

Protocol of the intercomparison at DSA, Oslo, Norway on May 21
to 26, 2026 with the travelling reference spectroradiometer
QASUME from PMOD/WRC

Report prepared by Gregor Hülsen

Operator: Christian Thomann
Local operator: Bjørn Johnsen

The purpose of the visit was the comparison of global solar irradiance measurements between the travelling reference spectroradiometer QASUME and the Bentham DM150-NRP spectroradiometer operated by DSA (Norwegian Radiation and Nuclear Safety Authority (DSA), former Norwegian Radiation Protection Authority (NRPA). The measurement site is located at Østerås at the outskirts of Oslo: Latitude 59.95 N, Longitude 10.60 E and altitude 130 m.a.s.l. The horizon of the measurement site is free down to 80° solar zenith angle (SZA). Measurements between 2:30 UT and 21:00 UT have been analysed.

A second Bentham spectroradiometer from DSA (Bentham DTM300-NR2) and a group of eight 19-channels model GUVis-3511 instruments and one 5-channels model GUV-541 (Biospherical Instruments, Inc) were run side-by-side the QASUME spectroradiometer throughout the campaign. In the group of GUVis/GUV instruments was also a 19-channel GUVis-3511, fitted with a rotating shadow band, that provided direct, diffuse and global spectral irradiances for the cosine corrections of the DSA's NRP and NR2 spectroradiometers. UVI data was submitted for the GUV-9280 for the blind test comparison with the QASUME spectroradiometer. This GUV instrument - replaced the former GUV-9277 which was operating at Østerås up to 2020 - one of 9 Norwegian UV monitoring stations (quality-controlled data from all stations 1995-2023 available at <https://github.com/uvnrpa>). Calibrations are traceable to QASUME/PMOD-WRC through participation in the FARIN campaign arranged in Oslo in 2005-See: Johnsen, B., et al. (2008), Intercomparison and harmonization of UV Index measurements from multiband filter radiometers, J. Geophys. Res., 113, D15206, doi:10.1029/2007JD009731; reports auf the QASUME site audits are available on webpage of PMOD/WRC, WCCUV department.

QASUME was installed on the measurement platform of DSA in the morning of May 21, 2026. The spectroradiometer was installed next between the Bentham spectrophotometer (NRP, from DSA) and the filter radiometers, with the entrance optic of QASUME within 2 m to the other instruments. The NRP and NR2 are Bentham DM150 and DTM300 spectroradiometers, respectively. NRP is equipped with a D6 entrance optic (Bentham Instruments) and NR2 is equipped with a UV-J1002 entrance optic (CMS-Schreder, where both optics are thermostatted, and protected by quartz domes. The intercomparison between QASUME and the spectroradiometers lasted five days, from the morning of May 21 to the afternoon of May 26.

QASUME was calibrated several times during the intercomparison period using a portable calibration system. Five lamps (T157824, T157824, T153061, T153062 and T68523) were used to obtain an absolute 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 $\pm 0.5\%$ during the intercomparison period. The internal temperature of QASUME was $27.48 \pm 0.07^\circ\text{C}$ and the diffuser head was heated to a temperature of $29.06 \pm 0.41^\circ\text{C}$.

The wavelength shifts relative to the QASUMEFTS (Gröbner et al., 2017) spectrum as retrieved from the matSHIC analysis were between ± 50 nm in the spectral range 290 nm to 540 nm.

Protocol:

The measurement protocol was to measure one solar irradiance spectrum every 30 minutes from 288 nm to 540 nm, every 0.5 nm, and 3.0 seconds between each wavelength increment. QASUME recorded the spectra with 0.25 nm increments and NRP and NR2 with 0.5 nm increment

DOY	Date	DAY	Weather	Comment (times are in UT)
141	21.May	Thursday	Rain in the morning Clear sky in the evening	Installed at 11:00 12:00 start UV measurements SSDS failure
142	22.May	Friday	Clear sky in the morning Mix of sun and clouds in the afternoon	06:17 Fix SSDS (Powercycle) 09:27 Calibration T157825
143	23.May	Saturday	Diffuse sky in the Morning with little rain Clear sky in the late afternoon	07:28 Calibration T157824 07:55 Calibration T157825 08:22 Calibration T68523
144	24.May	Sunday	Mostly diffuse sky in the morning Clear sky in the late afternoon	09:31 Calibration T157824
145	25.May	Monday	Mostly diffuse sky	07:30 Calibration T157825 07:56 Calibration T153062 08:26 Calibration T153061
146	26.May	Tuesday	Mostly diffuse sky in the morning Mix of sun and clouds after 9 UT	08:00 Calibration T157824 16:00 End of Campaign

Results:

In total 134/138 synchronised simultaneous spectra from QASUME and NRP/NR2 are available from the measurement period. Measurements between 2:30 and 20:00 UT have been analysed (SZA smaller than 90°). In addition, UVI data were supplied by DSA for the NRP and NR2 spectroradiometers, as well as for the network travelling filter radiometer GUV 9280.

Remarks:

DSA delivered two datasets for the NRP and NR2 spectroradiometer: One using a cosine correction, the other without cosine correction.

NRP (DM150):

1. The ratios between NRP and QASUME have on average an offset of -2% for wavelengths longer than 310 nm (figures NRP-C/QASUME).
2. The diurnal variation of the NRP to QASUME ratio is negligible. The cosine corrected dataset shows a slightly better performance.
3. The comparison of the erythema weighted irradiance shows an average offset of -2%.
4. The wavelength shifts of NRP relative to the high spectral resolution solar spectrum are between ± 20 nm in the spectral range 290 nm to 440 nm and ± 100 nm at longer wavelengths.

NR2 (DTM300):

1. The ratios between NR2 and QASUME have on average an offset of -2% for wavelengths longer than 310 nm (figures NRP-C/QASUME).
2. The diurnal variation of the NR2 to QASUME ratio is negligible for solar zenith angles smaller than 75°. Both datasets show a cosine error for higher zenith angles, and the cosine correction algorithm seems to overcorrect the data.
3. The comparison of the erythema weighted irradiance shows an average offset of -0.5%.
4. The wavelength shifts of NR2 relative to the high spectral resolution solar spectrum are between ± 50 nm in the whole spectral range.

GUV-9280:

1. The ratio of weighted irradiance UV data from the multifilter radiometer GUV-9280 to the local instruments have been analysed by Bjørn Johnsen (see section "Comments by the local operator"). The comparison of the erythema weighted irradiance shows an average offset of 0% with a higher diurnal variability, which could be due to the time stamp used to compare the different datasets.

Comparison to previous QASUME site visits

The long-term stability of NRP and NR2 was assessed by comparing QASUME visits performed since 2003.

As seen in figure 1, the campaign average ratio to QASUME has been stable to $\pm 2\%$ since 2010. The measurements in 2003 were lower than QASUME by -5 %.

Figure 2 shows that the campaign average ratio of NR2 to QASUME has been stable to within $\pm 3\%$ since 2019. As the NR2 was not synchronised to QASUME in 2019 only very few spectra could be used for the comparison.

