Stray light correction of array spectroradiometers for solar UV measurements

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OUTLOOK

- The problem and existing solutions
- Matrix-based approach: inclusion of the out-of-range stray light correction
- Setup at PTB for the characterisations
- Verification of the combined OoR and InR stray light corrections
- Tips and tricks on LSF characterisation: dynamic range, interpolation, comparability among instruments, etc.
- Summary

THE PROBLEM AND EXISTING SOLUTIONS

- Spectral stray light – major challenge for application of array spectroradiometers in the solar UV measurements
- Technology-based solutions: avoid the stray light generated outside the spectral range of interest (Egli et al., AIP Conf. Proc., 2013)
  - several concepts implemented also within this JRP
- Filter-based method: quantify and subtract the stray light signal generated at wavelengths above the spectral range of interest using long-pass filters (Shindo et al., AIP Conf. Proc., 2013)
  - could be straigth forward to use for the direct solar measurements
- Matrix method (Zong et al., Appl. Optics, 2006) based on measured LSF or modelled LSF (Kreuter et al., Rev. Sci. Instr., 2009)
  - universal and works well if no out-of-range (OoR) radiation gets into instrument
- A challenge for solar UV measurements: spectral range of an instrument 280 nm – 400 nm, however CCD sensitive up to 1100 nm
  - the OoR stray light overwhelms the one that is generated (and corrected) within intruments range 280 nm - 400 nm

INCLUSION OF THE OoR STRAY LIGHT CORRECTION

- Matrix notation for stray light (Zong et al., Appl Opt 2006):

$$\mathbf{Y}_{\text{meas}} = \mathbf{Y}_{\text{IB}} + \mathbf{D} \cdot \mathbf{Y}_{\text{IB}} + \boldsymbol{\Delta}$$

Stray light

In-range (InR)

$$\mathbf{Y}_{\text{s_spec}} = \mathbf{D} \cdot \mathbf{Y}_{\text{IB}} + \boldsymbol{\Delta}$$

out-of-range (OoR)

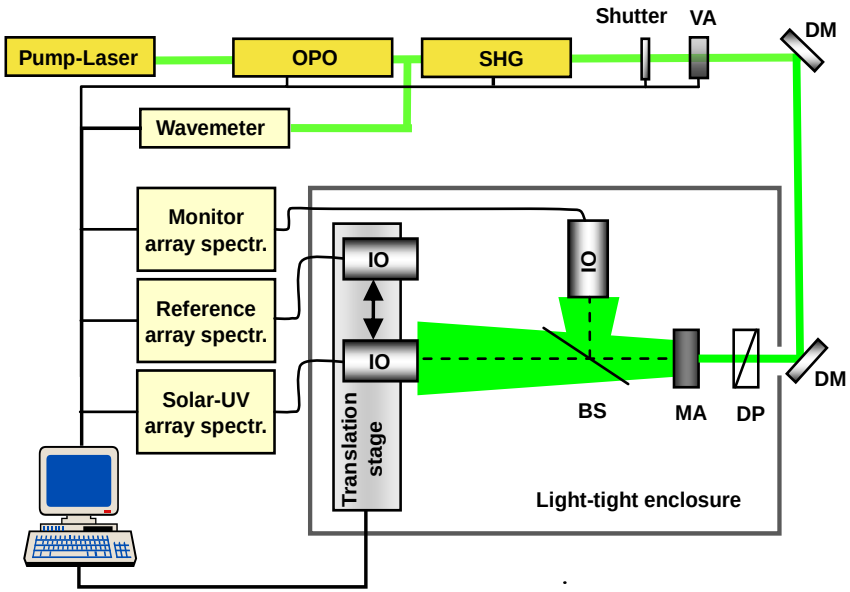
- In case $\boldsymbol{\Delta} \neq 0$: $\boldsymbol{\Delta} = \mathbf{s}_{\text{OoR}} \cdot \mathbf{E}_{\text{OoR}} \cdot \delta\lambda$
  - Note 1: $\mathbf{E}_{\text{OoR}}$ must be known (calibration data or extrapolation of $\mathbf{E}_{\text{InR}}$)
  - Note 2: $\mathbf{s}_{\text{OoR}}$ contains responsivity values
- OoR+InR stray light correction

$$\mathbf{Y}_{\text{IB}} = [\mathbf{I} + \mathbf{D}]^{-1} \cdot [\mathbf{Y}'_{\text{meas}} - \boldsymbol{\Delta}] = \mathbf{A}^{-1} \cdot [\mathbf{Y}'_{\text{meas}} - \boldsymbol{\Delta}]$$

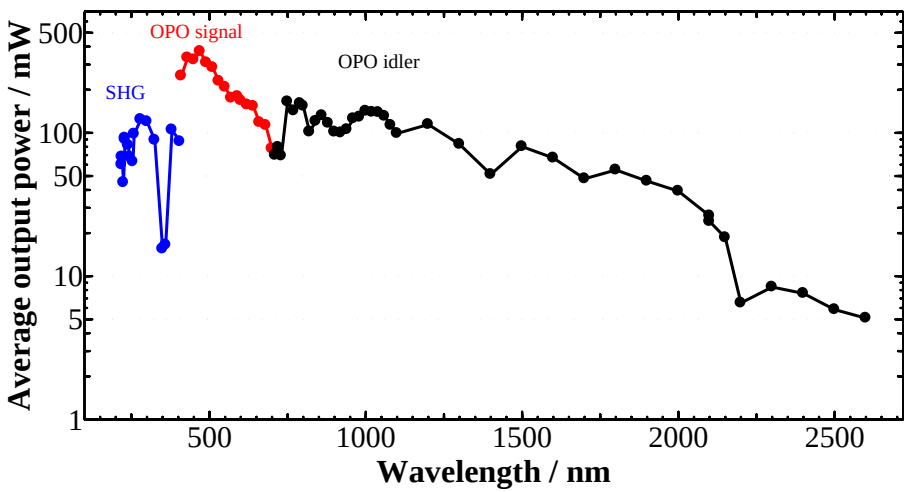
Nevas et al., "Stray light correction of array spectroradiometers for solar UV measurements," Appl. Optics **53**, 4313-4319 (2014)

