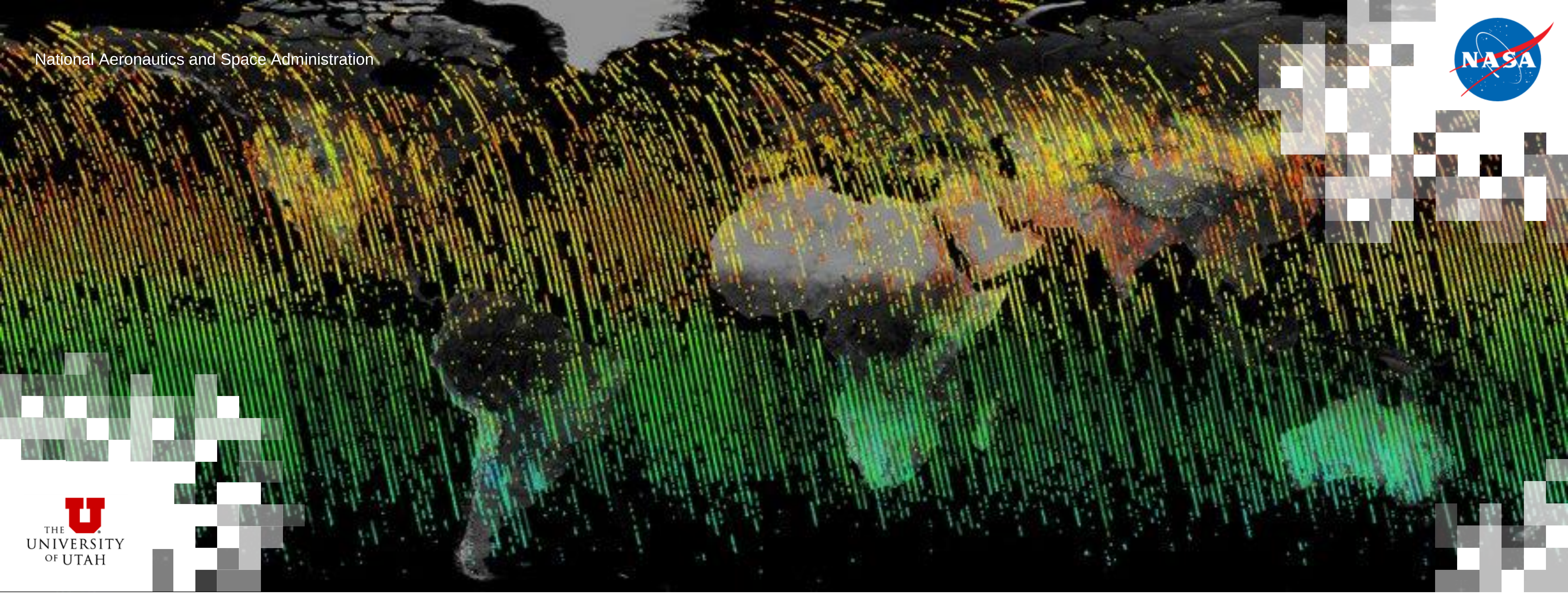


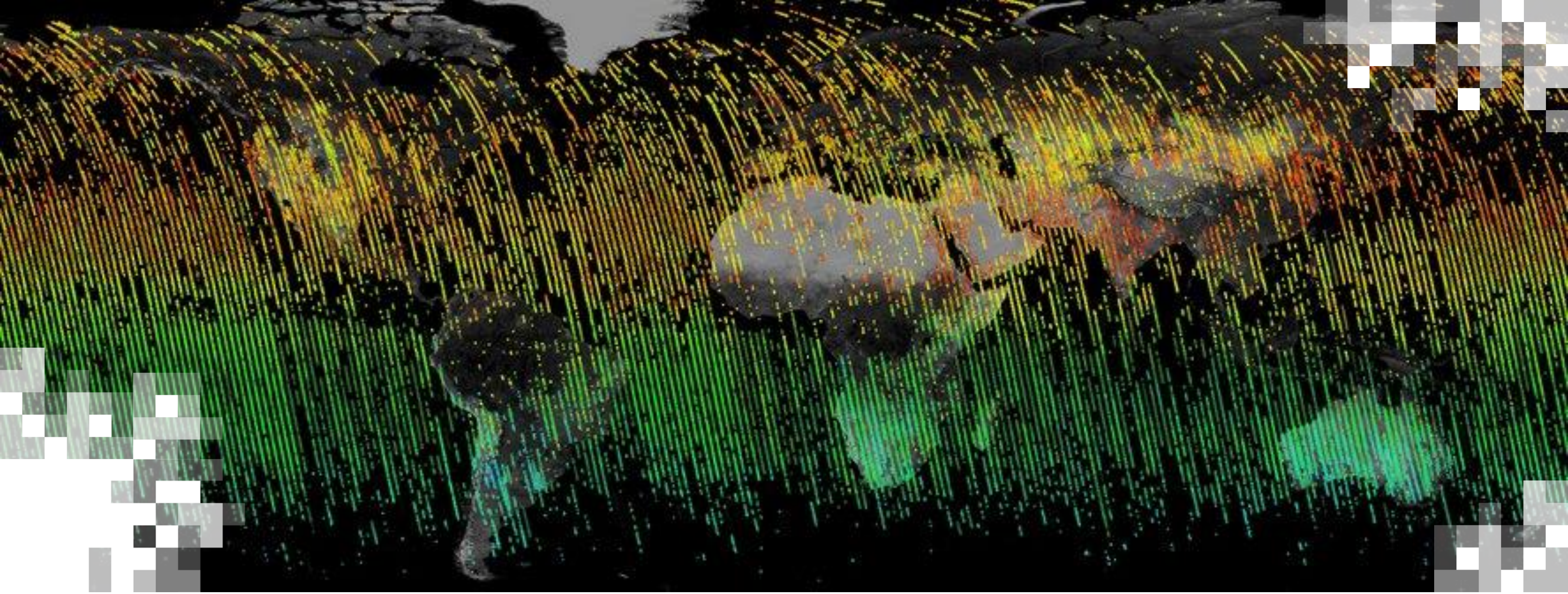

# Measuring Atmospheric Carbon Dioxide from Space in Support of Climate Studies: The $XCO_2$ Measurement from OCO-2 and OCO-3

Vivienne Payne, OCO-2 Project Scientist

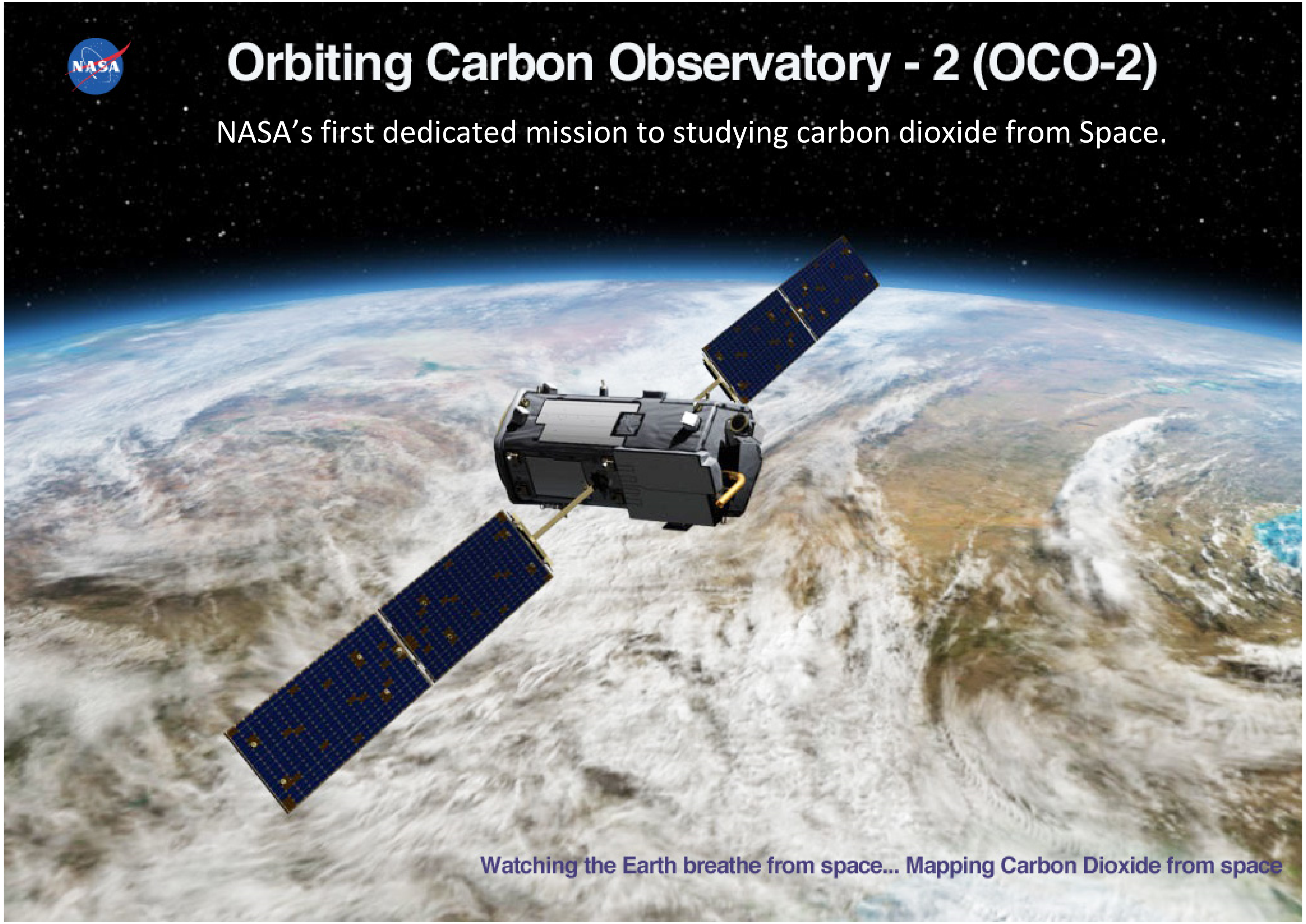
May 24, 2022

# Overview

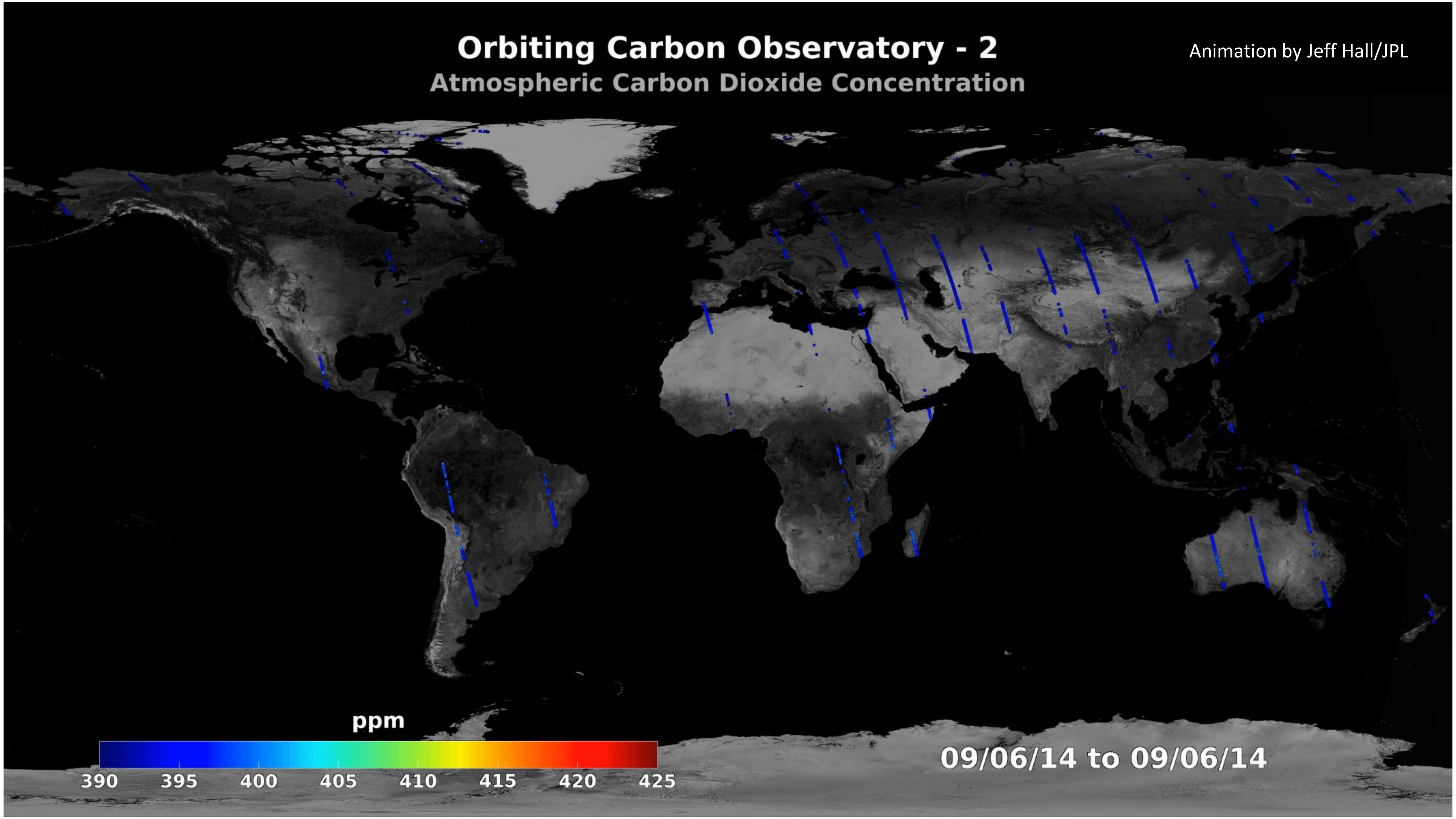
- Overview of OCO-2 and OCO-3
- What is the $XCO_2$ measurement and how is it measured?
- What are the characteristics of the measurement?
- What are the limitations of the measurement?
- How do you interpret the measurement?
- How has the data been validated?



