Status of OCO-2 and OCO-3 and Lessons Learned

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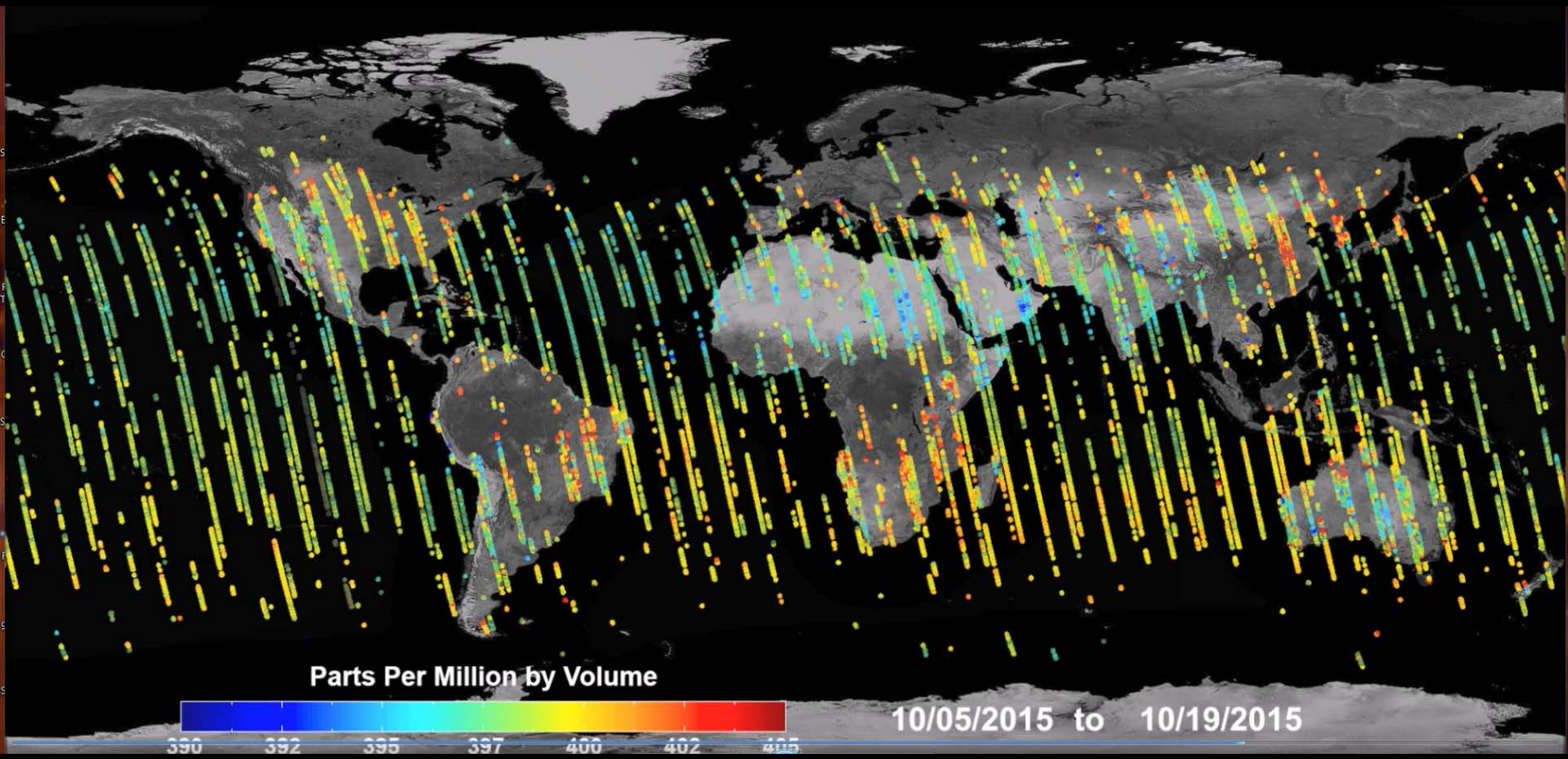
Agenda

- OCO-2 Spacecraft and Instrument status
  - Slight misalignment of OCO-2 and CALIPSO ground tracks
  - August 10 Instrument Safeing Event
  - On-Board Calibrator Alignment Issue
- Recent OCO-2 Science Highlights
  - Validation, El Niño, African fires, Anthropogenic emissions, total column water vapor
- OCO-3 Status