SETUP AT PTB FOR THE CHARACTERISATIONS

- PLACOS (Pulsed Laser for Advanced Characterisation of Spectroradiometers)



- affordable laser system
- pulsed operation (20 Hz, 5 ns)
- automatic change of wavelength
- easy to handle

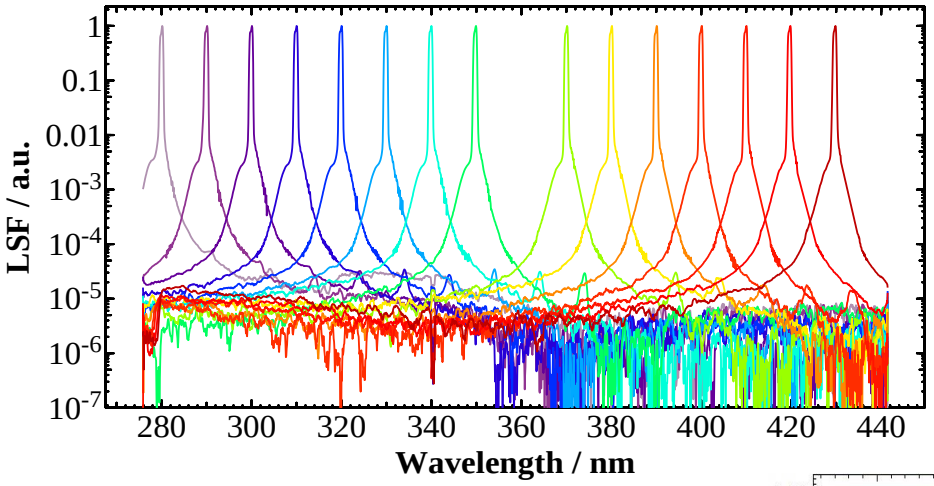


Nevas et al., "Colorimetry of LEDs with array pectroradiometers", MAPAN **24**, 153-162 (2009).

OPO: optical parametric oscillator
SHG: second harmonic generator
MA: microlens array
BS: beam splitter
DP: depolariser
DM: dichroic mirrors
IO: input optics (diffuser head)

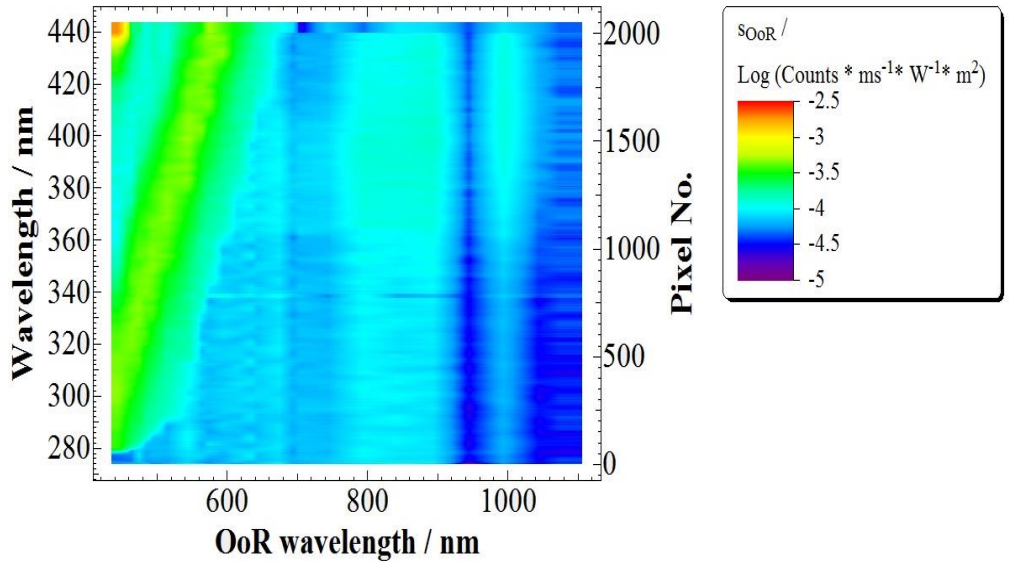
VERIFICATION OF OOR AND INR CORRECTION

- AVOS: AvaSpec-ULS2048; 280 nm - 440 nm, bandpass of 0.7 nm; 2048 pixel back-illuminated CCD



