Validating High-Resolution AOD and Surface Reflectance from Sentinel-2 for Urban and Industrial Applications

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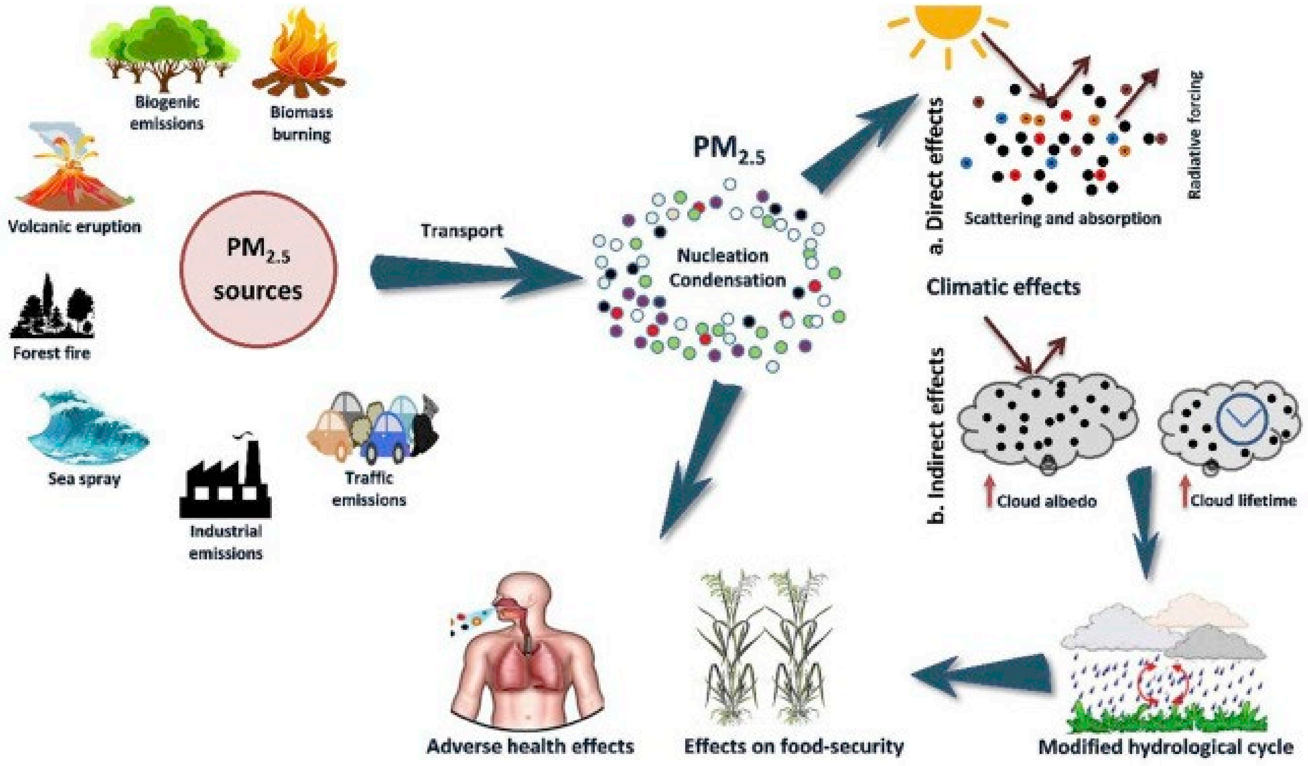
Aerosols: Background and Importance

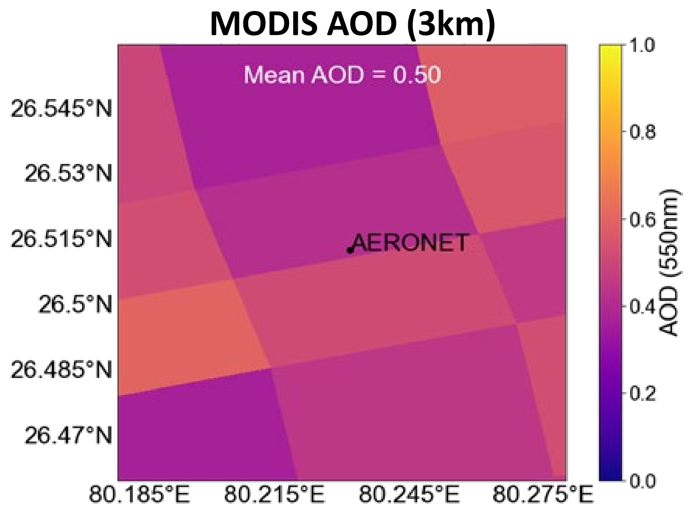
- **Aerosols** – Tiny solid particles/liquid droplets (10^{-3}–10^{2} µm) from natural & anthropogenic sources.
- **Aerosol Optical Depth (AOD)** – Column extinction coefficient (scattering + absorption) from surface to TOA, a proxy for total aerosol burden.
- **Why important?**
  - **Climate**: scatter/absorb radiation, modify clouds
  - **Health**: $PM_{2.5}$ impacts lungs/heart
  - **Environment**: visibility, precipitation
- **Measurement** –
  - **Ground:** AERONET, RadCalNet, lidar
  - **Satellite:** MODIS, VIIRS, MISR, SLSTR

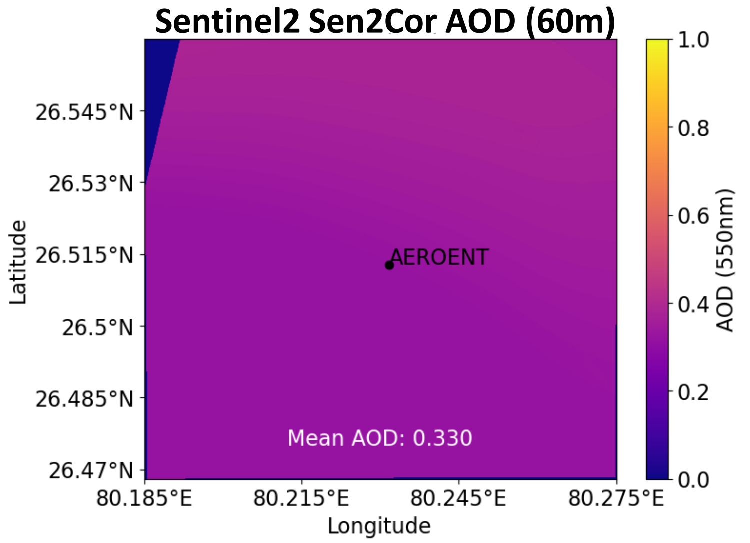


Overview of $PM_{2.5}$ sources, transport, and impacts

Research Gap in High-Resolution Aerosol Retrieval

- **Gap:** Most satellite AOD products (e.g., MODIS, VIIRS) **have coarse resolution (1–10 km)**, missing fine-scale urban and industrial pollution.
- **Reality:** Air pollution **varies sharply at <1 km** due to localised sources like traffic and power plants—requiring finer resolution for effective monitoring.
- **Opportunity:** Sentinel-2 provides **10–60 m imagery**, enabling aerosol mapping at the city-block scale.
- **Limitations of Existing Tools:** Algorithms (e.g., **Sen2Cor**) struggle over bright or heterogeneous surfaces, leading to AOD over- or underestimation or relying on CAMS AOD that fail to capture local aerosol variability.
- **Need:** A validated, physics-based algorithm that delivers—
  - **High-resolution AOD**
  - **Per-pixel uncertainty**
  - **Pollution source identification at urban-scale**





