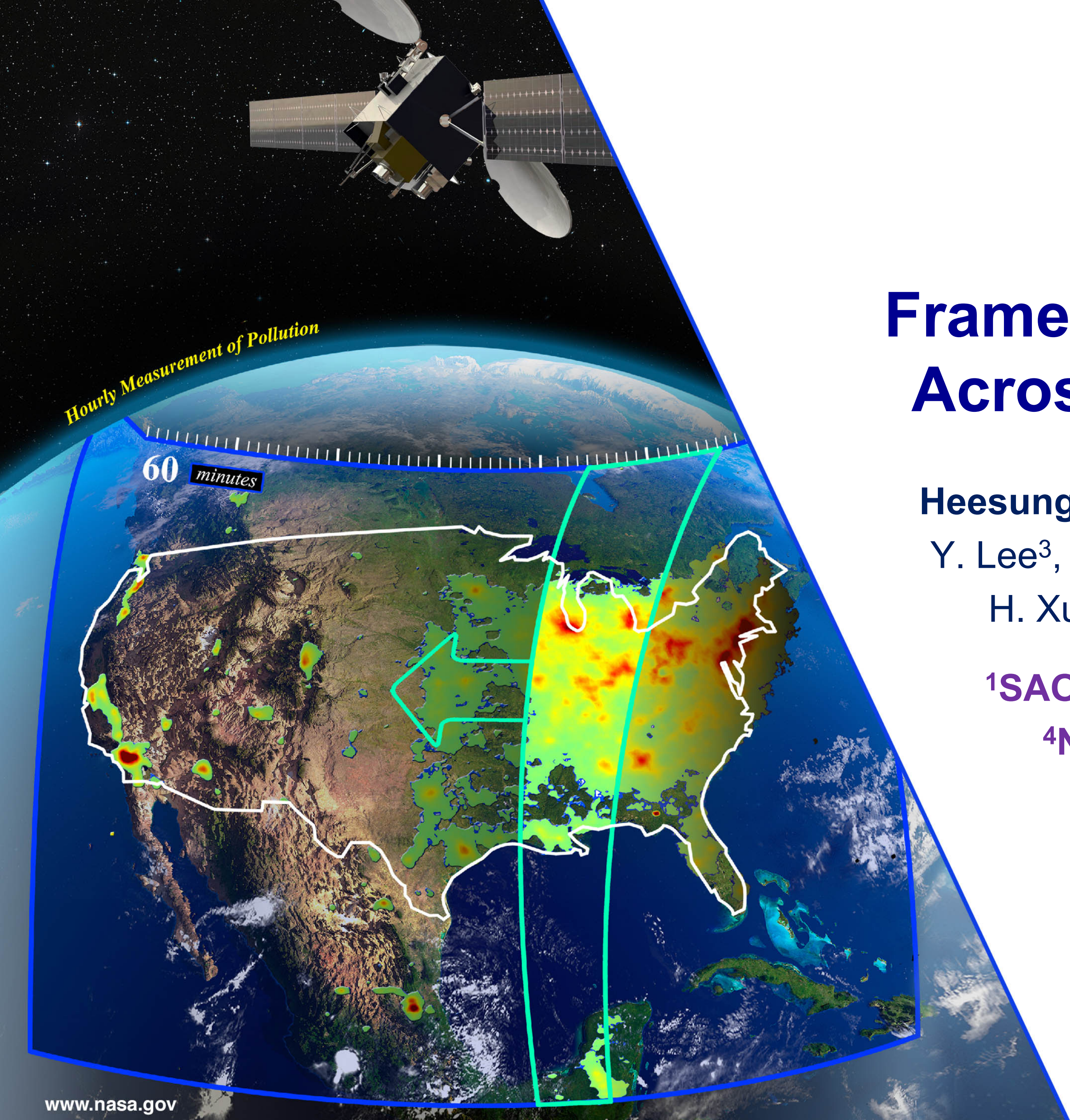


Tropospheric Emissions: Monitoring of Pollution

TEMPO

Framework for L1B Calibration Across Multiple GEO Sensors

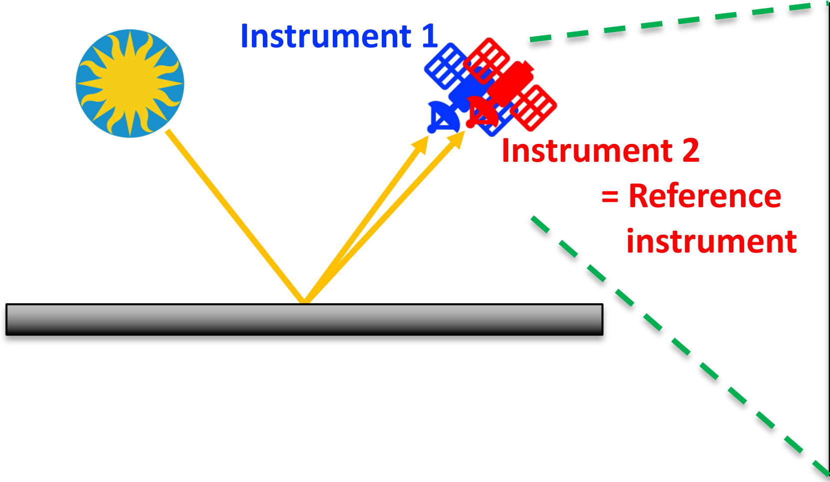
Heesung Chong[1], X. Liu[1], D.E. Flittner[2], M.-H. Ahn[3], Y. Lee[3], L. Flynn[4], J. Carr[5], J. O. Robaidek[6], X. Wu[4], H. Xu[4], B. Basnet[4], Y. Bai[4], C. Cao[4], D. Doelling[2]

[1]SAO, CfA [2]NASA LaRC [3]Ewha Womans Univ. [4]NOAA/NESDIS [5]Carr Astro. [6]UW–Madison

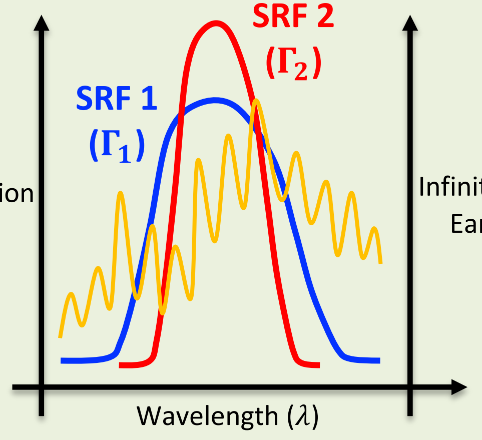
June 16, 2026

Smithsonian

Intercalibration



Normalized
spectral response function
(SRF, Γ)



