SPOT: tracking SO_2 facility by facility to constrain aerosol contributions to Earth's Energy Imbalance

CERES Science Team Meeting
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Outline

1 **The CERES record**
Trends in Earth's Energy Imbalance and its SW/LW and clear-sky/CRE decomposition

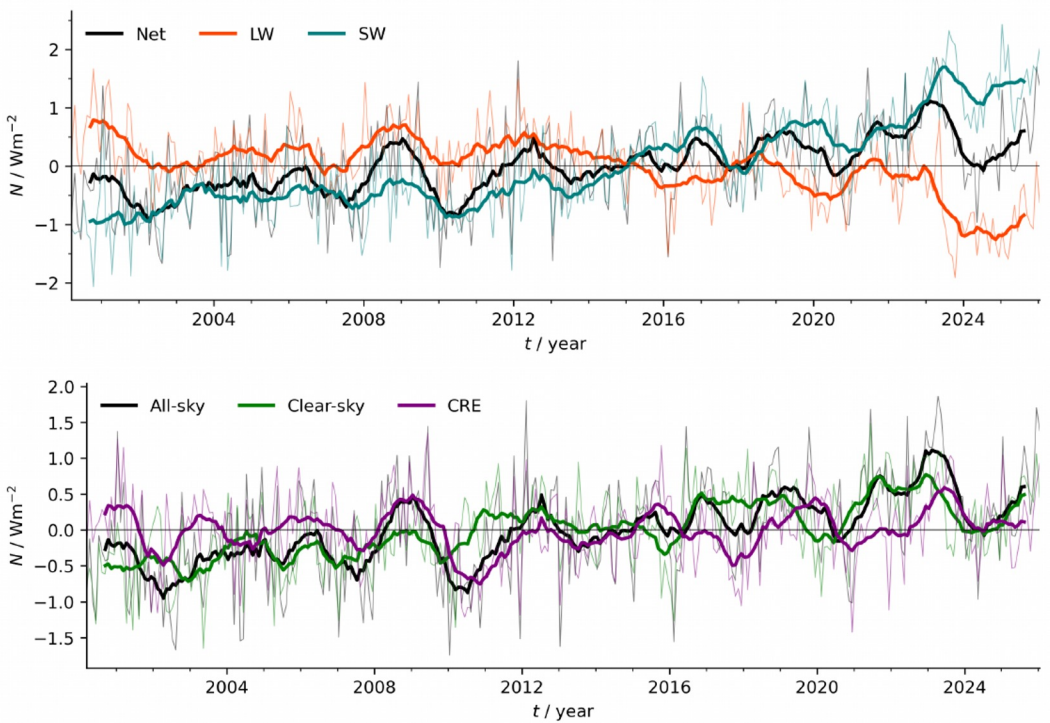
2 **The aerosol forcing trend**
Observation- vs model-based estimates and what each implies for S

3 **Observing the emission → aerosol → cloud chain**
What CLARO measures, and in which regimes

