TROPOMI in-flight calibration

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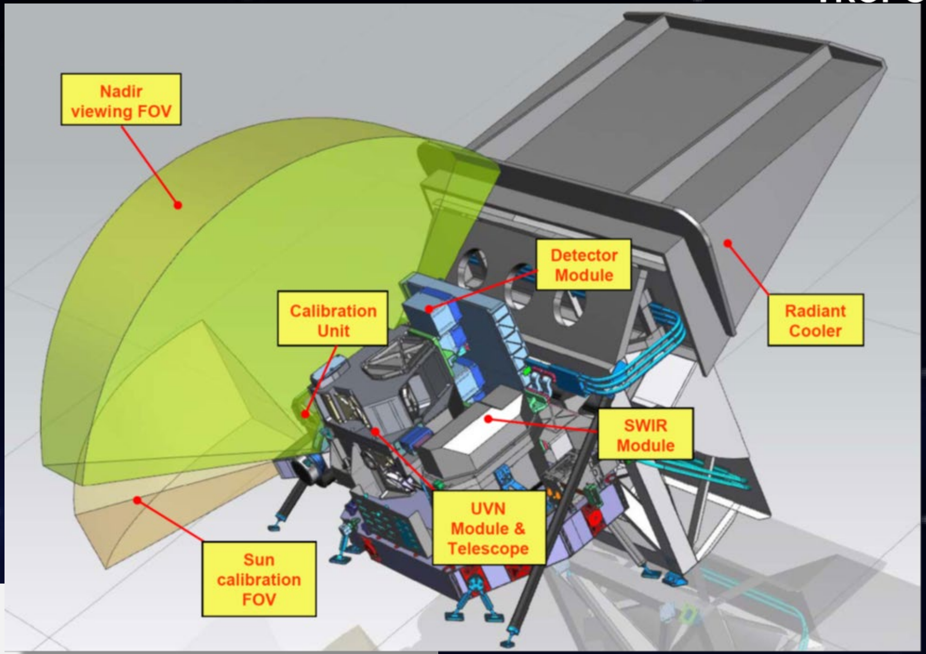
TROPOMI on-board Sentinel-5 Precursor

- Single payload
- Hyperspectral imager with 4 spectrometers
- Sun synchronous orbit (MLTAN 13.30)
- Pushbroom with ~ 2600 km swath
- High spatial sampling (down to 5.5 km x 3.5 km)
- Daily measurements of the Sun via Sun port
- Launched 10/2017
- Nominal operations since 30/4/2018



TROPOMI spectral bands – based on calibration data

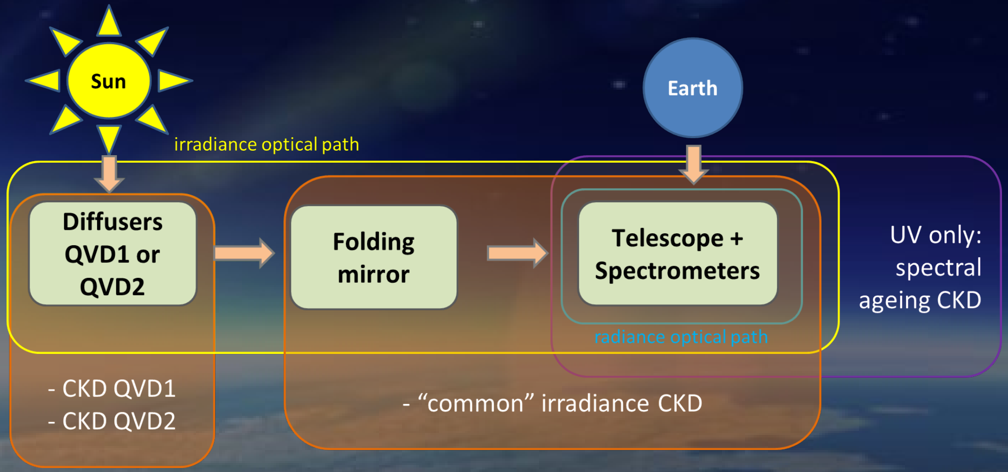
Spectrometer	UV		UVIS		NIR		SWIR	
Band ID	1	2	3	4	5	6	7	8
Spectral range [nm]	267-300	300-332	305-400	400-499	661-725	725-786	2300-2343	2343-2389
Spectral resolution [nm]	0.45 - 0.5		0.45 - 0.65		0.34 - 0.35		0.227	0.225
Spectral sampling [nm]	0.065		0.195		0.126		0.094	
Spatial sampling [km^2]	5.5 x 28	5.5 x 3.5	5.5 x 3.5		5.5 x 3.5		5.5 x 7	
Detector binning factor	16	2	2	2	2	2	1	1

