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# Overview of the TEMPO Level 0-1 processor

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Xiong Liu, John Houck, David E. Flittner, James Carr, Weizhen Hou, John E. Davis,

Raid M. Suleiman, Kelly Chance, Nischal Mishra, Christopher Chan Miller, Gonzalo González Abad,

Brian Baker, James Lasnik, Dennis Nicks, Juseon Bak, Caroline R. Nowlan, Huiqun Wang,

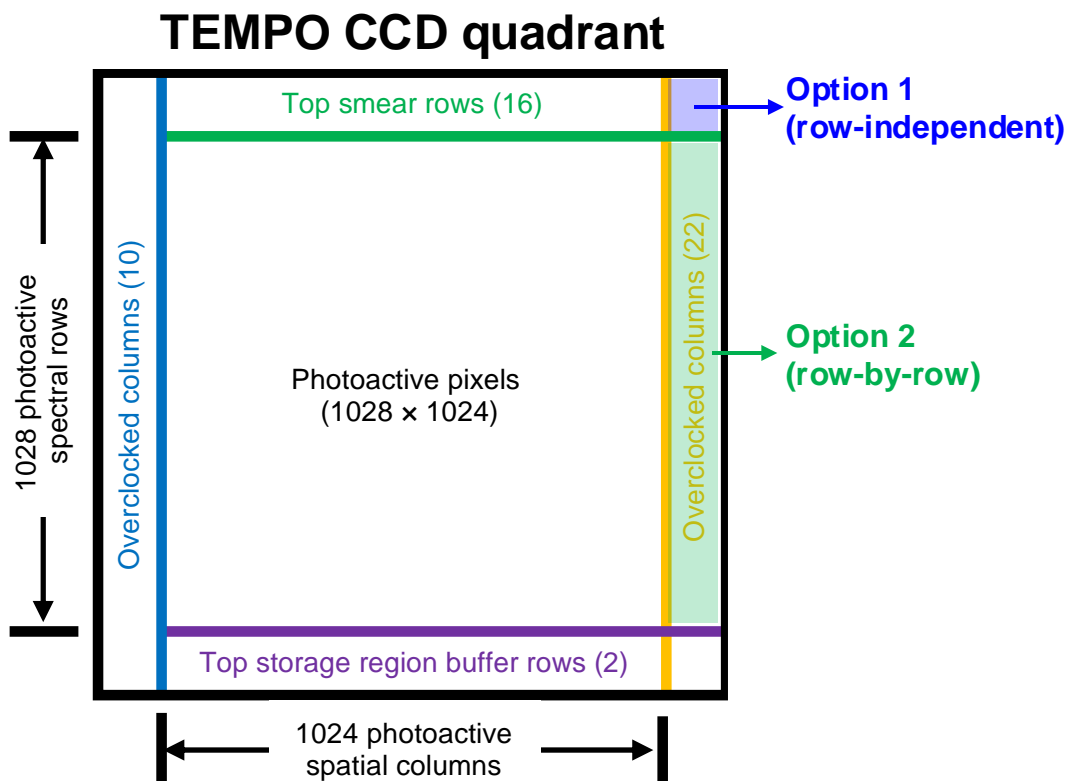Junsung Park, Ewan O'Sullivan, Jean Fitzmaurice, Laurel Carpenter, Colin Seftor, and Glen Jaross

August 26, 2024

# Outline

- Major updates to the TEMPO Level 0-1 processor through Version 3

$$\text{Radiance} = \{[(\text{L0} / \text{coadd} - \text{offset} - \text{nonlinearity} - \text{crosstalk}) * \text{gain} - \text{smear}] / (\text{integration time}) / \text{prnu} - \text{dark} - (\text{stray light})\} * (\text{calibration coefficient})$$

$$\text{Irradiance} = \{[(\text{L0} / \text{coadd} - \text{offset} - \text{nonlinearity} - \text{crosstalk}) * \text{gain} - \text{smear}] / (\text{integration time}) / \text{prnu} - \text{dark} - (\text{stray light})\} * (\text{calibration coefficient}) / \text{btdf}$$