Over Kanpur, India on 23 May 2021

Modified Sensor Invariant Atmospheric Correction (MSIAC)

- **Foundation:** MSIAC builds upon the **SIAC (Sensor Invariant Atmospheric Correction)[1]** framework, which uses the 6S radiative transfer (RT) emulator, a continental aerosol type, and a Lambertian surface assumption to ensure physically consistent atmospheric correction.
- **Key Advancement:** Unlike SIAC, which relies on **coarse-resolution priors** (e.g., 500 m MODIS SR, 40 km CAMS AOD), **MSIAC replaces them with high-resolution, Sentinel-2–derived priors.** This enables **per-pixel AOD retrieval at 60 m resolution** with **explicit uncertainty estimation**.
- **Three-Step Workflow:**
  1. Estimate prior SR
  2. Retrieve per-pixel AOD
  3. Refine SR using retrieved AOD

[1]Yin, F., Gomez-Dans, J. and Lewis, P. (2018) A sensor invariant atmospheric correction method for satellite images. IEEE, pp. 1804–1807.

MSIAC Framework

Prior Surface Reflectance (SR) Estimation :

- Two-Stage Approach for High-Resolution Prior SR

○ ***Stage 1: Candidate SR Database***

Clear-sky Sentinel-2 observation (2017- 2023) → MODIS/CAMS atmospheric inputs → 6S RT emulator → 🗂️ Candidate SR archive (target day excluded to avoid redundancy)

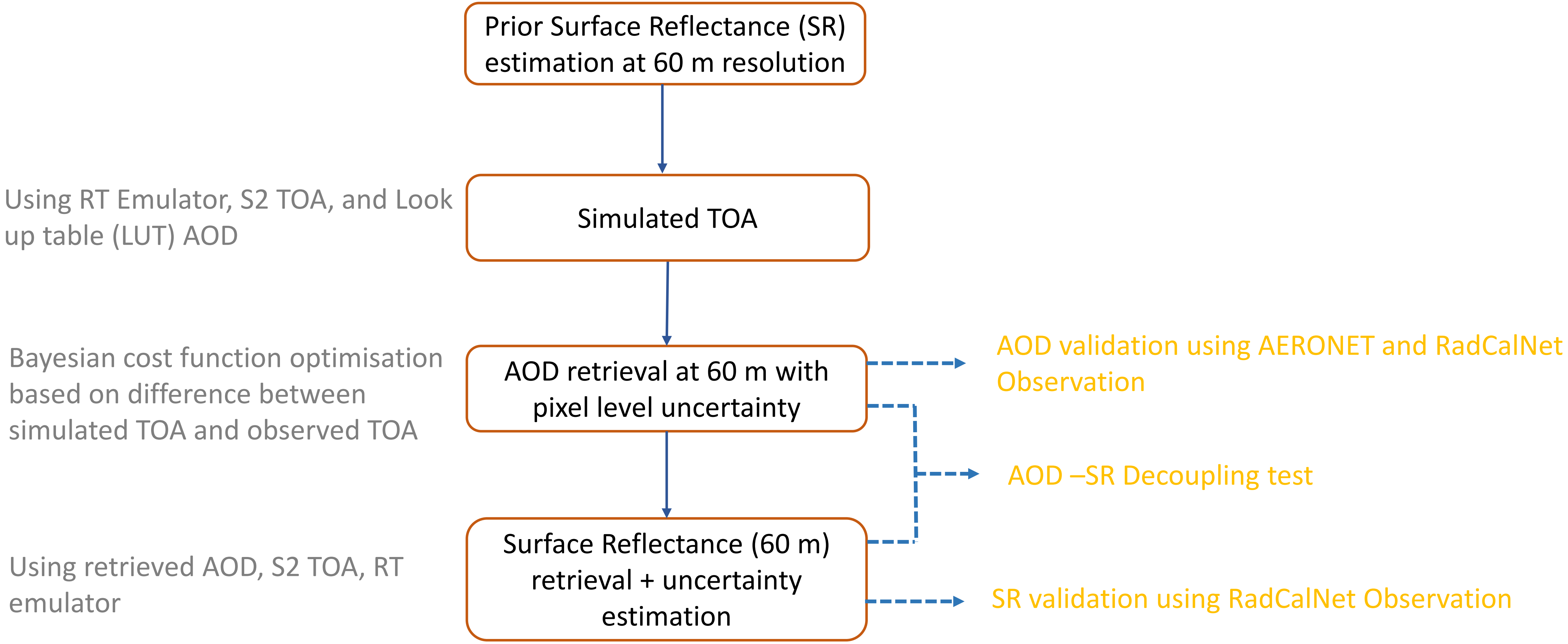
○ ***Stage 2: Target-Day Prior SR***

— For each pixel, identify 20 most spectrally similar candidates using Ball Tree search