In-flight calibration using solar measurements

Goal: Determine (and correct for) the instrument degradation

Degradation (long-term drift in signal)

- Multiplicative!
- Smoothness? spectrally/spatially. Pixel position vs pixel wavelength
- Monotonous?
- Cause. Leads to *degradation components (flavours):*
  - Diffuser only (IRR)
  - Instrument light path w/o diffuser (RAD, IRR)
  - Detector bleaching (RAD,IRR, CU)
  - Sharp detector features (RAD,IRR, CU)



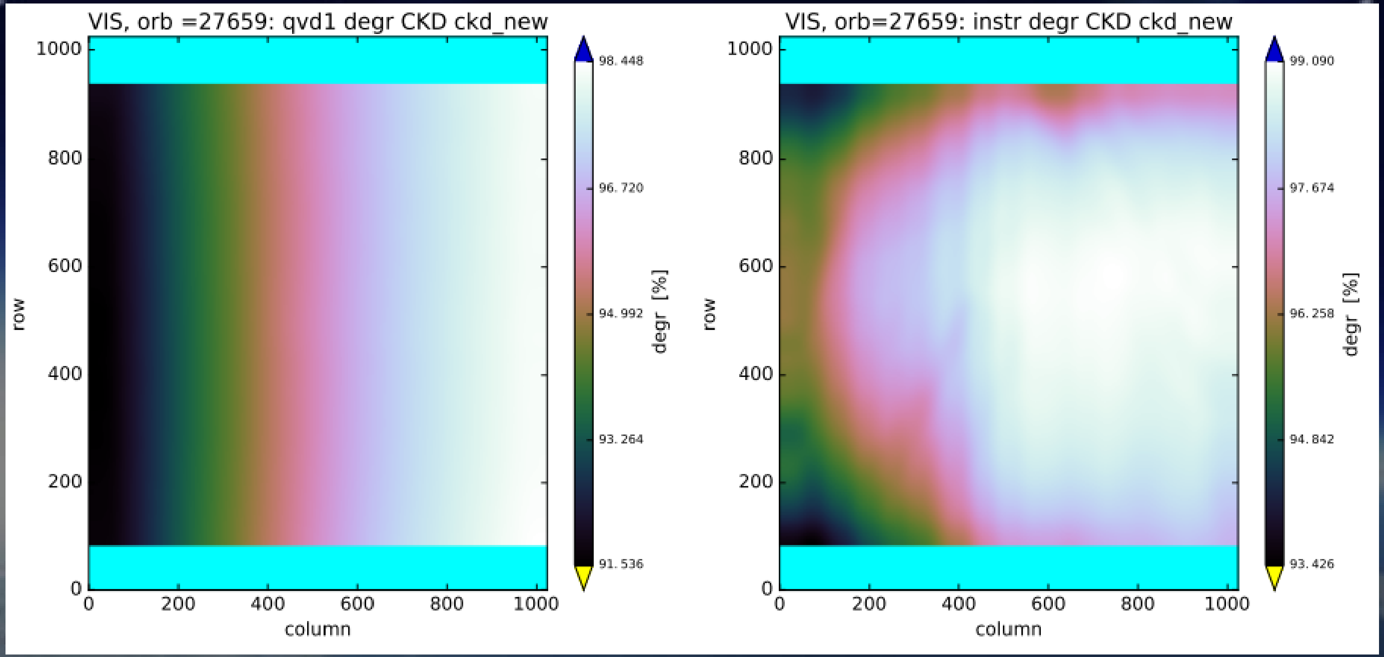
Degradation (1/3): diffuser, common instrument (main flavours)