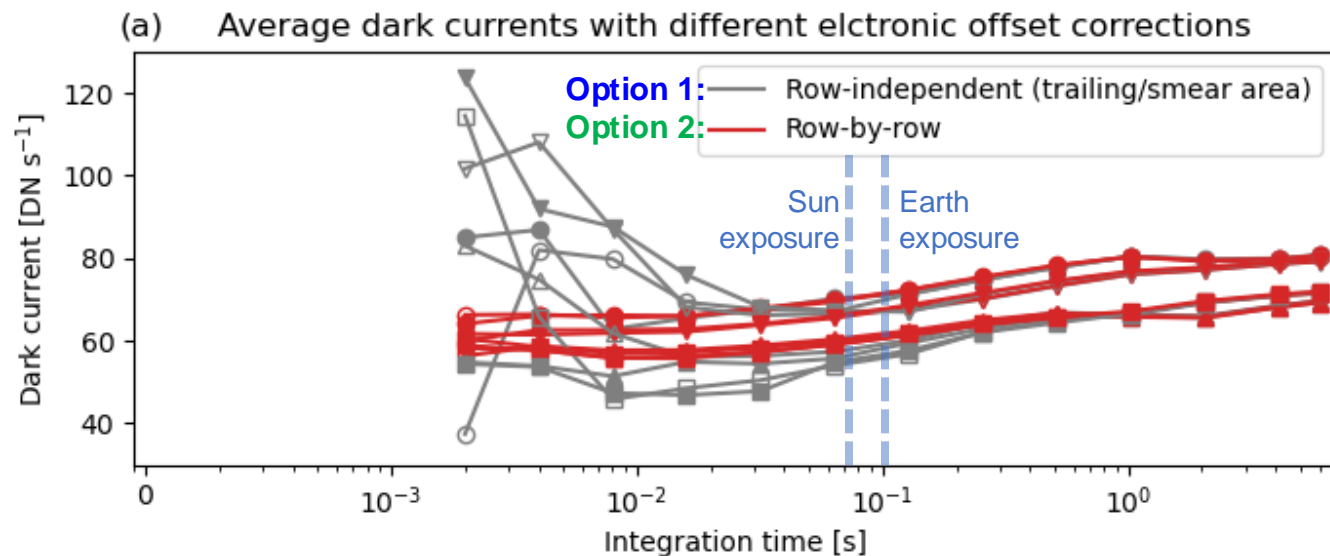(digital counts — electrons — electrons/s — photons/s/cm$^2$/nm(/sr))

- Electronic offset, smear, dark current, stray light, and BTDF corrections (BTDF = Bidirectional Transmittance Distribution Function)

- Overestimation of Sun-normalized radiance

\* Please see Weizhen Hou's poster for spectral calibration.

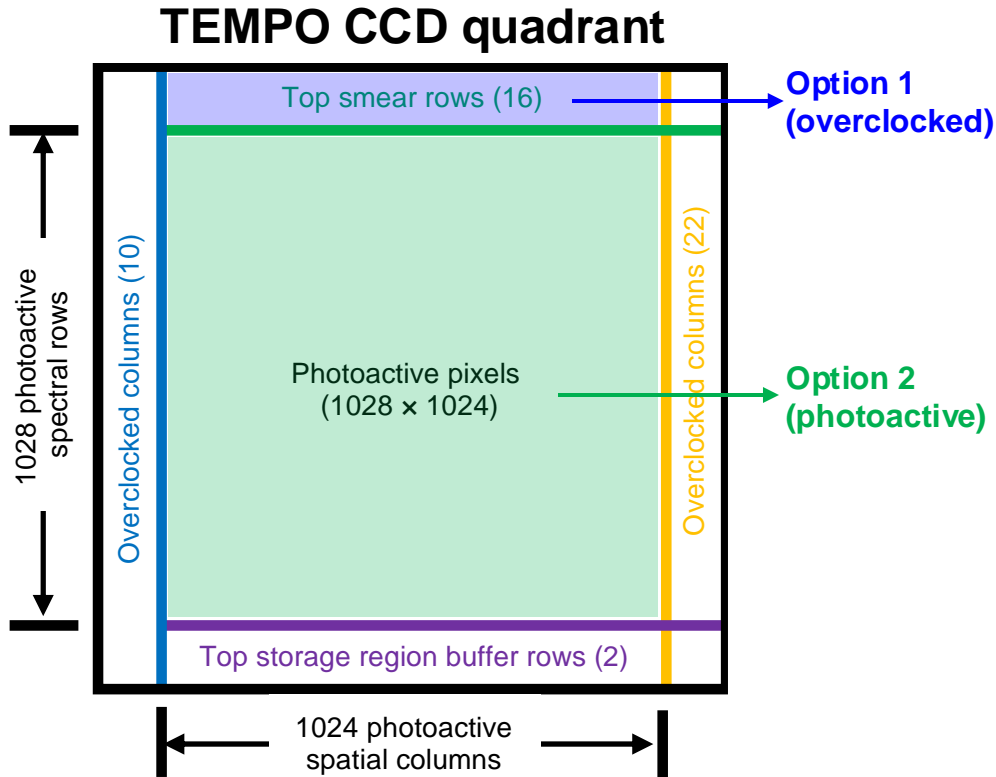# Level 0-1 processing: Electronic offset correction



**TEMPO CCD quadrant**

Top smear rows (16)

Option 1
(row-independent)

Overclocked columns (10)

Overclocked columns (22)

1028 photoactive spectral rows

Photoactive pixels
(1028 × 1024)

Option 2
(row-by-row)

Top storage region buffer rows (2)