— weighting: closer matches contribute more strongly

— Output:
Weighted mean → Prior SR
Standard deviation → SR uncertainty

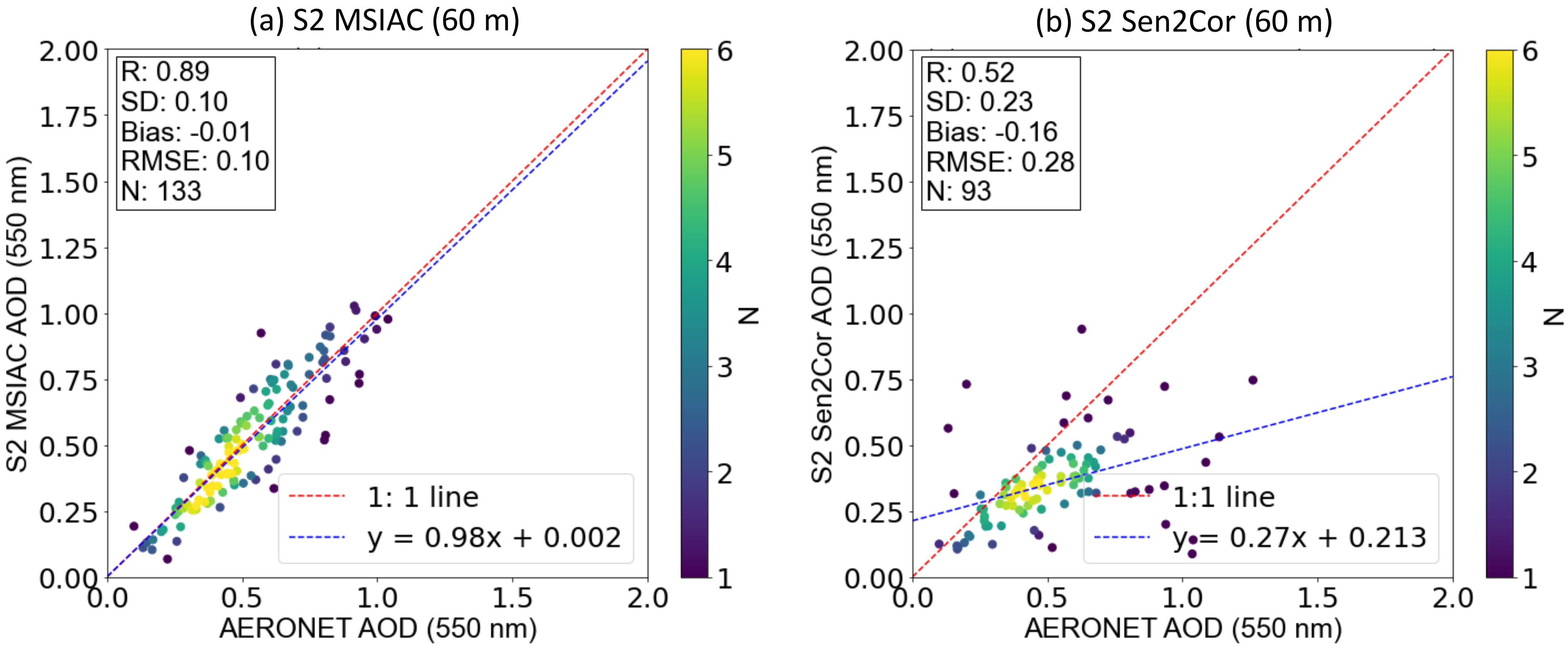
MSIAC Framework



MSIAC AOD Validation and Comparison

Study Site: Kanpur, India

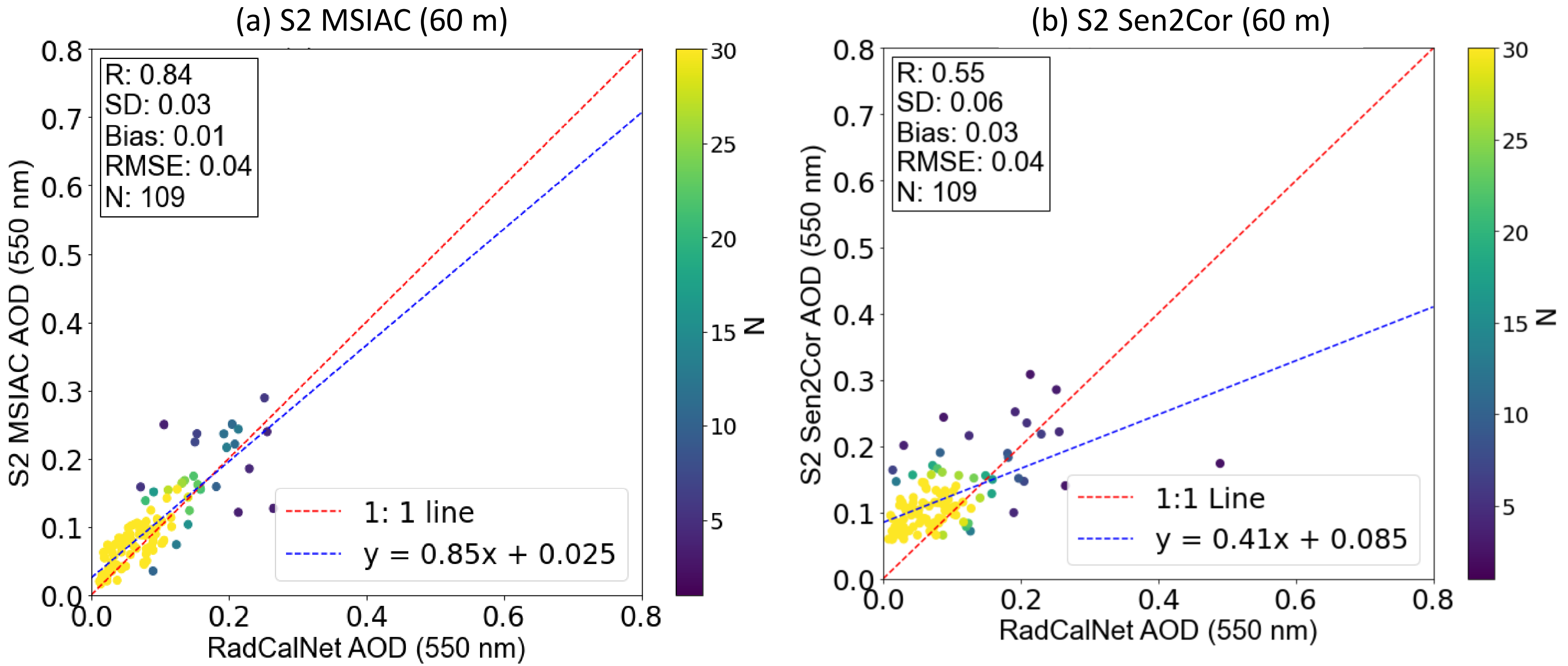
- Validation using **AERONET data (2020–2022)**
- **Land cover:** highly heterogeneous — **urban**, **industrial**, and **agricultural** areas
- **AOD range:** 0.10 – 2.67 (mean ≈ 0.62)
- Analysis limited to scenes with **≥ 80% cloud-free pixels**



