and climate

45 change.

With those broader aims in mind, we developed a new instrument with two new capabilities: Firstly, the ability to measure irradiances over the wider wavelength range from 285 to 600 nm (to be supplemented with diode array spectrographs measurements for longer wavelengths extending into the IR region), and secondly to be able to measure direct radiance as

50 well as global irradiances on a horizontal surface.

Critically, any new developments need to retain the quality and heritage of the previous generation of instruments. Here we demonstrate the capability of the new instrument, using data collected over several years of operation at Lauder. We describe this instrument in section 2 and the reference instruments in section 3. In section 4 we assess the instrument's performance

55 over time with comparisons to stability and calibration lamps, and this is supported in section 5 where we show comparisons of the measured global UV. In section 6 we assess the ozone products derived from global and direct irradiances to those from a Dobson spectrophotometer. Lastly, we study measurements of the aerosol optical depth (AOD) from the direct irradiance (7) before summarising our findings in section 8.

2 NIWA UV2 Spectrometer

60 This paper focuses on the use of the "NIWA" Bentham double monochromator system named UV2. This is a standard NIWA UV system (Bernhard et al., 2008; Tanskanen et al., 2007; Wuttke et al., 2006) except that the long wavelength limit is extended from 450 to 600 nm, and it also incorporates two entrance ports instead of one. The standard port is connected

via fibre-optic to a shaped PTFE diffuser designed to measured cosine weighted global irradiances, and the other port receives from a fibre-optic connected to a telescope mounted on a solar tracker. By using a motor-driven folding mirror,

65 UV2 alternates between the two sources. This is a novel approach which provides the global, direct, and therefore the diffuse, irradiance and is completely automated.

In line with our previous sampling strategy, the instrument is programmed to acquire global irradiance spectra at 15-minute intervals over the midday period, and at 5-degree steps in solar zenith angle (SZA) for SZA <=95 outside the 2 hours closest to solar noon. These are interleaved with measurements of direct beam irradiances. From the resulting irradiance spectra.

70 which have a resolution of 0.65 nm (oversampled to 0.2 nm), several useful integrated quantities are calculated. In this paper we principally use UVA and UVB irradiances which represent integrals over the wavelength ranges 315-400 nm and 280-315nm, respectively. We also integrate the spectrum above 400 nm for performance assessment.

3 Auxiliary Instrumentation

For direct comparison we use the collocated NIWA UV4 spectrometer, which is based on an Acton double monochromator

75 and is the primary global UV irradiance measurement at Lauder (NDACC, (Wuttke et al., 2006). The global diffuser used by UV4 is a commercial Schreder heated diffuser. As a reference for ozone, we make use of the Dobson #072 spectrophotometer, which measures direct sun total column ozone (TCO). Dobson #072 is a NOAA instrument that has been operating at Lauder since 1986. Its zenith-sky measurements have been automated enabling regular Umkehr profile measurements. Only direct sun TCO are used in this study to enable like-for-like comparison. Dobson #072's processed

80 data are submitted regularly to NDACC and WOUDC.

Lauder is, and has been since 1998, part of the Baseline Surface Radiation Network (BSRN, https://bsrn.awi.de/). As a component of the BSRN instrumentation, it hosts a 4 channel Middleton Solar SP02 radiometer mounted on an active solar tracker (Liley & Forgan, 2009). The system provides AOD observations calibrated by the Langley method at 412, 500, 610,

85 778nm as well as the tracking wavelength of 867nm. This dataset has been filtered for periods of unobscured sun and for solar zenith angles less than 85 degrees (Alexandrov et al., 2004). Liley and Forgan also note that the AOD at Lauder is some of the lowest in the world which presents a significant challenge to the accuracy of the spectral calibration. In this study, we use the AOD at 412 and 500nm, the latter of which is corrected for Ozone.

90 Aerosol observations at Lauder are also made using a Prede Skyradiometer providing measurements of aerosol optical depths (AOD), aerosol single scattering albedo (SSA) and the aerosol Ångström exponent (alpha). The Prede POM-02 Skyradiometer is an active sun-tracking radiometer with 11 wavebands from 340 nm to 2200nm. It has been operating at the Lauder site since 2011 as part of the SKYNET aerosol network, and it is used in ground-based validation by NIES of GOSAT data products. At regular intervals the instrument breaks from sun tracking to scan the sky in steps from the horizon

95 to the zenith and an almucantar from the solar azimuth through due north, plus less frequent gridded scans across the solar disk. The direct sun measurements are used to calculate AOD, SSA, and alpha, according to standard SKYNET protocols, at the Centre for Environmental Remote Sensing (CEReS), Chiba University (Japan) and are available from http://atmos3.cr.chiba-u.jp/skynet/lauder/lauder.html.

100 4 Stability and Calibration

The medium-term stability of UV2 is assessed by monthly spectral measurements of a 45W quartz-halogen lamp, with measurements being made in two modes: a constant lamp current mode and a constant intensity mode where a UVA diode is used in a feedback loop. These allow us to assess the radiometric stability of both the lamp and the spectrometer. Measurements are also undertaken using a low-pressure mercury lamp to monitor the stability of the line shape and 105 wavelength alignment.