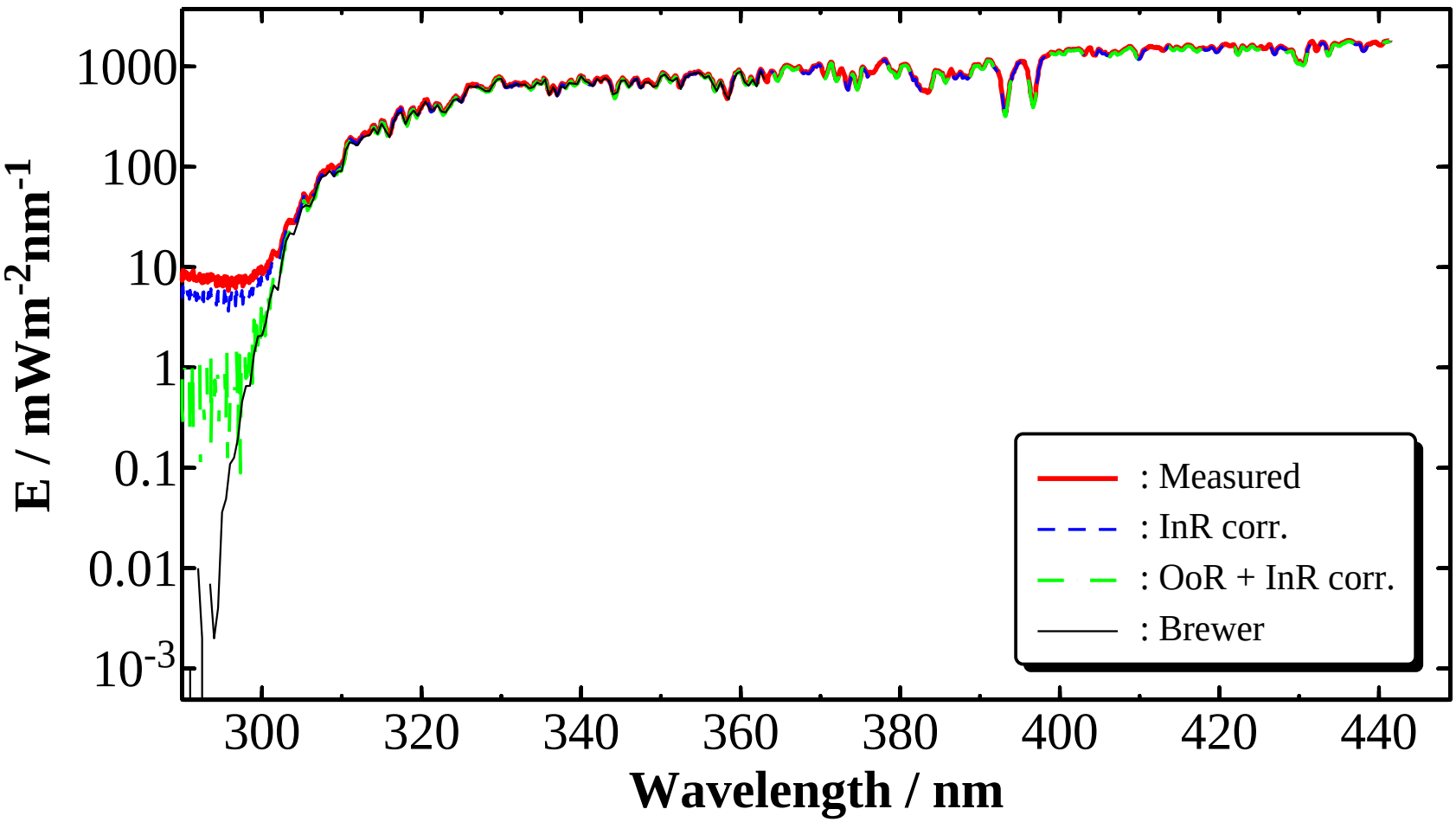
InR stray light

OoR stray light



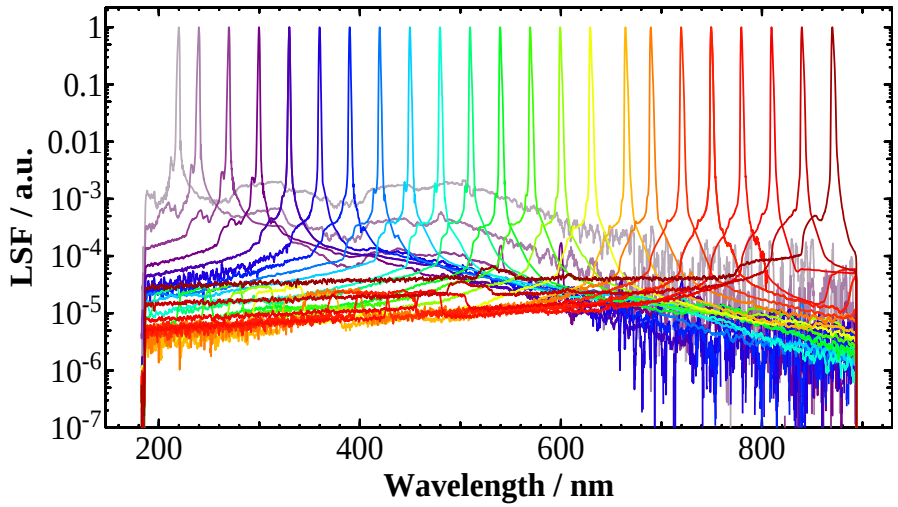
VERIFICATION OF OOR AND INR CORRECTION

- Solar UV irradiance @ 42° SZA



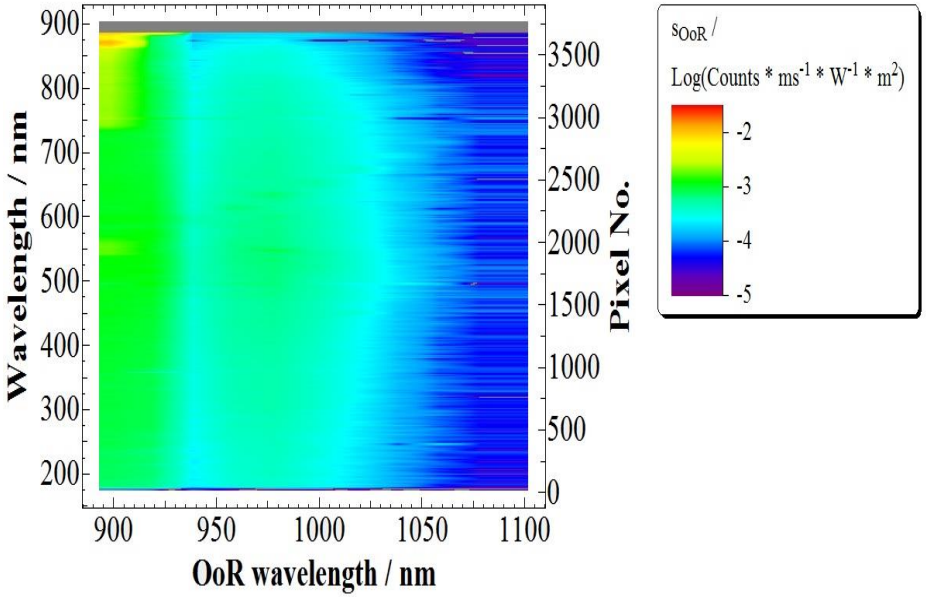
VERIFICATION OF OOR AND INR CORRECTION

- USB4000 of IMU: 200 nm - 890 nm, bandpass of 1.5 nm; 3648 pixel CCD



