Protocol of the intercomparison at ARPA, Aosta, Italy on July 2019 with the travelling reference spectroradiometer QASUME from PMOD/WRC

Report prepared by Julian Gröbner

Operator: Julian Gröbner
Local Operator: Henri Diémoz, Ilias Fountoulakis

The purpose of the visit was the comparison of global solar irradiance measurements between the spectroradiometer AAO operated by the Sezione Agenti Fisici - Radiazione Ultravioletta Solare, Agenzia Regionale per la Protezione dell'Ambiente (ARPA) and the travel reference spectroradiometer QASUME. The measurement site is located at Valle d'Aosta; Latitude 45.74 N, Longitude 7.34 E and altitude 569 m.a.s.l. The horizon of the measurement site is free down to at least 80° solar zenith angle (SZA). Measurements between 4:20 UT and 19:00 UT have been analysed.

QASUME was installed at ARPA Aosta 3 July 2019. The spectroradiometer was installed next to AAO with the entrance optic of QASUME within 1 m of AAO. The spectroradiometer in use at ARPA Aosta is a Bentham DTMc300 double monochromator. The intercomparison between QASUME and the ARPA spectroradiometer lasted four days, from the morning of July 4 to noon of July 8, 2019.

QASUME was calibrated several times during the intercomparison period using a portable calibration system. Two lamps (T685240 and T61252) were used to obtain a spectral irradiance calibration traceable to the primary reference held at PMOD/WRC, which is traceable to PTB. The daily mean responsivity of the instrument based on these calibrations varied by less than 1 %. The internal temperature of QASUME was 28.6±0.40 °C and the diffuser head was heated to a temperature of 31.0±2.7 °C.
The wavelength shifts relative to an extraterrestrial spectrum as retrieved from the matSHIC analysis were between ±50 pm in the spectral range 290 to 500 nm.

Protocol:

The measurement protocol was to measure one solar irradiance spectrum every 20 minutes from 290 to 500 nm, every 0.25 nm, and 1.0 seconds between each wavelength increment.

DOY	Date	DAY	Weather	Comment (times are in UT)
184	03-Jul	Wednesday	Cloudy, thunderstorms	Installed at 16:45
185	04-Jul	Thursday	Clear Sky, Hazy, some Cu	9:51 calibration using T685240
			in the afternoon	
186	05-Jul	Friday	Clear sky, hazy	5:40 UT AAO diffuser rotated by 180°
				6:20 UT AAO difuser back to original pos.
				9:33 calibration using T685240
187	06-Jul	Saturday	clear sky	AAO stops measuring.
				Moved to lab for maintenance
				8:10 T685240
				8:30 T61252
188	07-Jul	Sunday	Mix of Sun & Clouds	7:10 calibration using T685240
189	08-Jul	Monday	Cirrus & Cu	9:30 T685240
				End of campaign at 10:00

Results:

In total 129 synchronised simultaneous spectra from QASUME and AAO are available from the measurement period. Measurements between 4:30 UT and 19:00 UT have been analysed (SZA smaller than 90°).

The spectra from AAO were corrected for wavelength shift and convolved with a 1 nm triangular slit function before being submitted for the calibration.

Two datasets were submitted: The main dataset (A) was processed acoording to the standard procedure applied at ARPA Aosta. The second dataset (B) was corrected for the angular response of the diffuser of AAO. Where not otherwise noted the remarks and results refer to the main dataset (A).

Conclusions:

1. The spectral ratios between AAO and QASUME have on average an offset of -1.5 %.
2. The spectral ratios show a slight increase of up to 6% at SZA between 70° and 80°, correlated with wavelength. This is consistent with coming from a global cosine error of the AAO diffuser, as measured in the laboratory (see operator comments).
3. When a clear sky cosine correction is applied to the dataset (B), the diurnal variation at large SZA is reduced to less than 3%, and the average spectral ratio between AAO and QASUME is equal to 0.99.
4. **All 129 spectra from dataset A and dataset B are within the combined expanded uncertainties of AAO (4%) and QASUME (1.6%).**

Comparison of spectral irradiance standards from AAO and QASUME

On 6 July at 9:50 UT, QASUME measured the 1000 W reference standard of AAO (F698) in its dark room facility from 280 nm to 500 nm. An offset of -1.0% was observed between the spectral irradiance of F698 measured by QASUME and the spectral irradiance certificate of F698. The difference is within the combined expanded uncertainty of the QASUME measurement and the uncertainty stated in the certificate.

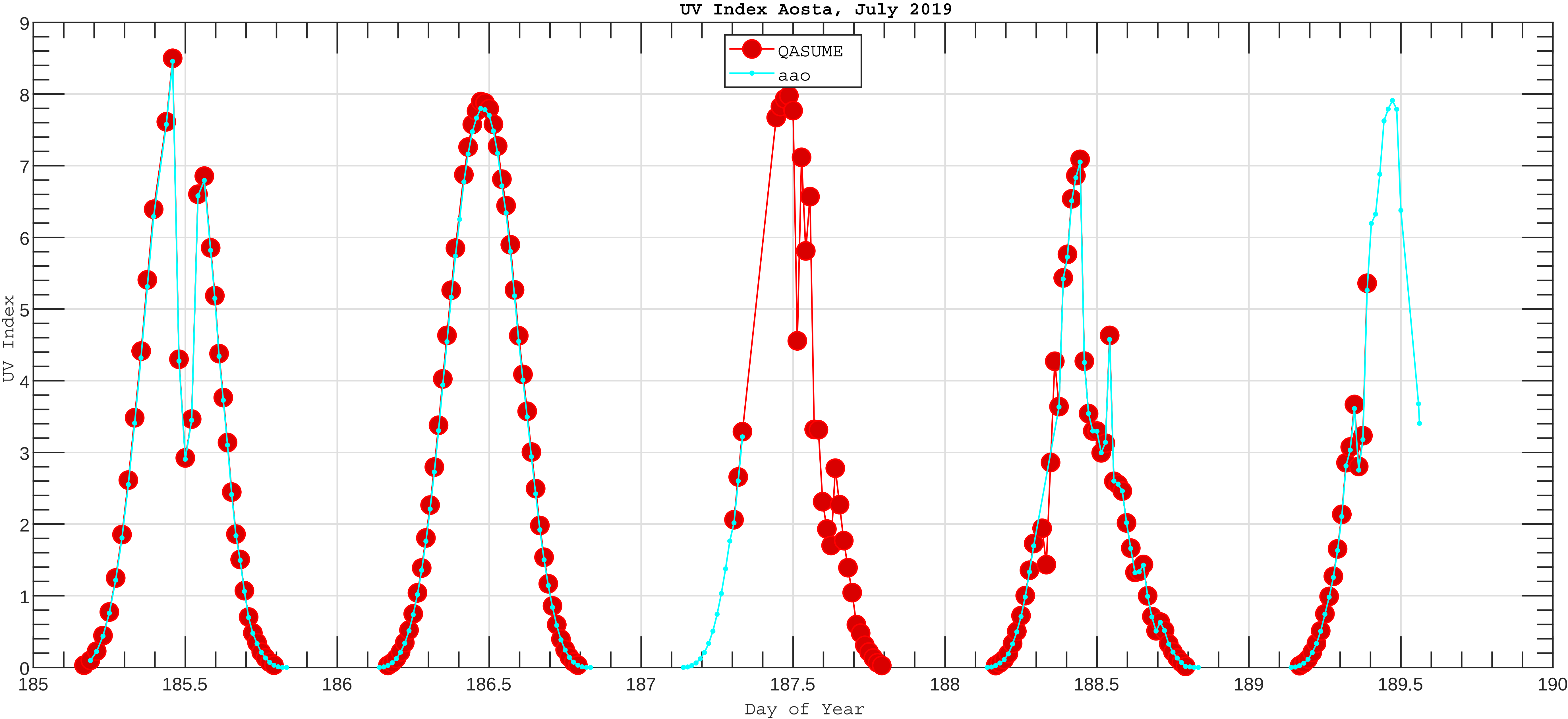
Remarks:

1. The diffuser rotation of 180° on 5^{th} July confirmed a slight azimuth dependence of 1% to 1.5% (see local operator comments for more details).
2. On 6 July 2019, AAO was moved in the laboratory for maintenance: the worm drives of both monochromators were checked and were found in good conditions. A small amount of grease was added to the gears.
3. The observed diurnal variation between AAO and QASUME is within the expanded combined uncertainties. Still, it represents the largest observed discrepancy, and can be linked to the angular response of the AAO diffuser.

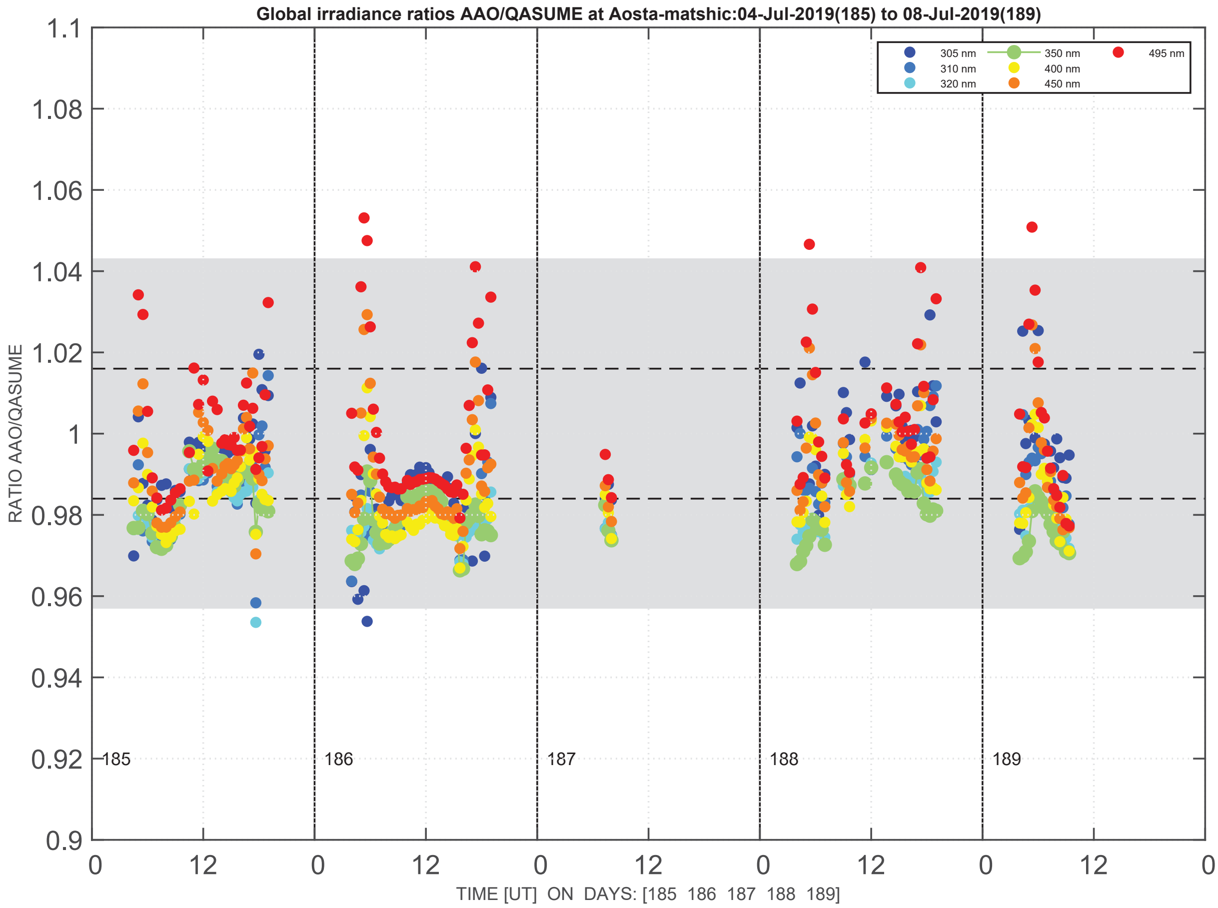
Suggestions:

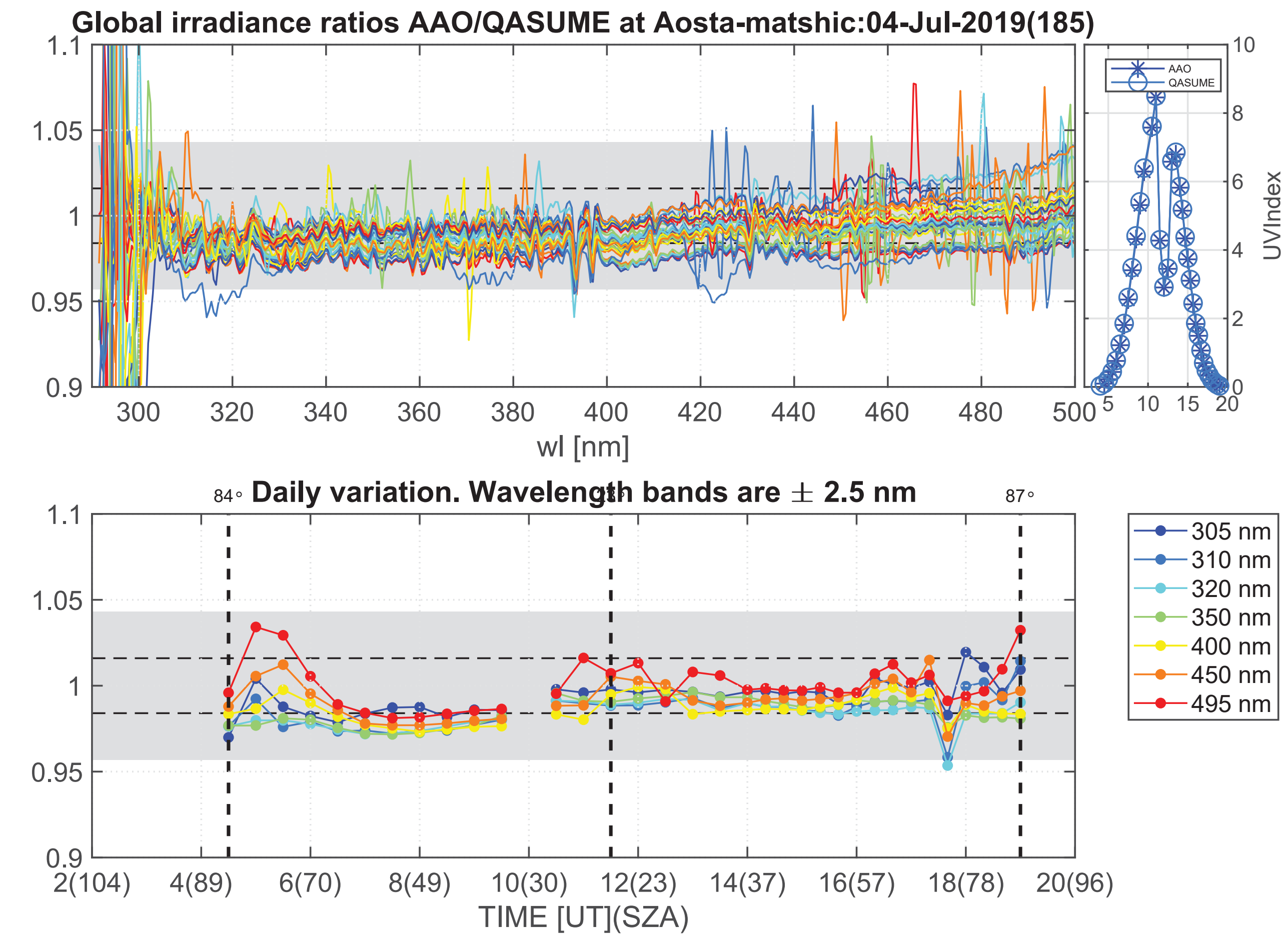
1. The Institute should consider accreditating its laboratory for spectral solar UV irradiance in order to become formally traceable to SI. The previous and specifically the latest comparison between AAO and QASUME demonstrates an excellent agreement between both instruments to within their combined uncertainties.
2. As discussed with the local operators, increasing the middle slit between the monochromators of AAO might reduce the sensitivity to small grating misalignments.