1024 photoactive spatial columns



**Dark current as a function of integration time (August 18, 2023)**

(a)    Average dark currents with different electronic offset corrections

Option 1:  Row-independent (trailing/smear area)
Option 2:  Row-by-row

Sun exposure    Earth exposure

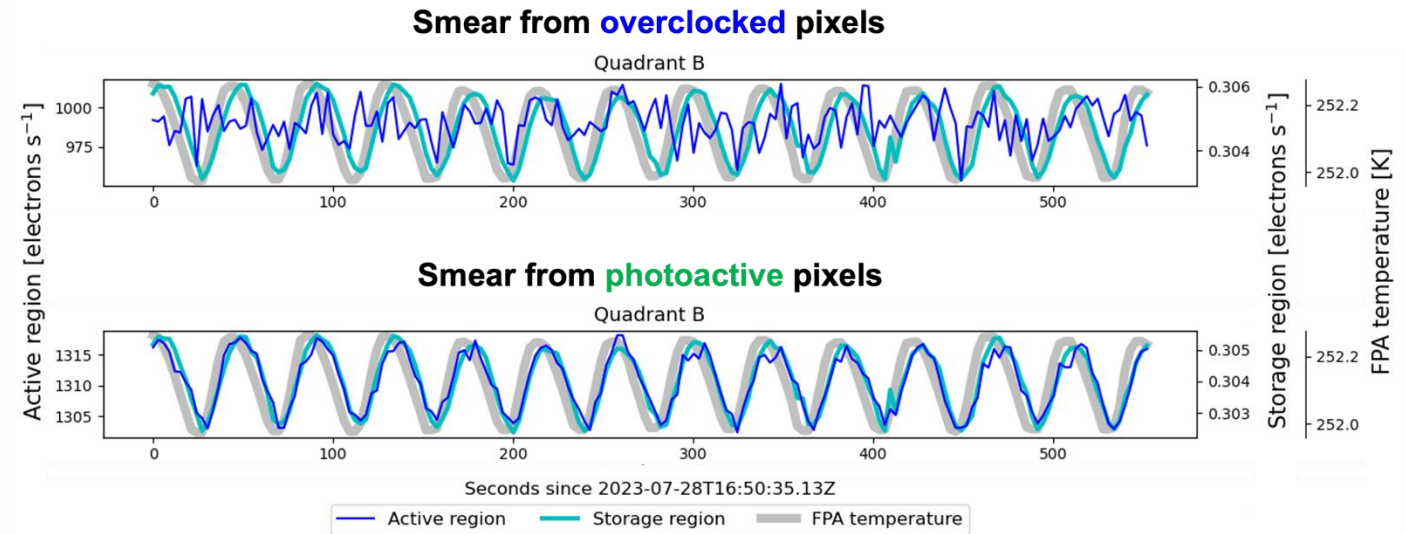- **Current implementation**: Row-by-row, frame-by-frame correction
- **Impact**: Increased accuracy at low signal levels

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# Level 0-1 processing: Smear correction

**TEMPO CCD quadrant**



**Option 1 (overclocked)**

**Option 2 (photoactive)**

Top smear rows (16)

Overclocked columns (10)

Overclocked columns (22)

Photoactive pixels (1028 × 1024)

Top storage region buffer rows (2)

1028 photoactive spectral rows

1024 photoactive spatial columns

**Dark current variation (**$\text{dark} = f(\text{FPA temperature})$**)** (FPA = Focal Plane Array)
(07/28/2023)



**Smear from overclocked pixels**
Quadrant B

**Smear from photoactive pixels**
Quadrant B

Seconds since 2023-07-28T16:50:35.13Z

— Active region    — Storage region    — FPA temperature

- **Current implementation**: Photoactive correction
- **Impact**: Increased accuracy at low signal levels

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# Level 0-1 processing: Dark current correction

The CCDs can't measure (ir)radiance and dark current simultaneously in the image regions. → Scale the pre-measured dark.

$$dark = f(\text{FPA temperature})$$

**Dark current scaling method verification** – Twilight measurement (03/17/2024, 11:11:00 UTC; 6-s exposure)
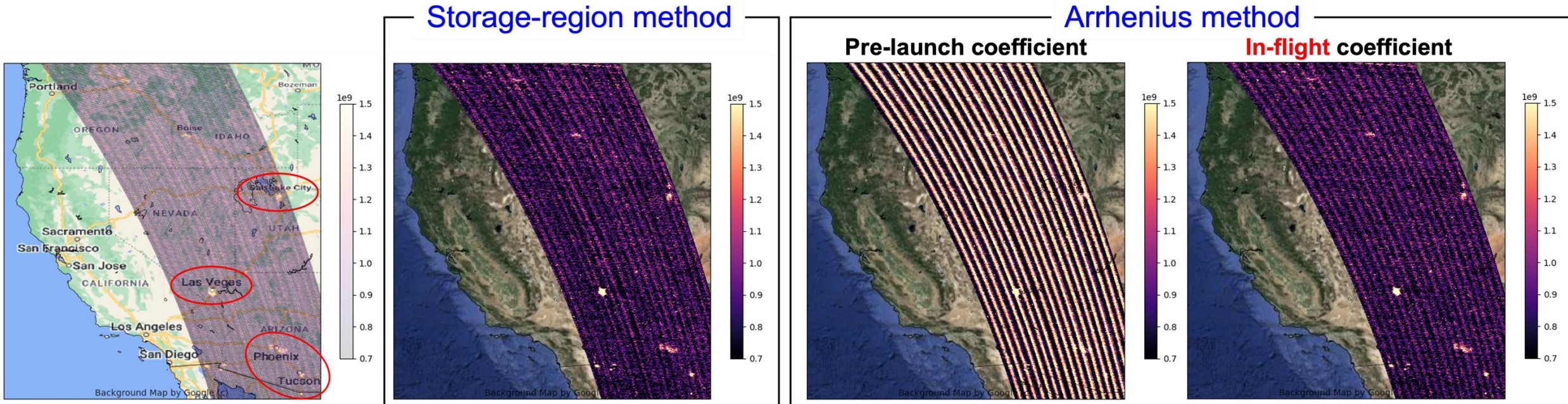