Infinitely-high-resolution
Earth radiance (I_{hr})

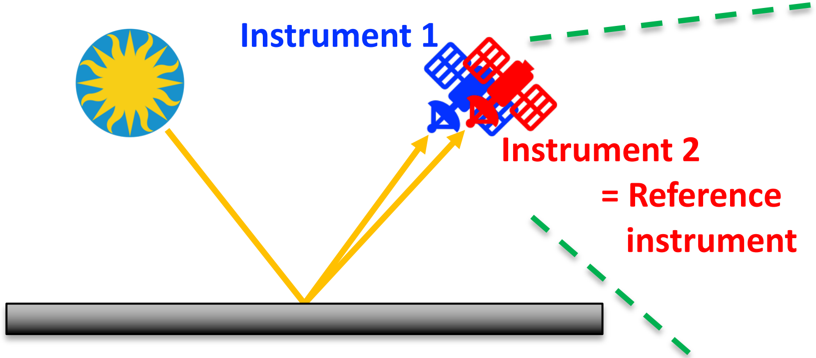
Calibration error

Radiance from Instrument 1 $$I_1 = \frac{\int (I_{hr} \times \Gamma_1) d\lambda}{\int \Gamma_1 d\lambda} + \varepsilon_1$$

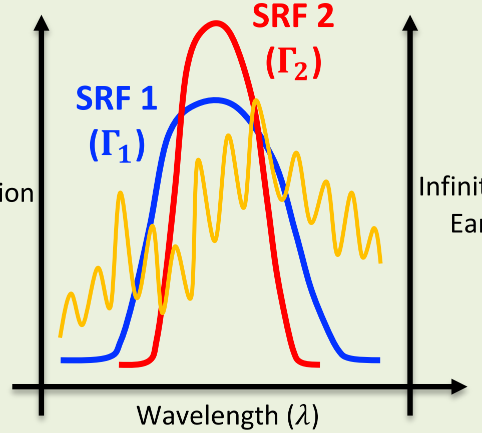
Radiance from Instrument 2 $$I_2 = \frac{\int (I_{hr} \times \Gamma_1) d\lambda}{\int \Gamma_2 d\lambda} + \varepsilon_2$$

If $\Gamma_1 \neq \Gamma_2 \rightarrow I_1 \neq I_2$
even with perfect calibration

Intercalibration



Normalized spectral response function (SRF, Γ)



Infinitely-high-resolution Earth radiance (I_{hr})

Calibration error

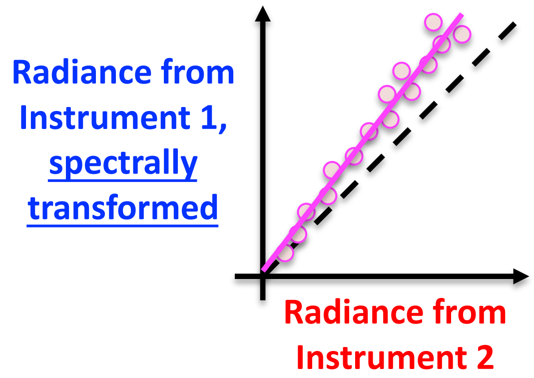
Radiance from Instrument 1 $$I_1 = \frac{\int (I_{hr} \times \Gamma_1) d\lambda}{\int \Gamma_1 d\lambda} + \varepsilon_1$$

Radiance from Instrument 2 $$I_2 = \frac{\int (I_{hr} \times \Gamma_1) d\lambda}{\int \Gamma_2 d\lambda} + \varepsilon_2$$

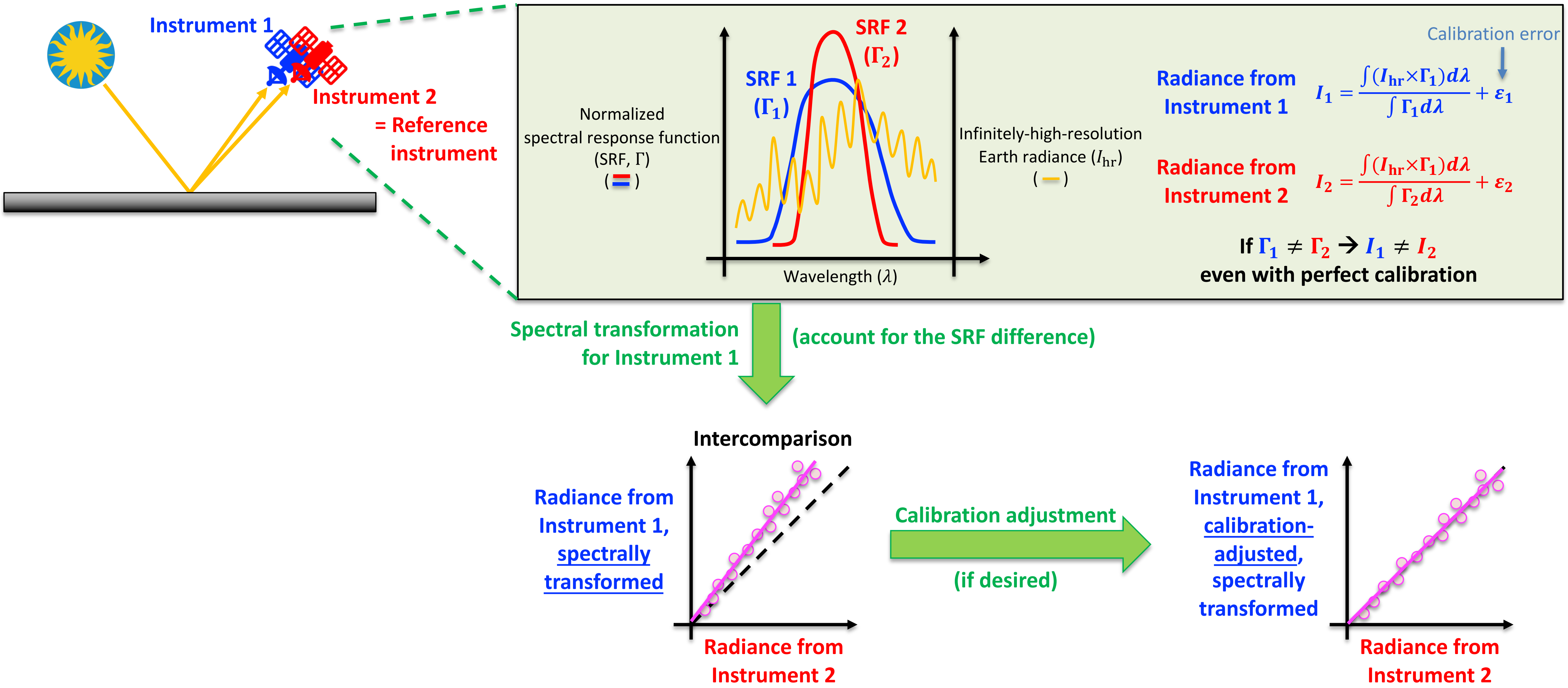
If $\Gamma_1 \neq \Gamma_2 \rightarrow I_1 \neq I_2$
even with perfect calibration