MSIAC AOD Validation and Comparison

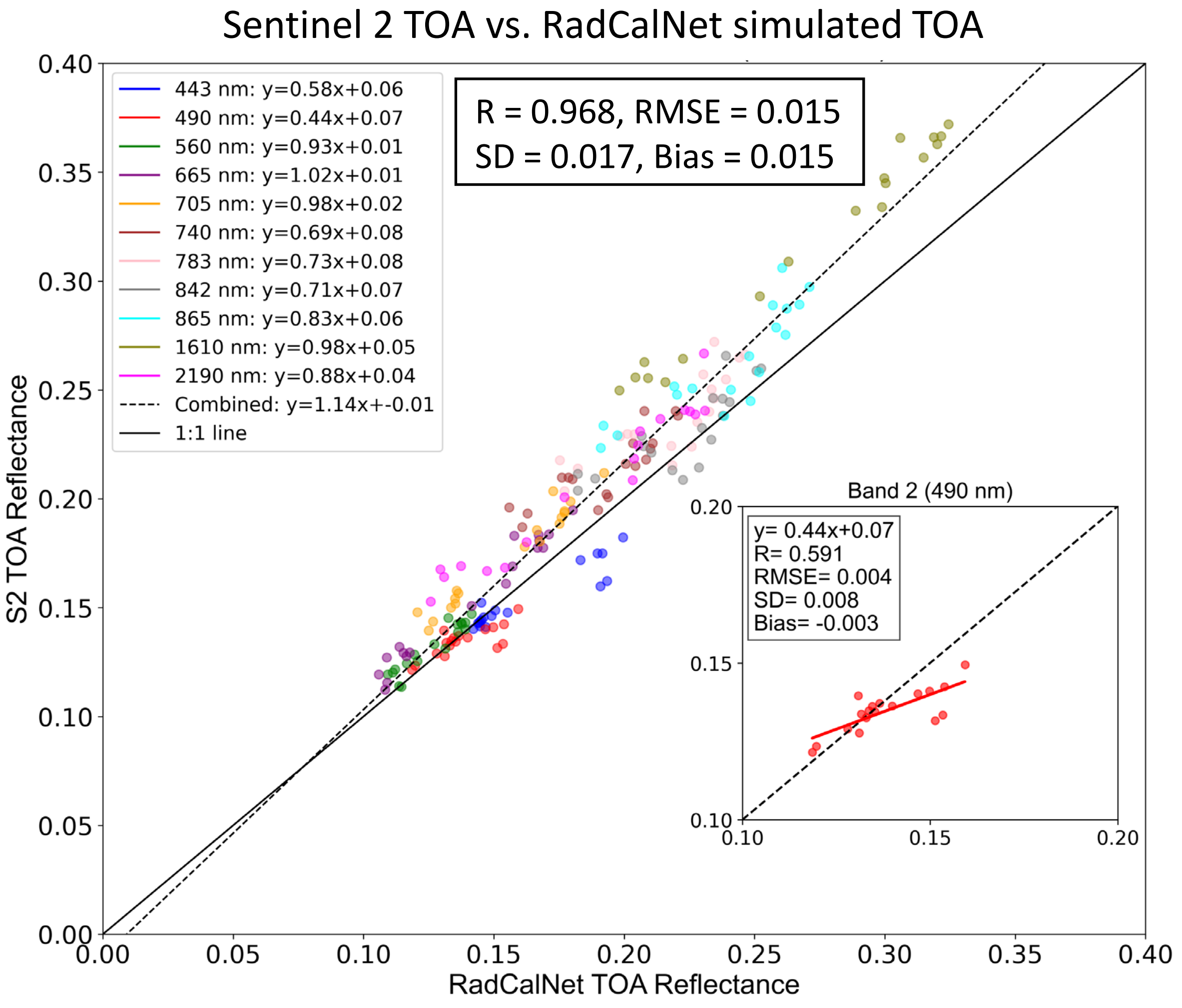
Study Site: La Crau, France

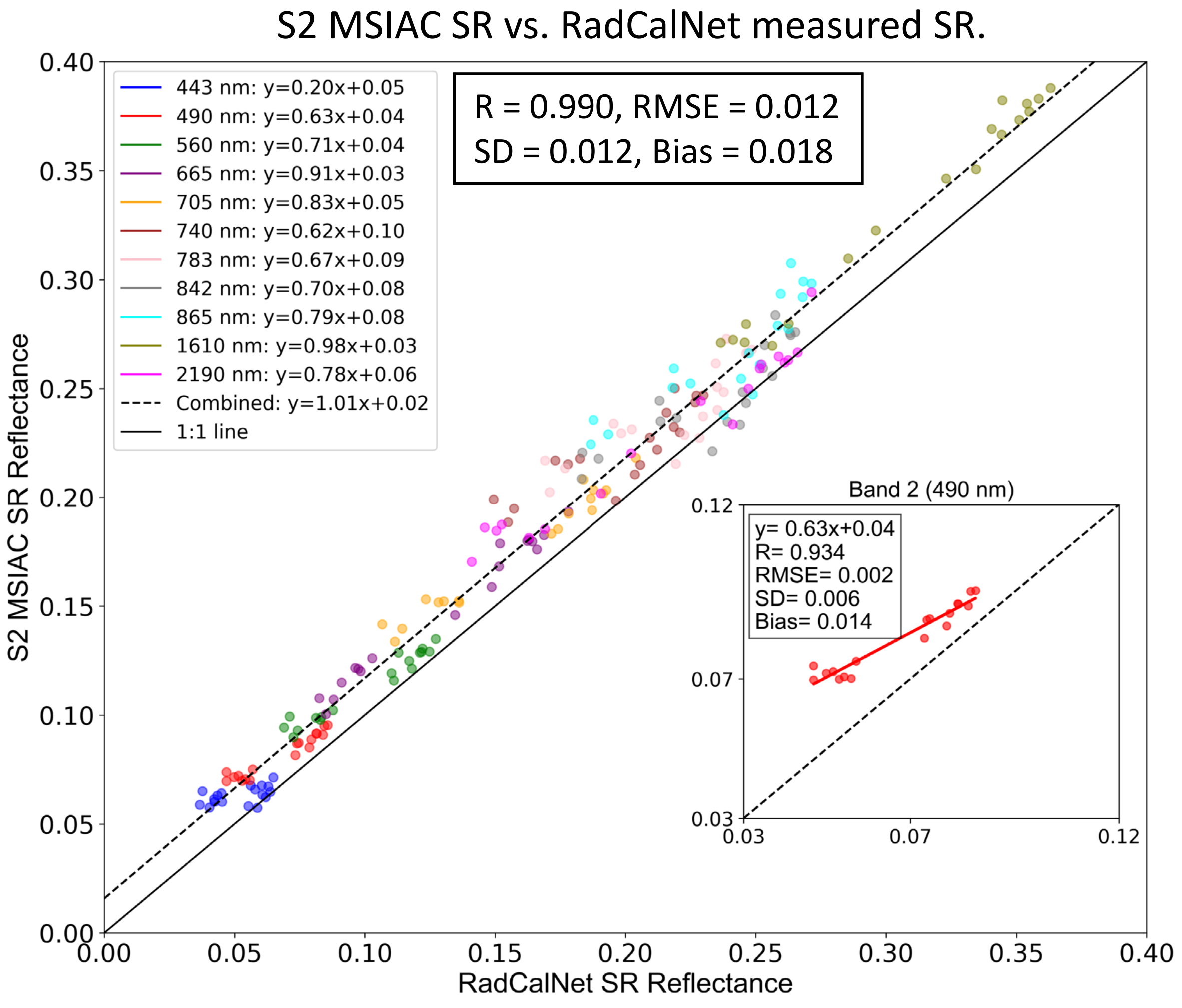
- Validation using **RadCalNet data (2020–2022)**
- **Land cover:** highly homogeneous surface with **sparse vegetation**
- **AOD range:** 0.01 – 0.52 (mean ≈ 0.13)
- Analysis limited to scenes with **≥ 80% cloud-free pixels**