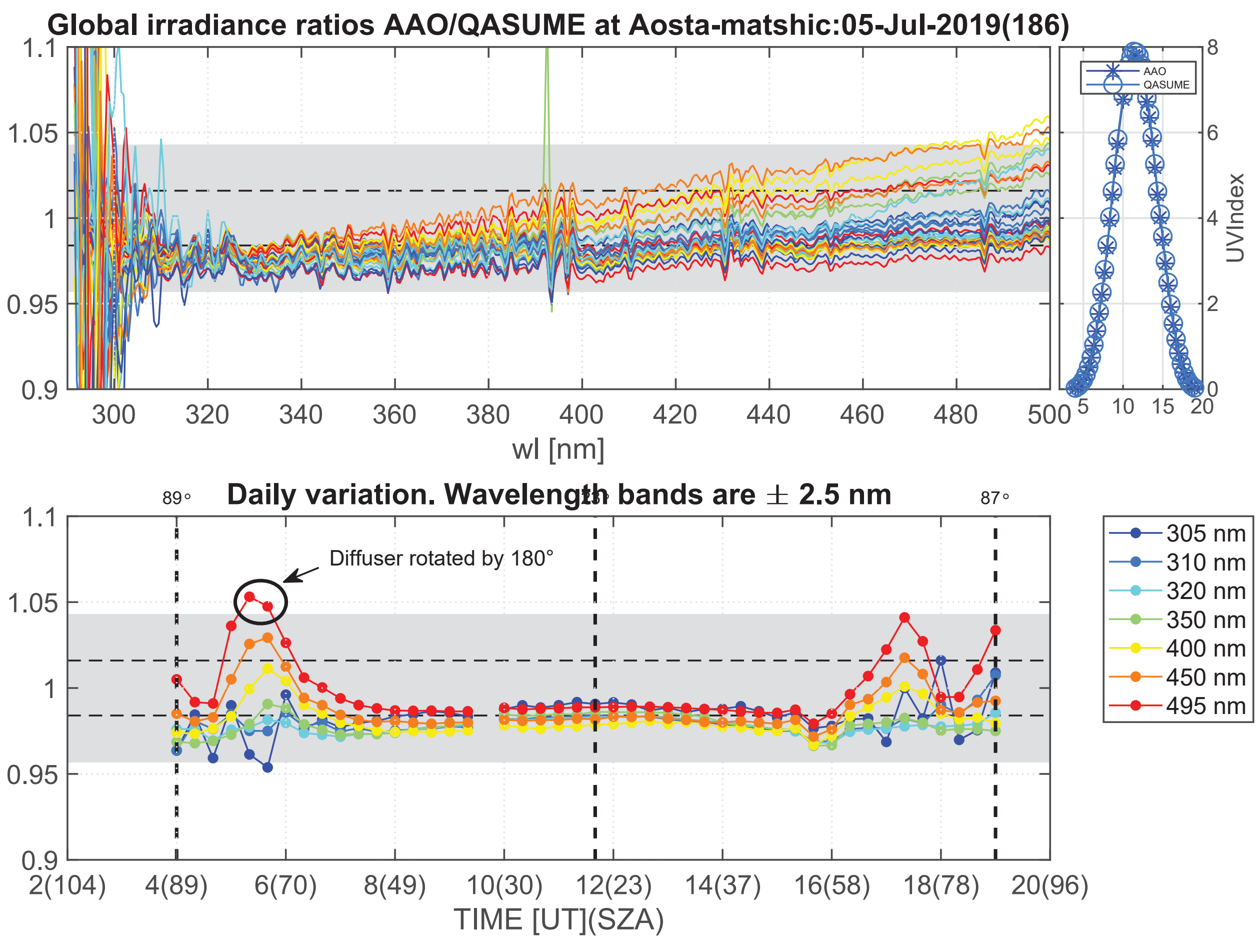
3. The spectral UV measurements of AAO at wavelengths longer than 400 nm show deviations of up to 4% at SZA between 70+ and 80° due to the angular response of the AAO diffuser. While this can be partly corrected by applying a cosine correction, this is only possible under either clear sky or completely overcast conditions. Therefore, the laboratory might consider purchasing a diffuser with an improved angular response to reduce the resulting cosine error.

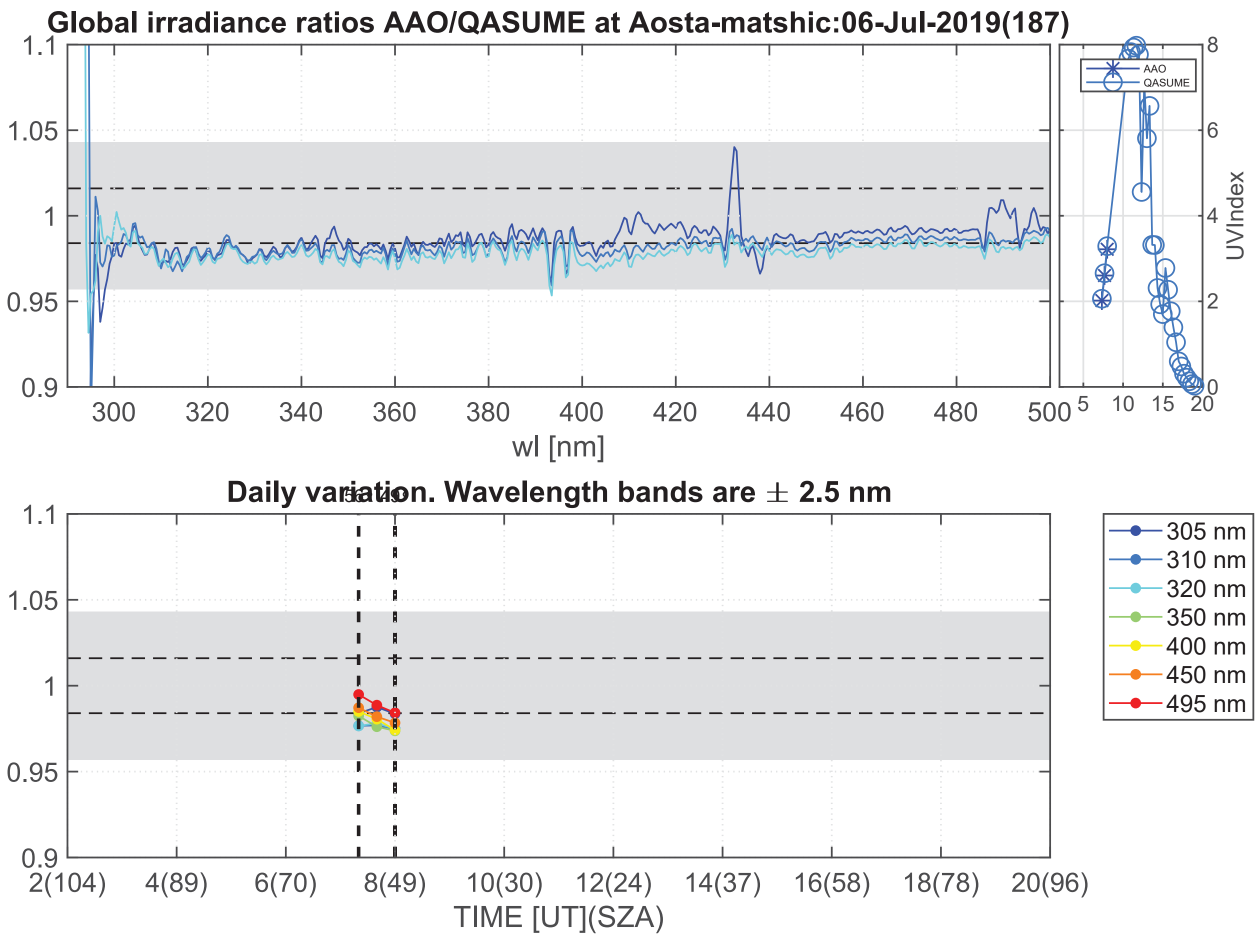


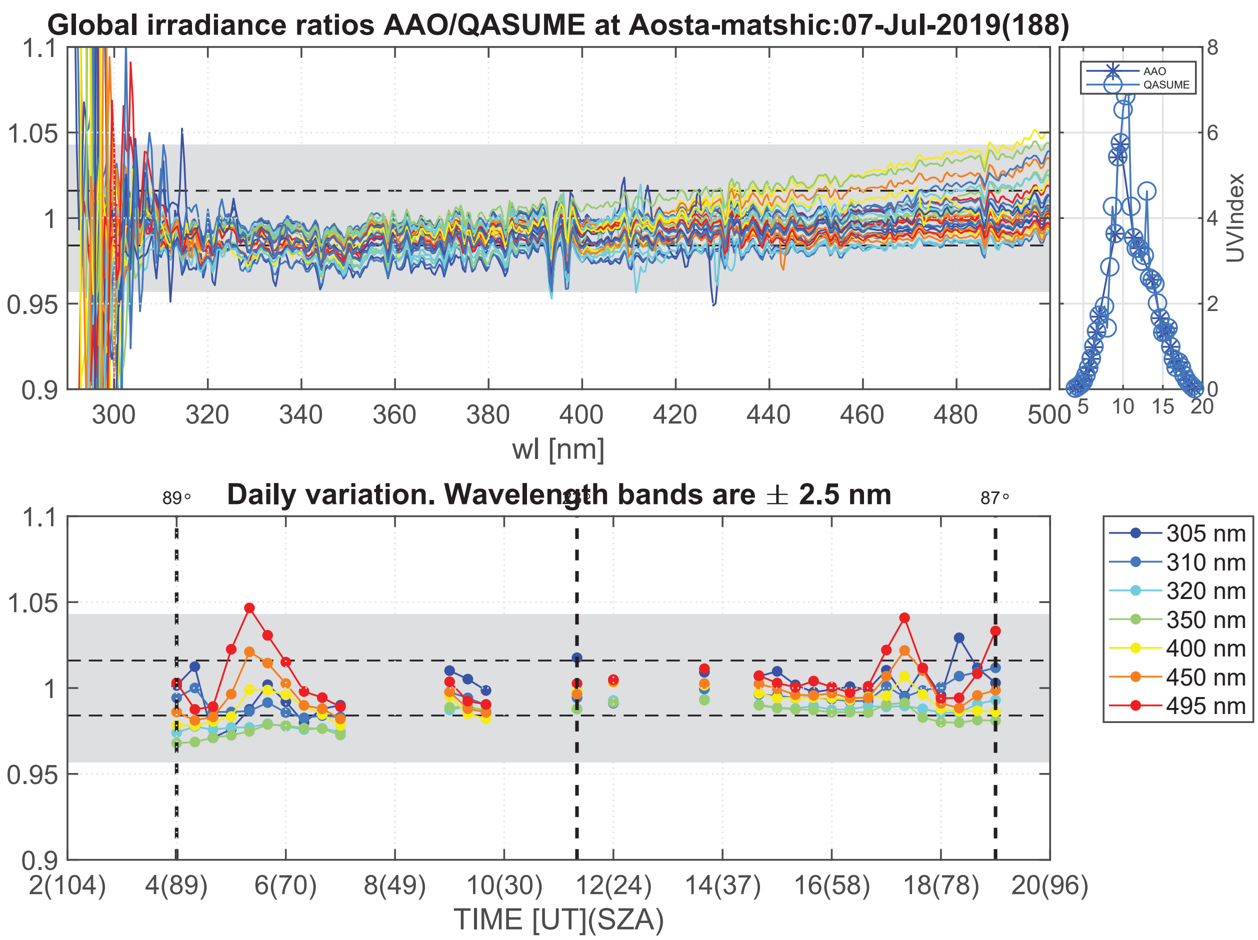
UV Index Aosta, July 2019
QASUME
aao
UV Index
Day of Year
0
1
2
3
4
5
6
7
8
9
185
185.5
186
186.5
187
187.5
188
188.5
189
189.5
190

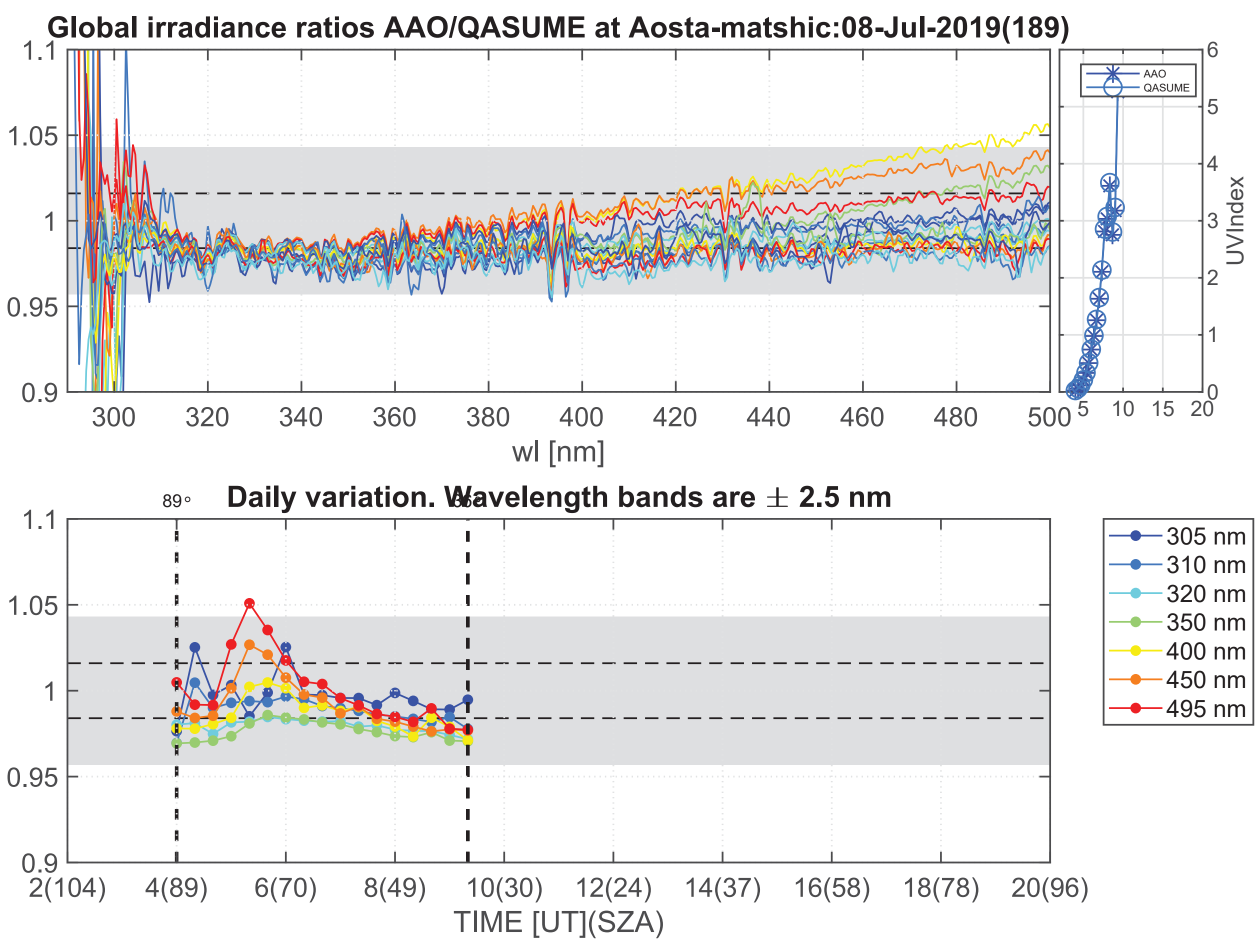

Global irradiance ratios AAO/QASUME at Aosta-matshic:04-Jul-2019(185) to 08-Jul-2019(189)
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm
RATIO AAO/QASUME
185
186
187
188
189
TIME [UT] ON DAYS: [185 186 187 188 189]

