Status of OCO-2, OCO-3 and GeoCarb

David Crisp, for the OCO-2, OCO-3 and GeoCarb Teams

Jet Propulsion Laboratory, California Institute of Technology

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Status Summary

OCO-2 Status

- Observatory Status: Nominal
  - Degradation of z-axis gyro in the inertial measurement unit
- Instrument Status: Nominal
  - Most recent decon - 4 - 11 March 2019 executed nominally
- Science Status: Nominal
  - ACOS/GOSAT version 9 – 2013 Run completed
  - "Build 10" testing ongoing

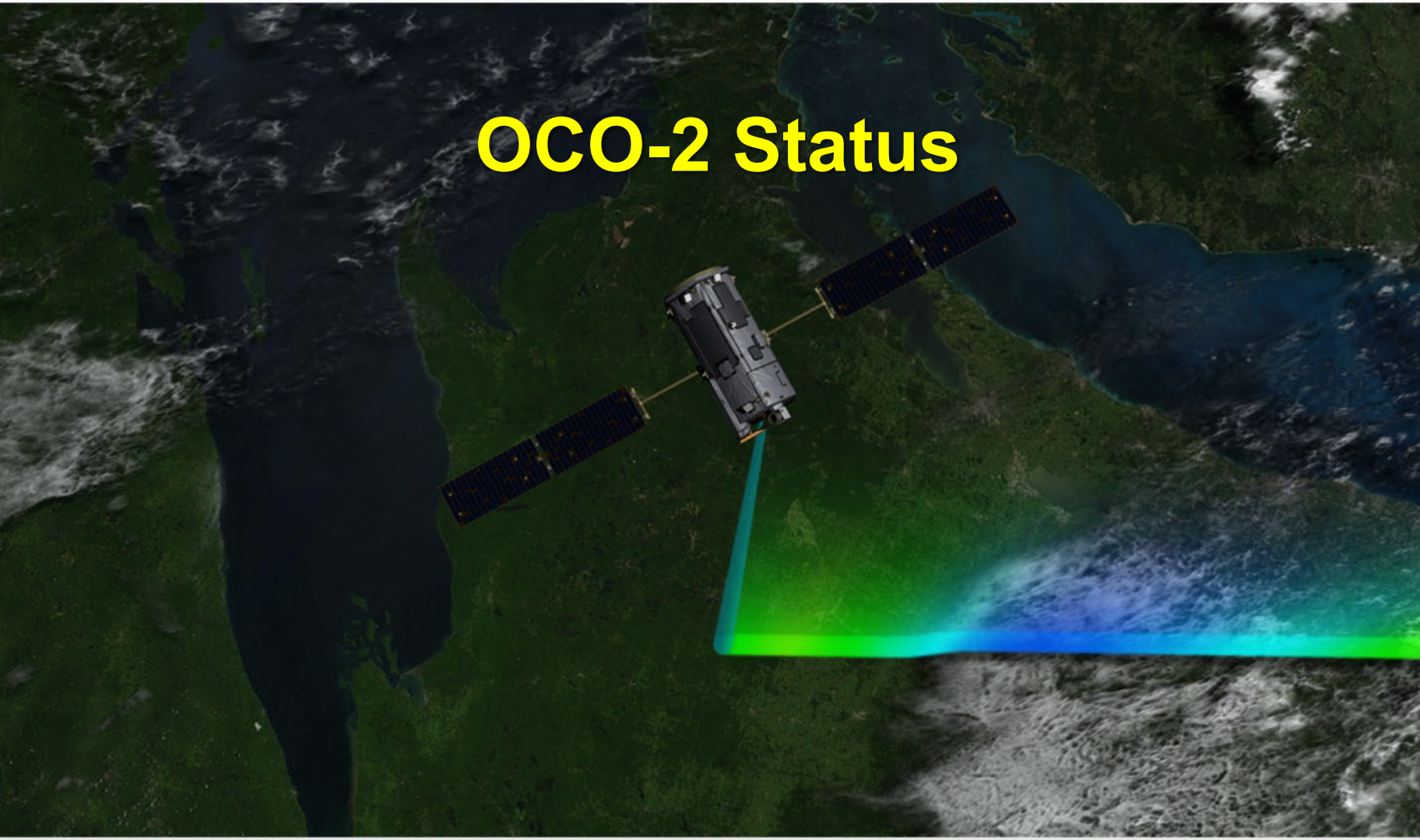
OCO-3 Status

- Successfully Launched on 4 May and docked with ISS on 6 May
- Installation on JEM-EF module on 10 May

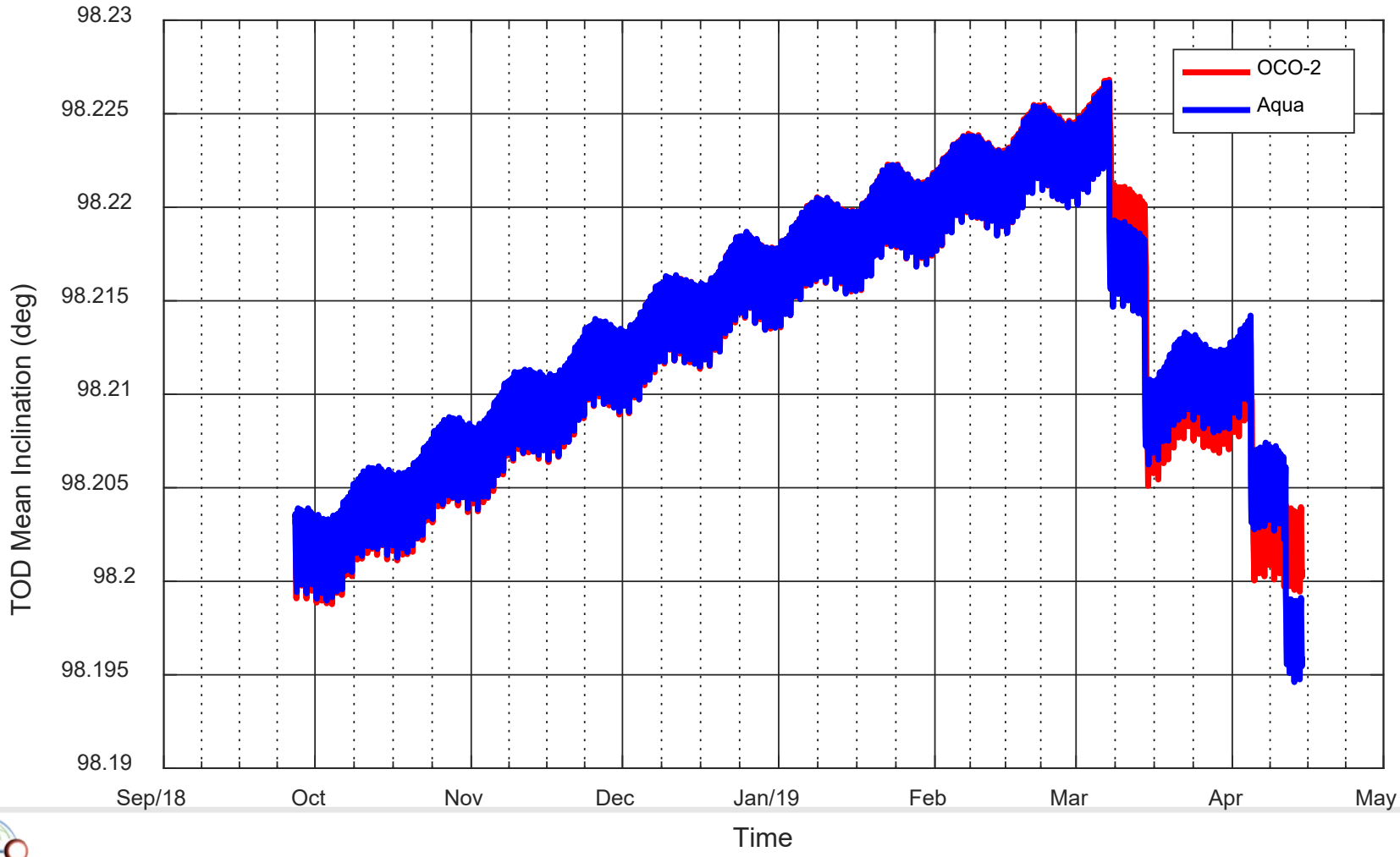
GeoCarb Status

- δ-PDR passed, preparing for Mission Confirmation Review

OCO-2 Status



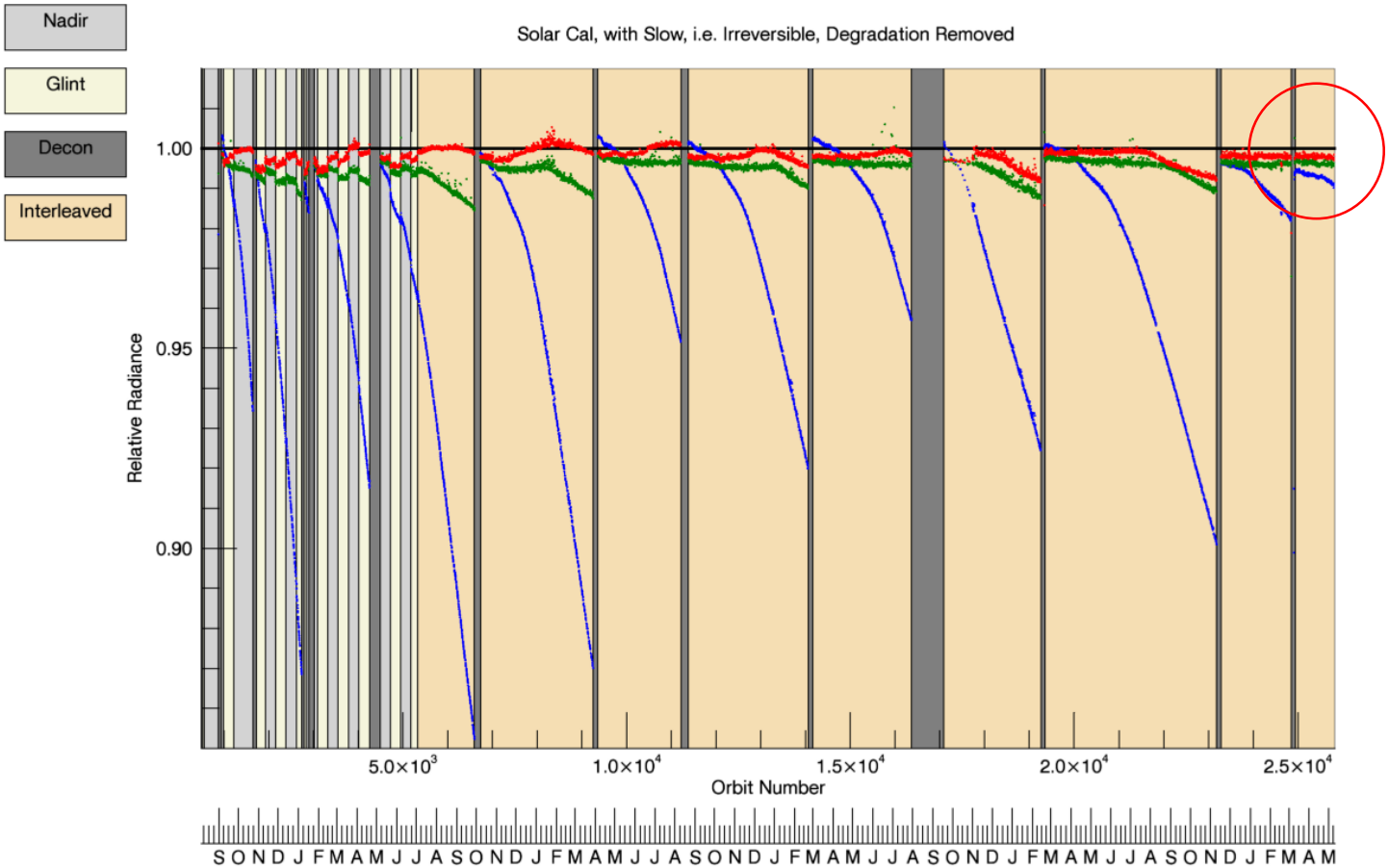
2019 Inclination Adjust Maneuver Complete



Inertial Measurement Unit Issue

- The OCO-2 attitude control system uses data from a star tracker, an inertial measurement unit (IMU), sun sensors, and a magnetometer to determine the spacecraft attitude.
- The IMU includes 3 ring laser gyros for monitoring rotation about the spacecraft's x, y, and z axes. The z-axis is gyro is degrading rapidly.
- The flight software must be patched to remove dependencies on the IMU. Those changes are currently under way
- Science impacts of the loss of the IMU
  - Will not affect nominal science operations
  - Will preclude future Full Moon Lunar Calibration and Solar Doppler calibration operations due to obscuration of star tracker field of view by the disk of the Earth – neither loss will compromised routine calibration
- The no-gyro operations mode will also complicate the scheduling of the second downlink each day to the Alaska Satellite Facility due to solar illumination of the star tracker
  - Other scheduling options are currently under investigation

Throughput Trending



March 2019 Decon restored throughput to > 99% in all 3 channels.

