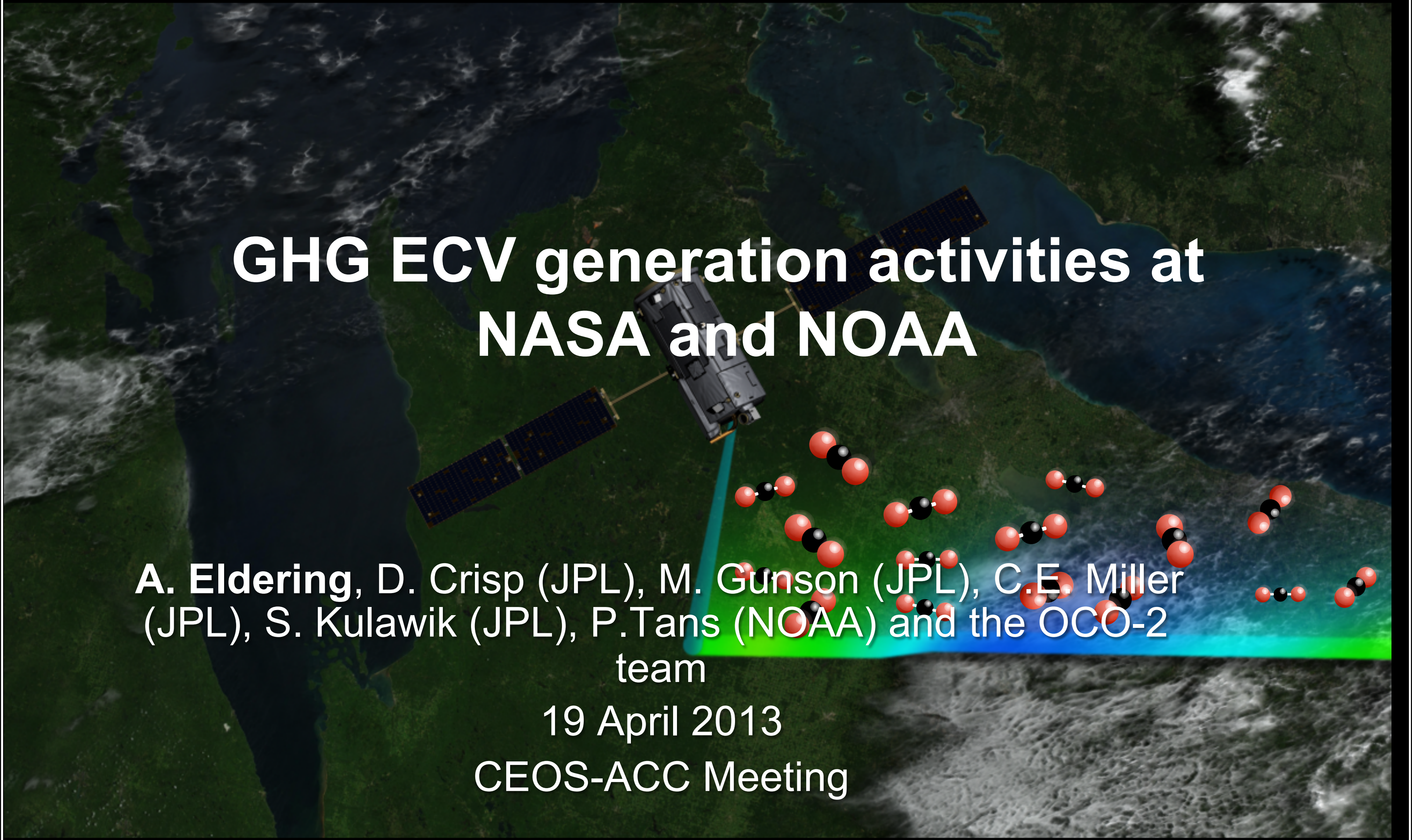
The Orbiting Carbon Observatory-2 (OCO-2) Mission

Watching The Earth Breathe…Mapping CO_2 From Space



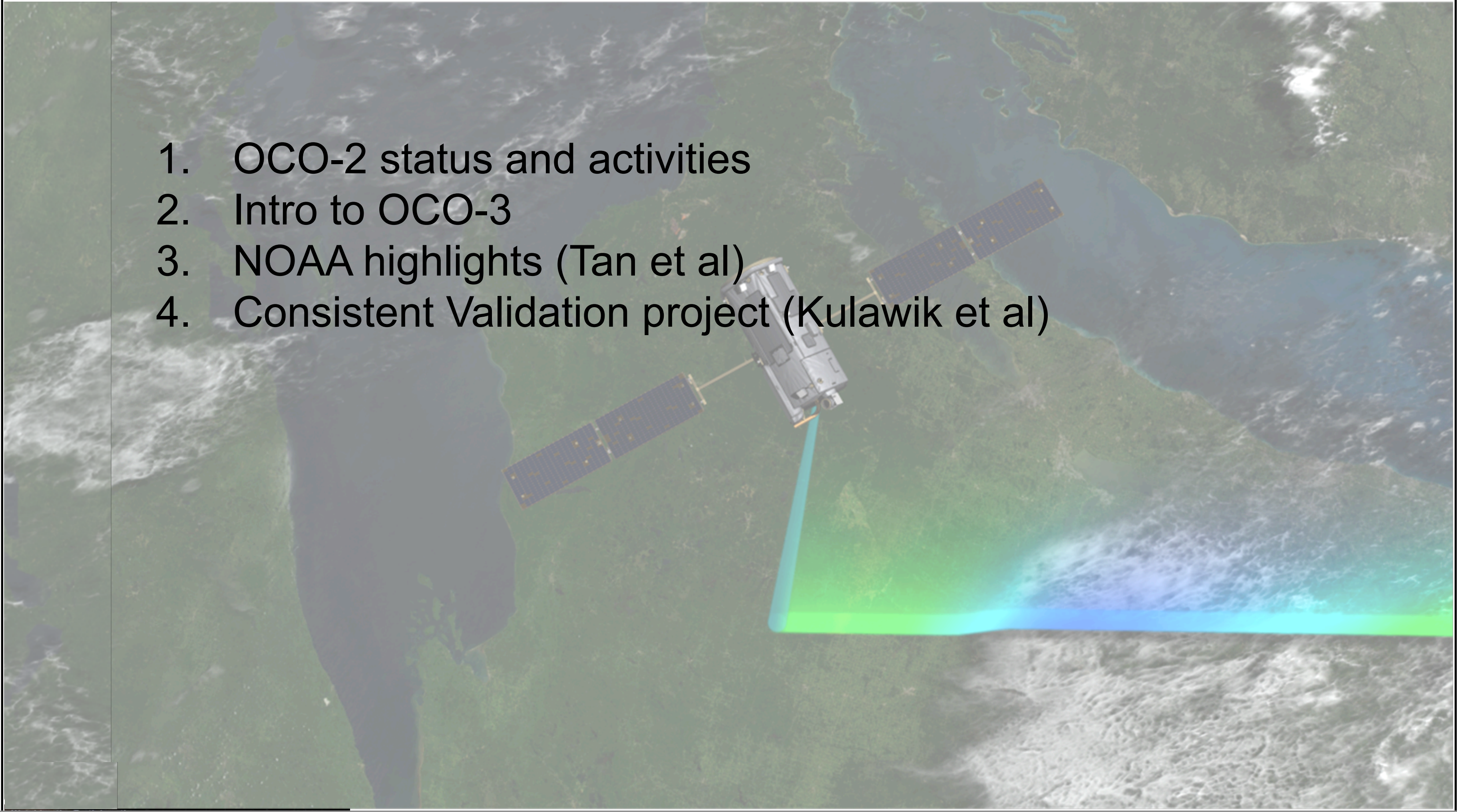
GHG ECV generation activities at NASA and NOAA