Spectral transformation for Instrument 1 **(account for the SRF difference)**

Intercomparison



Intercalibration



Intercalibration

- Key considerations
  - Reference instrument with reliable calibration
  - Temporal collocation
  - Spatial collocation
  - Viewing geometry alignment
  - Surface type
  - Cloudiness

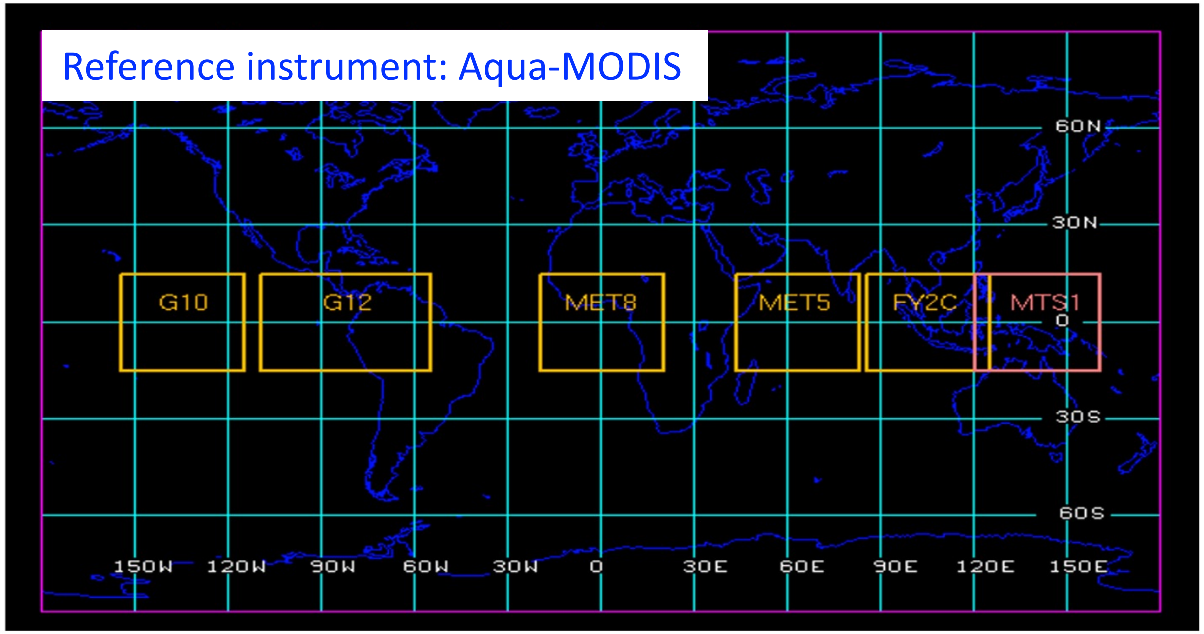
Some widely-used combinations:

Surface type	Cloudiness
Ocean	All-sky conditions
All surface types	Optically thick clouds
Desert	Clear-sky conditions

GEO Weather Constellation

➢ Most geostationary (GEO) weather satellite instruments provide measurements at the sub-satellite points. (i.e., over the Equator)

Figure 1 from Doelling et al. (2011): Calibration domains for GEOs.