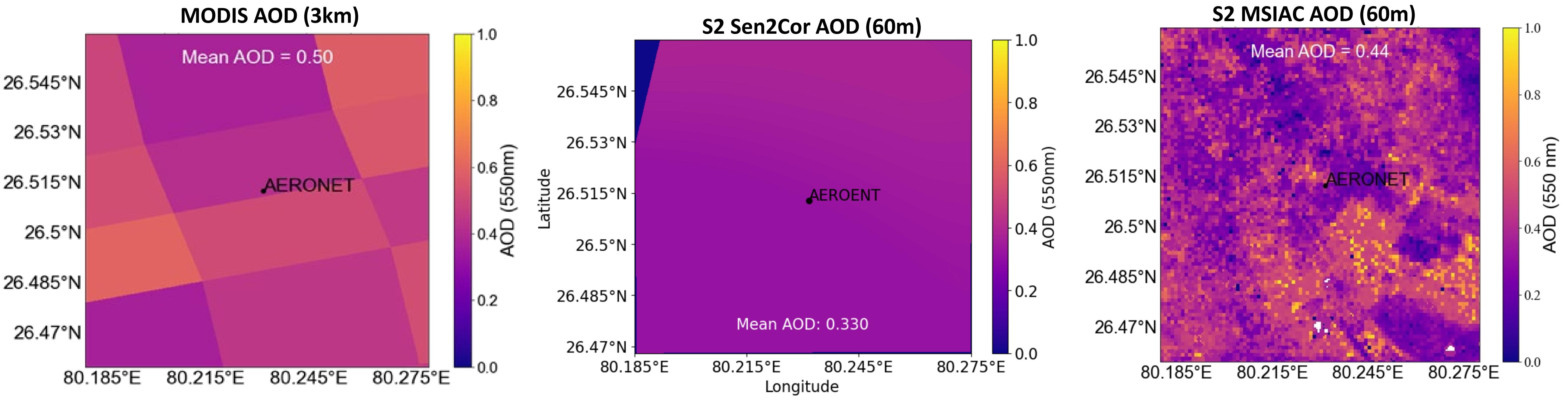
MSIAC SR Validation

- Validation of S2 MSIAC reflectance over La Crau (2020–2022) using RadCalNet data