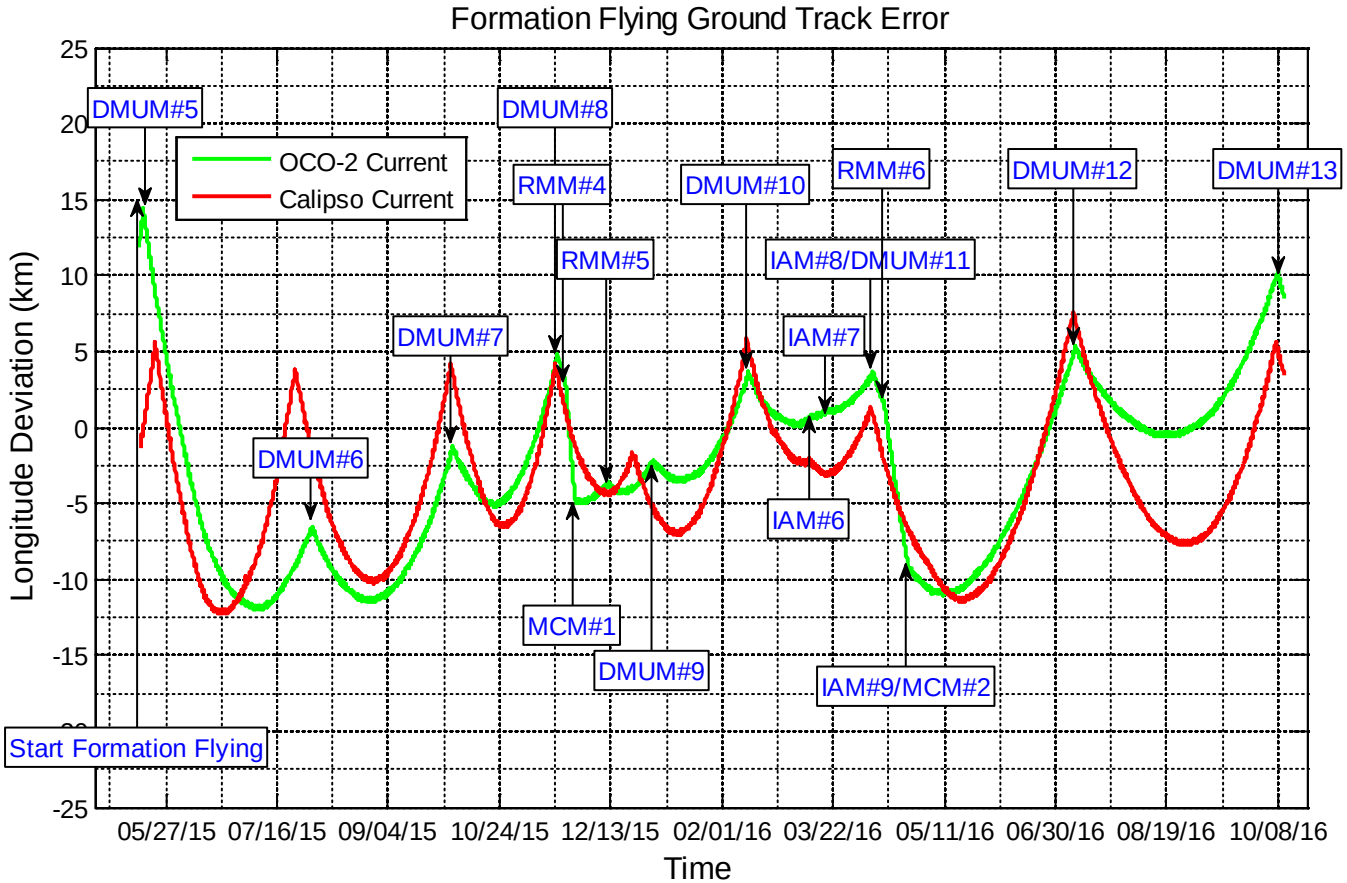
OCO-2 Spacecraft and Instrument Status



Observatory Status Summary

- The Project successfully completed the Prime Mission on 16 October 2016, meeting all top-Level Science Requirements and Objectives
- As we pass this major milestone, the Instrument and Spacecraft remain healthy, with no significant, irreversible degradation in performance
- The team continues to address occasional anomalies, including
  - Brief departure from tight formation flying with CALIPSO
  - August 10 instrument safeing event and associated On-Board Calibrator alignment anomaly (described below)
  - Other ongoing issues (e.g. bad pixels, ABO2 Focal plane array icing etc.)
- The Project is actively preparing for an extended mission
  - End of Prime Mission Review scheduled for 27 October
  - Preparations for the FY17 Senior Review, including the preparation and JPL review of a complete draft Senior Review Package (Due 7 November)

OCO-2 and CALIPSO formation Flying



After flying in a close formation for more than a year, the OCO-2 (green) and CALIPSO (red) ground tracks diverged in August-September 2016 due to an imperfect drag make-up maneuver (DMU).

August 10 Instrument Safeing Event

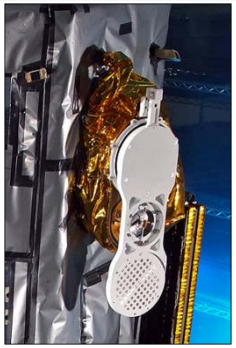
- At 4:28 UTC on Wednesday 10 August, just after OCO-2 few over Rio de Janeiro, the instrument performed a spontaneous reset and was shut down by the spacecraft fault detection system (Orbit 11212)
- After completing an anomaly investigation, the instrument was successfully powered on at 16:39 UTC on Sunday 14 August, and commanded to perform a standard 28 C decontamination cycle
- The instrument optical bench and FPAs were back at their operating temperatures and collecting science data on Sunday, 21 August (Orbit 11376)
- Level 2 science data production delayed due to an issue with the on-board calibrator, precluding routine data delivery

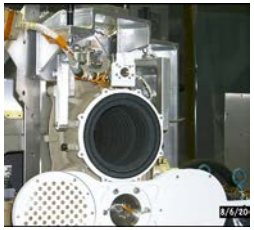
Baffle Calibrator Alignment Issue

- Observations

  Solar and lamp calibration observations collected following the August 2016 decon changed slightly

  - Spatial distribution of solar and lamp illumination exhibited a larger footprint-to-footprint dependence
  - Spectral dependence of illumination had not changed
  - Subsequent analysis indicated that the rotation angle of calibrator paddle had changed by a few steps, changing its alignment with the optical axis of the spectrometers