# The OCO-2 and OCO-3 Satellite Missions

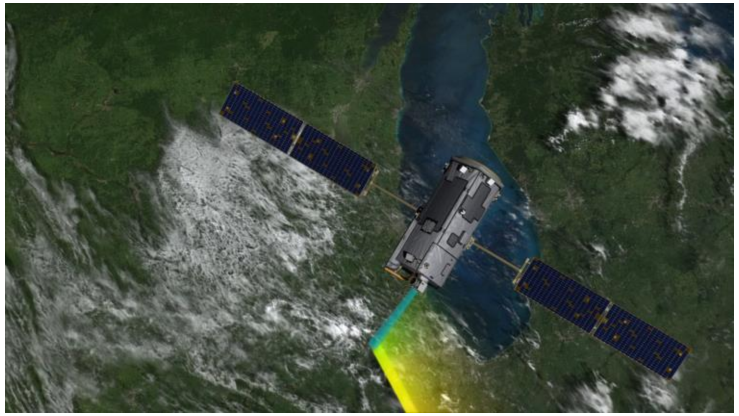

NASA
Orbiting Carbon Observatory - 2 (OCO-2)
NASA's first dedicated mission to studying carbon dioxide from Space.
Watching the Earth breathe from space... Mapping Carbon Dioxide from space

# OCO-2: Measurements Since September 2014

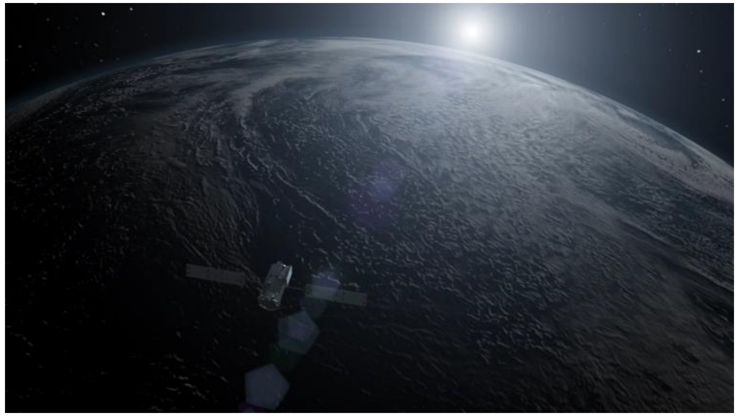


# What are the different observation modes for OCO-2?

OCO-2 collects science observations in 3 different modes: Nadir, Glint, and Target



Nadir Mode, or looking straight down, provides the highest spatial resolution on the surface and is expected to return more useable soundings in regions that are partially cloudy or have significant surface topography. Nadir observations may not provide adequate signal-to-noise over dark ocean surfaces.

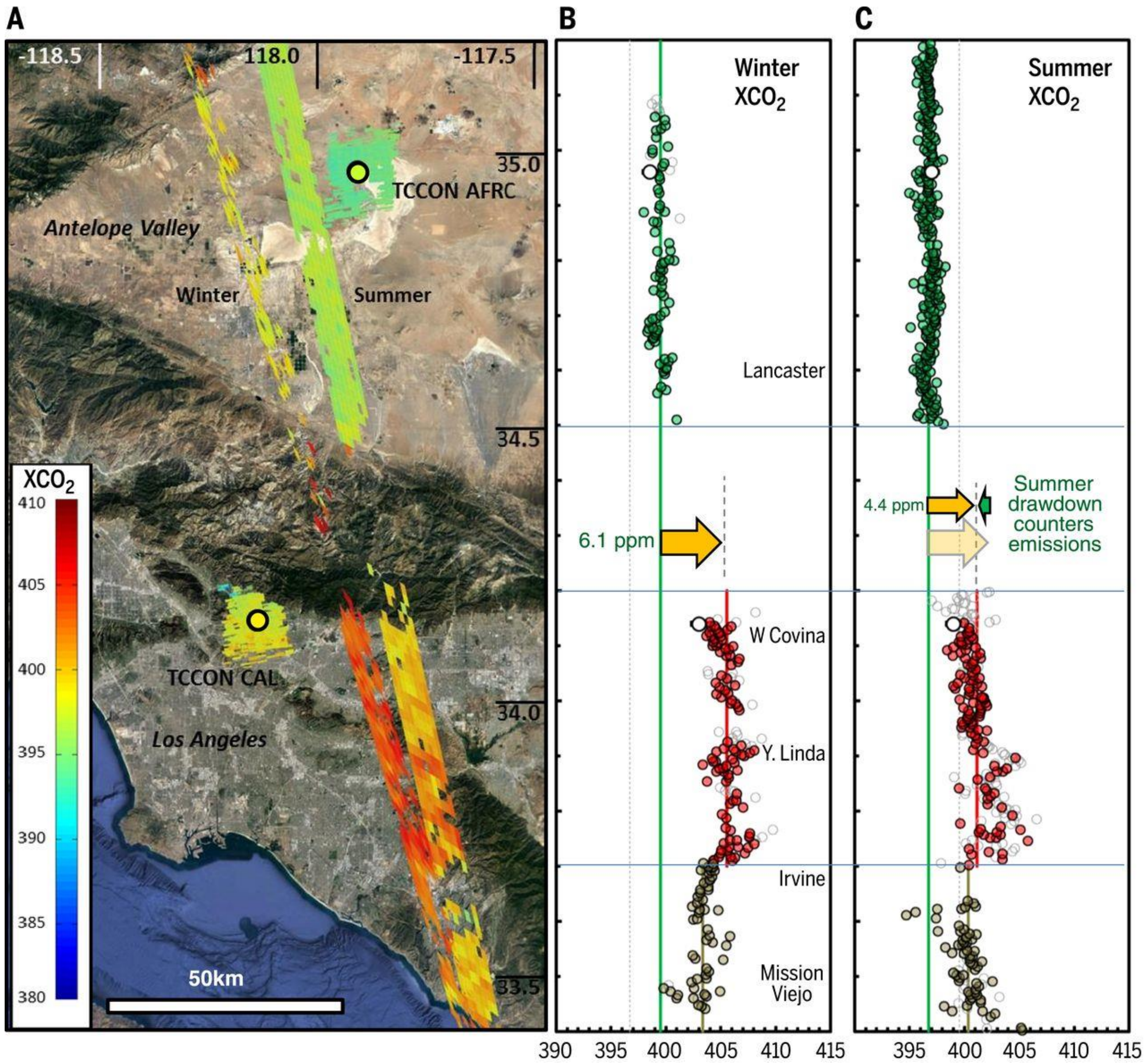


Glint Mode, the spacecraft points the instrument toward the bright "glint" spot, where solar radiation is reflected from the surface. At high latitudes over the ocean, observations of the bright glint spot provide up to 100 times as much signal as measurements collected while looking straight downward at the ocean surface. Thus, the use of glint measurements significantly improves the signal-to-noise ratio over the dark ocean.

Target Mode, the Observatory locks its view onto a specific surface location and retains that view while flying overhead. Comparison of space-based and ground-based measures provides a means to identify and correct systematic and random errors in the OCO-2 XCO2 data products.

Videos by John Howard/JPL

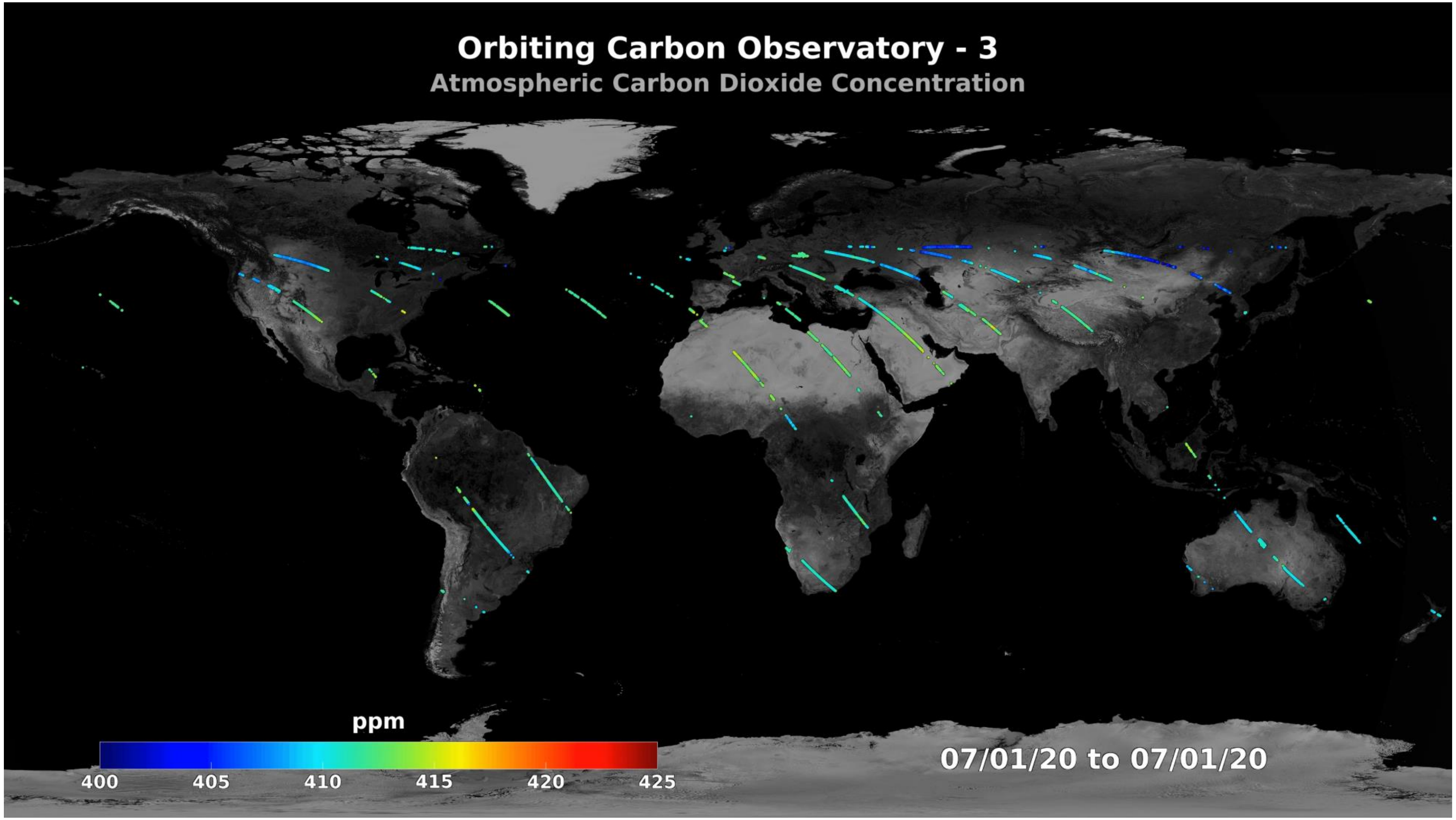
# Example: OCO-2 Nadir Tracks and Target Observations




Schwander et al., 2017, Science

# Orbiting Carbon Observatory– 3 (OCO-3)

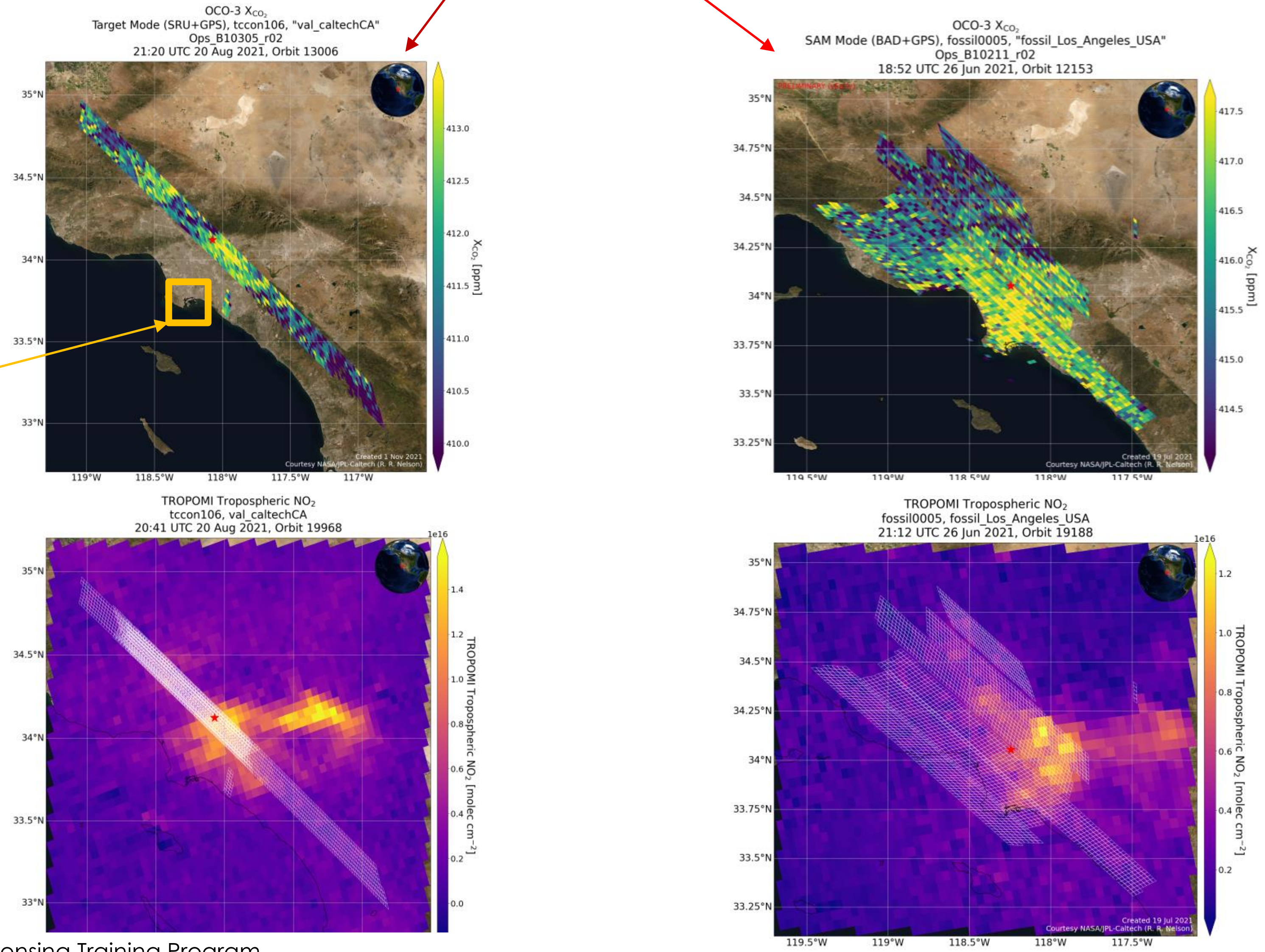
# OCO-3: Measurements Since August 2019




OCO-3 coverage is denser than OCO-2 but geographically more limited. In the regions where both datasets overlap, there will be science and applications that can be explored.

# What are the different observation modes for OCO-3?

OCO-3 collects science observations in Nadir, Glint, Target, and **Snapshot Area Map (SAM)** modes.