Primary irradiance calibrations are made using an independently calibrated 1000W Quartz Tungsten Halogen Lamp (QTH), typically at 6-month intervals. These calibrations allow the voltage response of the detectors to irradiance to be characterised as a function of wavelength. The calibrations are then applied by a time-weighted mean to real observations. Unfortunately, for budgetary reasons, during the first 5 years of operation these calibrations were much less frequent (only 2 or 3 over that 110 5-year period). Fortunately, the programme of stability measurements was continued so that a record of performance was maintained. However, no corrective actions were taken.

Figure 1 shows the change in the measured UVB, UVA, and the integral for wavelengths over 400nm for the global and direct diffusers using the 45W lamp in constant intensity mode. The data shown are processed assuming a fixed calibration 115 (orange) to highlight instrumental drift, and then with the time-weighted mean calibration (blue) to show the real irradiances.
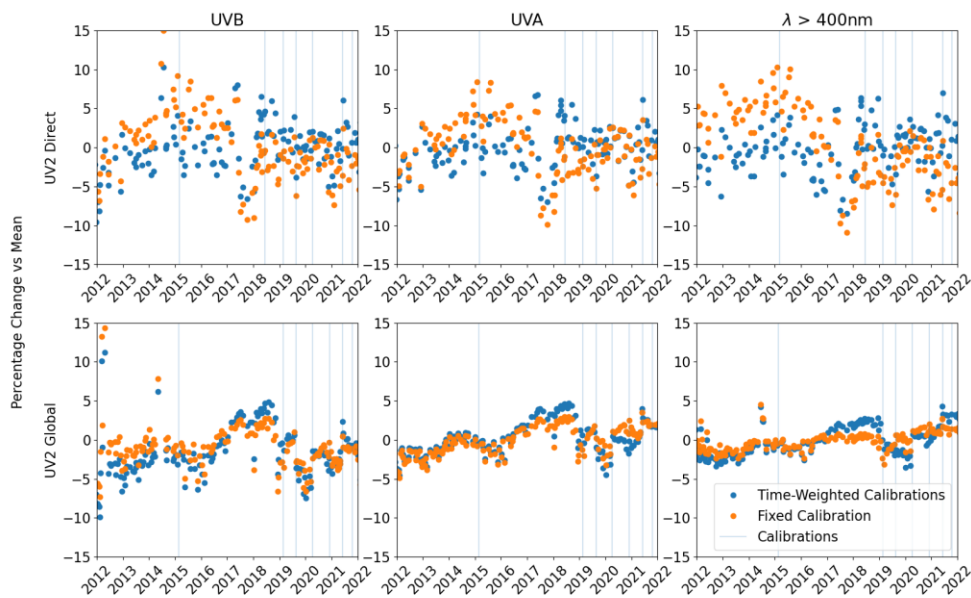
Figure 1: Constant intensity stability measurements for global and direct in the UVB, UVA and for wavelengths greater than 400nm. Results using a time weighted mean of 1000 W calibrations are shown in blue, and fixed calibration, where the original voltage response is used, in orange. Blue lines indicate when 1000 W calibrations were available and used in the time weighted mean.

For the direct measurements (upper panels), across the three bands, the instrument remained within 5% of the mean value over the entire period, albeit with a high degree of noise. There is also a clear feature in 2017 where the observed irradiance dropped before returning to normal. The trend through time is consistent across the wavelength regions, indicating that the variability is principally due to a changing throughput, with little spectral dependence. This change is therefore likely caused by a change in the instrument throughput from a shift in the fibre position. As expected, using the varying sensitivity reduces the magnitude of the differences from the mean compared to the fixed sensitivity case; the 1000W calibrations have, in part, corrected the instrumental drift. Due to the lack of calibrations before 2018, the 2017 discrepancy cannot be objectively corrected.

Results for the global diffuser are shown in the lower panels of Figure 1. Again, across all bands the instrument is stable to within 5%, and within 3% outside the UVB region. The 2017 feature is not present in the global irradiances, providing further evidence that it was caused by the direct fibre throughput. The results exhibit far less noise than in the direct beam irradiances, which shows that the global stability measurements are far more repeatable and therefore unlikely to suffer from the fibre coupling issues that beset the direct observations. There is a discernible drift in the instrument between 2017 and

2019, but it remains within 3%. There also appears to be a minor spectral dependence, with the UVB and longer wavelengths

140   both showing more variability and higher differences than UVA between the two measurement modes (time-weighted and

fixed calibrations). The lack of difference between the varying and fixed sensitivity results, for the UVA at least, shows that

the calibrated sensitivity has not changed significantly, hinting that the variations observed over time are potentially from the

variations in the 45 W lamp apparatus. These changes could include filament deposition or erosion, feedback diode position,

and performance changes.

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The mercury lamp measurements are used to determine the wavelength alignment of the spectrometer over time, which is

then incorporated into the data processing. As a consistency check, we also determine the stability of the observed

instrument line shape. For selected mercury lines, we fit a Gaussian function using a window of 5nm. A relative shift in the

line position is then calculated, with the 296.73nm line as a reference. The result of this analysis is shown in Figure 2.