A. Eldering, D. Crisp (JPL), M. Gunson (JPL), C.E. Miller (JPL), S. Kulawik (JPL), P.Tans (NOAA) and the OCO-2 team

19 April 2013

CEOS-ACC Meeting

Outline



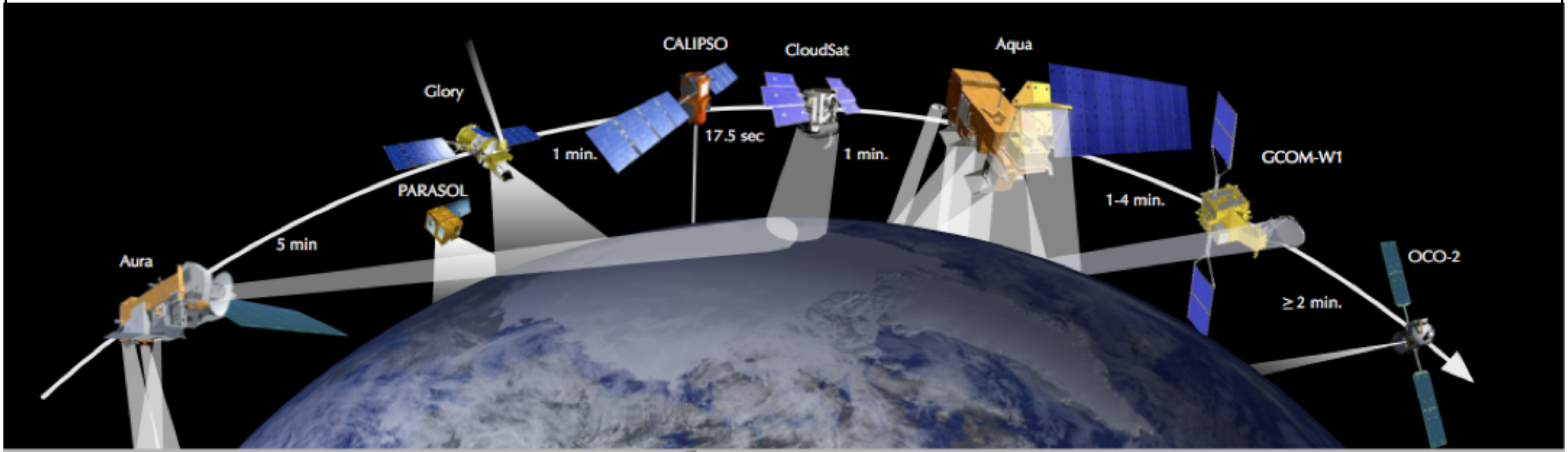
1. OCO-2 status and activities
2. Intro to OCO-3
3. NOAA highlights (Tan et al)
4. Consistent Validation project (Kulawik et al)

OCO-2: The Future Lead of the A-Train Constellation

Jet Propulsion Laboratory
California Institute of Technology

The Orbiting Carbon Observatory - 2 (OCO-2)

Watching The Earth Breathe…Mapping CO2 From Space



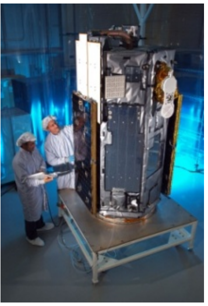
- OCO-2 will “lead” the A-Train in the slot just ahead of GCOM-W1 with a launch in July 2014

- NASA’s Orbiting Carbon Observatory (OCO-2) is designed to return space-based measurements of atmospheric carbon dioxide (CO_2) with the sensitivity, accuracy and sampling density needed to quantify regional scale carbon sources and sinks and characterize their variability.

ULA Delta II to Launch OCO-2 Observatory

3-Channel Spectrometer (JPL)

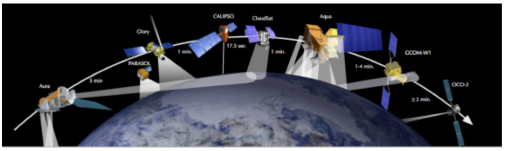
Dedicated Spacecraft Bus (OSC)



Delta II Launch Vehicle (ULA)

Mission Operations (OSC)

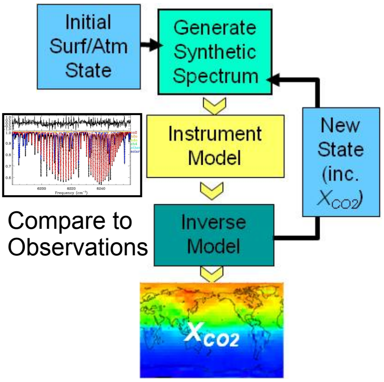
Formation Flying as Part of the A-Train Constellation



NASA GN (GSFC) and SN (TDRSS)

Science Data Operations Center (JPL)

L2 X_{CO2} Retrieval



Initial Surf/Atm State

Generate Synthetic Spectrum

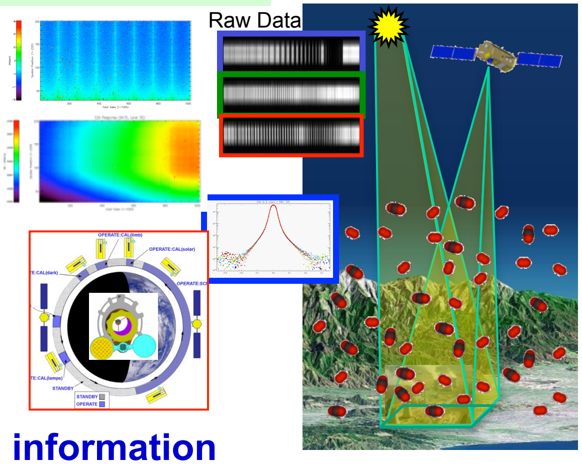
Instrument Model

Inverse Model

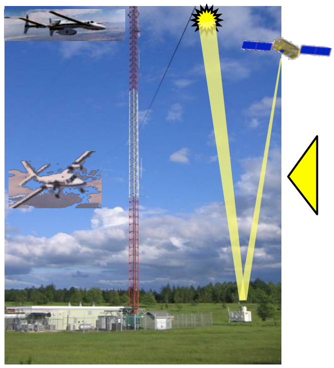
New State (inc. X_{CO2})

Compare to Observations

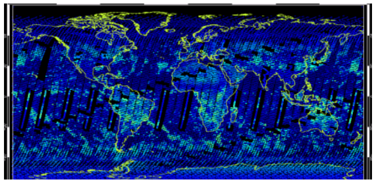
Calibrate Data

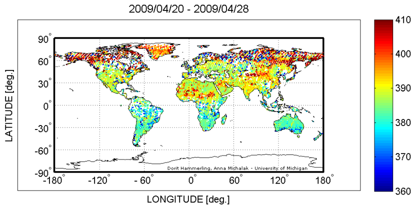


Validation Program



Products Delivered to the GES DISC

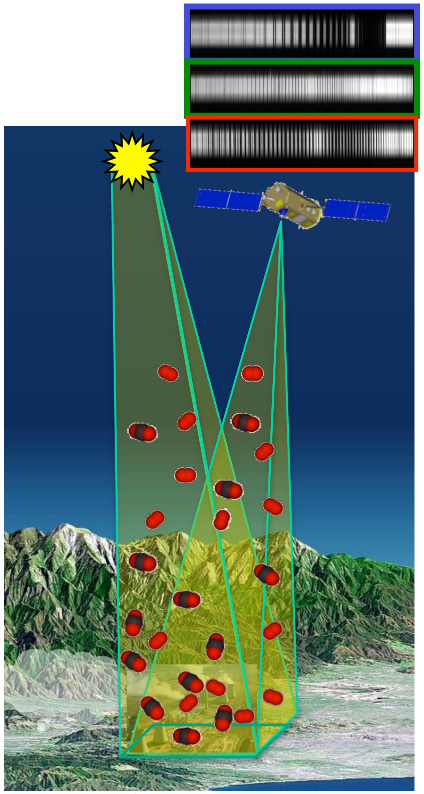




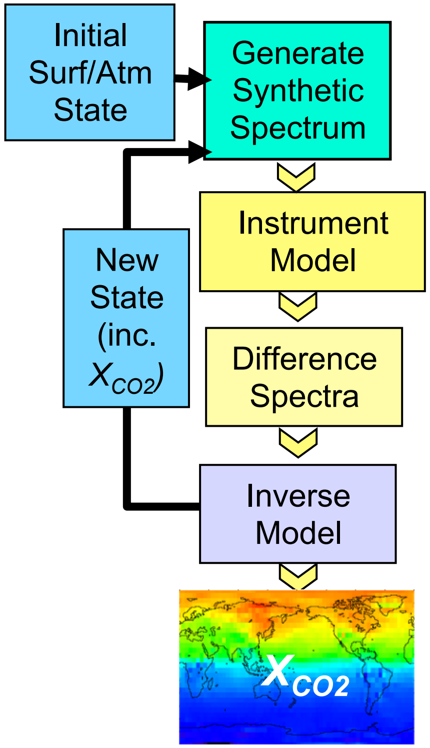
Please visit http://oco.jpl.nasa.gov for more information

Measurement Approach

Collect spectra of CO_2 & O_2 absorption in reflected sunlight over the globe



Retrieve variations in the *column averaged CO_2 dry air mole fraction, X_{CO2}* over sunlit hemisphere



Initial Surf/Atm State

Generate Synthetic Spectrum

Instrument Model

Difference Spectra

Inverse Model

New State (inc. X_{CO2})

X_{CO2}

Validate measurements to ensure X_{CO2} precision of 1 - 2 ppm (0.3 - 0.5%)