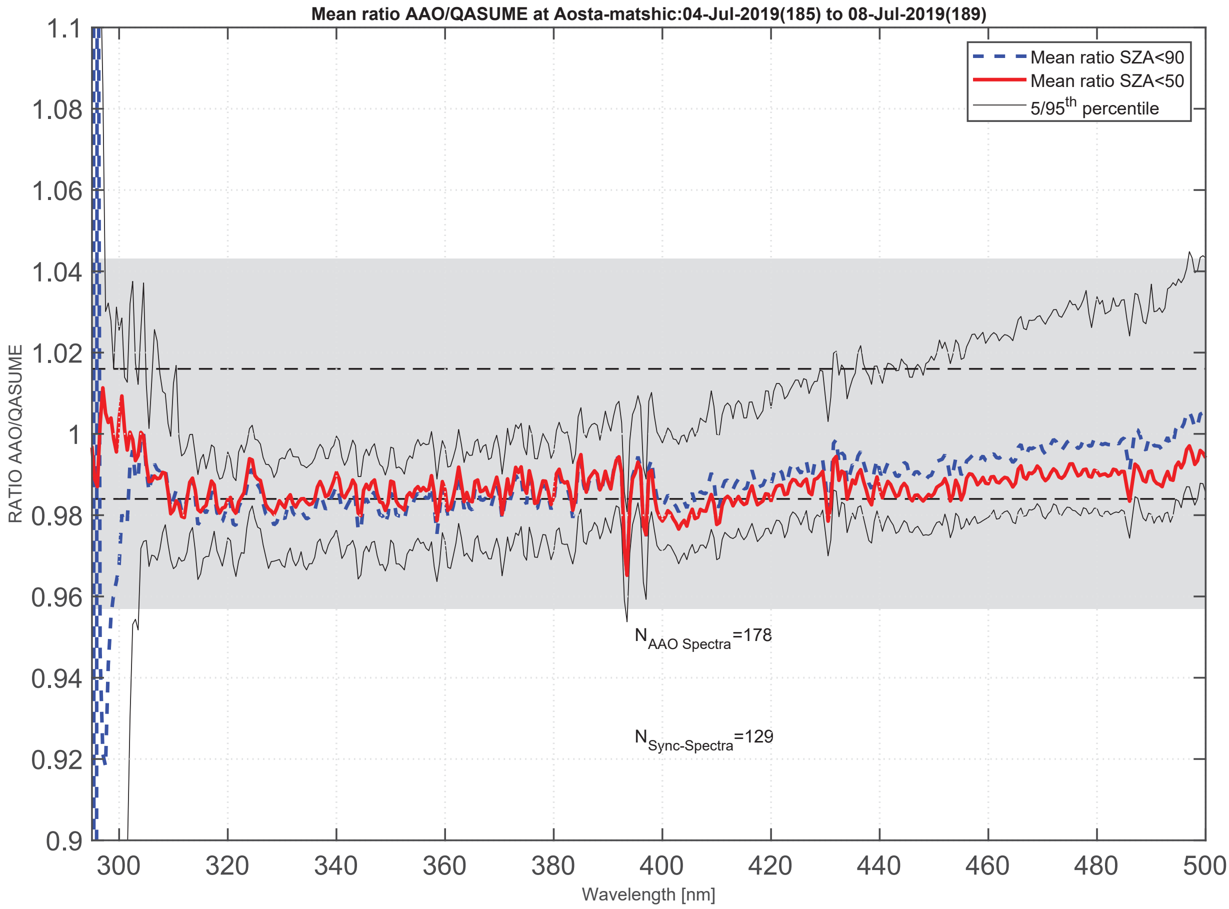

Global irradiance ratios AAO/QASUME at Aosta-matshic:04-Jul-2019(185)
wl [nm]
AAO
QASUME
UVIndex
Daily variation. Wavelength bands are ± 2.5 nm
84°
87°
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm
TIME [UT](SZA)

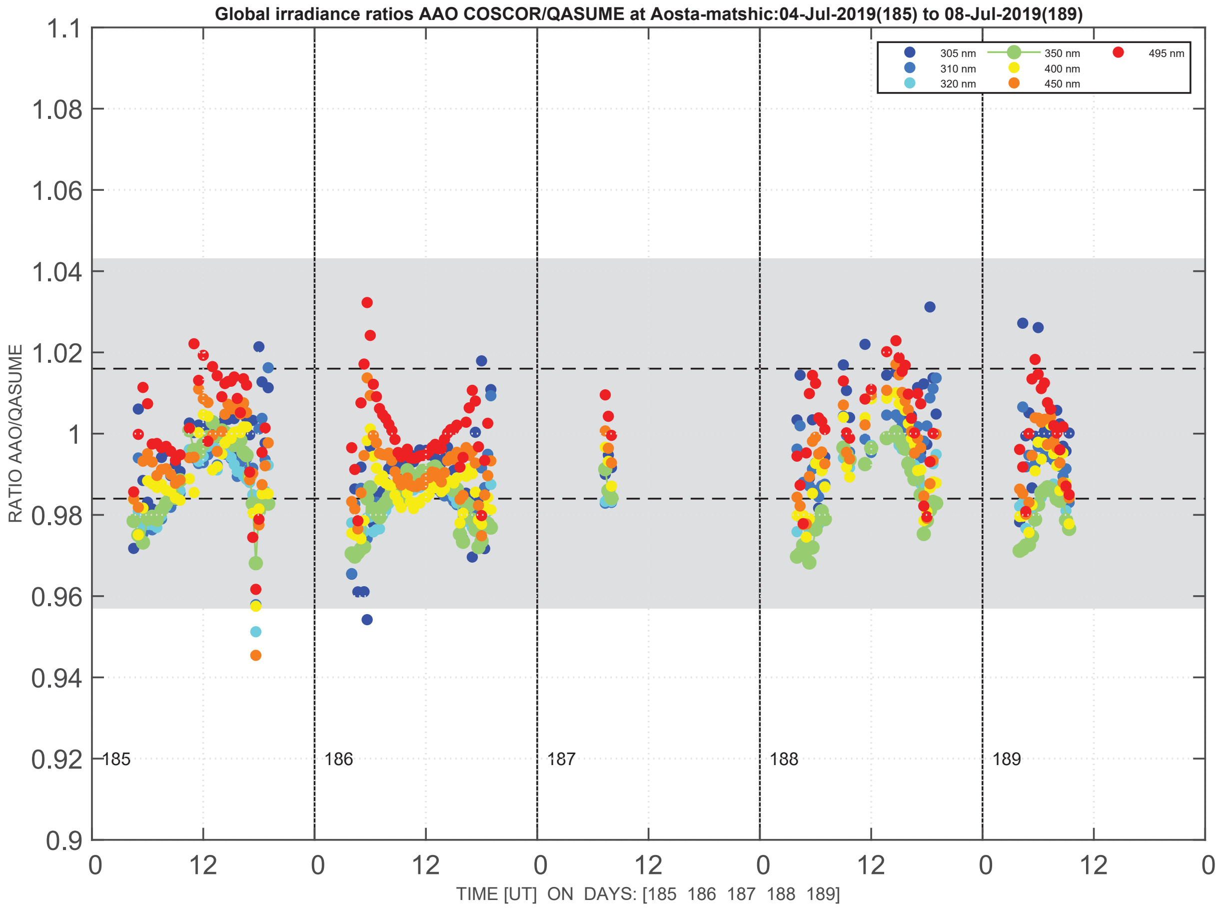

Global irradiance ratios AAO/QASUME at Aosta-matshic:05-Jul-2019(186)
wl [nm]
AAO
QASUME
UVIndex
Daily variation. Wavelength bands are ± 2.5 nm
89°
87°
Diffuser rotated by 180°
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm
TIME [UT](SZA)

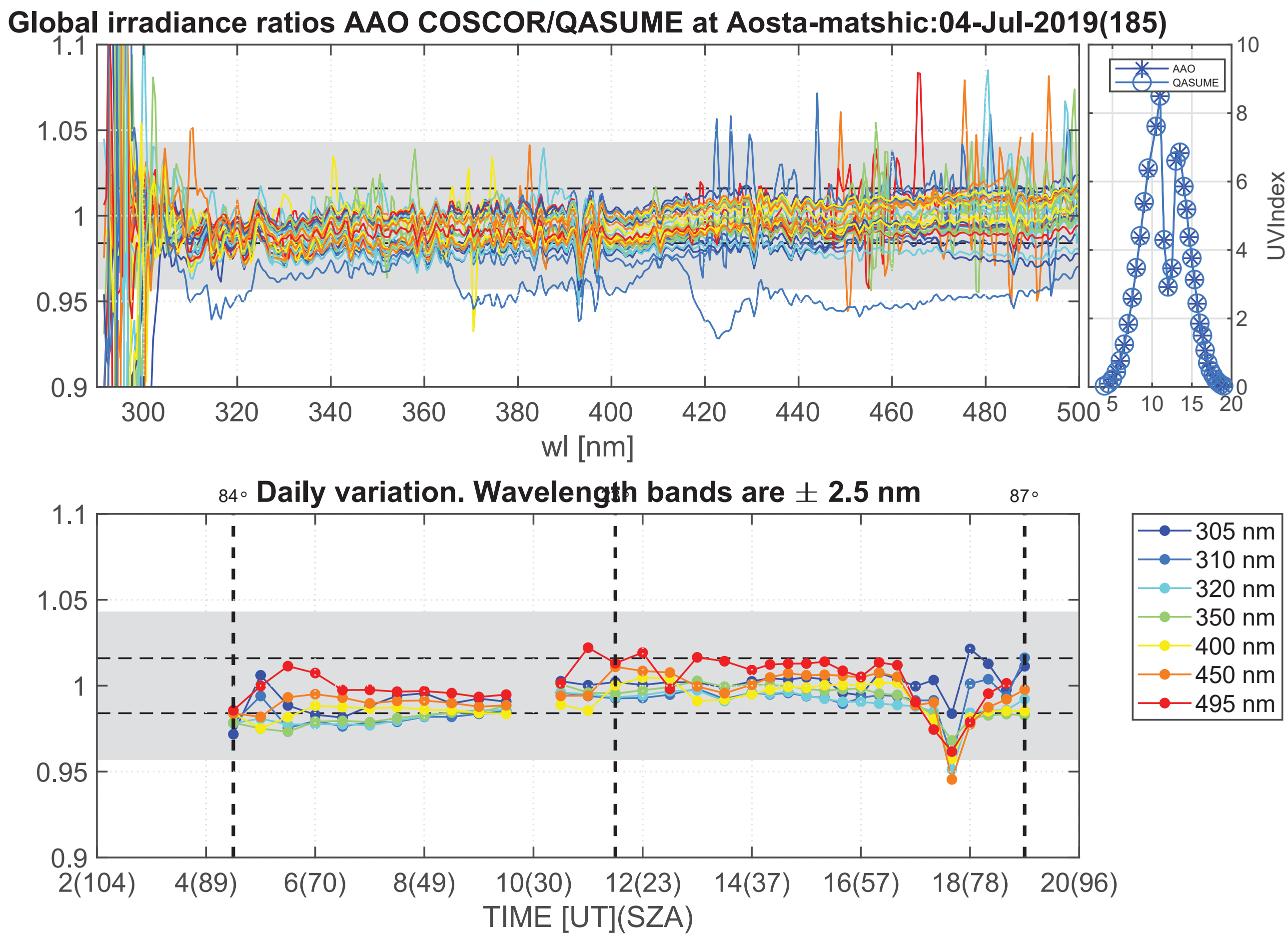

Global irradiance ratios AAO/QASUME at Aosta-matshic:06-Jul-2019(187)
wl [nm]
AAO
QASUME
UVIndex
Daily variation. Wavelength bands are ± 2.5 nm
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm
TIME [UT](SZA)

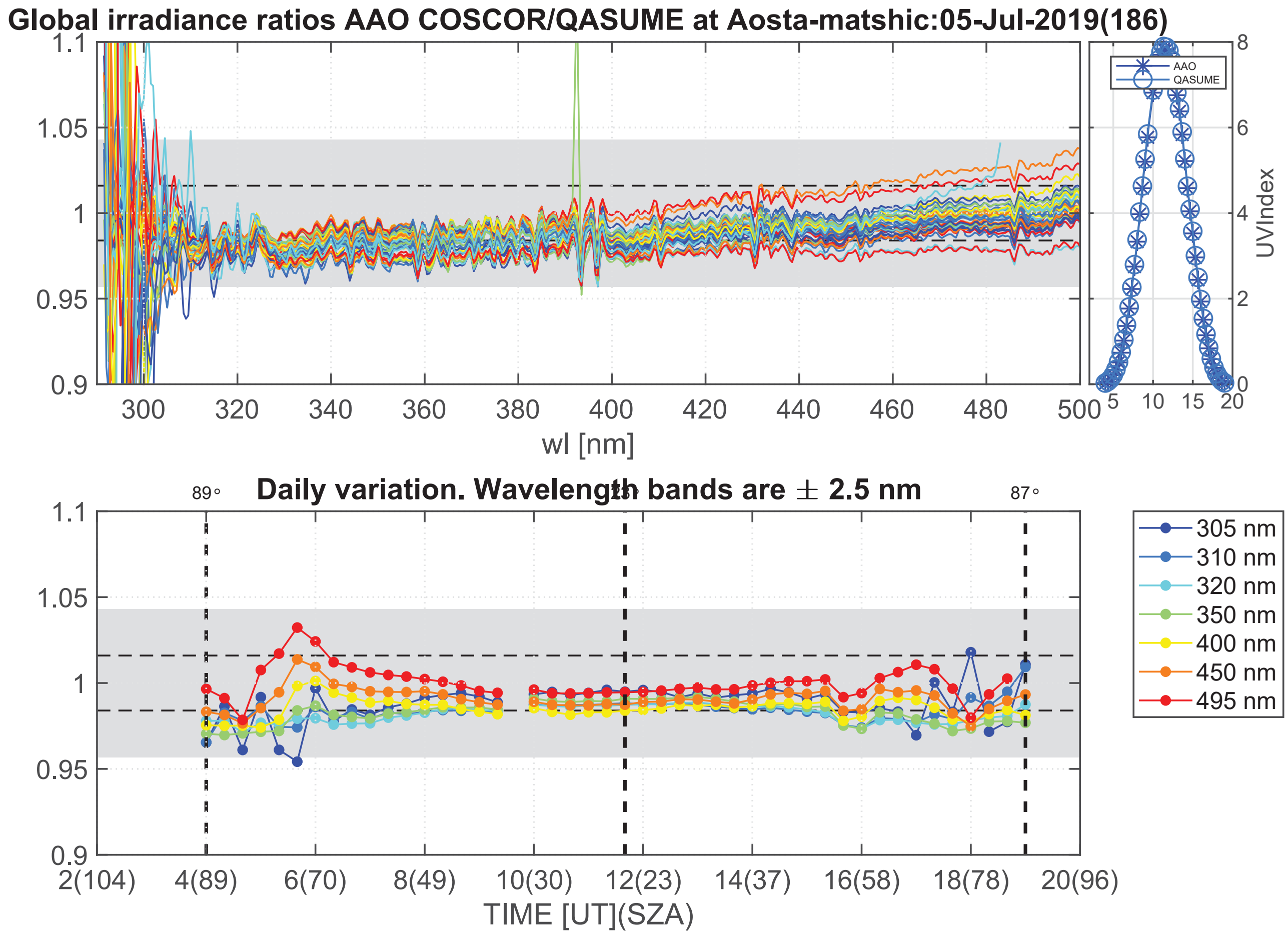

Global irradiance ratios AAO/QASUME at Aosta-matshic:07-Jul-2019(188)
wl [nm]
AAO
QASUME
UVIndex
Daily variation. Wavelength bands are ± 2.5 nm
89°
87°
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm
TIME [UT](SZA)
2(104) 4(89) 6(70) 8(49) 10(30) 12(24) 14(37) 16(58) 18(78) 20(96)

