High Resolution Remote Sensing of Rocket Launch Pollution

Connor Barker
Research Fellow at University College London

Eloise A. Marais, Daniel J. Varon

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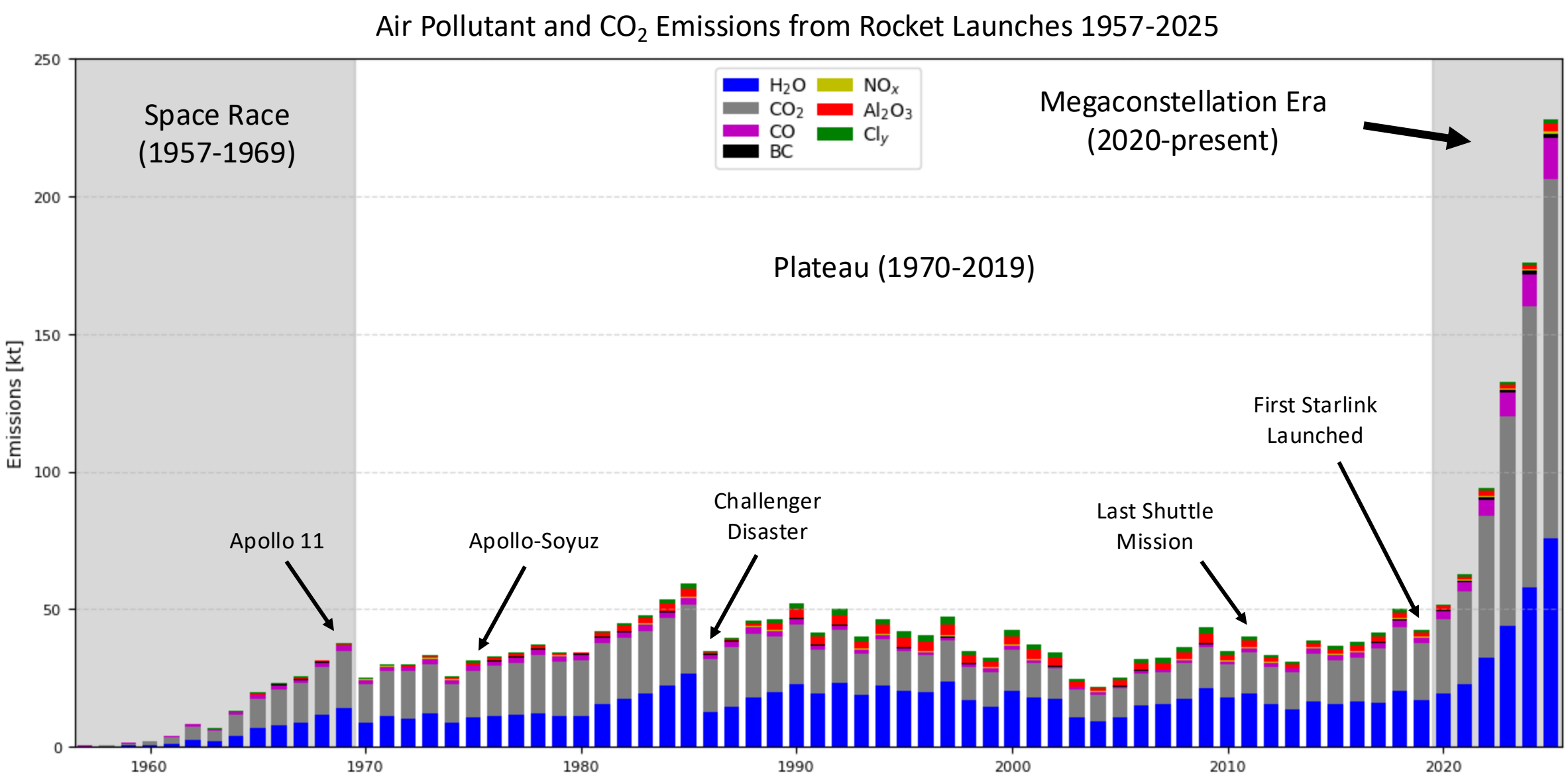
Seven decades of rising space emissions