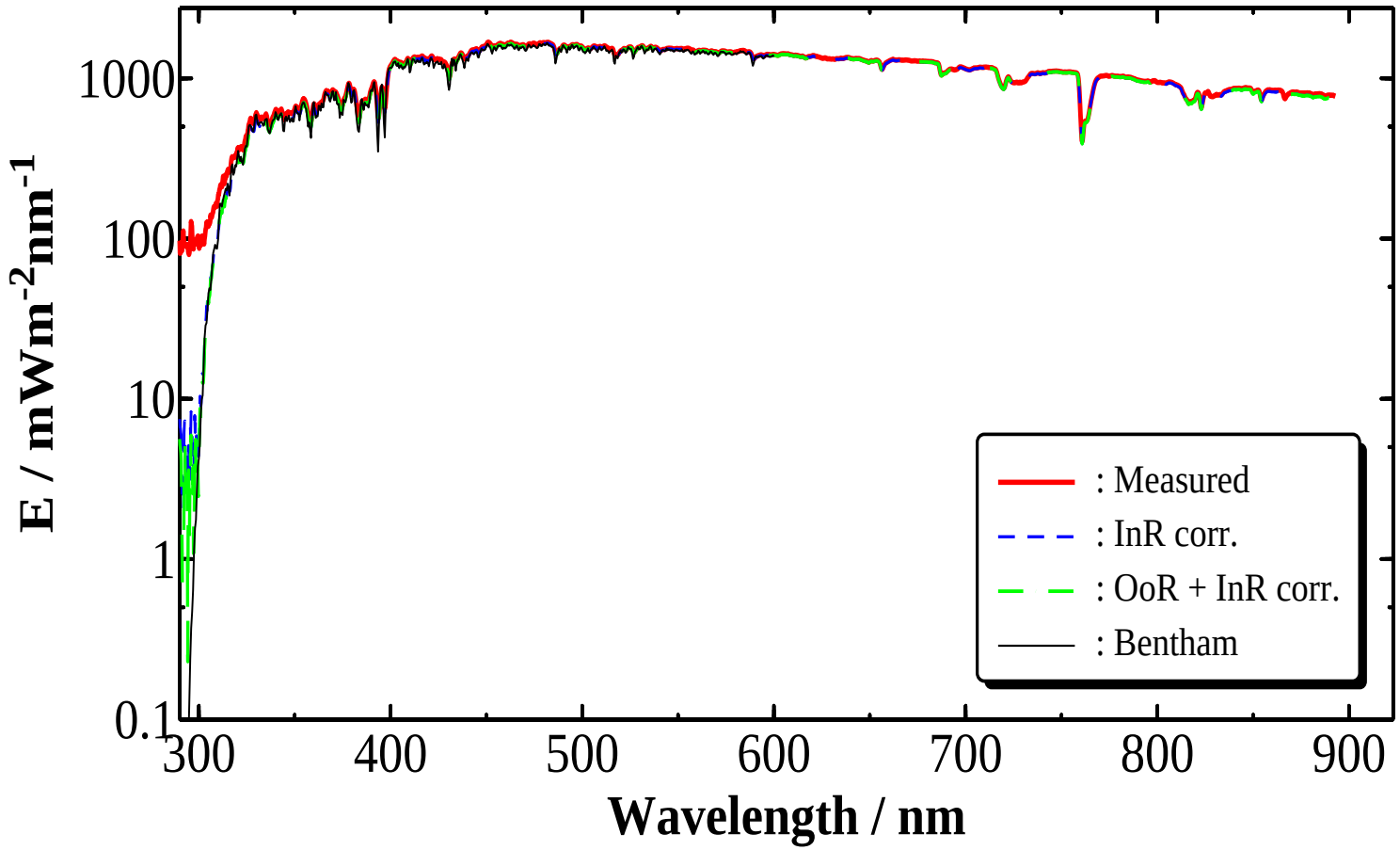
InR stray light

OoR stray light



VERIFICATION OF OOR AND INR CORRECTION

- Solar UV irradiance @ 27.4° SZA

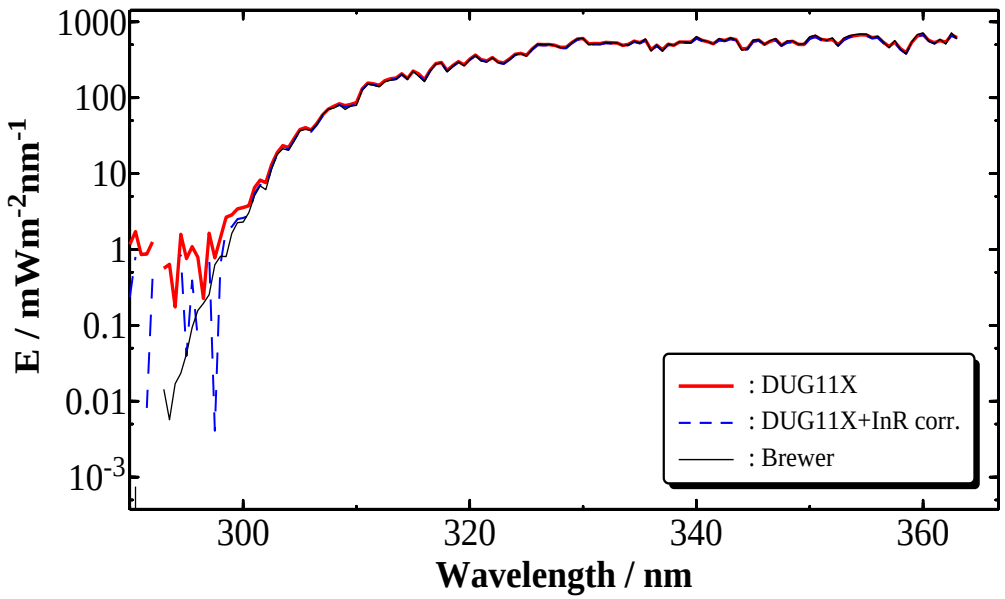


Verification of OoR and InR correction

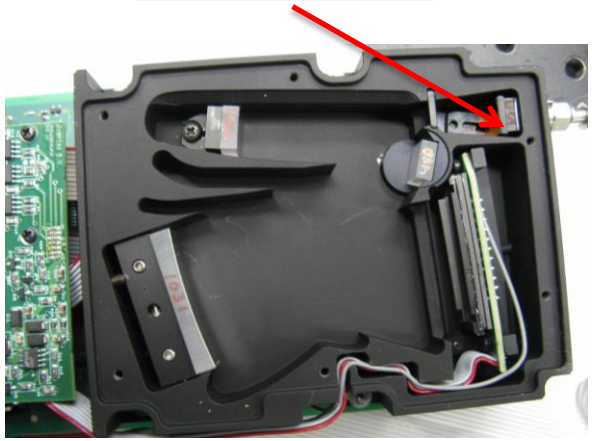
- Reduction of the stray light level by the corrections