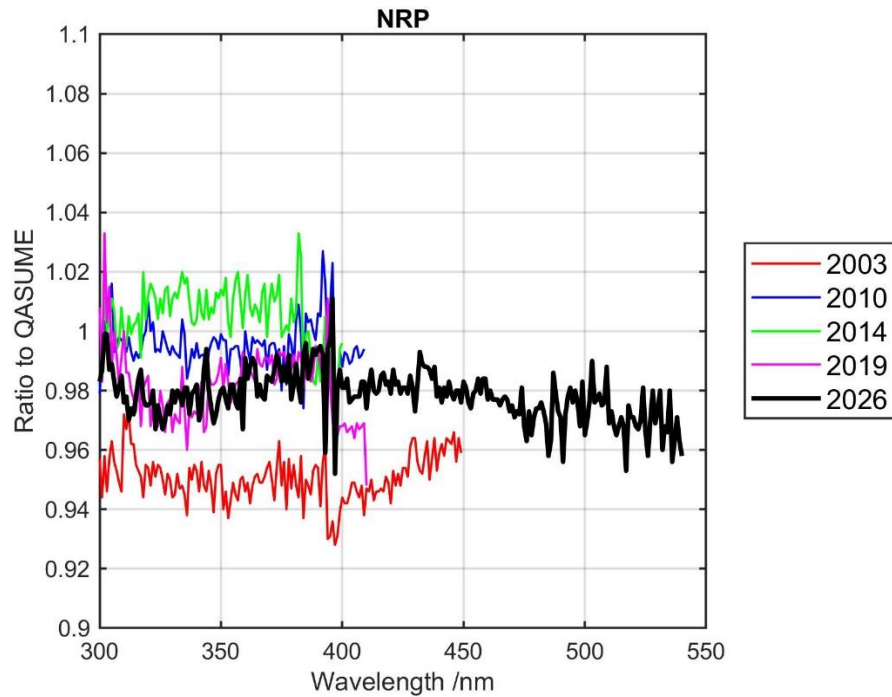


Figure 1 solar spectral ratios of NRP to QASUME averaged over each QASUME site visit.

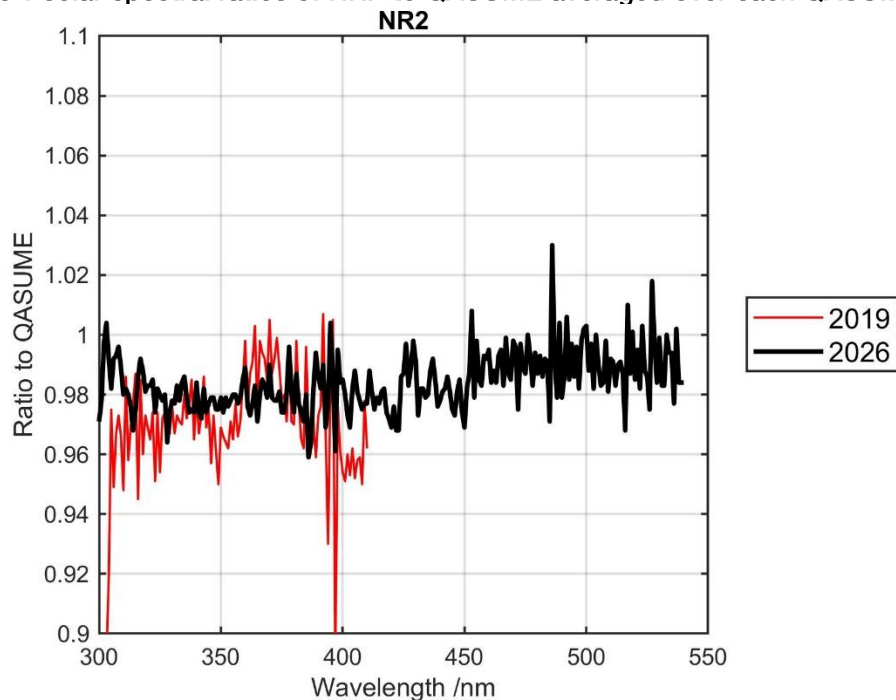


Figure 2 solar spectral ratios of NR2 to QASUME averaged over each QASUME site visit.

Summary:

The audit showed that the UV measurements performed at DSA with the Bentham NRP and NRP2 spectroradiometers are within the expected combined measurement uncertainty:

$$U_{\text{comp}} = \sqrt{U_{\text{qas}}^2 + U_{\text{DSA}}^2}$$

With $U_{\text{qas}} = 1.74\%$, $U_{\text{qas}} = 7.34\%$ ($\lambda < 310 \text{ nm}$) (Hülsen et al., 2016). U_{DSA} was estimated to be 4%.

The following points should be investigated in more detail:

- 1.) The combined expanded uncertainty of the comparison is shown in the Figures (see Appendix) as grey area (dotted lines show the uncertainty of QASUME). As the actual uncertainty budget of the test spectroradiometers are unknown a relative standard uncertainty of 2% (confidence level of 66%) was chosen. DSA derived an uncertainty budget for the UV measurements after the analysis of the campaign. A detail description is given in the section "Comments by the local operator".
- 2.) Both, the NR2 (DTM300) and the GUV9280 UVI data are in good agreement to the reference data.

References:

J. Gröbner, I. Kröger, L. Egli, G. Hülsen, S. Riechelmann, and P. Sperfeld, "The high-resolution extraterrestrial solar spectrum (QASUMEFTS) determined from ground-based solar irradiance measurements", *Atmos. Meas. Tech.*, 10, 3375-3383, 2017

G. Hülsen, J. Gröbner, S. Nevas, P. Sperfeld, L. Egli, G. Porrovecchio, and M. Smid, "Traceability of solar UV measurements using the Qasume reference spectroradiometer", *Appl. Opt.* 55, 7265-7275, 2016.

Comments by the local operator:

Calibrations, uncertainty budgets and data processing.

The two benthams of DSA were calibrated against the same lamp standard. A 1 kW FEL lamp purchased in 2017 from Gigahertz Optik, traceable to PTB. The same lamp was applied in the previous QASUME campaign at DSA in 2019.

On-situ measurements with two portable lamp standards (150 W lamp housings) showed an initial drop in responsivity by 2 % from the instrument were newly calibrated till they were installed at the solar platform. Lamp measurements stayed stable to within ± 1 % during the campaign period. Corrections for responsivity changes were applied daily.

The full data processing chain for both spectroradiometers is shown in figure 4. Uncertainty budgets are shown in Table 1.

Characterizations of ND-filters and cosine responses.

The DSA spectroradiometers use a moving filter wheel with ND-filters to ensure the photocurrent during a solar scan stays below 80 nA. This reduces diurnal hysteresis effects and non-linear performances. The spectral transmittance of each ND-filters (OD1-2-3-4) were measured in the lab prior to the campaign.

The cosine responses of the entrance optics were measured in eight azimuthal directions at wavelengths representative for their spectral working range, and next interpolated to a finer grid of SZA, AZI for all wavelengths in a solar spectrum.

Global cosine correction factors.

Corrections for cosine errors in global solar spectra (GCC) were based on the instrument's measured cosine responses, the location of the Sun and estimated ratios of direct/global and diffuse/global spectral irradiance. A co-located 19-channel GUVIS-3511 (300-1650 nm) sweeping the sky with a rotating shadowband (Bioshade, BSI) every 5 minutes enabled retrieval of these irradiance ratios. The location of Sun was identified from the 1020 nm channel, providing a distinct drop in irradiance as the band passed the Sun disc. If the drop in signal could not be identified, we used clear sky irradiance ratios modelled with the libradtran radiative transfer model as fallback.