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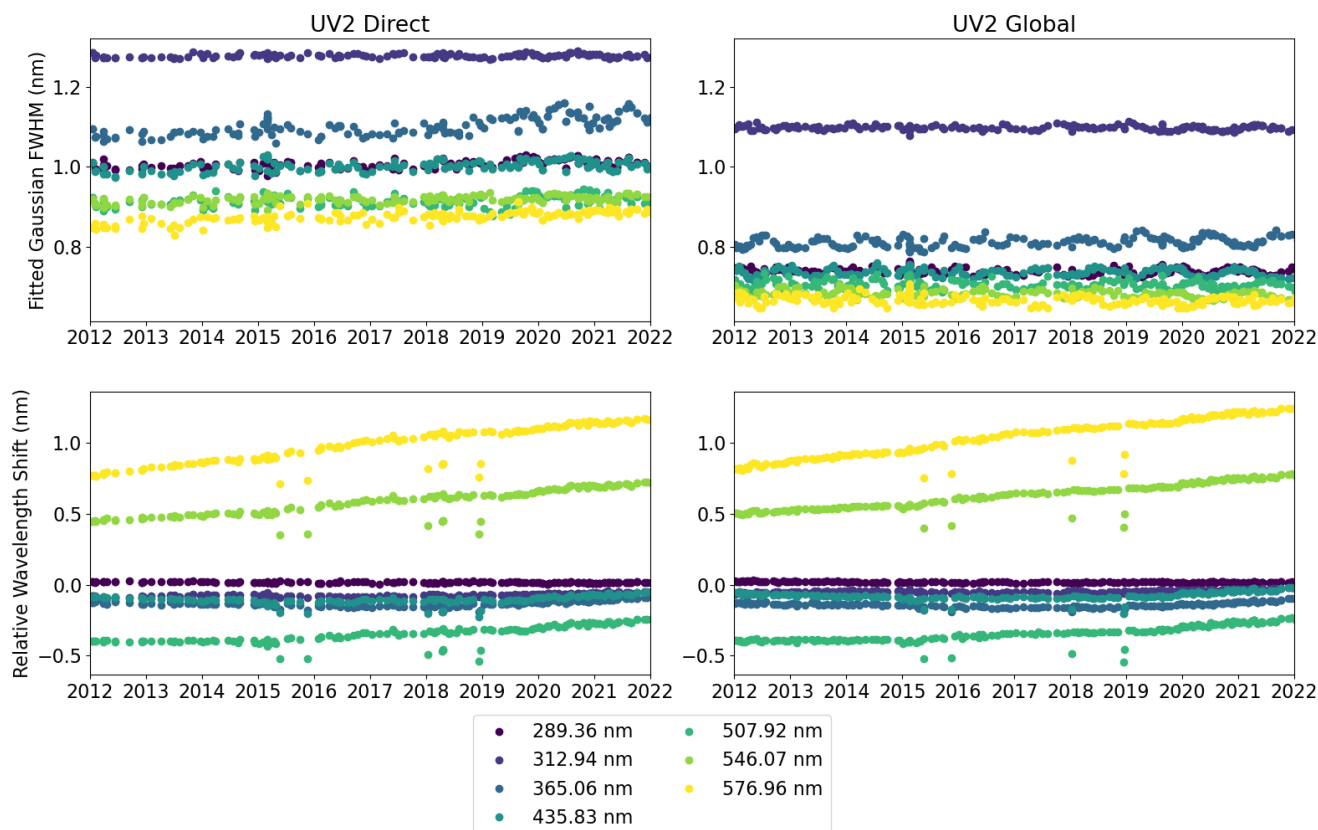
Figure 2: Fitted gaussian FWHM and wavelength shift relative to the mercury line at 296.73m for the direct and global

measurements.

155   The anomalously broader linewidth for the 312.94 'line' arises because it is actually a composite of several unresolved lines. The line near 365 nm is also a doublet. For the direct and global measurements, the full width at half maximum (FWHM) of the fitted slit function is consistent over time for all wavelengths. The direct FWHMs are larger than for the global, indicating a larger apparent effective entrance-slit width for the direct, caused by the lack of a diffuser in the spectrometer entrance aperture for the direct. Drift in the wavelength shift is observed and it is consistent between the global and direct.

160   This shows that there is no spectral dependence caused by the difference in apertures. The wavelength shift plots also highlight the non-linearity of the instrument. The wavelength shift is increasing with time, particularly for the longer wavelengths, indicating that the monochromator drive system is wearing. However, this is corrected for in real observations by applying a time weighted average of the observed shifts.

165   In summary, the instrument has performed well in its 10 years of operation. For the global observations, we can confidently estimate a radiometric accuracy of better than 5% throughout. For the direct measurements, while the majority of measurements are within 5%, there is additional noise caused by varying throughput and a period of a significantly reduced throughput in 2017 which could cause misleading results. However, these changes appear to affect all wavelengths similarly, meaning that outputs like ozone, which depend on the ratios between wavelengths rather than absolute values, should be

170   unaffected. The wavelength alignment and line shape stability has been excellent throughout, with only the expected ageing of the drive system causing any changes. Such changes are captured and incorporated into the spectra processing algorithm.