4 **Roadmap and SPOT**
Pathfinder → operational mission → constellation

5 **Open Questions and Next Steps**

The trend in EEI is shortwave-driven

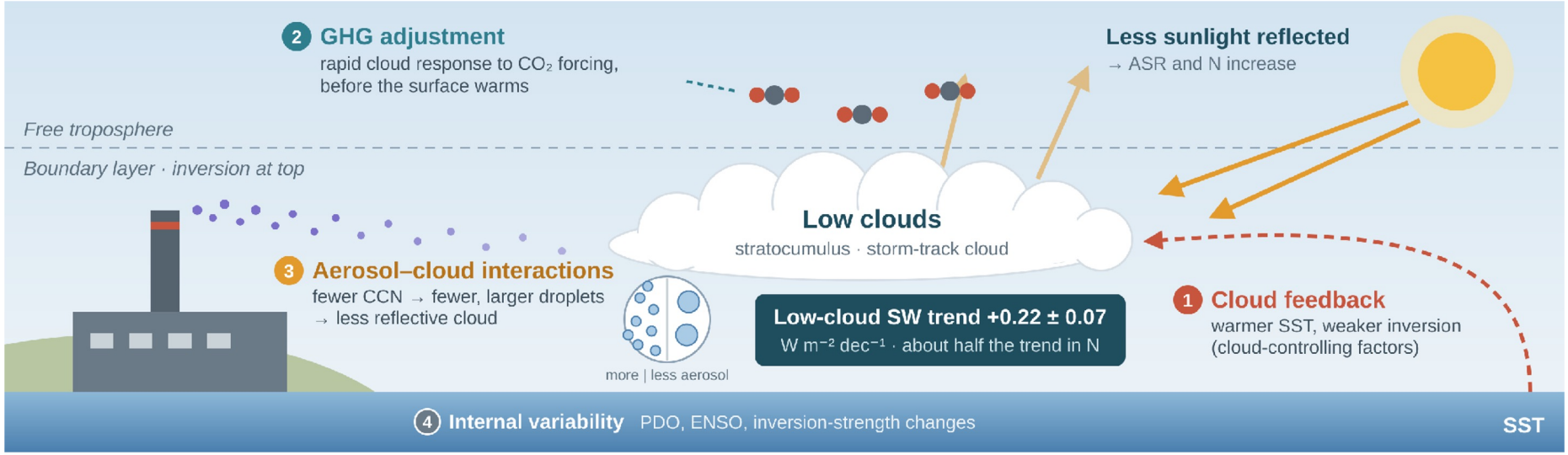


CERES EBAF monthly anomalies, Mar 2000–Jan 2026: net, LW, SW (top); all-sky, clear-sky, CRE (bottom). Stevens et al. 2026, Fig. 2.

- N doubled: 0.5 ± 0.2 → 1.0 ± 0.2 W m⁻² between the first and second decades (Loeb et al. 2024).
- Reduced cloud reflection ≈62% of the ASR trend, 2002–2020 (Loeb et al. 2021)
- Low clouds: 0.22 ± 0.07 W m⁻² dec⁻¹, about half the N trend, 2003–2024 (Ceppi et al. 2026).

Stevens et al. 2026, Ringberg workshop report, Figs. 2 and 5; Loeb et al. 2024; Loeb et al. 2021; Hoogeveen et al. (preprint); Ceppi et al. 2026

What controls the low cloud trend?



CONTRIBUTIONS TO THE LOW-CLOUD SW TREND, JUL 2003–JUN 2024 (W m⁻² dec⁻¹, ±1σ)

1 Cloud feedback

Response to warming via cloud-controlling factors

0.09 ± 0.02

2 GHG adjustment

Rapid response to GHG forcing, independent of surface warming

0.05 ± 0.03

3 Aerosol adjustment

Smallest term, largest relative uncertainty; inferred statistically

0.03 ± 0.03

4 Internal variability

Weak but poorly constrained (inversion-strength trend)

0.01 ± 0.085

Forced terms (1–3) explain ~74% of the low-cloud trend · Ceppi et al. 2026, ACP

→ term 3 is what CLARO targets

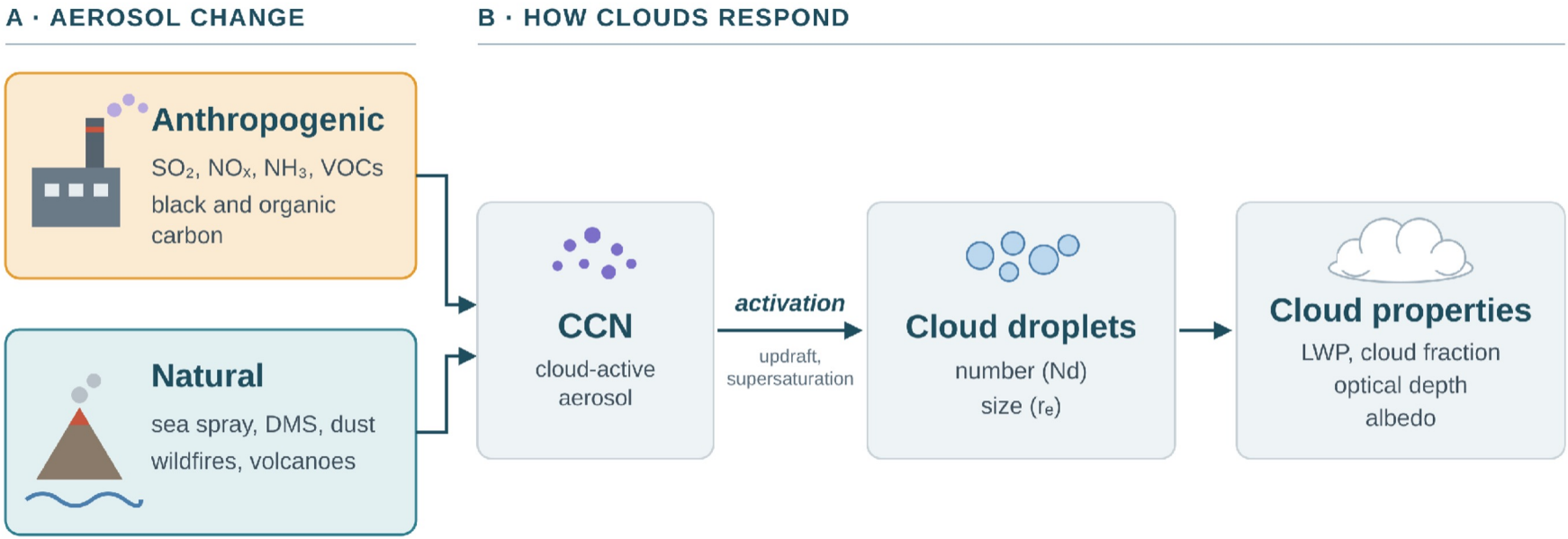
Estimates of aerosol contribution to the low cloud trend disagree:

$\dot{F}_{\mathrm{aer}}/\mathrm{W\,m^{-2}\,dec^{-1}}$	Method	Notes (Aerosol data, time-period, ref)
0.058(31)	Observations	CAMS SO_4, 2003-2023, [21, 22]
−0.004(25)	”	Merra-2 SO_4 2003-2023, [21, 22]
−0.006(28)	”	MODIS AI/N_{d}, 2003-2023 [21]
0.200(65)	Modeling	CMIP6 forcing from CEDS, 2001-2019, [23]
0.17(4)	”	CEDS, since 2001, [24]

Table 1: Estimates of the aerosol forcing trend over the CERES period. Observationally-based estimates are statistical inferences combining CERES, aerosol load estimates and reanalyses of meteorological data, to estimate the SW, $\mathrm{ERF_{aci}}$ from low-clouds at latitudes equatorward of 60°, this being the dominant contribution also in the modeling studies. Numeric estimates are from Ref. [21]. Ref. [22] combines aerosol forcings to produce a single estimate whose value, $0.03(3)\,\mathrm{W\,m^{-2}\,dec^{-1}}$, spans the difference in estimates from Ref. [21].

Table from Stevens et al. 2026, Ringberg workshop report.

What controls the aerosol effect on clouds?

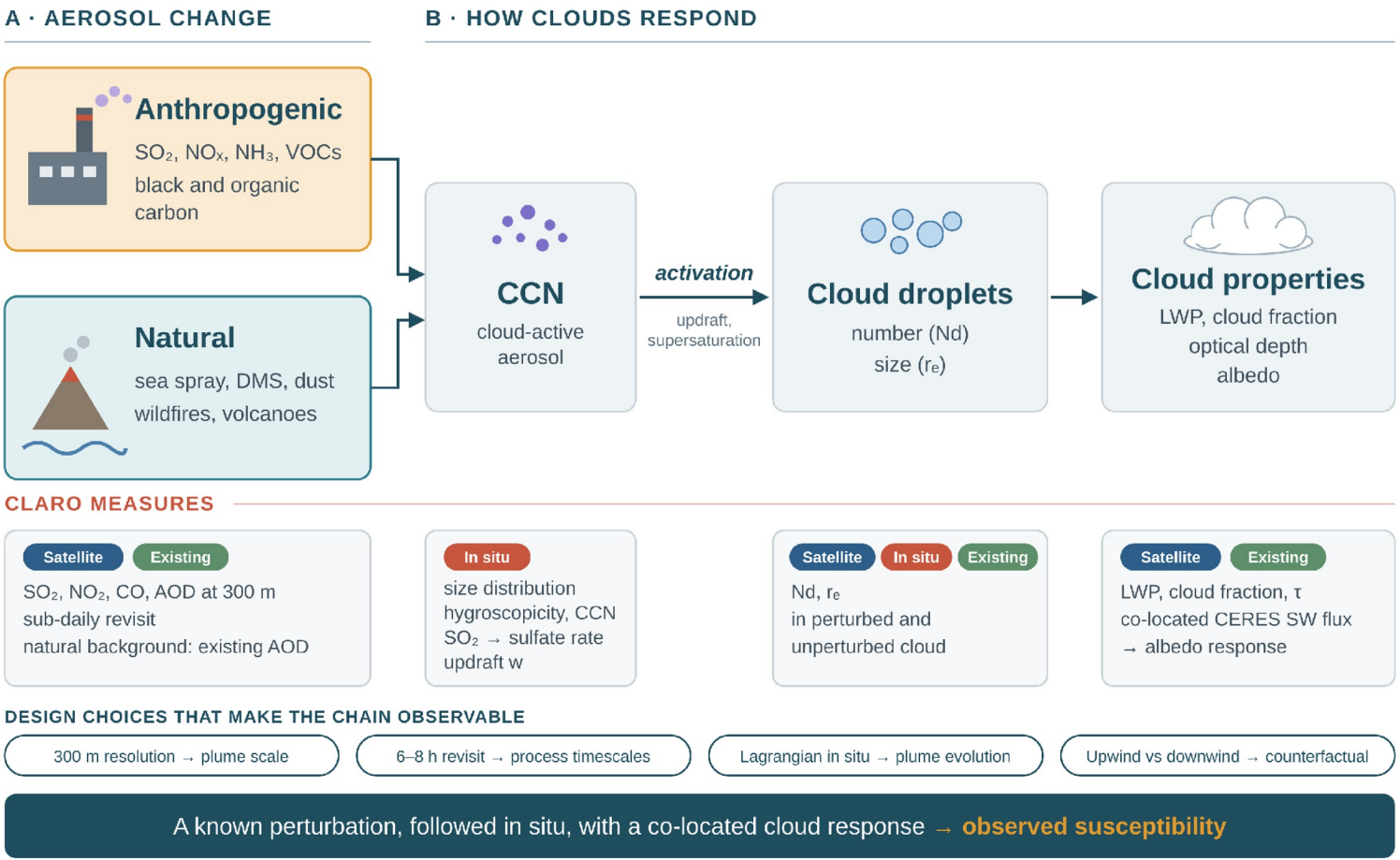


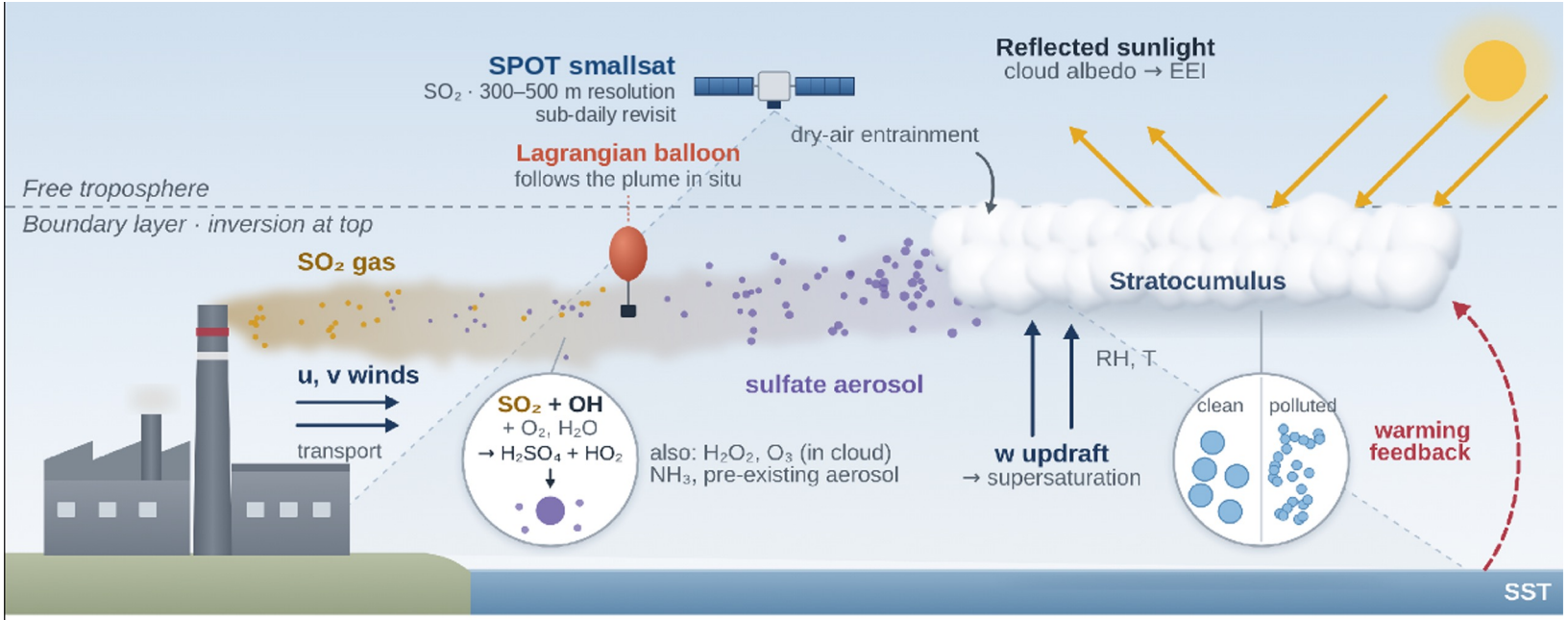
Confounded by meteorology, background chemical conditions, dilution and mixing, timescale of phenomena, cloud regime, etc …

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CLARO Overview

Can we better understand this causal chain?





WHAT CONTROLS EACH STEP — AND HOW CLARO OBSERVES IT

1 Emission
SO_2 flux
stack height, plume rise
co-emitted NO_x, CO_2
Satellite

2 Plume chemistry
u, v winds, BL height
OH, H_2O_2, O_3, NH_3
sunlight, T, RH
Satellite · Balloon

3 Aerosol → droplets
size distribution
hygroscopicity (κ), CCN
updraft w
Balloon

4 Cloud response
droplet number, r_e, LWP
cloud fraction, drizzle
entrainment, inversion
Satellite · Balloon · Existing

5 Reflectivity & EEI
cloud albedo
reflected sunlight
absorbed sunlight
Satellite · Existing

Data integration & machine learning
emissions inversion · causal attribution · parameterisations · emulators

→ **Aerosol vs feedback attribution**
→ ECS, TCR, carbon budget, interventions

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SPOT: A High Resolution Spectral Imager for SO_2