Figures 1 and Figure 2 show global cosine correction factors applied for the NRP and NR2 spectroradiometers for the campaign period days 142-146 and the almost cloud free day 148. The entrance optic of the NR2 was rotated 90 degrees towards North during the campaign as the cosine characterizations made prior to the campaign had shown that this would provide almost symmetric cosine response around noon (red curve 'Orientation 2026').

Observations

Some interesting observations can be made from the comparison of DSA and QASUME spectra (ratio curves provided in the main report):

The spectra measured with the two DSA instruments show 2-3 % lower response than the QASUME reference. Possibly the calibration lamp of DSA is biased low due to e.g. overuse in the lab. Hence, calibration of the lamp by PMOD-WRC may show if this is the case and help reduce the uncertainties in DSA measurements.

We also note discrepancies at low SZA angles (> 77 degree), especially for the NR2 instrument. The discrepancies are almost the same with and without cosine corrections and increases with wavelengths exceeding 450 nm. We suspect this is related to a switchover from use of PMT to Silicon photodiode at 450 nm. In figure 3 it is shown that the ratio of spectral irradiance measured with the photodiode gets low relative to the PMT for SZA > 80 degree, indicating the photodiode signal may become increasingly biased low with lower irradiance.

Table 1. Uncertainty budget for the NRP (DM150) and NR2 (DTM300) benthams of DSA.

Source of uncertainty	DM150 <400 nm (%) k=1	DM150 400-540 nm (%) k=1	DTM300 <450 nm (%) k=1	DTM300 450-540 nm (%) k=1
Radiometric calibration				
Standard FEL lamp calibration	2.0	1.5	2.0	1.5
Calibration transfer / alignment	0.2	0.2	0.2	0.2
Lamp ageing / drift	1.0	0.5	1.0	0.5
150W relative lamp standard	0.5	0.5	0.5	0.5
ND filter transmittance	0.5	0.5	0.5	0.5
Measurement				
Random noise / repeatability	0.7	0.7	0.7	0.2
Detector non-linearity	0.5	0.5	0.5	0.5
Wavelength shift	0.5	0.2	0.5	0.2
Temperature dependence	0.5	0.5	0.5	0.5
Humidity / envirobox	0.5	0.5	0.5	0.5
Long-term responsivity drift	0.5	0.5	0.5	0.5
Residual cos. corr.	1.0	1.5	1.0	3.0
Calibration uncertainty (RSS)	2.4	1.7	2.4	1.7
Measurement uncertainty (RSS)	1.7	1.9	1.7	3.2
Total combined uncertainty	2.9	2.6	2.9	3.6
Expanded uncertainty (k=2)	5.8	5.2	5.8	7.2

Daily Global sky correction factors for the NRP spectroradiometer.