- **Current implementation**: Storage-region method for RADT (twilight); Arrhenius method for RAD and IRR
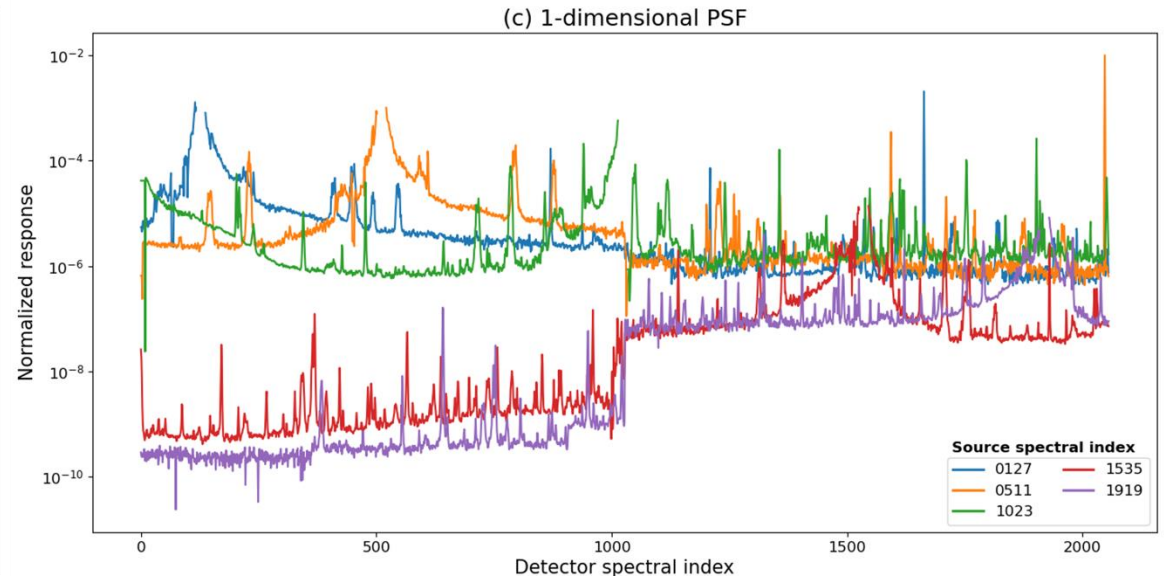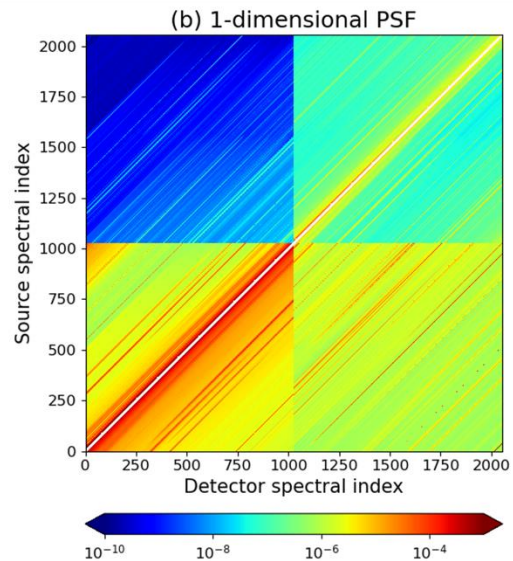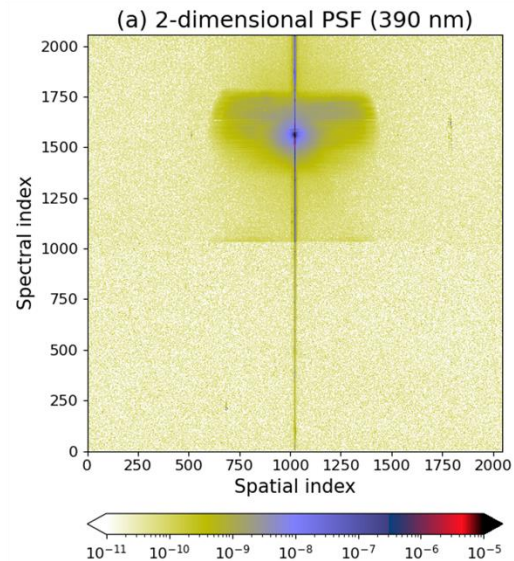- **Impact**: Increased accuracy at low signal levels → Twilight signals detected in V3

(For details, see James Carr's presentation at 15:50 today.)

# Level 0-1 processing: Stray light correction

**1-dimensional point spread function (PSF)**

$$R_{\text{meas}} = [I + D] \cdot R_{\text{meas}}^{\text{ib}} \quad \rightarrow \quad R_{\text{meas}}^{\text{ib}} = [I + D]^{-1} \cdot R_{\text{meas}} \quad \text{(Zong et al., 2007)}$$

Measured signals    Identity    In-band signals (without stray light)



(a) 2-dimensional PSF (390 nm)

(b) 1-dimensional PSF

(c) 1-dimensional PSF

[PSF data processing: David Flittner]

- **Current implementation**: 1-dimensional PSF
- **Impact**: Increased accuracy at low signal levels → Total ozone diurnal variation improved in V3

(For details, see Junsung Park's presentation at 14:30 today.)