- Actions Taken

  Nominal science data collection was continued

  Processing and delivery of products temporarily suspended

  First Re-initialization of Calibrator did not resolve offset

  Double Initialization of Calibrator returned to it nominal position

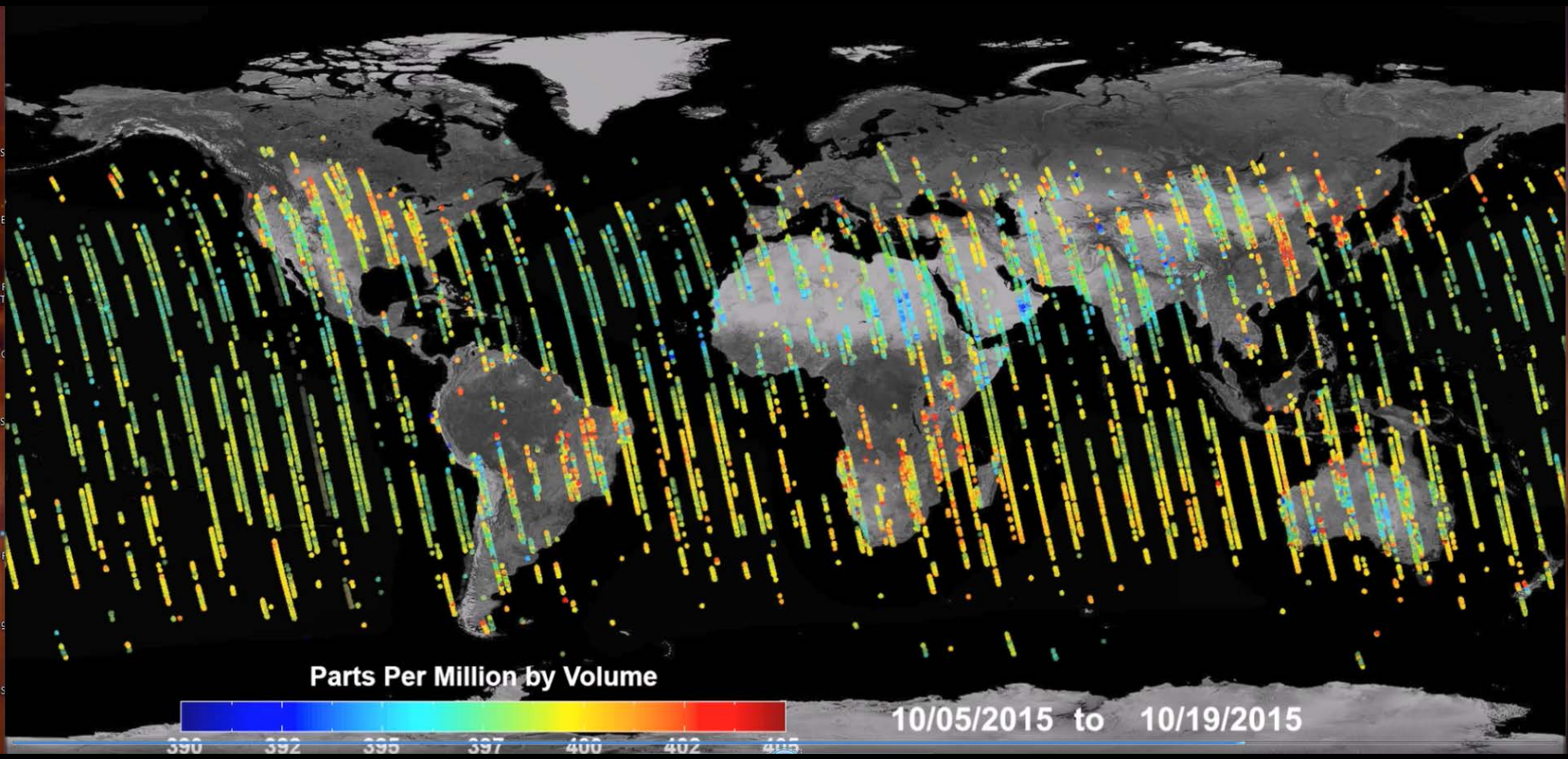
Data Production Resumed

Message added to the GES DISC

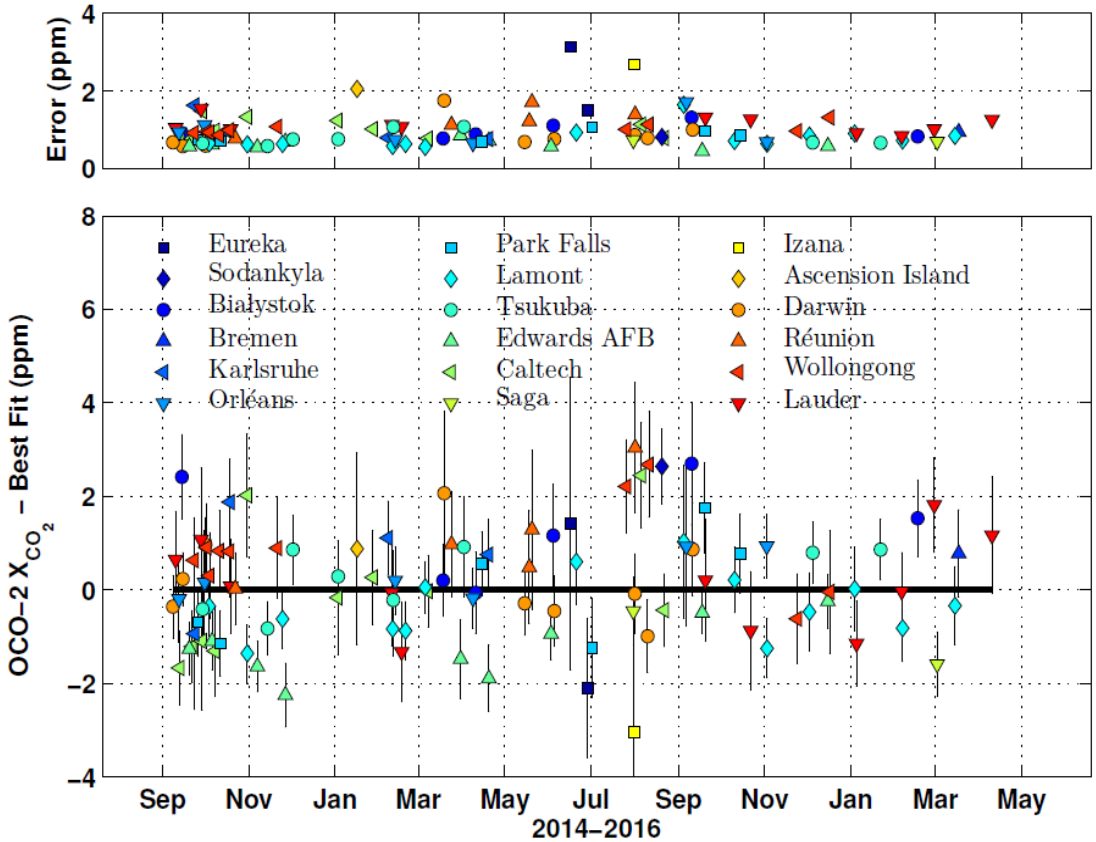
The OCO-2 instrument experienced an anomaly that interrupted routine operations at 4:28 UTC on August 10, 2016 (Orbit 11212). The cause of the anomaly was resolved, and the instrument recovery process was initiated on August 14 by conducting a standard, week-long decontamination cycle. The decontamination cycle was completed, and the instrument's optical bench and detectors were at their nominal operating temperatures on 21 August (Orbit 11376). An initial analysis of the data indicated that, while the instrument was working nominally for science observations, its on-board calibration mechanism had not initialized properly, and was out of alignment, precluding the routine production and delivery of calibrated science data products. The calibrator alignment issue was diagnosed and resolved on 20:34 UTC on September 15, 2016. After validating the quality of the data, the standard version 7 (v7) forward streams for L1B and L2 data were reinitiated on September 20, 2016.