Approximate size of OCO-2 target observation over LA

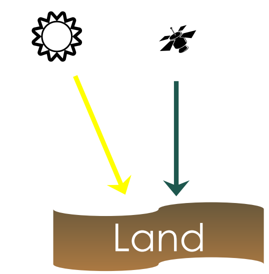
OCO-3 $XCO_2$

TROPOMI $NO_2$

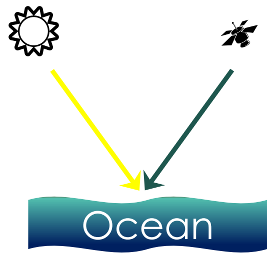
# OCO-2 vs. OCO-3 Instrument Overview

| | OCO-2 | OCO-3 |
|---|---|---|
| **launch** | 02 July 2014 | 04 May 2019 |
| **orbit** | sun-synchronous, A-Train | precessing, ISS, 51.6° inclination |
| **coverage** | pole-to-pole, 1330h ect | 52°S – 52°N, variable |
| **footprint size @nadir** | 3 km$^2$ | 3.5 km$^2$ |
| **spectrometer** | 3 bands: 0.765 µm, 1.61 µm, 2.09 µm, 20,000 resolving power (OCO-3 was built as the OCO-2 spare) | |
| **observed species** | $CO_2$ dry-air column ($XCO_2$)<br>solar-induced fluorescence (SIF) | |
| **observation modes** | nadir, glint, target | nadir, glint, target, **SAM** |
| **off-nadir viewing** | move spacecraft | **pointing mirror assembly** two mirrors: azimuth and elevation, moving independently |
| **repeatability of observations** | same local time every orbit; spatial repeat after 233 orbits (16 days) | **none!** local time a little earlier each day; day-by-day change in latitude coverage |

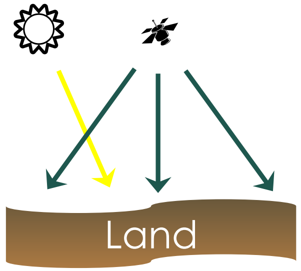
Nadir




Glint

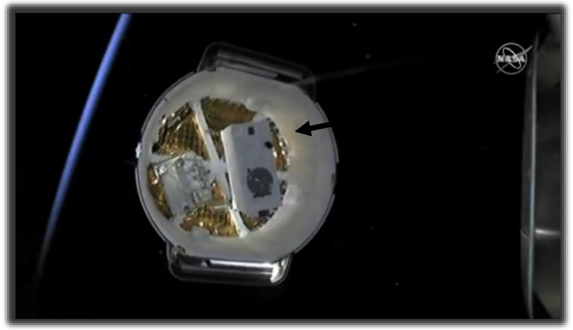



Target, SAM

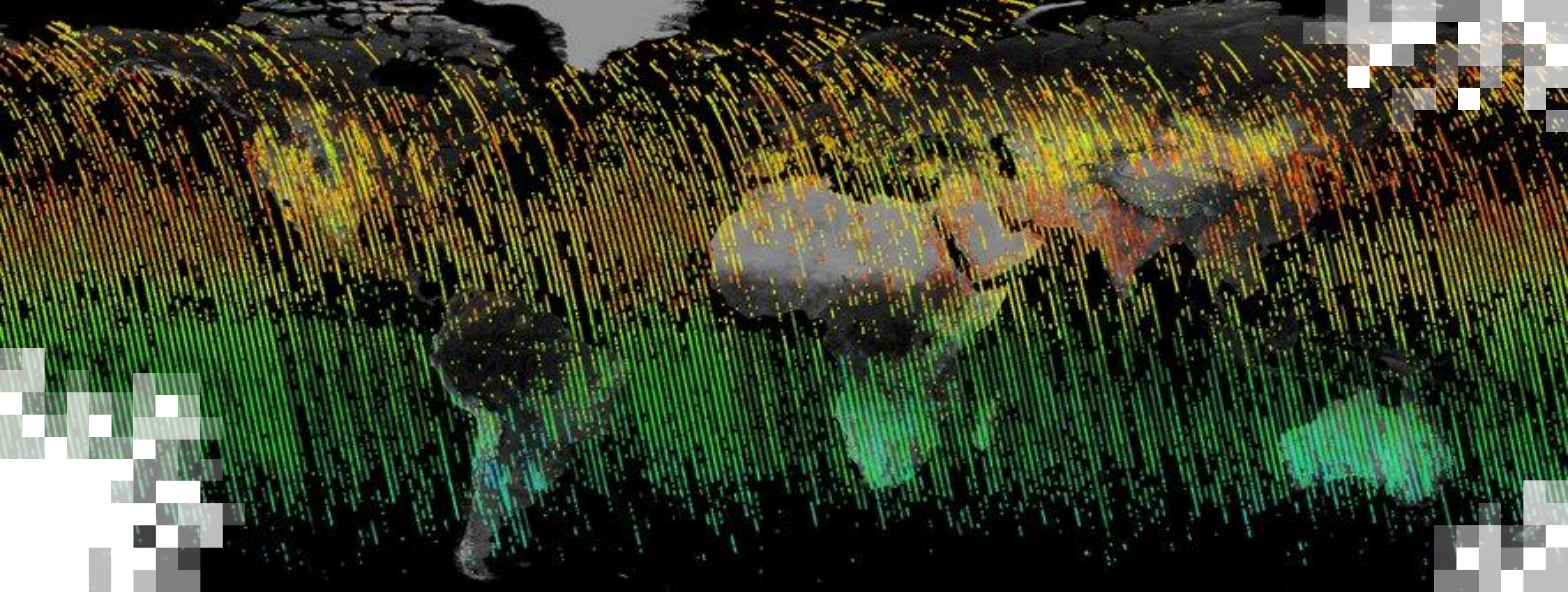



4 May 2019: OCO-3 SpaceX 17 Launch Falcon 9/Dragon Capsule

👁 of Dragon Capsule from the Falcon 9 Stage 2 After Separation



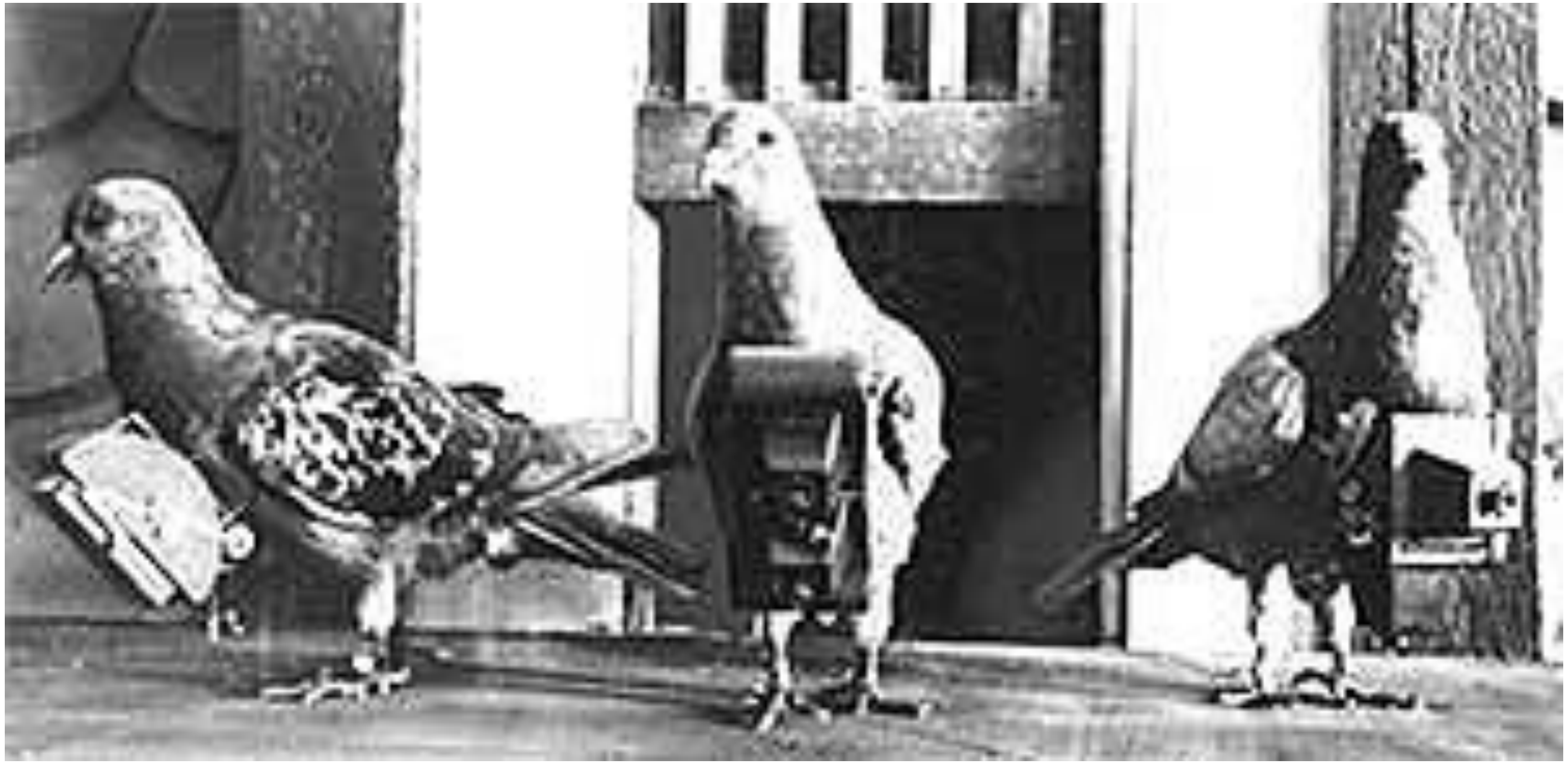
OCO-3 on the Japanese External Module

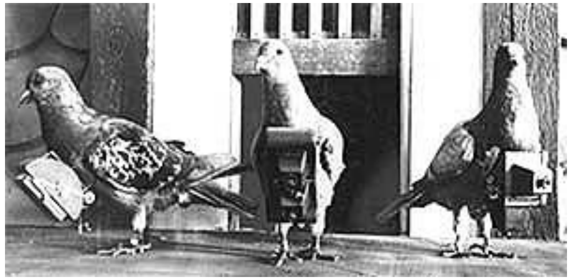


# What is the $XCO_2$ measurement and how is it measured?

**Remote Sensing:** "The acquisition of information about an object or phenomenon without making physical contact with it." (Wikipedia)

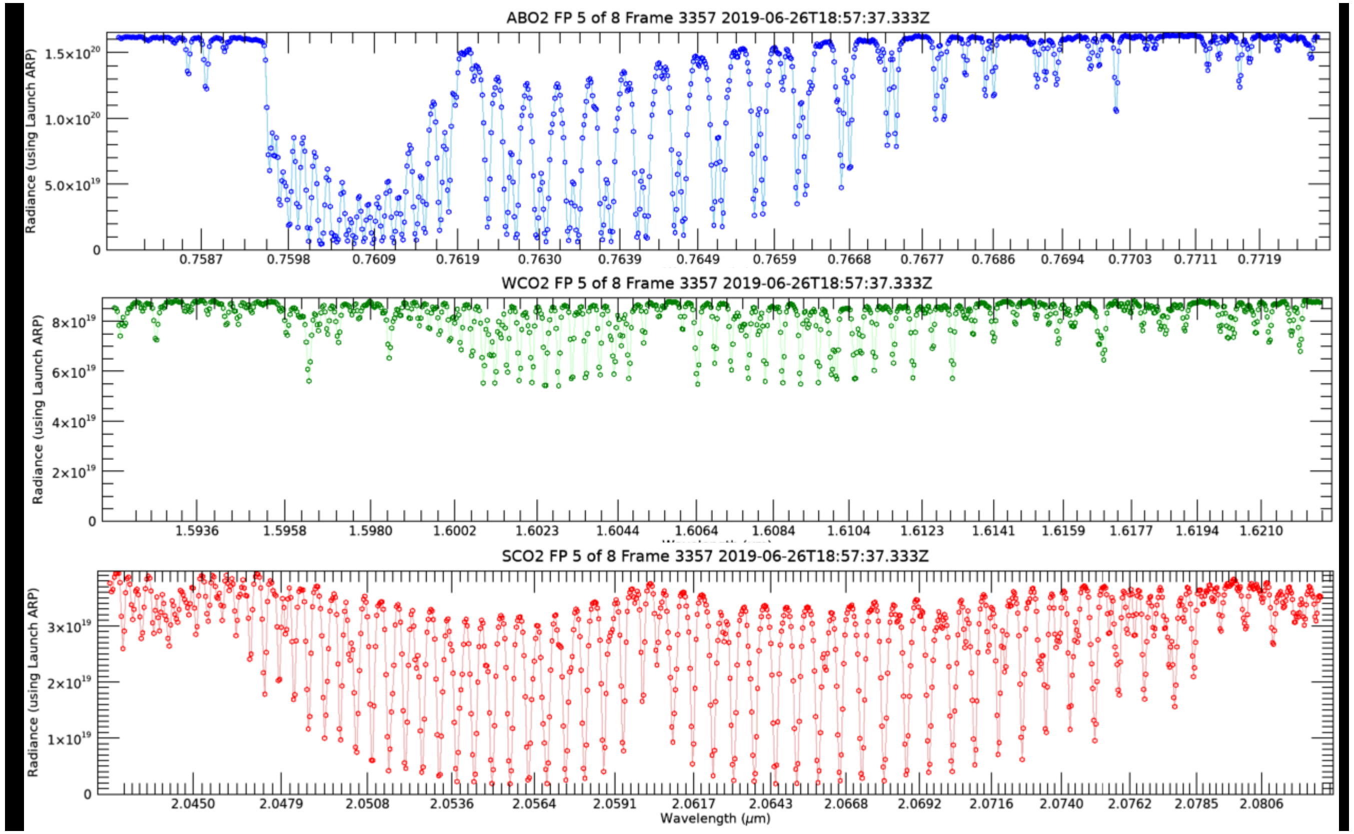
In 1903, pigeons were sent out with cameras to take aerial photographs over Europe. Image Credit: NASA





# Radiance Spectra from the OCO-2 Spectrometers

"First light" spectra from the (a) $O_2$ A-band (ABO2), (b) 1.61 µm $CO_2$ weak band (WCO2) and (c) 2.06 µm $CO_2$ strong band (SCO2). Each 1016-element spectrum has a resolving power, $\lambda/\Delta\lambda \cong 19{,}000$, to resolve the individual $O_2$ and $CO_2$ absorption lines from the adjacent continuum.