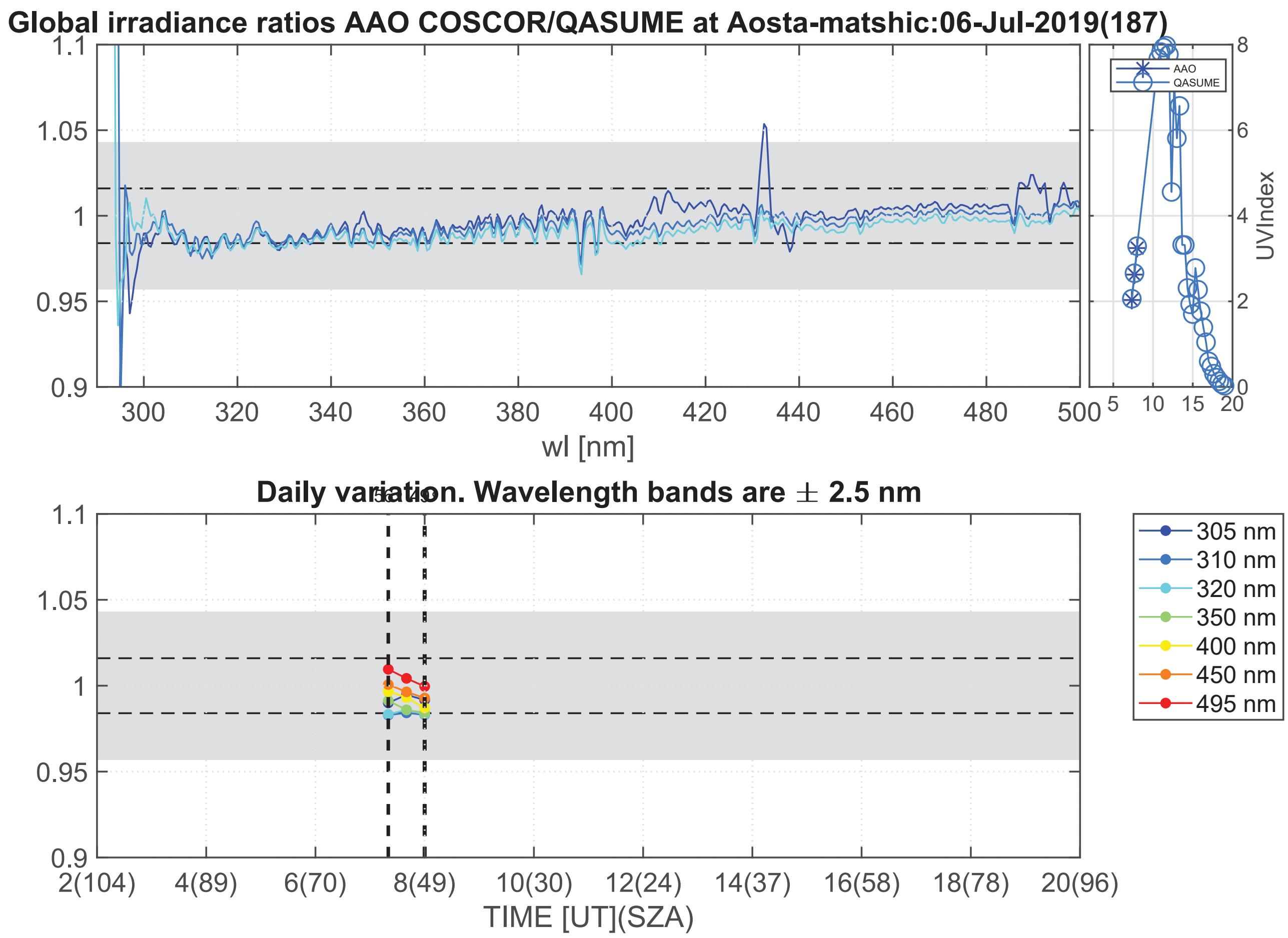

Global irradiance ratios AAO/QASUME at Aosta-matshic:08-Jul-2019(189)
wl [nm]
AAO
QASUME
UVIndex
Daily variation. Wavelength bands are ± 2.5 nm
89°
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm
TIME [UT](SZA)
2(104) 4(89) 6(70) 8(49) 10(30) 12(24) 14(37) 16(58) 18(78) 20(96)

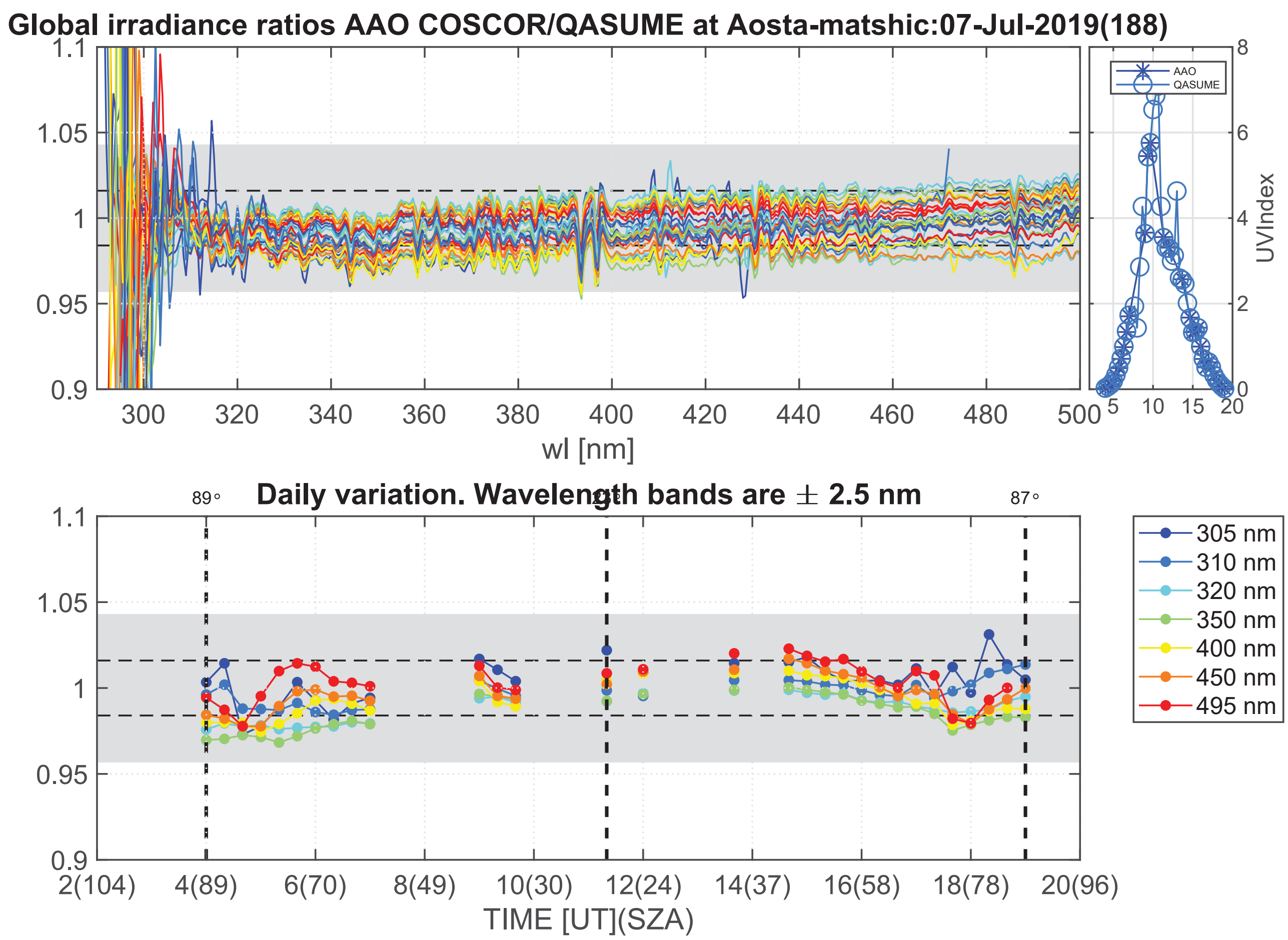

Mean ratio AAO/QASUME at Aosta-matshic:04-Jul-2019(185) to 08-Jul-2019(189)
Mean ratio SZA<90
Mean ratio SZA<50
5/95th percentile
N AAO Spectra=178
N Sync-Spectra=129
RATIO AAO/QASUME
Wavelength [nm]
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
300
320
340
360
380
400
420
440
460
480
500

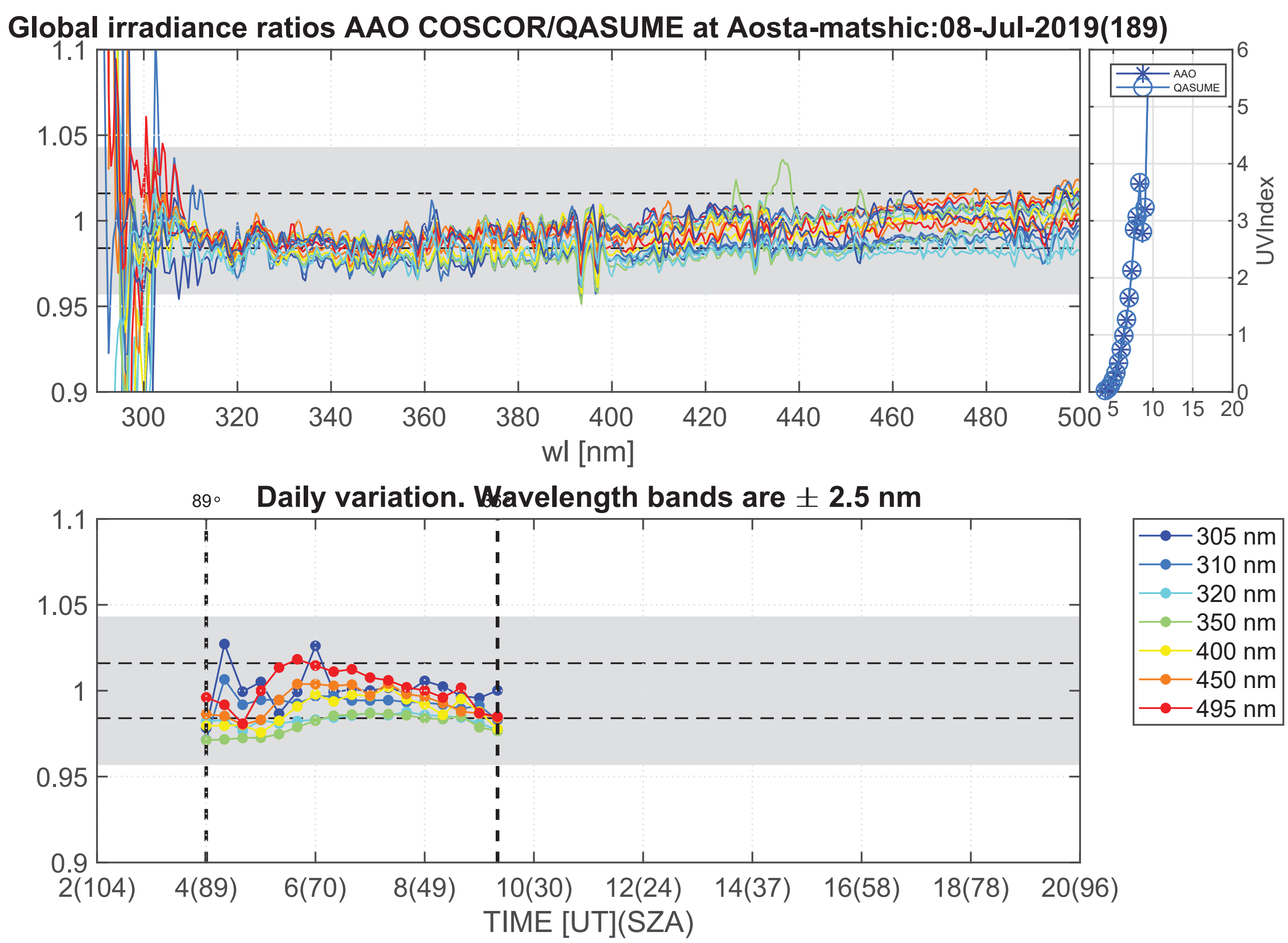

Global irradiance ratios AAO COSCOR/QASUME at Aosta-matshic:04-Jul-2019(185) to 08-Jul-2019(189)
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm
RATIO AAO/QASUME
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
185
186
187
188
189
0
12
TIME [UT] ON DAYS: [185 186 187 188 189]

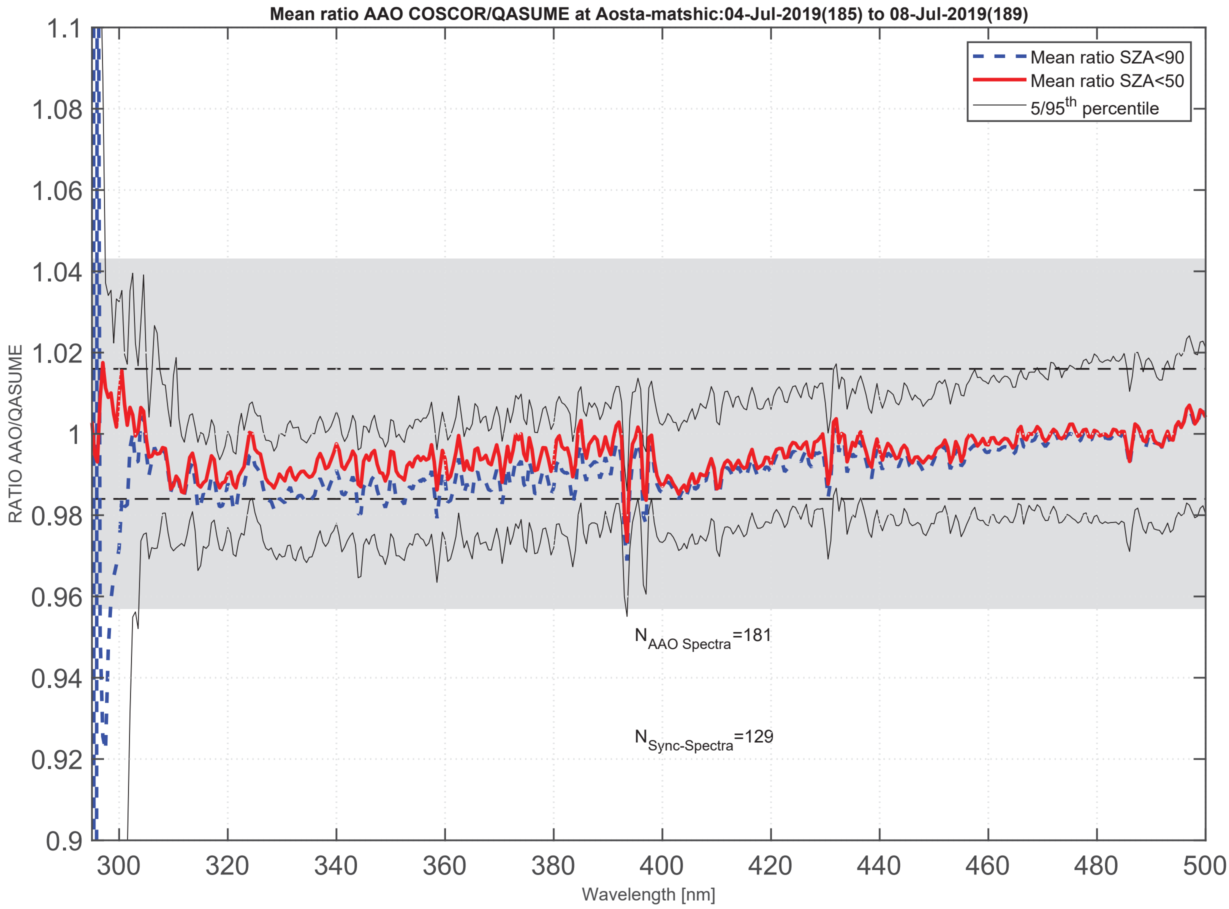

Global irradiance ratios AAO COSCOR/QASUME at Aosta-matshic:04-Jul-2019(185)
1.1
1.05
1
0.95
0.9
300
320
340
360
380
400
420
440
460
480
500
wl [nm]
AAO
QASUME
UVIndex
10
8
6
4
2
0
5
10
15
20
84°
Daily variation. Wavelength bands are ± 2.5 nm
87°
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm
2(104)
4(89)
6(70)
8(49)
10(30)
12(23)
14(37)
16(57)
18(78)
20(96)
TIME [UT](SZA)

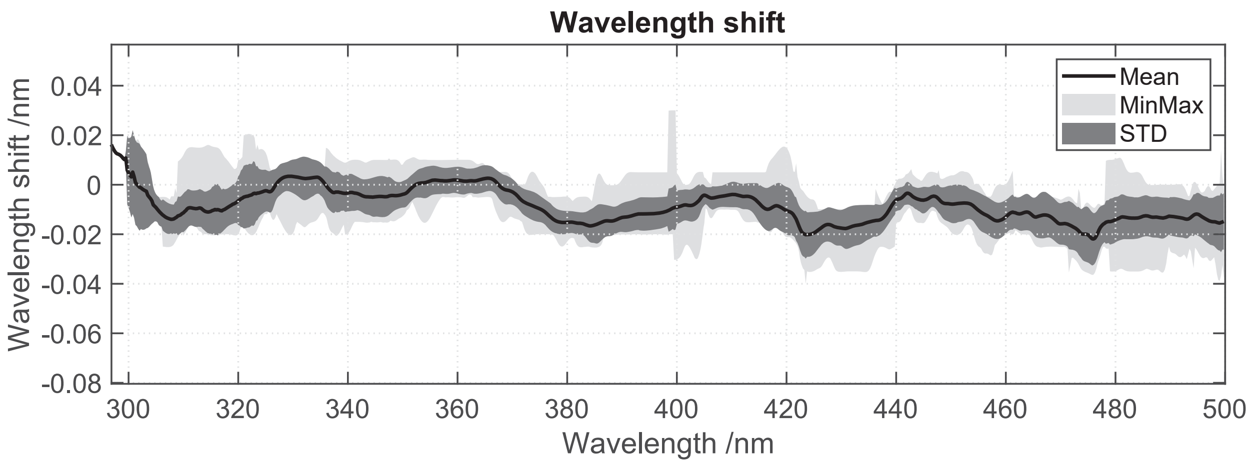

Global irradiance ratios AAO COSCOR/QASUME at Aosta-matshic:05-Jul-2019(186)
wl [nm]
AAO
QASUME
UVIndex
Daily variation. Wavelength bands are ± 2.5 nm
89°
87°
TIME [UT](SZA)
2(104)
4(89)
6(70)
8(49)
10(30)
12(23)
14(37)
16(58)
18(78)
20(96)
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm

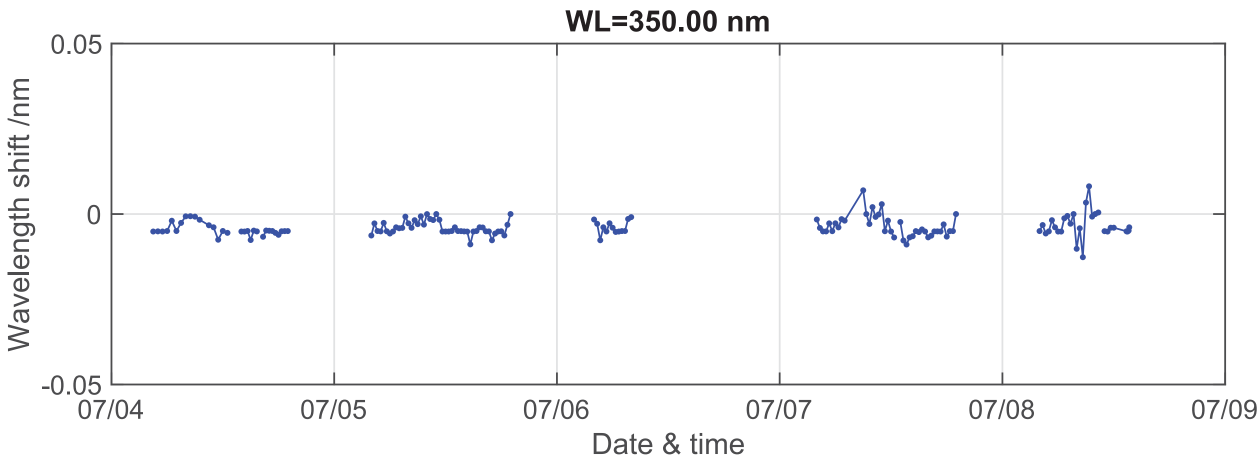

Global irradiance ratios AAO COSCOR/QASUME at Aosta-matshic:06-Jul-2019(187)
wl [nm]
AAO
QASUME
UVIndex
Daily variation. Wavelength bands are ± 2.5 nm
TIME [UT](SZA)
2(104)
4(89)
6(70)
8(49)
10(30)
12(24)
14(37)
16(58)
18(78)
20(96)
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm

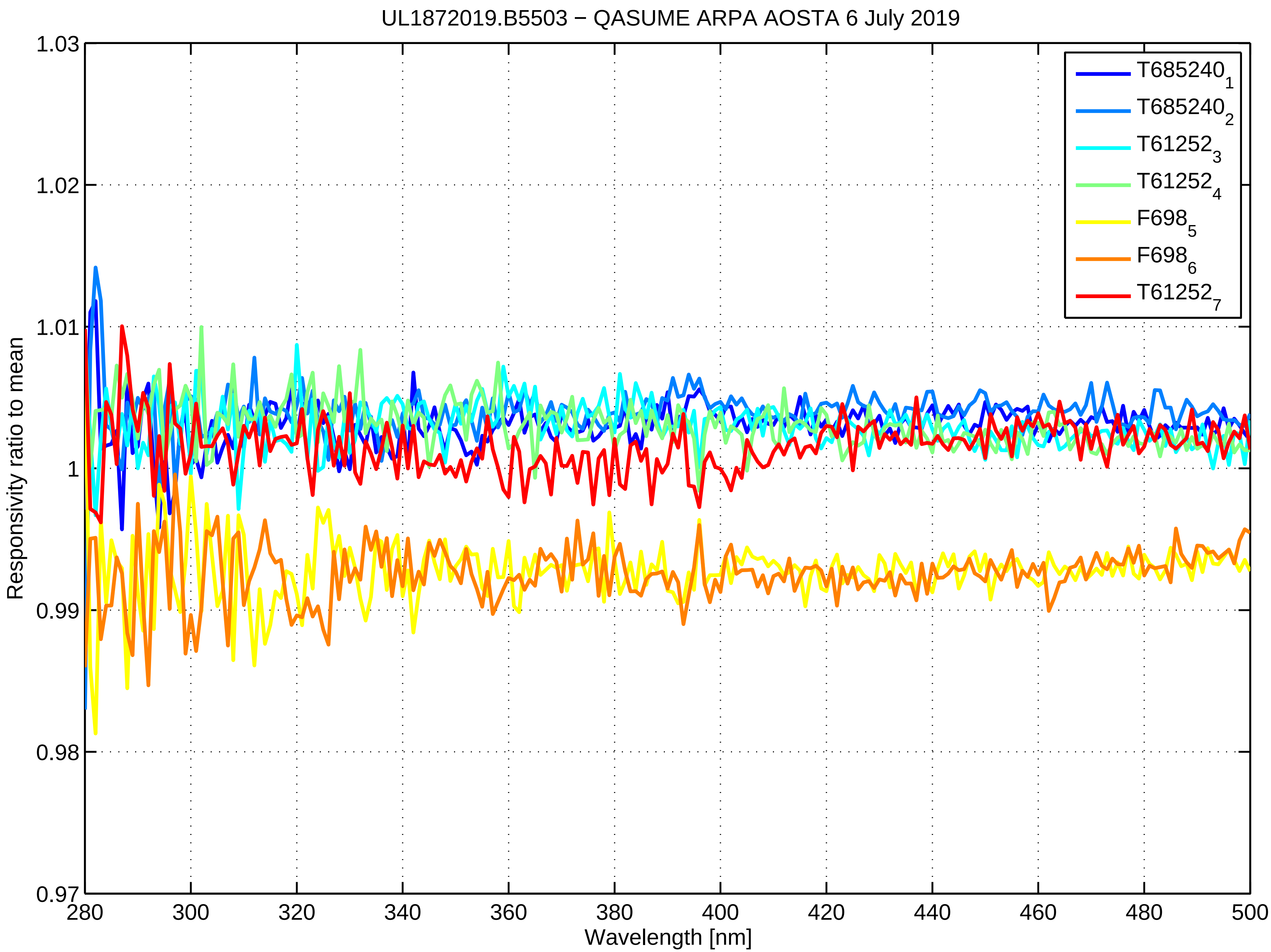

Global irradiance ratios AAO COSCOR/QASUME at Aosta-matshic:07-Jul-2019(188)
1.1
1.05
1
0.95
0.9
300 320 340 360 380 400 420 440 460 480 500
wl [nm]
AAO
QASUME
UVIndex
0 2 4 6 8
5 10 15 20
Daily variation. Wavelength bands are ± 2.5 nm
89°
87°
2(104) 4(89) 6(70) 8(49) 10(30) 12(24) 14(37) 16(58) 18(78) 20(96)
TIME [UT](SZA)
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm

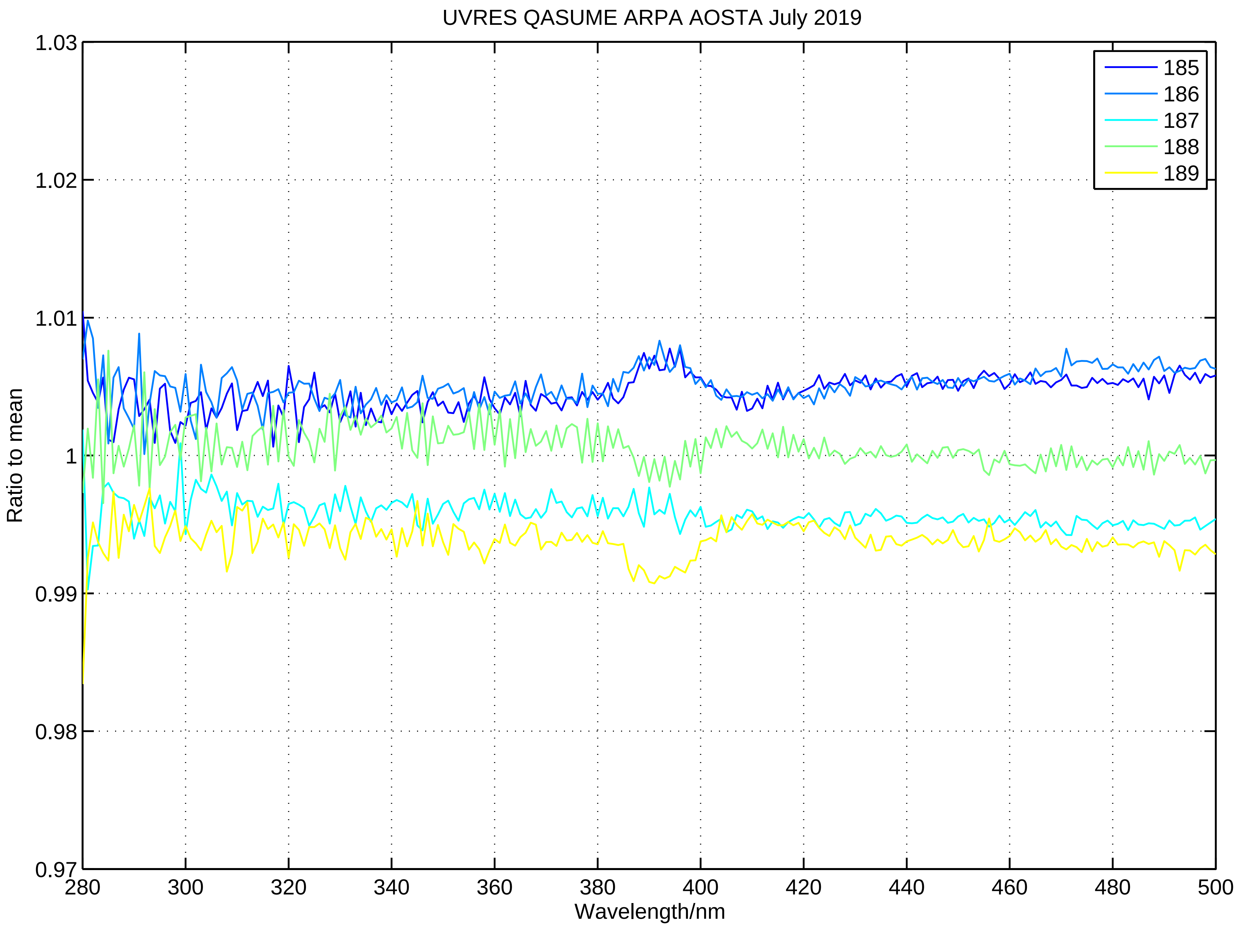

Global irradiance ratios AAO COSCOR/QASUME at Aosta-matshic:08-Jul-2019(189)
1.1
1.05
1
0.95
0.9
300 320 340 360 380 400 420 440 460 480 500
wl [nm]
AAO
QASUME
UVIndex
0 1 2 3 4 5 6
5 10 15 20
Daily variation. Wavelength bands are ± 2.5 nm
89°
2(104) 4(89) 6(70) 8(49) 10(30) 12(24) 14(37) 16(58) 18(78) 20(96)
TIME [UT](SZA)
305 nm
310 nm
320 nm
350 nm
400 nm
450 nm
495 nm

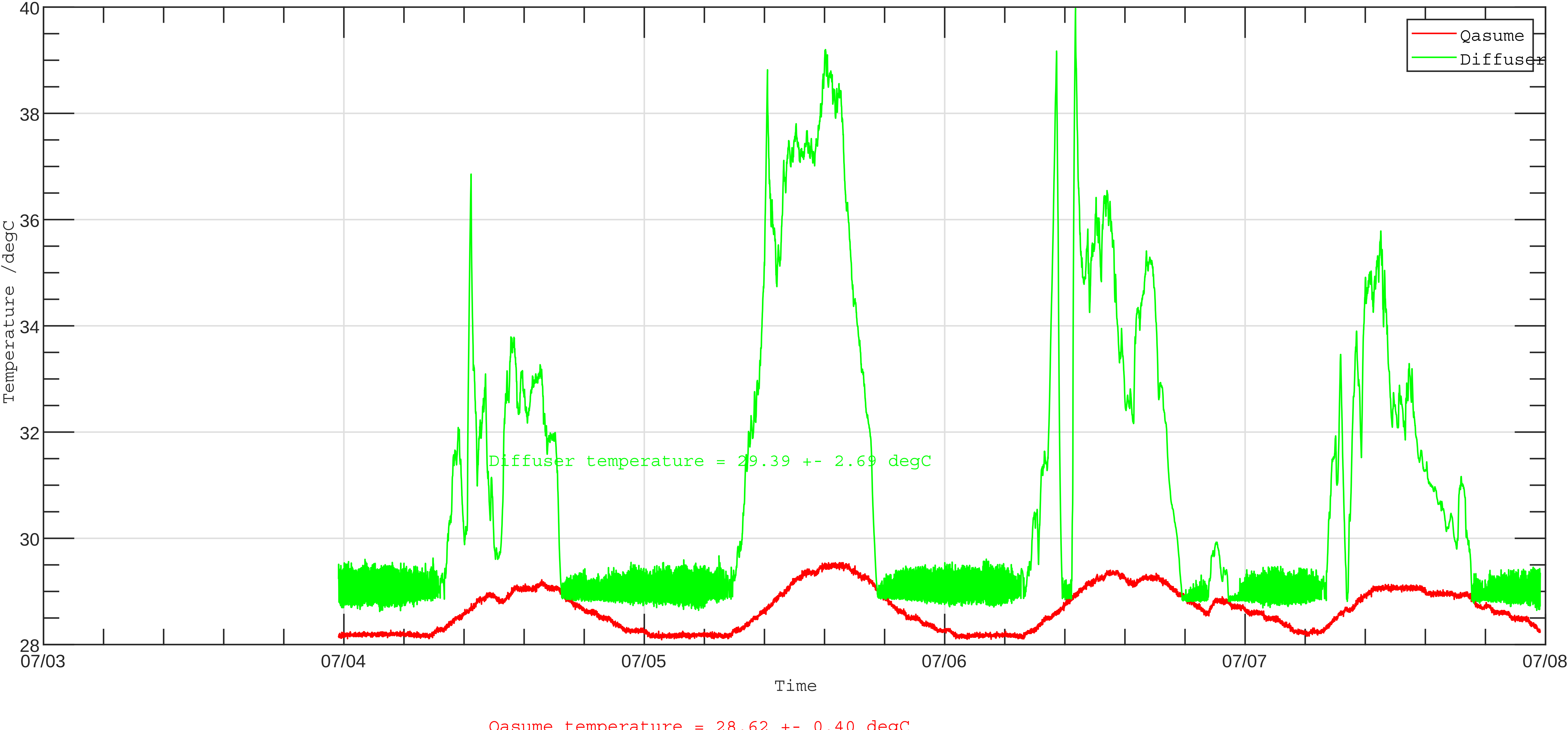

Mean ratio AAO COSCOR/QASUME at Aosta-matshic:04-Jul-2019(185) to 08-Jul-2019(189)
Mean ratio SZA<90
Mean ratio SZA<50
5/95th percentile
RATIO AAO/QASUME
N AAO Spectra =181
N Sync-Spectra =129
Wavelength [nm]