Data	AVOS		USB4000	
	Irradiance (290 nm - 300 nm)		Irradiance (290 nm - 300 nm)	
	mW/m²	Stray light reduction	mW/m²	Stray light reduction
Measured	77	-	951	-
InR corrrected	54	-30%	51	-95%
OoR corrected	29	-63%	933	-2%
OoR+InR corrected	5.7	-93%	32	-97%
Reference data	3.3		7.6	

VERIFICATION OF OOR AND INR CORRECTION



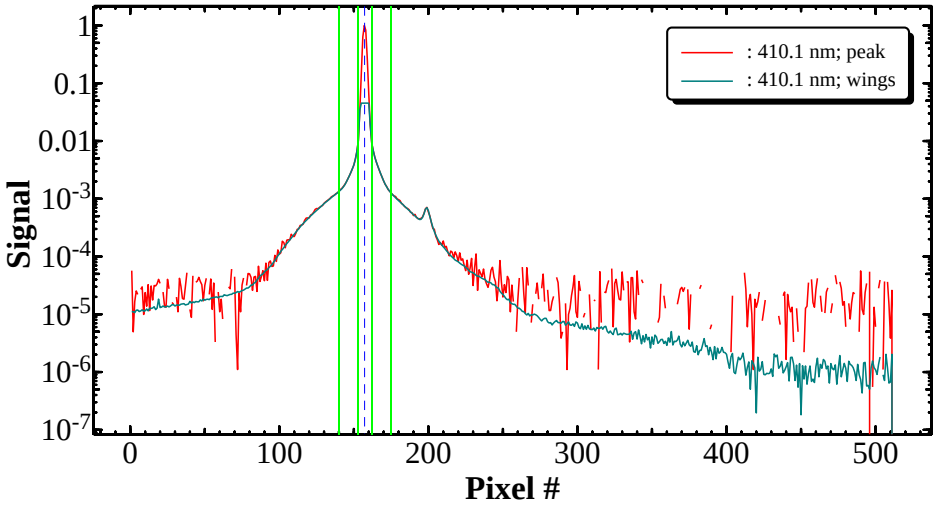
- AVOS with DUG11X filter

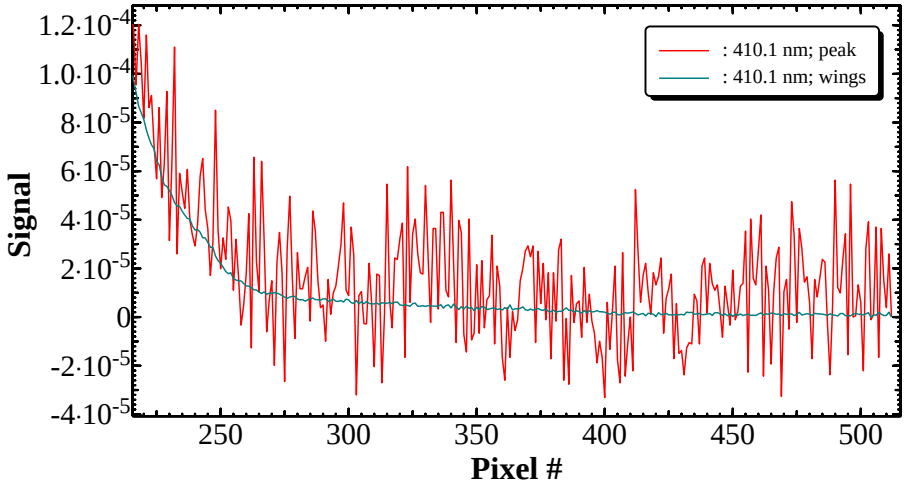


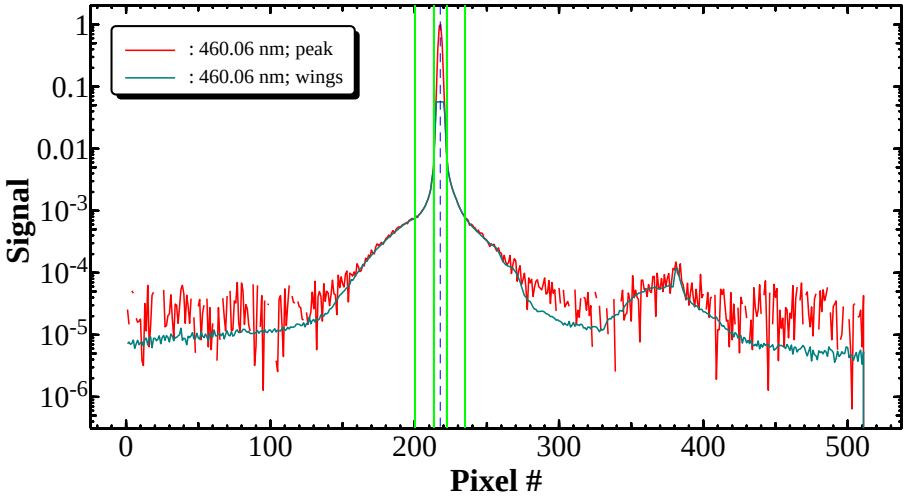
Data	Irradiance (290 nm – 300 nm) mW/m^2
Brewer	4.0
AVOS + DUG11X	12.6
AVOS + DUG11X +InR corr.	4.5