There will be a permanent data gap from August 10 (Orbit 11212) to August 21 (Orbit 11376) because no science observations were collected during that period. The L1B and L2 science data collected between August 21 and September 20, while the calibrator was not aligned properly, will not be processed as part of the forwardv7 data stream, but will be processed as part of the August and September retrospective products (v7r). These data will be processed using a non-standard calibration product. Users should report any issues that they encounter with these data.

Recent OCO-2 Science Highlights



OCO-2/TCCON Time Series – Target Data (Wunch et al, ATMD, 2016)



Comparisons of X_{CO2} estimates from OCO-2 and TCCON (ground-based validation dataset,) show that, after bias correction, the OCO-2 X_{CO2} estimates, agree well globally with the TCCON for nadir, glint, and target observations

- median differences less than 0.5 ppm
- RMS differences typically below 1.5 ppm.

These statistics are shown for aggregated target measurements (thousands of soundings go into each point on the figure)

OCO-2 provides the most accurate X_{CO2} observations ever collected from space

El Niño Impacts in Pacific seen by OCO-2
(Chatterjee et al., in prep)

- **Problem**: Quantify the effects of El Niño on carbon flows from the Pacific Ocean
- **Results**: OCO-2 X_{CO2} estimates shows the impact of reduced ocean outgassing caused by warmer waters, and later increased atmospheric CO_2 caused by increased respiration and biomass burning in South America
- **Significance**: OCO-2 provides the first direct regional observations of the impacts of El Niño on the carbon cycle

Figure courtesy of Abhishek Chatterjee.

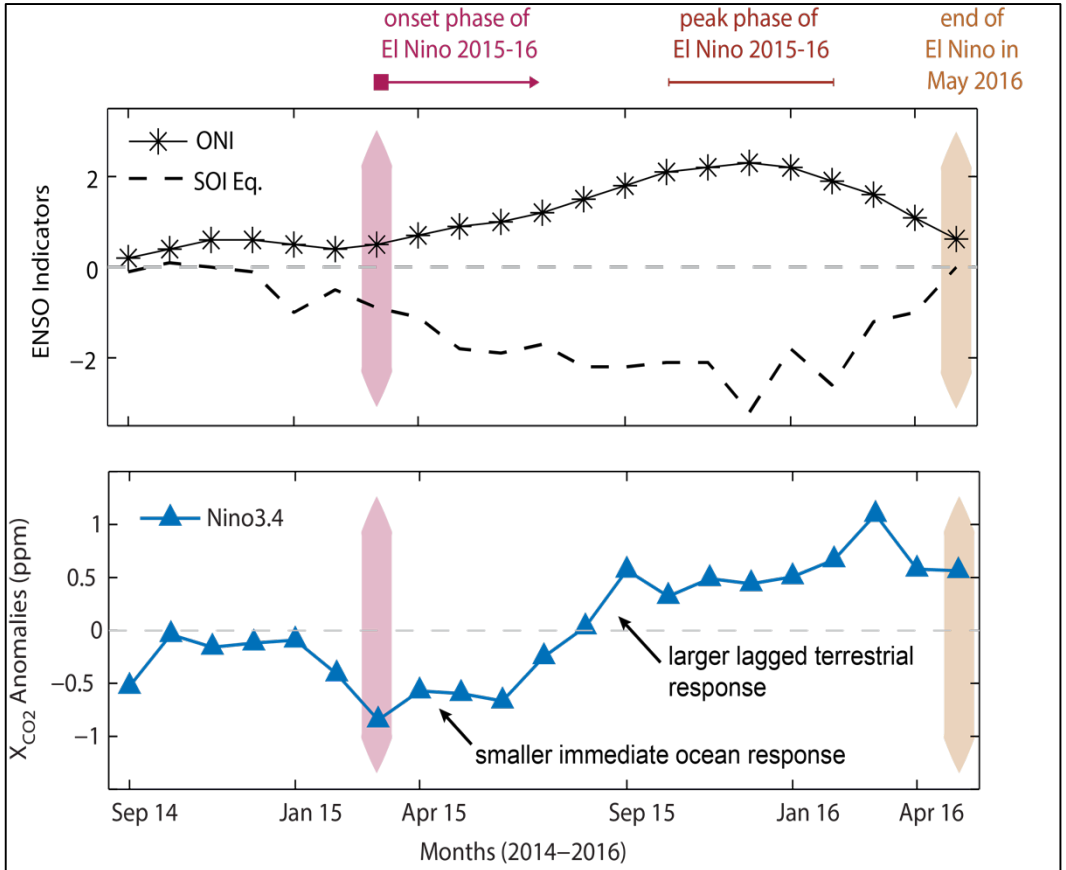
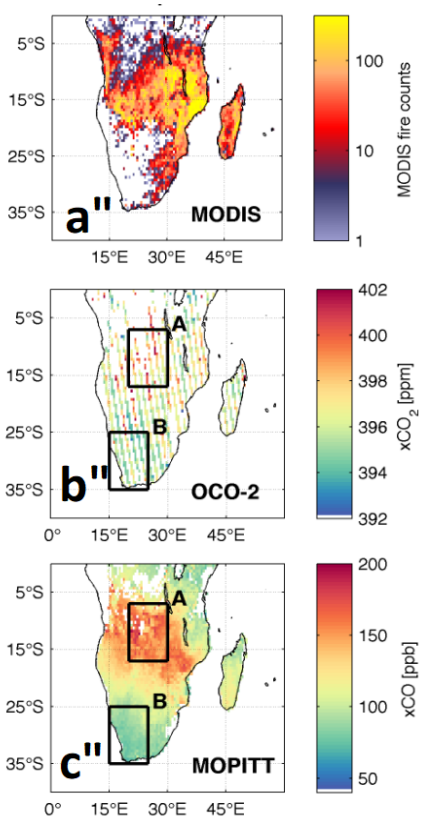
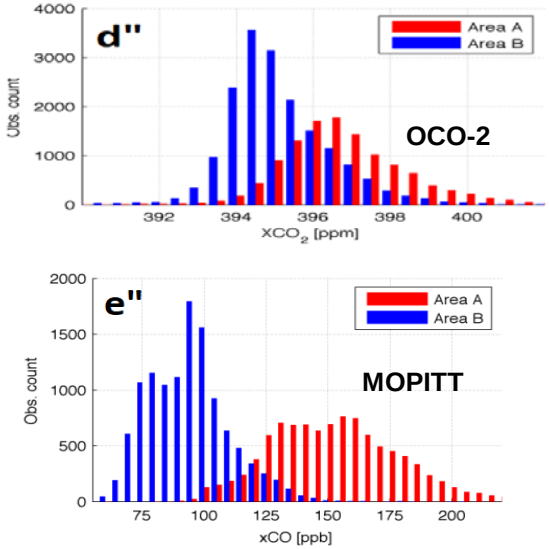