Wavelength shift
Mean
MinMax
STD
Wavelength shift /nm
Wavelength /nm

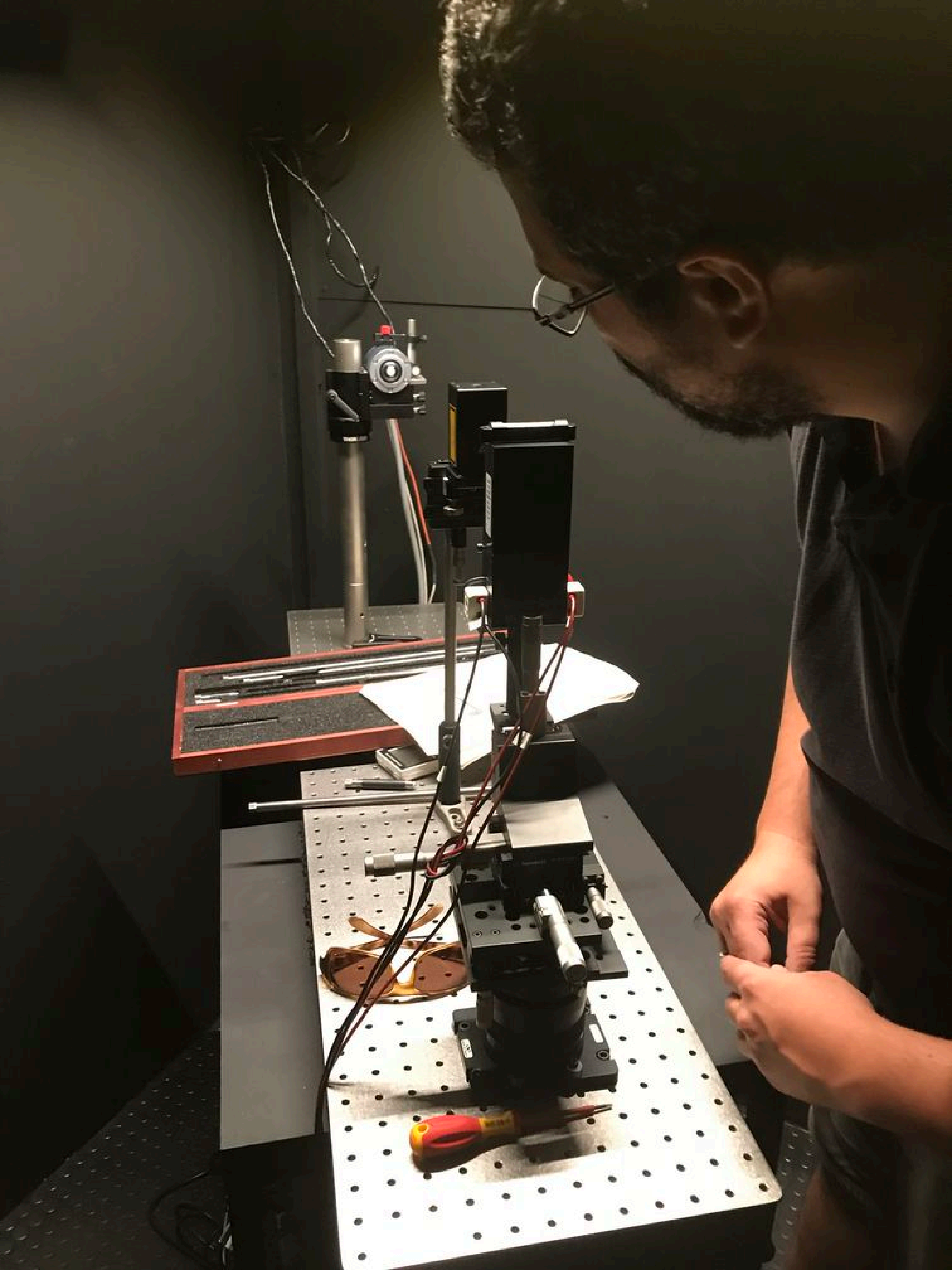

WL=350.00 nm
Wavelength shift /nm
Date & time


UL1872019.B5503 − QASUME ARPA AOSTA 6 July 2019
Responsivity ratio to mean
Wavelength [nm]
1.03
1.02
1.01
1
0.99
0.98
0.97
280
300
320
340
360
380
400
420
440
460
480
500
T685240_1
T685240_2
T61252_3
T61252_4
F698_5
F698_6
T61252_7


UVRES QASUME ARPA AOSTA July 2019
Ratio to mean
Wavelength/nm
1.03
1.02
1.01
1
0.99
0.98
0.97
280
300
320
340
360
380
400
420
440
460
480
500
185
186
187
188
189



Qasume
Diffuser
Diffuser temperature = 29.39 +- 2.69 degC
Temperature /degC
40
38
36
34
32
30
28
07/03
07/04
07/05
07/06
07/07
07/08
Time
Qasume temperature = 28.62 +- 0.40 degC



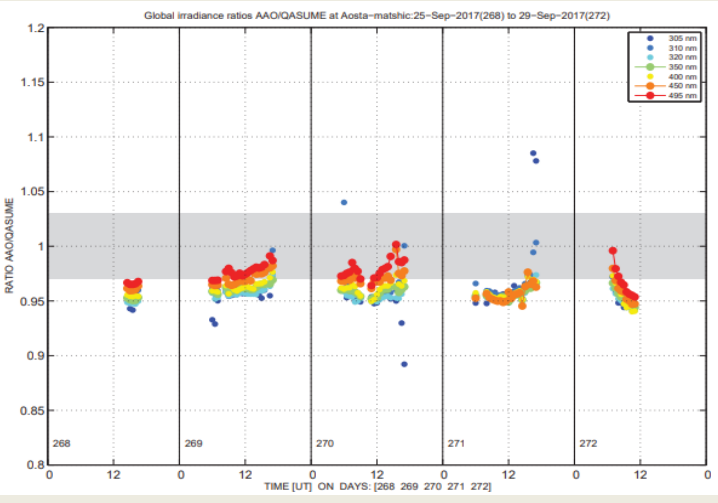

pmod wrc

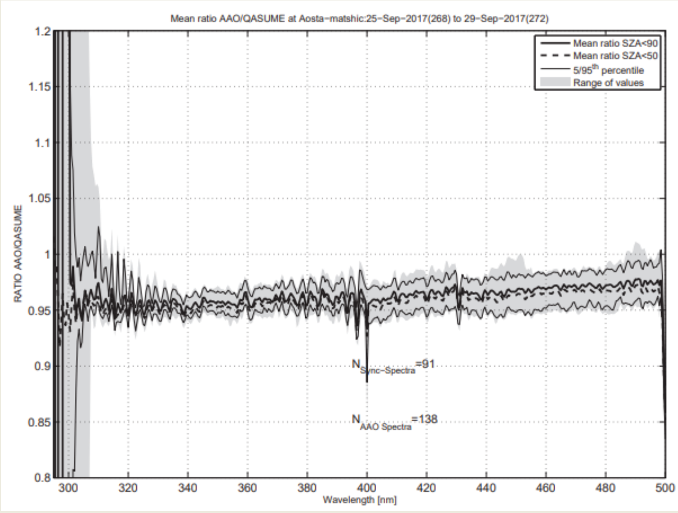
Comments from the local operator:

Bentham characterization and remaining issues

2017 QASUME inter-comparison

- AAO irradiance on average 4% below QASUME
- Strong spectral dependence of the ratio





What was investigated

1. Effect of temperature on the teflon diffuser
2. Linearity
3. Angular response
4. Calibration factors
5. Wavelength shift

1. Temperature

- A number of tests were done to check if the applied temperature correction works properly
  - Measurements with 200 Watt lamps during one day (34 – 40°C)
  - Laboratory measurements during one day (18 – 41°C)
- In order to check if the real temperature of the diffuser is recorded by the thermistor we used an infrared camera

Temperature – outdoor measurements with 200 Watt lamps

- clear sky day - measurements using two 200 Watt KS lamps at different times
- Long calibrator setup (with extender)
- Temperature of the diffuser in the day → ~34 - 40 °C
- representative temperature range for summer months

Temperature – outdoor measurements with 200 Watt lamps

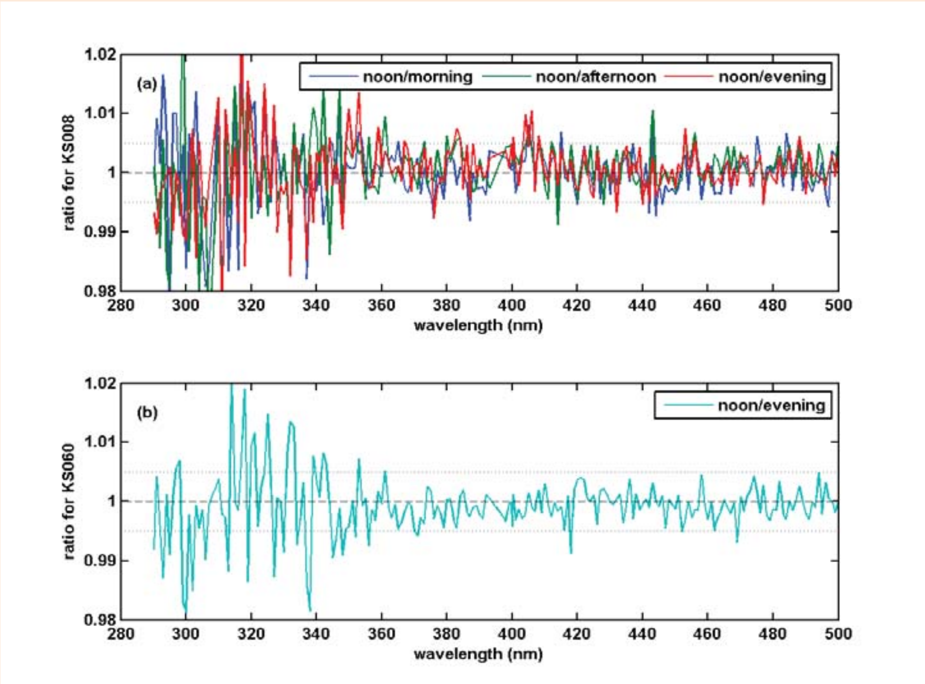


Figure: Ratio between measurements performed at morning (temperature ~ 34 °C), afternoon (~39 °C), and the evening (~38 °C), and noon (~40 °C) with lamps (a) KS008 and (b) KS060. All measurements are corrected for the effect of temperature.

Temperature – Laboratory measurements

- Temperatur stabilization of the OH turned off
- temperature of the calibration room (and the OH) was regulated to 18 °C
- Temperature of the room (and the OH) gradually increased to more than 40 °C
- measurements using different setups -1000 Watt lamps and 200 Watt lamps (short &long setup) – at different temperatures

Temperature – Laboratory measurements

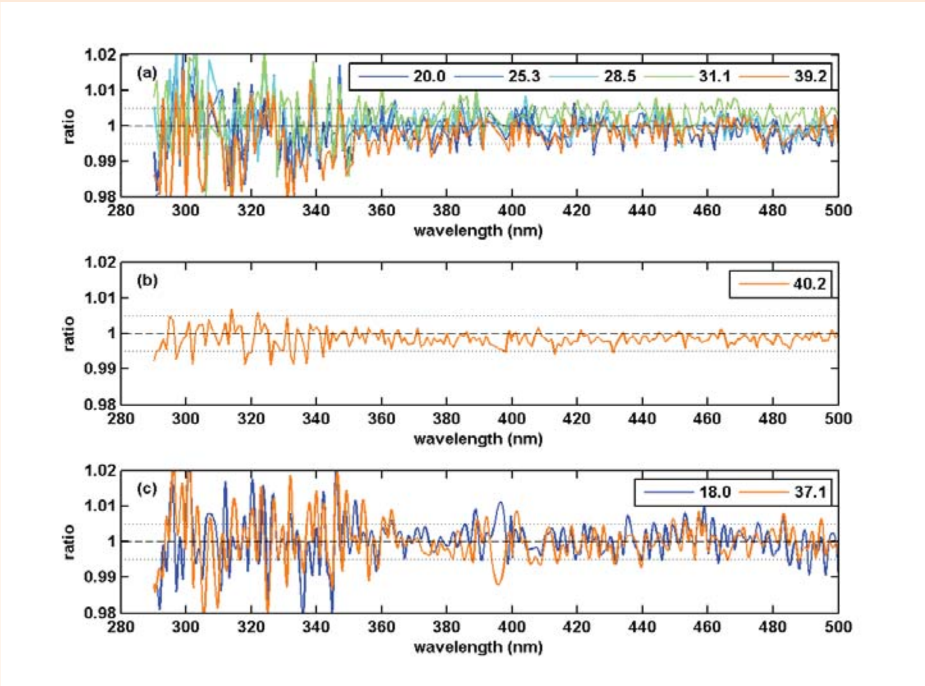


Figure: Ratio between measurements performed at different temperatures and a reference spectral scan using (a) the 200 Watt lamp calibration setup with the extender (temperature of reference scan: 34 °C), (b) the 200 Watt lamp calibration setup without the extender (temperature of reference scan: 35 °C), and (c) the 1000 Watt lamp calibration setup (temperature of reference scan: 33 °C). The temperatures in the legends are those recorded at the beginning of the scan. All measurements are corrected for the effect of temperature.

Temperature – diffuser warming

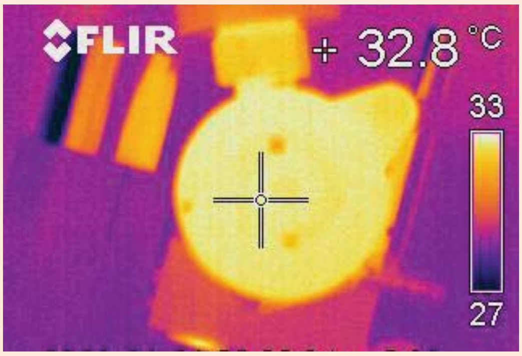


Figure: Temperature of the optical head after temperature stabilization at 32.7 °C

- A number of photos were taken using a thermal camera before and after measurements with 200 Watt lamps
- The dome was removed before each photo with the camera
- The results were consistent within 2 °C with the recordings of the thermistor

Temperature – calibration factors re-evaluation

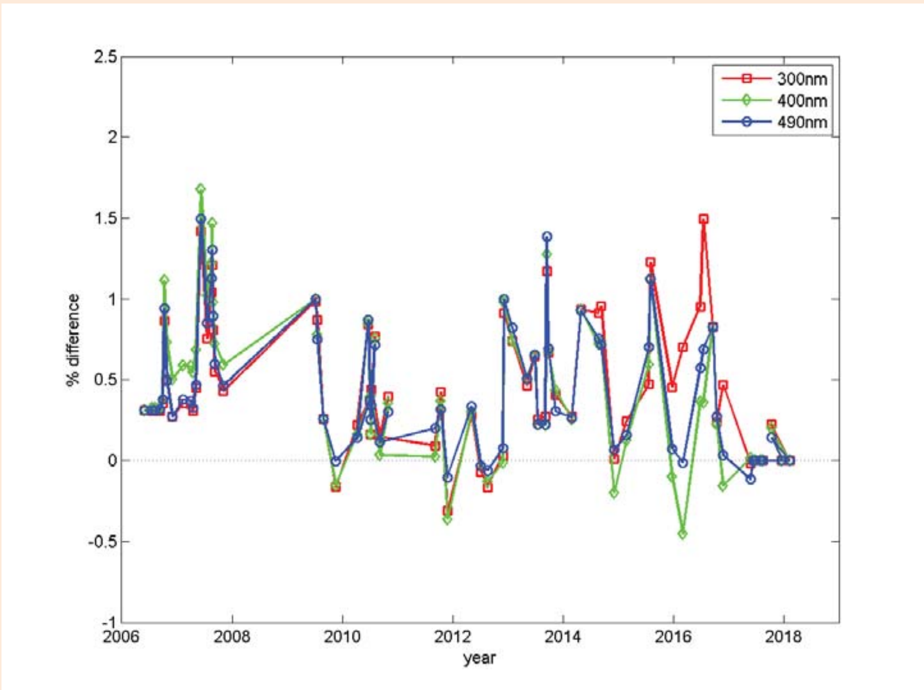


Figure: Ratio between the corrected and un-corrected responses for the effect of temperature for the period 2006 – 2018. The presented changes led to reduced variability in the response.