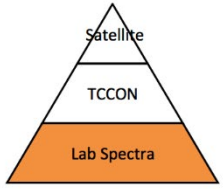
B10 changes and their drivers

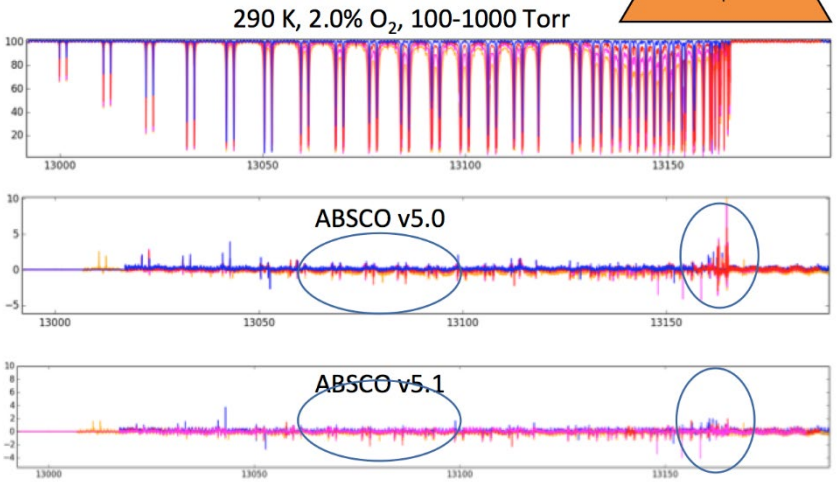
Accepted
In Test
Work to go
If time allows

- Positive updates to L2 Model inputs:
  - Spectroscopy (ABSCO 5.1)
  - Solar Continuum Model (TSIS-SIM)
  - CO_2 Prior (from TCCON group)
  - L1B Radiances (degradation correction, bad sample lists)
  - Aerosol prior and apriori covariance constraints
- L2 algorithm Updates (requires more testing)
  - Surface pressure prior constraint
  - Surface Albedo parameterization (e.g. linear→quadratic)
- Other
  - ABO2, IMAP Updates
  - Filtering, Bias Correction Methodology updates

O2A Spectroscopy Update

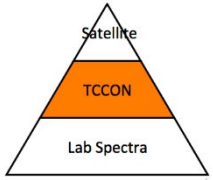
New multispectrum fits for O_2:
Laboratory residuals, CRDS

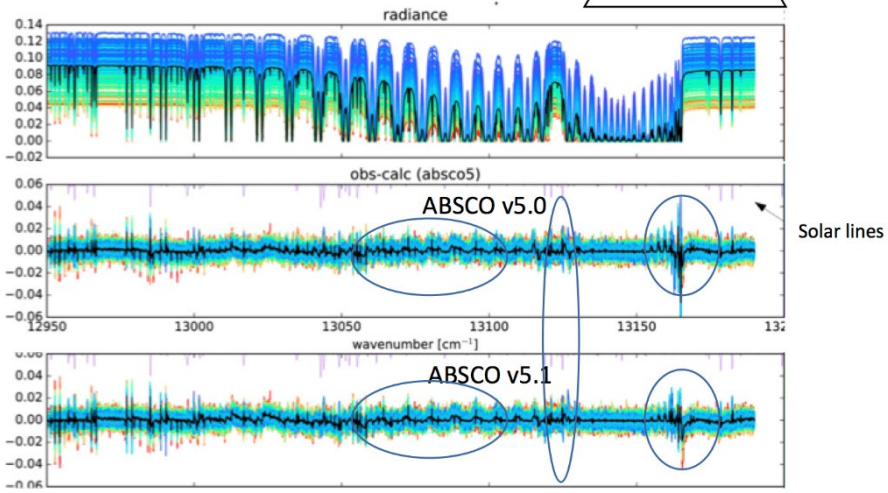




Lab figures: B. Drouin

Evaluation with Lamont TCCON spectra





Improvements:
At R branch bandhead
Between P&R branches

Degradation:
At low wavenumber end
P-branch, between doublets

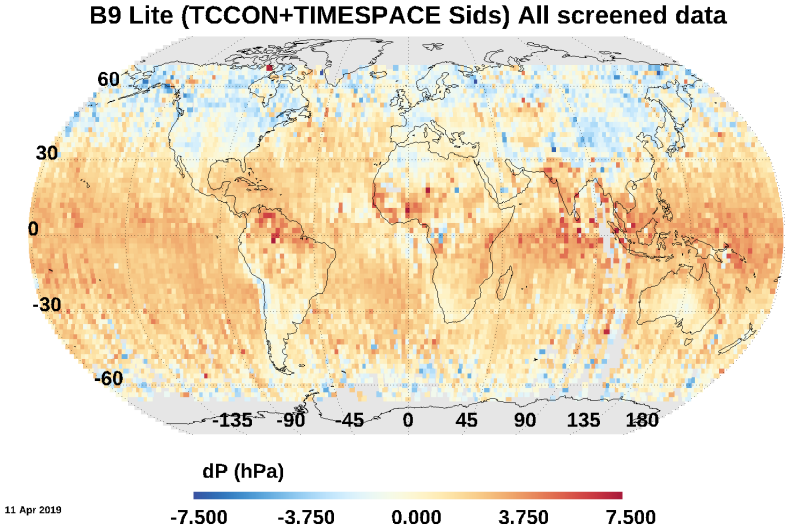
TCCON residual figures: F. Oyafuso

A-Band spectroscopy updates reduce spectral residuals relative to laboratory measurements (left) and TCCON spectra (right).

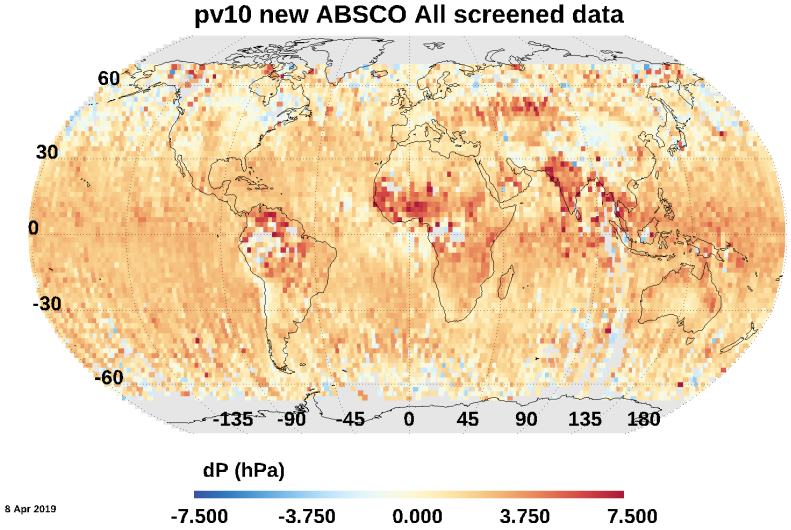
Vivienne Payne, ABSCO Team

ABSCO Effect on dPsurf

- Biases correlated with the difference between the retrieved and prior surface pressure (dP bias) is the largest contributor to bias correction in the OCO-2 B8 and B9 XCO_2 products
- ABSCO 5.1 yields a flatter dP bias vs. latitude and reduced land-ocean dP bias, but additional changes are needed to fully address the



Difference between B9 retrieved surface pressure and a priori

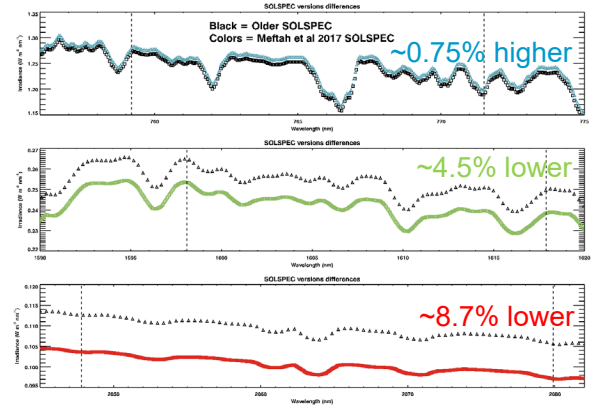


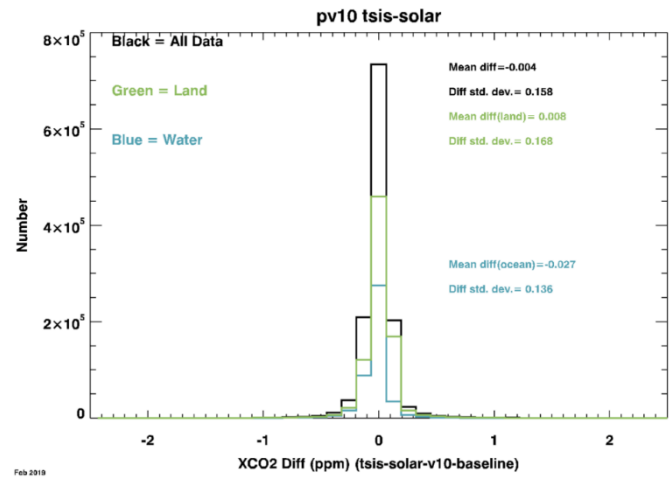
Difference between B10 retrieved surface pressure and a priori

Solar Continuum Update

- Recent Solar ISS and TSIS-SIM measurements indicate that the ATLAS SOLSPEC solar fluxes, on which the OCO-2 solar continuum was based, are biased.
- TSIS-SIM data indicate that the continuum should be:
  - Lowered 1.3% in the ABO2 channel
  - Lowered 3% in the WCO2 channel
  - Lowered 6.5% in the SCO2
- These changes introduced no significant changes in XCO_2
- Small changes in dP, slightly increased dP land-ocean bias.
- Slightly reduced retrieved wind speed over ocean