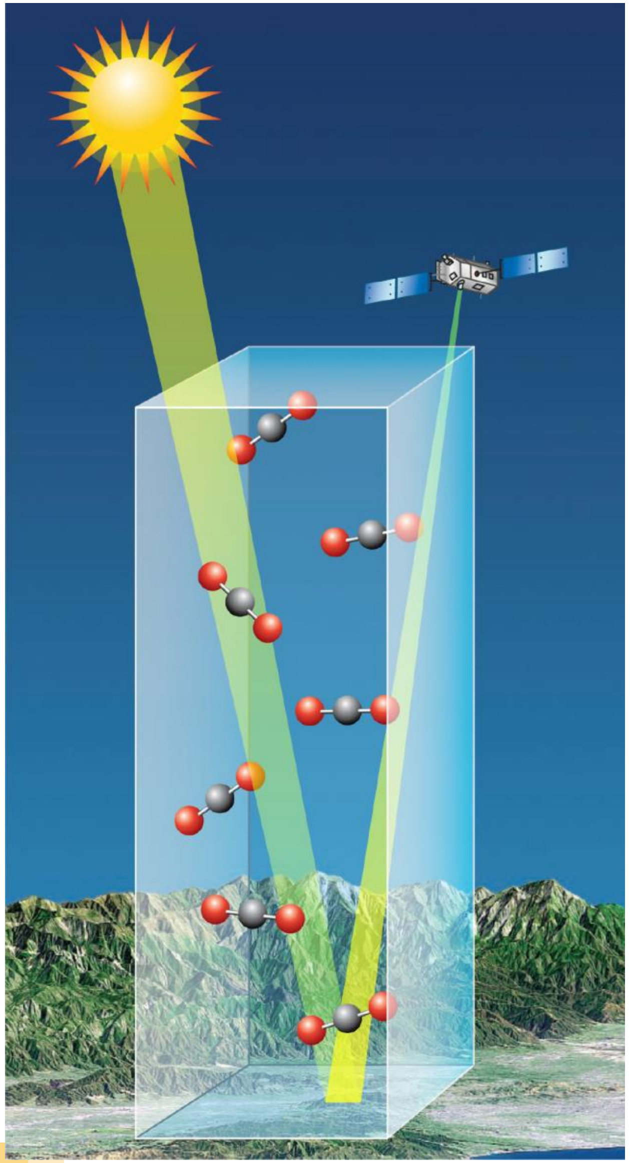

$O_2$ *A* band, 0.765 µm

Weak $CO_2$ band, 1.61 µm

Strong $CO_2$ band, 2.06 µm

Gas molecules in the Earth's atmosphere absorb the sunlight at specific wavelengths. When light passes through the Earth's atmosphere, the gases that are present leave a distinguishing "fingerprint" that can be captured.

# What is the $XCO_2$ measurement and how is it measured?

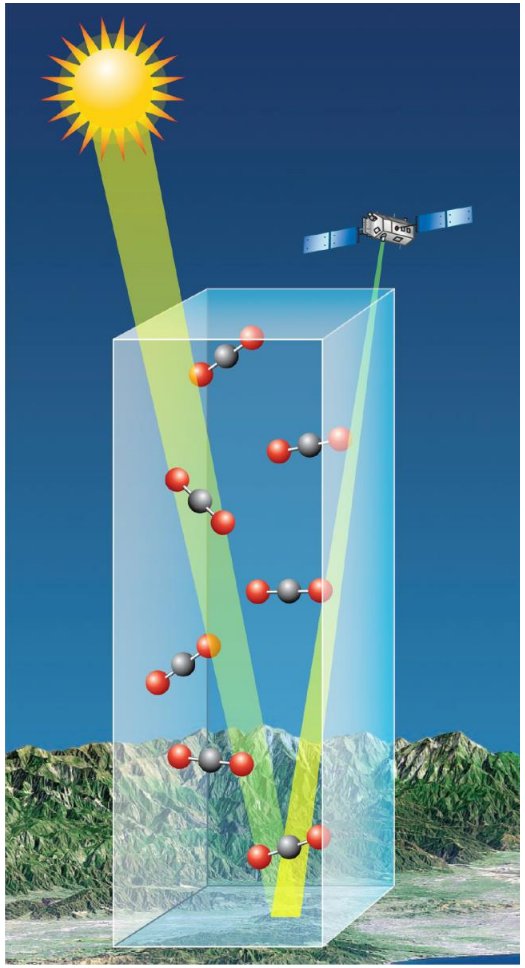


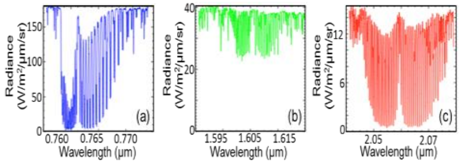
$XCO_2$ is the column average volume mixing ratio. This is a measure of the amount of carbon dioxide in the atmosphere.

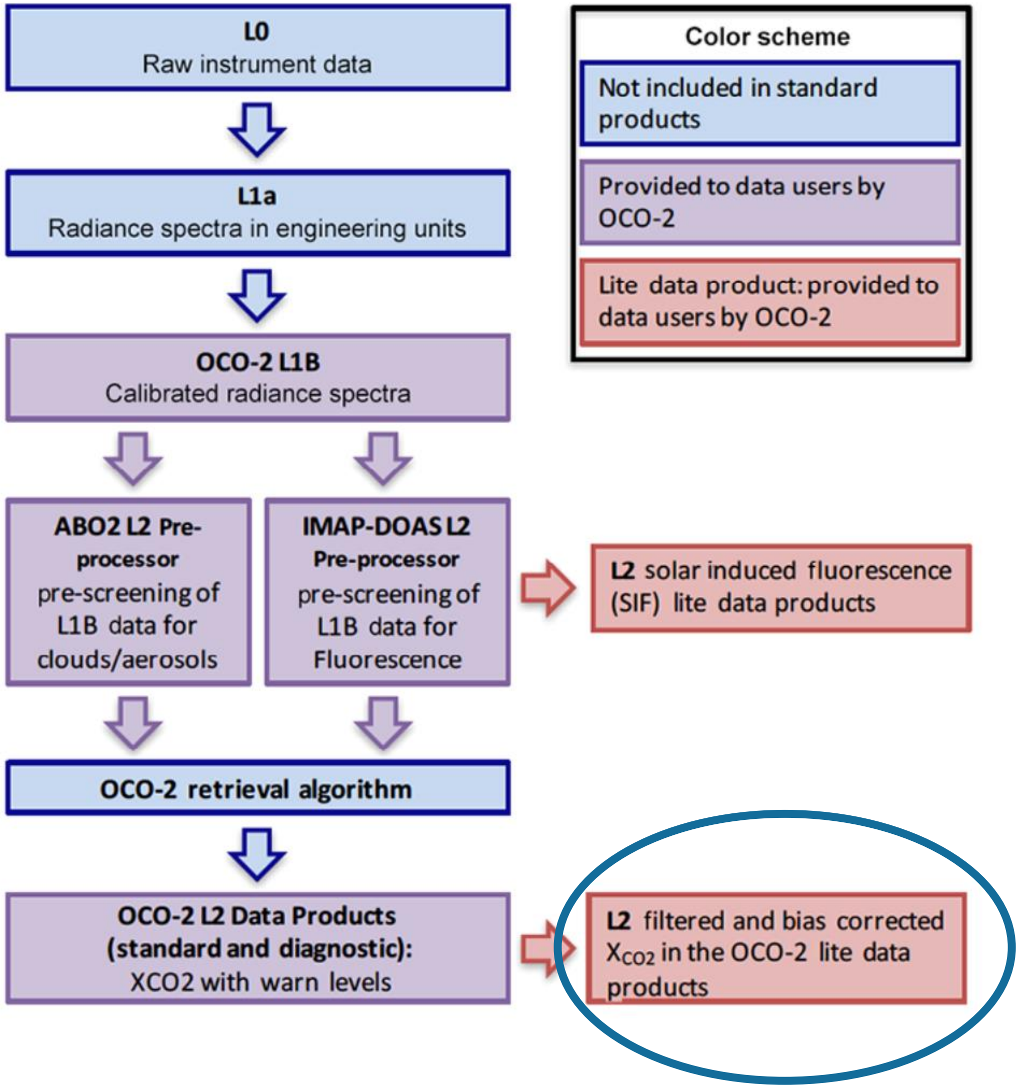
Gas molecules in the Earth's atmosphere absorb the sunlight at specific wavelengths. When light passes through the Earth's atmosphere, the gases that are present leave a distinguishing "fingerprint" that can be captured.

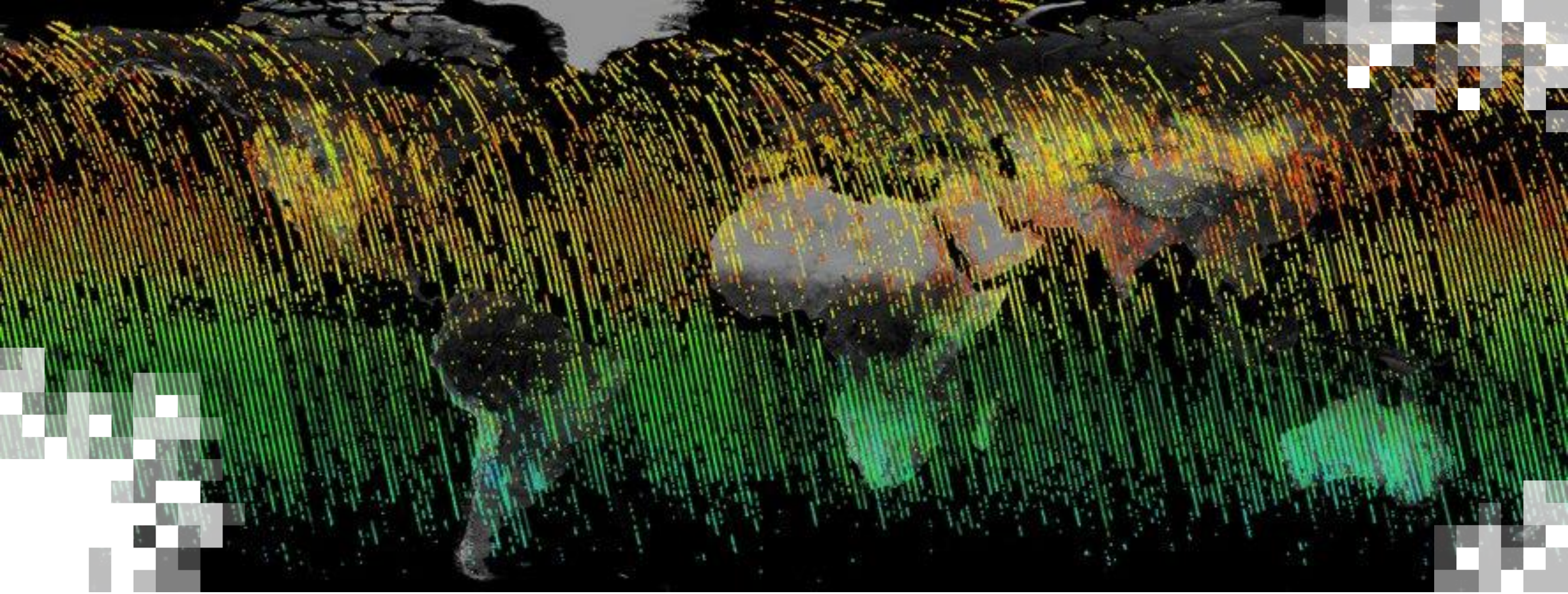
The OCO-2 and OCO-3 spectrometers, working like cameras, detect these molecular "fingerprints". Then the absorption levels shown in these spectra, like a captured image, tells us how many molecules were in the region where the instrument measured.

# What is the $XCO_2$ measurement and how is it measured?







What are the characteristics of the measurement?

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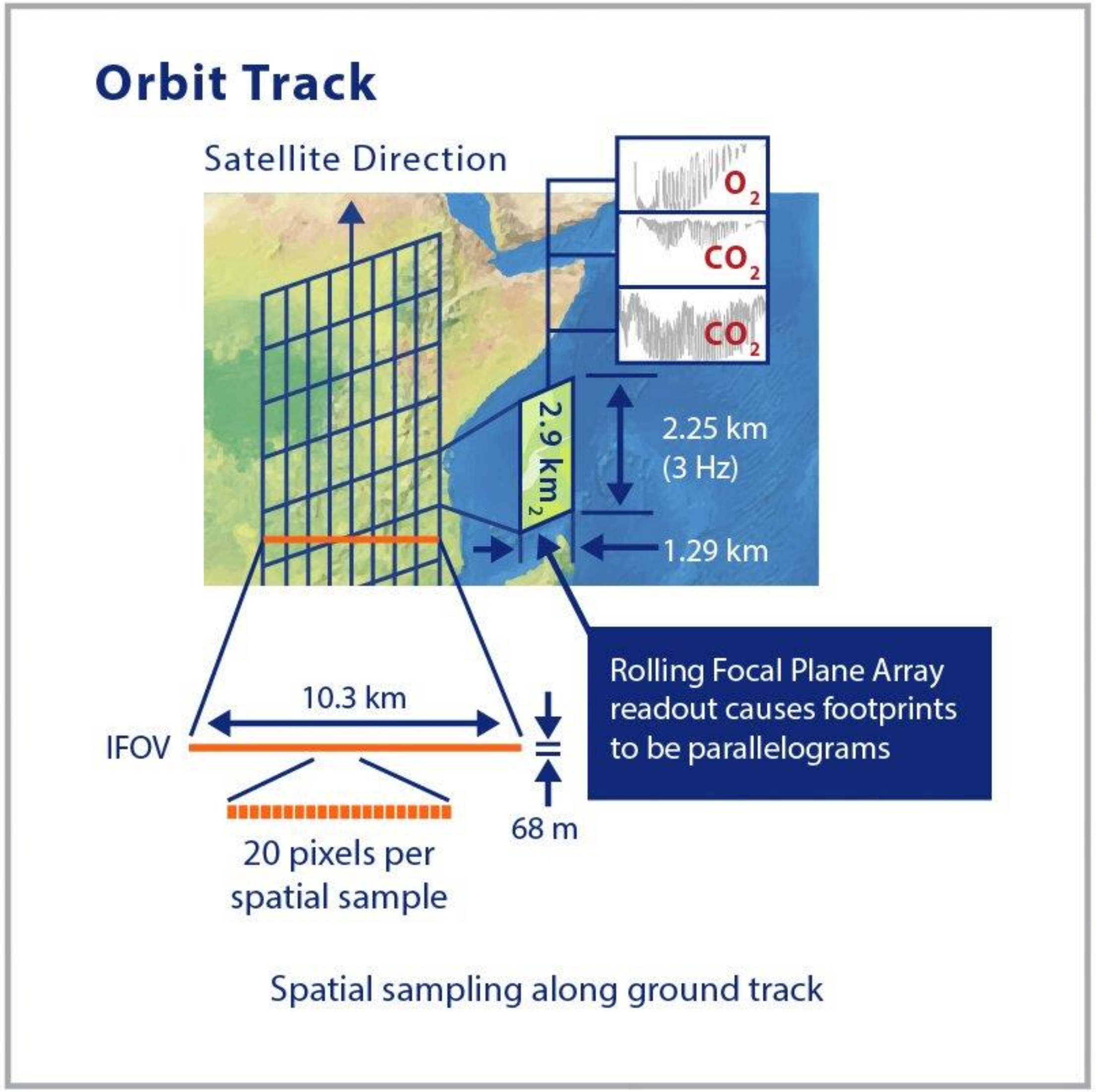
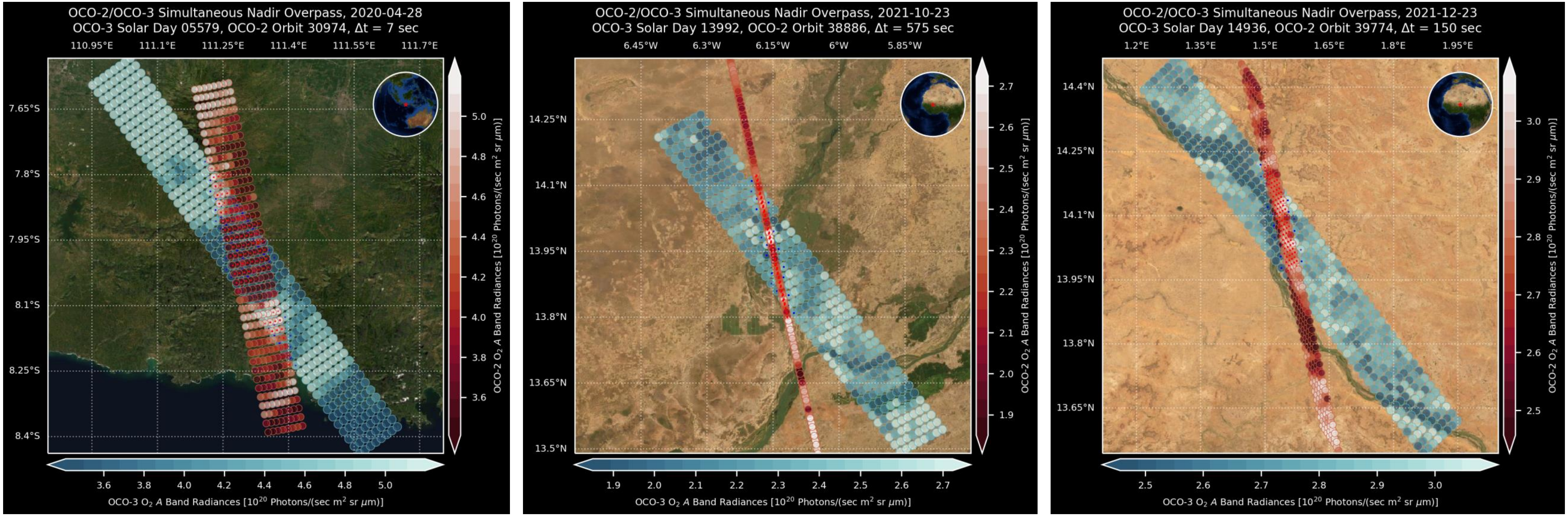