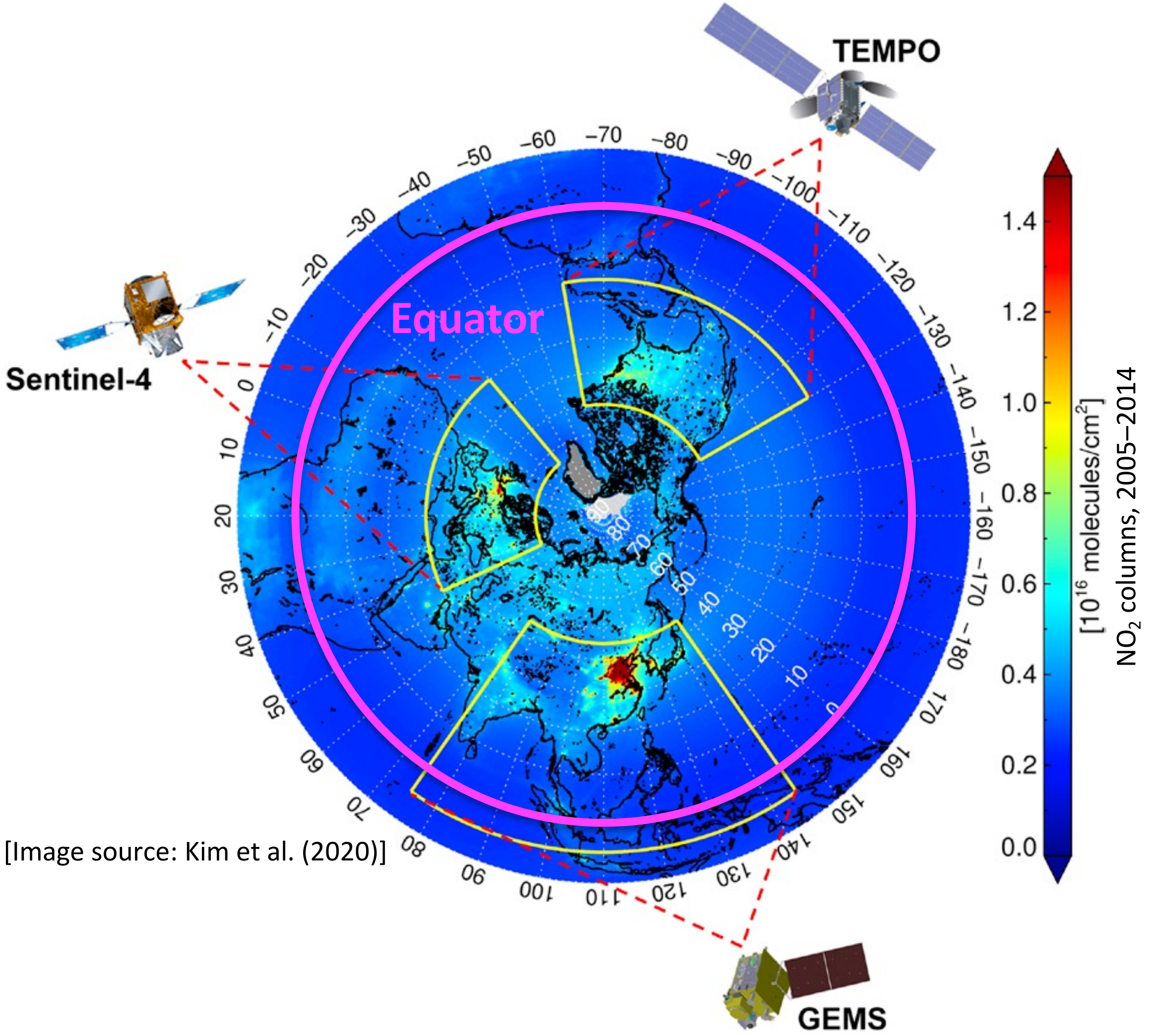


➢ A widely-used intercalibration method: Compare radiances from a GEO sensor with those from a reference low-Earth-orbit sensor near the Equator.

→ Benefits of using the sub-satellite point

- Thinnest atmospheric path
- Reduced bidirectional reflectance
- Easier spatial matching
- Minimum pixel distortion

GEO Air Quality Constellation



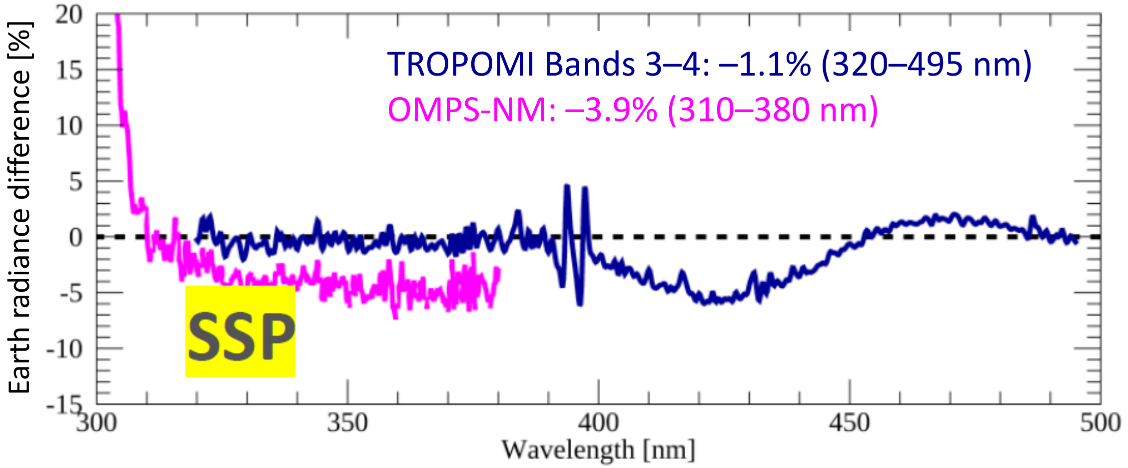
[Image source: Kim et al. (2020)]

- To date, GEMS is the only GEO air-quality sensor whose sub-satellite point lies within its field of regard.
- Other approaches beyond using the sub-satellite points are necessary to intercalibrate all three GEO air-quality sensors.

GEMS vs. Low-Earth-orbit Instruments

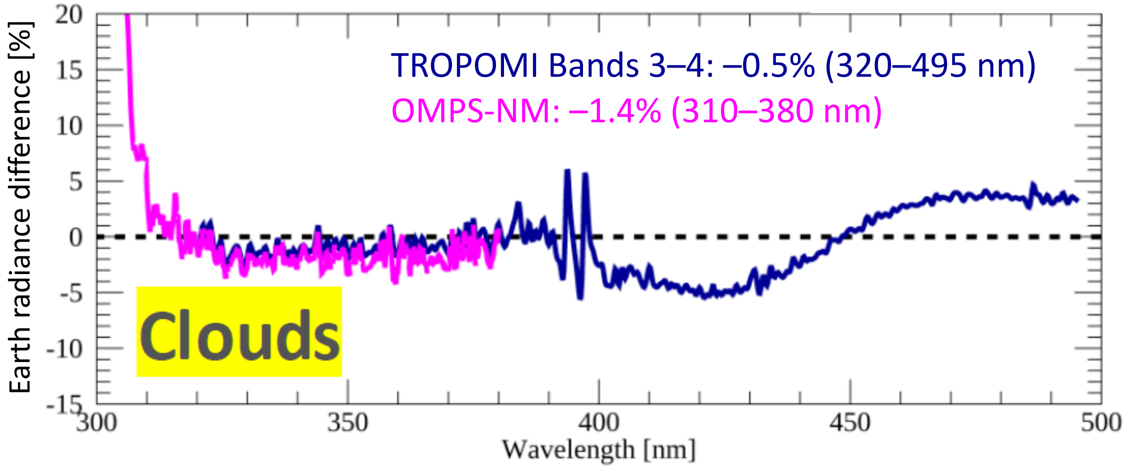
- **Temporal coverage:** January–December 2021
- **Reference instruments:** TROPOMI (every 5 days) & OMPS-NM (every day)

Sub-satellite point of GEMS (0.5°×0.5° box)



No constraints on surface type, but a scene homogeneity test

Clouds within the hourly GEMS field of regard



Constraints on scene homogeneity and brightness

Other constraints on ray matching: temporal collocation, spatial collocation, viewing geometry alignment, and absolute viewing and solar angles

Under proper constraints, using clouds within the GEO's hourly field of regard can yield reliable intercalibration.
(Potential limitation: dynamic range)

[Credit: M.-H. Ahn & Yeeun Lee]