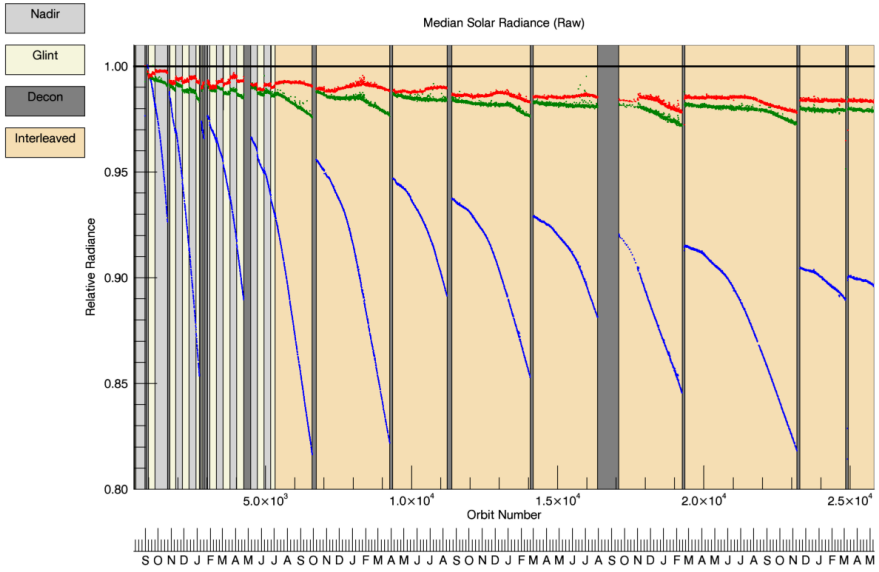
Solar ISS values are:



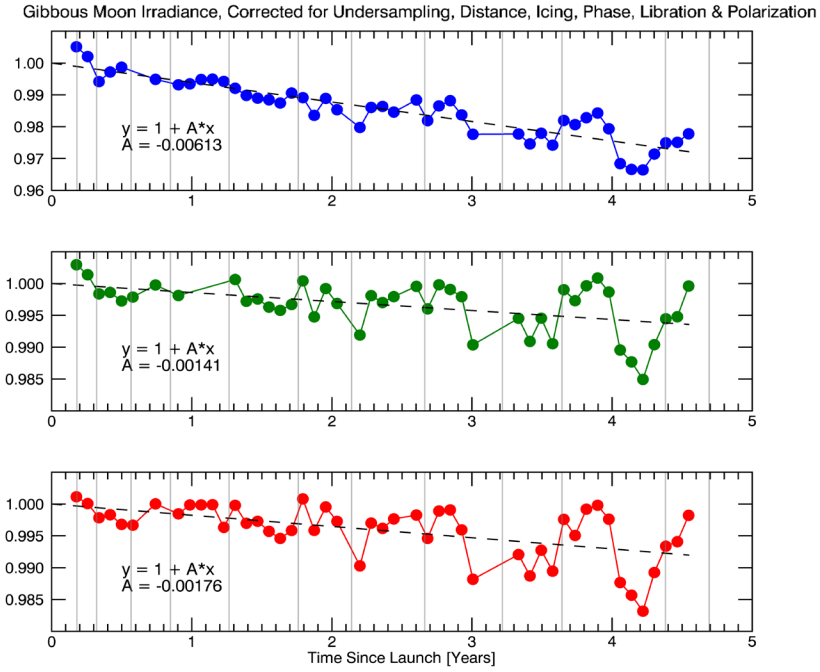


Crisp, Kuai

Gain Degradation Sources



Observations of the sun using the solar diffuser show signal losses from icing that are reversed with decontamination, along with an irreversible trend (2.2%/yr ABO2, 0.4%/yr WCO2, 0.4%/yr SCO2). These trends combine instrument throughput and diffuser degradation components.



Observations of the ¾ gibbous moon show consistent trends in instrument throughput degradation (0.6%/yr, < 0.2%/yr, < 0.2%/yr). Fit residuals are highly correlated in all 3 channels, indicating that they are associated with sampling biases.

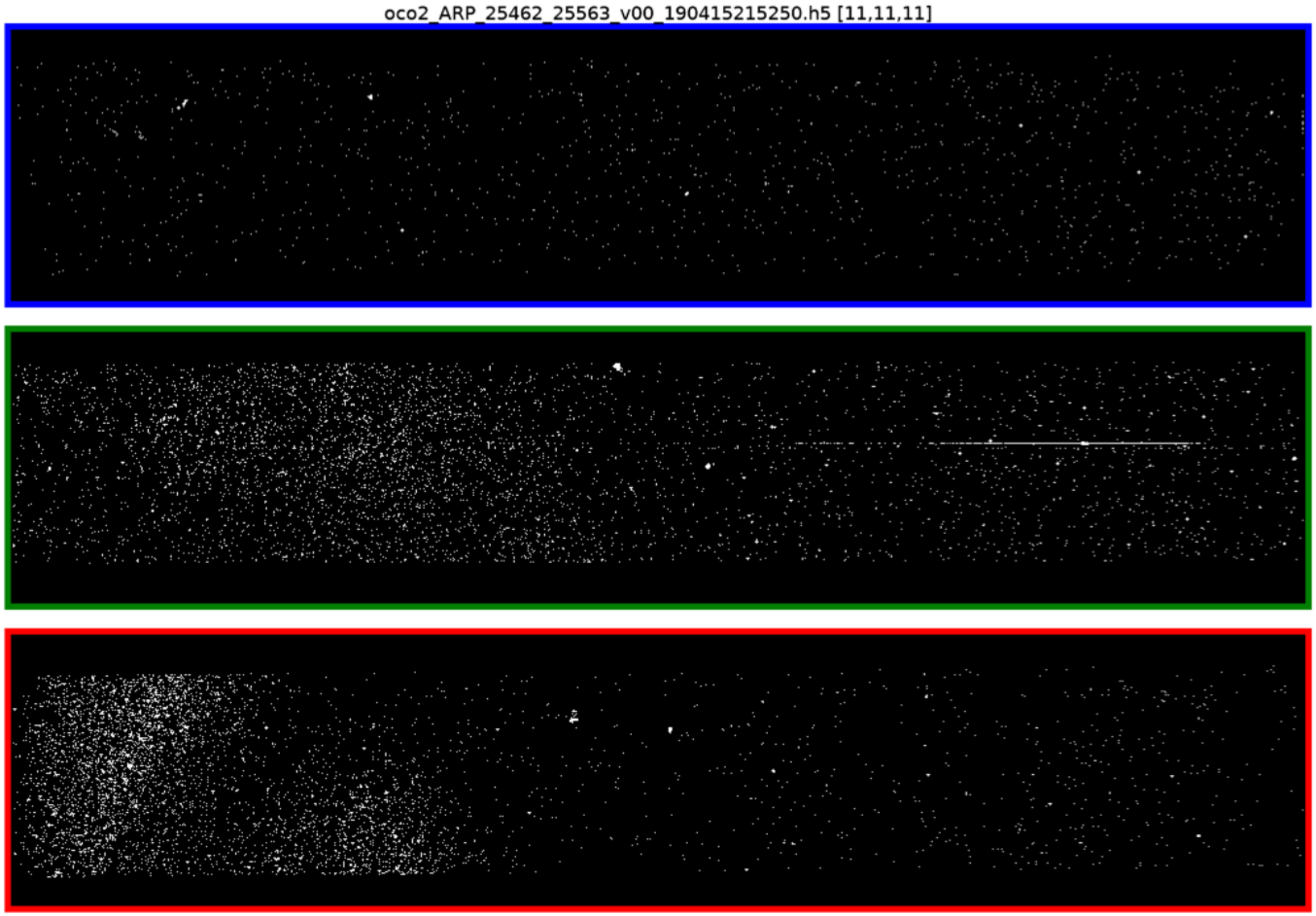
B8-B10 L1B Changes: Gain Degradation

- ABO2 Gain Degradation: Regular lamp observations track icing, solar calibrator corrects lamp aging, but what about solar diffuser aging?
  - B7: all solar degradation interpreted as instrument throughput degradation (radiances too high after correction)
  - B8: all solar degradation attributed to diffuser, none to instrument (radiances too low after correction)
  - B10: some solar degradation attributed to diffuser, and some attributed to instrument, based on lunar calibration trends
  - Also tracking OCO-2/MODIS ratio over pseudo-invariant desert sites
- WCO2/SCO2 Gain Degradation: much smaller than ABO2
  - B7, B8: Band Medians (1 coefficient describes 8128 samples)
  - B10: Footprint Medians (8 coefficients describe 8128 samples)
- ZLO, Dispersion Trending, SNR Model, Dark, etc. consistent with B8
- L2 products based on updated L1B files currently being evaluated

OCO-2 B8-B10 Changes: Bad Samples

- A Bad Pixel Map (BPM) is used to identify and exclude bad pixels from the irreversible, on-board process that sums ~20 spatial pixels together to yield spectral samples as part of the onboard data compression approach
  - Machine learning used to identify bad pixels and new maps were loaded in August 2018
- Bad Sample List (BSL), an ancillary radiometric product (ARP) variable that can be revised on the ground to discard bad samples – not irreversible
- Philosophy changed for B10 Bad Sample lists:
  - B7: Defined by O'Dell based on 2015 B7 test of spectral residuals
  - B8: Previous list incrementally updated as new features appeared
  - B10: New results from machine learning classifier augmented by results from ARP validation
    - One BSL for ARPs covering BPM 6-8 period (Sep 2014 – Nov 2014)
    - One BSL for ARPs covering BPM 9 period (Nov 2014 – Feb 2015)
    - One BSL for ARPs covering BPM 10 period (Feb 2015 – Aug 2018)
    - One BSL for ARPs covering BPM 11 period (Aug 2018 – Mar 2019)
    - Rolling 10R will incorporate new bad samples as they arise

OCO-2 BPM [11,11,11] – Loaded Aug 2018



1213 bad

5262 bad

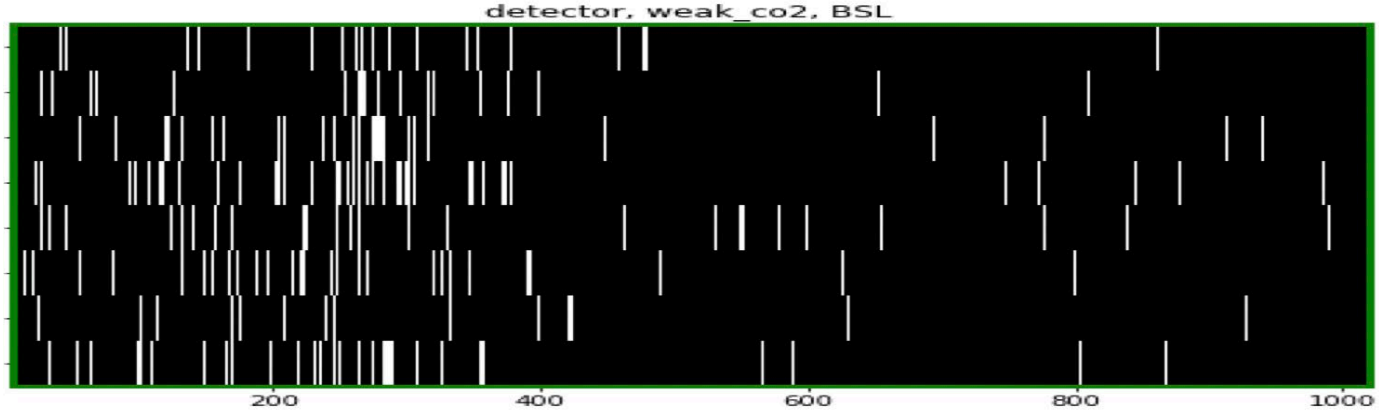
5192 bad

Updated bad pixel maps (BPM 11) were uploaded to the instrument in Aug 2018

BSL for WCO2 and SCO2 Matching BPM 10

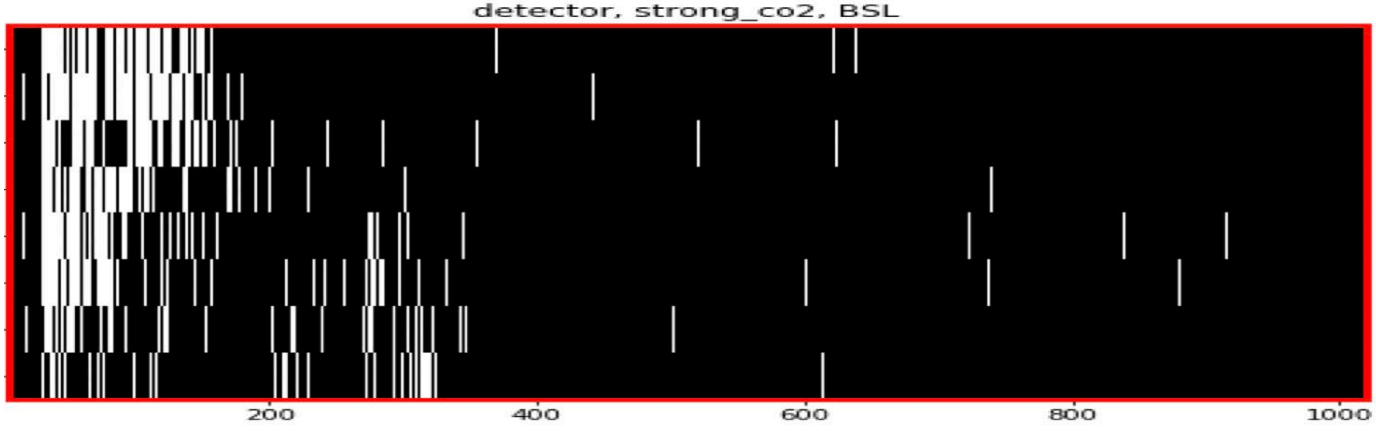
New BSL (426)

