Author's response amt-2017-240:

The authors thank the referees for their helpful comments. Our responses to all comments are described below.

(1) Comments from referee 2

1. The authors do not provide enough information in the paper to (1) assess the effectiveness of the filter-based method to eliminate stray light and (2) evaluate signal to noise ratio especially as applied to the direct sun irradiance measurements at different solar zenith angles.
2. The authors compare direct solar irradiance spectra measured by their new BTS instrument and QASUME. Further they compare TOC derived from BTS and QASUME. However, the differences in derived TOC cannot be directly related to the differences in the spectral measurements since different TOC retrieval schemes were used. I would strongly recommend applying the same retrieval analysis to both QASUME and BTS datasets for consistency.

Minor comments:
1. p2. Please describe the spectrometer used in BTS2048-UV-S: focal length, f/#, grating, manufacturer, etc.
2. p2. Please provide more information about the detector (e.g. CCD manufacturer, pixel size, well depth, dark current and typical operational temperature)
3. p2. Please explain how SiC photodiode enables fast time resolved radiometric measurements.
4. p2. Please provide a figure showing long-pass filter and four interference filters transmission curves.
5. p3, What is the practical application of the long-pass OoR correction in the system that has multiple band-pass filters? OoR with a long-pass filter is not very accurate due to non-zero transmission in the wavelength of interest.
6. p3, L. 22-23. Please describe "tunable laser systems" used for dispersion characterization. How many wavelengths were measured, what is the wavelength accuracy of the laser line centers.
7. p3, L26. How was the SLF as a function of wavelength described for convolution with high-resolution absorption cross sections? How stable is SLF as a function of temperature and instrument "motion".
8. p4, L3. Reference for linearity characterization methods is missing.
9. p4, L9. What was non-linearity before the correction was applied?
10. p4, L17. How was absolute radiometric calibration performed in the field?
11. p4, L18. Is 1% stability applicable to all wavelengths?
12. p5 L8. The Izaña Atmospheric Observatory (IZO) altitude is 2373 m a.s.l.
13. p5, L9. Less then 0.1°C is extremely good temperature stability for an outdoor system. Where was temperature sensor located relative to the electronics and spectrometer? What was the set temperature inside the enclosure, what was the outside temperature? What is the temperature controller used? What is the enclosure material?
14. p5, L11. Please show a figure with the instrument field of view measurements (in X and Y direction).
15. p5, L12. Please describe how solar tracking accuracy was measured? Tracking accuracy of better than 0.01° is extremely good. How was the tracking actually done to ensure such accuracy?
16. p5 L15. Did the integration time change as a function of solar zenith angle or was it constant at 8 seconds per full spectrum independent of SZA? Figure 8 caption suggests a constant integration time.
17. p6, L5. The reported 1.025 ratio of BTS to QASUMI spectra is mainly applicable to the 305 -350 nm wavelength range. What causes such large residuals at wavelength larger than 350 nm? Were the spectra aligned relative to each other to correct for potential wavelength changes during the measurements? What was the stability of wavelength scale during the field measurements?
18. p6. Figure 4 shows comparison of QASUMI and BTS spectra for a small AMF. It will be very informative to show similar plots for measurements at SZA 80° and 85°. Please describe sources of noise at high SZA in this part of the paper. Provide full wavelength range: 280 – 430 nm. Evaluating signal below atmospheric cutoff will give a better idea about instrument internal stray light correction.
19. p7, L5. Information content of figure 5 can be significantly improved for the purposes of this paper by using more appropriate for O3 measurements wavelength ranges (A: integrated between 305 and 310, B: integrated between 340-350 nm, C: 330+/-1 nm and D: 355+/-1 nm). Please specify what AMF is plotted in Fig.5. Is it direct + scattered AMF? If yes, can you please show in addition direct sun AMF. Figure 5 shows different pattern in the morning and afternoon for UV-A irradiance ratios. Is it possible that solar tracking accuracy was azimuth angle dependent on that day? Is this behavior present during measurements on other clear sky days?
20. P8, L6. Application of the pre-set aerosol properties in forward radiative transfer calculations does not provide any evidence of "robustness of the applied algorithm". Please rephrase.