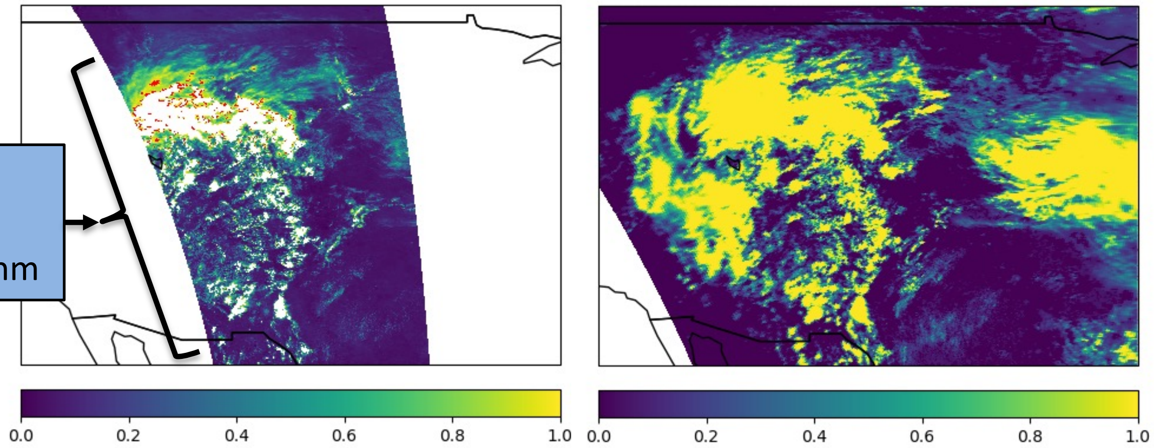
TEMPO vs. Low-Earth-orbit Instruments

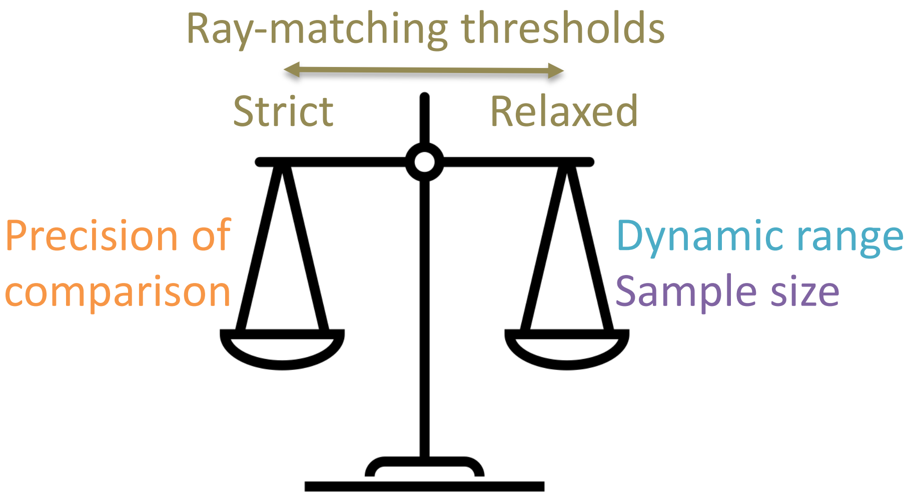
- **TEMPO measurements over clouds:**
  Elevated probability of saturation over fully cloudy scenes, in return for high signal-to-noise ratios over clear-sky scenes

Cloud fractions (2023/08/02)

TEMPO cloud fraction (V03) | **TROPOMI cloud fraction (OCRA algorithm)**

White: saturated
Red: cloud fraction = 1.0, no saturation at 466 nm





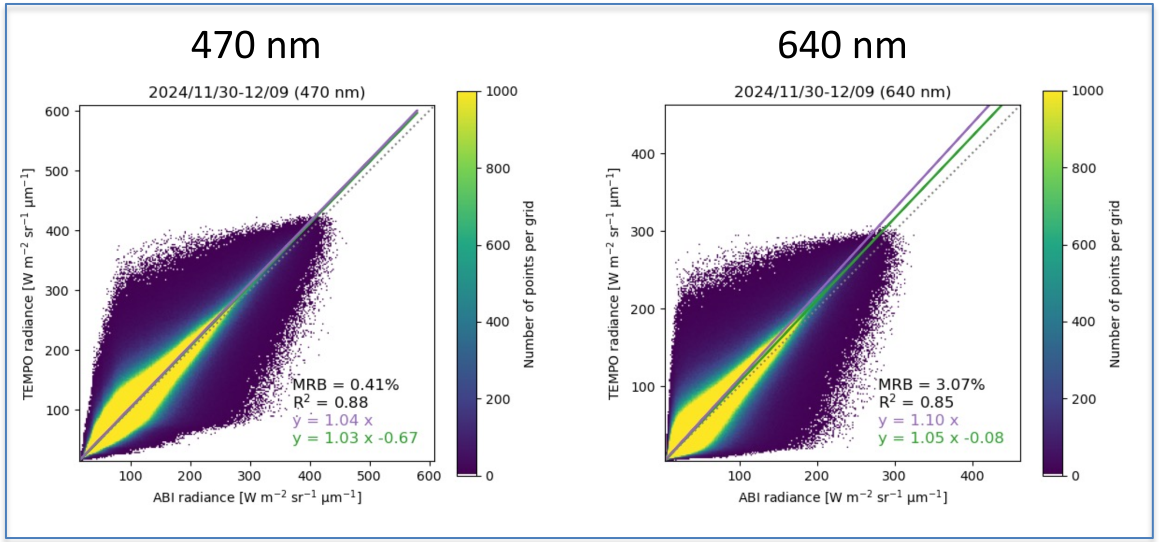
Relatively challenging to derive reliable statistics
from ray-matching between TEMPO and a low-Earth-orbit instrument