Bad samples shown in white



New bad sample lists have been developed for the period spanned by bad pixel map #10 (BPM 10).

New BSL (676)

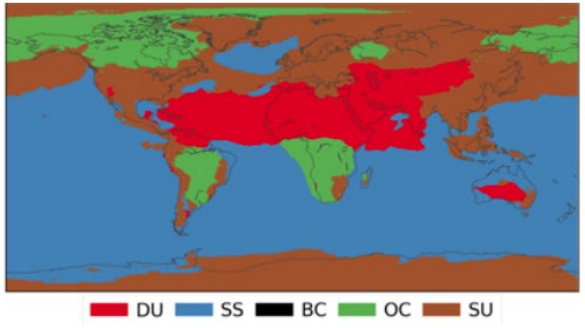


Updated bad sample lists for the period spanned by BPM 11 (Aug 2018 to present) are under development.

Aerosol Prior Updates

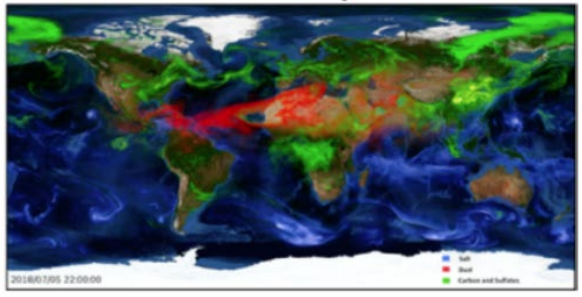
- Replaced MERRA-2 monthly aerosol climatology, with 3-hourly GEOS-5 FP-IT aerosols
- FP-IT types + AODs as prior for the two tropospheric aerosol types
- Aerosols prior uncertainty changed to 25% of B8/B9 (called "aerosol_half" because we're using an uncertainty of ln(AOD) = 0.5 instead of ln(AOD) = 2.0
  - Also tested an "aerosol_quarter" case with ln(AOD) = 0.25 instead of 2.0, but decided to go with aerosol_half case to not over-constrain aerosols
- The "TimeSpace" Quick Test Set (QTS) with ~2.3 million soundings was used in these tests

MERRA-2 Monthly Climatology



B8/B9 Prior

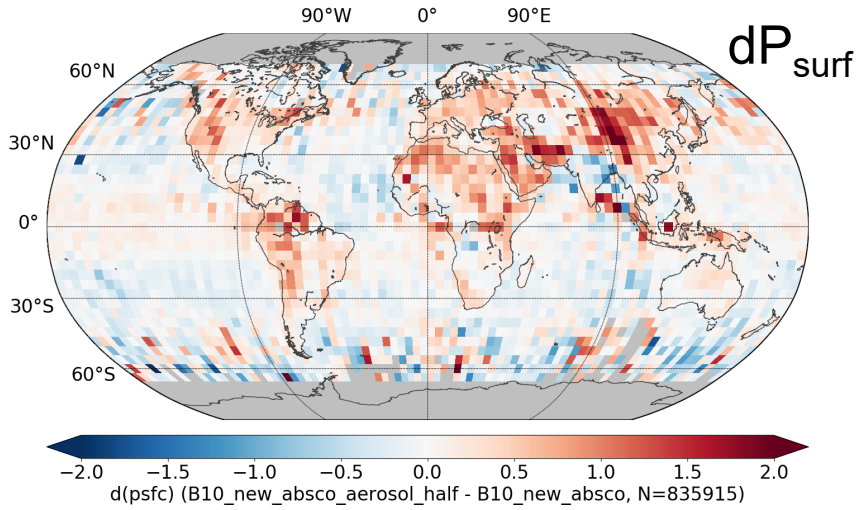
GEOS-5 3-Hourly Aerosols

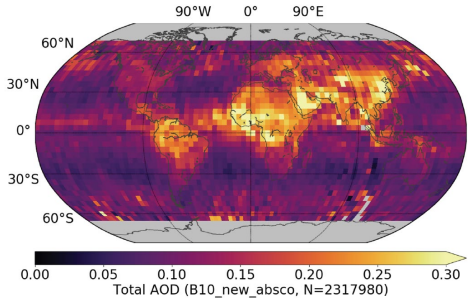


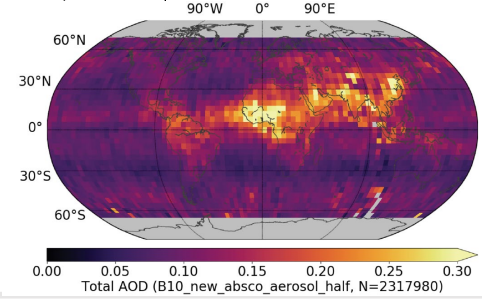
New Prior

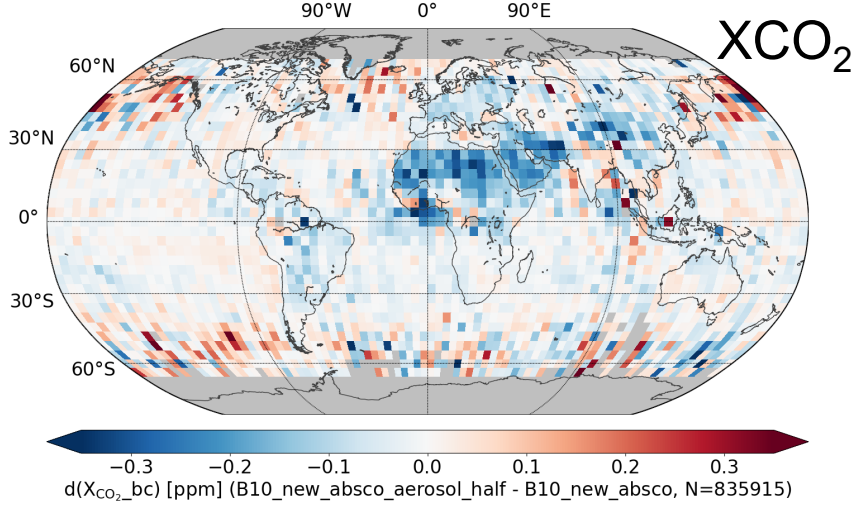
Aerosol Prior Test Results

- The largest changes were seen in dusty regions over North Africa and Central Asia
  - Reduced differences between the retrieved and prior surface pressure
  - Reduced AOD
  - Reduced high biased XCO_2





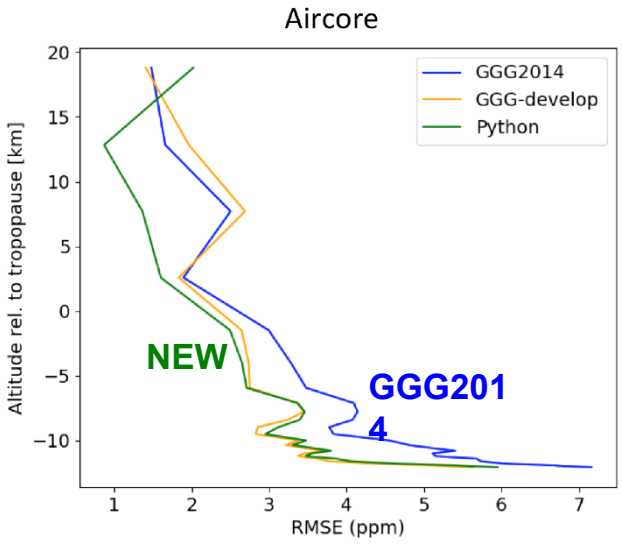


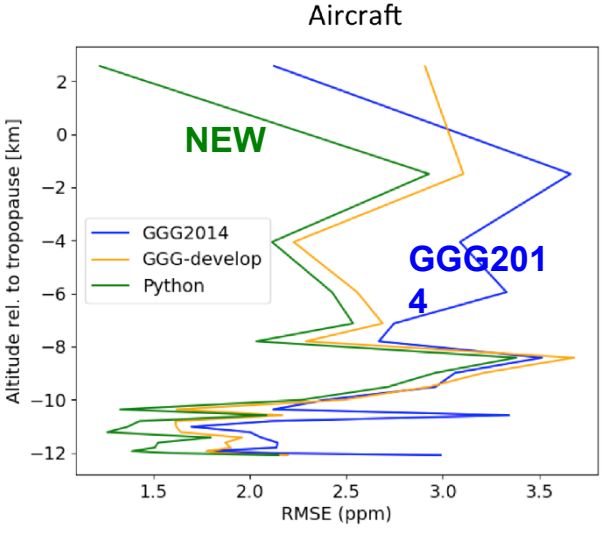


New TCCON CO2 Prior

The new TCCON prior includes:

- Updated Stratospheric prior from Arlyn Andrews
  - Requires calculation of "equivalent latitude", based on full fields of Potential Temp & Potential Vorticity (p.i.b.)
  - Tied To Mauna Loa/Samoa long-term record
- New Tropospheric Prior
  - Changed to be consistent with stratosphere
  - Tied To Mauna Loa/Samoa record
- Needs to be coded and tested for B10





B10 Development Timeline

- Delivery of B10 L2 Code: September 2019
- Delivery of quality flag & Bias Correction: October 2019
- Start of Production Runs: November 2019
- Delivery of products to DAAC: April 2020

2019 Railroad Valley Campaign

	Day of year		OCO-2	orbit	OCO-3 ISS	GOSAT	GOSAT-2	RRV 2019	
Cycle			16			3	6		
24-Jun-19	175	Monday	7	139		no path		LA	
25-Jun-19	176	Tuesday	8	none		36	72	JPL, Caltech	Data downlink twice
26-Jun-19	177	Wednesday	9	137	above RRV 19:40	37	73	LA (Caltech)	Data downlink twice
27-Jun-19	178	Thursday	10	none	Close UT12:20 Too early	no path		LA (CH4 site)	
28-Jun-19	179	Friday	11	none		36		JPL LA (CH4 site)	Data downlink twice
29-Jun-19	180	Saturday	12	none	Close 18:44	37		Move	Data downlink twice
30-Jun-19	181	Sunday	13	none	Close 17:53	no path		RRV	
1-Jul-19	182	Monday	14	none		36	72	RRV	Data downlink twice
2-Jul-19	183	Tuesday	15	none		37	73	RRV	No GOSAT observation due to solar eclipse,
3-Jul-19	184	Wednesday	16	138	above RRV 16:56	no path	>35deg	RRV	
4-Jul-19	185	Thursday	1	none	Close 9:35 too early	36		RRV	Data downlink twice
5-Jul-19	186	Friday	2	136		37		RRV	Data downlink twice
6-Jul-19	187	Saturday	3	none	Close 15:59	no path		JPL	
7-Jul-19	188	Sunday	4	none	close 15:08	36	72	Move	Data downlink twice
8-Jul-19	189	Monday	5	none		37	73	TKY	Data downlink twice

- During the campaign, 3 over paths for GOSAT, GOSAT-2 , 2 (?) paths for OCO-2 and ? paths for OCO-3,
- July 2: Solar Eclipse : GOSAT suspend its observation to save power consumption for 13 hours. GOSAT-2 has enough battery power supply
- OCO-3 geometry (pointing coverage)
- Unusual weather in the west coast: very few clear sky data in 2019. Even in May, almost cloudy every day.
- July 1,2,3: GOSAT-2 view the playa with CT: +18.9, -11.9, and -36.5 deg (slant view), respectively.