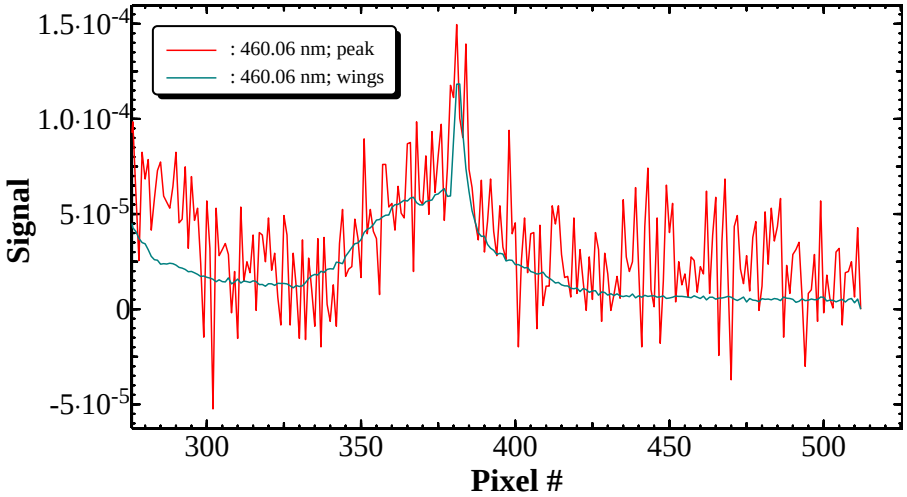
TIPS AND TRICKS: DYNAMIC RANGE

- 15 bit instrument, high sensitivity, no obvious blooming



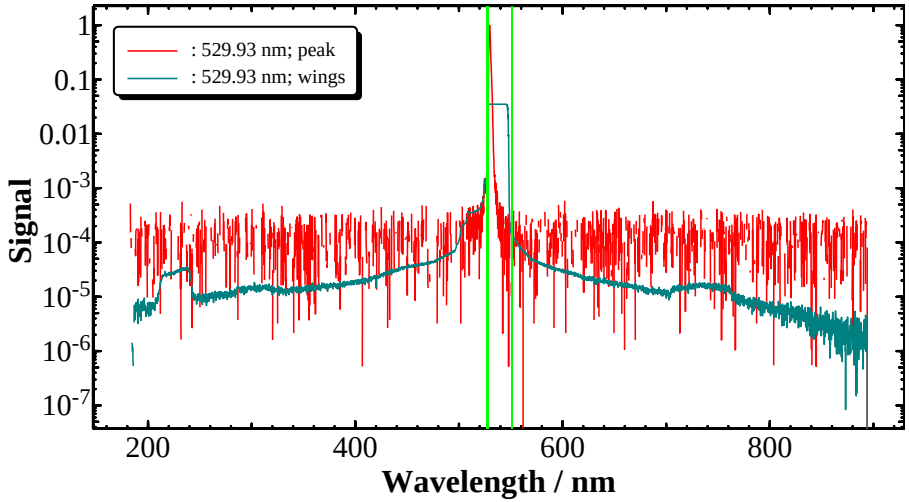


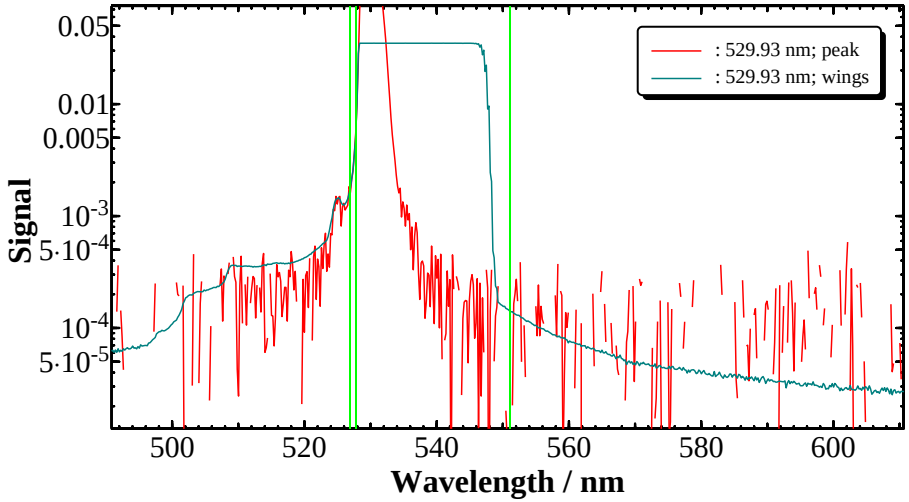


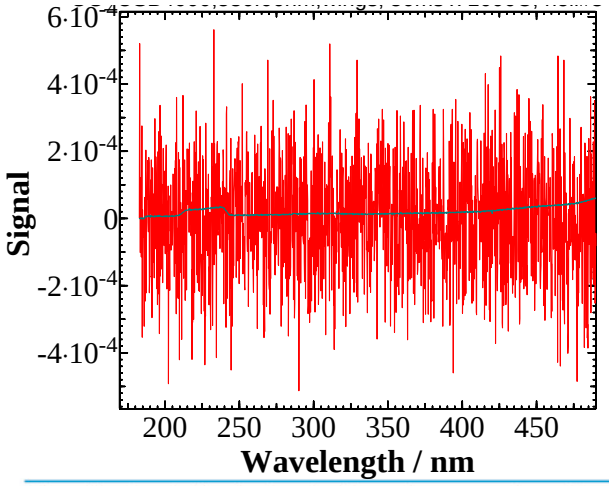


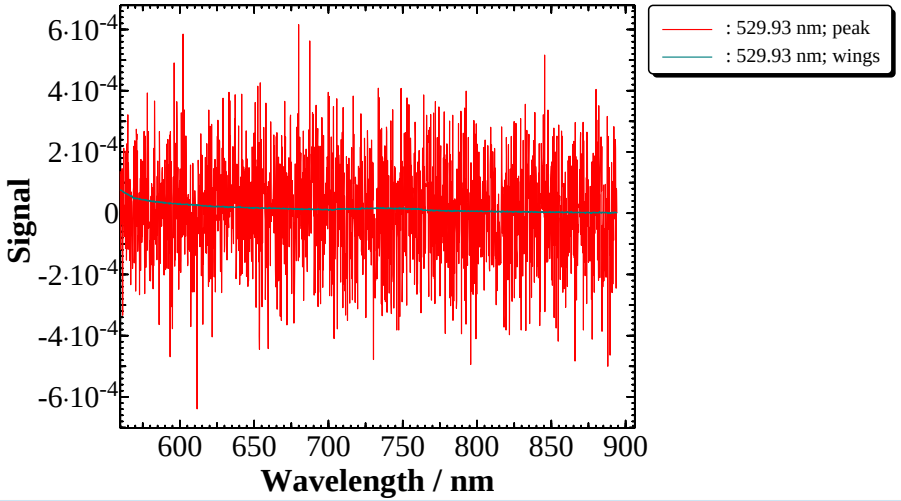