GEO as a Transfer Standard

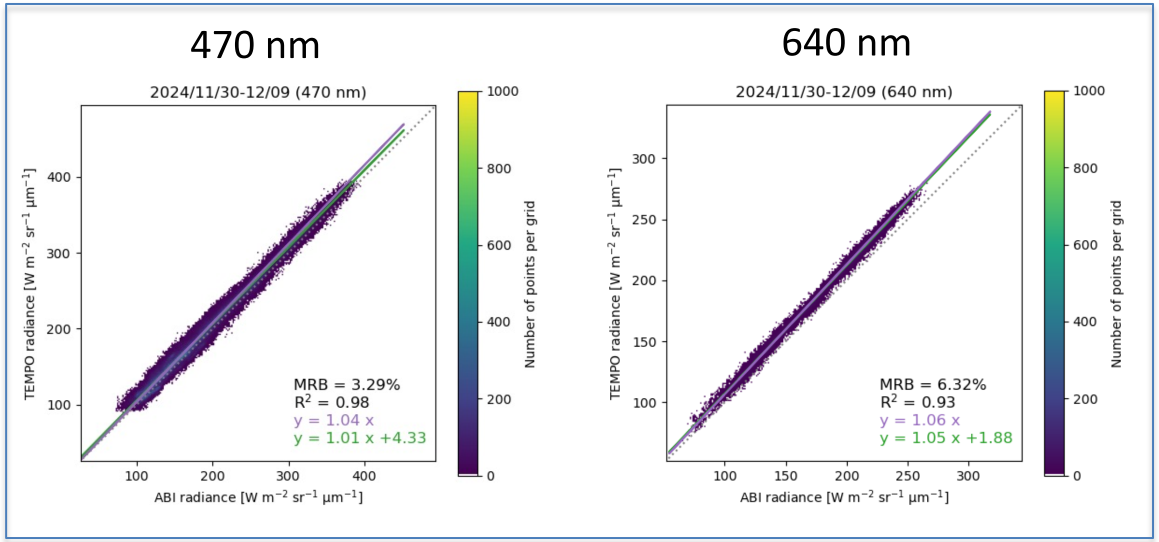
- **Primary standard instrument:** VIIRS (GSICS-recommended, low-Earth-orbit)
- **Proposed idea:** Use the GOES-East ABI instrument as a transfer standard for the TEMPO-VIIRS comparison.
- **Satellite longitudes:** 91.0°W (TEMPO) vs. 75.2°W (ABI)

- **Comparison between TEMPO V03 and ABI (GOES-16) radiances (75.2–91.0°W, 2024/11/30–12/09)**

All-sky conditions + No constraint on scene homogeneity



Fully-cloudy conditions + Constraint on scene homogeneity

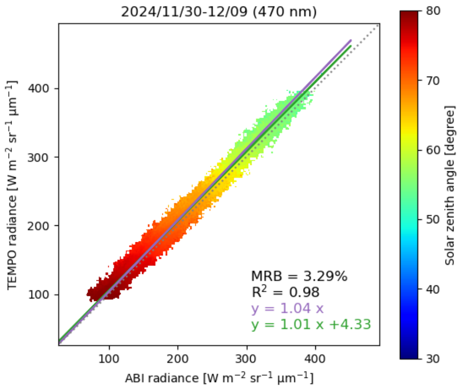
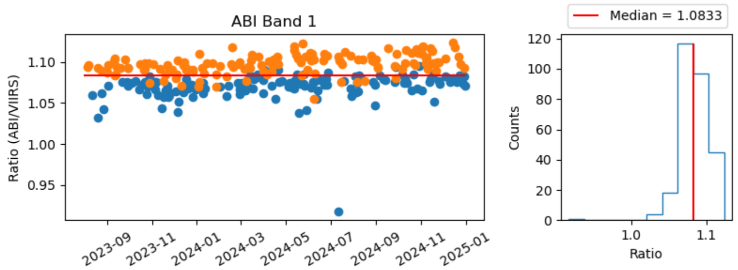
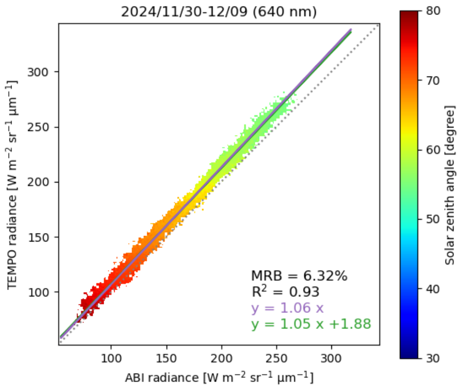
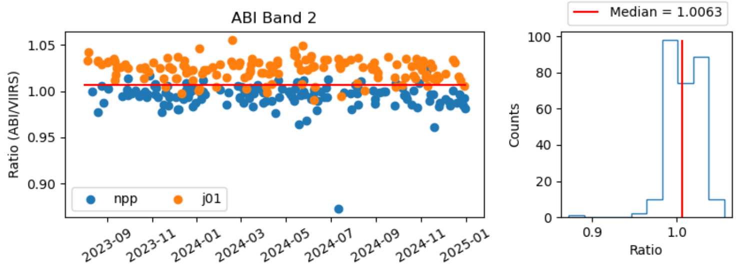


Other constraints on ray matching: temporal collocation, spatial collocation, viewing geometry alignment, and absolute viewing and solar angles

GEO as a Transfer Standard

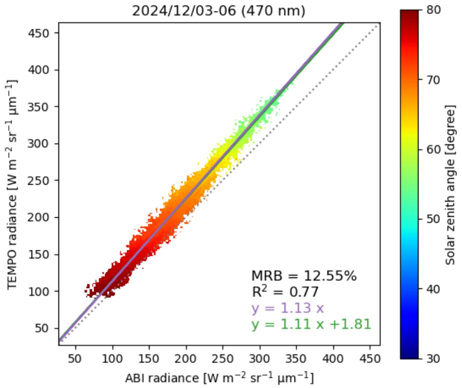
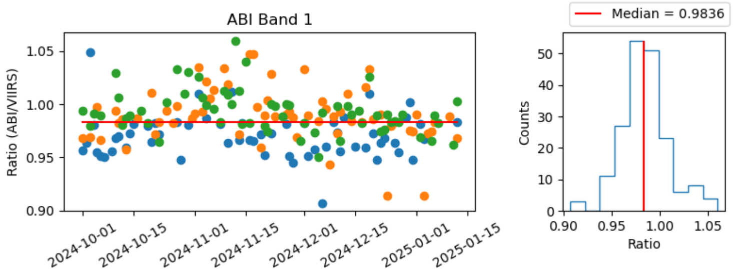
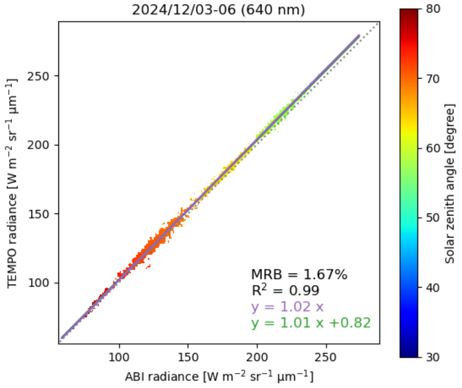
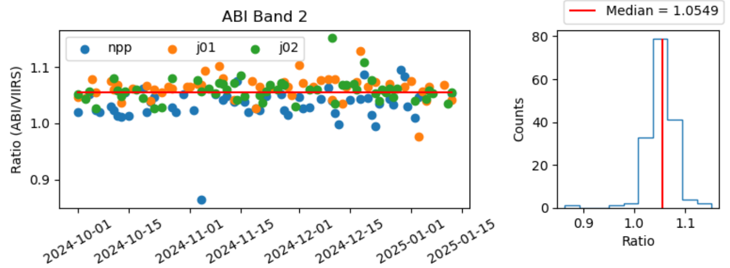
- **(TEMPO vs. ABI) + (ABI vs. VIIRS) → (TEMPO vs. VIIRS)**