- Diffusers (QVDs) degrade
- QVD1 (main, daily) more than QVD2 ~~(backup~~ weekly) (proportional to exposure)
- → Separate diffuser-only degradation and common/instrument degradation (spectrometer &/ FMM)
- Degradation strongest for short wavelengths; NIR and SWIR so far almost or no degradation

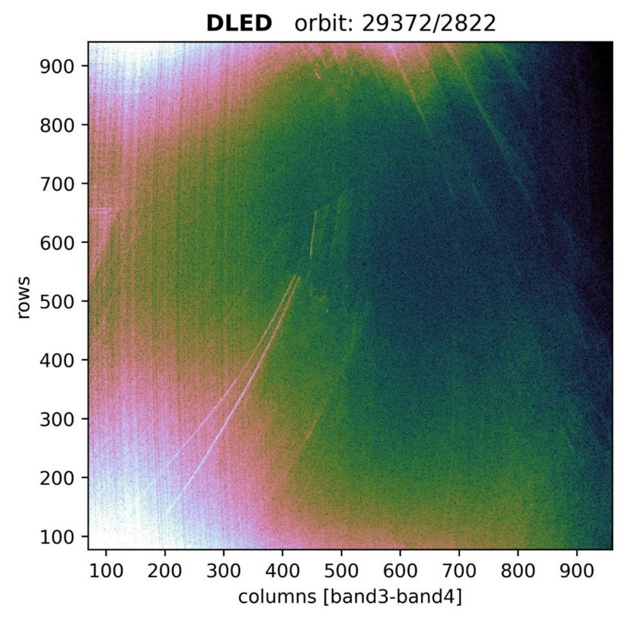
→ Correction applied in L1b product since July 2021

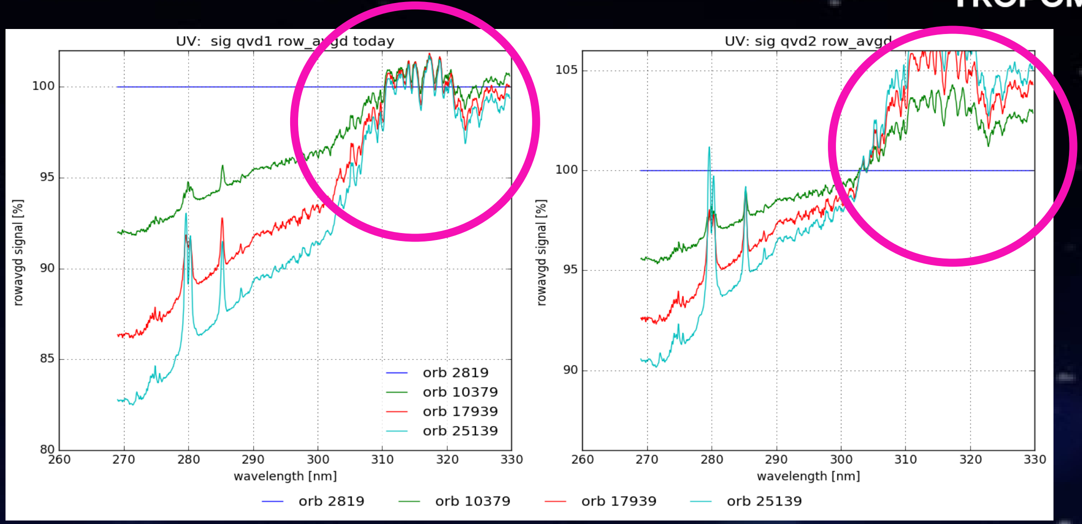
Diffuser CKD

Common instrument CKD



Degradation (2/3): HF flavours





i) UVIS detector:

- 'scratches' visible in degradation images
- In IRR, RAD, *and* in CU LED measurements → on detector surface

ii) UV detector:

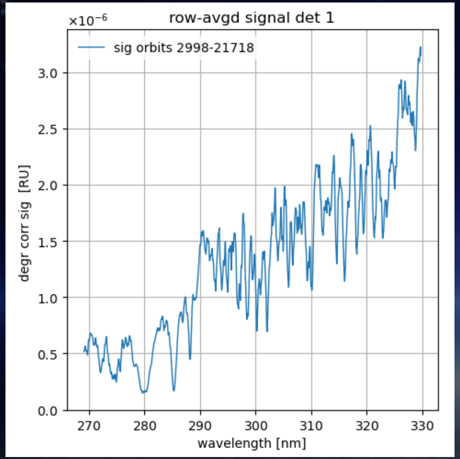
- Measurements show signal *increase* correlated with solar lines
- In region 312-330 nm comparison with band 3 possible
- Suspect bleaching close to or on/within the detector

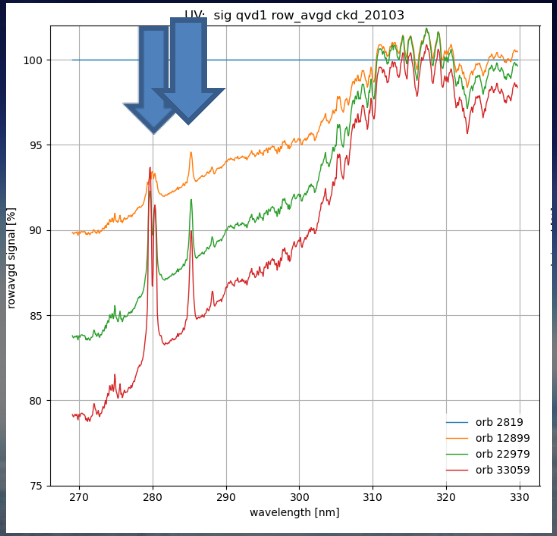
Degradation (3/3): False flavours

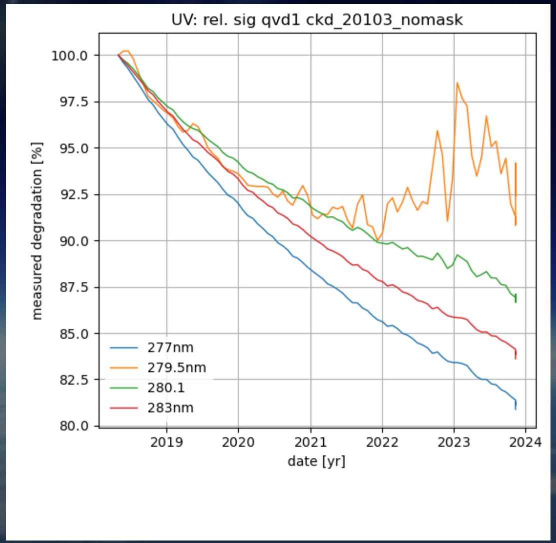
- In the UV detector, the degradation images show increasing positive peaks at 280 and 286 nm (where the absolute signal is minimal), suggesting an *additive* term, this is also an observation from O3-profile retrievals in UV.
- This contradicts the detector bleaching hypothesis. Bleaching correlates with absolute signal → peaks caused by uncorrected-for offset?
- → main residual offset candidate is (far-field) straylight.
- **We first need a proper UV straylight correction before addressing degradation**. With uncorrected straylight, we have a 'false' degradation flavour, not suitable as calibration key data.