# Level 0-1 processing: Diffuser goniometry
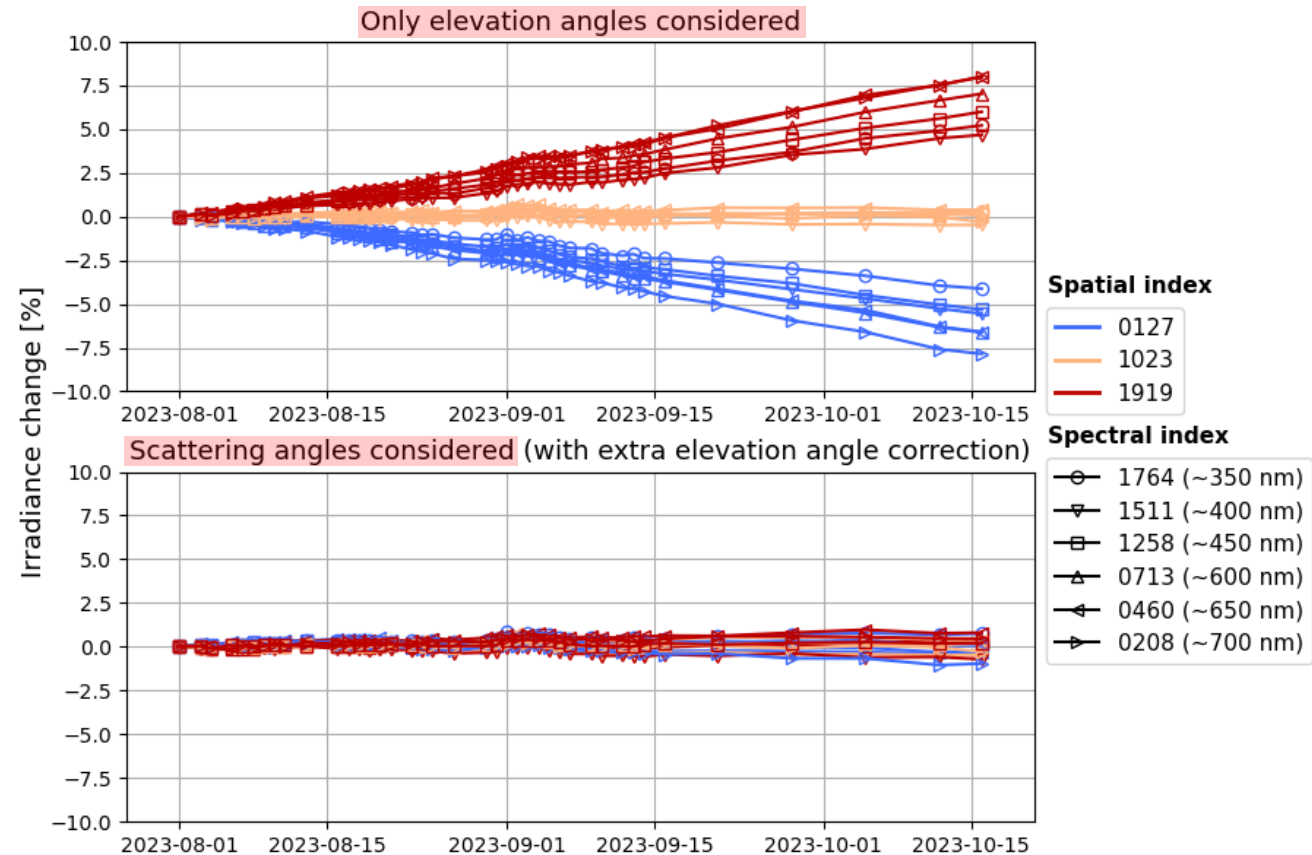


- **Current implementation**: Scattering angle correction applied
- **Impact**: Spatial and temporal gradient in solar irradiance reduced significantly

# Overestimation of Sun-normalized radiance
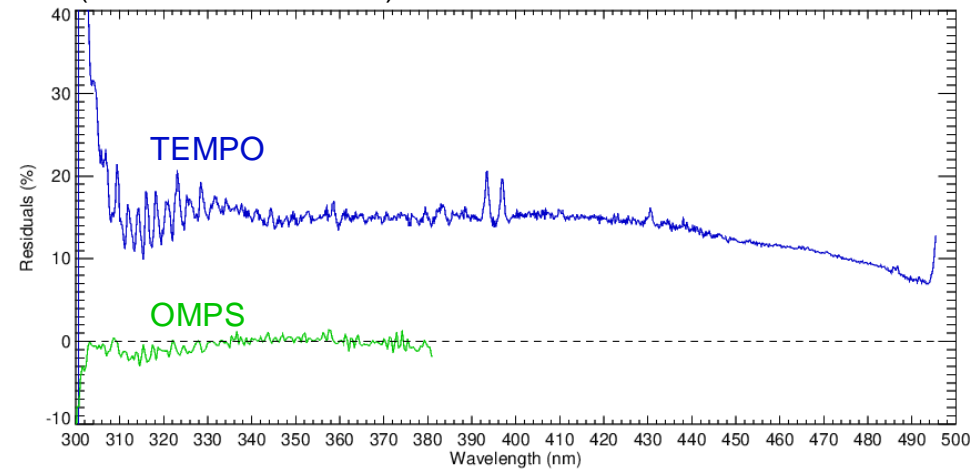
**Comparisons against two radiative transfer models**