The Need for High Precision

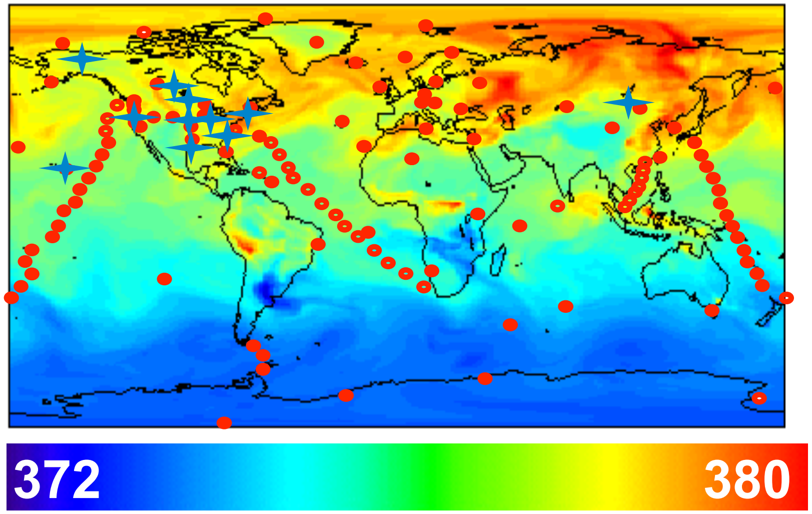
CO_2 sources and sinks must be inferred from spatial variations in the (>380 ppm) background CO_2 distribution

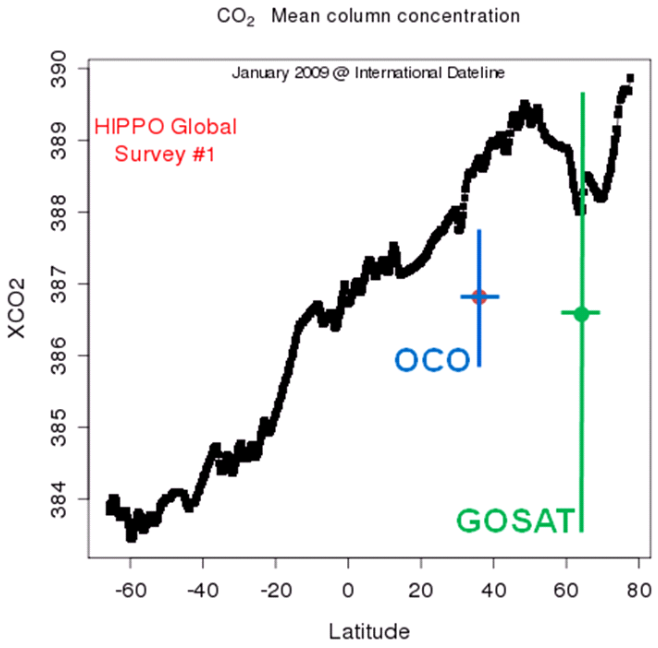
- Largest variations near surface

Space based NIR measurements constrain column averaged CO2, X_{CO2}

High precision is essential to resolve small (<2%) spatial variations in X_{CO2}

- OCO precision: <0.3% (1 ppm) verified at validation sites seasonally (over 100 soundings)



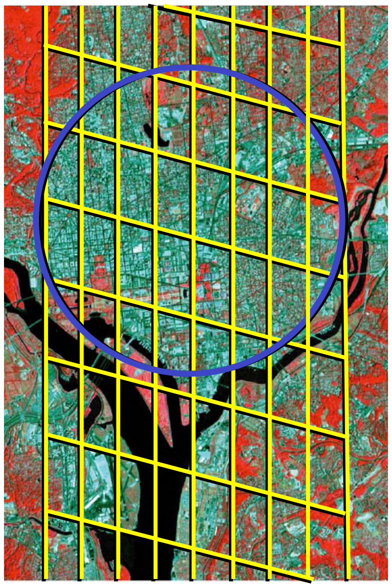


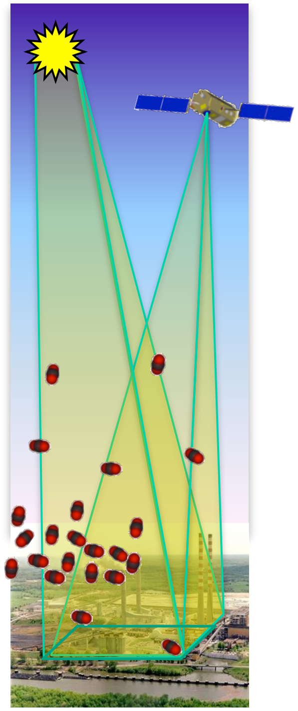
The nominal, regional scale X_{CO2} precision targets for the OCO and GOSAT instruments (blue and green, as indicated) are compared to the X_{CO2} cross-section measured by recent transects of the NSF HIAPER aircraft (S. Wofsy, private communication, 2009).

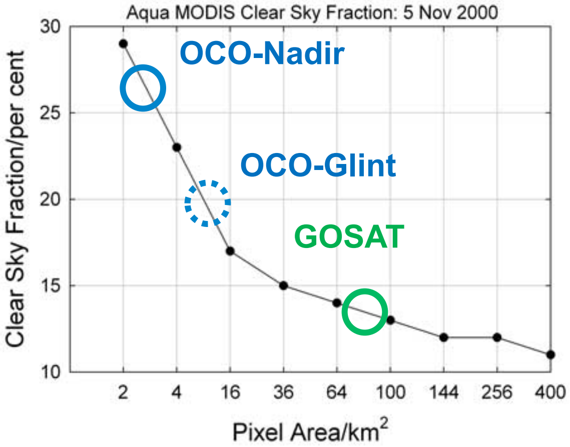
High Spatial Resolution Is Also Needed

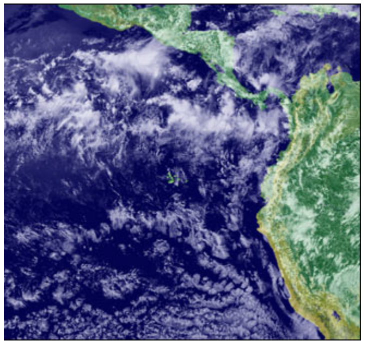
A small sounding footprint increases:

- Ability to record cloud free soundings in partially cloudy regions
    - Probability decreases with increasing optical path length and footprint area
    - Footprint 1.3km x 2.25km
- Ability to clearly discriminate discrete point sources
- Sensitivity to discrete CO_2 point sources
    - For a given precision (e.g. 1 ppm), detection limit (kg of CO_2) scales as 1/footprint area





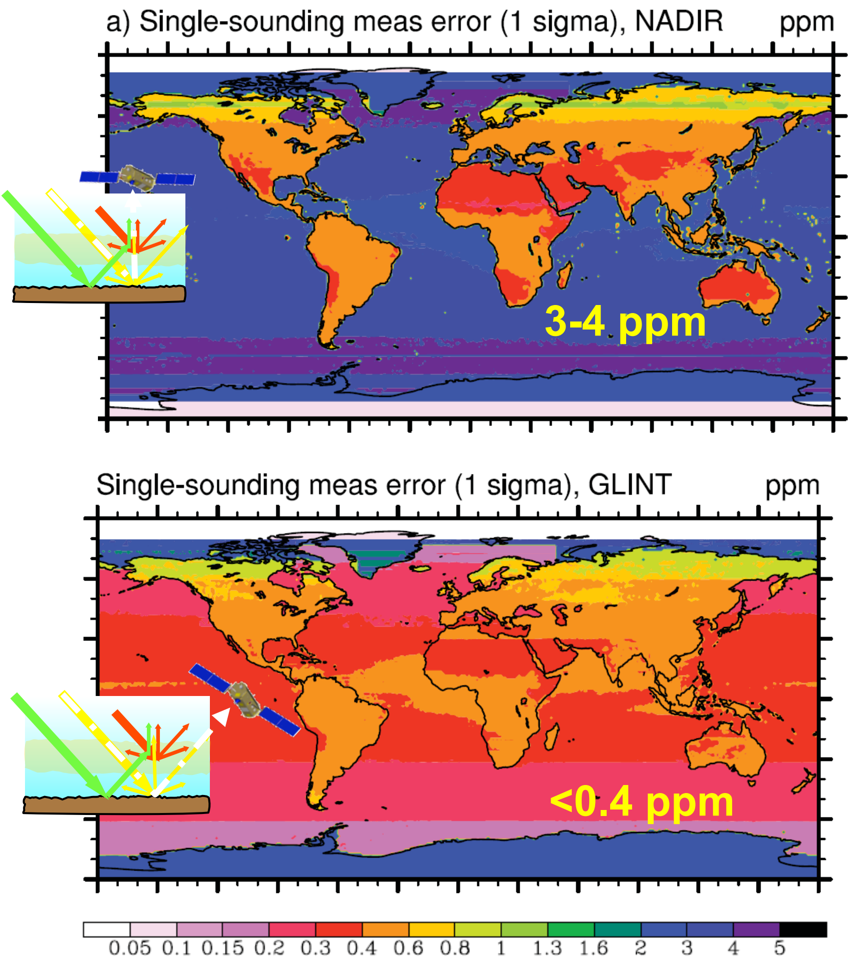




High SNR Coverage Needed over both Continents and Oceans

Full global coverage is needed to:

  - Resolve sources and sinks over both land and ocean;
  - Track air masses over the full range of latitudes, minimizing errors introduced as CO_2 is transported in an out of field of regard
- Nadir Observations:
  - More homogenous, cloud-free scenes over continents
  - Low Signal/Noise over dark surfaces
- Sun Glint observations
  - High signal/noise over dark ocean and ice covered surfaces
  - Somewhat more cloud interference