Sun-normalized radiance comparison provided by NOAA
→ Converted to Earth radiance comparison

Channel	TEMPO V03 vs. ABI (GOES-16)	ABI (GOES-16) vs. VIIRS	TEMPO V03 vs. VIIRS
470 nm			$\frac{TEMPO}{VIIRS} = \frac{TEMPO}{ABI} \times \frac{ABI}{VIIRS} = 1.0329 \times 1.0833 = 1.1189$ **TEMPO V03 bias (470 nm): 11.89%**
640 nm			$\frac{TEMPO}{VIIRS} = \frac{TEMPO}{ABI} \times \frac{ABI}{VIIRS} = 1.0632 \times 1.0063 = 1.0699$ **TEMPO V03 bias (640 nm): 6.99%**

GEO as a Transfer Standard

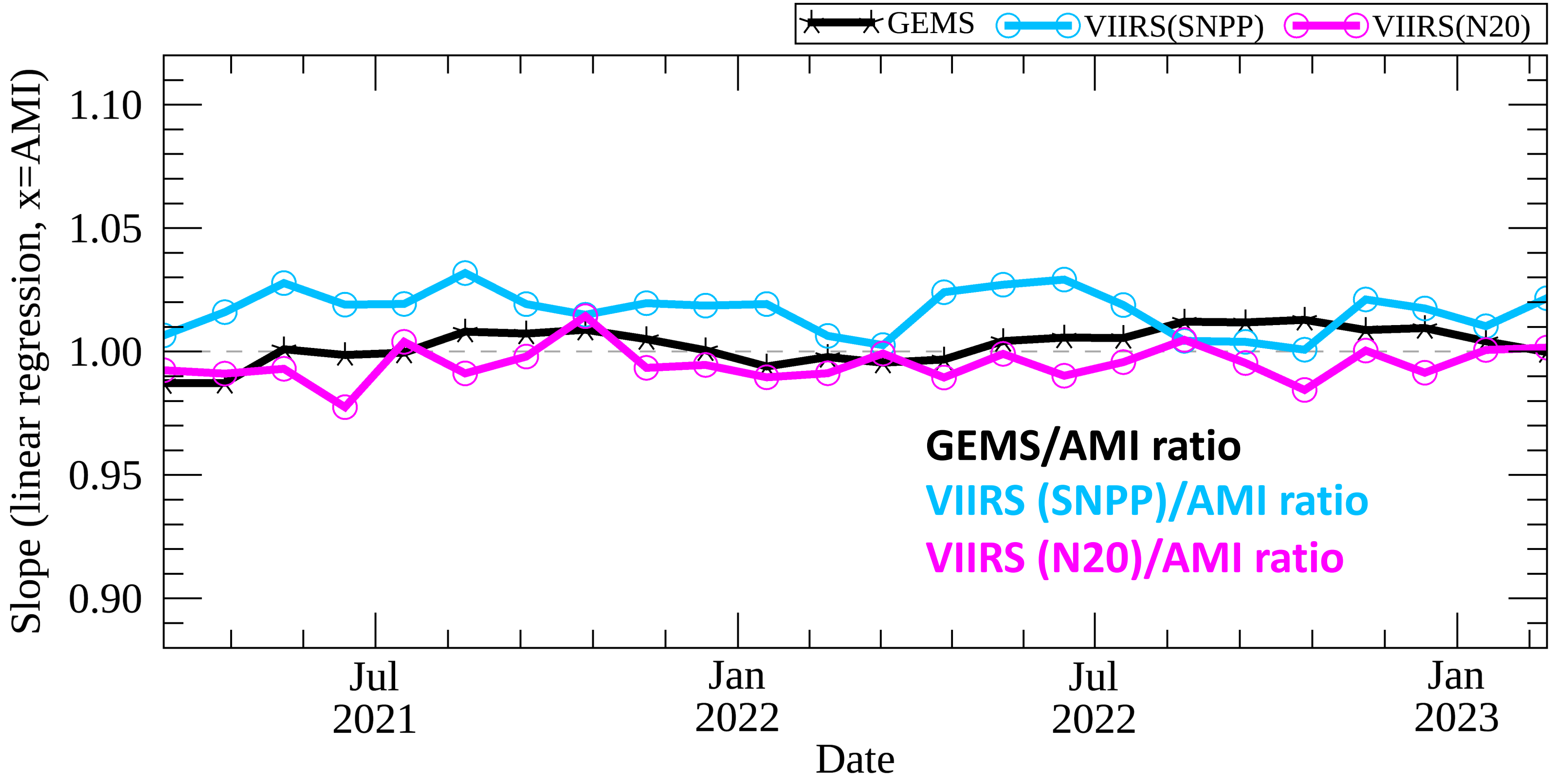
- **Using GOES-19 checkout data to evaluate consistency (2024/12/03–2024/12/06)**
- **Checkout position:** 89.5°W (only 1.5° away from TEMPO)

Channel	TEMPO V03 vs. ABI (GOES-19)	ABI (GOES-19) vs. VIIRS	TEMPO V03 vs. VIIRS
470 nm			$\frac{TEMPO}{VIIRS} = \frac{TEMPO}{ABI} \times \frac{ABI}{VIIRS} = 1.1255 \times 0.9836 = 1.1070$ **TEMPO V03 bias (470 nm): 10.70%** **(GOES-16 result: 11.89%)**
640 nm			$\frac{TEMPO}{VIIRS} = \frac{TEMPO}{ABI} \times \frac{ABI}{VIIRS} = 1.0167 \times 1.0549 = 1.0725$ **TEMPO V03 bias (640 nm): 7.25%** **(GOES-16 result: 6.99%)**