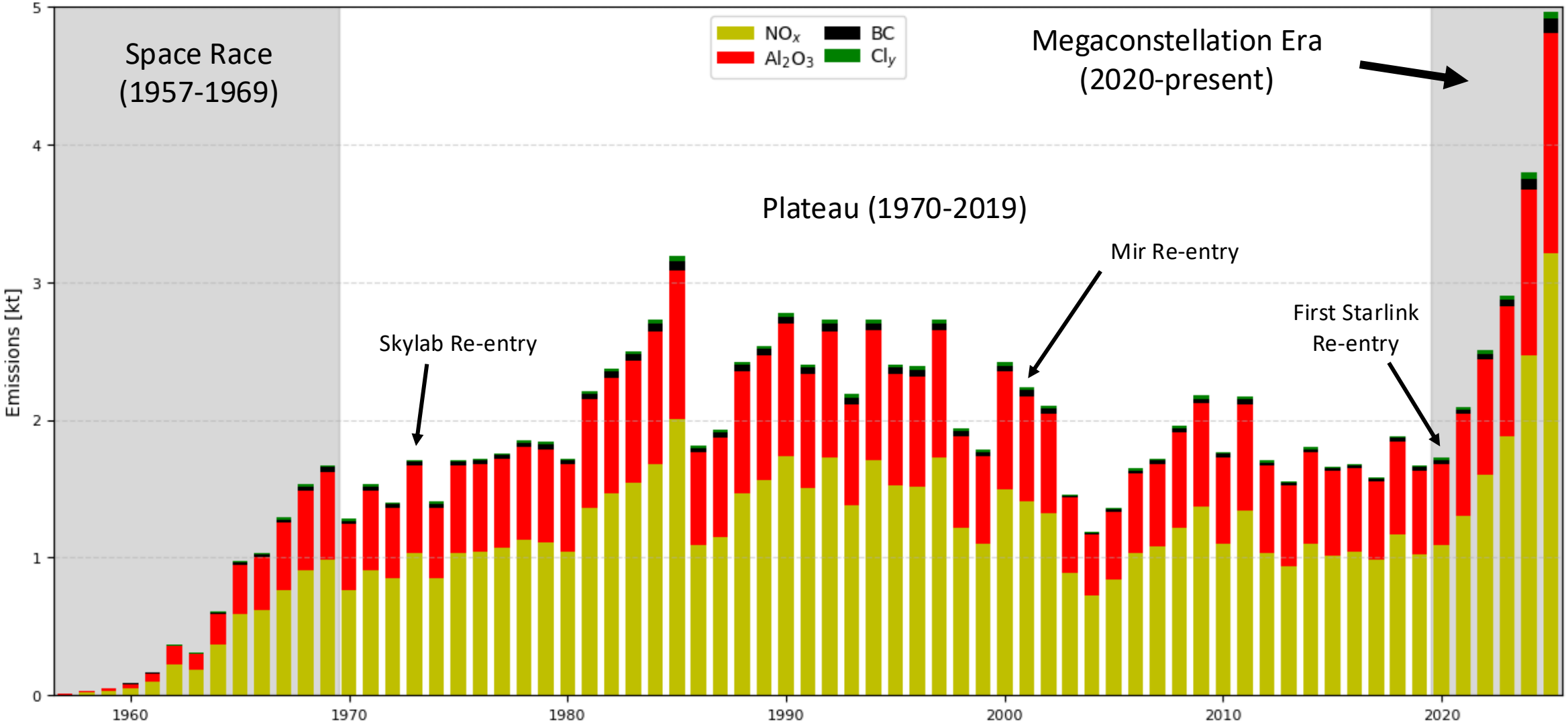


We are in a new era of unprecedented space activity growth

[Barker *et al.* (in draft)]

Seven decades of rising space emissions

Air Pollutant and CO_2 Emissions from Re-entries 1957-2025

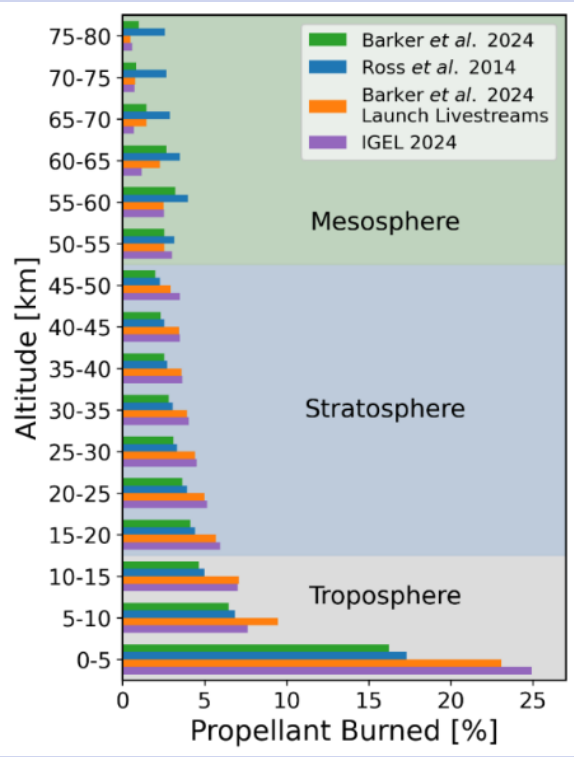


We are in a new era of unprecedented space activity growth

[Barker *et al.* (in draft)]