PATHWAY TO SPOT AND BEYOND



We are here

Mission concept design

OSSE studies:
simulated plumes → radiances

Feasibility studies:
retrieval and detection limits

Mission requirements:
300–500 m, sub-daily revisit

Phase I

Pathfinder: SPOT

Smallsat demonstrator
SO_2 at 300–500 m

Targeted in situ campaigns

End-to-end pipeline
on natural experiments

Operational

First operational satellite

Sustained targeting
of priority regions

Phases II–IV

Constellation

Four coordinated satellites

6–8 h revisit

Integrated with climate
and process models

Stage-gated: SPOT must show that high-resolution sulfur observations **improve understanding of aerosol–cloud interactions**

High SNR at chosen wavelengths

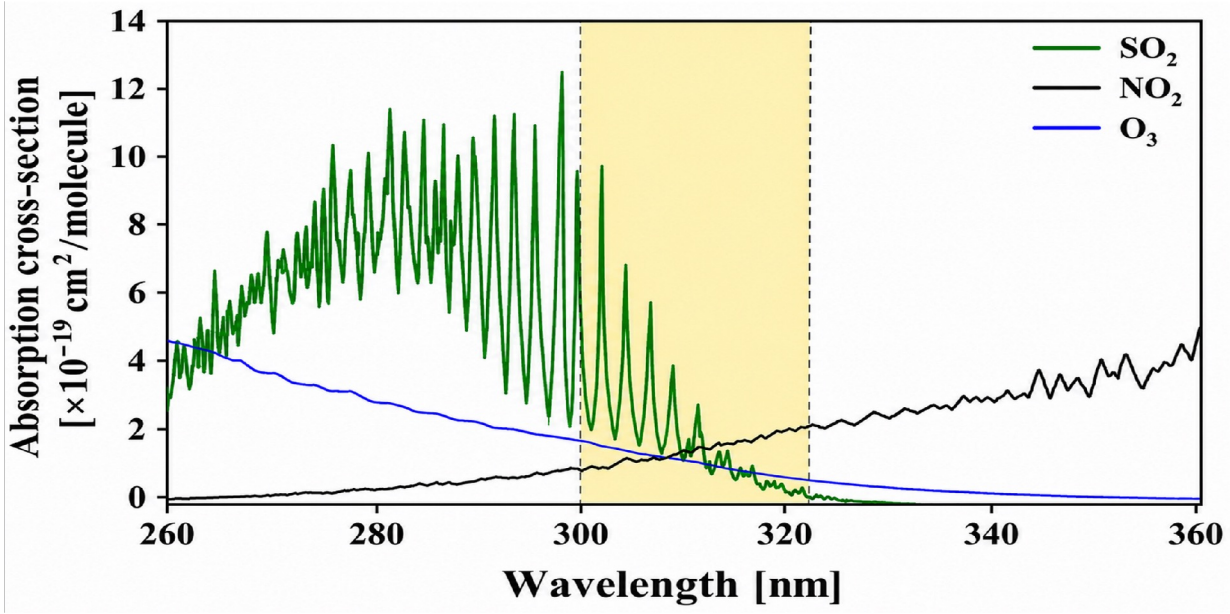
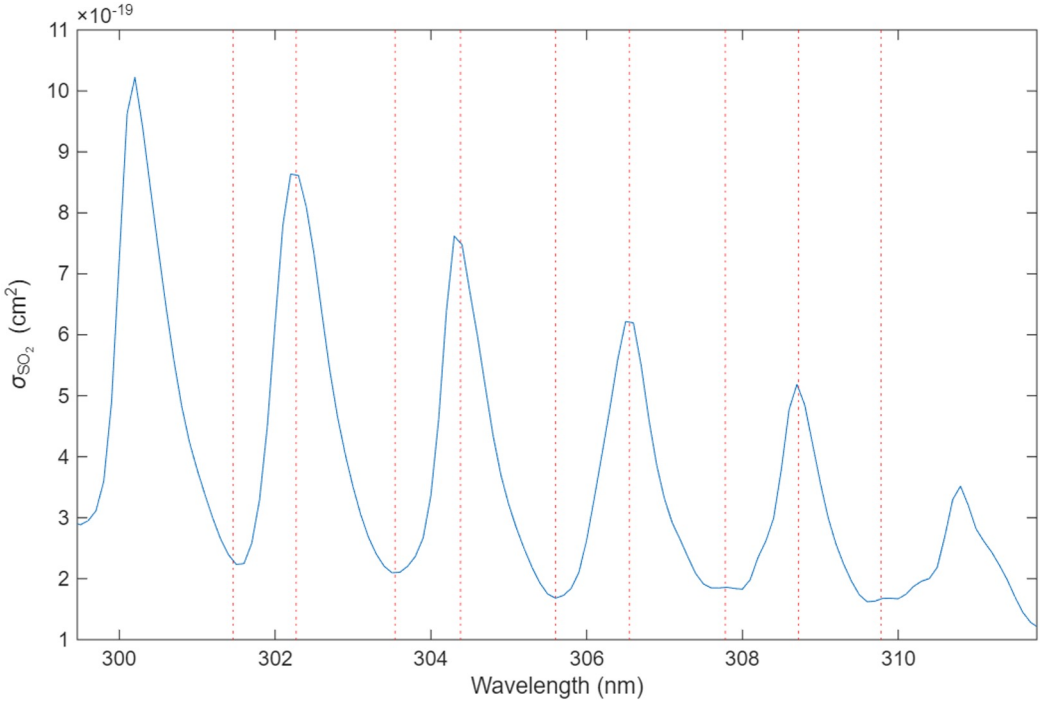


Figure1 : Absorption cross-sections of SO_2, NO_2, and O_3 as a function of wavelength. The highlighted spectral region contains strong SO_2 absorption features.