Call for Contributions to a Special Issue of Remote Sensing on CO_2 and CH_4

remote sensing

IMPACT FACTOR 3.406

Special Issue

Remote Sensing of Carbon Dioxide and Methane in Earth's Atmosphere

***Special Issue* Editor:**

Dr. Prabir K. Patra
Japan Agency for Marine-Earth Science and Technology
Dr. David Crisp
Jet Propulsion Laboratory, California Institute of Technology
Dr. Thomas Lauvaux
Pennsylvania State University

Website: www.mdpi.com/si/18603
Submission Deadline: 31 May 2019

Carbon dioxide (CO_2) and methane (CH_4) are the two most important greenhouse gases that have led to a significant fraction of the increase in earth's surface temperature in the past 100 years. This Special is dedicated to the past progress and new developments in satellite remote sensing of long-lived greenhouse gases, with a focus on CO and CH_4.

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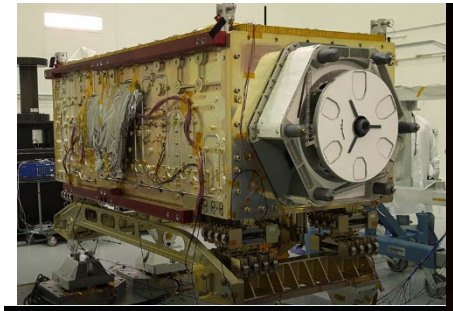
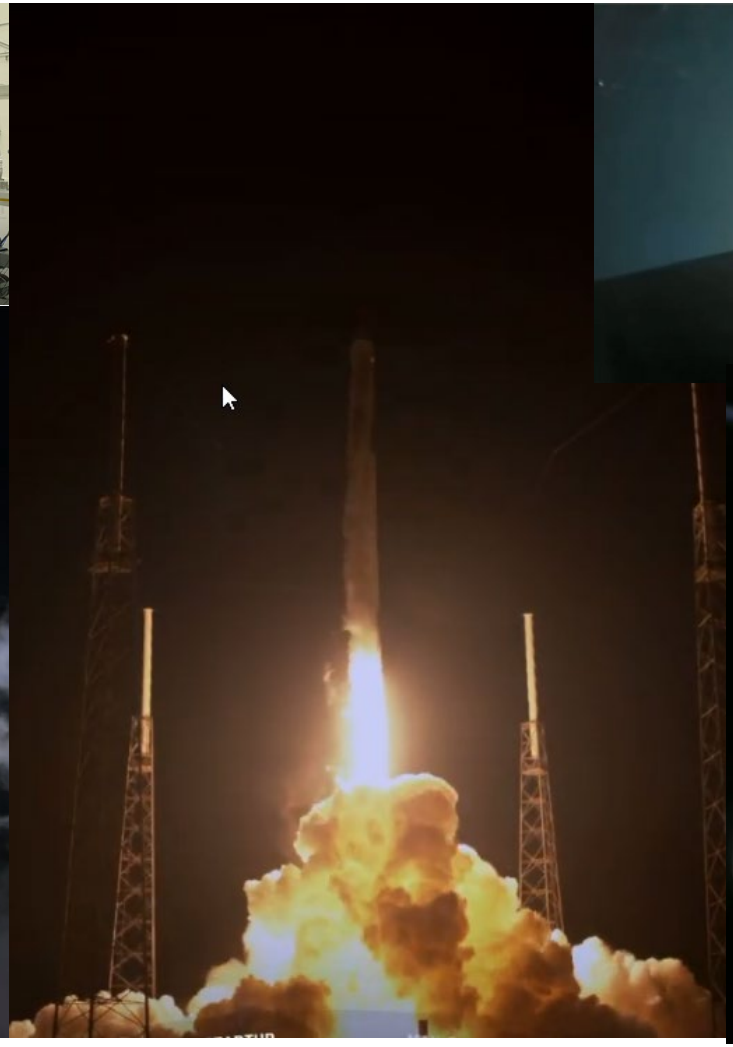
OCO-3 Status

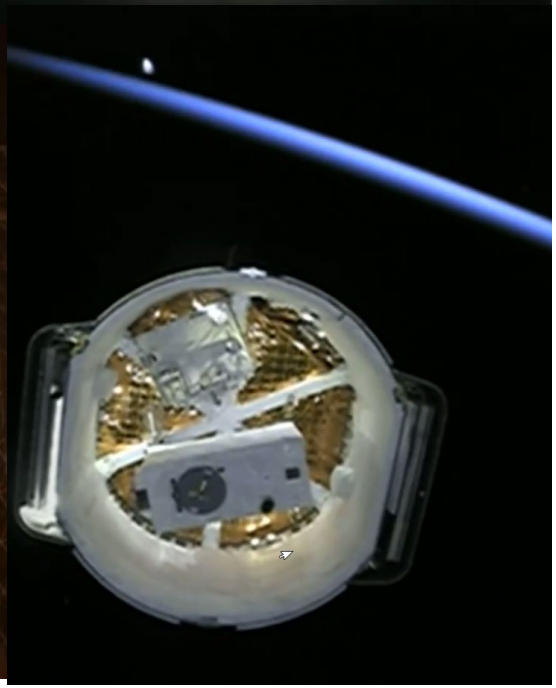
OCO-3 Status and Near Term Plans

- OCO-3 was successfully launched into orbit aboard SpX-17 on May 4th at 0648 UTC.
- SpaceX reported a nominal orbit insertion, successful Dragon deployment from the second stage, and successful deployment of the solar arrays.
- OCO-3's survival heater power draw was nominal.
- Rendezvous with ISS and Dragon berthing on ISS Node 2 Nadir was successful on May 6th (Monday).
- Robotic extraction of OCO-3 is tentatively scheduled for late May 9th (Thursday) with installation on JEM-EF on May 10th (Friday) in the early morning hours.
- JAXA has also given OCO-3 the "Go" for installation on the JEM-EF
- We then have 90 days to prepare OCO-3 for the next three years of science operations!

OCO-3 Launch: May 4th 0648 UTC







Dragon berthed it on the ISS at 6:32 AM PDT 6 May 2019

Initial Status Report (1 of 2)
(based on Matt Bennett's 10 May Report)

Initial telemetry upon our arrival at JEM-EF Site 3 showed that the payload was still quite warm due to our warm survival heater set points in the trunk. Main power was enabled to OCO-3 at 2:10 am PDT this morning (5/10). After observing that the electrical system voltages were stable, we proceeded with limited functional testing. Highlights include:

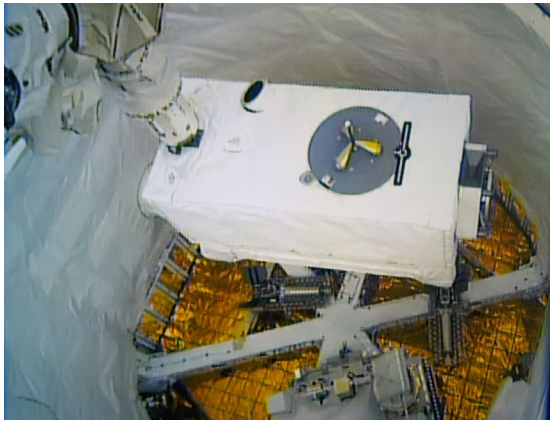
- The flight computer (CEU) and flight software (FSW) are **running smoothly**. The computer performance is **nominal**.
- The GPS is operating **nominally**. Constellation acquisition was faster than anything we saw in ground testing, and we're generally tracking 6-9 GPS satellites at any given time. We are observing occasional tracking drop-outs, as expected, but these outages are even shorter than predicted (20 seconds actual vs. 90 seconds predicted).
- We are currently running the receiver in a mode that provides detailed performance telemetry for the next week to better assess performance and characterize the outages better. The outage period appears to be on the order of an orbit (and may be related to the solar arrays in that case).
- The Inertial Measurement Unit (IMU)is operating **nominally**, showing excellent agreement with expected ISS pitch rate.
- The Stellar Reference Unit (SRU) is operating **nominally** and providing quaternions while tracking at least 10 stars continuously. We will assess outages over the week, but none were observed during our casual monitoring.

Initial Status Report (2 of 2)
(based on Matt Bennett's 10 May Report)

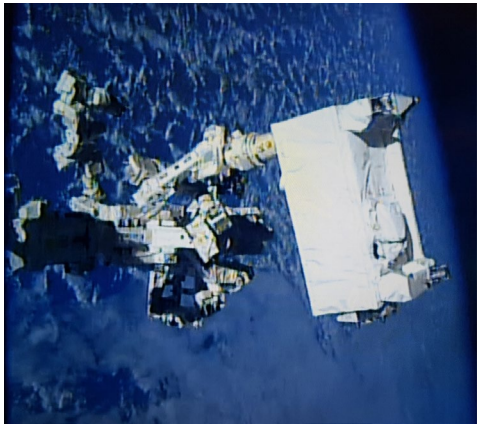
- The PMA launch lock release was **successful** and one of the "cleanest" releases we've seen (i.e. smallest recoil).
- Operating temperatures are **well within limits**. All operational heaters are **cycling nominally**. Thermo Electric Coolers (TECs) turned on and off as commanded, and will be run more consistently next week when we drop to a 12 ºC decon temp. the Cryocooler was successfully uncaged, and the electronics operating **nominally**.
- The Remote Electronics Module (REM) and Analog Front-end Electronics (AFE) performed **nominally** during limited functional tests. We are, very anxious to take the detectors cold after decon and see how the instrument is performing post-launch!
- Both context cameras are also operating **nominally** and are imaging as expected. We hope to have images from our ISS field-of-regard survey, some first "Earth light" images over Japan, and calibrator lamp images to share with you tomorrow! :-)

In short, our CO2-sensing instrument is off to a good start! The instrument is now at decontamination temperatures, and will perform a three-week-long decon cycle with some potential PMACal operations being conducted early. More updates as they come.