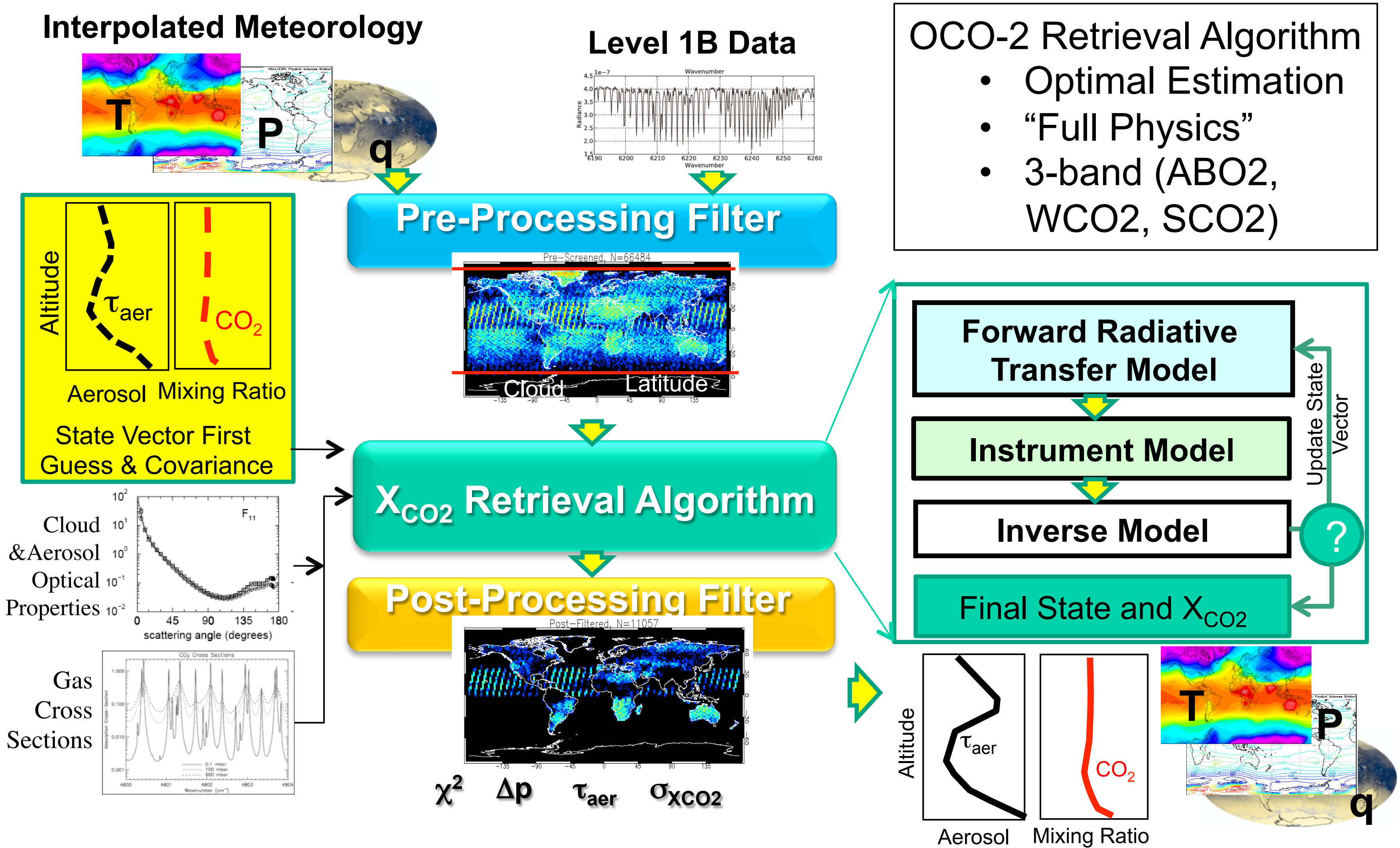
Single sounding random errors for nadir and glint [Baker et al. ACPD, 2008].

Global Measurements Every 16 Days

Jet Propulsion Laboratory
California Institute of Technology

OCO will provide uniform global coverage, collecting about 16 million measurements of atmospheric carbon dioxide every 16 days.

Retrieving X_{CO2} from OCO-2 Spectra



OCO-2 Retrieval Algorithm

- Optimal Estimation
- "Full Physics"
- 3-band (ABO2, WCO2, SCO2)

Pre-Processing Filter

State Vector First Guess & Covariance

X_{CO2} Retrieval Algorithm

Post-Processing Filter

χ^2 Δp τ_{aer} σ_{XCO2}

Forward Radiative Transfer Model

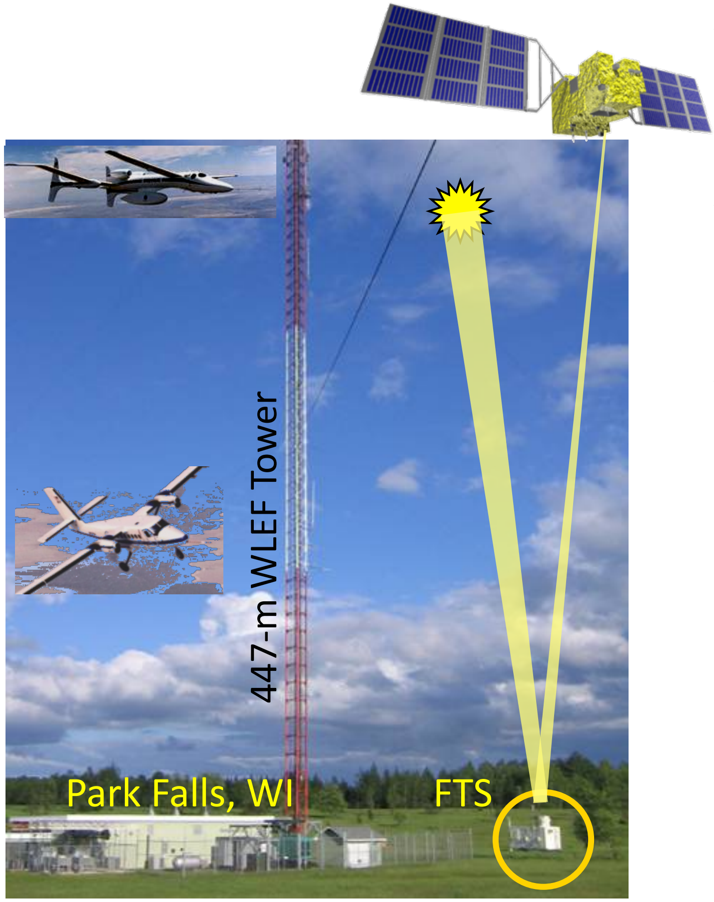
Instrument Model

Inverse Model

Final State and X_{CO2}

The ACOS Project: Processing and Validating X_{CO2} from GOSAT

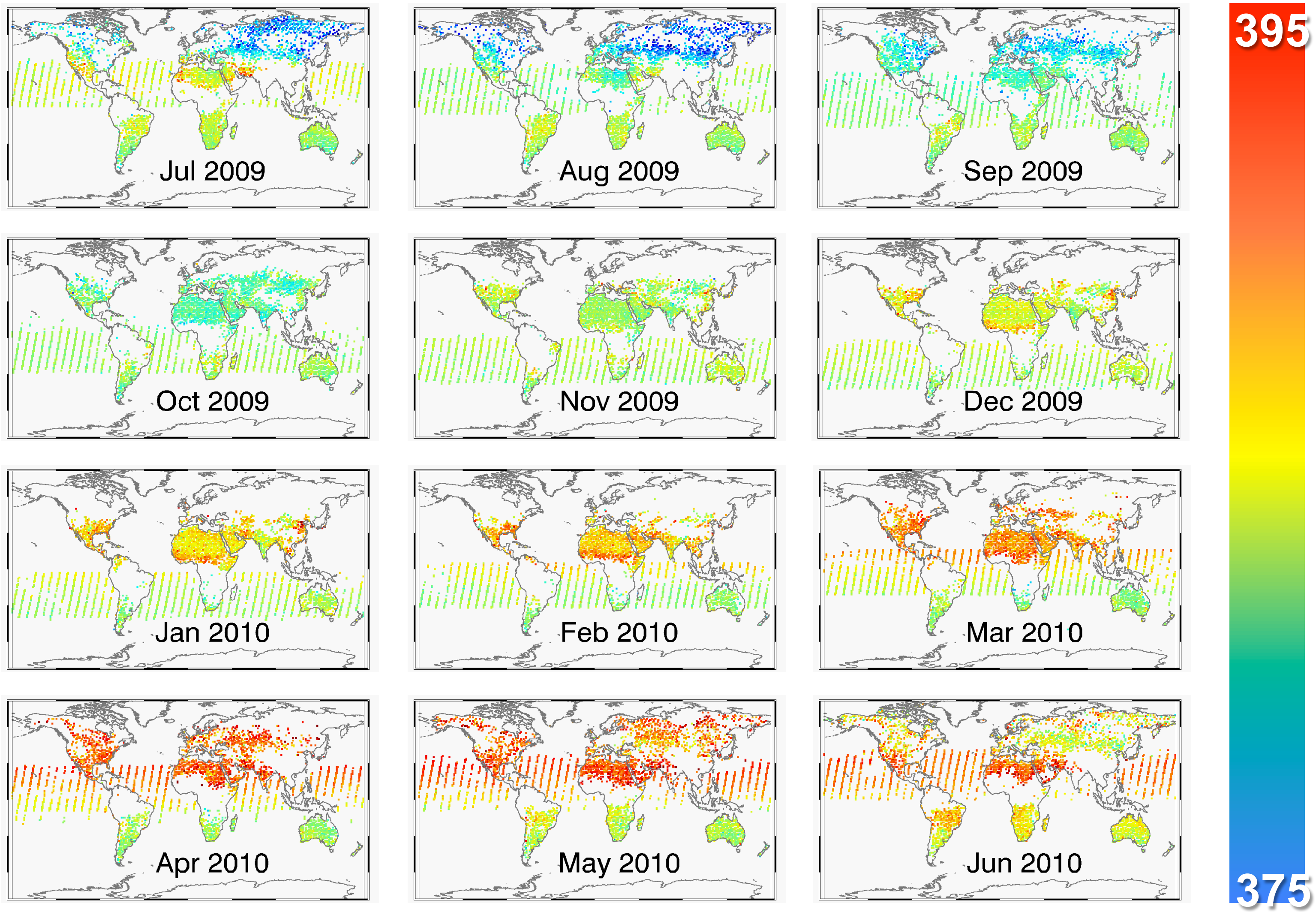
Jet Propulsion Laboratory
California Institute of Technology