Figure 2: OCO-2 observes the response of the carbon cycle for an entire El Nino event

African fire emissions as seen by OCO-2
(Bloom et al., in prep)

- **Problem**: Do fires explain the elevated X_{CO2} that OCO-2 observes over Africa?
- **Results**: *September-October 2014 fire season:* OCO-2 L2 data revealed elevated CO_2 over southern Africa. CO (from MOPITT; dominated by fires in the tropics) is also elevated over the southern Africa fire region.
- **Significance**: Correlation between atmospheric CO_2 and CO anomalies (r=0.41) and atmospheric CO2:CO (16:1; consistent with bottom-up inventories, in-situ observations and CO_2 and CO model simulations) indicate enhanced CO_2 is largely due to fires.





Figures a-c: September-October 2014 0.5° × 0.5° MODIS fire counts (**a**) mean OCO-2 dry column CO_2 (**b**) and mean MOPITT dry column CO (**c**).

Figures d-e: Histograms of CO (**d**) and CO_2 (e) within fire region (area A) and background region (area B).

Study lead by Anthony Bloom, John Worden and Annmarie Eldering at JPL. Manuscript submitted to GRL.

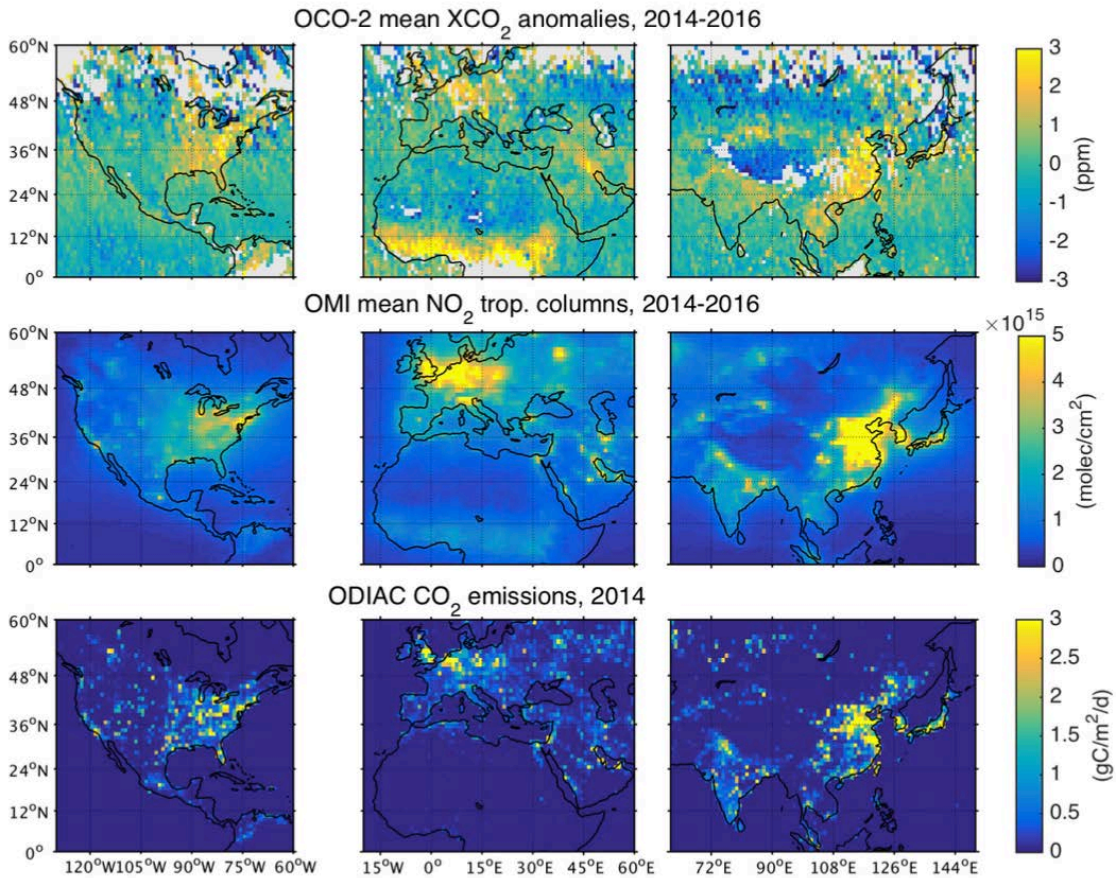
Direct space-based observations of anthropogenic CO_2 emission areas from OCO-2 (Hakkarainen et al., GRL, in press)

Issue: Can spaceborne observations discriminate anthropogenic emissions of CO_2?