Day 142 DM150 Global Cosine Correction Factors vs Time

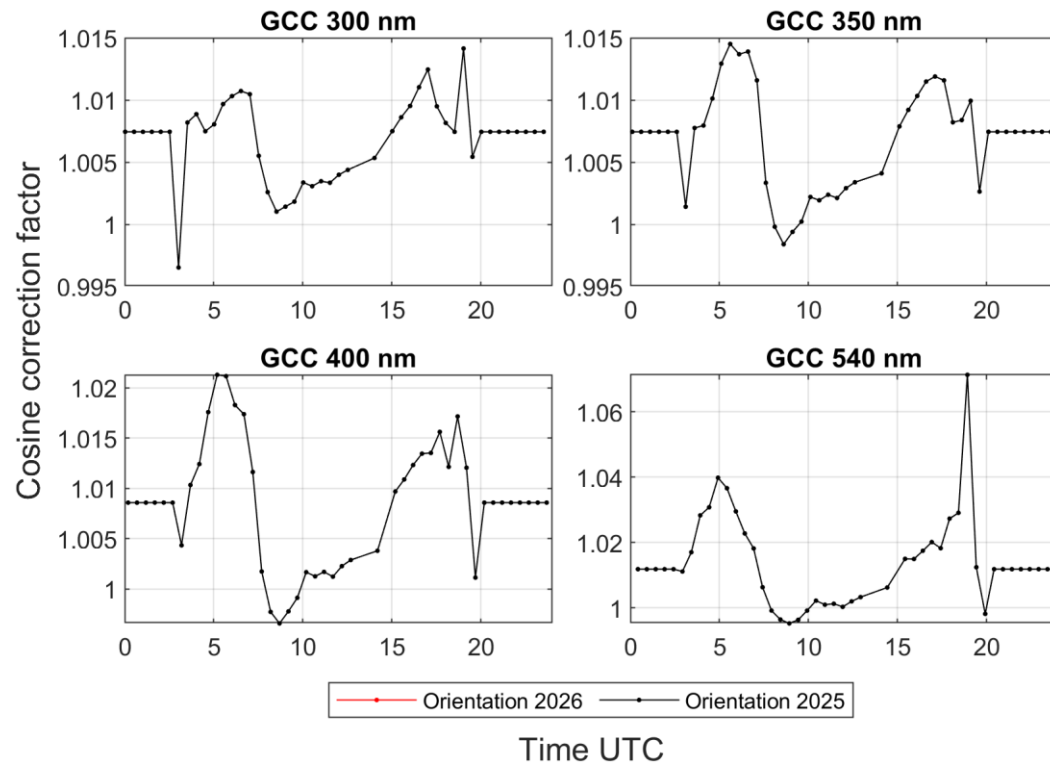
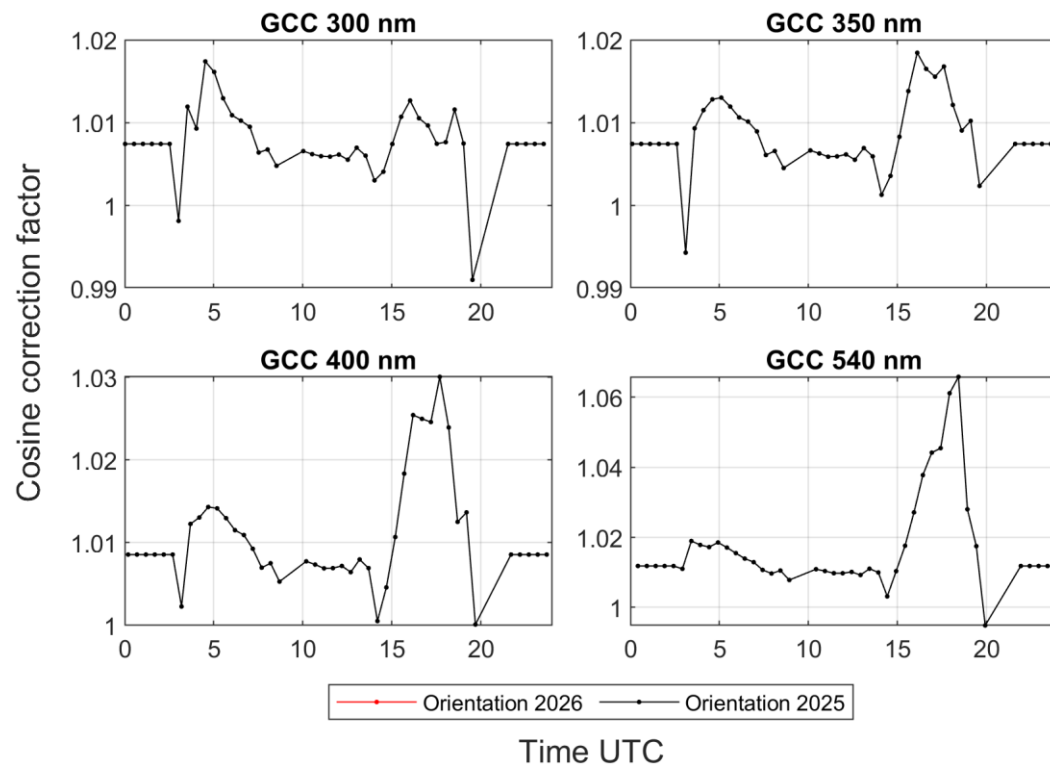
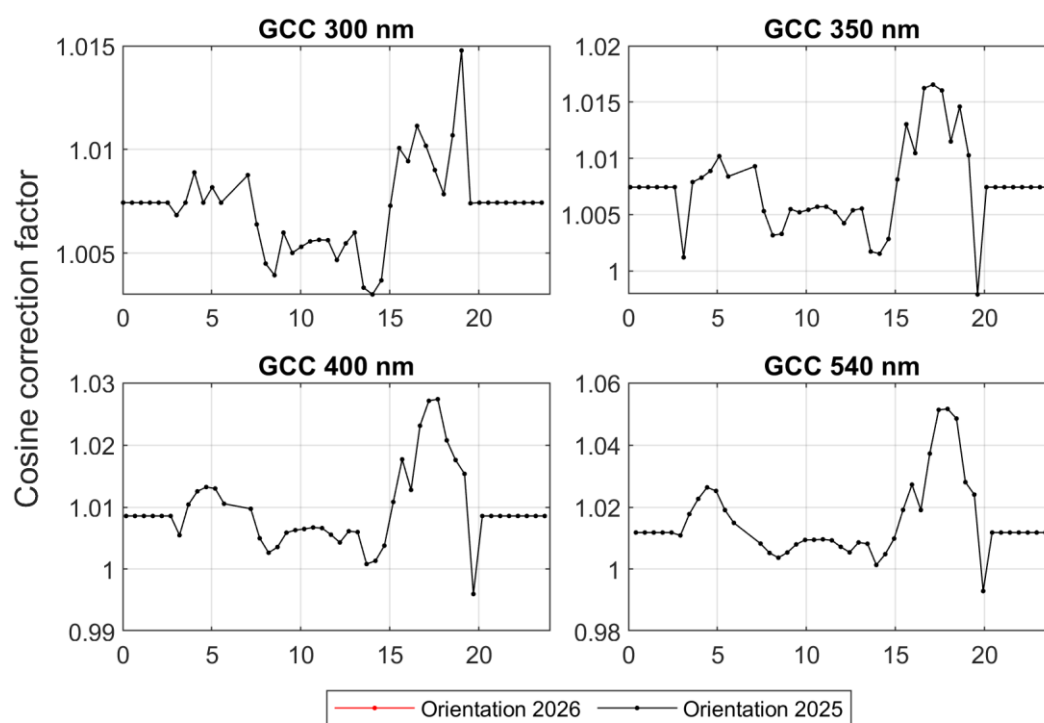
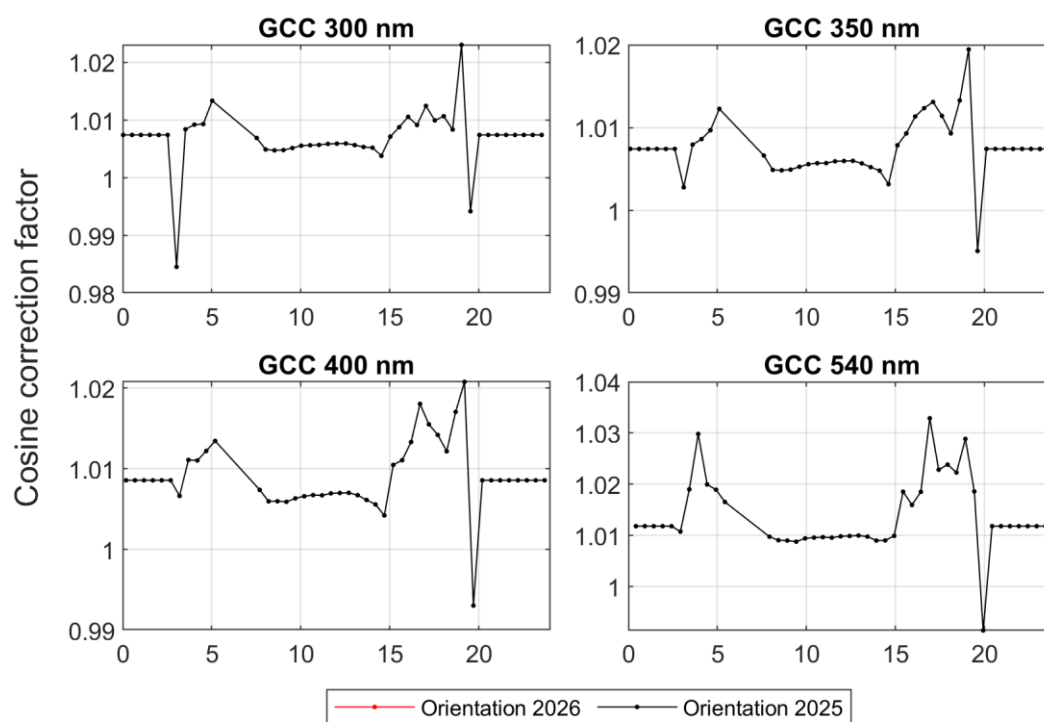


Figure 1 GCC of NRP (bentham DM150) for day 142. The orientation of the entrance optic was the same in 2025 and 2026 (Qasume).