The OCO-2 instrument acquires a large number of densely-spaced samples, or “footprints”.

There are 8 footprints across the swath.

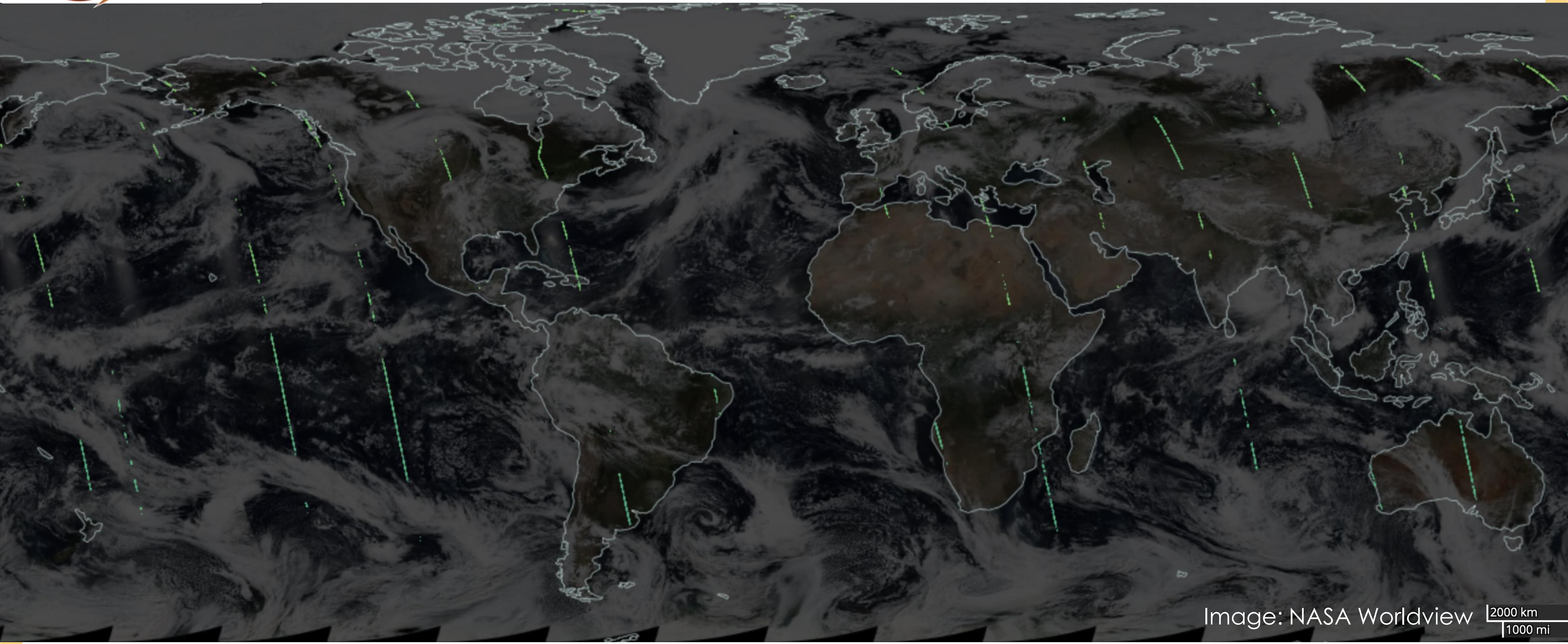
Each footprint covers an area of about 3 km$^2$ when the instrument is looking straight down (nadir) along the spacecraft's ground track.

# What are the characteristics of the measurement?



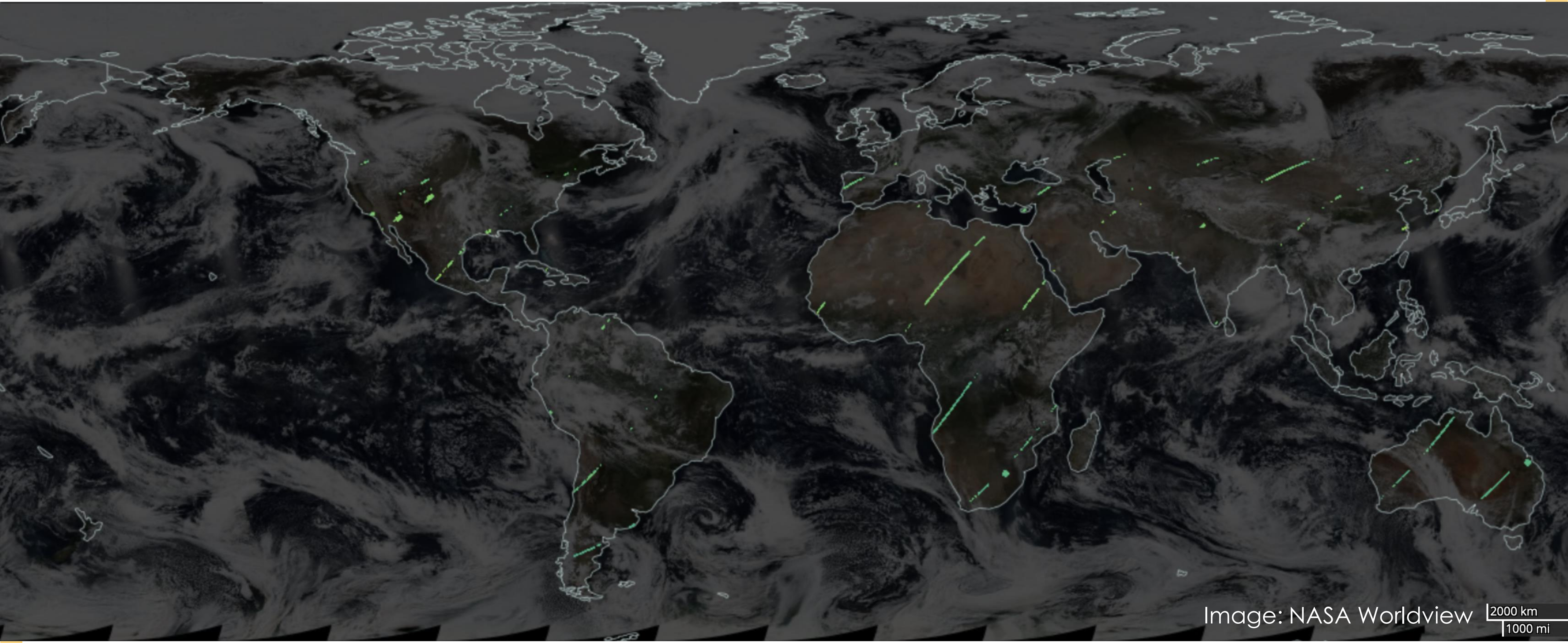

The OCO-2 swath changes in width throughout the orbit as the spacecraft rotates along the orbit path. The OCO-3 swath width is more uniform. These examples show A-band radiances for OCO-2 and OCO-3 simultaneous nadir overpasses (within 7 seconds). Figures: Thomas Kurosu

# What are the characteristics of the measurement?



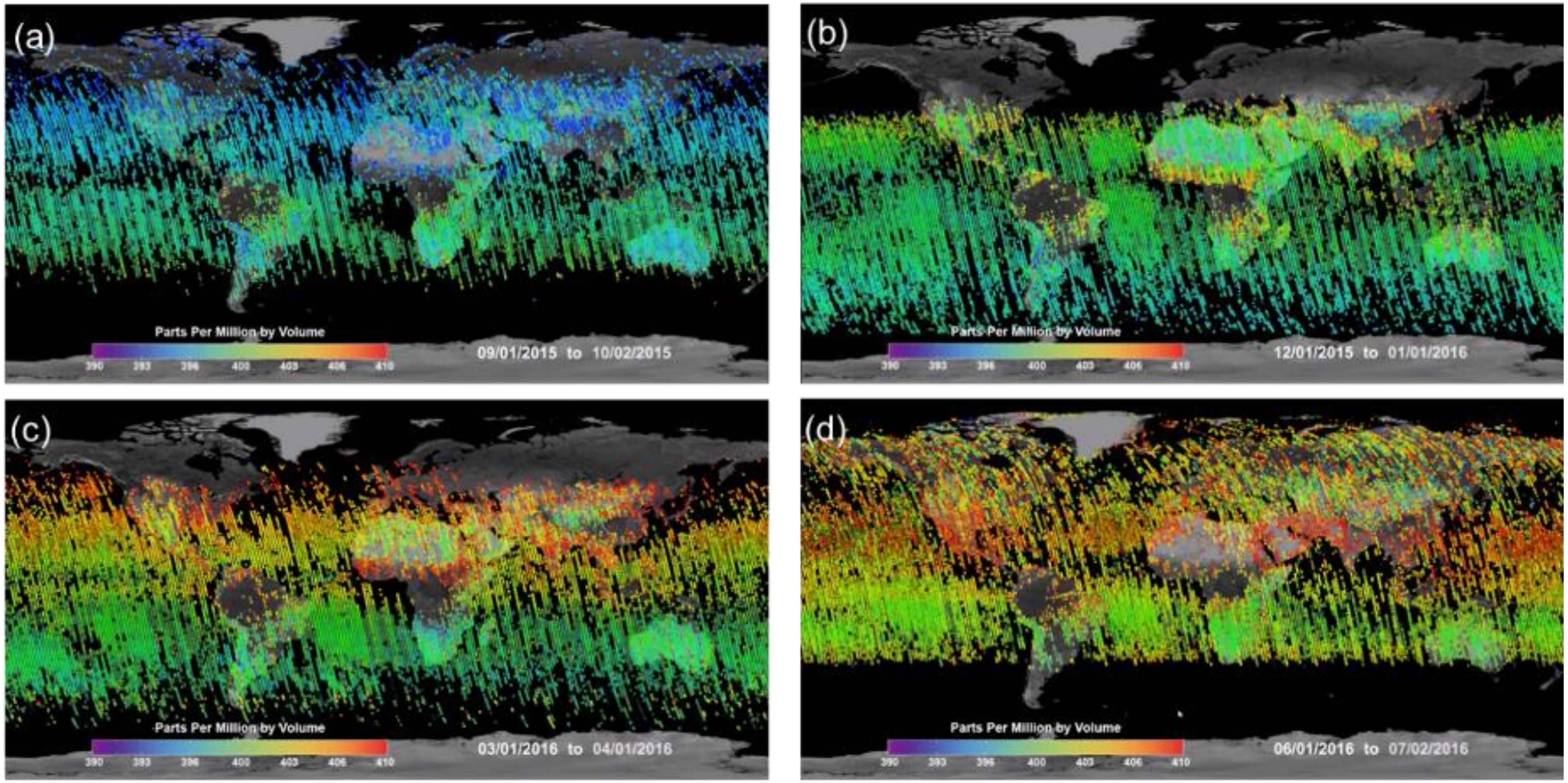

OCO-2 orbits the Earth 14.5 times a day, gathering data over sunlit, cloud-free regions.
This image shows the locations of successful $XCO_2$ measurements for a single day (24th May 2021).

# What are the characteristics of the measurement?




OCO-3 also samples cloud-free, sunlit regions, with orbital sampling that follows the track of the ISS.
This image shows the locations of successful $XCO_2$ measurements for a single day (24$^{th}$ May 2021).

# What are the limitations of the measurement?




Maps of $XCO_2$ along OCO-2 orbit tracks for (a) September 2015, (b) December 2015, (c) March 2016, and (d) June 2016, illustrating the $XCO_2$ variations and latitude coverage as a function of season. The footprint size is exaggerated for visibility. The color bars all extend from 390 to 410 ppm. Persistent clouds and the availability of sunlight limits the latitude coverage in the winter hemisphere.

The presence of clouds and optically-thick aerosols can present challenges in measuring $XCO_2$ in the complete atmospheric column.

Uneven terrain such as mountains can also impact the quality of the $XCO_2$ estimate.

High solar zenith angles also make it more challenging to obtain a good quality $XCO_2$ measurement.