5 UV Irradiances

To assess instrumental performance for measurement of the irradiance we compare the UVA and UVB irradiances between UV4 and UV2, shown in Figure 3. UV2 and UV4 have simultaneous measurements with the global diffusers so that the data

175   points shown should correspond in time. Data points are additionally screened for cloud conditions. Only cases where UVA transmittance is greater than 0.3 are considered, avoiding cloud contamination. Additionally, cases where the standard deviation of the diffuser diode divided by the mean diode is greater than 0.01 are ignored. Such cases are likely to be partially cloud affected.

180   The agreement between the two instruments is good, with UV2 biased low by 2.4% in the UVB and 3.3% in UVA. The standard deviation of the percentage differences is higher for UVB (5.61% compared to 4.2%), where the signal to noise ratio of the spectrometer is lower. There is a clear seasonality to the differences, with negative differences during summer and positive during winter, suggesting either a solar zenith angle or temperature dependence which needs to be further investigated. This could likely be linked to the temperature dependence of PTFE diffusers used in measurements of UV

185   irradiance (McKenzie et al., 2005), particularly as the UV4 diffuser is heated and UV2 unheated, but monitored and corrected (McKenzie et al., 2005).
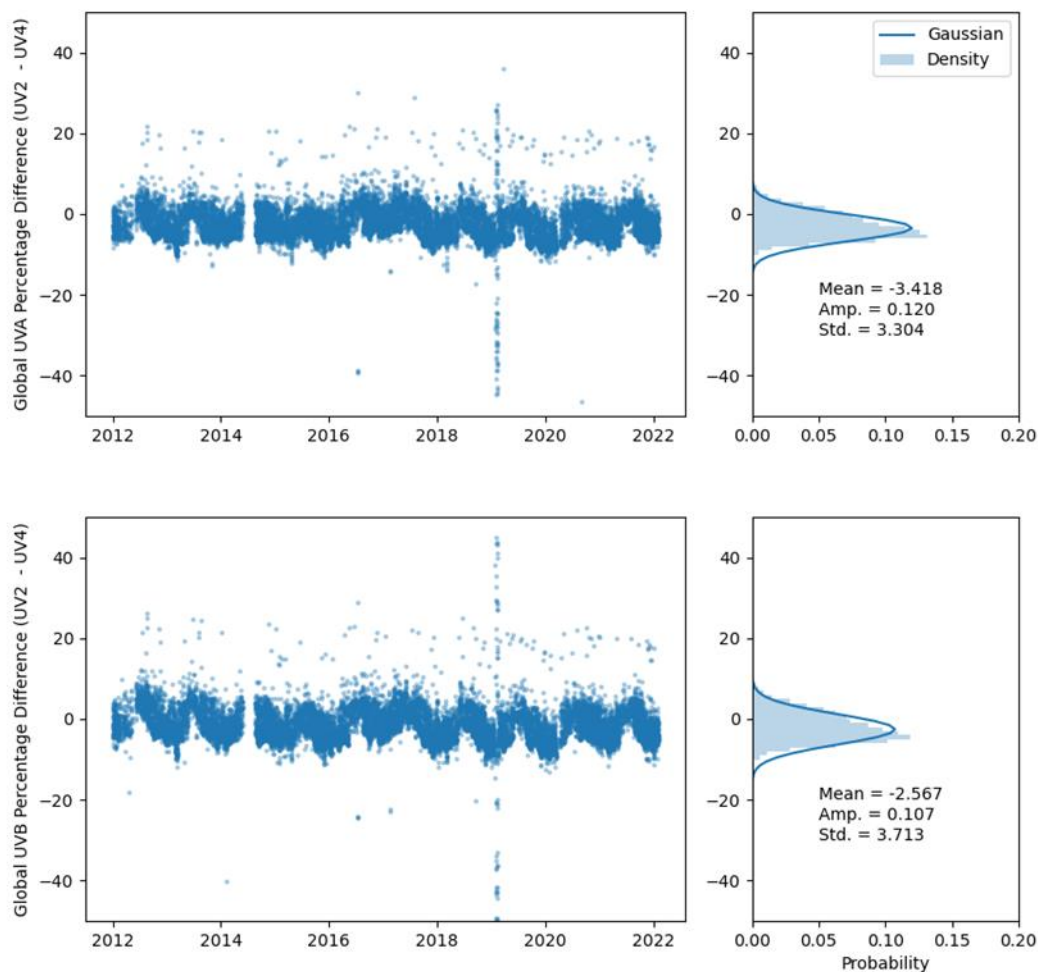
Figure 3: Comparison of the global irradiance measurements of UVA and UVB from UV4 and UV2. Panels on the left show

190   the percentage differences between the instruments with the probability density function shown on the right, with a fitted

gaussian and the relevant parameters.

While there is no directly comparable UV comparison available for the direct measurements from UV2, the good agreement

195   between the global measurements of UV4 and UV2, coupled with the results of the stability measurements, gives sufficient

confidence to the time series and will be further tested by the ozone and aerosol retrievals.