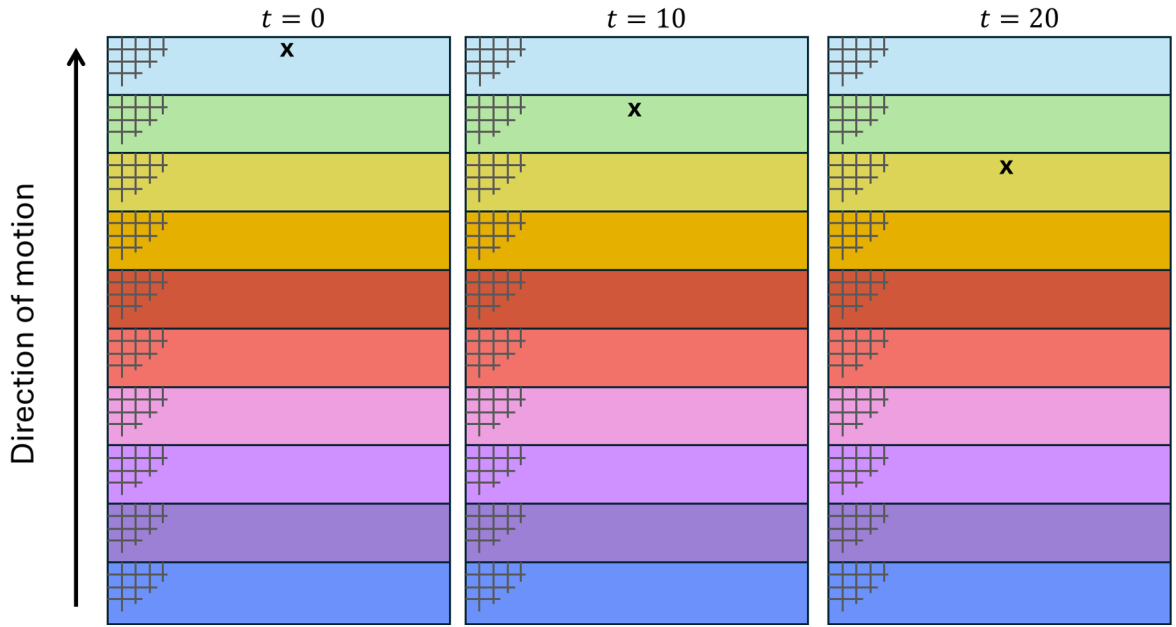
High SNR at chosen wavelengths

- Motivated by SNEEZI (Matheson et al 2024)
- Target a discrete set of lines matching SO_2 absorption features.
- High SNR @ target wavelengths, at the expense of broader spectral information.
- Use narrow band-width filters, high throughput, no moving parts.