Key Results

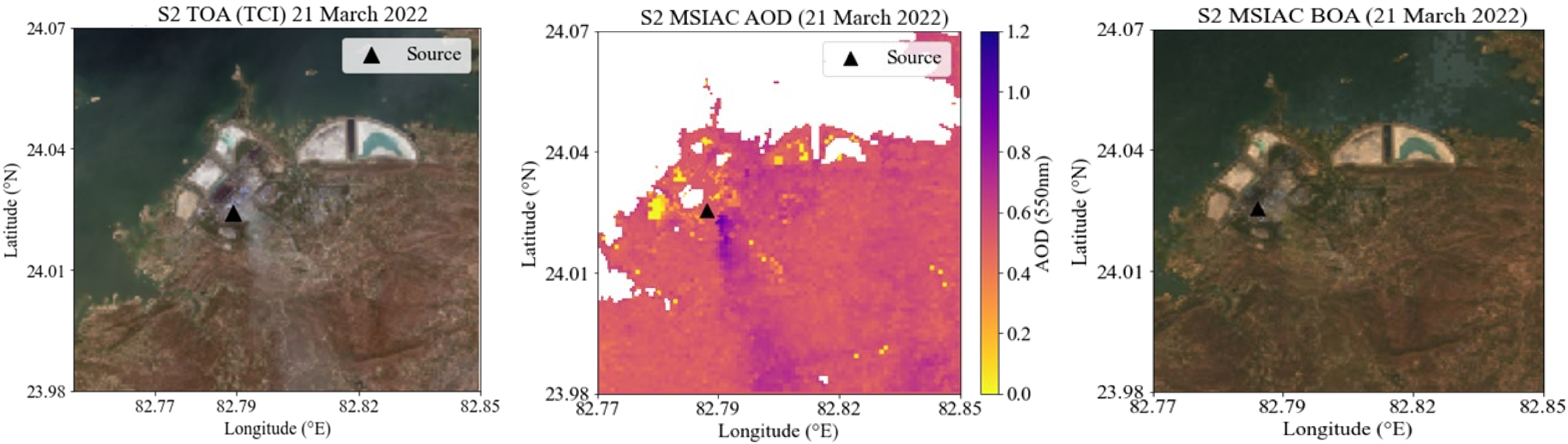


AERONET AOD = 0.38

Over Kanpur, India on 23 May 2021

Real World Applications of MSIAC

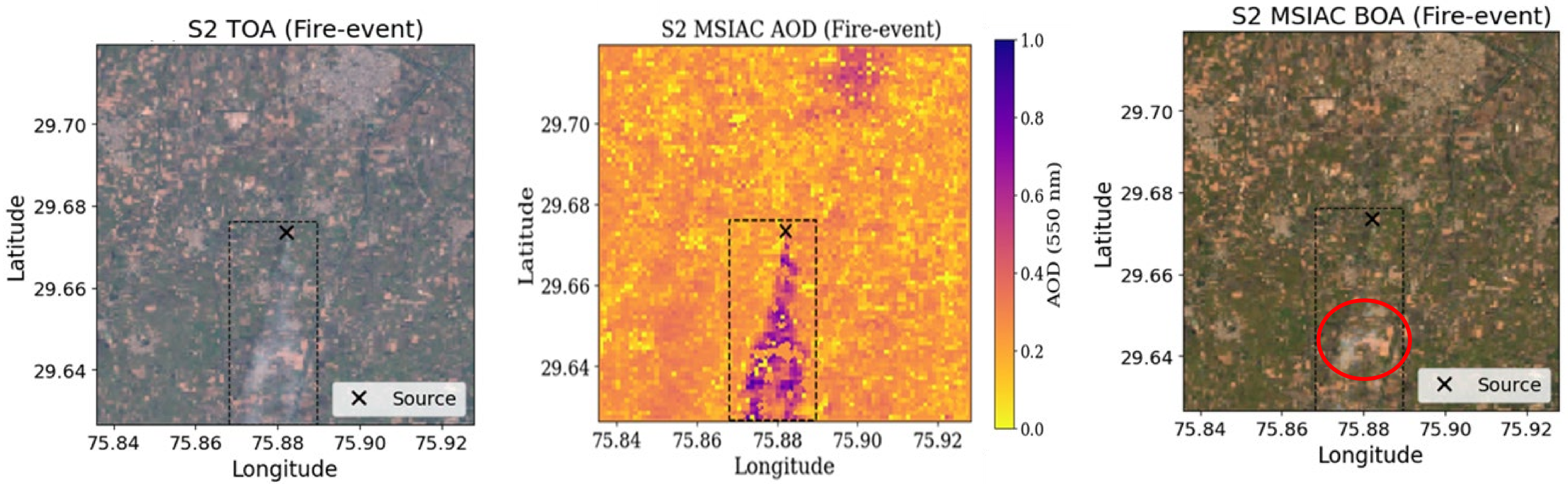
Power Plant Emission Detection over Rihand Thermal Power Plant in India (21 Mar 2022)



TOA= Top Of Atmosphere; BOA= Bottom of Atmosphere or Surface Reflectance; TCI= True Colour Image

Real World Applications of MSIAC

Crop Residue Burning Identification in Hisar, Haryana, India (19 Oct 2020)



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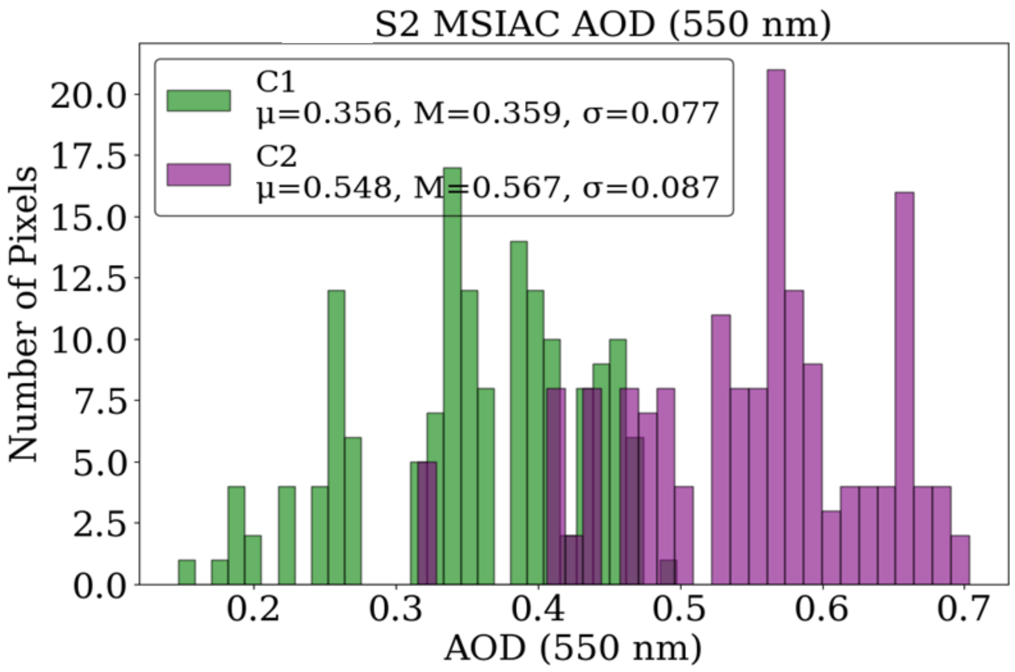
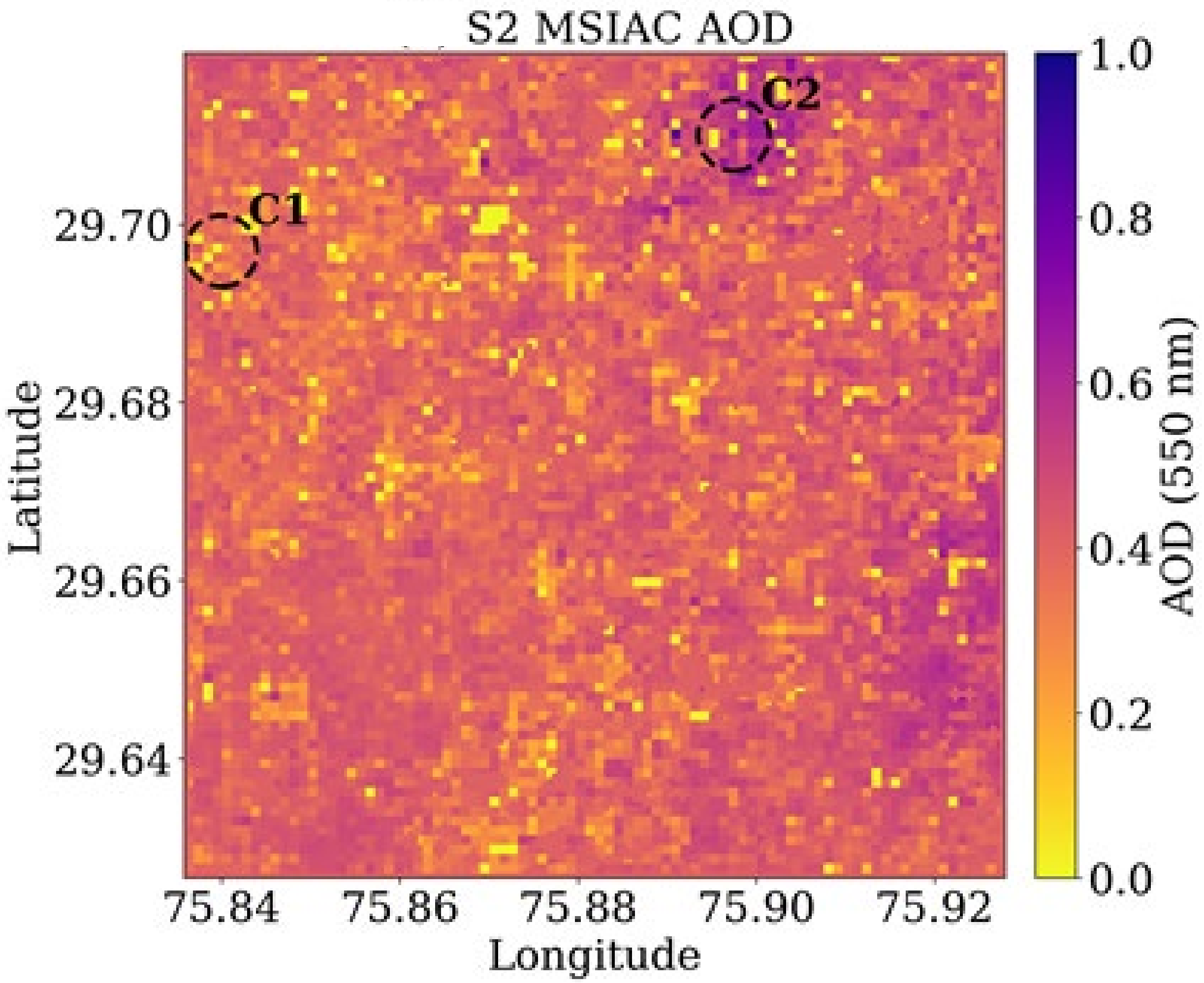
Real World Applications of MSIAC