6 Ozone

For the direct sun measurements of Ozone by UV2 we use the same approach as in retrievals from Dobson spectrometer,
200   which is an application of Beer's Law. The ozone layer thickness is calculated by comparing the intensity of UV radiation at
strong and weakly absorbing wavelengths. In the case of the Dobson, a variable attenuator is used to measure the ratio of the
intensities at two wavelengths.

For UV2, the ratio of the intensities is taken from the measured UV spectrum. To remove any wavelength dependencies
205   introduced by unknown aerosol extinctions, two pairs of wavelengths are used with the resulting formula for wavelengths
pairs i and j for total column ozone, X, being;

$$X_{ij} = \frac{(N_i - N_j) - [(\beta - \beta')_i - (\beta - \beta')_j]\frac{mp}{p_0}}{[(\alpha - \alpha')_i - (\alpha - \alpha')_j]\mu}$$

210   Where;

$$N = \log_{10}\left(\frac{I_0}{I'_0}\right) - \log_{10}\left(\frac{I}{I'}\right)$$

For the wavelengths pairs i and j, with I and I' being the measured intensity at the ground at the short and long wavelengths
215   respectively of the wavelength pair. I0 and I0' are the intensities of the two wavelengths but for the solar radiation outside of
the atmosphere. The ozone absorption coefficient (αij) and Rayleigh scattering coefficient (βij), respectively, for the i and j
pairs. The airmass factor (m) is the ratio of the actual and vertical paths of the solar radiation and μ is the ratio of the actual
and vertical paths of the solar radiation through the ozone layer assuming an ozone layer altitude of 22 km and site altitude
of 0.370 km. The mean station pressure (p) is 970mb and the mean surface pressure, p0 is 1013 mb. The wavelengths pairs
220   used at Lauder are the AD pairs and the CD pairs, the CD pair applying when μ is greater than 3.0.

Wavelength Pair	Wavelengths (nm)	$\alpha - \alpha', [(atm - cm)^{-1}]$	$\beta - \beta', [atm^{-1}]$
A	305.5 – 325.0	1.806	0.114
C	311.5 – 332.4	0.833	0.109
D	317.5 – 339.9	0.374	0.104
AD		1.401	0.0049
CD		0.467	0.0071

Table 1: α and β values for the individual wavelength pairs along with the combined values (i.e $(\alpha - \alpha')_i - (\alpha - \alpha')_j$) for the AD and CD pairs used in this study.

225 The ozone absorption coefficients used for UV2 are the same as those given in (Komhyr, 1980) and the Dobson slit functions, parameterised as trapezoids (Komhyr, 1980) are also applied to the UV2 Spectra to ensure consistency between the two instruments. This means that the UV2 retrievals of ozone will still be susceptible to the known stratospheric temperature issues, as is the case for normal Dobson retrievals (Bernhard et al., 2005; Brinksma et al., 2000; Komhyr, 1993; Van Roozendael et al., 1998). In short, the Dobson method assumes an ozone cross section at a fixed temperature (229K)

230 whereas the stratospheric temperature varies throughout the year, which can potentially introduce a false seasonality to observations. In terms of validating UV2's performance however, if we are consistent in the assumptions made, an intercomparison is possible, and given the Dobson's high degree of traceability and heritage, is an appropriate path to take.

Ozone can also be calculated using the global irradiances from the UV spectrometers from the ratio of 305 to 340 nm

235 irradiance (Stamnes et al., 1991). In this method, a table of ratios as a function of SZA and ozone is precomputed using the TUV radiative transfer model (Madronich & Flocke, 1998) and measured ratios are compared to find the best matching ozone value with those ratios. A limitation of the method is that it typically assumes a fixed surface albedo and aerosol load. Departures from those can lead to systematic errors.