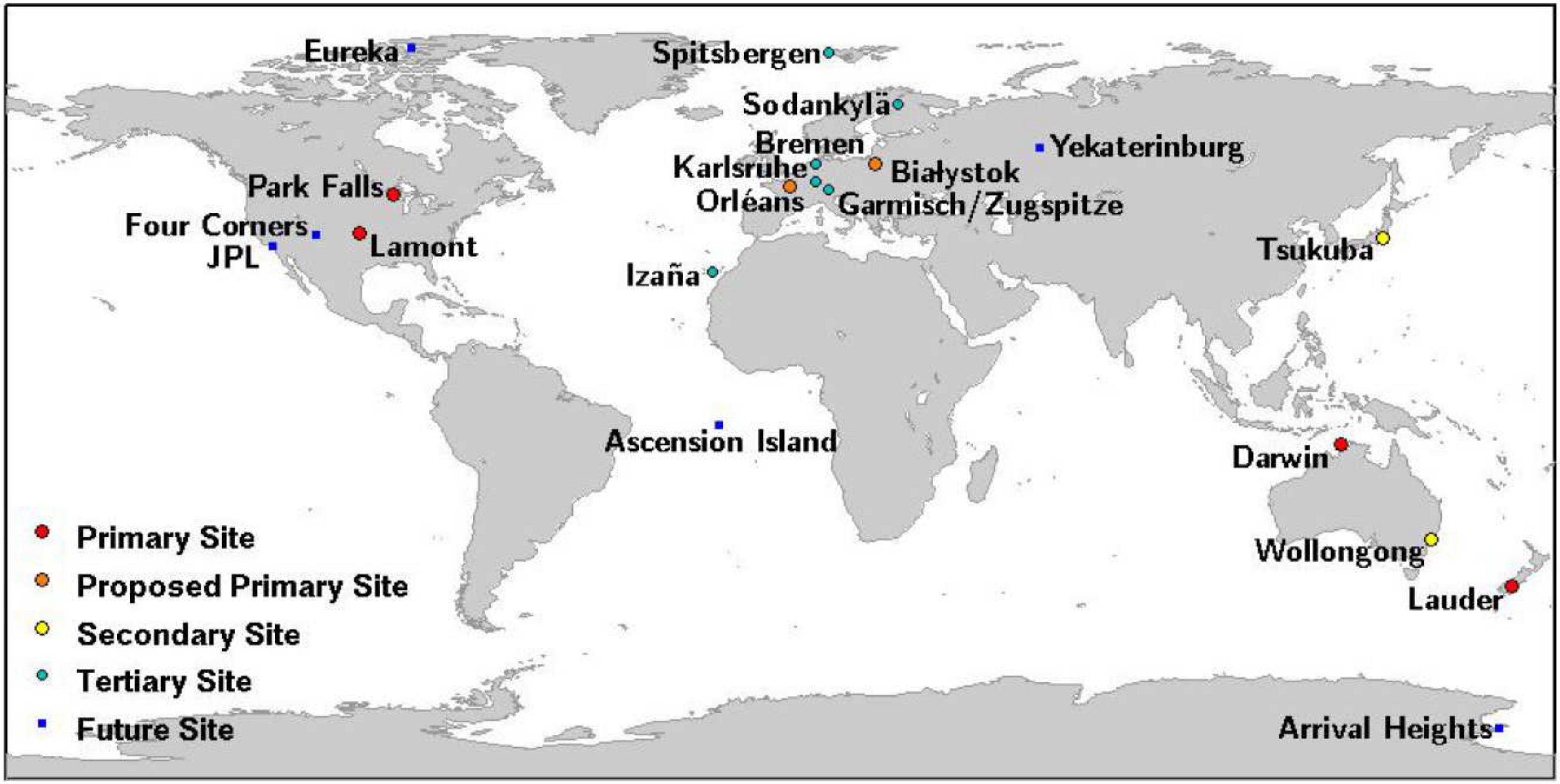
- The Japanese GOSAT satellite is measuring over the same spectral region as OCO-2 with an FTS (TANSO-FTS)
- These measurements are being processed through the OCO-2 retrieval algorithm
- A critical element of the validation strategy was the Total Carbon Column Observing Network (TCCON)
  - High resolution FTS's measure the absorption of direct sunlight by CO_2 and O_2, in the same spectral regions used by the TANSO-FTS.
- We are now comparing the ACOS X_{CO2} from GOSAT measurements with the TCCON validation data.

Watching the Earth breathe.... mapping CO2 from space.
Orbiting Carbon Observatory