Results: OCO-2 X_{CO2} & OMI NO_2 combined to produce global maps of anthropogenic CO_2 emissions

- High CO_2 over eastern USA, central Europe, and China consistent with fossil fuel use inferred from OMI NO_2 and fossil fuel emission inventories.
- CO_2 emissions from fossil fuel extraction activities in the Middle East clearly seen in OCO-2 maps, but not tracked in inventories.
- High CO_2 emissions over central Africa and Southeast Asia are due to intense biomass burning rather than fossil fuel combustion.

Significance: These results demonstrate the power of spaceborne data for monitoring anthropogenic CO_2 emissions.



OCO-2 CO_2 anomaly data (top row), OMI NO_2 data (middle row) and an emission inventory (bottom row) were used in a cluster analysis to discriminate CO_2 emissions from fossil fuel use (northeast USA, Europe, China) fossil fuel extraction (Middle East), and biomass burning (Africa)

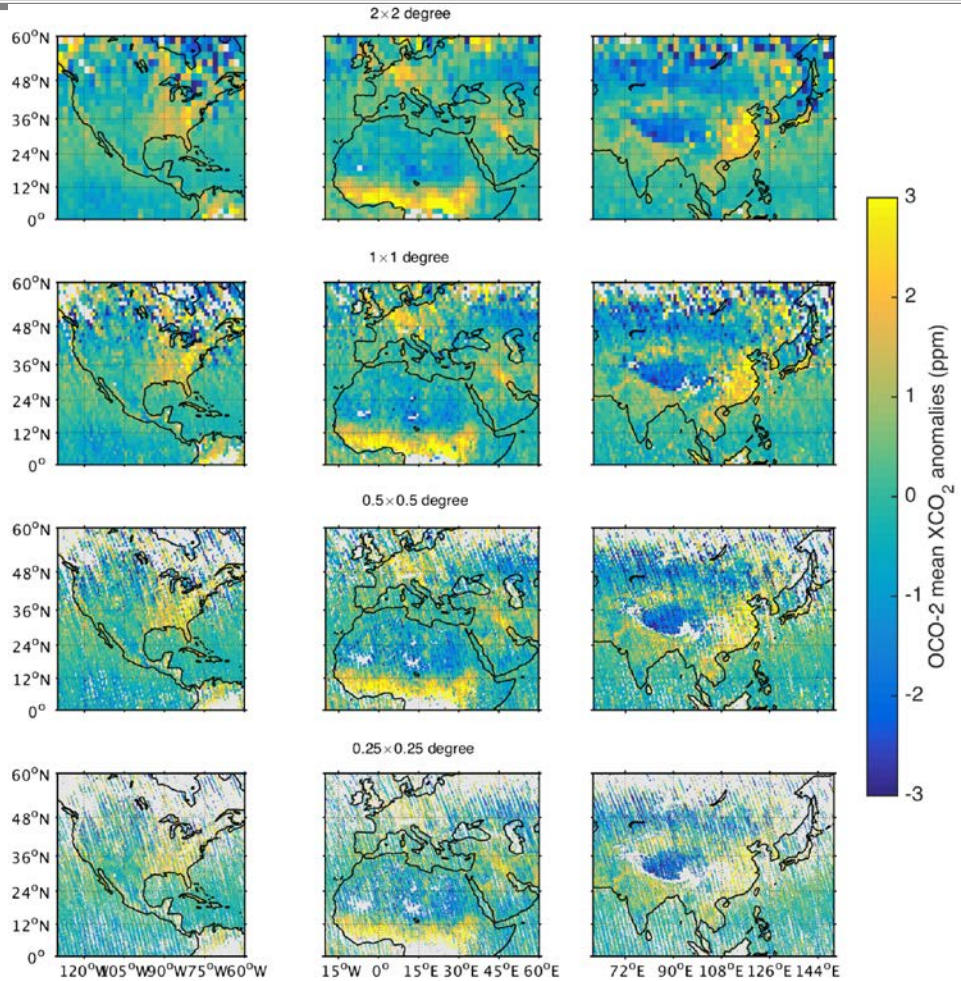
Impact of Spatial Averaging on Anomaly Detection and Characterization

Issue: What is the optimal spatial sampling and averaging for detecting and characterizing X_{CO2} anomalies?

Results: For a mission like OCO-2, with a narrow swath:

- Small scale features become harder to detect as the spatial resolution decreases
- Large scale features become easier to detect and quantify as the spatial resolution decreases

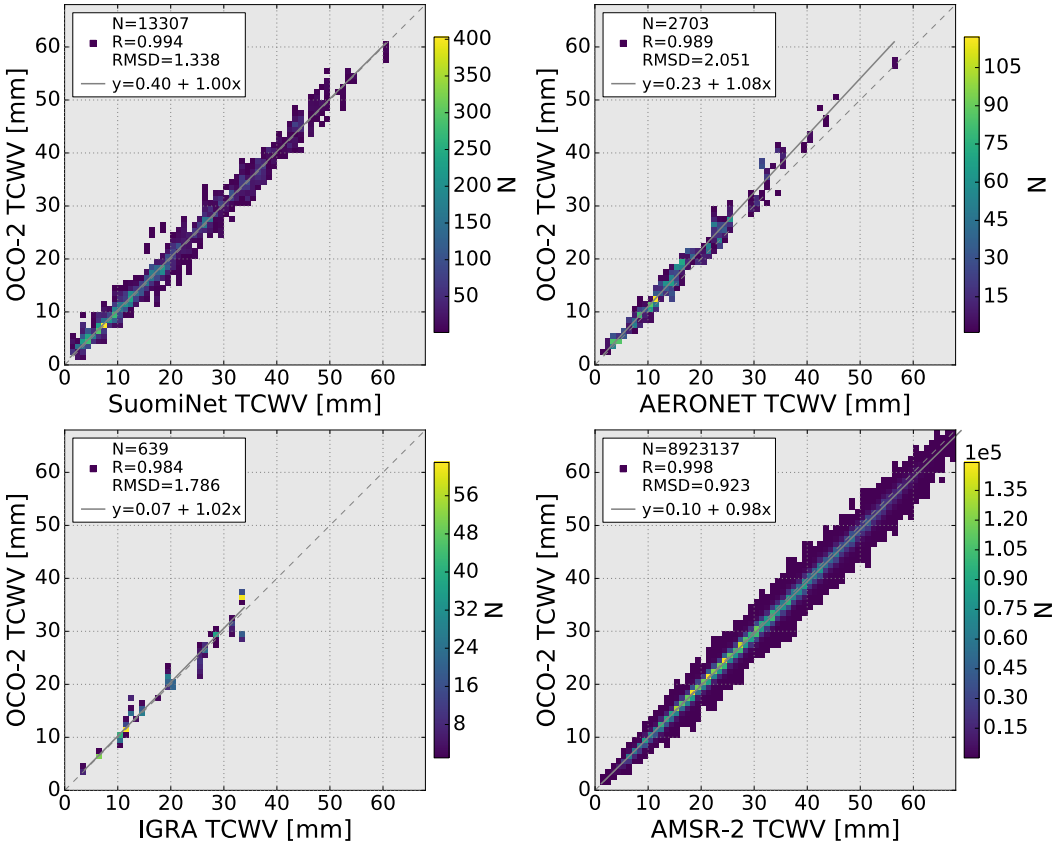
Significance: High spatial resolution is essential for characterizing emission anomalies from small scale sources.