- A *second* 'false flavour' stems from the solar variability: Our light source (i.e. the Sun) is not constant. (example: 279.5nm signal contains both SL and solar cycles)

Absolute signal





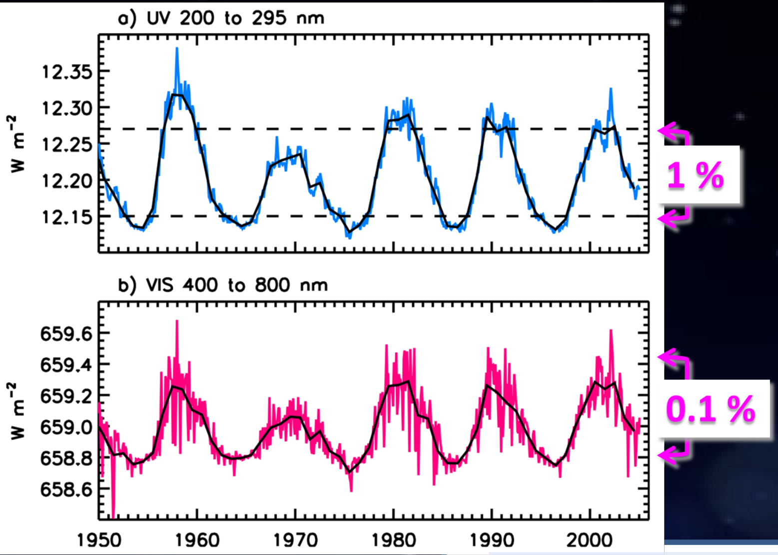


False flavour: Stability of the Sun

- **Solar cycle SSI signal is small and spectrally dependent.**
- Sun as stimulus is almost constant almost everywhere (especially in early TROPOMI years)

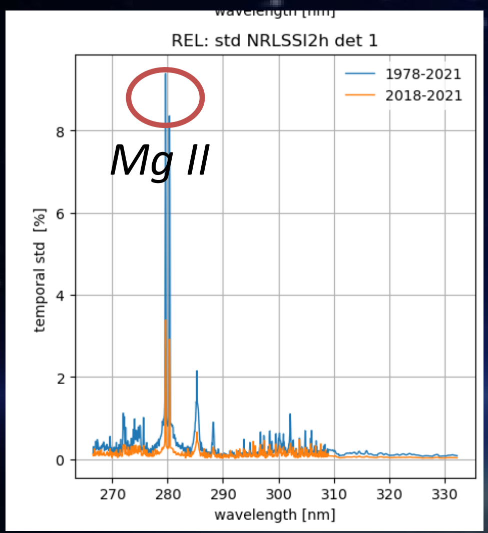
For reference, we use **NRLSSI2h daily time series**

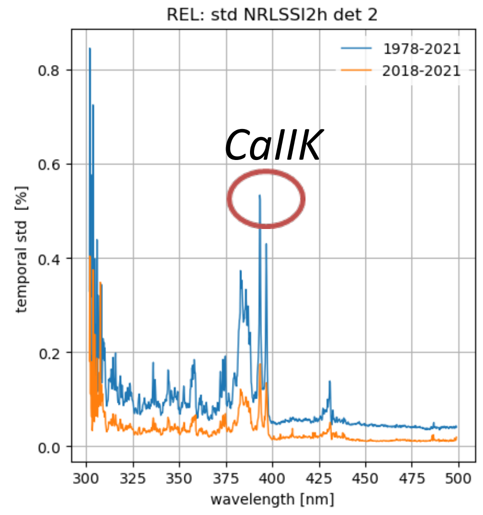
Tool 1: Use stable wavelength intervals to assess instrument degradation, but ***mask*** the unstable intervals



Repr. from: D. Rind et al., JGR-A 113, D24103 (2008)