ACOS GOSAT B2.10 X_{CO2} Retrievals



Current (and Future) TCCON Sites



TCCON Measurements Validated Against Aircraft Observations

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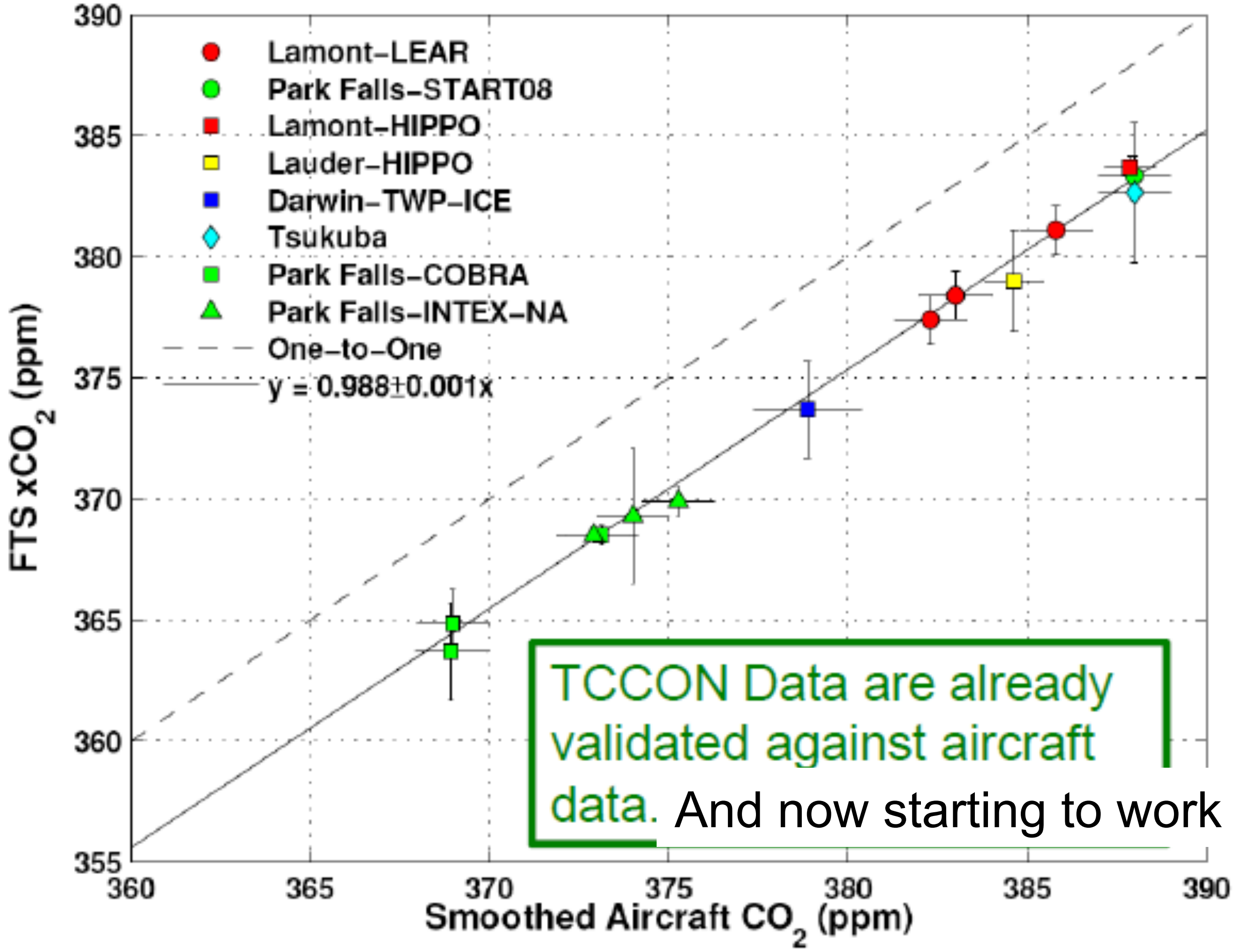
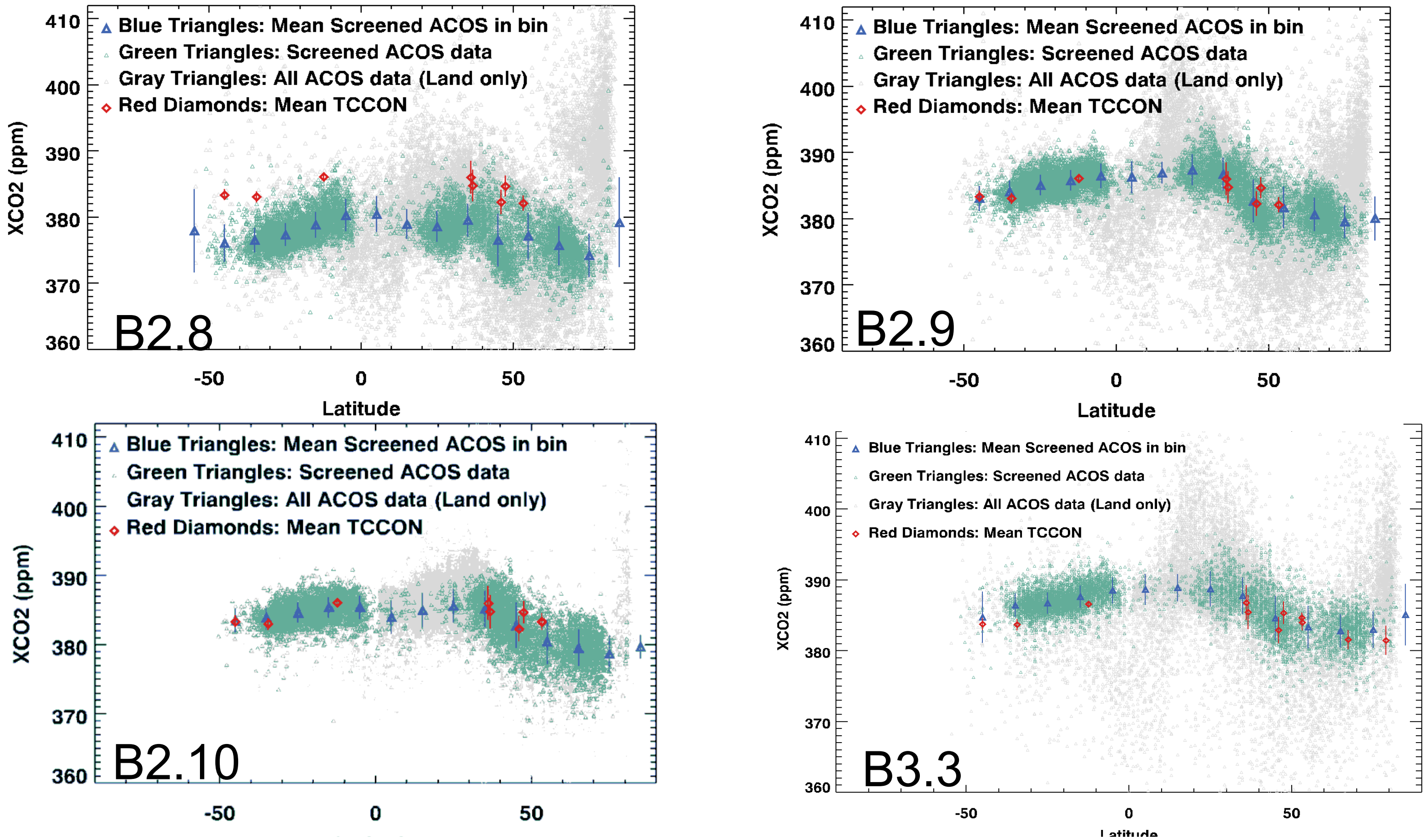
California Institute of Technology



TCCON Data are already validated against aircraft data. And now starting to work with AIRCORE

TCCON Comparisons Show Improvements in ACOS GOSAT X_{CO2} Bias and Random Error



Zonal profiles of ACOS/GOSAT XCO2 estimates (green and grey triangles) are compared to the monthly mean XCO2 estimates from TCCON stations (red diamonds) for July 2009. The precision (scatter), bias, and yield of the ACOS/GOSAT products have improved over time (Crisp et al. 2011).

Benefits of OCO-3* Carbon Cycle Science

Jet Propulsion Laboratory
California Institute of Technology

- The OCO-2 spare instrument will become OCO-3 after OCO-2 is launched

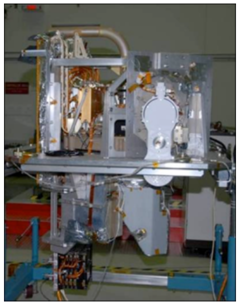
- OCO-3 on ISS has proposed to:
  - **Advance carbon cycle science and build on the capability to determine regional sources and sinks**
  - **Provide X_{CO2} data bridging the potential gap between the OCO-2 and ASCENDS missions, with highest data density at mid-latitudes**
  - Reduce errors of the carbon cycle flux in the **terrestrial biosphere** with measurements of X_{CO2} and chlorophyll fluorescence across all sunlit hours
  - Investigate the small scale **patterns of ocean carbon flux** suggested by eddy-resolving models with dense sets of glint X_{CO2} measurements
  - Detect and quantify the **spatial variability of fossil fuel emissions** in rapidly developing urban centers as opportunistic science

OCO-3* transitioned into Phase-A in Nov 2012, and will be ready for installation on ISS in early 2017

*Proposed Mission

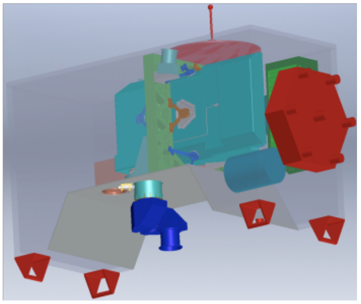
OCO-3* Mission Overview

Spare OCO-2 Instrument



Integrate with Payload Bus in JEM-EF compatible enclosure

OCO-3 Payload



Integrate with Dragon (in trunk)

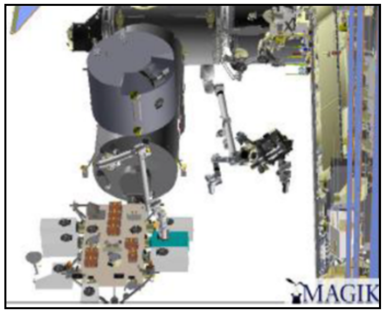
SpaceX Dragon Transfer Vehicle

Falcon-9 LV

Dragon docks with ISS

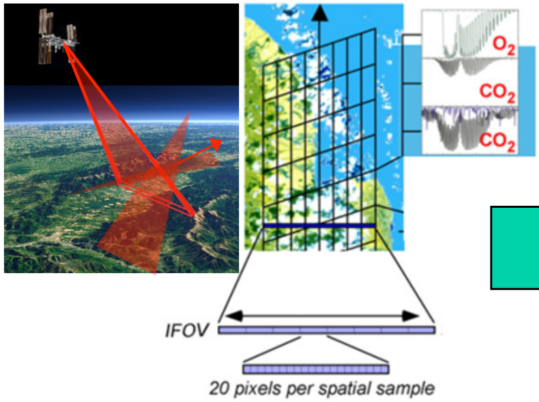
Robotic installation on JEM-EF

Installation on JEM-EF

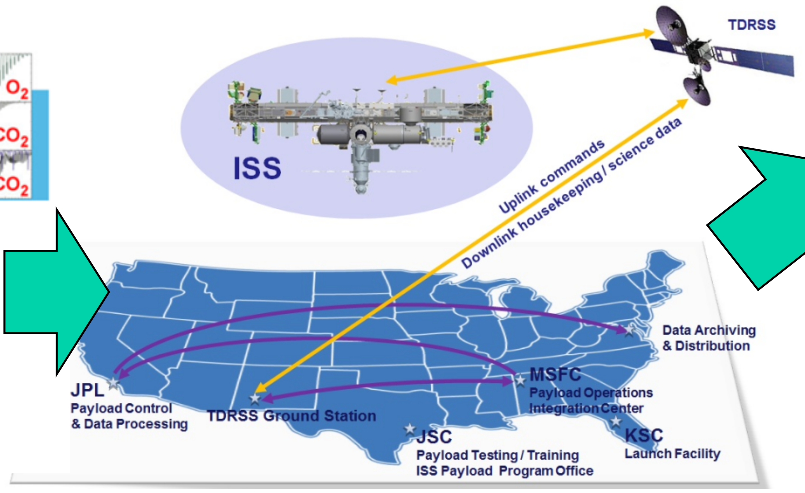


Science Operations

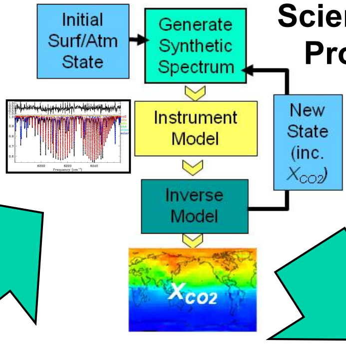
(3 years after 3 month checkout)