Quantifying rocket launch emissions

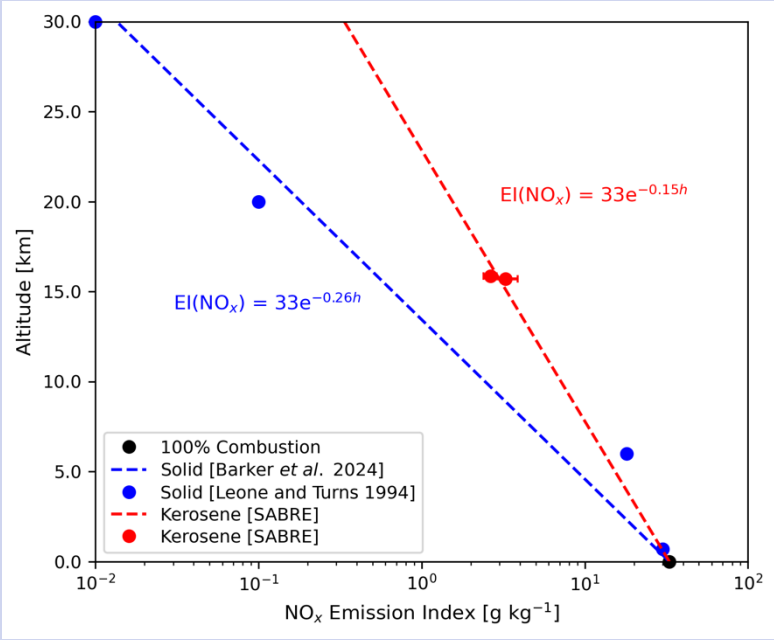
Propellant Consumption Profile



Calculated using Ross *et al.* (2014) mass profile or using launch-vehicle dependent trajectory

×

Emission Indices



Obtained from literature or calculated using in-engine modelling

→

Exhaust Species

↓

Validation?

[Barker *et al.* (2026), Herberhold *et al.* (in review)]

Validating bottom-up inventories

Airborne Platforms

- In-situ collection of rocket launch emissions using stratospheric balloons, sounding rockets, aircraft.
- Difficult to scale across vehicles, propellants, and launch sites.

Sparse & costly to obtain

Remote Sensing

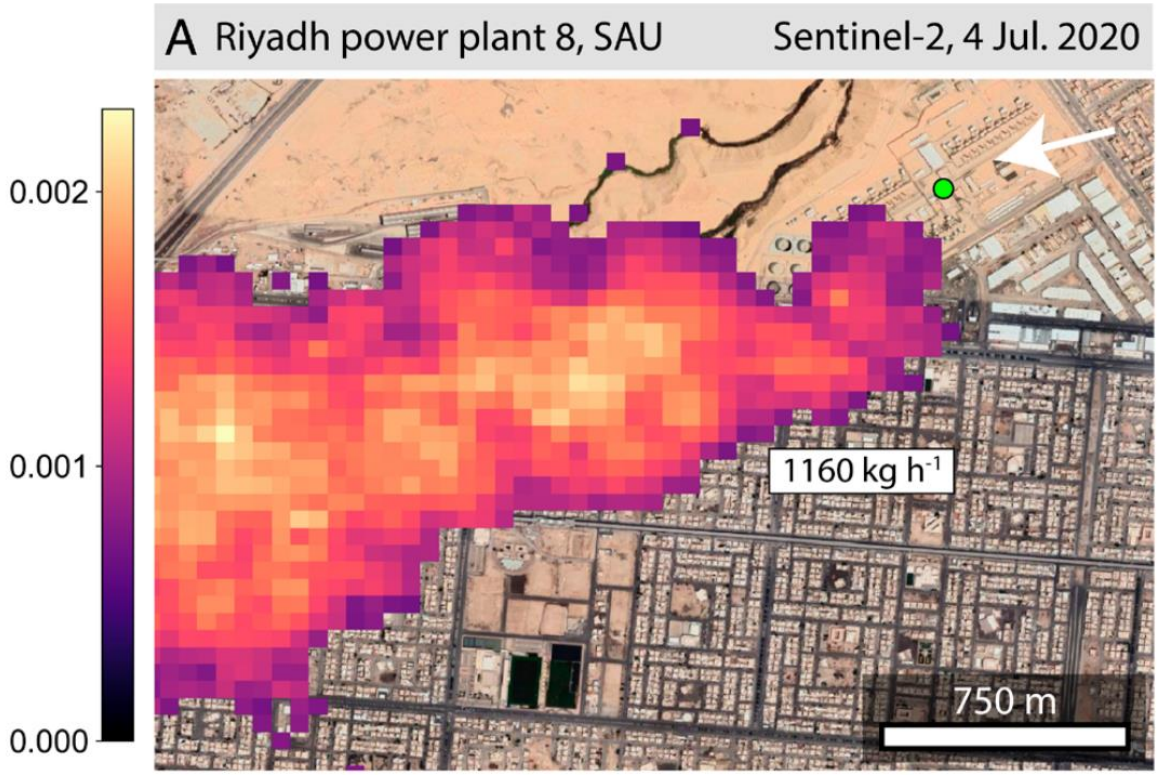
- Existing satellites are already routinely monitoring launch sites.
- Able to sample many vehicles, propellants, and launch sites.