21. P9, L11. In the introduction a statement was made that varying integration times and filters can optimize BTS measurements for different purposes. Taking full spectrum from 200 to 430 nm when only 305-310 and 330-360 nm windows are used and fixing the integration time at 8 sec at all solar zenith angles, does not seem to provide an optimal SNR for direct solar irradiance measurements. Please explain why limitations were put in place not to realize full BTS capabilities, as stated in the introduction, for TOC measurements? Figure 8 also shows that the TOC measurements start degrading at SZA around 71-74° which potentially suggests that dynamic range of the system is smaller than stated earlier.

Table 1: Please add TOC standard deviation for each measurement averaging period. Comments to figures: Please use brackets to distinguish units from fraction symbol in all figures and table.
Figure 1: Please expand the information provided, especially in the sensor system part. Provide instrument dimensions.
Figure 4: Please correct the units on the left axis: Solar direct irradiance [W/m2/nm]. Right axis: irradiance ratio (BTS/QASUME). Legend: capitalize QASUME. Please add: averaged BTS/QASUME.
Figure 5: Left axis: Irradiance ratio (BTS/QASUMI)
Figure 6: Please provide left axis scale for the insert graph. Dobson Unit is not a SI unit, please define DU = 2.69E16 molecules/cm2
Figure 7: Left axis: Irradiance ratio (BTS/LibRadtran) Specify date/time of the measurement
Figure 8: OMI TOC is hard to see. Digitization of the BTS TOC is not entirely clear. Please explain in the text.

(2) Author's response

Comments:

General: We appreciate the detailed comments of the referee. The overall goal of the article is a feasibility study rather than a detailed technical report on the various components of the instrument. Although justified by general curiosity, not all examinations requested by the reviewer have been performed. Therefore the focus of our manuscript is on the application and characterization of the BTS device to direct solar irradiance measurements and not in technical engineering details of the meter itself.

1: We think that the effectiveness of the filter-based stray-light elimination has been demonstrated by the comparison to spectral measurements of QASUME instrument which is illustrated in the logarithmic plot. We agree that a plot at a different SZA is beneficial, hence we added a figure showing spectra taken at different SZA to demonstrate the effectiveness of the method and the limitations of the instrument.
2: We agree, that the application of the TOC algorithm to QASUME data would grant a better comparability if we would introduce the same algorithms for both instruments. However, in practice this is difficult or impossible to achieve due to the necessary scanning of wavelengths of the QASUME instrument. A highly sophisticated lookup table with a wavelength per wavelength retrieval of corresponding SZA values would be necessary and its development is beyond the scope of this paper which focuses on the BTS instrument. Our intention is to show that a measurement system which is based on a stock UV spectroradiometer adapted and characterized for direct solar irradiance measurements can determine with the introduced TOC evaluation algorithm comparable results to other systems which use an established TOC algorithm. Another publication is planned about this measurement campaign with all the measurement devices which took part in the intercomparison.

Minor Comments:

1: The authors think it is beyond the scope of this manuscript to present all the details of every single optical part of the spectrometer unit. The important features have been already described and we added even more details.
2: We added the manufacturer and the operational temperature (see section (3) author´s changes).
3: This section is removed, it is not important for the paper.
4: The measurement could be achieved by a different set of optical filters and there is no need to use exactly these filters. A sentence has been added to address this fact (see section (3) author´s changes).
5: The OoR correction method using the long-pass filter is mainly an alternative to the solar bandpass-filter method. It could be used for faster measurements. But due to the limited accuracy it has not been used for the results presented in the paper.
6: The tuneable laser system and its wavelength accuracy is described in the cited Nevas et. Al., 2014 publication and was not part of the feasibility study. The measurements took place every 5 nm over the entire spectral range of the instrument. Figure 2 demonstrates that no significant change of the bandpass function could be observed.
7: For the convolution, a symmetrical bandpass of 0.6 nm was assumed for the spectral range of interest. The temperature and temporal dependence of the bandpass has not yet been investigated. For this paper we assumed that within the temperature change below 0.1 °C no significant change in this will be observable.
8: Reference added (see section (3) author´s changes).
9: Before the linearization the linearity was sufficient for typical measurements, however for low saturation (below 500 cts) the nonlinearity rises above 1% to about 3-5 % for single pixels. This is why a linearization was applied. We added more information (see section (3) author´s changes).
10: For calibration checks, an optical bench with standard lamps was installed in the Izana Labs. The instrument was removed from the tracker and recalibrated in the Lab. We added a statement (see section (3) author´s changes).
11: For the spectral range of solar measurements used in this paper (280 nm to 420 nm), yes.
12: Corrected following observatory website
http://izana.aemet.es/index.php?option=com_content&view=article&id=21&Itemid=21&lang=en
13: Additional information on the temperature sensor will be added to the paper (see section (3) author´s changes). Further information on controller and enclosure material is property of the instrument manufacturer.
14: Figure 3 has been extended with this data.
15: The tracking accuracy of 0.01° is stated by the company EKO for their stock product which is described in the paper. They use a four quadrant diode for precise fine tracking. Further details have not been investigated, but even if the tracking uncertainty would be higher, it would not be relevant due to the size of solar disc (0.5°) and the FOV of 2.8°.