Urban Hotspot Identification in Hisar, Haryana, India (19 Oct 2020)

TOA= Top Of Atmosphere; BOA= Bottom of Atmosphere or Surface Reflectance; TCI= True Colour Image

Conclusions

- **MSIAC** Retrieves both AOD and surface reflectance at **60 m** from all Sentinel-2 bands, with per-pixel uncertainty (AOD: ±0.01–0.08; SR: ±0.008–0.014).
- **Accurate and stable:** Validated against **AERONET (R = 0.89)** and **RadCalNet (R = 0.84)**, MSIAC performs reliably from **clean to polluted scenes**, maintaining **AOD deviations < 10 %** even near strong emission sources.
- **High-fidelity surface retrievals:** Visible-band **slopes > 0.91** and **biases < 0.01** confirm physical consistency and temporal stability at reference sites.
- **Urban-scale clarity:** MSIAC resolves **< 6 km aerosol contrasts**—capturing city-scale plumes and hotspots that remain invisible to coarser products such as **MODIS (3 km)** or **Sen2Cor (60 m)**.
- **Next steps:** Expanding validation across more **AERONET–RadCalNet sites**, improving **cloud masking** for optically thick clouds, and targeting stations with **simultaneous AOD–SR observations** will further enhance robustness.
- **MSIAC** paves the way for **Sentinel-2 to be used for high resolution air-quality monitoring** and **pollution mapping**, bridging the gap between global satellite products and actionable urban insights.

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Thank You!

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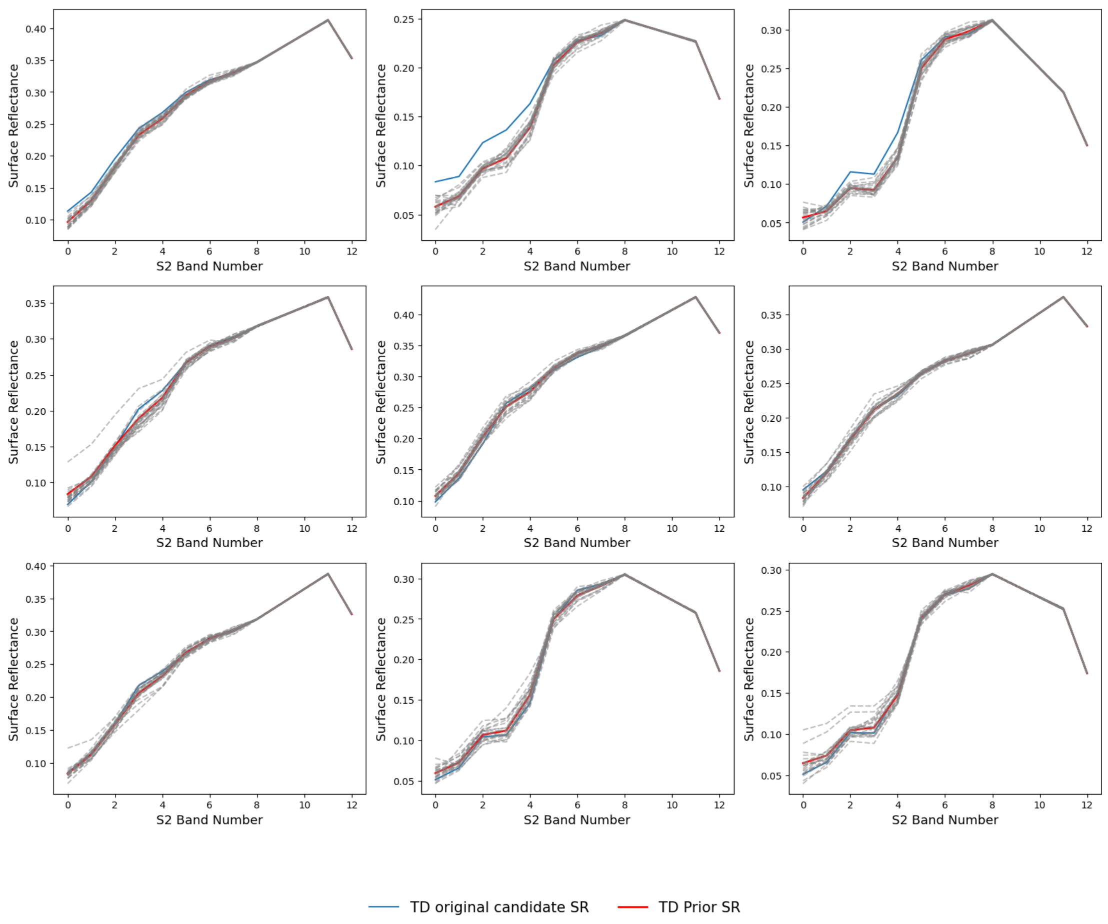


Prior SR estimation for 26 April 2021 over Kanpur, India. The figure compares the target day (TD) original candidate SR (solid blue line), the target day (TD) prior SR (solid red line) derived as a weighted mean of the 20 most spectrally similar candidates, and individual candidate SR profiles (dashed lines). Results are shown for a subset of pixels across Sentinel-2 Bands 1–8A, 11, and 12, illustrating spectral variability and refinement through weighted averaging.