Radiance (11/06/2023, scan 009, granule 02)
/ Irradiance (10/26/2023)



Selected pixels
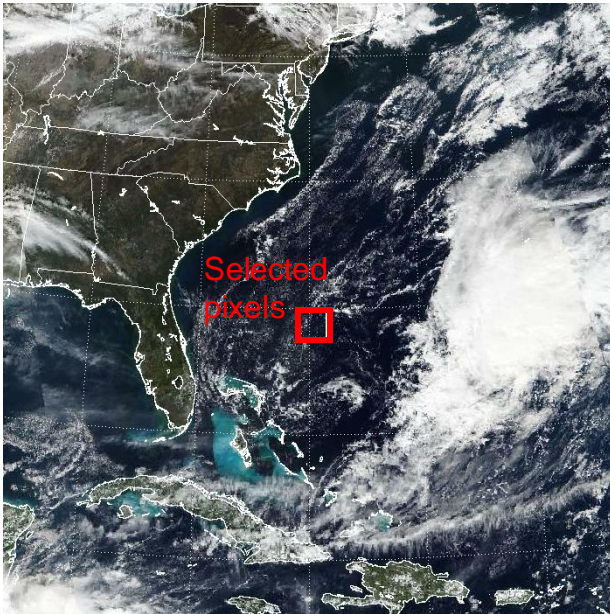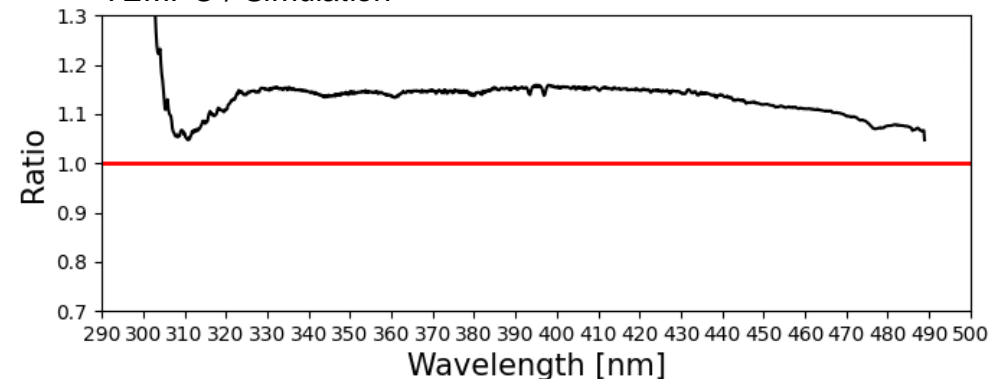
[VIIRS RGB, Credit: Colin Seftor]

**TOMRAD**

(TEMPO – Simulation) / Simulation × 100



TEMPO

OMPS

[Credit: Colin Seftor]