16. We stated that the measurement interval is given with 8s. The integration time changed within these 8 seconds for the different bandpass filters and for different SZA. We added a sentence (see section (3) author´s changes).
17: This change can be explained with slightly different optical bandpasses of the instruments even after applying a convolution. Since the sun exhibits many Fraunhofer lines this is a typical ratio in such intercomparisons. A sentence has been added (see section (3) author´s changes).
18: We agree and added a second plot by a different SZA. In the spectral range below the solar edge in the UV-B, noise of the 16 bit ADC is dominant and not stray light. This is due to no averaging of the BTS data was used (this was not possible within 8 seconds measurement interval) and the high dynamic of a solar measurement. We wanted to show that even under these circumstances a sophisticated spectroradiometer can perform well for TOC determination. Changes see section (3) author´s changes.
19: We changed the content of Figure 5 accordingly. We specified the figure caption to clarify the airmass given in the figure.
The step of up to 0.5 % occurring around noon indeed is apparent at other days too, but is always connected to the time after QASUME was shortly taken off operation to check its calibration.
20: We removed the statement, since our intention why no special emphasis is given for the aerosol modelling is explained sufficiently in the sentences following that statement.
21: The integration time was adapted for each measurement with each filter (see comment 16). Although the TOC evaluation model only uses the spectral bands between 305 nm to 310 nm and 340 nm to 350 nm, the whole solar UV spectrum was measured. This allowed the spectral comparison to QASUME. We assume that future TOC evaluation models can utilize further parts of the solar spectrum and we could already demonstrate the capability of spectral measurements. Due to a measurement interval of 8 seconds no averaging or very long integration times were performed which limits the BTS capabilities at high SZA.

Table 1: The TOC uncertainty evaluation was evaluated in the paper of Vaskuri 2017 which is cited. The representation of the units on the x and y axis is following the ISO 80000-1:2009 specifications.
Figure 1: More information is provided (see section (3) author´s changes).
Figure 4: We corrected the left axis according to the recommendation of the reviewer to “solar direct irradiance / W/m2/nm”. The right axis was corrected to “irradiance ratio (BTS / QASUME)”. We capitalized the “QASUME” in the legend and added “averaged BTS/QASUME”.
Figure 5: We adapted the figure as recommended.
Figure 6: We adapted the graph and introduced the DU unit definition in the manuscript.
Figure 7: We added date/time of the measurement
Figure 8: A sentence has been added (see section (3) author´s changes).

(3) Author's changes

The green text was added, red deleted:

1: Additional figure at different SZA added.
2: -

Minor Comments:
1: -
2: Sentence modified: The spectrometer uses a temperature controlled (8 °C) back-thinned Hamamatsu CCD detector with 2048 pixels and an electronic shutter integrated in a compact optical bench with 16 bit analogue digital converter (ADC) resolution.
3: -
4: Sentence modified: In the device one longpass filter, a bandpass filter (298 nm to 390 nm) and four interference filters (center wavelength: 254 nm, 285 nm, 300 nm and 400 nm) are integrated.
5: -
6: -
7: -
8: Reference added: Tomi Pulli, Saulius Nevas, Omar El Gawhary, Steven van den Berg, Janne Askola, Petri Kärhä, Farshid Manoocheri, and Erkki Ikonen, "Nonlinearity characterization of array spectroradiometers for the solar UV measurements," Appl. Opt. 56, 3077-3086 (2017)
9: Sentence added: "For spectral measurements the instrument saturation is kept below 80% to operate the instrument in an optimum between saturation and linearity. By using the solar bandpass-filter method, with adapted spectral integration times for each sub-measurement, the dynamic range of the instrument could be extended. Whenever the nonlinearity exceeded 1% (at very low signals) a nonlinearity correction is automatically applied.
10: Sentence added: "During the campaign, the instrument was removed from the tracker at night to perform calibration measurements on a portable optical bench."
11:-
12: 2390 m →2373 m
13: Sentence added "(measured close to the spectrometer unit, set temperature 38°C)."
14: Figure 3 edited and additional reference added in the description.
15: -
16: Senctence added "The duration of this measurement interval is mainly accused by filter movement and dark-signal measurements, whereas the integration time for the measurements with different bandpass filters was optimized and varied with different solar zenith angles (SZA)."
17: Sentence added "The higher frequent ratio (grey line) can be explained due to a slightly different optical bandwidth even after the convolution to 1 nm triangular bandpass between BTS/QASUME."
18: Sentence added "At higher SZA and lower input signal the integration time and the noise of the CCD array are increasing which is reducing the signal to noise ratio."
19: -
20: Sentence deleted "and therefore shows the robustness of the applied algorithm"
21: -
Table 1: Column standard deviation added.
Figure 1: Figure provides now more information.
Figure 4: We corrected the left axis according to the recommendation of the reviewer to "solar direct irradiance / $W/m^{-2}{\cdot}nm^{-1}$". The right axis was corrected to "irradiance ratio (BTS/QASUME)".
We capitalized "QASUME" in the legend and added "averaged BTS/QASUME".
Figure 5: We adapted the figure as recommended.
Figure 6: We adapted the graph and introduced the DU unit definition in the manuscript. (one Dobson Unit (DU) is equivalent to 0.4462 $mmol{\cdot}m^{-2}$ (Basher, 1982)).
Figure 7: We added date/time of the measurement
Figure 8: A sentence has been added.

(4) Further Author's changes

In addition the abstract has been slightly rephrased to address the comments:

Abstract. A compact array spectroradiometer that enables precise and robust measurements of solar UV spectral direct irradiance is presented. We show that this instrument can retrieve total ozone column (TOC) accurately. The internal stray light, which is often the limiting factor for measurements in the UV spectral range and increases the uncertainty for TOC analysis, is physically reduced so that no other stray light reduction methods, such as mathematical corrections, are necessary. The instrument has been extensively characterised at the Physikalisch-Technische Bundesanstalt (PTB) in Germany. During an international total ozone measurement intercomparison at the Izaña observatory in Tenerife, the high-quality applicability of the instrument was verified with measurements of the direct solar irradiance and subsequent TOC evaluations based on the spectral data measured between 12 and 30 September 2016. The results showed deviations of the TOC of less than 1.5 % to most other instruments in most situations not exceeding 3 % compared to established TOC measurement systems such as Dobson or Brewer.

1. Sentence added in the discussion & results section: "In the spectral range below the UV-B solar edge the deviation rises mostly due to slight differences in the wavelength calibration and insufficient signal to noise ratio since no averaging of the BTS data or longer integration time was possible for the 8 s measurement interval."
2. Sentence added in the discussion & results section: "Based on the results and the experience gained during the measurement campaign the design and the sensitivity of the BTS measurement systems could be further improved by a factor of 4. This will very likely improve the performance of the system especially at higher SZAs and shall be tested at future measurement campaigns."
3. Sentence rephrased in the Acknowledgement section: "This work has been supported by the European Metrology Research Programme (EMRP) within the joint research project EMRP ENV59 ATMOZ "Traceability for atmospheric total column ozone". The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union. Many measurements have been carried out in the framework of the EMRP project ENV59 ATMOZ at the Izaña observatory in Tenerife."