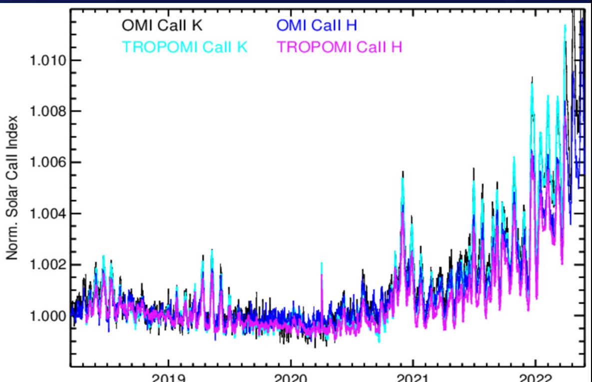
UV **UVIS**





Tool 2: use solar line indices (core-wing ratios) and their correlations.

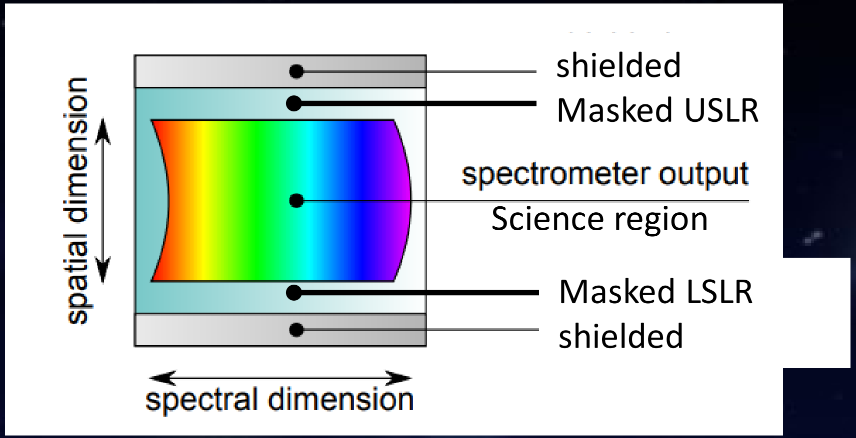
→ The stable Ca IIK index at least suggests that current straylight correction in UVIS is OK