# How do you interpret the measurement?

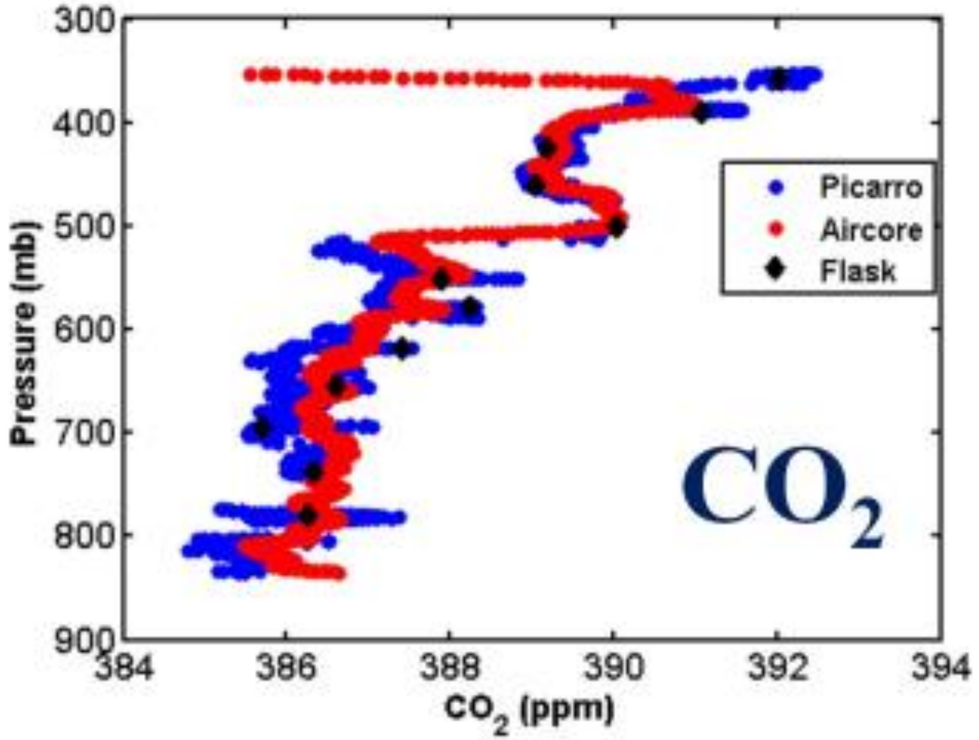


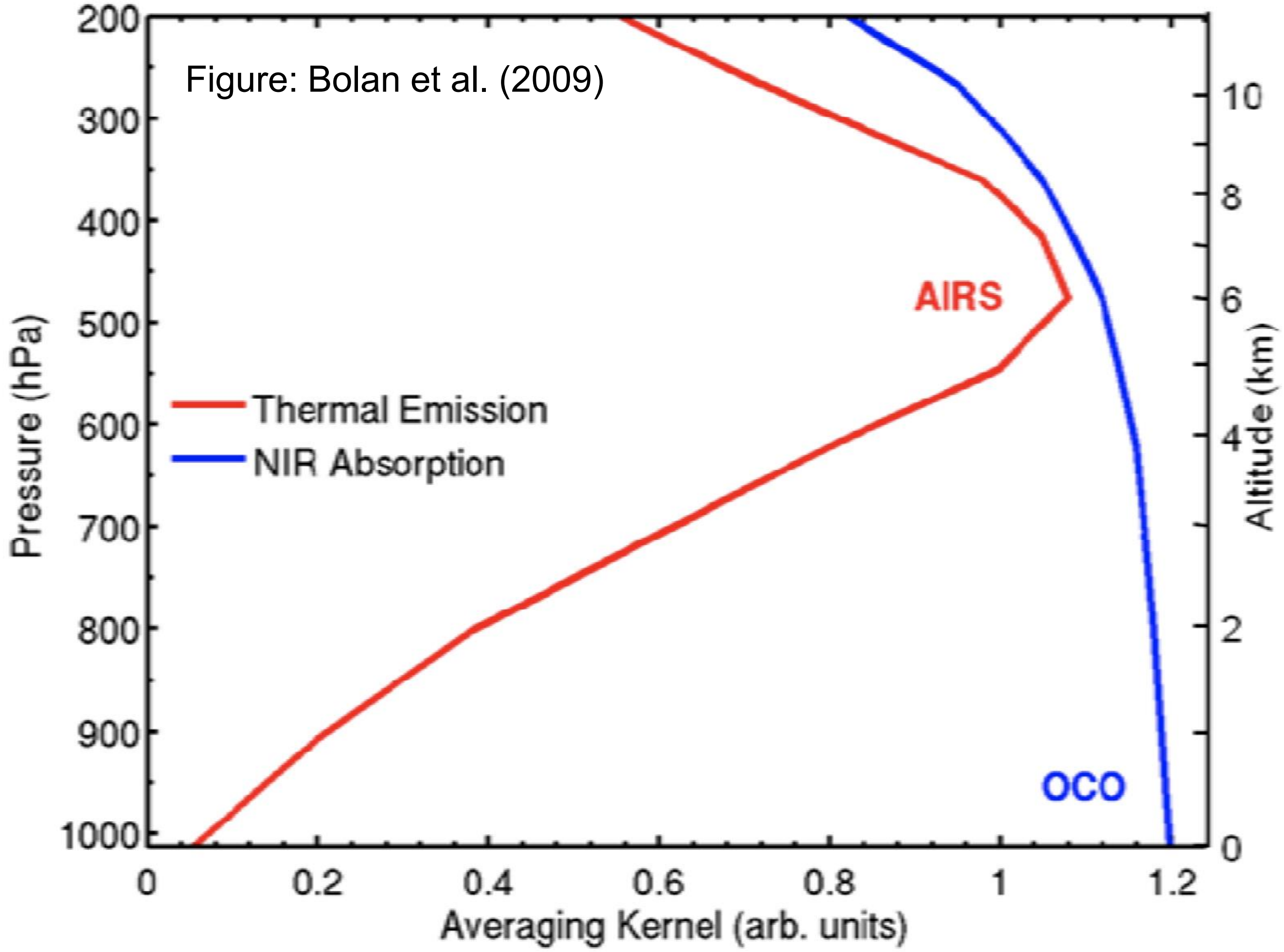

Image: https://gml.noaa.gov/ccgg/aircore/

This figure shows an example of a $CO_2$ profile measured by three different in situ measurement techniques from airborne/balloon platforms. The OCO-2 and OCO-3 satellite products provide an estimate of the total column average.

The $XCO_2$ in the OCO-2/OCO-3 data product is the column average volume mixing ratio. This is a measure of the amount of carbon dioxide in the atmospheric column as a whole.

This is **not directly comparable** to a measurement at a single point, such as an in situ measurement at a surface site, or at a single point in the atmosphere.

# How do you interpret the measurement?



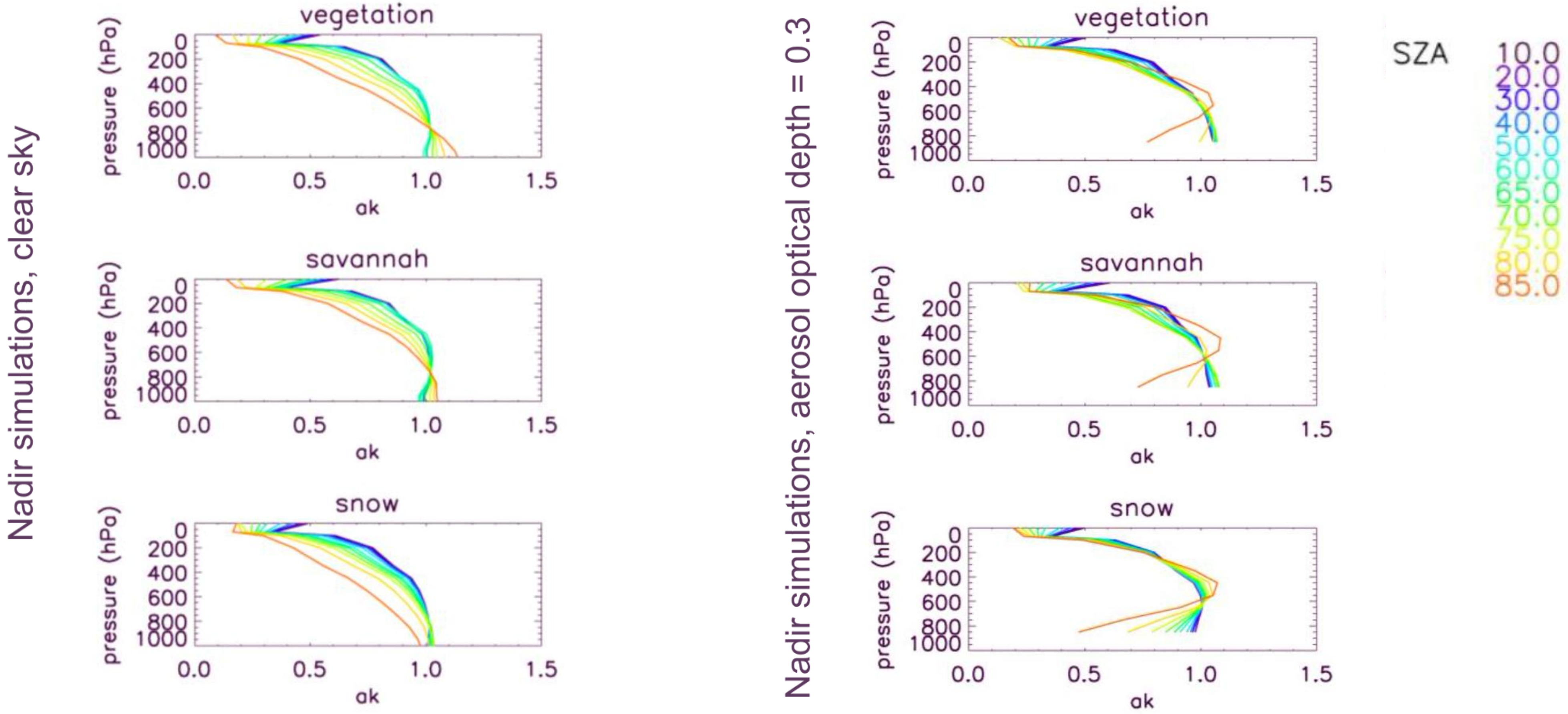

Spectrally resolved radiances in the near-infrared (NIR) $CO_2$ bands, such as those from the OCO missions, are sensitive to $CO_2$ throughout the atmospheric column and can be used in the estimation of surface sources and sinks.

Spectrally resolved radiances in the thermal infrared $CO_2$ bands are primarily sensitive to $CO_2$ in the mid- and upper-troposphere.

The figure shows example column averaging kernels for AIRS and OCO-2, which provide an estimate of the sensitivity of the remotely-sensed measurement to the true atmospheric profile. Column averaging kernels are provided as part of the data product.

# How do you interpret the measurement?

The vertical sensitivity of the remotely-sensed $XCO_2$ measurement is scene-dependent. Examples below show averaging kernels for simulations over different surfaces, solar zenith angles, and aerosol conditions.