Hakkarainen et al., GRL, in press

Total Column Water Vapor from OCO-2 is as good as existing estimates (Nelson et al., submitted)

- **Problem**: How accurate are OCO-2 total column water vapor (TCWV) measurements?
- **Results**: Water vapor must be retrieved, or it introduces a bias OCO-2 X_{CO2} retrievals.
  - OCO-2 TCWV measurements are highly accurate and nearly unbiased over land and ocean, with root mean square differences of 1.3 mm vs. SuomiNet
  - These results also agree well with other standards including AERONET (2.1 mm), IGRA (1.8 mm), and AMSR-2 (0.9 mm)
- **Significance**: The OCO-2 sampling limits operational use of our data, but this demonstrates a accurate new approach for remote sensing of TCWV.



Comparisons of OCO-2 Total Column Water Vapor (TCWV) retrievals with those from other standards including SuomiNet, AERONET, radiosondes (IGRA) and microwave instrument (AMSR-2)

Figure courtesy of Robert Nelson..

OCO-3 Status

Comparison of OCO-2 and OCO-3 Measurements

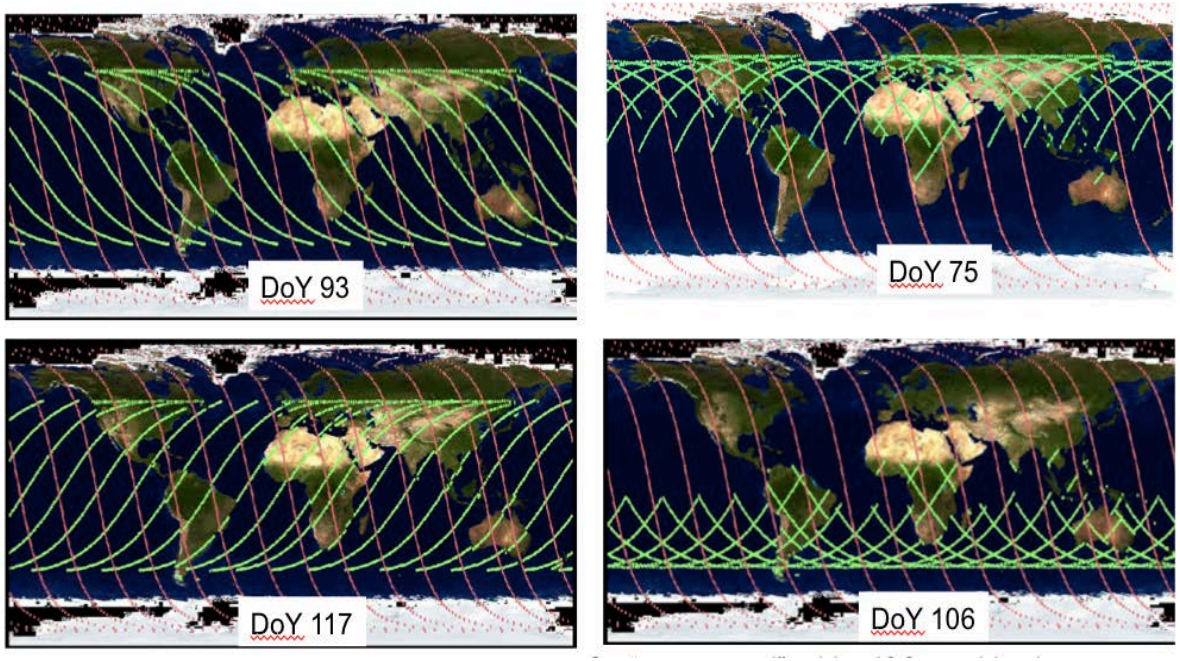
	OCO-2	OCO-3 on ISS
Latitudinal coverage	+/- 80 degrees	+/- 52 degrees (on ISS)
Local time of day sampling and repeat	~1:30pm with 16 day routine and repeated measurements	Ranges across all sunlit hours with variable revisit (0 to multiple per day)
Land Sampling	Every day (using glint and nadir measurements)	Every day
Glint/Ocean Sampling	16 days on/16 days off (originally)	Every day
Target/mapping mode capability	Target mode achieved with spacecraft pointing	Target and mapping expanded with pointing mirror assembly
Polarization approach	Keep instrument slit in principal plane (actually 30 degrees off)	Collect data at wide range of polarization angles

As an integrated dataset:

- The OCO-2 and OCO-3 missions in series provide an extended time series of X_{CO2}
- OCO-3 has different sampling characteristics and therefore different error characteristics, this will need to be accounted for when using the datasets together
- Existing retrieval algorithm does not need to be modified for use with OCO-3 data