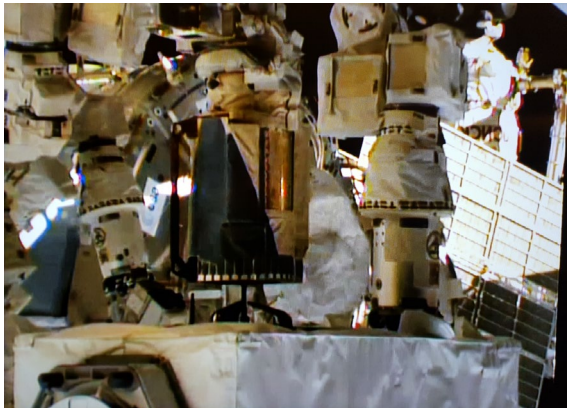
Extraction and Berthing Operations



Extraction from Dragon Trunk

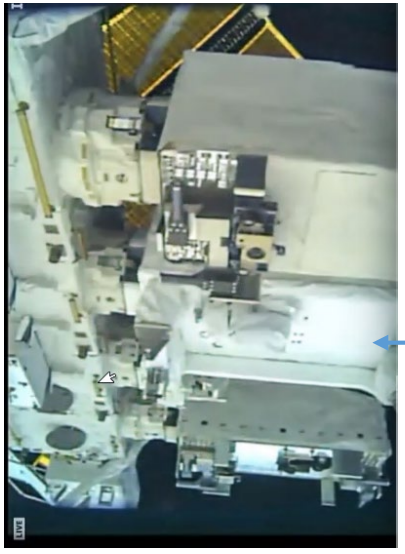


Transfer from Dragon to JEM



Handoff from the Canadarm to JEM Arm

Transfer to JEM-EF by JEM Arm

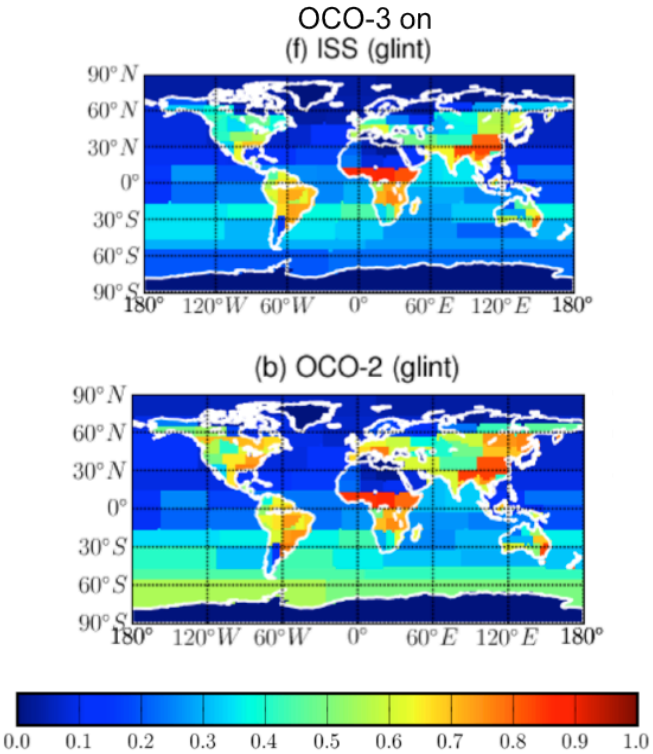


OCO-3 Berthed on the JEM-EF

Higher resolution Pictures coming

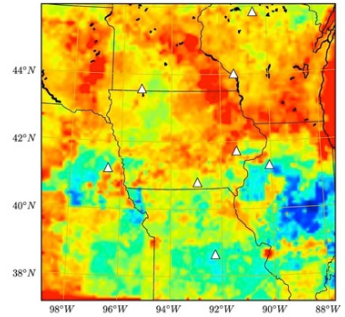
OCO-3 Science Overview

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

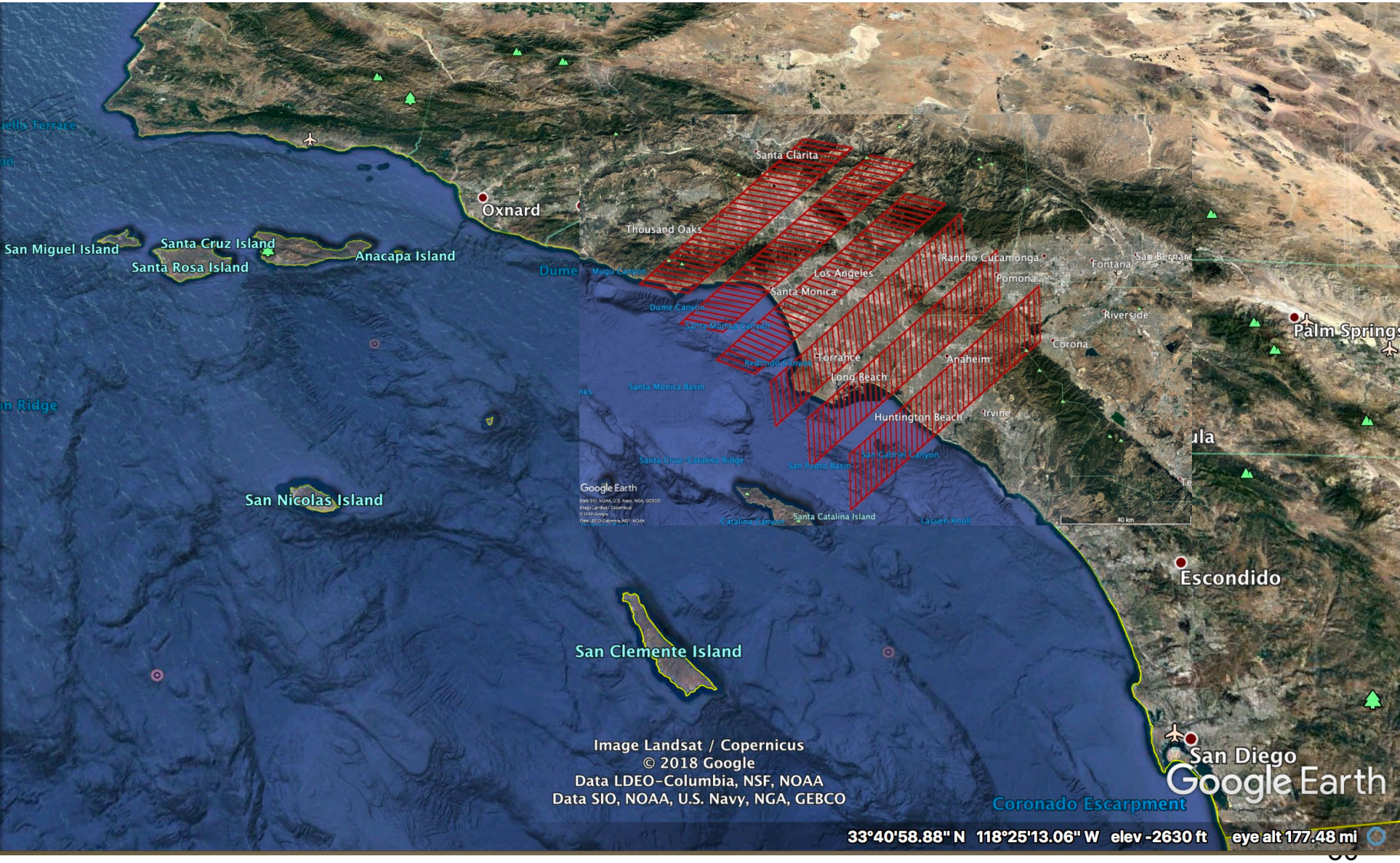
Terrestrial Carbon Cycle

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 Scan Area Maps



OCO-3 Milestones in IOC and Early Ops

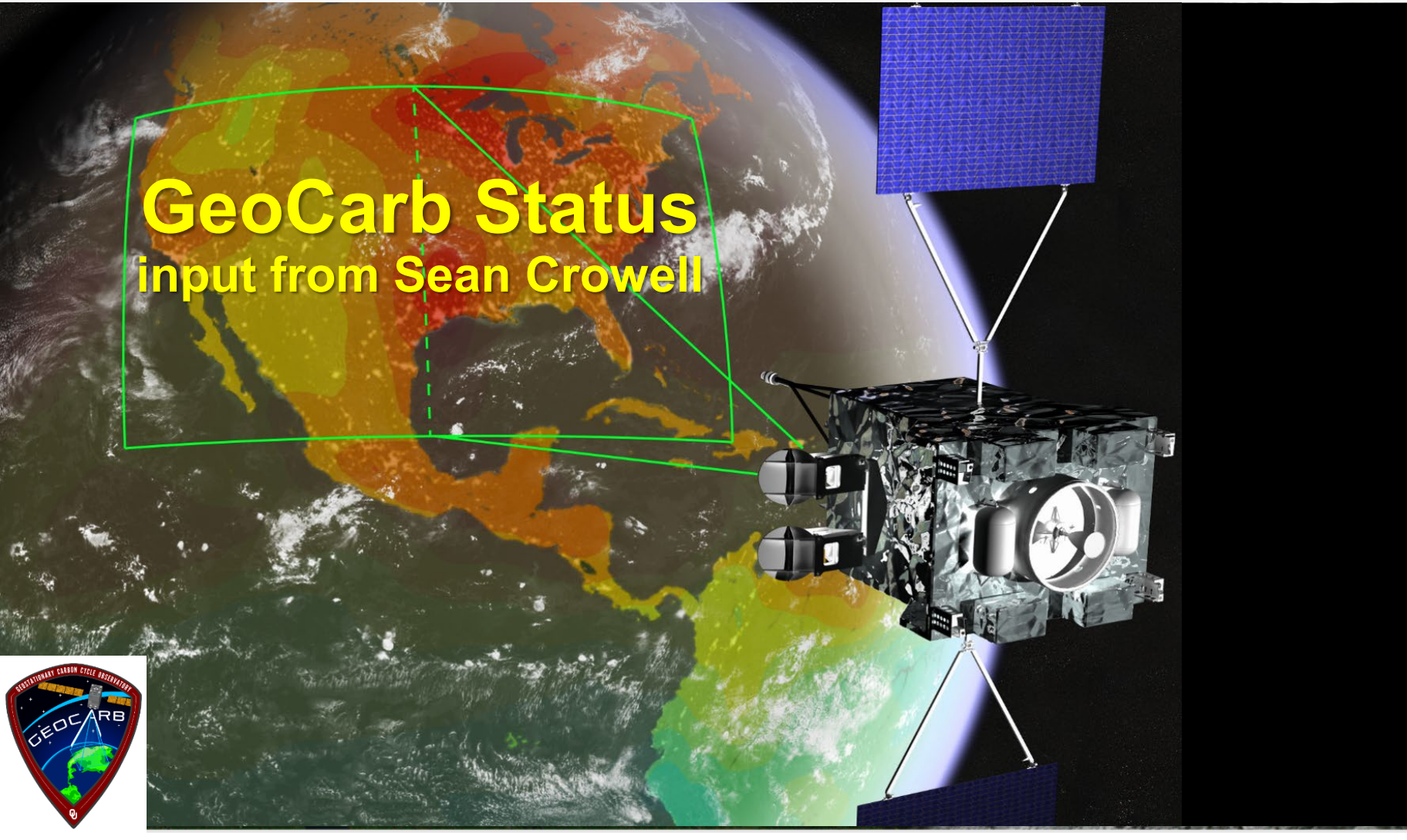
- First light in mid-June (exact timing depends on decon, PMACal, etc)
- Nominally 3 weeks from first light to end of IOC
  - First week: data collection without updating any calibration parameters
  - Second week: initial updates and further analysis
  - Third week: final updates, confirm necessary updates executed successfully
  - Dark correction can be updated after ~50 orbits
  - Need to check how well lamps compare to TVAC 3 signal levels
  - ~100 orbits each of lamp and dark data can be used to update the bad pixel map
- After a successful BPM update, the Cal Team will be ready to exit IOC
  - Cal team will focus on Radiometric Calibration during IOC, but will also check Geometric, Spectral, and Polarimetric calibration in early ops
- Nominal end of IOC – on or before July 31, 2019
- L1b public release: No later than October 31, 2019