Scalable & already in orbit

[Images from NOAA, NASA]

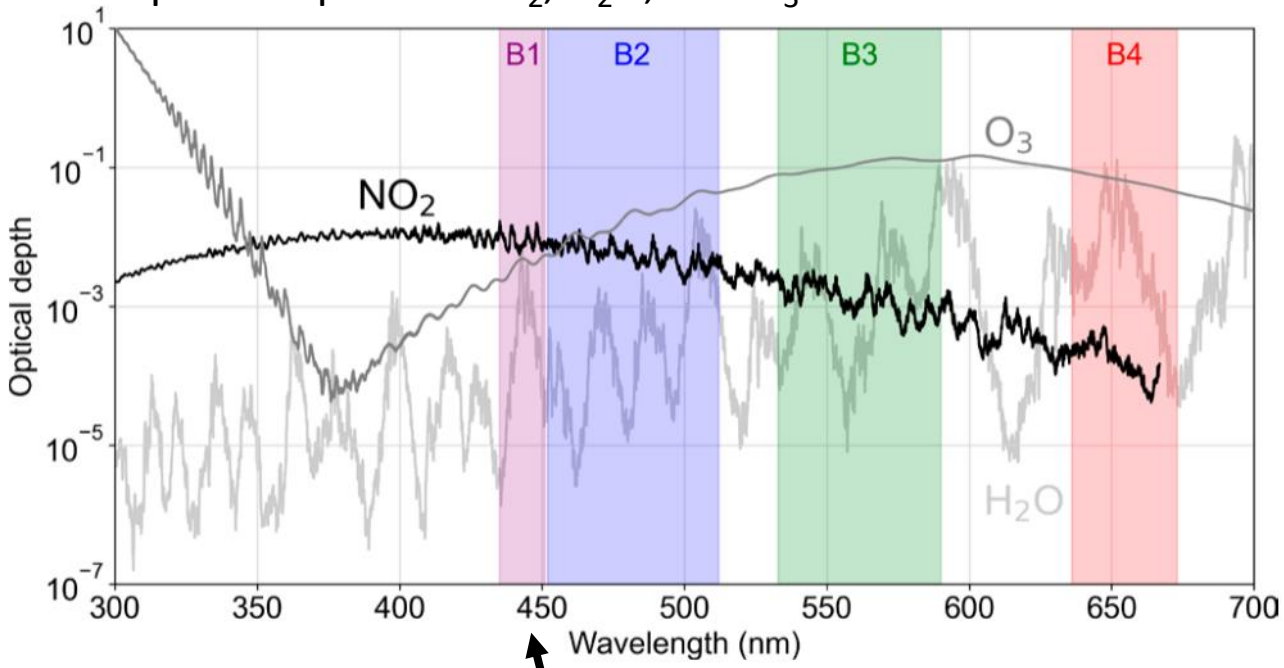
Detecting NO_x point sources using high-resolution satellite observations

Retrieved plume NO_2 enhancement [mol m^{-2}]



Paper demonstrated use of broadband sensors (Sentinel-2, Landsat) to retrieve NO_2 plumes at high resolutions (10-60m).