240 **6.1 Results**

Here we compare the times series of the direct Dobson, UV4 (global) and the global and direct observations from UV2 which are filtered using the same criteria as in Section 6. The average of these measurements are found for observations within +- ± 15 minutes of all direct sun Dobson measurements. The resulting differences are shown in Figure 4.
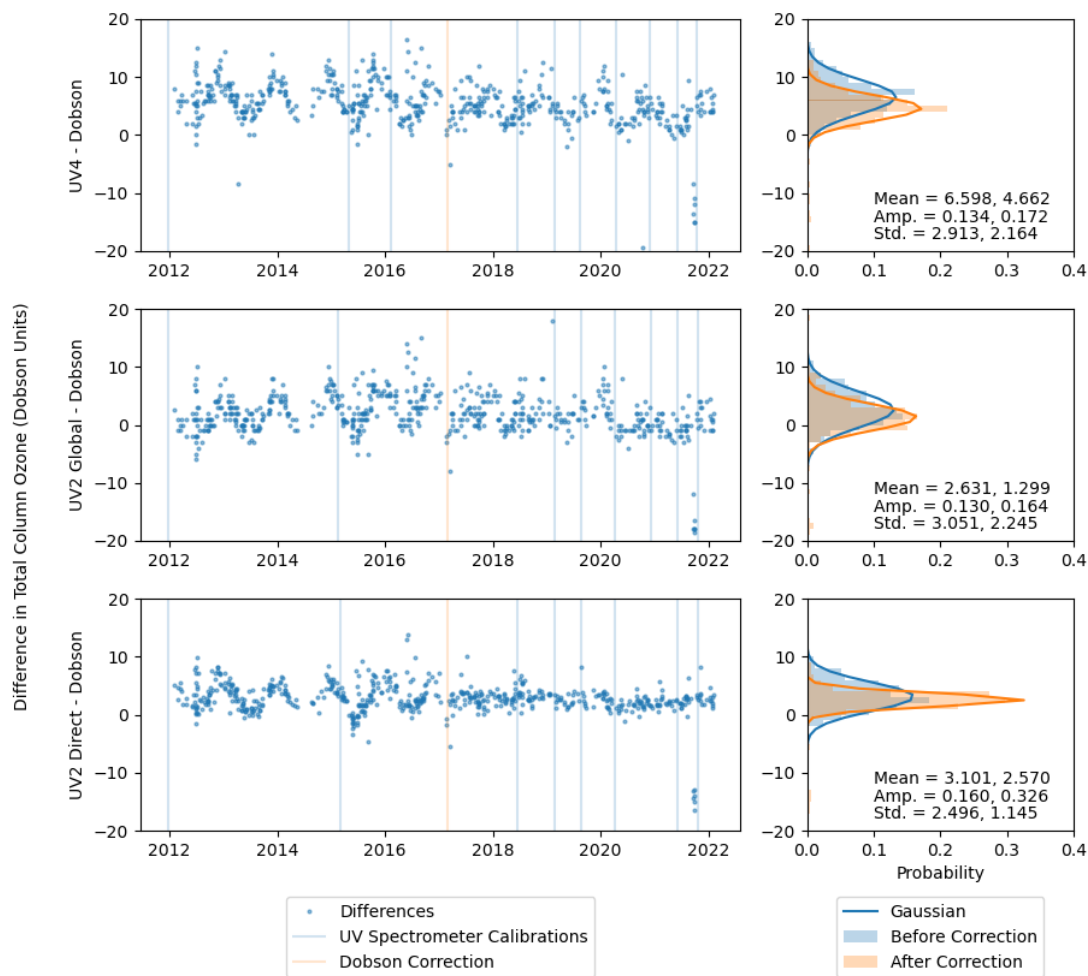
Figure 4: Differences with respect to the Dobson in total column ozone for UV4 and both UV2 measurements. Calibration dates of the UV spectrometers are shown by blue lines and the Dobson intercomparison corrections in orange. The panels on the right show the distribution of differences before the Dobson was corrected (blue) and after (orange) along with the mean, median and standard deviation of the fitted Gaussian respectively.

As can be seen, there is significant variation for all instruments prior to 2017, indicating a seasonal variation in the Dobson data. In February of 2017, the Dobson was compared with the regional standard and correction factors were applied, thereafter the comparisons improve significantly. The two global measurements, which utilise lookup tables, perform well, with a mean bias of 4.7 and 1.3 Dobson Units (DU) for UV4 and UV2 respectively, both with a standard deviation of

approximately 2.2 DU. As expected, the UV2 direct observations are excellent, while there is a modest mean bias of 2.6 DU, the standard deviation has improved to less than 1.2 DU. The Dobson method used by UV2 direct does not rely on the radiometric calibrations and therefore does not suffer from the lack of calibrations discussed earlier. This can be seen for the period prior to the mid 2018 calibration and after the Dobson intercomparison in early 2017, where the differences are
260   consistent with 2018 onwards.

Consistent agreement with Dobson values to within its the measurement uncertainties suggests that the spectrometer system could eventually supersede the need to maintain measurements with the Dobson system. This would have huge implications for lowering operational costs and improving data frequency.

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7 Aerosol

Aerosol optical depth is also calculated using Beer's Law with direct sun observations. A bottom-of the-atmosphere reference spectrum is computed using TUV with zero aerosol and a fixed ozone amount of 300 D.U for each direct sun measurement of UV2. The fixed ozone amount is so that it compares directly with the Prede Sky radiometer. By combining
270   the observed spectra, converted to a horizontal surface, we can deduce the extinction due to aerosol alone. Multiple scattering is ignored as for the direct beam it is a negligible effect. This was done for the AOD bands of the Sky radiometer and SP02 (400nm, 412nm and 500nm).

7.1 Results

275   Observations of aerosol optical depth by Prede and SP02, both at 1-minute intervals, were interpolated to the times of observations by UV2; the mean of AOD observations within += 15 minutes of a UV2 measurement. The SP02 AOD algorithm, from the Australian Bureau of Meteorology, inherently filters out cloud-obstructed data, and by restricting to these times we have screened for clouds across all datasets. Similarly, the preliminary dataset provided by CEReS has also been cloud filtered. The UV2 direct observations are filtered in the same way as for ozone observations. The aerosol optical
280   depth was then calculated for wavelengths of 400nm and 500nm for comparison to the Prede, and 412nm and 500nm for the SP02. The differences at 400/412 nm are shown in Figure 5 and for 500nm in Figure 6, with the probability density function