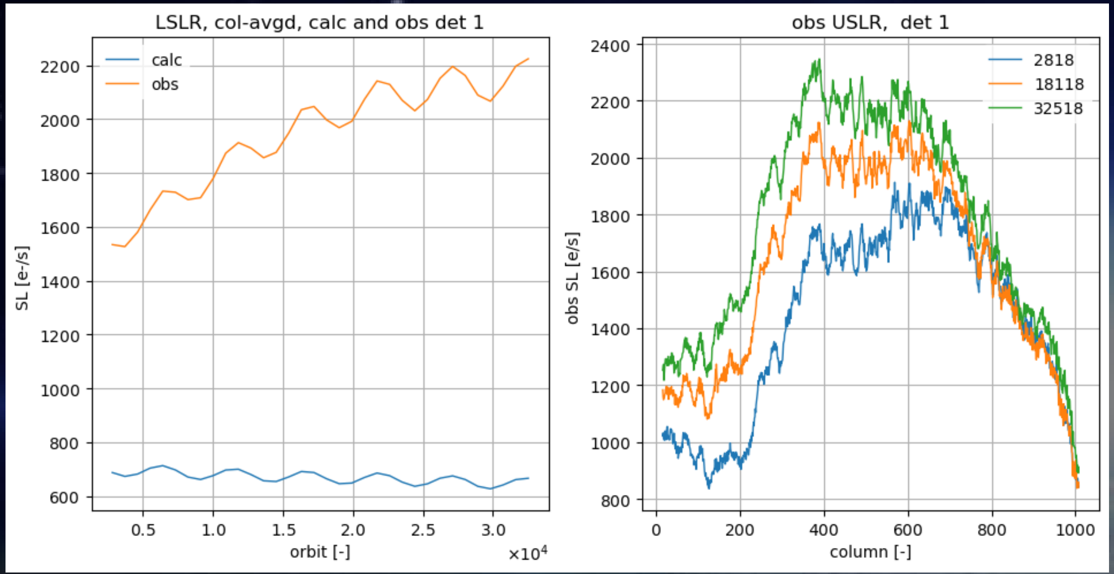


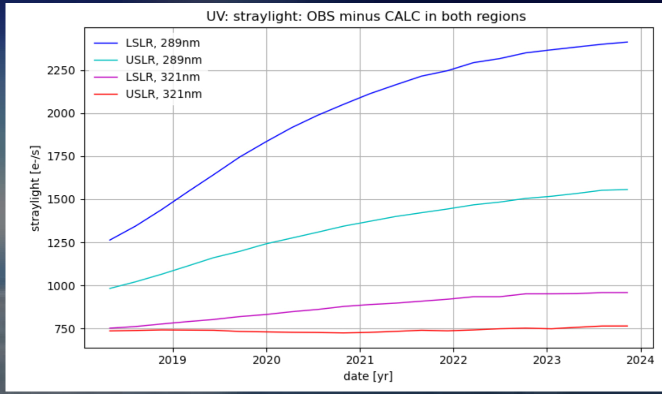
From: Marchenko et al

In-flight straylight monitoring and how to use it

- On each detector there are masked rows (“upper and lower straylight regions”, USLR & LSLR); they do not receive direct light
- Signals in these regions are monitored for all (ir-)radiance measurements, all scanlines
- We monitor *calculated* (using the straylight convolution kernel CKD) and *observed* (measured signal before SL correction) signals.
- → Observed straylight is both too high AND smoothly increasing!
- → The ‘observed-computed’ difference can be used in a *dynamic straylight correction:* interpolation to science region **(Tool 3)**





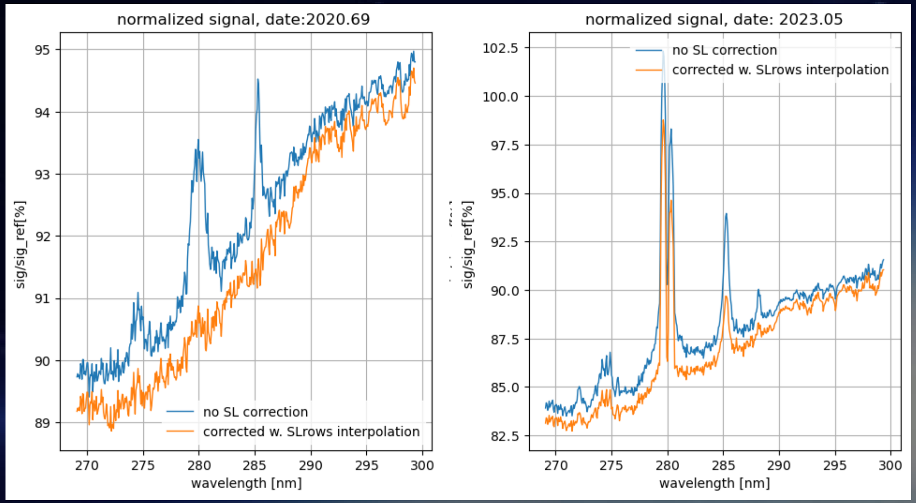


Straylight and solar variation: tools

- **Dynamic straylight correction** works at least for the first TROPOMI years, when solar cycle is still small.
  Success criterion: the normalized signal (after this new correction) has no positive peaks, and the multiplicative optical degradation is spectrally smoother, as in the other detectors.
  (Note: a LF additive (straylight) signal above a low baseline (FL) gives, relatively, a single hump (blue))