Day 143 DM150 Global Cosine Correction Factors vs Time

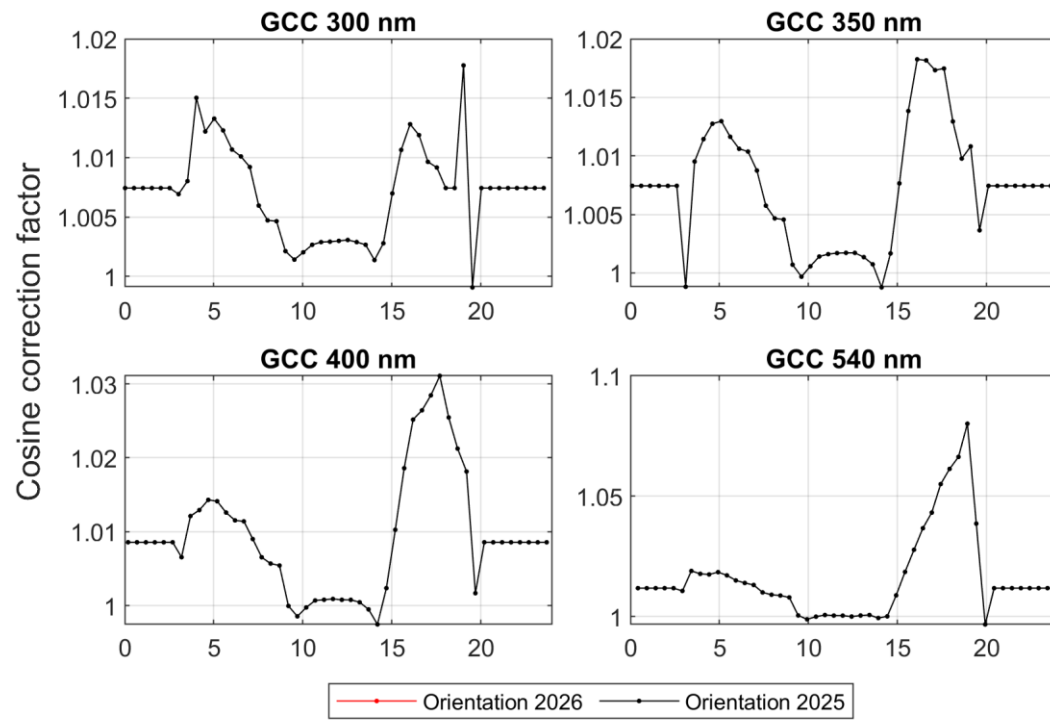


Day 144 DM150 Global Cosine Correction Factors vs Time

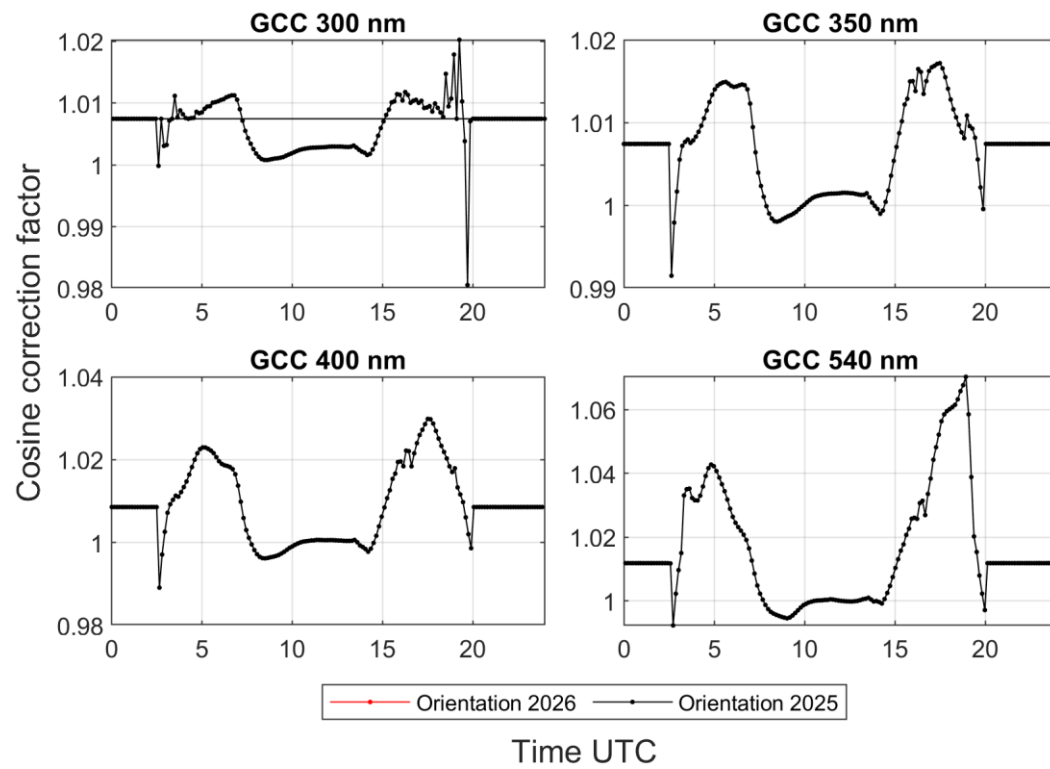
Time UTC
Day 145 DM150 Global Cosine Correction Factors vs Time

Time UTC

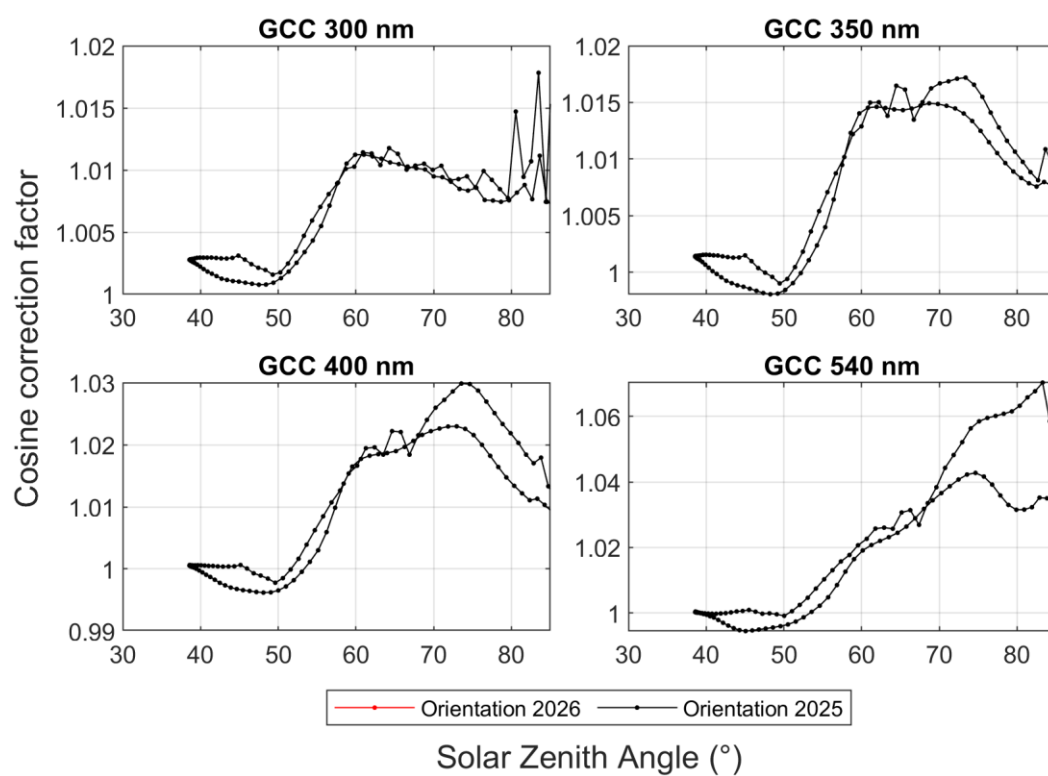
Day 146 DM150 Global Cosine Correction Factors vs Time



Day 148 DM150 Global Cosine Correction Factors vs Time



Day 148 DM150 Global Cosine Correction Factors vs SZA



Daily Global sky correction factors for the NR2 spectroradiometer.