Optical depths of NO_2, H_2O, and O_3 with Landsat bands



NO_2 absorbs strongly in the "ultra-blue" band (~430-450 nm)

Launch NO_x emission rates far exceed power plant NO_x emissions, but launches are transient

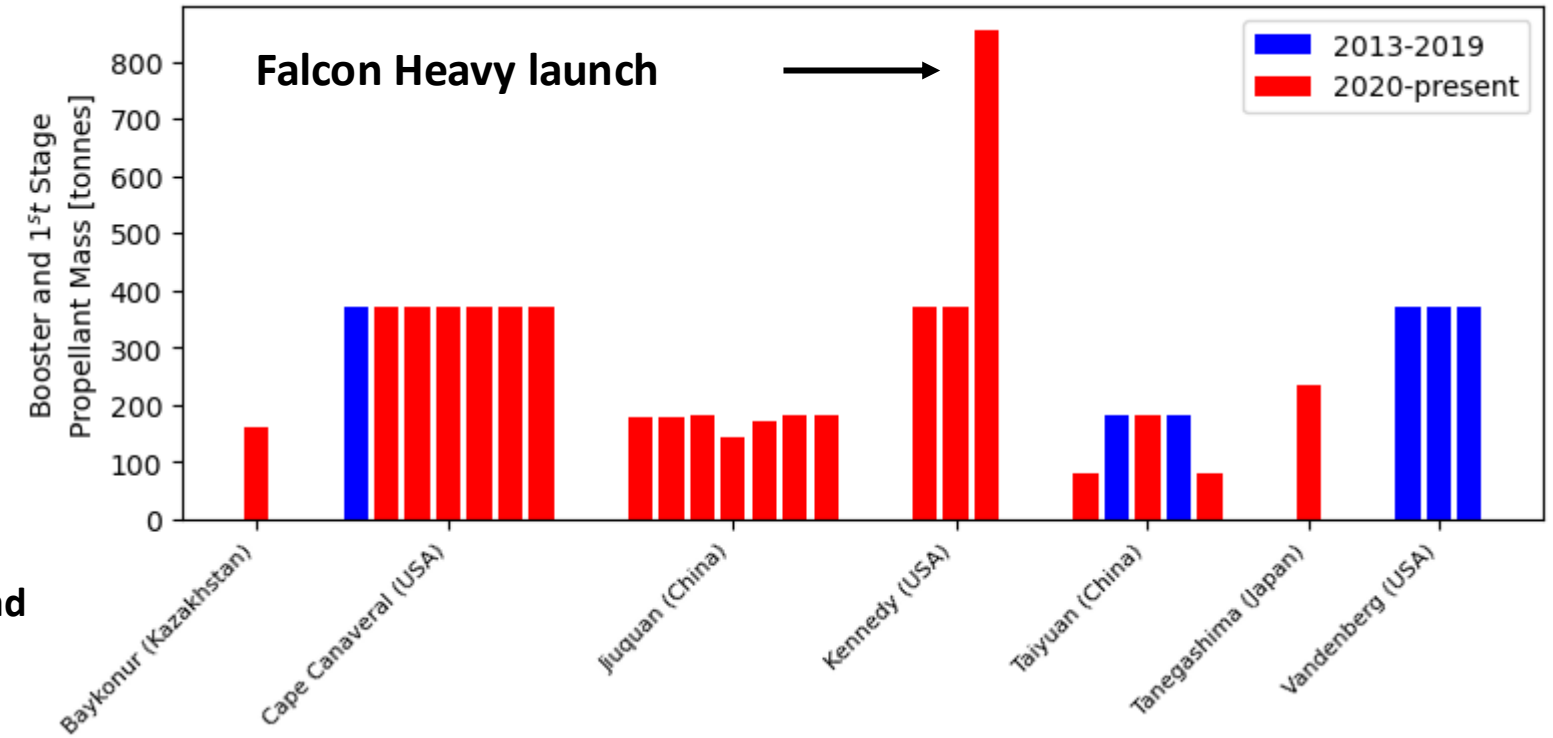
[Varon et al., PNAS, 2024]

Locating launch-coincident overpasses

Sentinel-2 (2A, 2B, 2C)
60m resolution (UB)
5-day revisit time
Since 2015
290 km swath

Landsat 8-9
30m resolution
8-day revisit time
Since 2013
185 km swath

Combined Landsat / Sentinel-2 cloud-free launch-coincident overpasses (2013-present)



Launchpad names:

2015 launches from 2013-present

↓ 1.3%

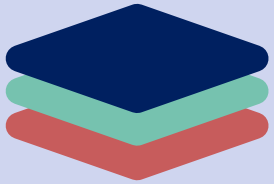
27 cloud-free launch-coincident overpasses

↓

? Suitable targets

Retrieval Method

1 Building the Reference



Identify similar reference scenes using red band, then combine into one 'idealized' reference

2 Normalized Reflectance Ratio

scale factor

target

$$r = \frac{c\,R_i}{R_j}$$

reference

Account for scene-wide reflectance offsets and isolate plume signal

3 NO_2 Vertical Column

$$\Delta\Omega_V = -\frac{\ln(r)}{\sigma \times AMF}$$

scattering air mass factor

absorption cross-section

Convert the ratio to the NO_2 vertical column ($\Delta\Omega_V$) in units of mol m^{-2}.