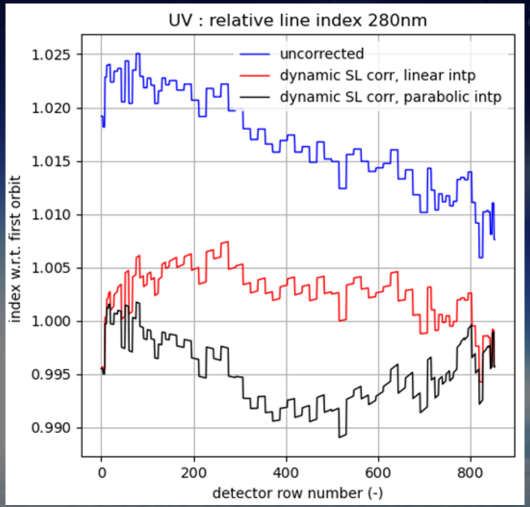
- **More general**, in active periods, look at the solar line indices: stable under multiplicative degradation, sensitive to additive changes. Thus, after a proper dynamic straylight correction:
  - The MgII line index has less spatial dependency… (red line vs blue line)
  - … and should follow known solar time series (e.g. Mg II Bremen index)

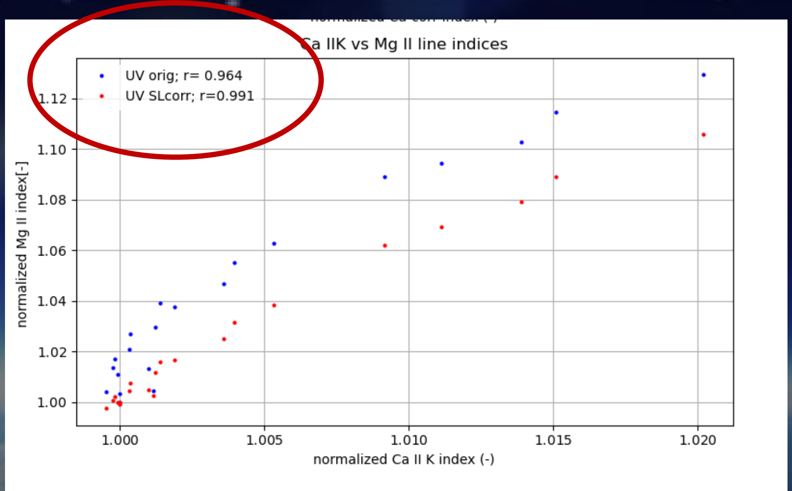
- Finally, correlation between MgII (280nm, UV detector) and Ca II K (393nm, UVIS detector) should be high…



2020
(solar minimum)

2023





Conclusions

- **The Tropomi L01b Processor corrects for optical degradation using in-flight calibration**.
    - Method: irradiance measurements with two diffusers AND understanding of light paths and instrument components
    - The degradation can be **separated** in several components, with their own CKDs.
- Proper degradation correction requires absence of offsets, both at start of mission and forever after.

- **The Tropomi L1b Processor corrects for straylight.**
- However, *temporal* growth of straylight is observed from in-flight monitoring;
    - A robust *additional* dynamic straylight correction based on in-flight straylight monitoring is being tested.
    - This correction removes unwanted offset in UV, thereby again enabling proper degradation correction.

- **Sun is not a stable stimulus** for certain wavelength intervals: masking is needed
- Straylight affects the same intervals where Sun is unstable, making analysis more difficult. Existing datasets like NRLSSI2h and the Bremen MgII index help, as does the MgII-CaII correlation.

- **Why it matters:**
    - We do not want to calibrate towards monthly/11yr cycle of the Sun
    - Wrong multiplicative correction of additive straylight invalidates *radiance* degradation correction

Thank you!

general information: http://www.tropomi.eu/

more on TROPOMI calibration: Kleipool et al. 2018 https://doi.org/10.5194/amt-11-6439-2018

Ludewig et al. 2020 https://doi.org/10.5194/amt-2019-488

→ Also see posters:
"TROPOMI shard detector feature correction" – Edward v Amelrooy
"TROPOMI radiance in-flight calibration" – Emiel vd Plas

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