(PDF) of the differences and the parameters of a Gaussian fitted to the PDF also shown.
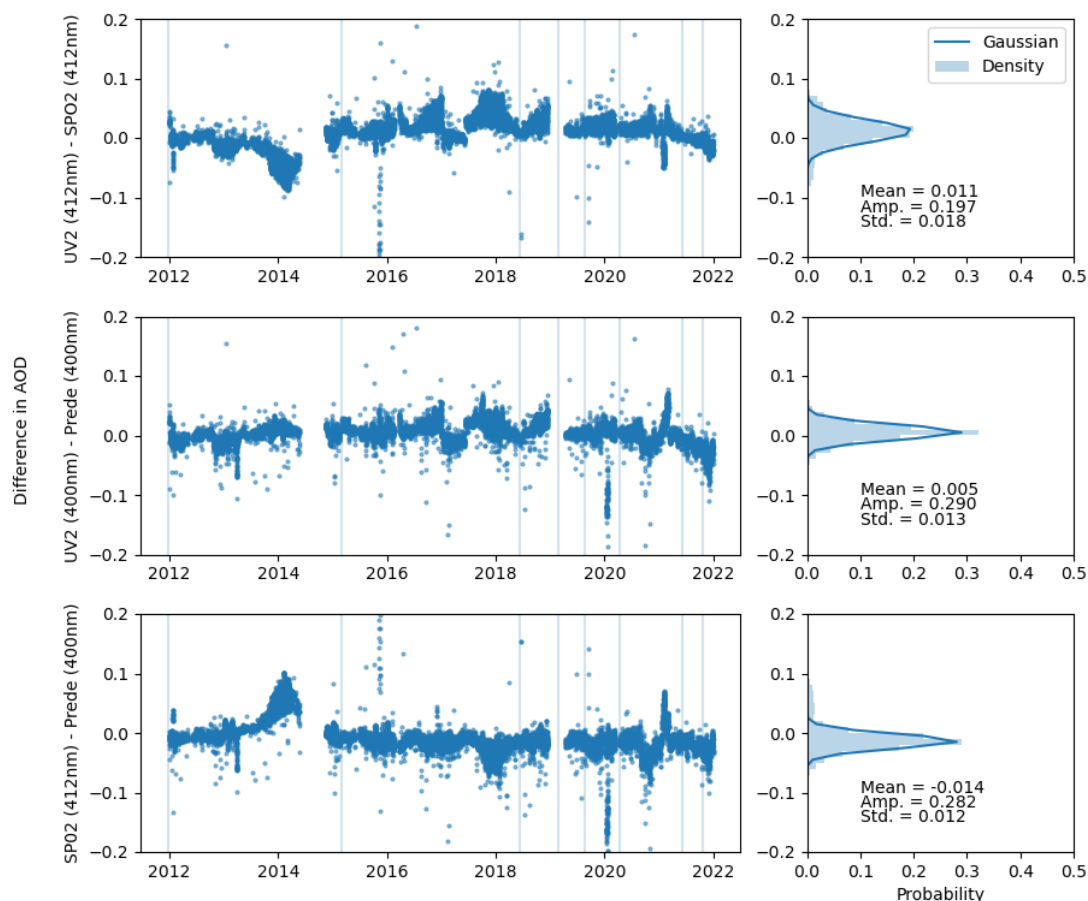
Figure 5: Differences in the aerosol optical depth between UV2 at 400 and 412nm and SP02 at 412nm and the Prede at 400nm. Panels on the right show the distribution of differences and a fitted Gaussian with its associated parameters.

At 400-412nm the agreement between all three instruments is favourable. UV2 is shown to agree with SP02 and the Prede to a comparable accuracy and precisions as SP02 and the Prede agree with each other. In all cases, the mean bias is less than 0.015 and the standard deviation less than 0.02. There are however several pronounced features in the three time series. At 412nm, during 2014 there is a marked difference of 0.05 AOD, with UV2 significantly underestimating AOD with respect to the SP02. This is not present in the 500nm AOD, and on review it is apparent from the diurnal variation on clear days that the 412 nm AOD data are faulty from October 2013 until June 2014, when the SP02 sensor was sent to the Bureau for

recalibration and replacement of the damaged 412 nm filter. The discrepancy with UV2 is corrected by 2015, when another full calibration of UV2 was made. There are also several spikes in the Prede data, notably early 2020, that are yet to be

295 resolved. They are however short lived, suggesting that they are a result of dust build up before being cleaned, and do not affect the comparison significantly. UV2 also appears to have improved following regular calibrations from 2018 with a reduction in prolonged periods of differences such as those seen from 2015 to mid-2018.

Much of the same is true when we look at 500nm, however the comparisons to UV2 aren't quite as favourable when