2. Linearity

- In order to examine the linearity of the system we performed the following tests:
  - Spectra were recorded with a very high frequency for 10 consecutive summer days (27 June – 6 July 2018). Measurements with 200 Watt lamps at the beginning and at the end of that period.
  - Measurements with 200 Watt lamps throughout a clear-sky day (noon UVI ~7.5).
  - Measurements using different (or no) slits in order to increase the recorded signal.
  - Lamp measurements while the Bentham was not measuring for a few days

Linearity – high frequency measurements for a long period

- Non-stop spectral scans (2 min frequency) at 290 – 400 nm from 27-06 to 06-07-2018 (10 days)
- 200 Watt lamp measurements at the beginning and the end of the period
- Response did not change

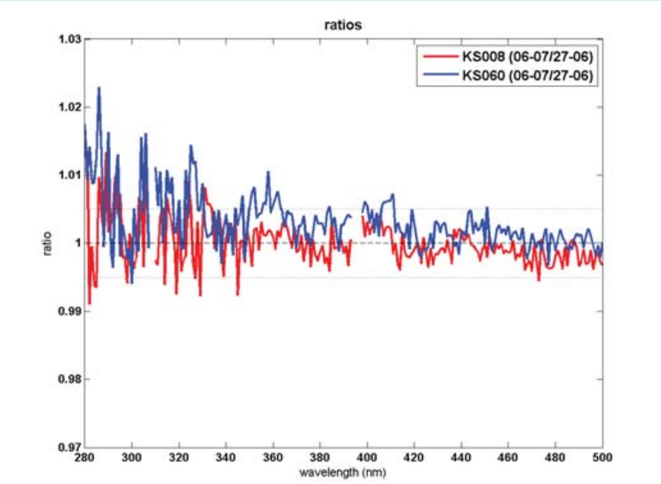
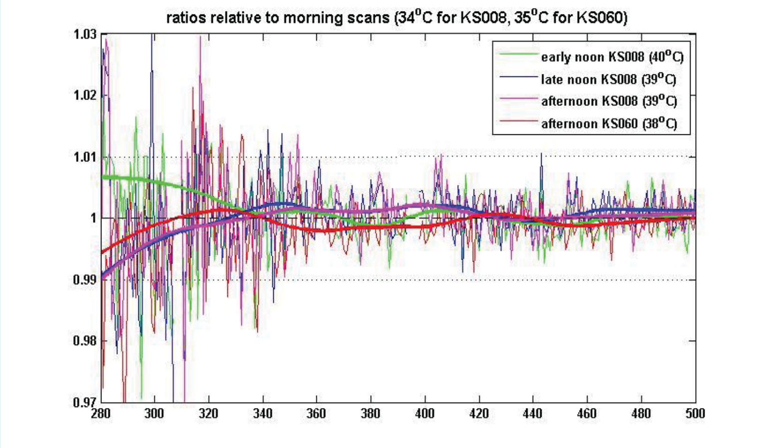


Figure: Ratios between the lamp measurements at the beginning and the end of the test period for the two lamps.

Linearity – does the response change in the day?

- 19-07-2018 → measurements with 200 Watt lamps in the day (noon UVI ~7.5)
- Non-stop spectral scans in the range 290 – 500 nm
- No change in the response



Linearity – Measurements using wider slits

- Non-stop spectral measurements from morning to noon using wider slits
- Lamp measurements before and after
- Signal level (at noon) 4-5 times higher than regular maximum signal in Aosta (~ 2 times higher than in Davos 2014 inter-comparison)

Linearity – Measurements using wider slits

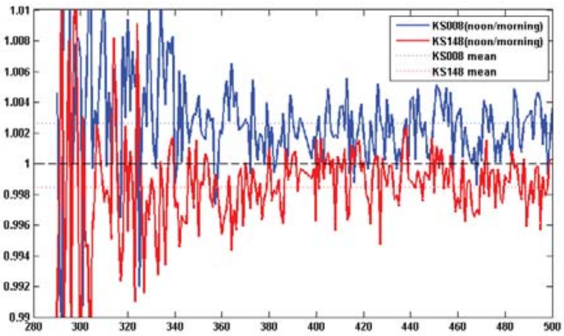


Figure 1: Ratios between measurements with 200 Watt KS lamps at morning and noon.

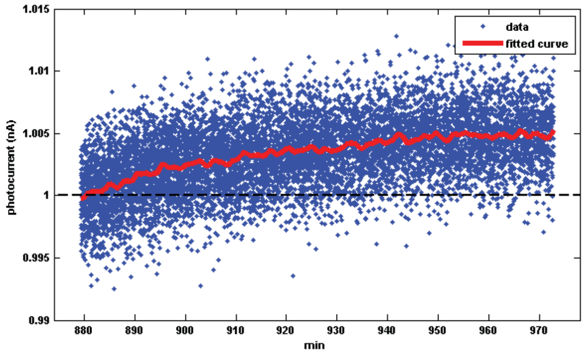


Figure 2: Continuous measurements at a single wavelength (low signal - irradiance from lamp) after stopping spectral scans.

Linearity – measurements without slits

- Non-stop spectral measurements from morning to noon
- Lamp measurements before and after
- Signal level (at noon) ~10 times higher than maximum signal in Aosta (~ 4-5 times higher than in Davos 2014 inter-comparison)

Linearity – measurements without slits

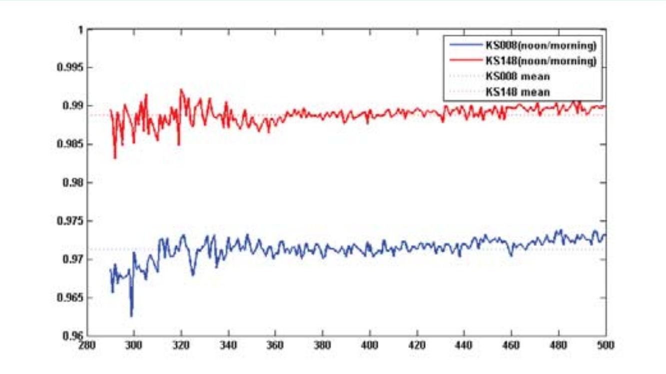


Figure 1: Ratios between measurements with 200 Watt KS lamps at morning and noon (after performing consecutive spectral scans without slits).

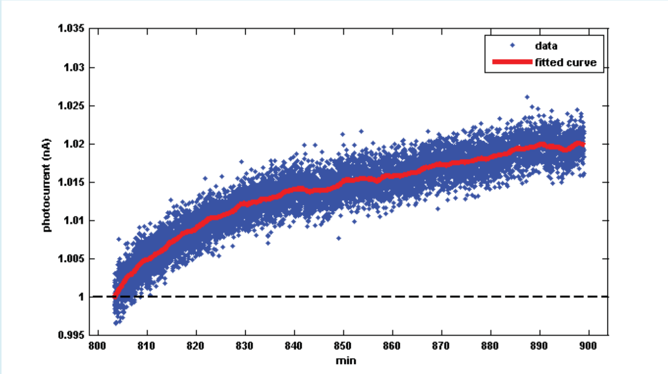


Figure 2: Continuous measurements at a single wavelength (low signal - irradiance from lamp) after stopping spectral scans

Linearity – stop measurements for a few days

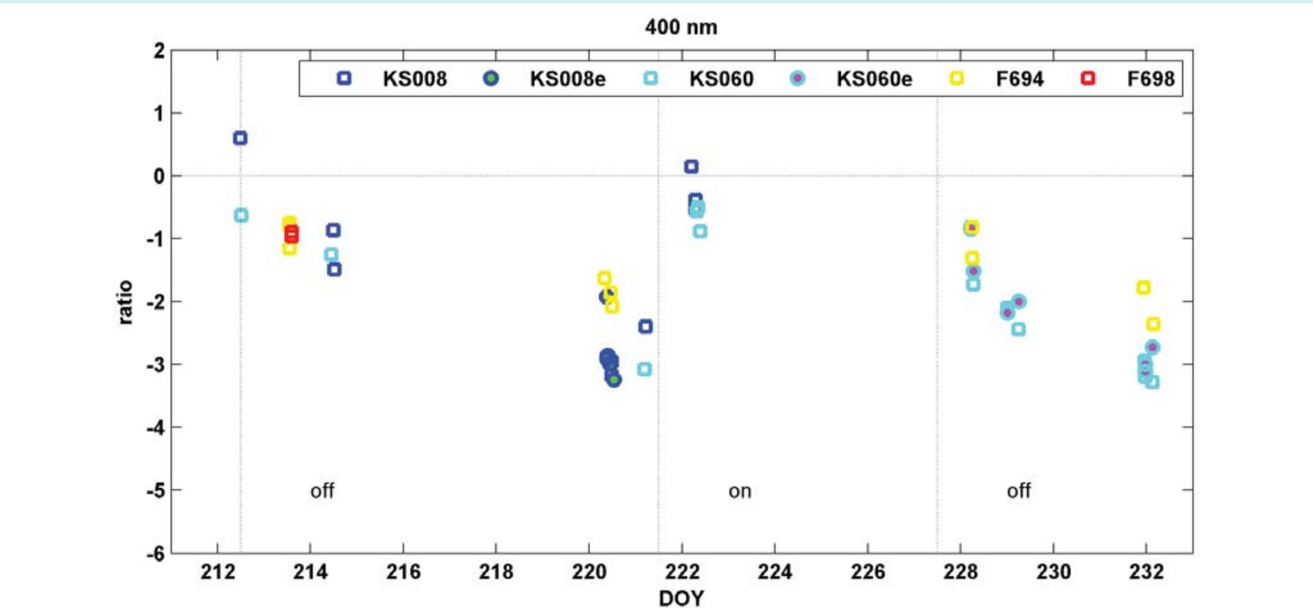


Figure: Change % of the response at 400 nm (390 – 410 nm average) as measured using different calibration setups and lamps. When the Bentham is not measuring for some hours/days, the response decreases (up to ~3% in 10 days).

In the summer, even a stop of 1-2 hours is enough to see a ~0.5% decrease in the response

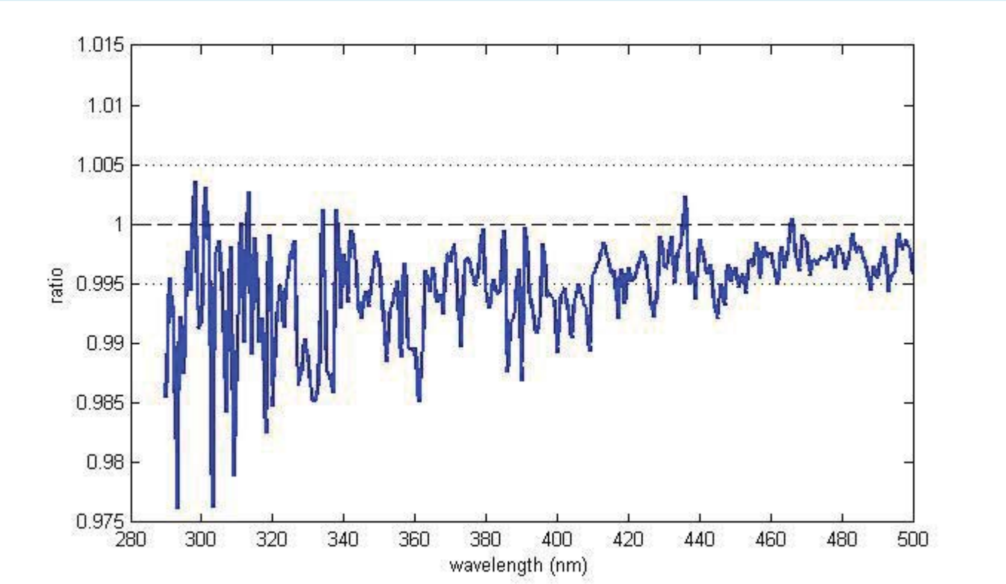


Figure: Ratio between the average response before and after a ~1 - 1.5 hour break

3. Angular response

- Cosine error – effect on the inter-comparison results, especially after the optics of QASUME changed (2017) – same optics before 2017.
- Error when we use the instrument's bubble after 2014 – should always use the leveling cup
- Small azimuth dependence – different possible explanations

Angular response – cosine error

- Part of the variability (1-2%) in the inter-comparisons can be explained by differences in the cosine response of the two instruments

- Similar results for the old and new QASUME optics.

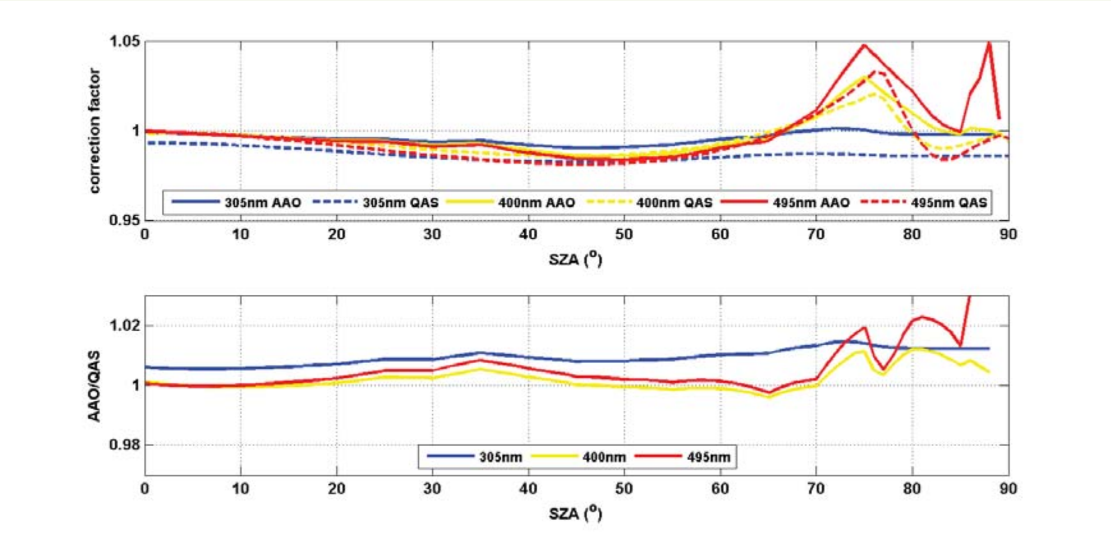
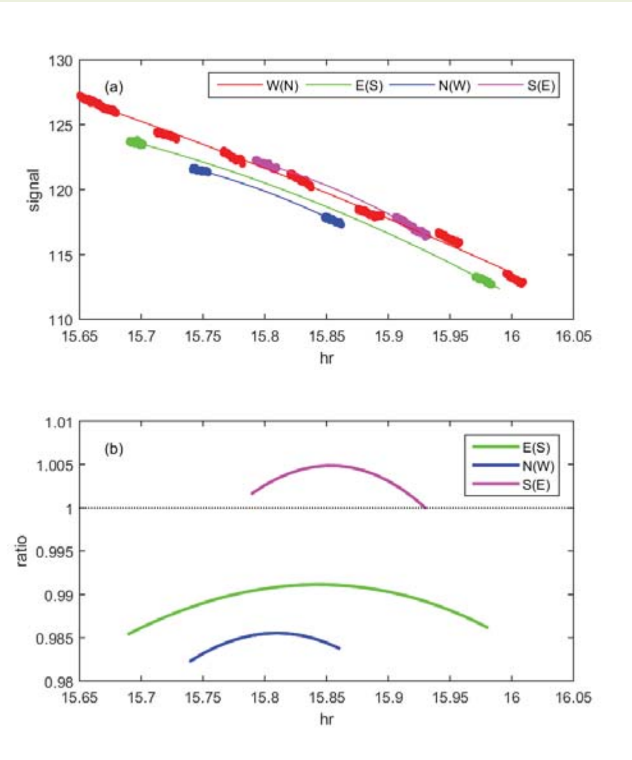


Figure: Correction factors for the effect of cosine error on the global irradiance modeled for Aosta (DOY 196/2015) **(a)** for O3=330 DU and AOD=0.1

Azimuth dependence of the response



(a) Measured signal for different diffuser orientation

(b) Ratios between the polynomials for each direction and the polynomial for the silica jell case (SJC) oriented to the North

•letter in the parenthesis → direction of the SJC

•letters outside the parenthesis → azimuth angle of the sun at which the result would be the same without rotating the diffuser

•Consistent results with Gregor's measurements (QASUME report 2015)