Key Dates for Science Community

Date	Data release
2-4 weeks after IOC ends (~ end of July)	Prelim orbit segments of XCO2 and SIF – to show early data and provide realistic file samples
During L1b development (~Sept)	Prelim examples of TCCON target and SAMs
90 days after IOC ends (**15 Oct 2019**)	**L1b release**
Focused Science Team Meeting	22-24 October at NCAR
~AGU timeline	Prelim 1 month of data
90 days after L1b release (**15 Jan 2020**)	**L2 release**

GeoCarb Status

input from Sean Crowell



GeoCarb Project Overview

NASA Earth Venture Mission 2 (EVM-2)

- PI Led; Modified Class D Mission, Berrien Moore (U. Oklahoma, PI, Sean Crowell Deputy PI)
- Cost capped at $170.9M (RY$)

Objectives:

- Significantly improve knowledge of terrestrial fluxes of CO_2 and CH_4 at science & policy relevant scales
  - Transformational advance in determination of processes
  - Directly addresses unanswered questions
- Solar-Induced Fluorescence (SIF) application provides c
  - Drought Index
  - Monitor growing conditions

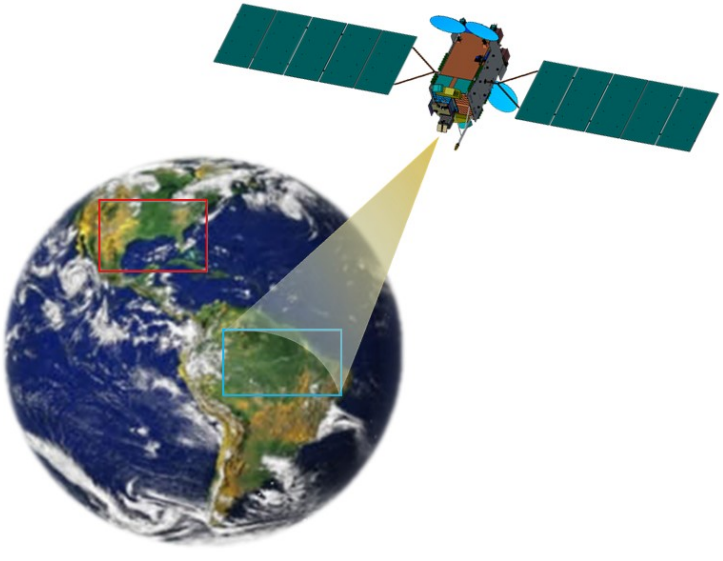
Complete mission

- Instrument
- Hosted Spacecraft
- Mission Operations
- Ground Operations
- Science Operations
- Communications & Public Outreach

Current launch opportunity with SES is at 103 W with launch in June 2023

- 11 months later than July 2022 target launch date

Experienced International Team at the forefront of carbon cycle science



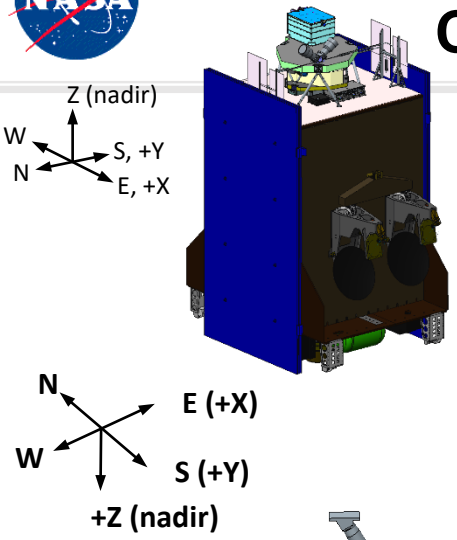
GeoCarb Status

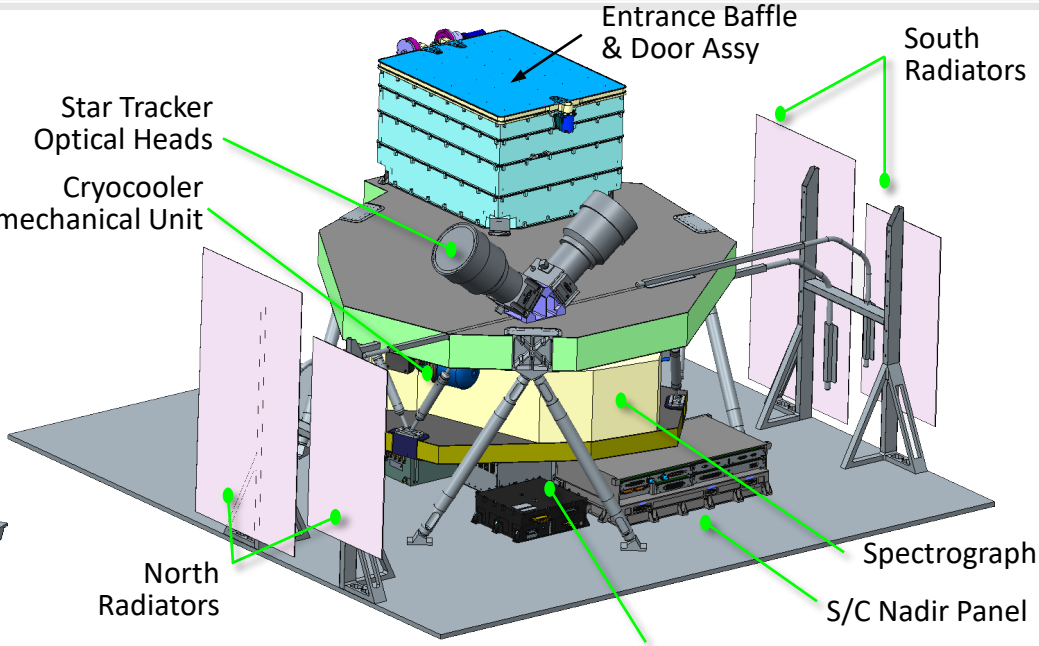
- A successful δ-PDR was held on 20-21 February
  - The Standing Review Board was impressed with team's ability to implement a project-wide descope that reduced cost but also kept the mission scientifically viable
  - Increased their confidence in the GeoCarb management strategy and ability to handle issues that arise downstream

- Current best hosting opportunity at 103 W (baseline was 85 W)
  - Introduces large air masses for eastern-most tip of South America affected
  - Simulations being conducted to assess impact of accuracy and coverage

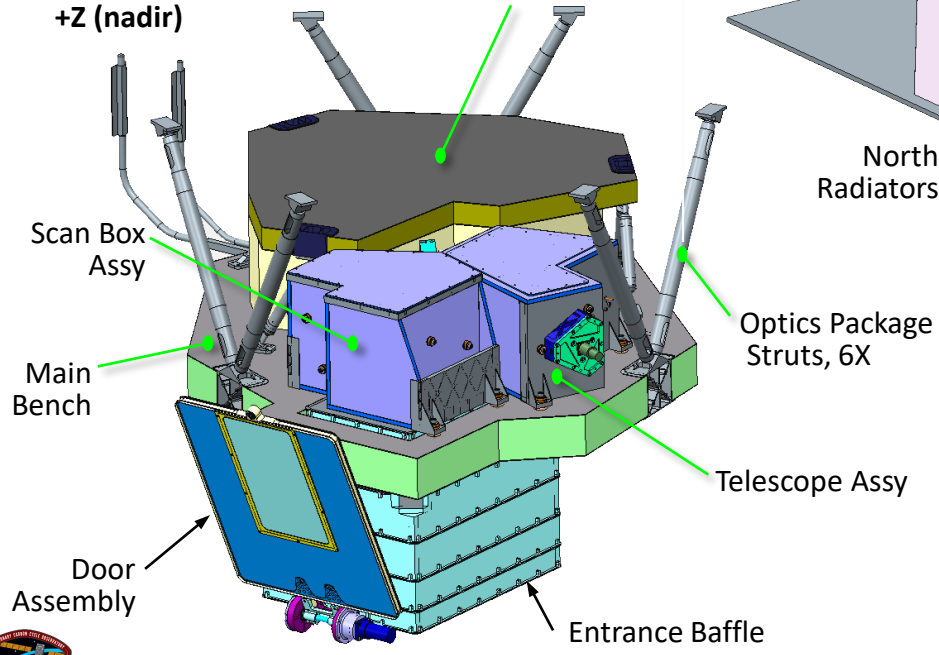
- Next step: Key Decision Point C (KDP-C, or "confirmation")
  - May 21st at NASA HQ
  - Executive leadership at NASA HQ will vote

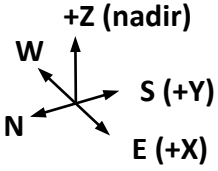
Instrument Implementation on a Commercial Communications Satellite at GEO





Nadir Panel Mounted Components
- GeoCarb Electronics Box (GEB)
- Focal Plane Electronics Box (FPE)
- Star Tracker Electronics Unit (STEU)
- Decoder Electronics Box (DEB)
- Cryocooler Electronics (CCE)





Instrument Optical Layout

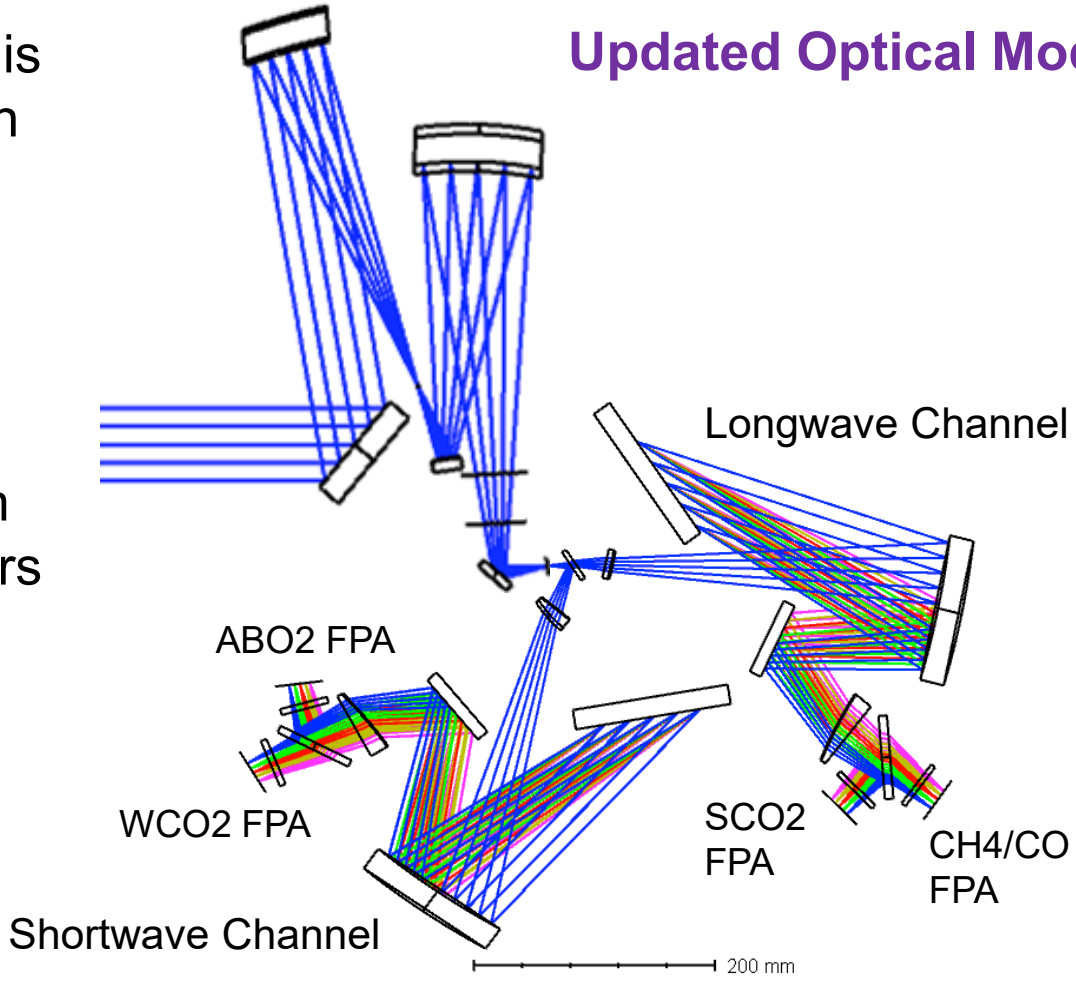
The GeoCarb instrument is a 4-Channel spectrograph split between:

- ABO2 +WCO2
- SCO2+CH4/CO

Echelle gratings used in multiple orders with beam splitters and blocking filters to isolate bandpasses.