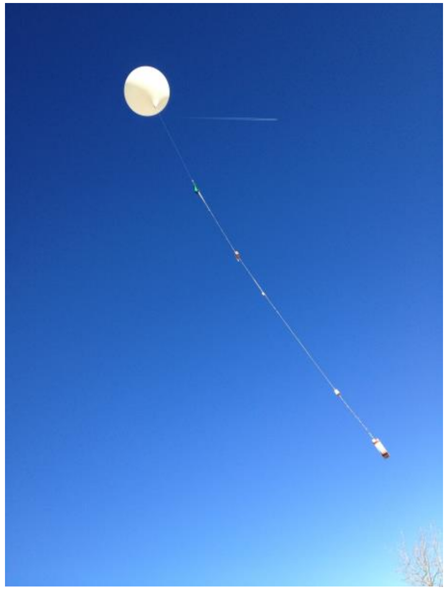



Figures: Boesch et al., 2011

# How has the data been validated?

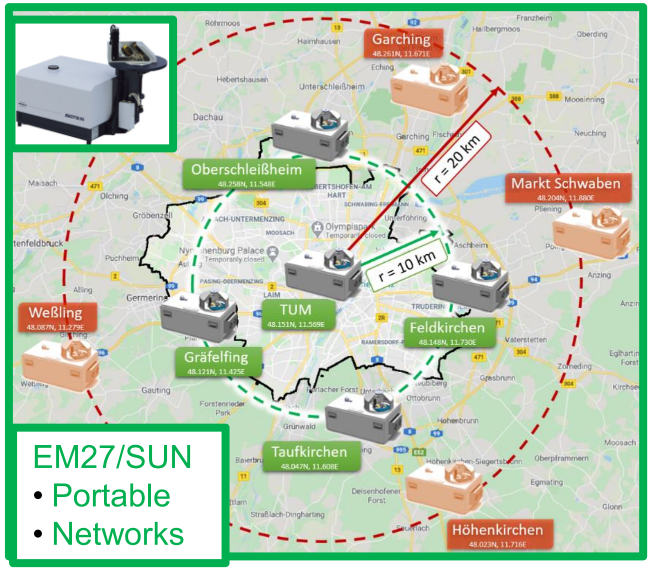
Image Credit: TCCON

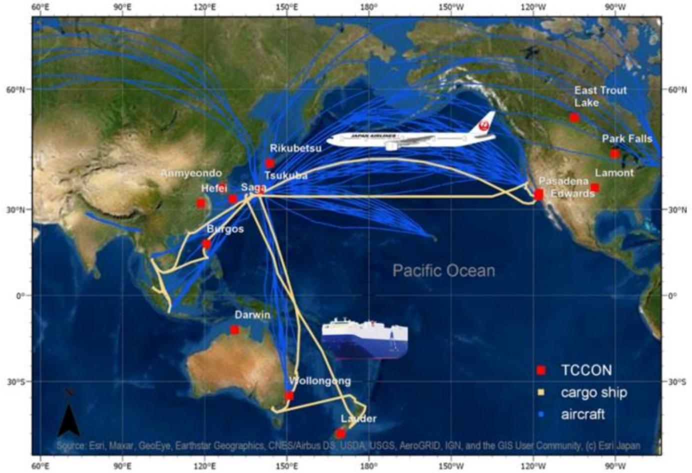
Image Credit: TCCON



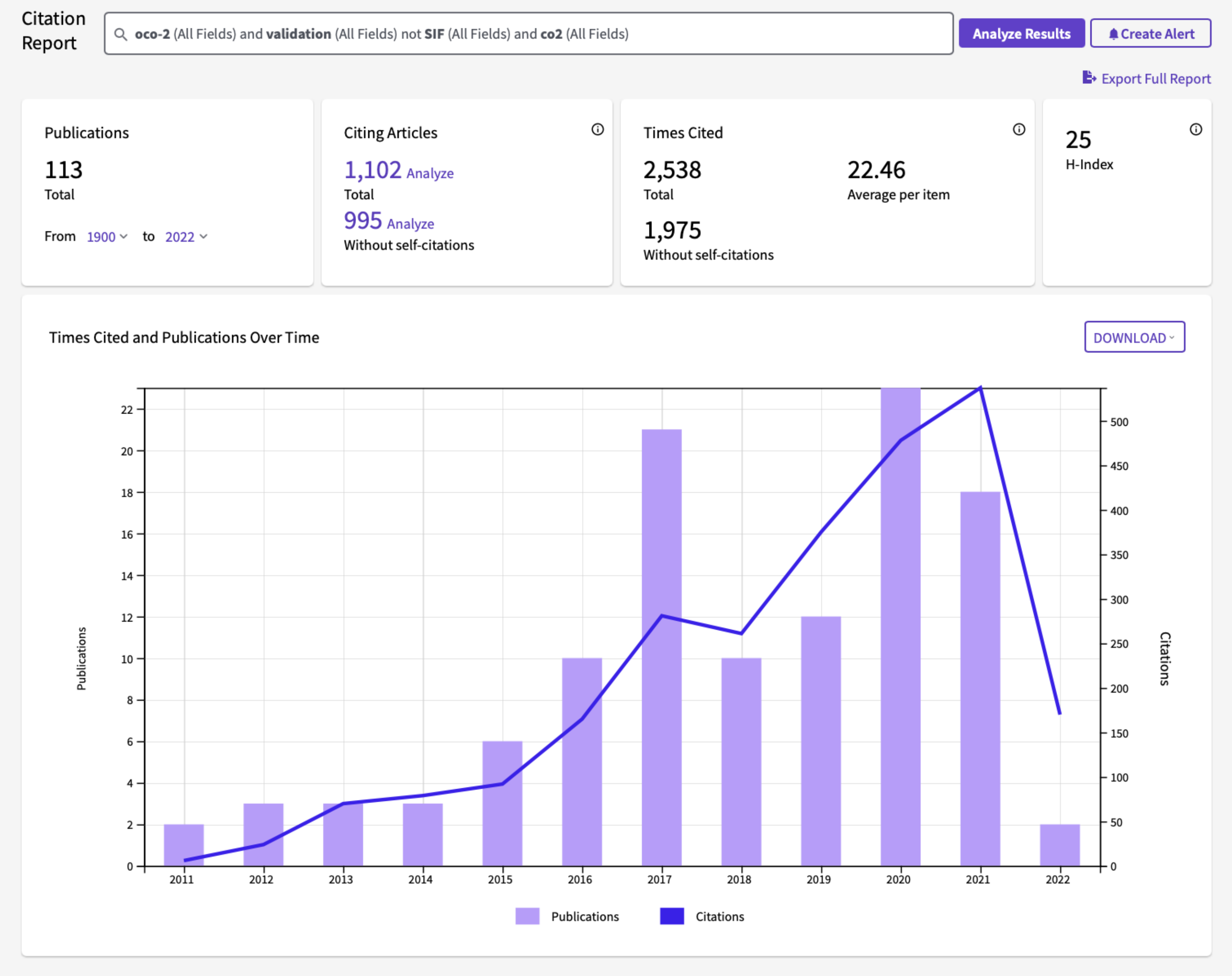
https://gml.noaa.gov/ccgg/aircore/


https://gml.noaa.gov/ccgg/aircraft/



# How has the data been validated?




From Web of Science, 20220502

TCCON

total carbon column observing network

# How has the data been validated?


The Total Carbon Column Observing Network (**TCCON**) is a network of ground-based Fourier Transform Spectrometers recording direct solar spectra in the near-infrared spectral region. From these spectra, accurate and precise column-averaged abundance of **$CO_2$** (as well as a range of other gases) are retrieved. TCCON provides an essential validation resource for OCO-2, OCO-3, the Greenhouse Gases Observing Satellites GOSAT and GOSAT-2, the Sentinel 5P instrument TROPOMI, TanSat, and other missions.
For the latest TCCON information, please visit the TCCON Wiki at https://tccon-wiki.caltech.edu.

# Are there quality flags?

**Yes!**

"When using the data contained in the Lite files, filtering can be done with xco2_quality_flag ("0" is good). This filter has been derived by comparing retrieved *XCO2* for a subset of the data to the various truth proxies and identifying thresholds for different variables that correlate with poor data quality. It applies quality filters based on a number of retrieved or auxiliary variables that correlate with excessive *XCO2* scatter or bias."

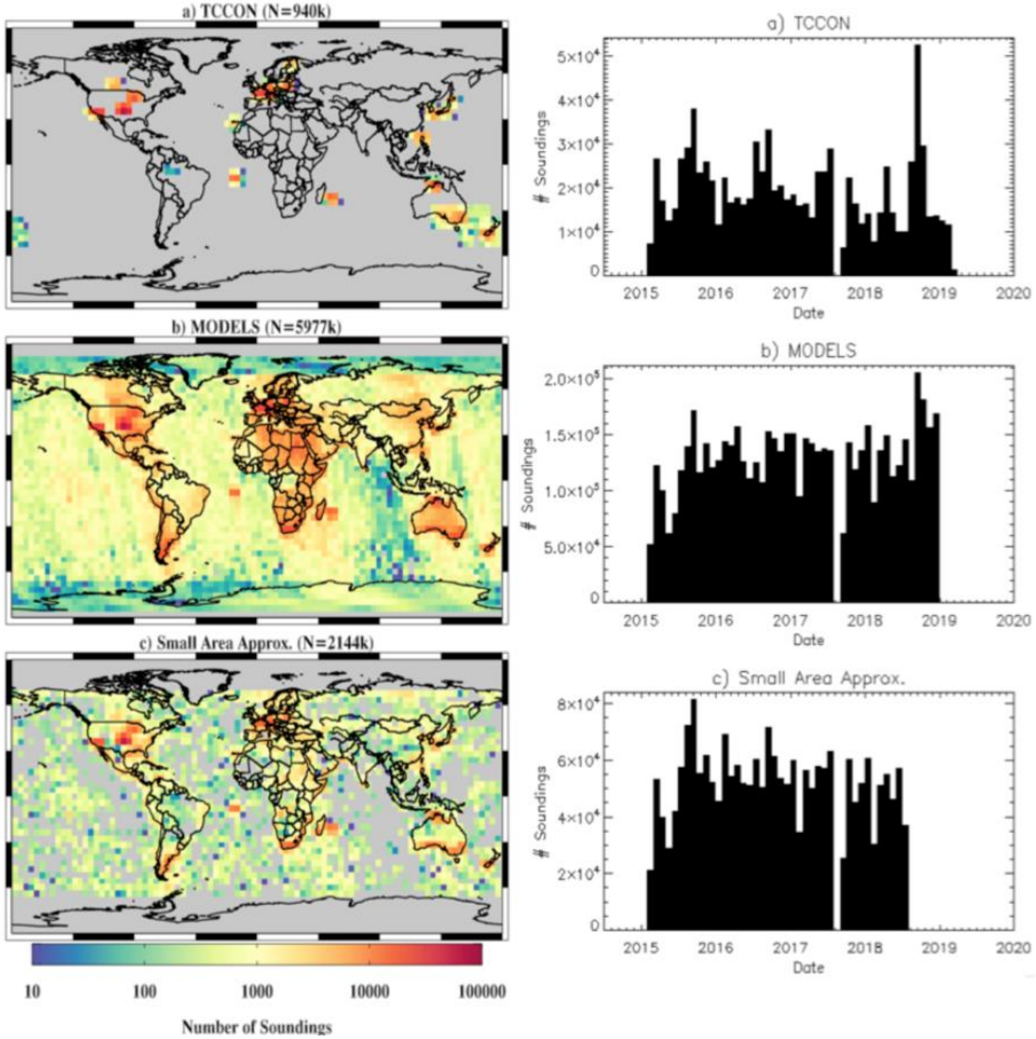
- *OCO-2 Level 2 Data User Guide*

# Filtering and Bias Correction of the Satellite $XCO_2$ Measurements

In order to develop both the screening criteria and bias correction parameters for OCO-2 and OCO-3, a set of "truth proxies" are defined:

1. **TCCON $XCO_2$**
2. The "Small Area Analysis", in which *XCO2* is assumed to be constant for OCO-2 observations taken over distances <~ 100 km within the same orbit.
3. A multi-model mean of models that have all assimilated in-situ data, and only using soundings for which all the model values agree with each other to within a specified tolerance.

The process for using the truth proxies to develop screening and bias correction criteria and the full screening/bias correction process is available in O'Dell et al., (2018) with specifics for the latest version provided in the Level 2 Data User Guide.




Sounding density maps and time series of soundings for datasets used in guiding the OCO-2 v10 filtering and bias correction (from Data User Guide)

# Are there any biases with the data?

## The Good News:

**OCO-2 and OCO-3 Lite products that are available at the GES DISC have already been filtered and bias-corrected.**

The process for filtering and bias correction are described in the OCO-2/OCO-3 Level 2 Data User Guide.

Step 1: Correction of footprint-dependence

Step 2: Use regional analysis to identify terms within the OCO-2 records that predict bias or unexplained variance in the $XCO_2$

Step 3: Global bias correction against TCCON reference


Orbiting Carbon Observatory-2 & 3
(OCO-2 & OCO-3)

Data Product User's Guide,

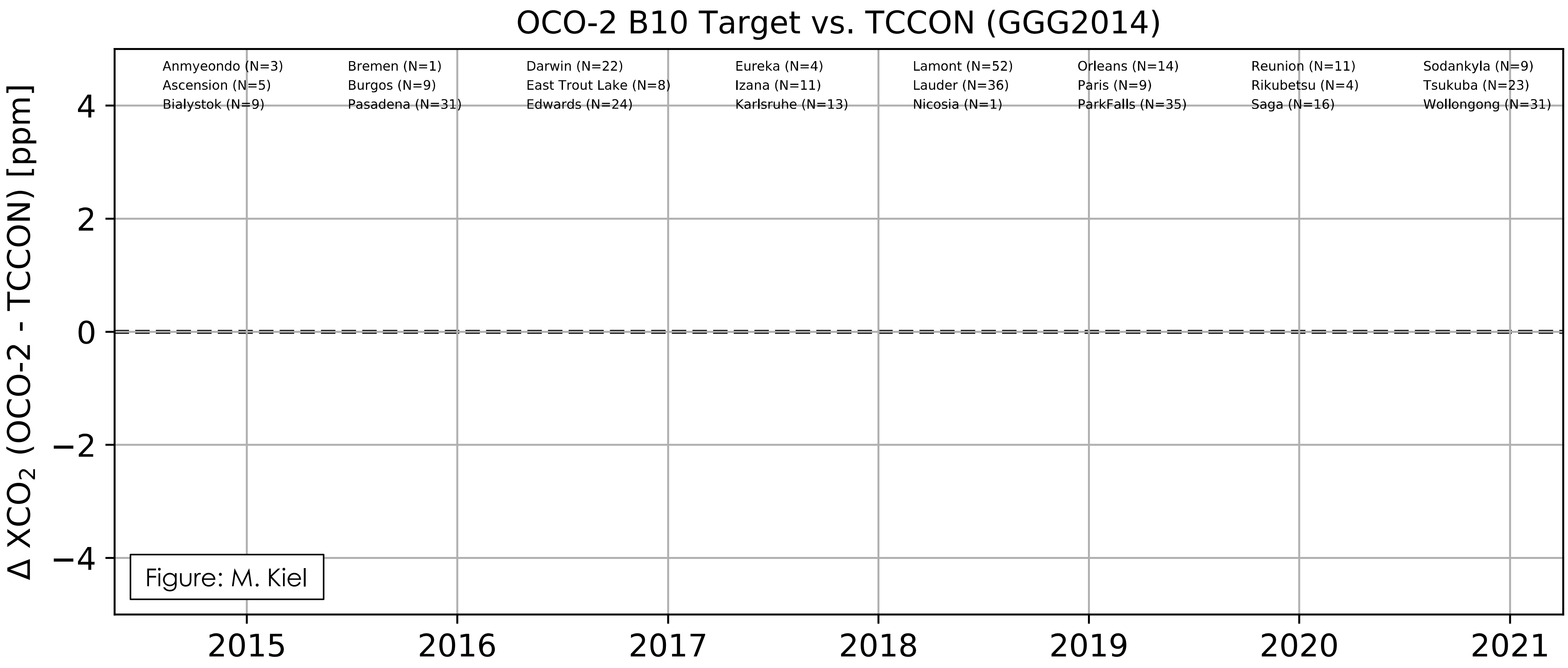
## Caveat:

There are very few in situ or remote sensing measurements that can be used for validation in the regions where the satellite $XCO_2$ measurements show the largest differences from current global models.

# Are there any biases with the data?

For OCO-2: There is no evidence of any significant time dependence in the OCO-2 v10 $XCO_2$ relative to TCCON.

For OCO-3: The latest version of the data (v10.4) includes a correction to account for time-dependent L1B calibration issues.