TIPS AND TRICKS: DYNAMIC RANGE

- 16 bit instrument, lower sensitivity, strong blooming



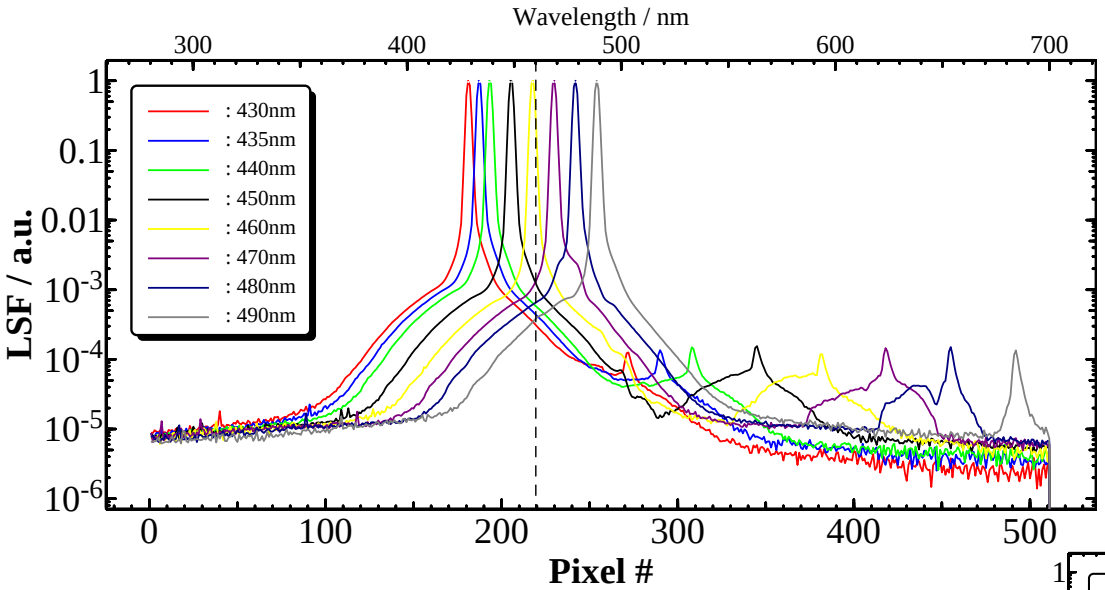


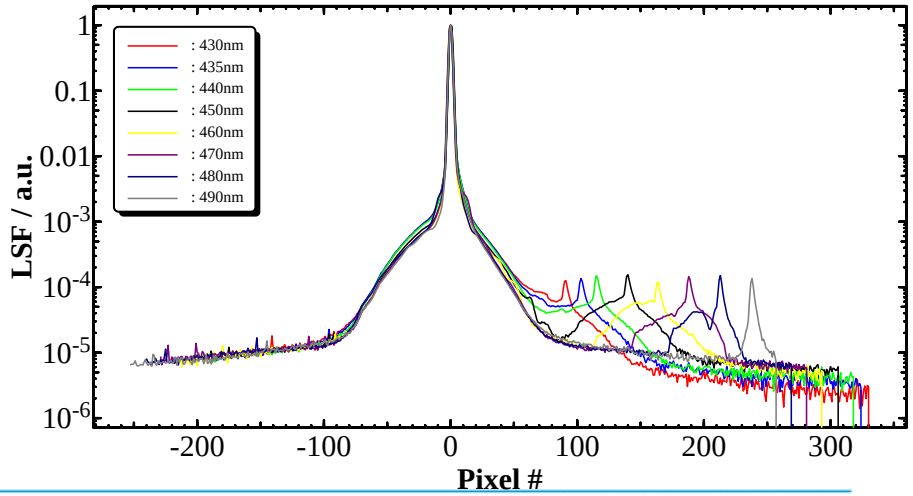




TIPS AND TRICKS: INTERPOLATION

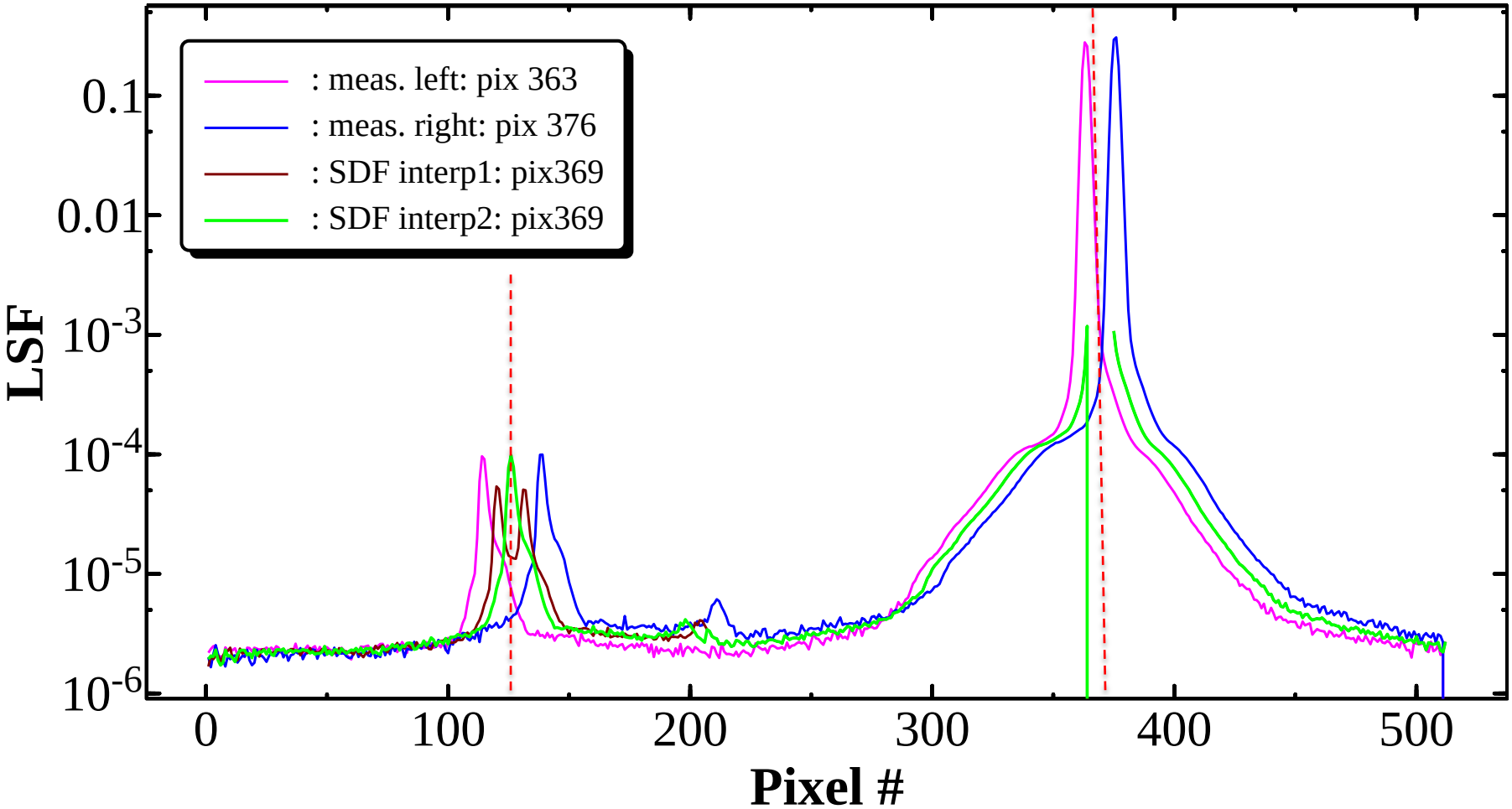
- How many LSFs needed to be measured?