4 Plume Detection

Smooth and use a percentile filter to detect the plume

5 Second Retrieval

Repeat the retrieval process, this time removing plume pixels from the scale factor calculation

6 Integrated Mass Enhancement

$\Delta\Omega_V$ →

Convert the NO_2 vertical column to rocket launch NO_x emissions

Retrieved plume NO_2 concentrations from satellite data (Sentinel-2)

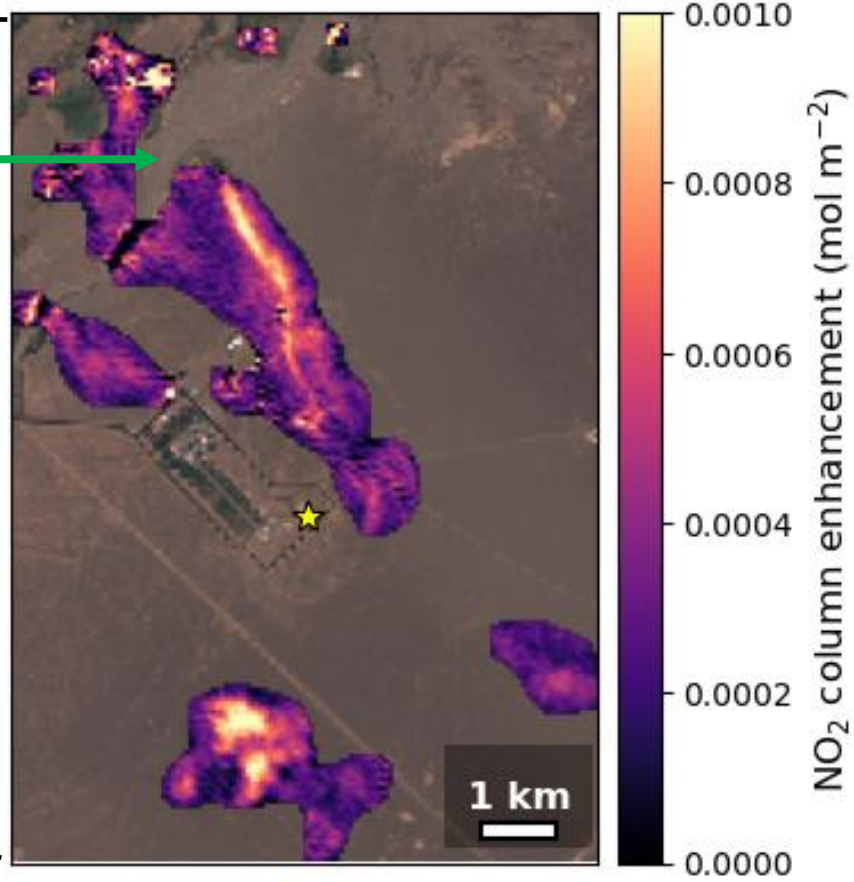
Preliminary results of launch plume NO_2 at the Jiuquan Satellite Launch Centre in Northwest China:

Sentinel-2 RGB image of the launch site

29 Jul. 2021
15 min after liftoff

Surface water may "break up" the plume.