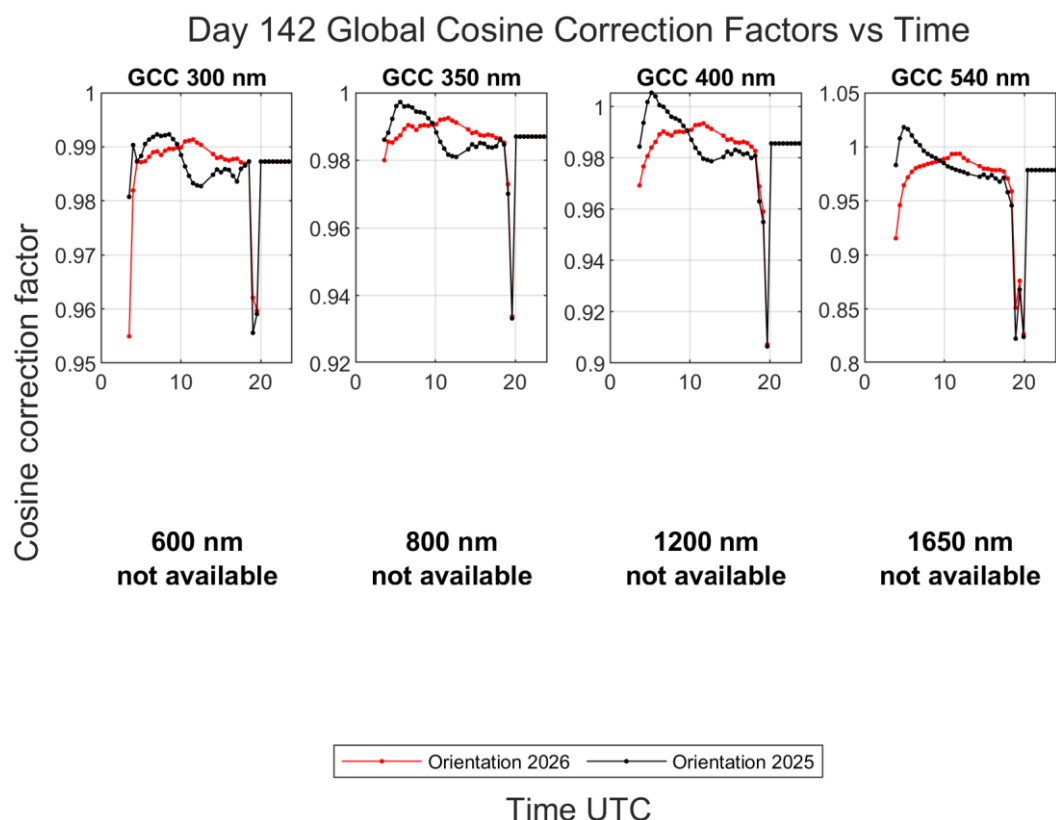
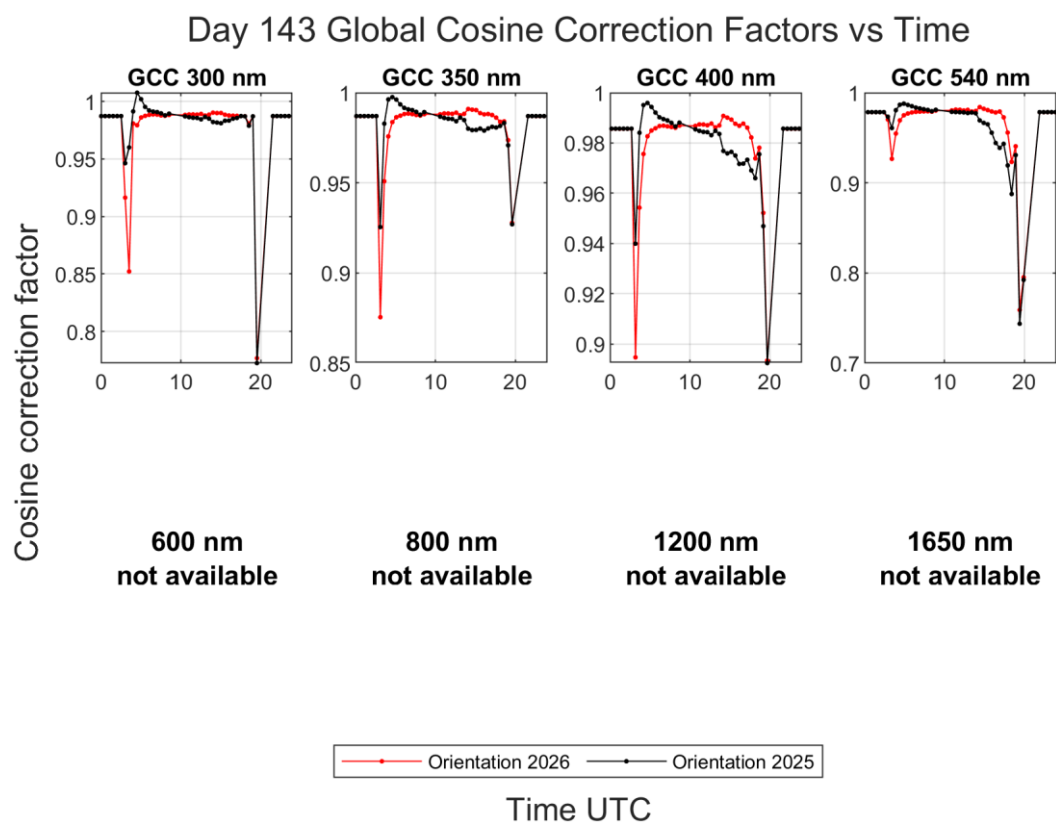
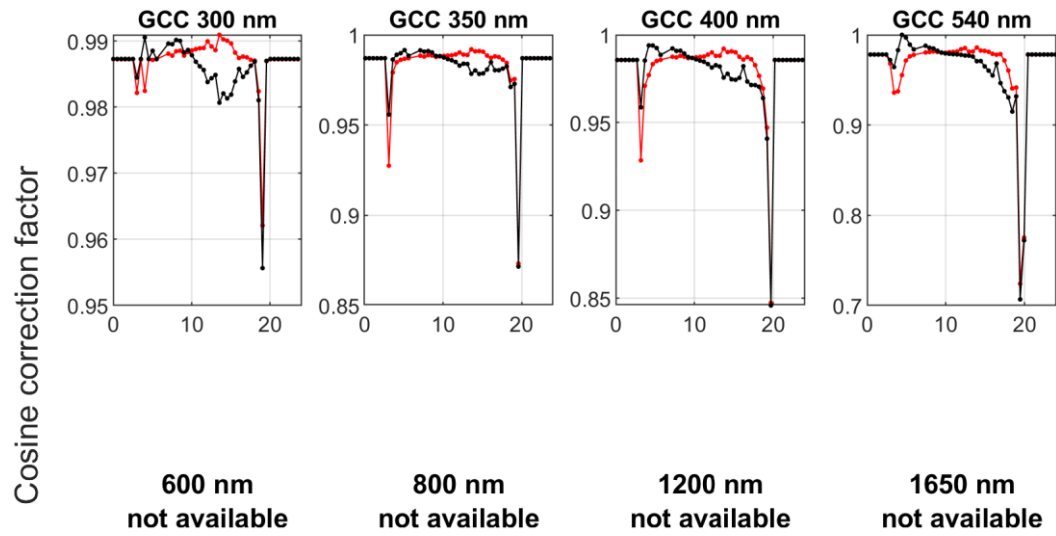


Figure 2 Global cosine correction factors for the NR2 on day 142 for selected wavelengths. Red curve applies to the QASUME-2026 campaign, where the reference point of the entrance optic (drying cartridge) was oriented towards North to minimize azimuthal asymmetry around noon. Black curve corresponds to the orientation of entrance optic during the summer 2025.