Seasonal and Latitudinal Variations of OCO-3 Sampling from ISS

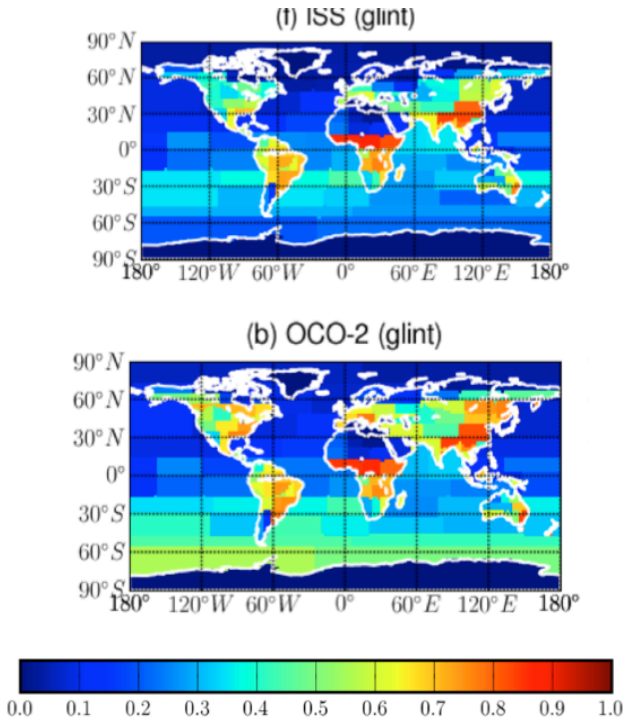
- Sampling would be dense at mid-latitudes, while providing good coverage of tropics and sub-tropics
- The 2-axis pointing system would enable new operations concept with nadir *and* glint observations taken on every orbit, increasing the number of useful samples over oceans as compared to OCO-2



Proposed OCO-3/ISS orbits (green) and OCO-2 (pink).
On "turn-around" orbits, ISS would provide better coverage of mid latitudes of one hemisphere.

OCO-3 Science Overview

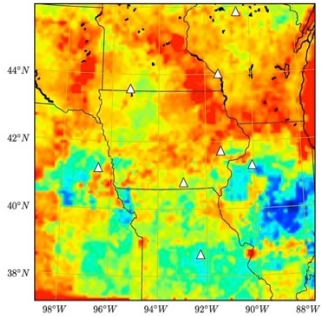
Global Flux Estimates: OCO-2 and OCO-3 impacts (simulated)



Flux error improvement for January

Palmer et al., 2011

Unique Science Opportunities with OCO-3



Midwest Carbon Flux

From Schuh et al., 2013

Terrestrial Carbon Cycle

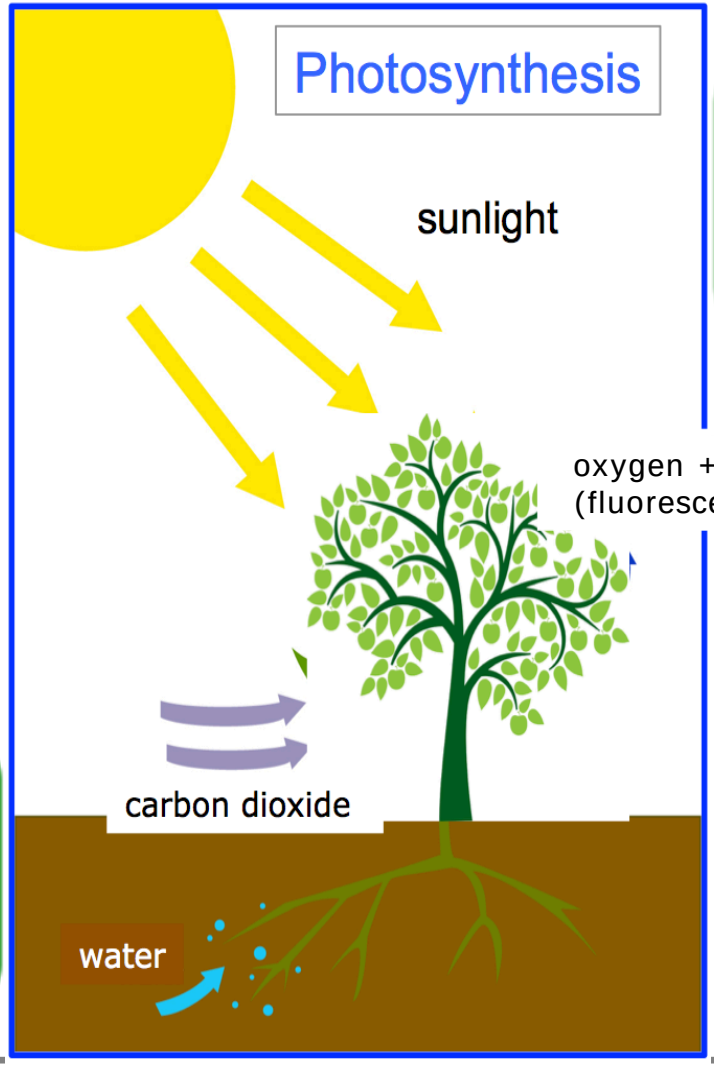
Process studies enabled by measurements at all sunlit hours, including SIF. ISS will contain complementary instrumentation.

Anthropogenic Emissions

Enabled by enhanced target mode using pointing mirror assembly

OCO-3, ECOSTRESS and GEDI: the ISS Carbon Cycle Opportunity

Plant species distribution and physiology



CO_2 & Fluorescence

Evapo-transpiration

Biomass

OCO-3 Status and Near Term Plans

- OCO-3 "Thermo-Vacuum Test 0" completed Aug – Sept 2016
  - The OCO-2 Flight Spare Instrument was in storage since Fall 2013
  - The TVAC-0 is a thermal vacuum test conducted in the OCO-2 Flight Spare Instrument configuration.
  - The purposes of the test were:
    - Repeat the tests performed on the instrument during at its last thermal vacuum test (TVAC-1C) to ensure that the baseline performance had not changed significantly
    - Assess the A-Band sensitivity variations seen on OCO-2
  - The OCO-2 flight spare passed the success criteria
- Subsequent TV tests will integrate progressively more of the OCO-3 dedicated hardware
- Still on track for a March 2018 payload delivery and an October 2018 installation on ISS