SIAC and MSIAC

Key methodological differences/improvement in MSIAC

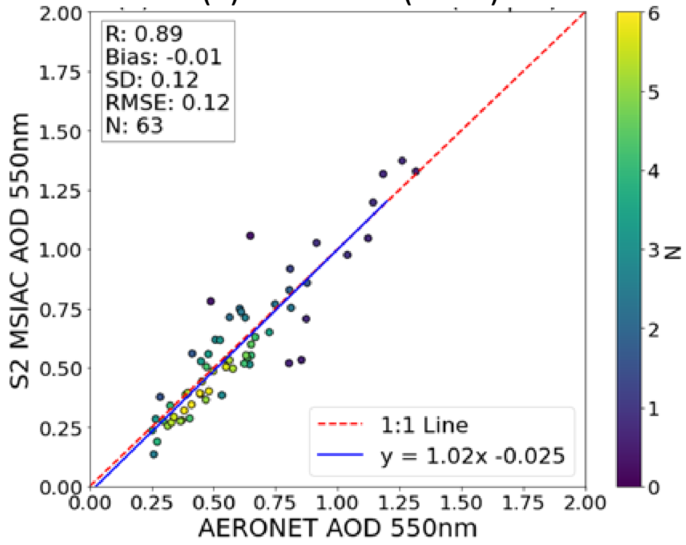
Feature	SIAC	MSIAC
Prior SR Input	MODIS SR (500m)	Sentinel-2 derived Prior SR (60 m)
Prior Aerosol Input	CAMS AOD (40 km)	MODIS AOD (1 km), aggregated as the median over the area of interest (AOI)
AOD Retrieval Resolution	500 m	60 m
AOD Uncertainty Estimation	Hessian-based curvature	Quadratic (parabolic) approximation
Surface Reflectance Output	60 m SR (all spectral bands) using scene average AOD across AOI	60 m SR (all spectral bands) using per pixel AOD
Applicable Sensors	Sentinel-2 and Landsat-8	Sentinel-2

Core similarities between SIAC and MSIAC

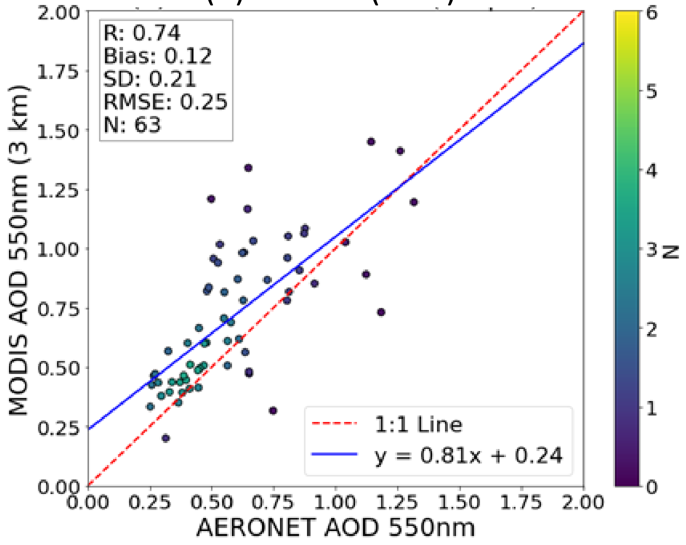
Common Feature	SIAC and MSIAC
Aerosol Type Assumption	Continental aerosol model
RT Emulator	6S RT emulator
Atmospheric Trace Gas Inputs	CAMS TCWV and TCO_3
Inversion Approach	Bayesian optimal estimation

MSIAC AOD Comparison

(a) S2 MSIAC (60 m)

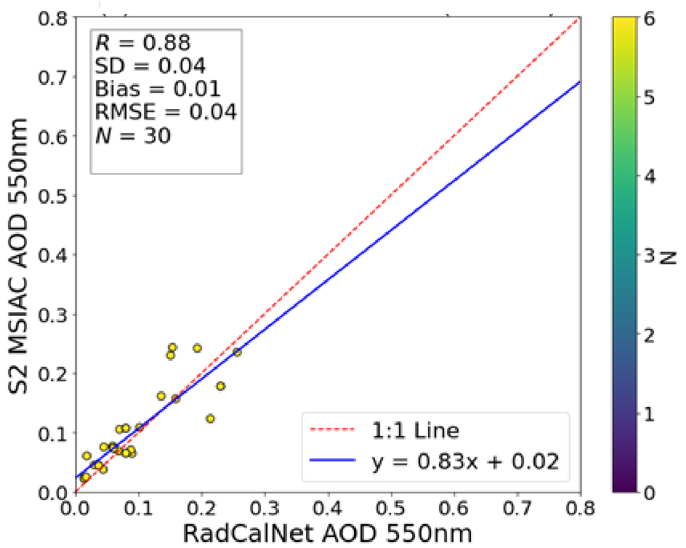


(b) MODIS (3km)

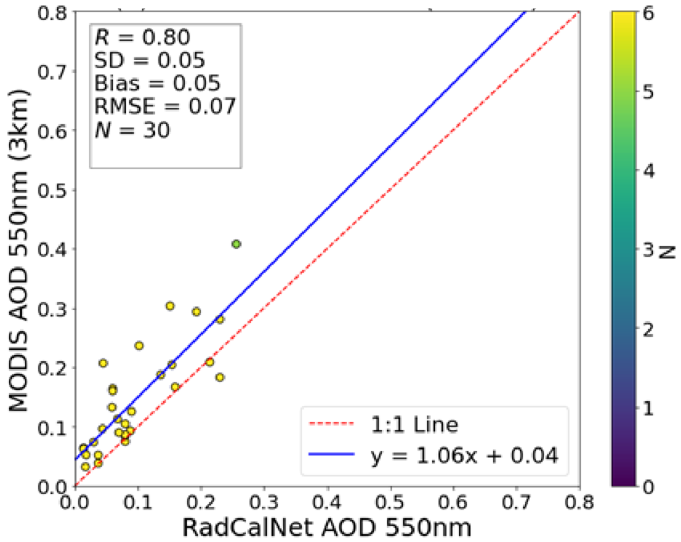


Over Kanpur, India using AERONET data (2020-2022) with 80% cloud free pixel

(c) S2 MSIAC (60 m)



(d) MODIS (3 km)



Over La Crau, France using RadCalNet data (2020-2022) with 80% cloud free pixel