# Can you combine OCO-2 and OCO-3 data?

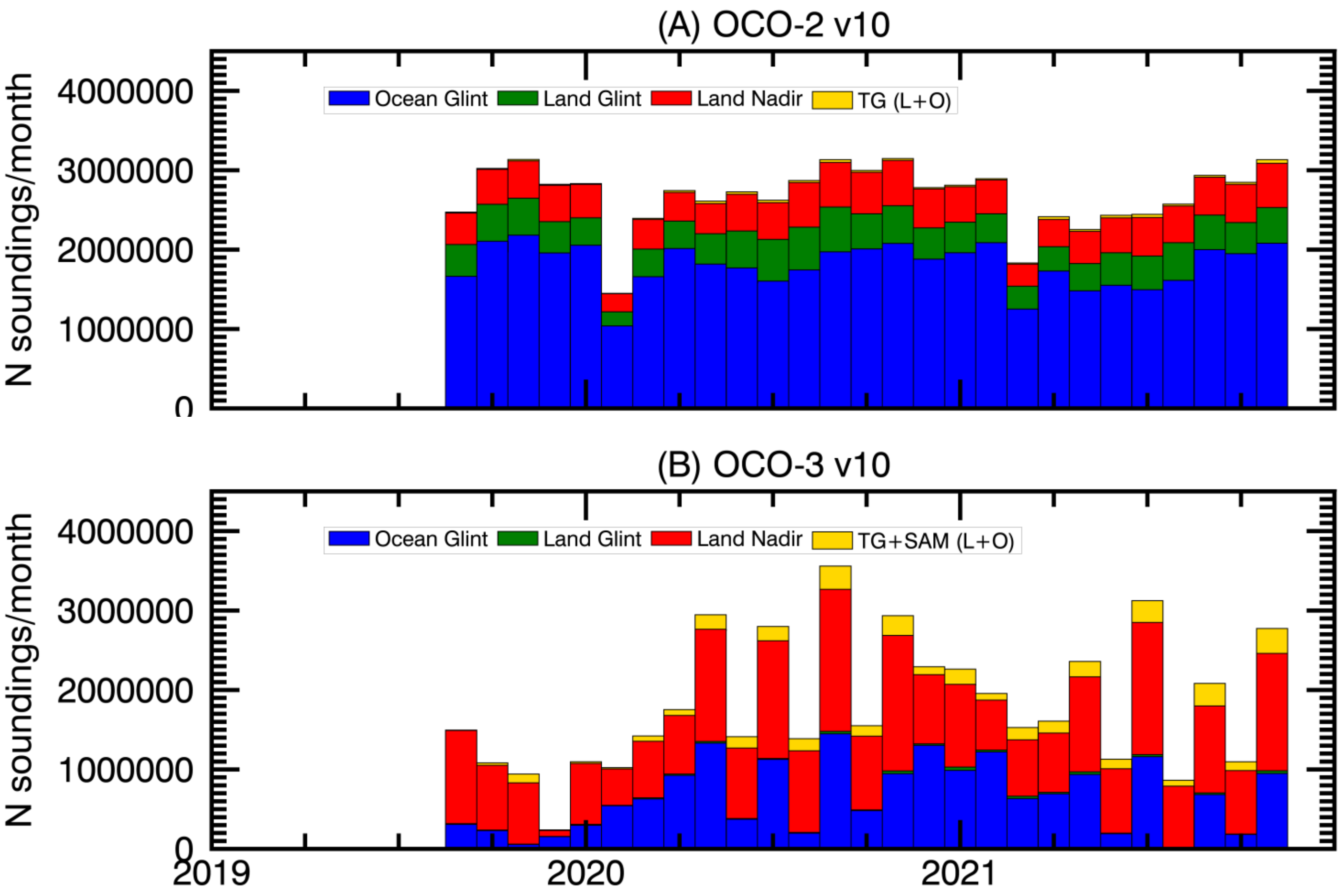
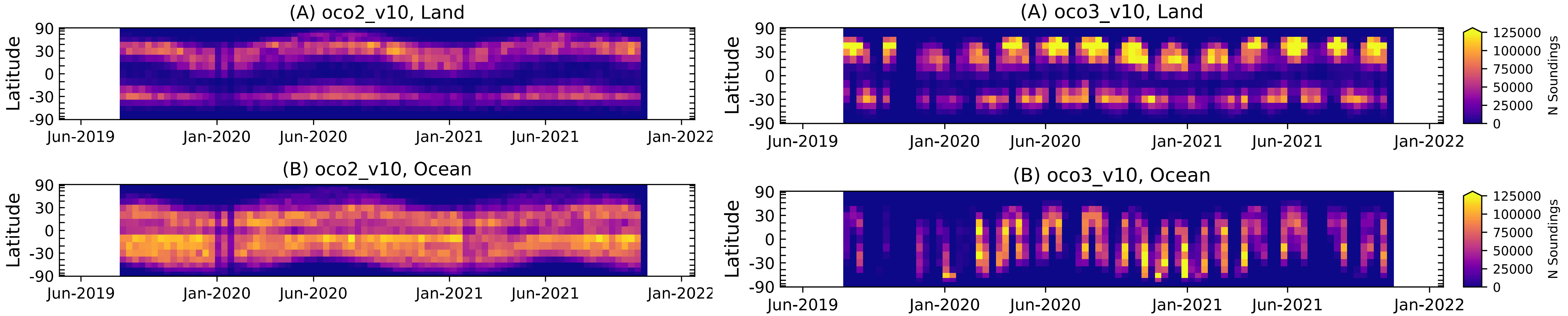



Figure Credit: Tommy Taylor, CSU

Yes, you can! The two datasets have different, but complementary, coverage. The figures above show numbers of soundings for the duration of the OCO-3 mission so far. OCO-2, launched in 2014, provides a longer time record than OCO-3, launched in 2019. OCO-2 also provides more extensive latitudinal coverage. OCO-2 observations are more numerous over oceans, while OCO-3 provides more dense coverage over land. In the regions where both datasets overlap, there will be science and applications that can be explored.

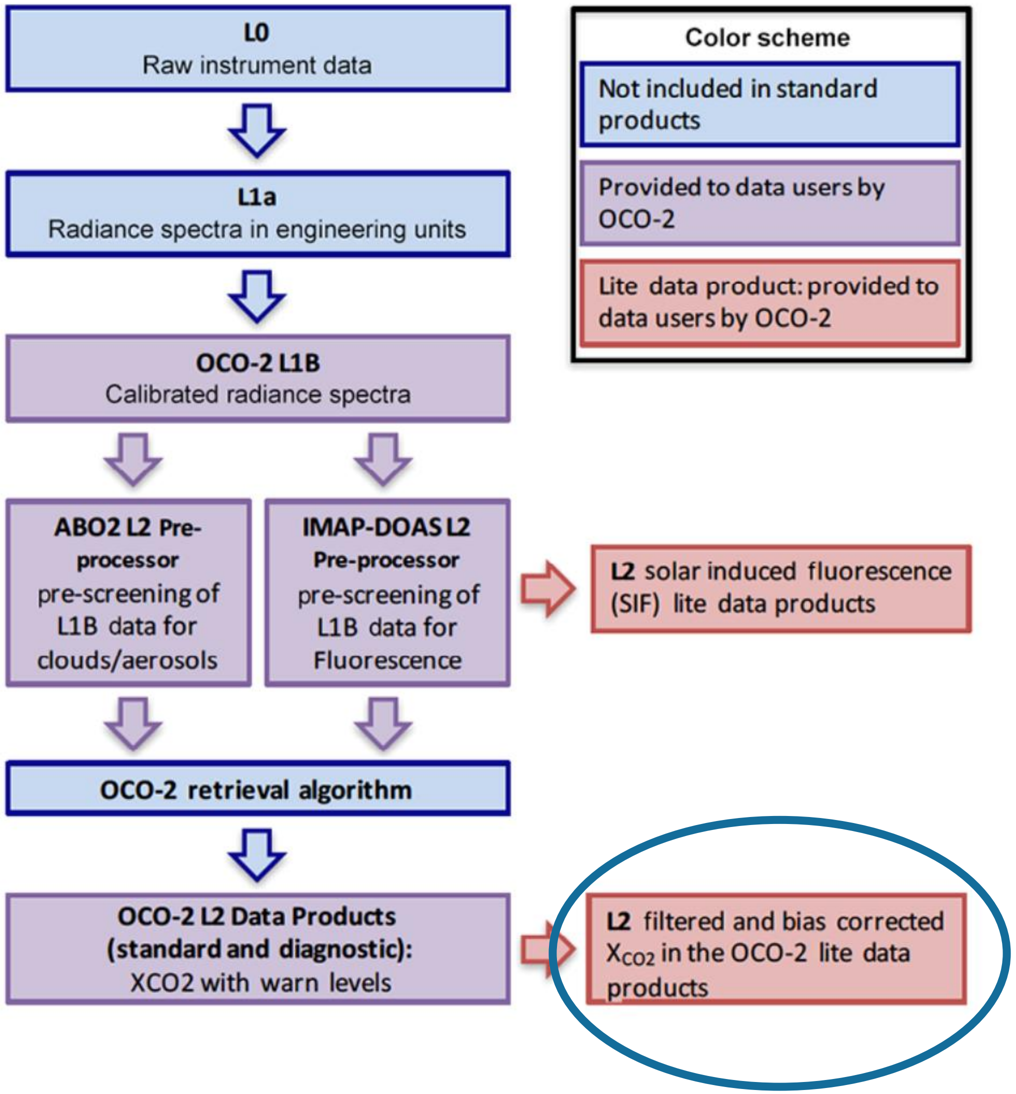
# Can you combine OCO-2 and OCO-3 data?

Figure Credit:
Tommy Taylor, CSU




Yes, you can! The two datasets have different but complementary coverage. The figures above show another way of looking at the density of the OCO-2 and OCO-3 coverage side by side.

# Data Products



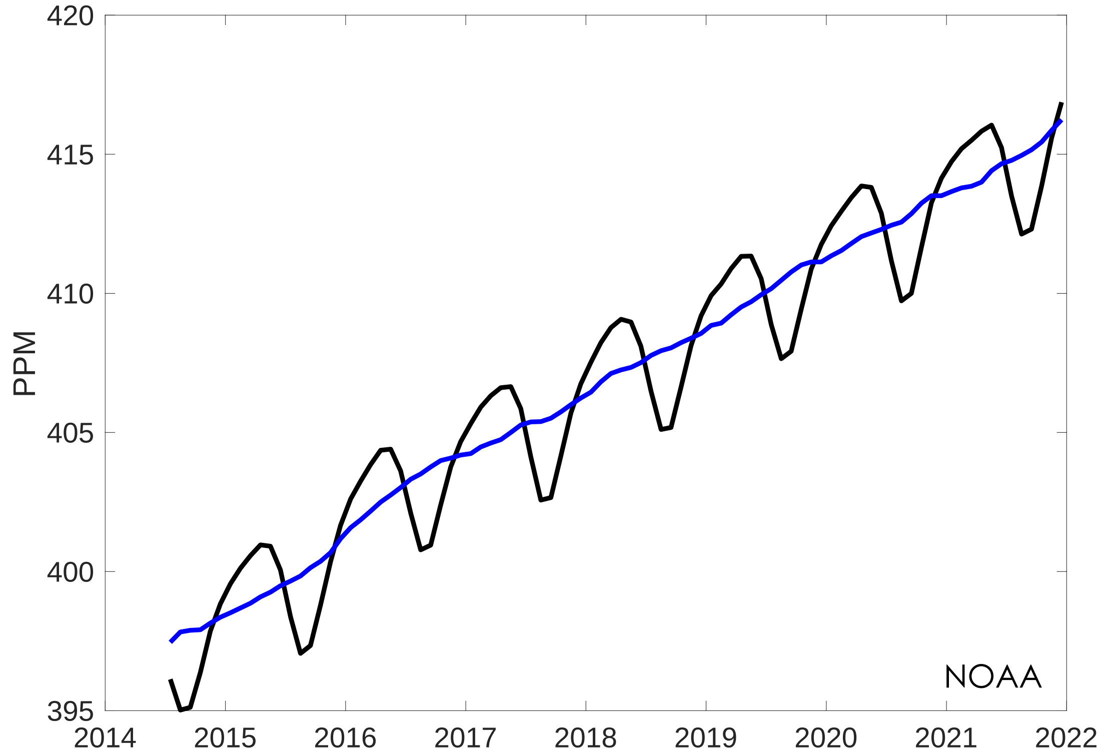

This presentation has focused on Level 2 products (native sampling of the instrument).

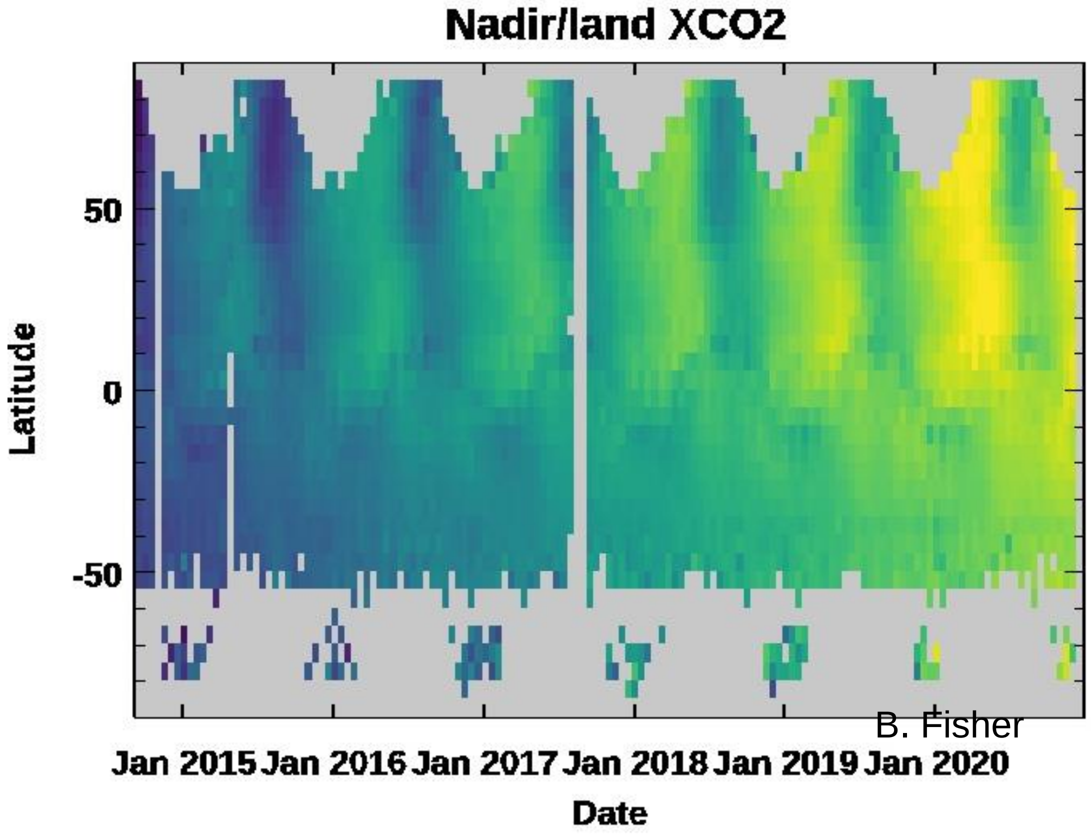
**Higher level products not covered here:**

- Level 3: Gridded in latitude, longitude, time
- Level 4: CO2 fluxes

More info in Part 3 on May 31st!

# The measurements continue…




- Since the launch of OCO-2, global $CO_2$ increased from 397.5 ppm to 418.7 ppm as of March 13th, 2022; increasing ~20ppm, about ~5% relative to the $CO_2$ level of July 2014.
- The OCO-2 and OCO-3 measurements continue to provide new insights into sources and sinks of $CO_2$.

# Contacts

- Trainer:
  - Vivienne Payne: vivienne.h.payne@jpl.nasa.gov
- Training Webpage:
  - https://appliedsciences.nasa.gov/join-mission/training/english/arset-measuring-atmospheric-carbon-dioxide-space-support-climate
- ARSET Website:

  https://appliedsciences.nasa.gov/arset
- Twitter: @NASAARSET

# Webinar Agenda

**Part 1: An Introduction to $XCO_2$ with OCO-2 and OCO-3**

- EDT (UTC-4:00)
- Tuesday, May 24, 2022
- Trainers: Vivienne Payne (JPL)
- Background of the XCO2 measurement and how it is measured
- Description of the OCO-2/OCO-3 sensors
- Characteristics, limitations and validation of the measurement
- Q&A

**Part 2: A Demonstration on how to Access and Visualize OCO-2/OCO-3 Data**

- EDT (UTC-4:00)
- Thursday, May 26, 2022
- Trainers: Karen Yuen (JPL)
- Use of Jupyter Notebook to access, search, filter and display $XCO_2$ data
- Q&A

**Part 3: $XCO_2$ in Support of Global and Regional Climate-Related Studies**

- EDT (UTC-4:00)
- Tuesday, May 31, 2022
- Trainers: Abhishek Chatterjee (JPL)
- Global and regional carbon flux estimation, and carbon cycle response to climate variability and changes in anthropogenic emissions
- Q&A

**Part 4: $XCO_2$ in Support of Local and Regional Climate-Related Studies**

- EDT (UTC-4:00)
- Thursday, June 2, 2022
- Trainers: John Lin (University of Utah)
- Climate impacts from localized emissions, air quality, and urban density
- Q&A

# Thank You!