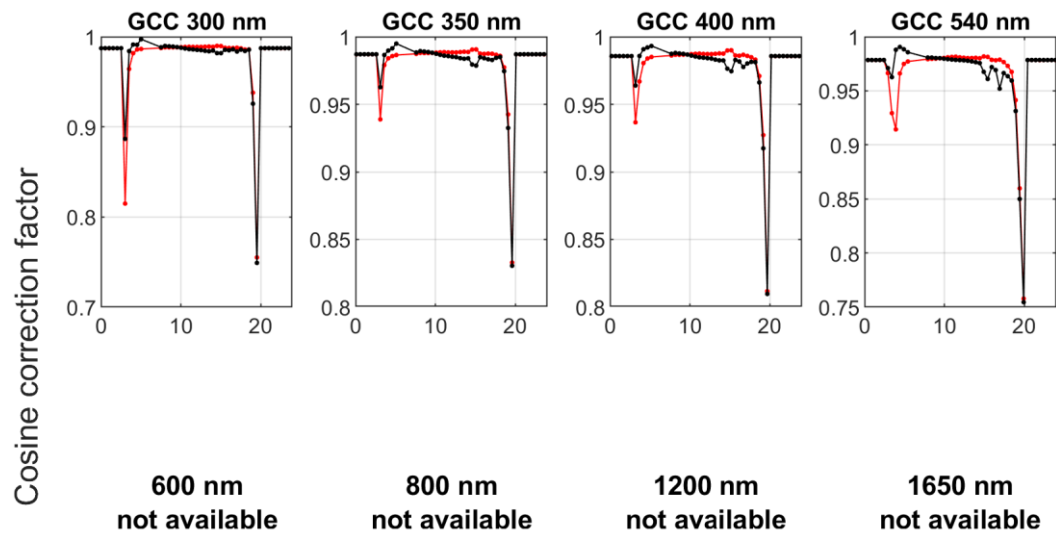


Day 144 Global Cosine Correction Factors vs Time



—•— Orientation 2026 —•— Orientation 2025

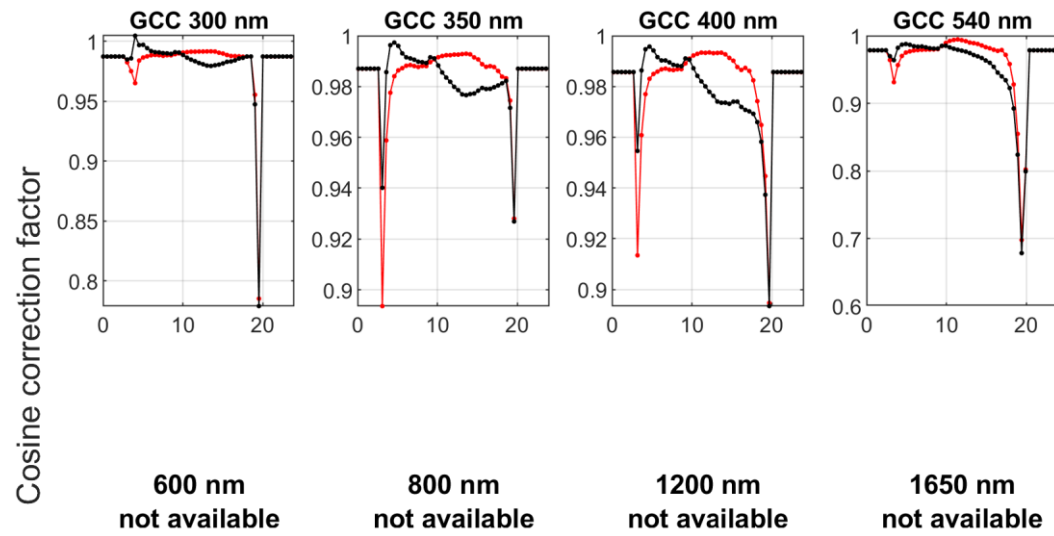
Day 145 Global Cosine Correction Factors vs Time