Command and Data Flow



Science Data Processing



Initial Surf/Atm State

Generate Synthetic Spectrum

Instrument Model

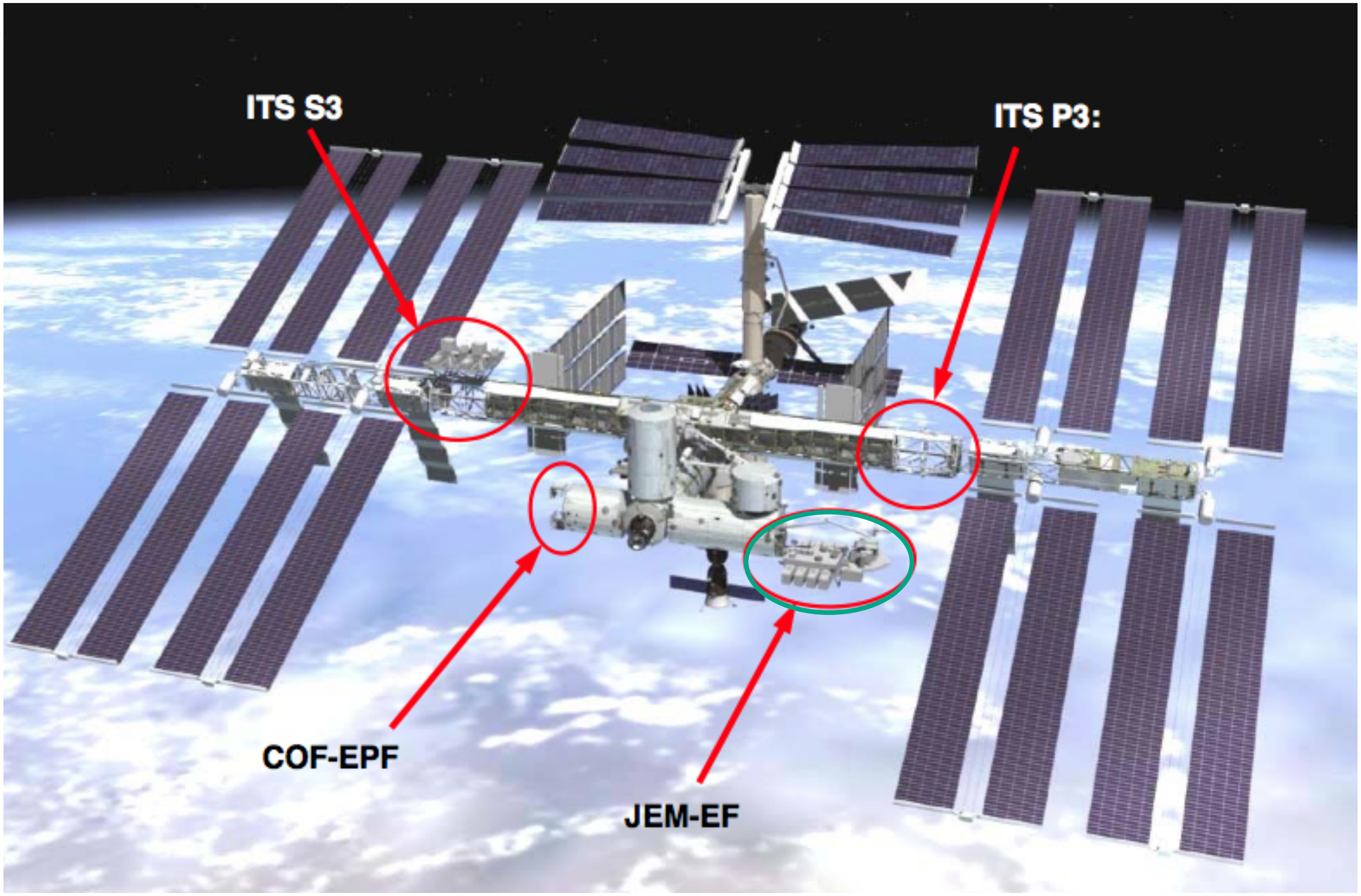
New State (inc. X_{CO2})