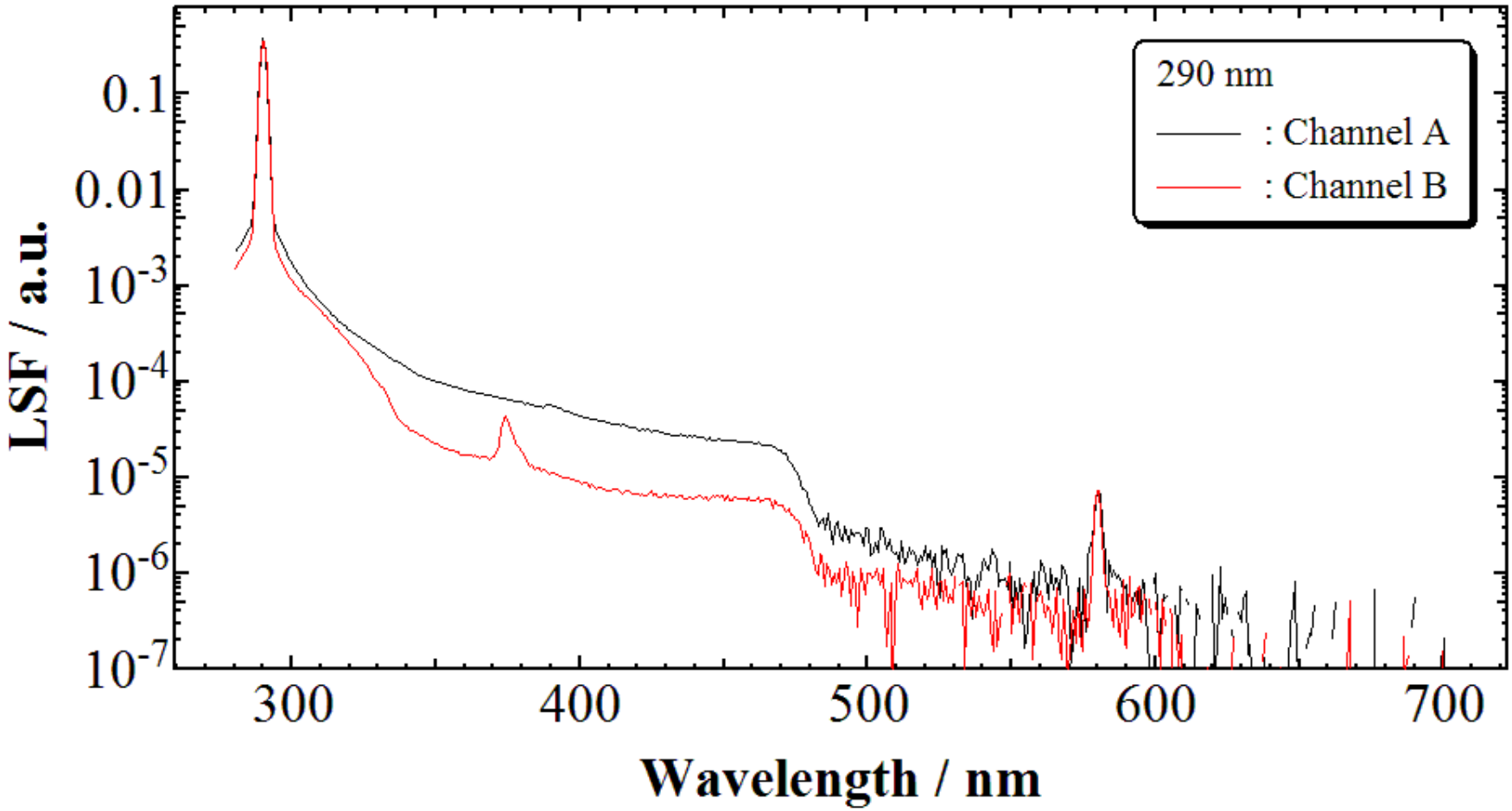
TIPS AND TRICKS: INTERPOLATION

- Handling of the multiple peaks by the interpolation: interp1 – 1-peak interpolation, interp2 – 2-peak interpolation



TIPS AND TRICKS: PORTABILITY

- Stray light signatures of even same type instruments are not identical



SUMMARY

- Poor stray light suppression of array spectroradiometers can be improved both by hardware modifications and corrections.
- Array spectroradiometers for solar UV measurements: out-of-range (OoR) stray light needs special attention.
- The OoR stray light can be characterised (reponsivity to the OoR irradiance) and corrected. The OoR irradiance that is not measured by the instrument itself could be estimated using e.g. reference spectrum and a normalisation.
- A suitable filtering technique, though, is simpler in application.