GEMS, AMI, and VIIRS

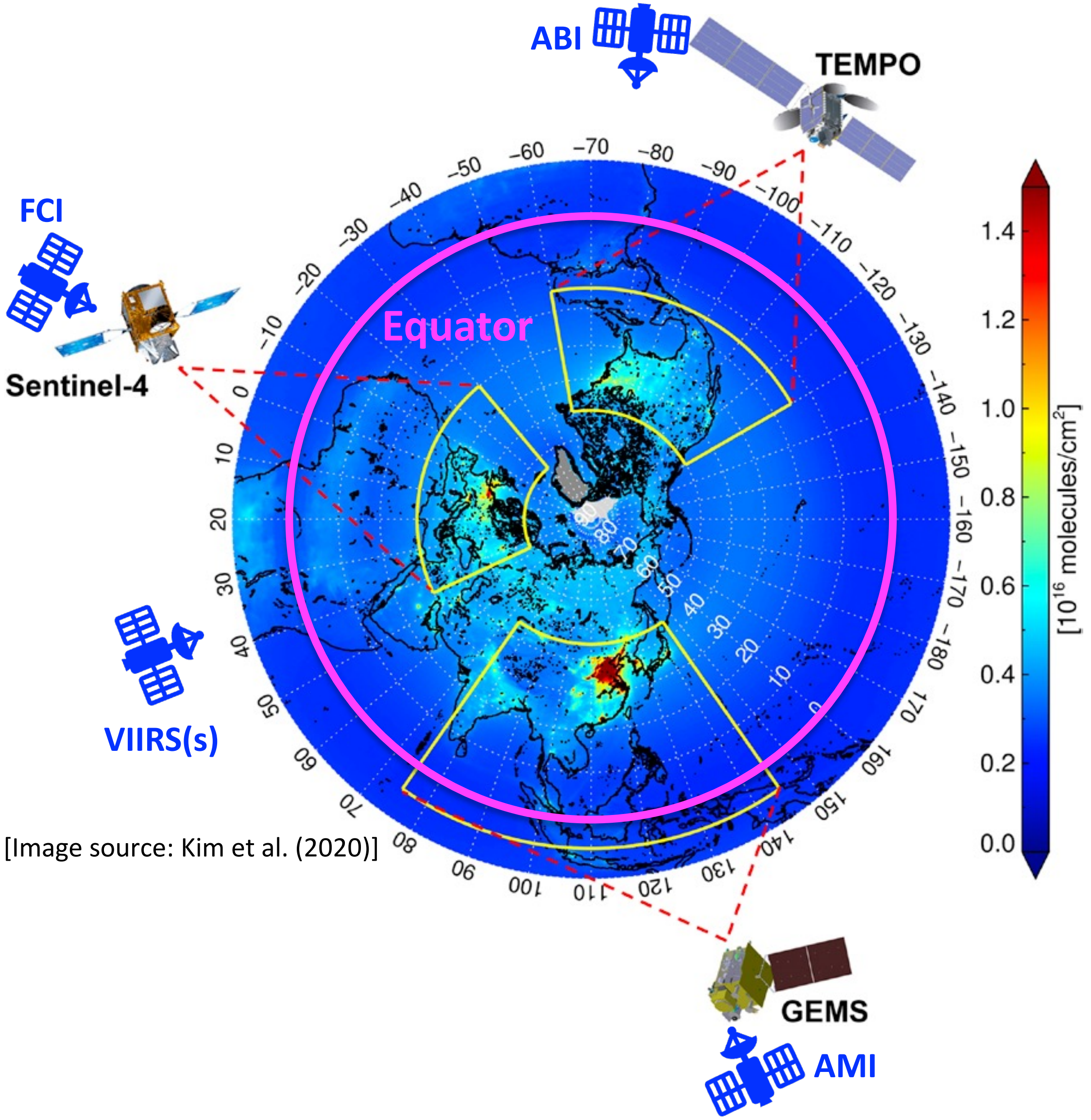
- **AMI (Advanced Meteorological Imager)**: Geostationary weather sensor flying at the same longitude as GEMS (128.25°E)
- GEMS-AMI intercalibration work is ongoing (led by M.-H. Ahn's team at Ewha Womans University).
- Involving the VIIRS instruments enables indirect intercomparison between GEMS and TEMPO.

Regression slopes of 470-nm reflectance
(X: AMI, Y: VIIRS or GEMS)



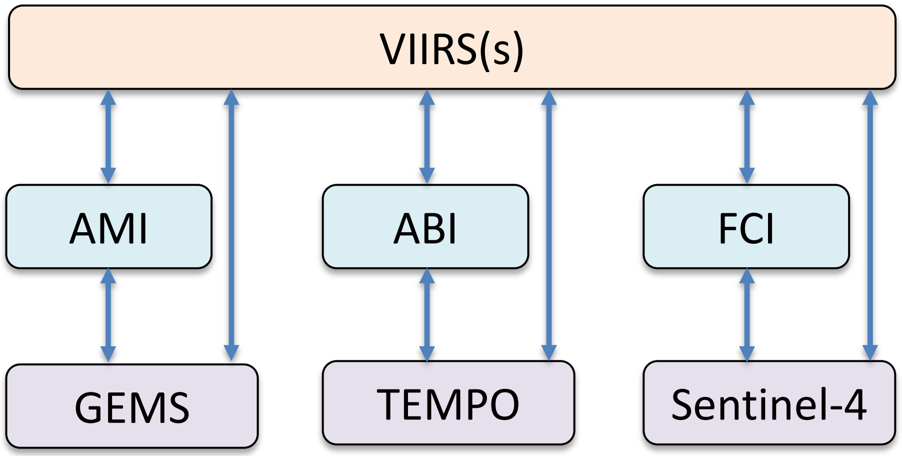
[Credit: M.-H. Ahn & Yeeun Lee]

Geo-Ring Intercalibration



[Image source: Kim et al. (2020)]

- Considerable structure



- Challenge to address:
  Expanding spectral coverage of intercalibration
  → Involving Sentinel-5/UVNS could be considered.

- Engage in Global Space-based Inter-Calibration System (GSICS) activities.

Thank you for your attention!