300 compared to the differences between SP02 and the Prede. There the mean of the Gaussian PDF is -0.006 with a standard deviation of 0.007. Further work is needed to improve the calibration of UV2 at longer wavelengths, where, as shown previously, the impact of shifts in wavelength alignment is felt most strongly. In addition, absorption by ozone is present in this region and may not be adequately corrected.
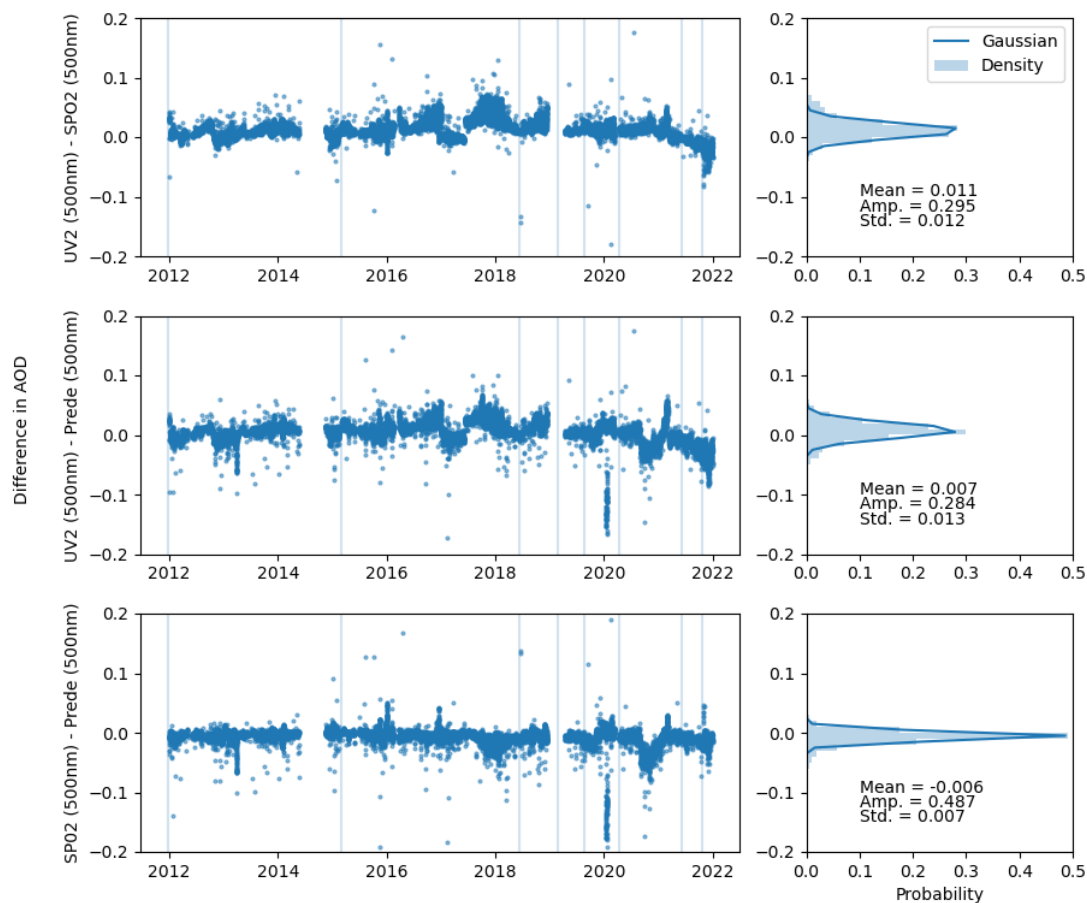
Figure 6: Differences in the daily mean aerosol optical depth between UV2, Prede and SP02 at 500nm. Panels on the right
305 show the distribution of differences and relevant statistics.

8 Summary

We have demonstrated the utility of the UV2 instrument with its capability of near-simultaneous direct and global UV
irradiance measurements. It has proven stable over the past 10 years with only minor issues with the direct measurements in
310 2017-2018, which have since been corrected. With the direct measurements we were able to measure ozone to well within 6
D.U of the Dobson. This is an ideal complement to the Dobson time series as it is fully automated, so providing several
estimates of ozone throughout daylight hours, and thus allowing for data gaps to be filled. Aerosol optical depth was also
computed and compared to the SP02 and Prede observations, with UV2 comparing well to both, with the difference in
measured optical depths typically within 0.015. It should be noted however, that the AOD is extremely low at Lauder, with
315 values above 0.1 being exceptionally rare. As such, uncertainties will approach the detection limit of the instrument. Again,
we have shown that UV2 is a complementary measurement system. It can extend the measurements of AOD to cover various
wavelengths and can be used as an intermediate comparison between the Prede and SP02 based measurements. Further work
is needed to improve the agreement at 500nm, where wavelength alignment and ozone effects will be present. Measurements
will continue at Lauder and longer-term tests will be made to determine whether the instrument can be used to supersede
320 Dobson and aerosol radiometer measurements. In addition, the utility combining global and direct measurements has yet to
be fully explored and will be a topic of future research now that the instrument performance has been characterised.

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are also grateful to Bruce Forgan who, as part of the Australian Bureau of Meteorology (BoM) was instrumental in the
development of aerosol measurements from the SP02 system.

Data Availability

330 UV2 and SP02 data is available from authors on request. Dobson and UV4 data is available from the NDACC and the Prede
Skyradiometer data is available from http://atmos3.cr.chiba-u.jp/skynet/lauder/lauder.html.

Author Contributions

Alex Geddes was responsible for the analysis of UV2 spectra and intercomparisons with other datasets, and was the primary author of the paper. Ben Liley and Richard McKenzie supported the writing and analysis. Michael Kotkamp maintained the
335 instruments used in the study. Richard Querel was responsible for the Dobson dataset and supported the writing effort.

Competing Interests

The authors declare no financial interest beyond their benefits from employment.

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