NO_2 enhancement retrieved from Sentinel-2

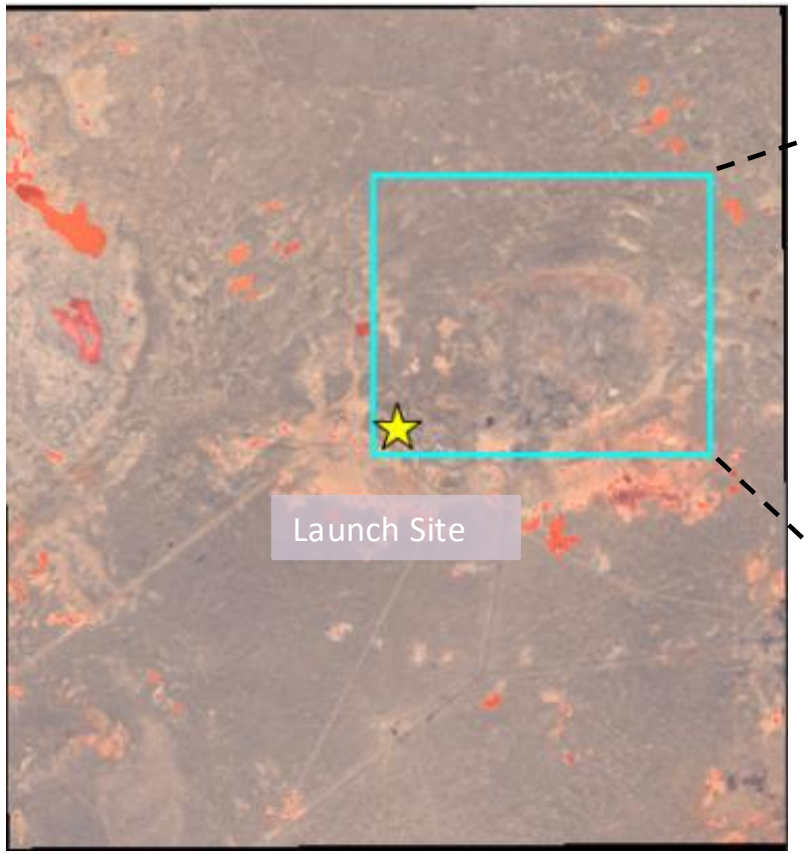


Chang Zheng 2D
Hypergolic propellant

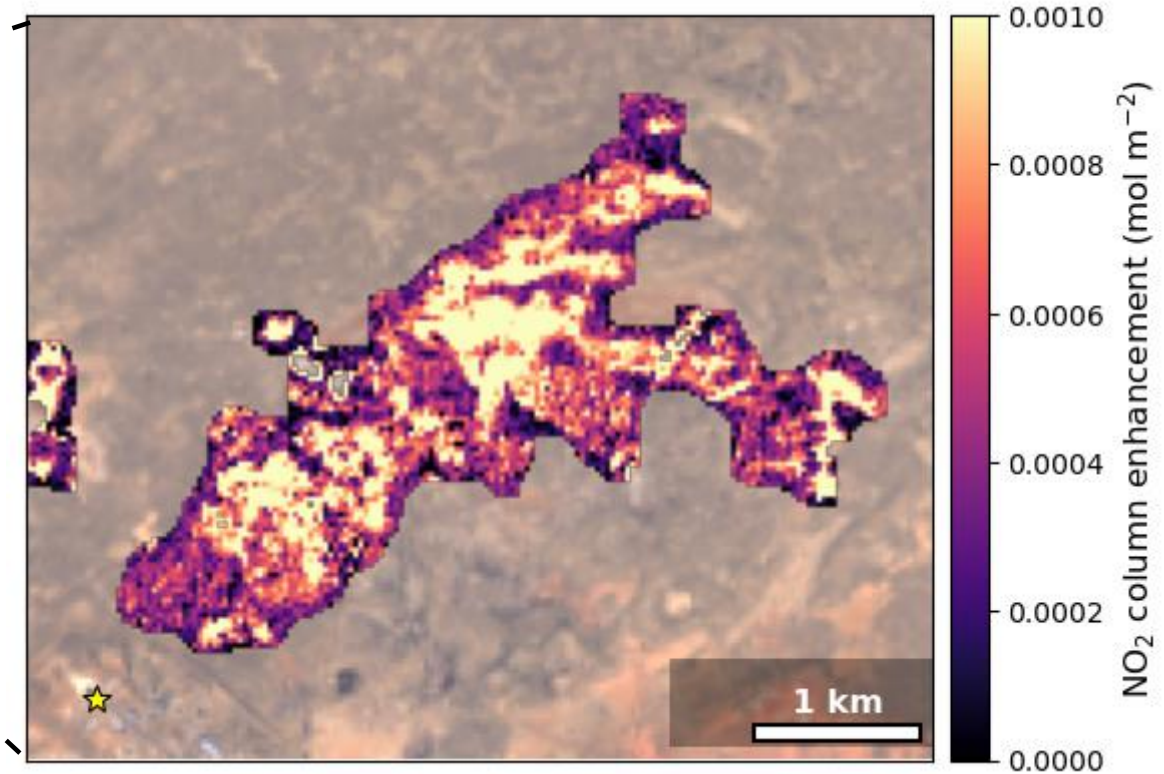
Retrieved plume NO_2 concentrations from satellite data (Landsat 8/9)

Preliminary results of launch plume NO_2 at the Baikonur Launch Centre in Kazakhstan:

Landsat RGB image of the launch site



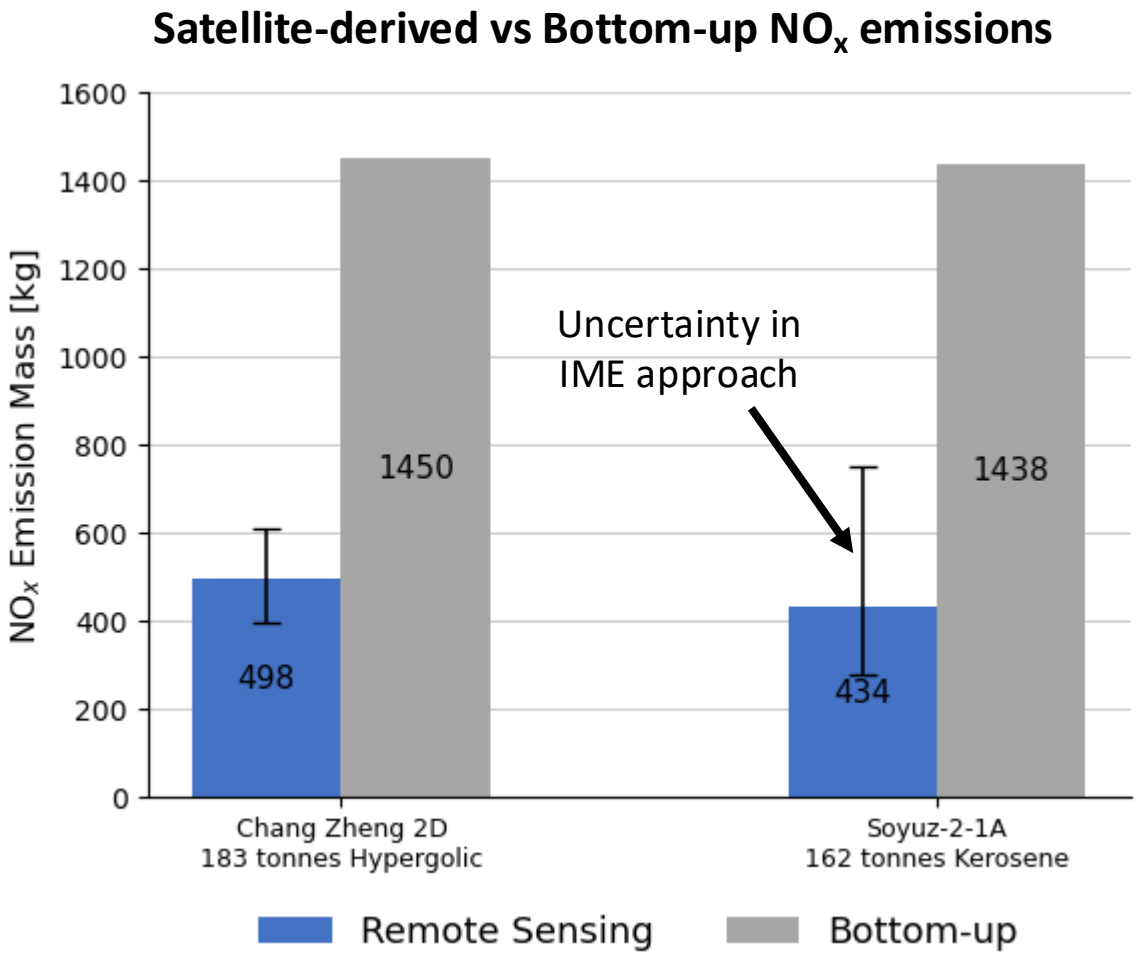
NO_2 enhancement retrieved from Landsat



8 Apr. 2025
41 min after liftoff

Soyuz-2-1A
Kerosene propellant

Deriving total NO_x emissions



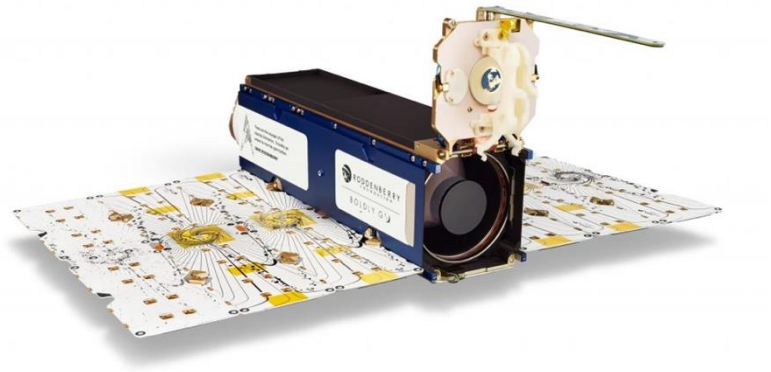
The satellite-derived NO_x emissions are consistent across overpasses, but much lower than bottom-up estimates.

Take-Home Messages and Next Steps

- Initial results demonstrate potential of space-based sensors to calculate rocket launch NO_x emissions.
- High-resolution broadband retrievals are currently limited to barren desert scenes.

Next steps:

- Additional scenes could be found using private satellite data from the Planet SuperDove constellation, which has 3m resolution and a daily revisit time. This greatly increases the chances of a suitable target.



Planet SuperDove satellite

69 scenes identified using Planet SuperDove