—•— Orientation 2026 —•— Orientation 2025

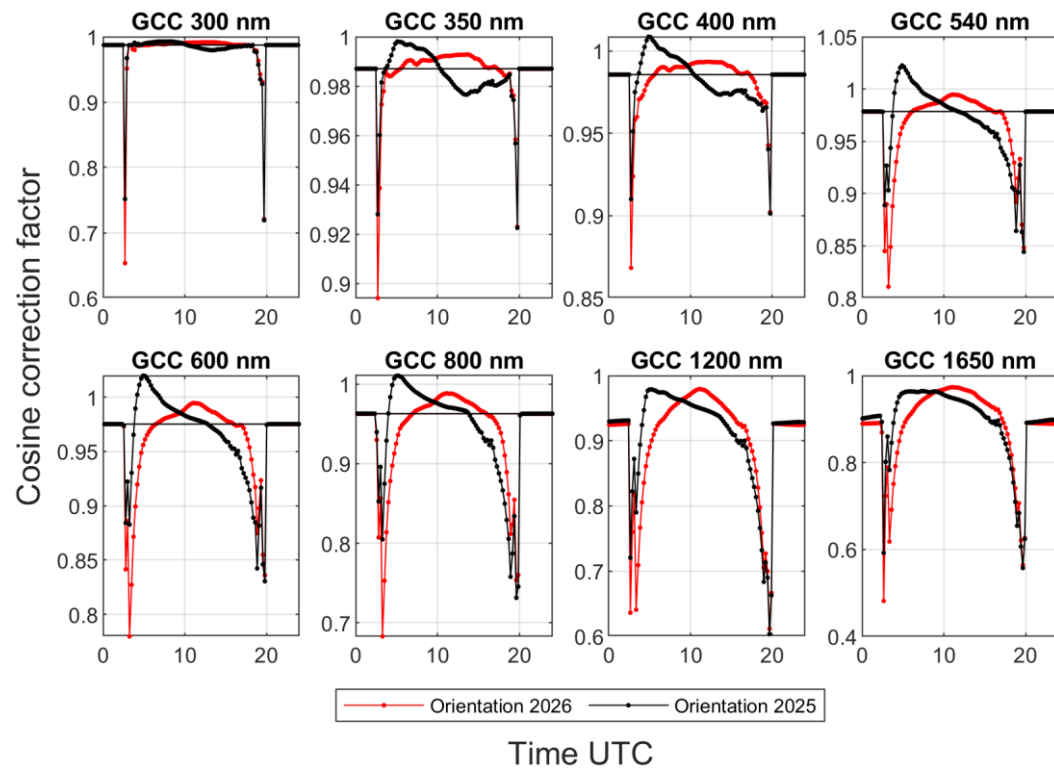
Time UTC

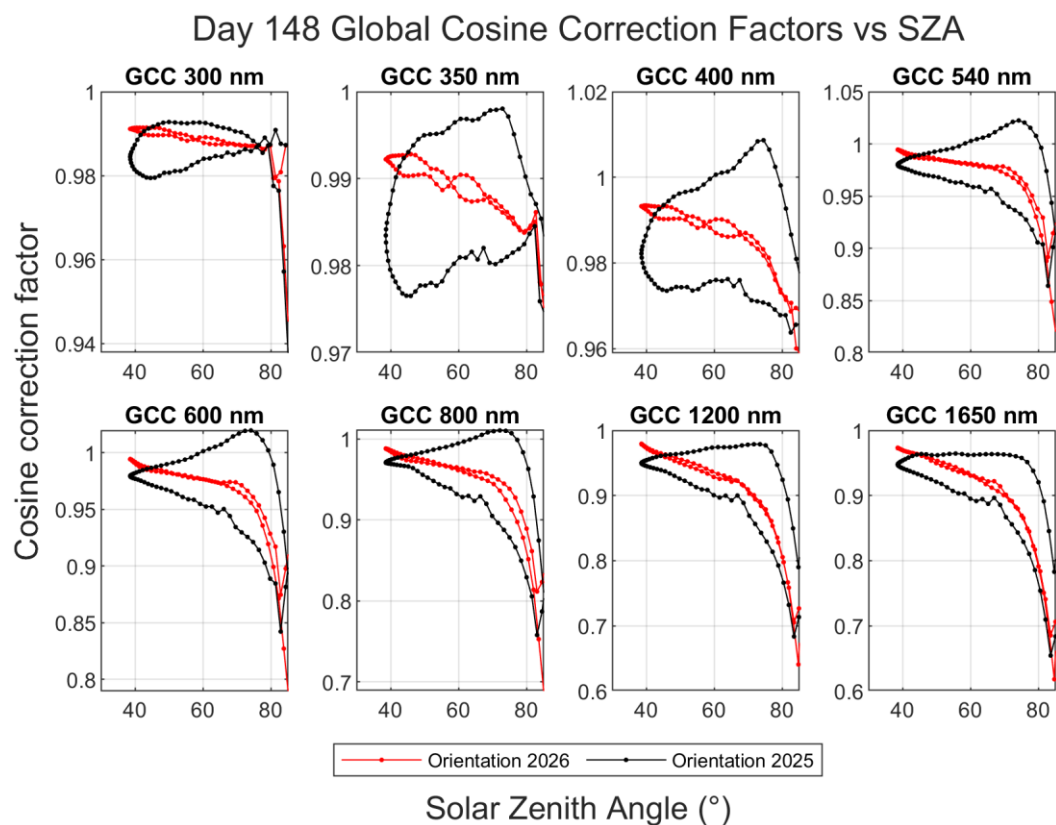
Day 146 Global Cosine Correction Factors vs Time



—•— Orientation 2026 —•— Orientation 2025

Day 148 Global Cosine Correction Factors vs Time





Day 148: 450 nm PMT/Si step diagnostic using CorrScan

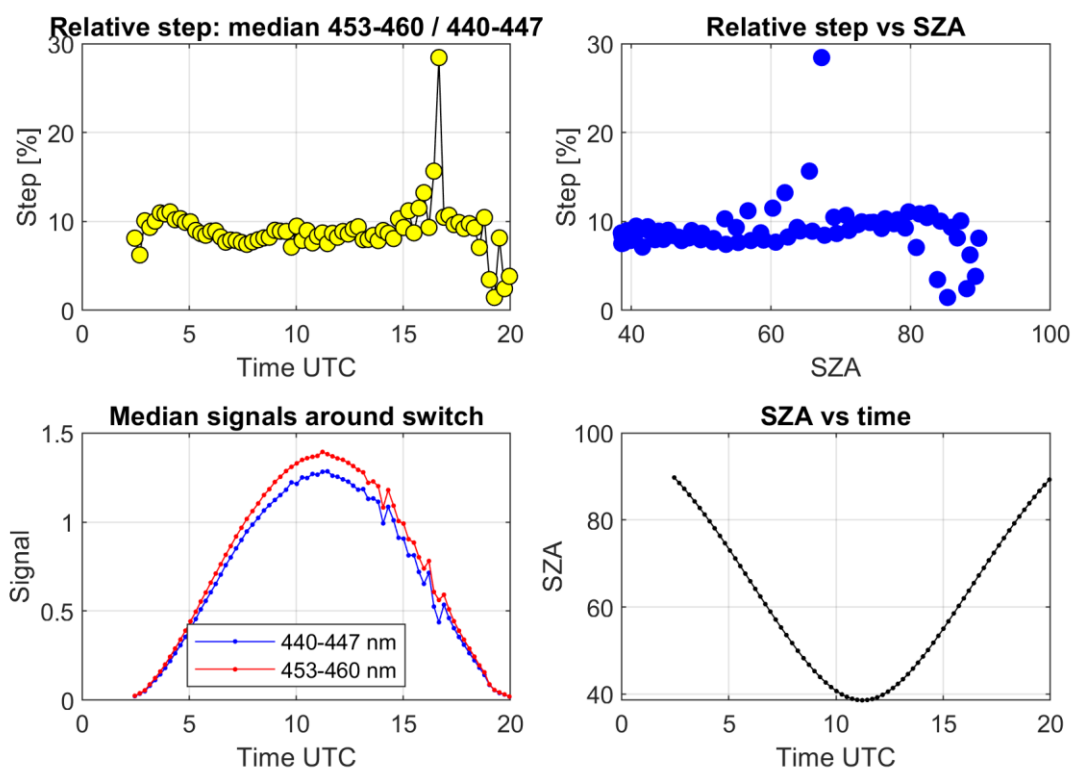


Figure 3 Irradiance ratios for the NR2 spectroradiometer around the switchover wavelength 450 nm, where photodetection sensor changes from PMT to photodiode operation.

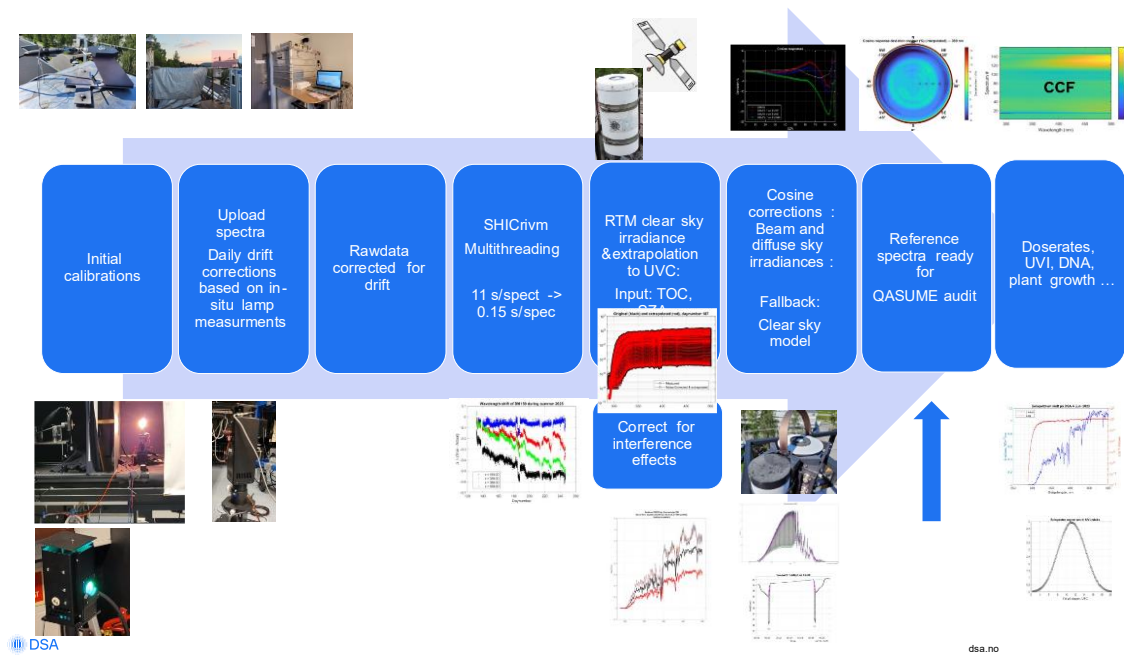


Figure 4 Data processing steps for the NRP and NR2 benthams. The correction steps to reduce optical interference were not implemented because stacked ND-filters had been replaced with single ND-filters.

Appendix

Detailed results for NRP and NR2 spectrophotometers and GUV-9280 with respect to the reference spectroradiometer QASUME