**VLIDORT (TEMPO ozone profile algorithm)**

TEMPO / Simulation


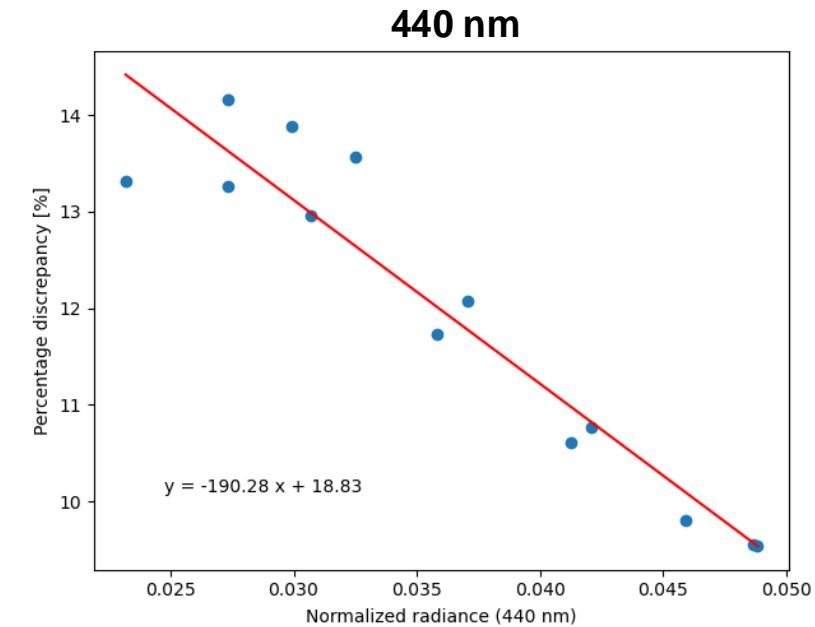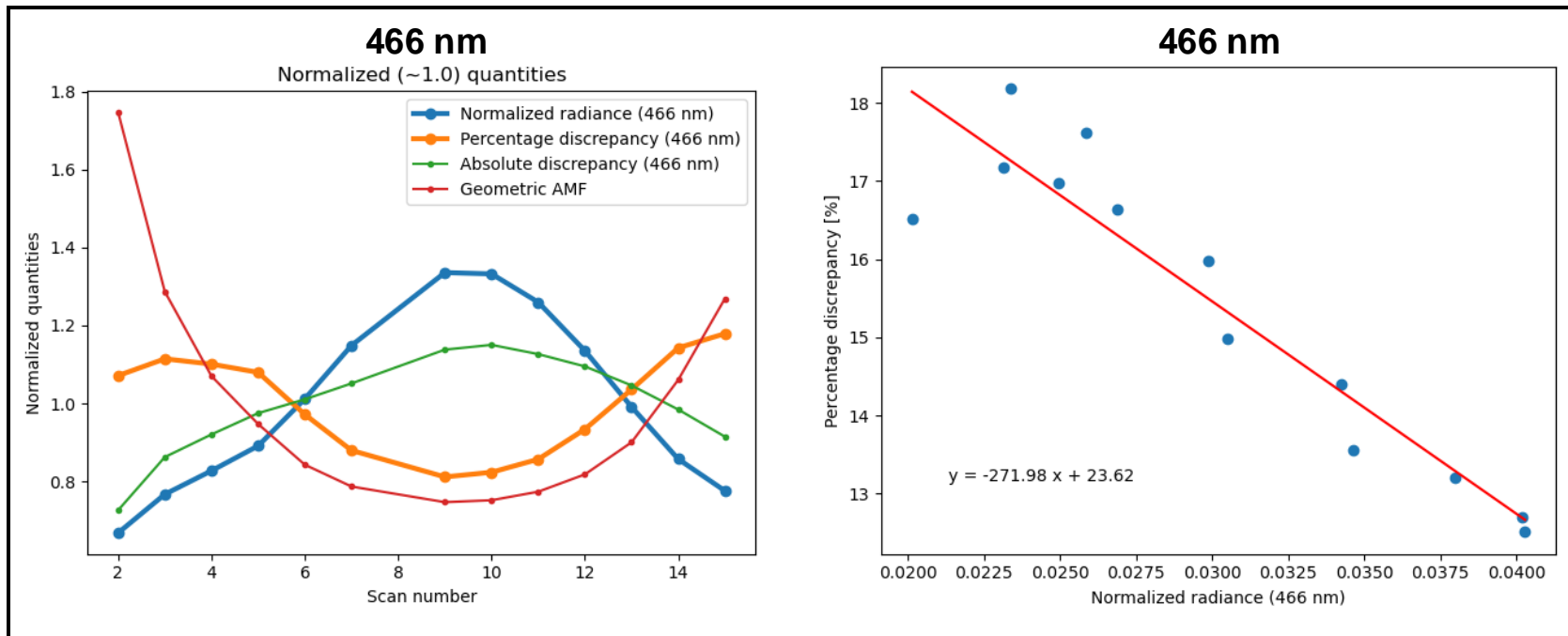
[Credit: Junsung Park]

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# Overestimation of Sun-normalized radiance

**Comparison of normalized radiance at 466 & 440 nm**

**TEMPO cloud look-up tables (VLIDORT)** (constructed by the OMI cloud team at NASA GSFC)

Clear-sky pixels at Lake Michigan, 05/30/2024, scans 002–015

# Overestimation of Sun-normalized radiance

**Investigations into the root causes**

|  | digital counts | electrons | electrons/s | photons/s/cm²/nm(/sr) |
|---|---|---|---|---|

Radiance = {[(L0 / coadd – offset – nonlinearity – crosstalk) ∗ gain – smear] / (integration time) / prnu – dark – (stray light)} ∗ (calibration coefficient)

Irradiance = {[(L0 / coadd – offset – nonlinearity – crosstalk) ∗ gain – smear] / (integration time) / prnu – dark – (stray light)} ∗ (calibration coefficient) / btdf

[ Possible sources of errors that are not canceled out in normalized radiances ]

- Electronic offset

- Non-linearity

- Uncorrected stray light

- Diffuser BTDF

- No direct on-ground irradiance calibration

- Uncorrected polarization

[ Ongoing analyses ]
- Revisiting each calibration step
- Quantification of impact on normalized radiances using partial derivatives
- More comparison against simulations and measurements, including those during RRV 2024 CAL-VAL campaign