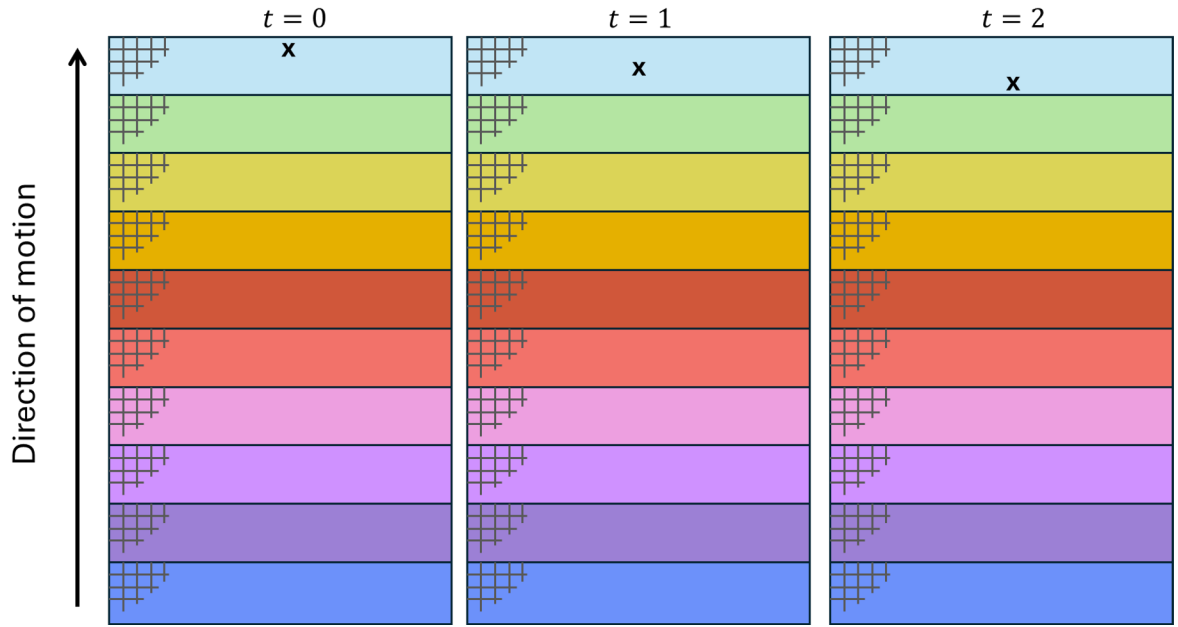
Push-broom multispectral imaging

- Butcher block filter - multiple bands on a single substrate.
- Using the satellite motion, the same spot (x) is imaged through each spectral band.
- No moving parts required.



Oversampling for increased SNR

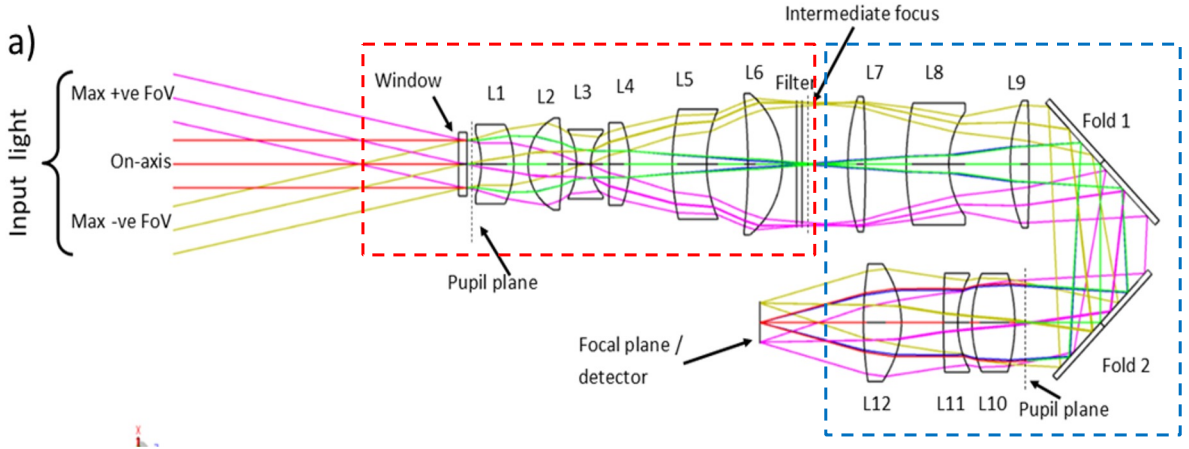
- A ground pixel (x) is imaged through the same spectral band multiple times.
- These multiple images of the same scene can be summed together.
- This can give significant SNR boost.



$$I^{Total}_{ground\ pixel}(\lambda_1) = I_{ground\ pixel}(\lambda_1, t_0) + I_{ground\ pixel}(\lambda_1, t_1) + I_{ground\ pixel}(\lambda_1, t_2) + \ \ldots$$

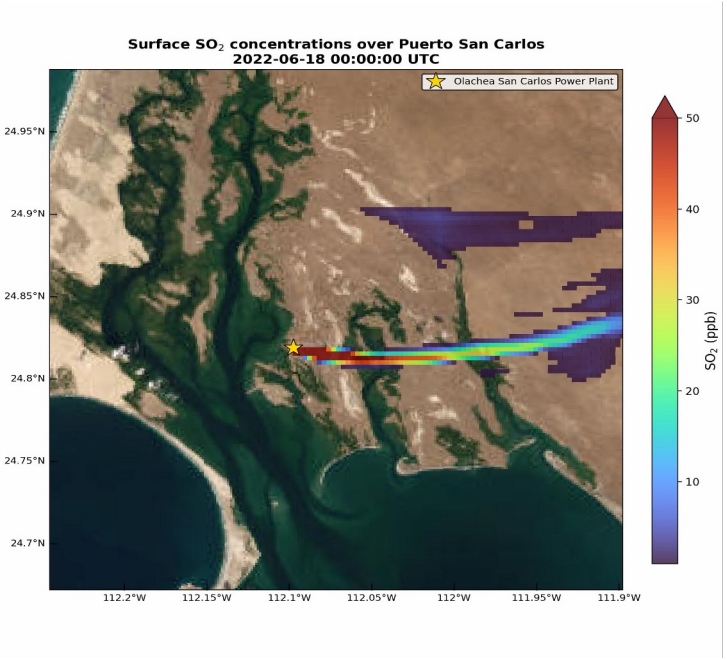
Proposed satellite instrument design

- Collection optics focus light onto filter array.
- Reimaging optics focus onto a CMOS detector.