Azimuth dependence of the response

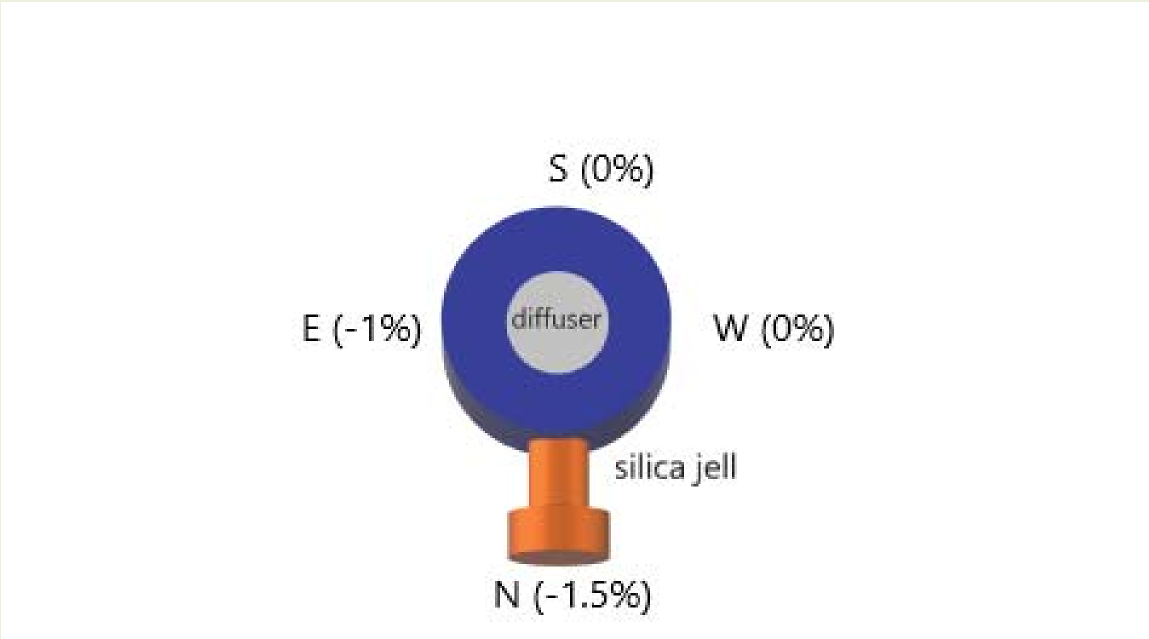
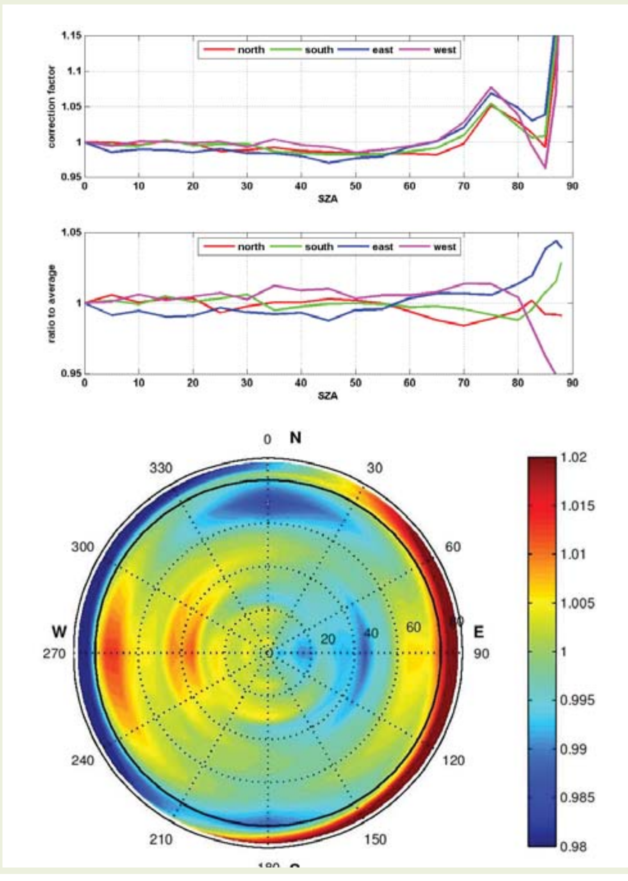


Figure: Response change relative to 0 azimuth when SZA is 60°

Azimuth dependence of the response

- Possible reasons:
  - Fiber misplacement
  - Diffuser inhomogeneity
- In any case → below desired uncertainty
- Probably does not worth re-align fiber or do anything else

Results from characterization in Davos



OH bubble

- After disassembling and reassembling the OH in 2014, using the leveling bubble introduces a miss-leveling of ~0.6 - 0.8° towards the south-west direction.

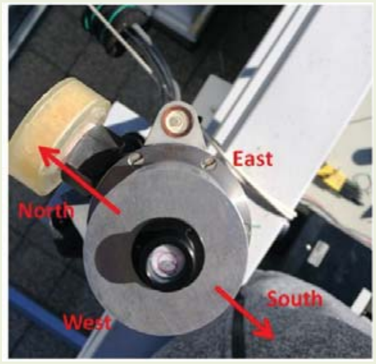
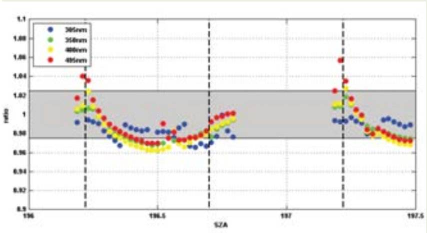
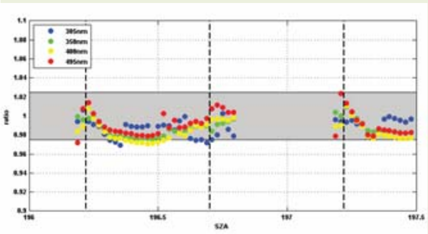


Figure: Mis-leveling of the diffuser.





- Recalculating the AAO/QASUME ratio for 2014 and taking this effect into account (modeling the effect) improves the results for the clear sky days of the campaign.

4. Calibration

- 2017 intercomparison → AAO on average ~4% below QASUME

- Difference could be explained if the used spectral response was problematic

- No problem was detected at the time of the inter-comparison

- Problem in the used lamp certificates?

Re-evaluation of the lamp certificates

- new calibration facilities (end of July of 2018) → comparison between the new 1000 Watt lamps and the KS 200 Watt lamps.

- Wavelength depended difference of 2-3% toward the expected direction

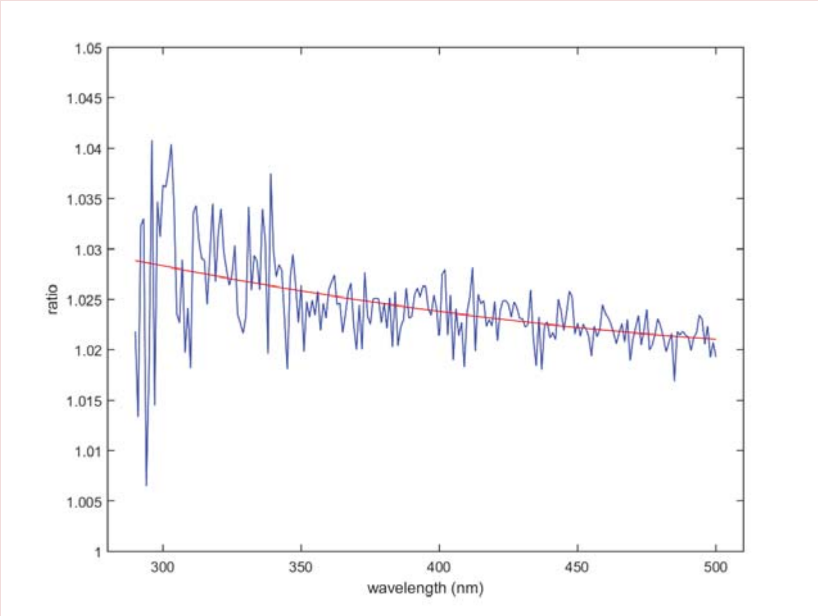


Figure: Ratio between the average response from lamps KS008 and KS060, and the average response from lamps F694 and F698, as it was calculated in July 2018.

Re-evaluation of the lamp certificates

- Previous re-calibration of KS lamps → end of 2015 at Davos

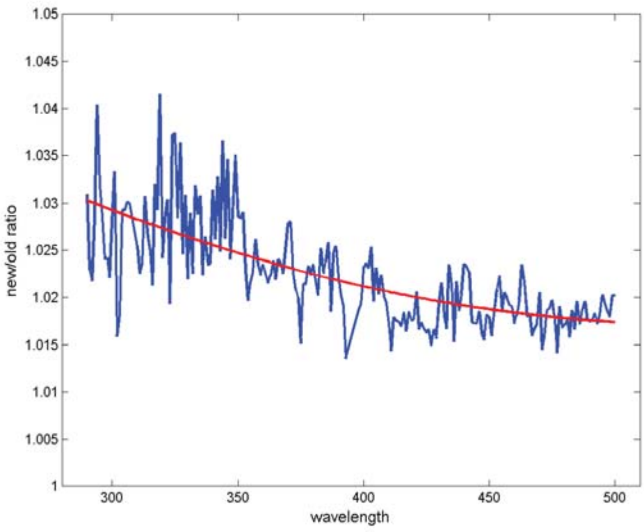
- KS060 → same as before

- KS052 → change of the lamp irradiance by 2-3%

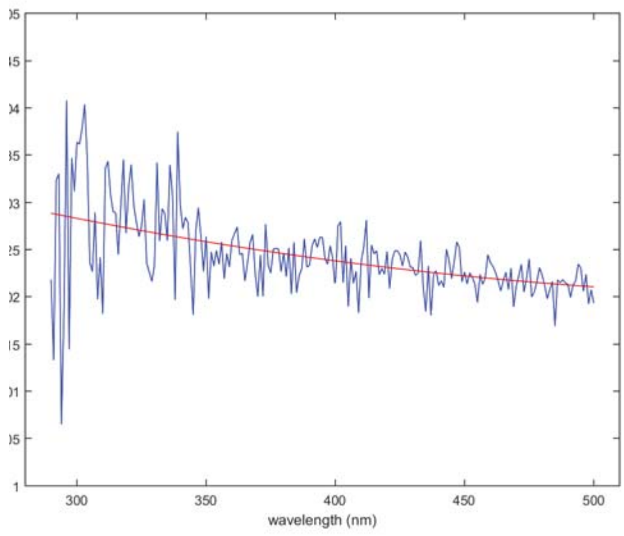
- KS052 → became unstable/ stop being used when it came back

- If KS052 was used instead of KS060 the average difference in 2017 intercomparison would be ~ -1.5%

Re-evaluation of the lamp certificates



Ratio between the irradiance of KS052 after and before the last calibration in Davos.



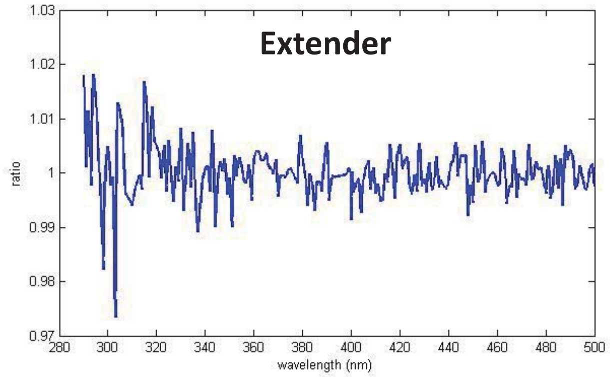
Ratio between the average response from lamps KS008 and KS060, and the average response from lamps F694 and F698, as it was calculated in July 2018.

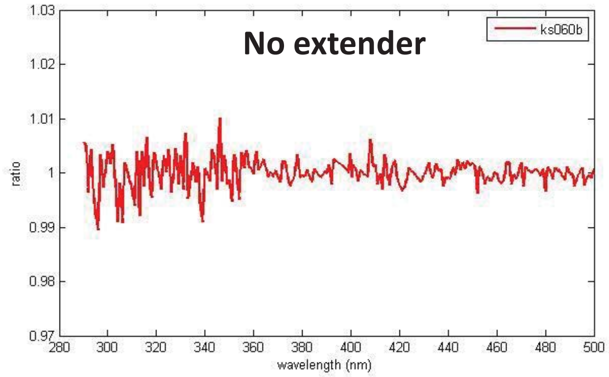
Comparison with other instruments

- Trying to detect the timing of possible change
- Comparison with:
  - Erythema and UVA from broadband
  - Pyranometer (400 - 500nm average to total VIS)
  - 318-322nm average from Brewer
  - Simulated UVA and erythema from libradtran
- Small SZA intervals for morning/evening
- Even then variability is larger (in all cases >3%) than the change we are looking for
- Too many problems near the time when the last (2015) KS irradiances were first used → cannot get safe conclusions by checking the calibration record

Other calibration issues

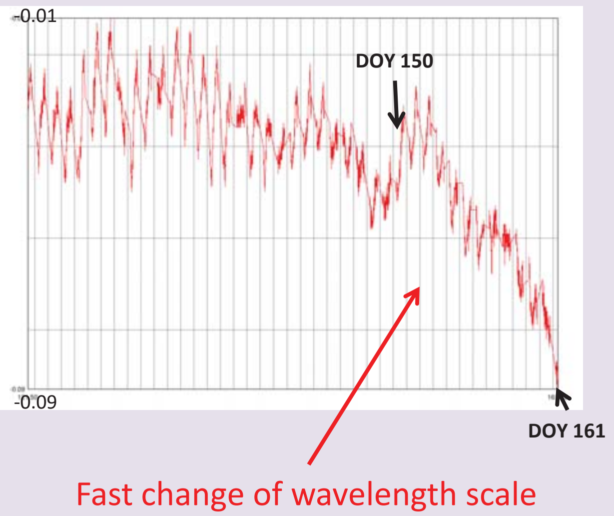
- KS lamp calibrator:
  - More consistent measurements with extender (calibrator without the extender is unstable)
  - More noise with extender
  - Better agreement with 1000 Watt lamps with extender

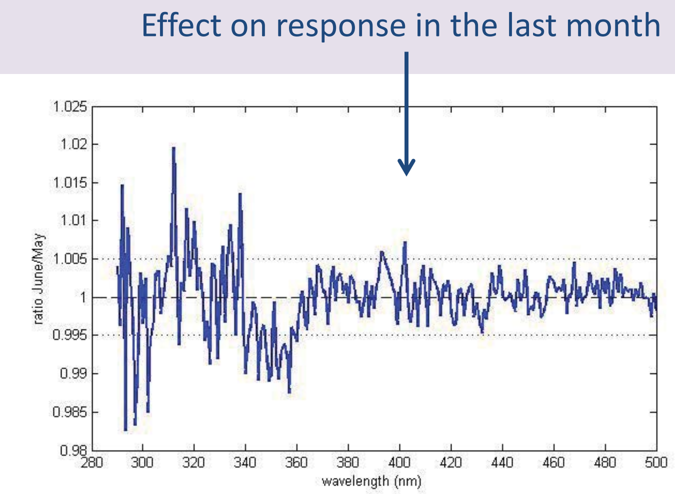




5. Wavelength shift

- Does the spectrometer need maintenance?





Wavelength shift

- MATshic ➔ Some settings affect the results below 320nm – e.g. rescrit

- However, we have to check again the results

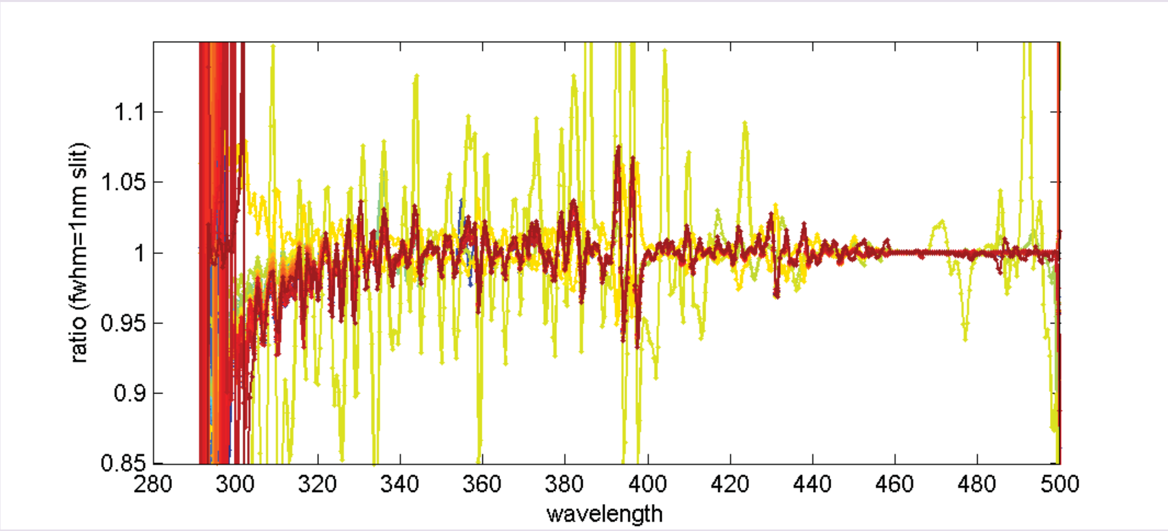


Figure: Ratio between the MATshic outputs for 15 July 2014 for rescrit=”2.2 2.0” and rescrit=”1.0 1.0”.