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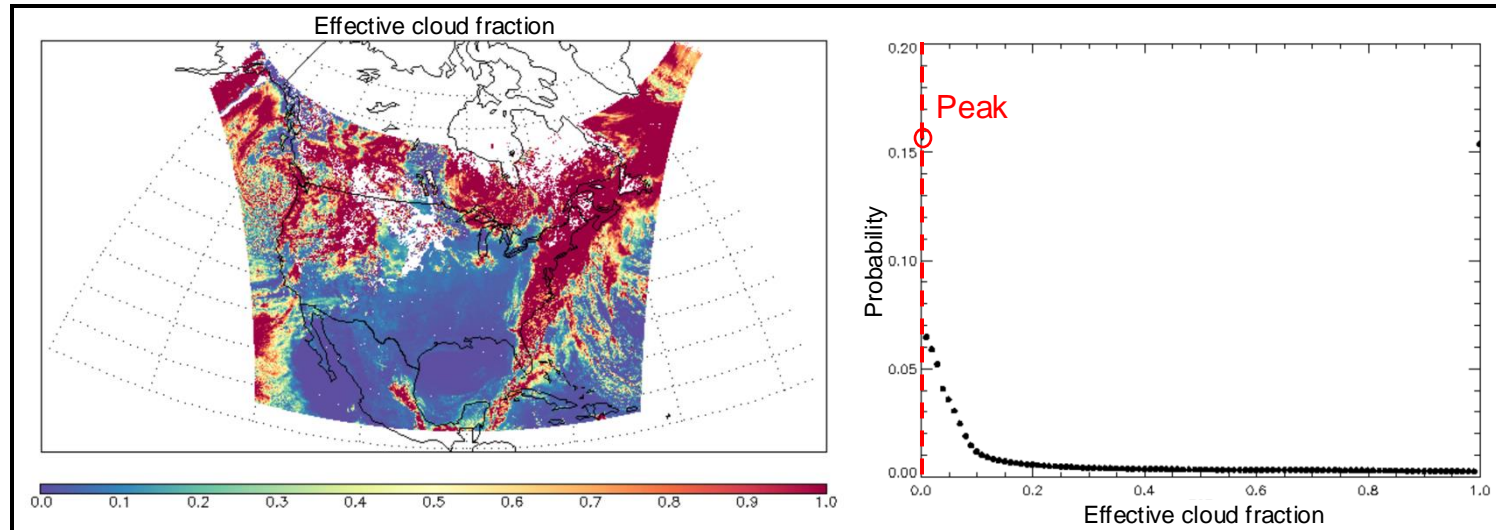# Overestimation of Sun-normalized radiance

**Preparations for potential empirical correction**



**Without correction**
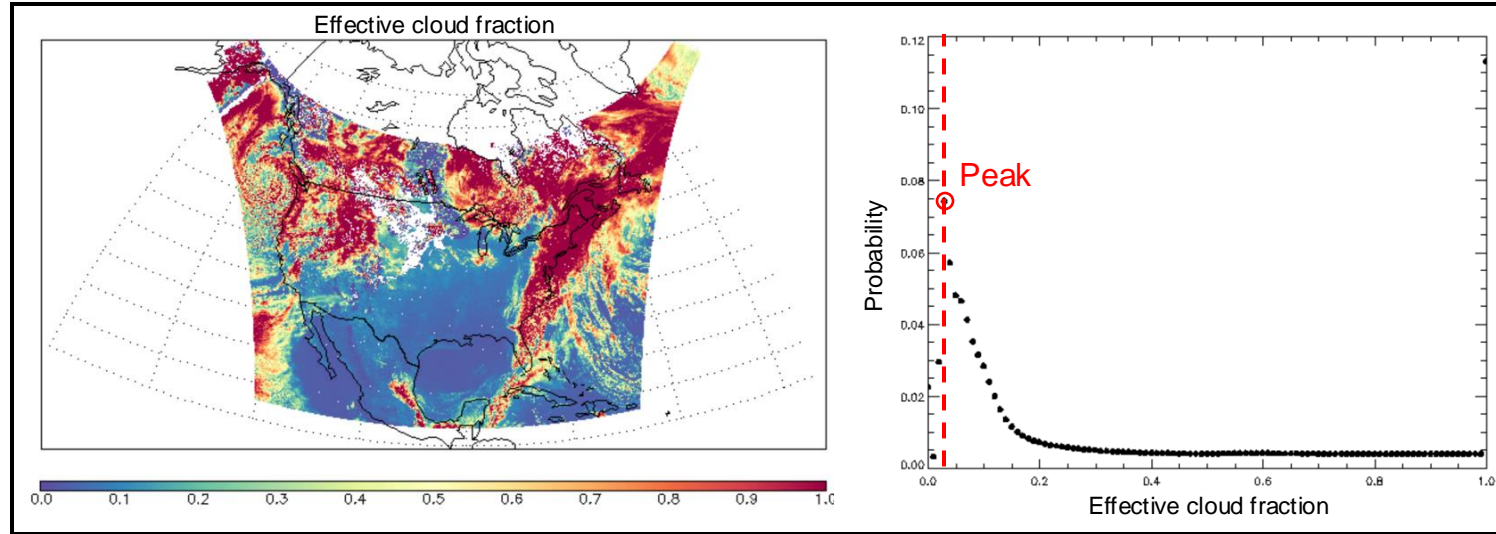
**Empirical correction for normalized radiance at 466 nm**

(Linear equation from Lake Michigan, 05/30/2024)

[Credit: Huiqun Wang]

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# Summary

- Through multiple version updates, the TEMPO Level 0-1 processor has undergone significant enhancements to improve the radiometric and spectral performance.

- However, TEMPO Level 1 data assessments indicated overestimations of Sun-normalized radiances compared to radiative transfer calculations.

- Investigations into the root causes and preparations for potential empirical correction are underway, including polarization correction.

# Thank you for your attention!