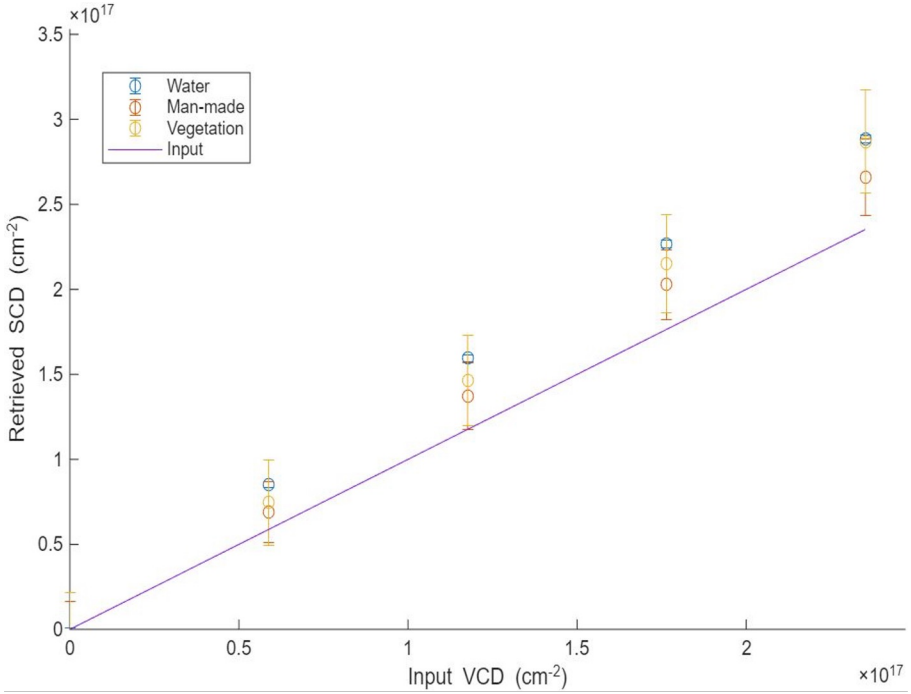


(based on SNEEZI; Matheson et al 2024)

First simulations: the plume is retrievable



Simulated plume, Agustín Olachea power plant, Mexico (14.1 t day^{-1})



Retrieved SCD tracks input VCD over water, vegetation and man-made surfaces

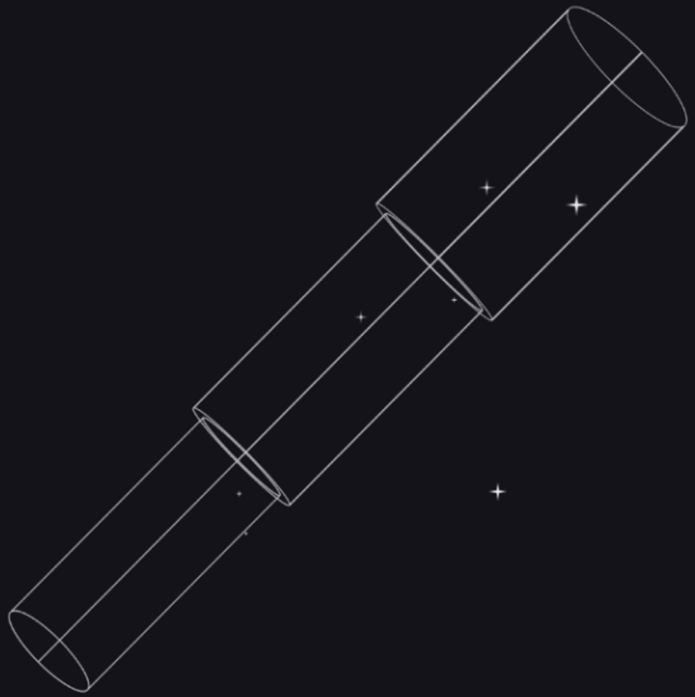
Specifications

USER REQUIREMENTS

Ground Sampling Distance	300 m
Swath width	300 km
SO_2 detection limit	$< 5 \times 10^{16}$ molec cm^{-2}
Observation mode	2-3 target regions per orbit
Revisit interval	Sub-daily

TECHNICAL SPECIFICATIONS - PAYLOAD

Instrument type	Multispectral imager
Spectral design	9 bands CWs: 301.5 nm, 302.3 nm, 303.5 nm, 304.4 nm, 305.6 nm, 306.6 nm, 307.8 nm, 308.7 nm, 309.8 nm FWHM: 1 nm
Instrument aperture	5 mm diameter
Instrument Field of View half angle	32 degrees
Detector type	CMOS – Fairchild HWK4123
Payload power draw	40W
Payload volume	2U
Payload mass	< 4kg
Data rate	300 MB/target ROI



Thank you.
Questions?