Four (1024^2) HgCdTe H1RG detectors

Updated Optical Model



Science Impacts of Instrument De-scope

- Optical redesign: reduction of SNR from smaller aperture area - <u>doubled stare time to meet SNR reqts</u>
  - SNR has margin in all channels, despite the presence of increased noise from thermal glow
  - Areal coverage rate retained by removal of double sampling
- Removal of Secondary Solar Calibration Drum: redundancy to assess changes in primary diffuser – <u>already planned lunar observations will be sufficient</u>
  - Lunar observations will be used to assess changes in the calibration over time. This methodology has been demonstrated by OCO-2. Working with lunar cal experts to adapt the OCO-2 approach for GeoCarb sampling
- Removal of IMU: expected pointing knowledge is reduced by ~0.1km, but it <u>still meets MDRA requirements</u>

GeoCarb meets all Level 1 requirements and satisfies the mission hypotheses with the de-scoped project, though with reduced performance margin

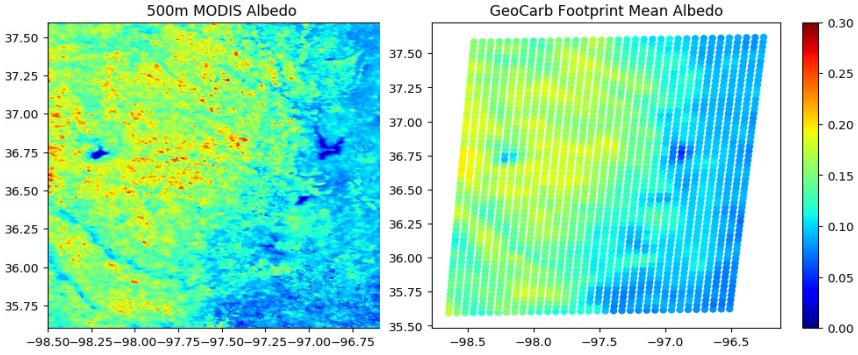
Significant Changes

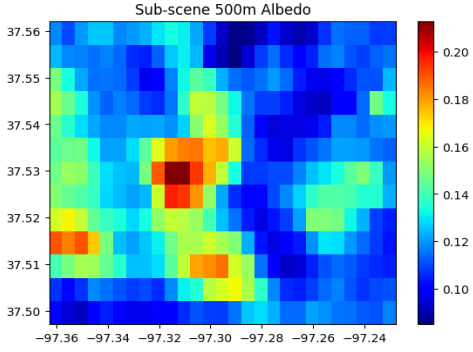
Item	PDR	DPDR	% change
Instrument Mass (CBE/MEV)	186 kg / 213 kg	157 kg / 183 kg	-16% / -14%
Instrument Power (CBE/MEV)	406 W / 538 W	393 W / 521 W	-3% / -3%
Data Rate	18.7 Mbps	9.3	-50%
Funded Schedule Reserve	71 days	71 days	0%

Descope efforts have significantly increased the financial health and key contingencies of GeoCarb while maintaining performance that satisfied the Level 1 Requirements and mission objectives

Impacts of Non-uniform Illumination

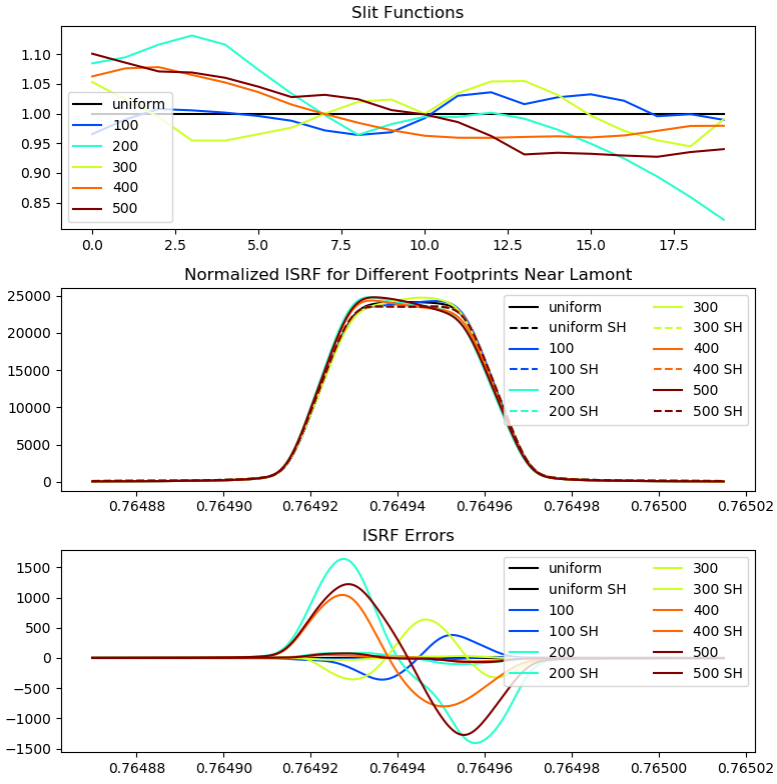
- Spatial variations in illumination across the slit introduce biases by modifying the instrument line shape (ILS)
- Modification of ILS tested using 500m MODIS albedo variations for a 2°x 2° degree region around Lamont, OK



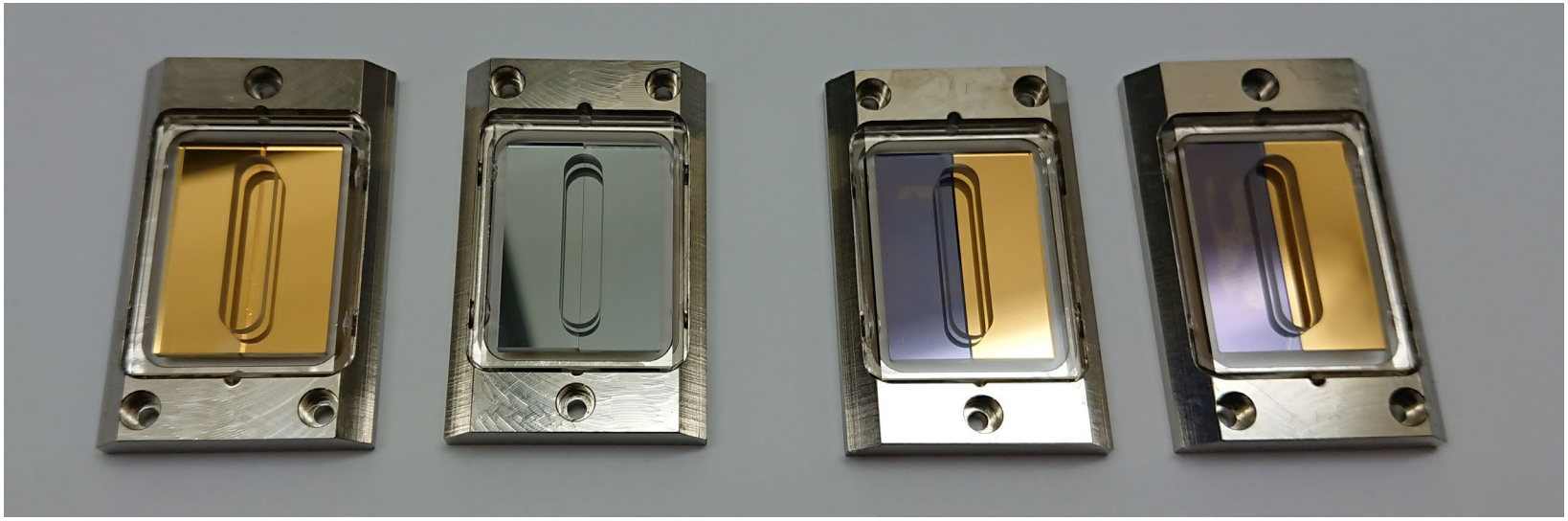


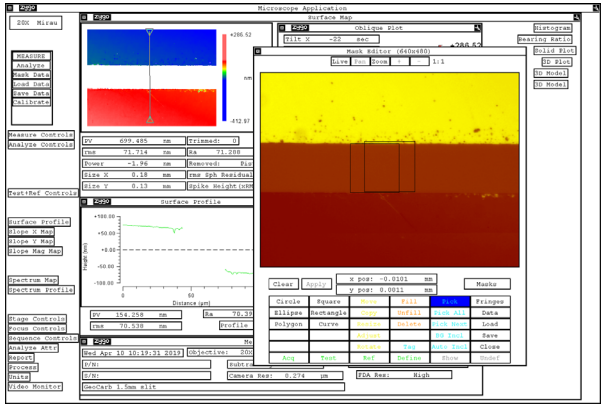
Albedo Variations within a Footprint

Sample ILS with and w/o a 1-D slit homogenizer for different variations in albedo across the slit



Slit Homogenizer Development





- Non-flight 1-d slit homogenizers have been fabricated by two vendors and shipped to ITO for testing (3 depths X 2 from each)
- Initial quality checks look good
- Slit widths 33-34 um
- Flight models will be ordered by end of June

Significant Accomplishments Since PDR

- **Project descope increased cost reserves and reduced instrument mass**
  - Instrument descope
  - Science prioritization
  - Ground system processing reductions and optimization
  - Completed assessment and impact of descopes on Level 1 & 2 requirements
  - Updated concept of operations
  - Revised project plan to increase project cost reserves
- **Science:**
  - Improved model used for in-depth study of scene inhomogeneity, instrument calibration/characterization, and error budgets
  - Level 2 algorithms are producing CO/CH4/CO2 – plan to test on TROPOMI
  - Level 2 retrievals coupled to performance results from the instrument model
- **Instrument**
  - Descoped instrument to achieve mass and cost reductions
  - Still meet Level 1 requirements
  - Engineering progress continues to mature the instrument baseline
- **Ground System**
  - Determined cost savings from reduction in data rate due to instrument descope
  - Exploring cost reduction opportunities through the use of cloud-based and existing NASA computing resources – retrieval timing tests, throughput

Key Near Term Activities

Planned Date	Activity Description
13-17 May	ESA Living Planet Symposium, Milan, Italy
21-22 May	NOAA ESRL GMD Annual Conference, Boulder
2 Jun	GeoCarb Science Team Meeting, Sapporo, Hokkaido, Japan
3-5 Jun	IWGGMS-15, Sapporo, Hokkaido, Japan
10-12 Jun	CEOS AC-VC, Tokyo, Japan
17-20 Jun	CALCON, Logan Utah
17 Jun	OCO-3 First Light
30 Jun-5 Jul	2019 RRV Campaign
7-18 Jul	27th IUGG General Assembly 8-18 July, Montreal, Canada
26-29 Aug 2019	Chapman Conference: Carbon-Climate Feedbacks, San Diego
October 31	OCO-3 L1b Product Delivered