Inverse Model

EOL Payload disposal via Dragon Trunk re-entry

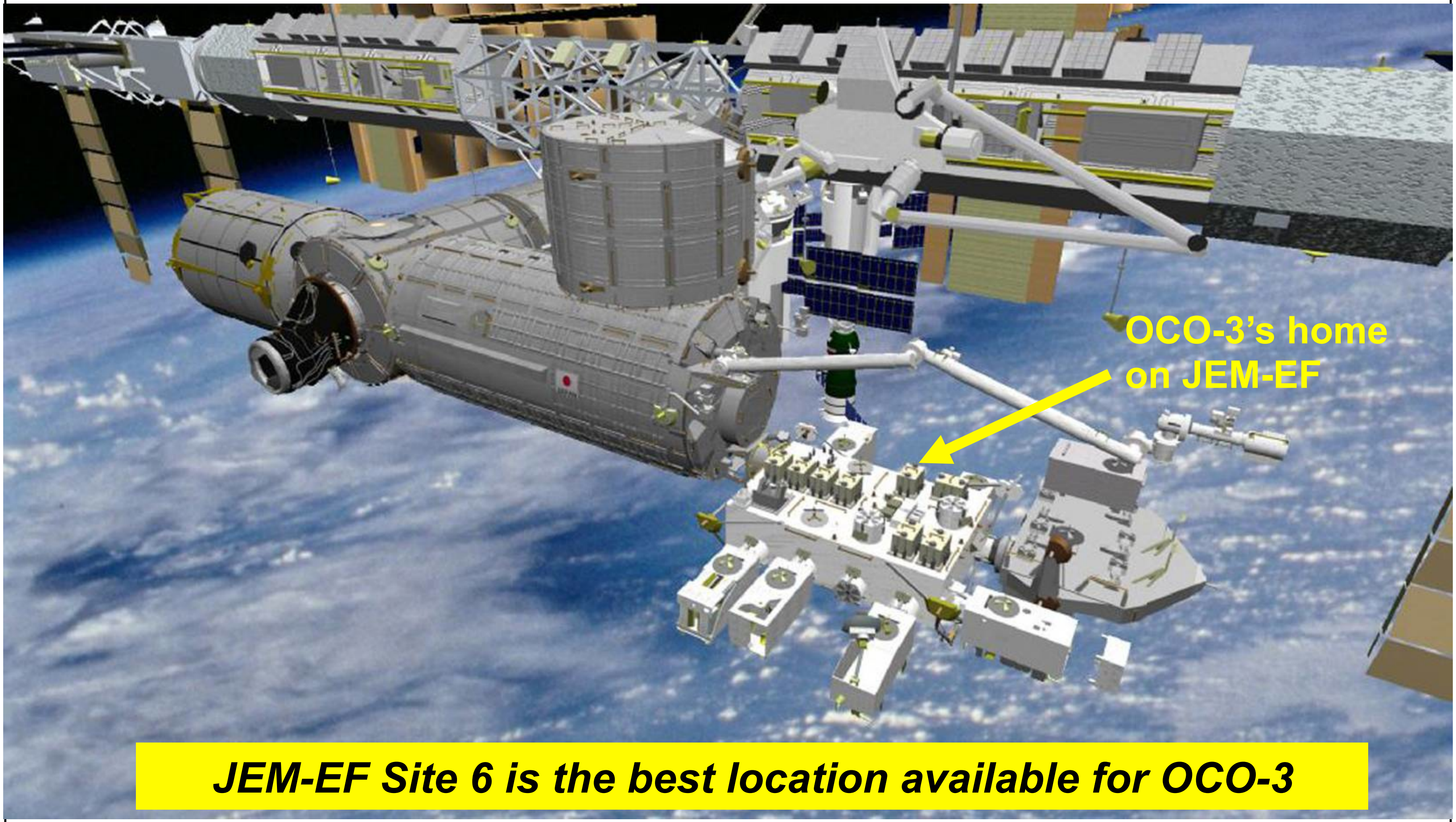
*Proposed Mission

ISS External Payload Options



*Proposed Mission

OCO-3* Accommodation on the JEM-EF



JEM-EF Site 6 is the best location available for OCO-3

*Proposed Mission

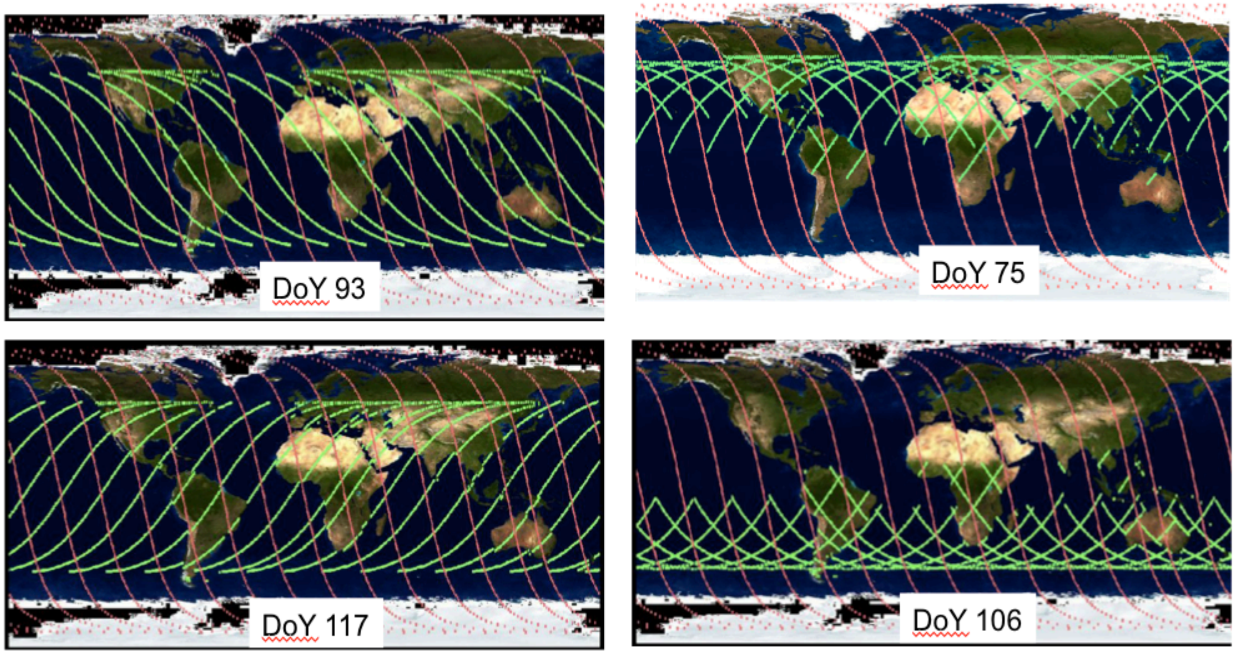
Comparison of OCO-2 and OCO-3*

	OCO-2	Proposed for OCO-3
Land Sampling	Every day (using glint and nadir measurements)	Every day
Glint/Ocean Sampling	16 days on/16 days off	Every day
Latitudinal coverage	+/- 80 degrees	+/- 52 degrees (on ISS)
Local time of day sampling	~1:30pm	Ranges across all sunlit hours (on ISS)
Expected XCO_2 single sounding precision	≤ 1%	≤ 1%
Expected XCO_2 precision for collection of 100 cloud-free soundings	≤ 0.3% (1 ppm)	≤ 0.3% (1 ppm)
Nadir and glint mode	Yes	Yes
Target mode capability	Yes	Yes
City mode capability	No	Yes

*Proposed Mission

Seasonal and Latitudinal Variations of Proposed OCO-3* Sampling from ISS

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

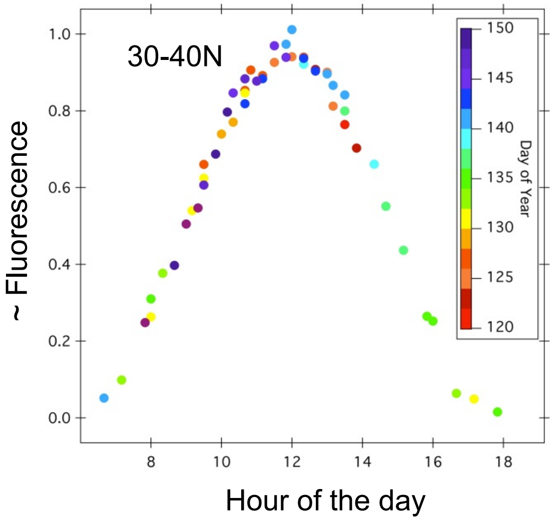


Proposed OCO-3/ISS orbits (green) and OCO-2 (pink). On "turn-around" orbits, ISS would provide better coverage of mid latitudes of one hemisphere.

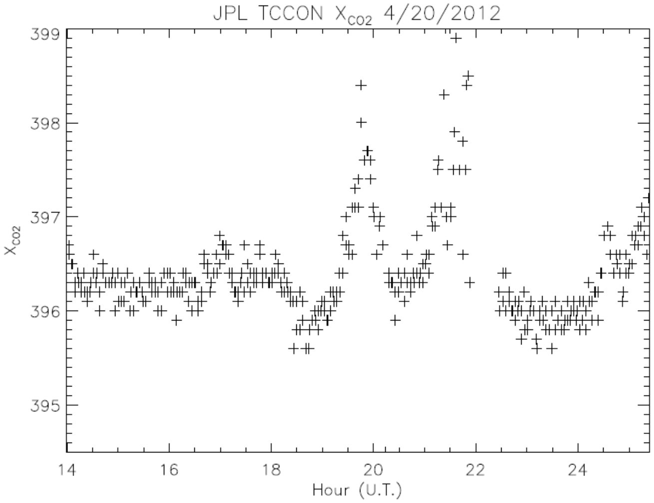
*Proposed Mission

OCO-3*: Measurements over the Diurnal Cycle

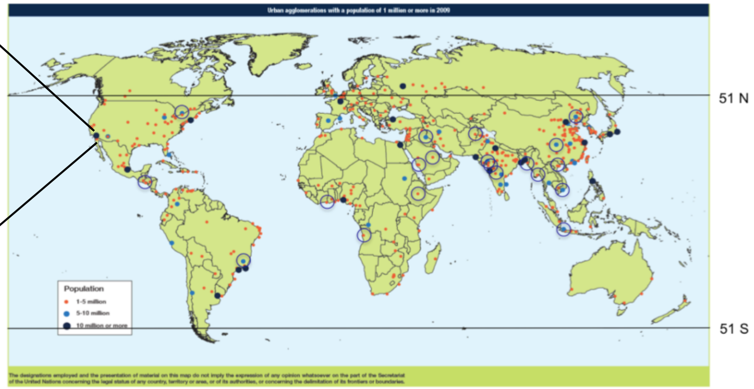
- Deployment on ISS allows sampling across all sunlit hours, facilitating studies of diurnal variations in
  - Chlorophyll fluorescence
  - Detection limits for diurnal variations in emissions from mega cities



Fluorescence amplitude vs. hour of day and season at 30 – 40 N.



TCCON observations of emission plumes over JPL.



○ Urban agglomerations predicted to grow beyond 5 million people by 2015 (Cohen, 2004)

World Urbanization Prospects: The 2009 Revision United Nations, 2010

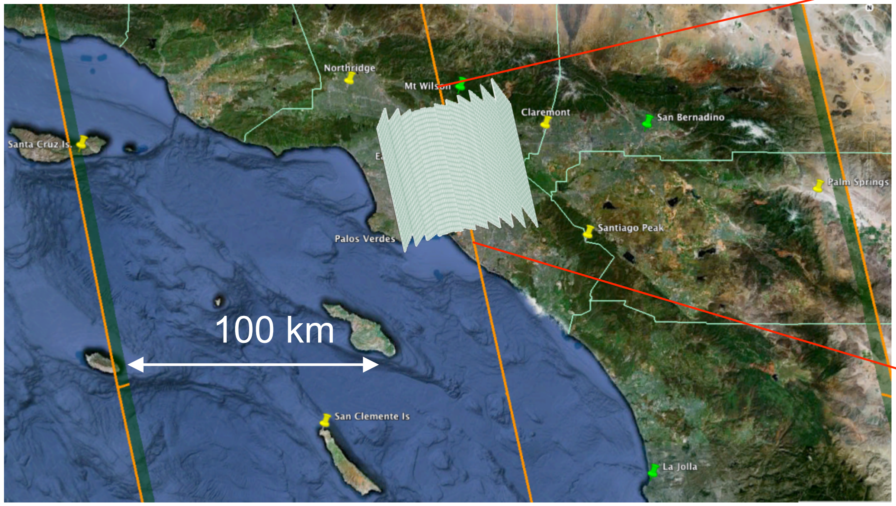
Fastest growing mega cities.

*Proposed Mission

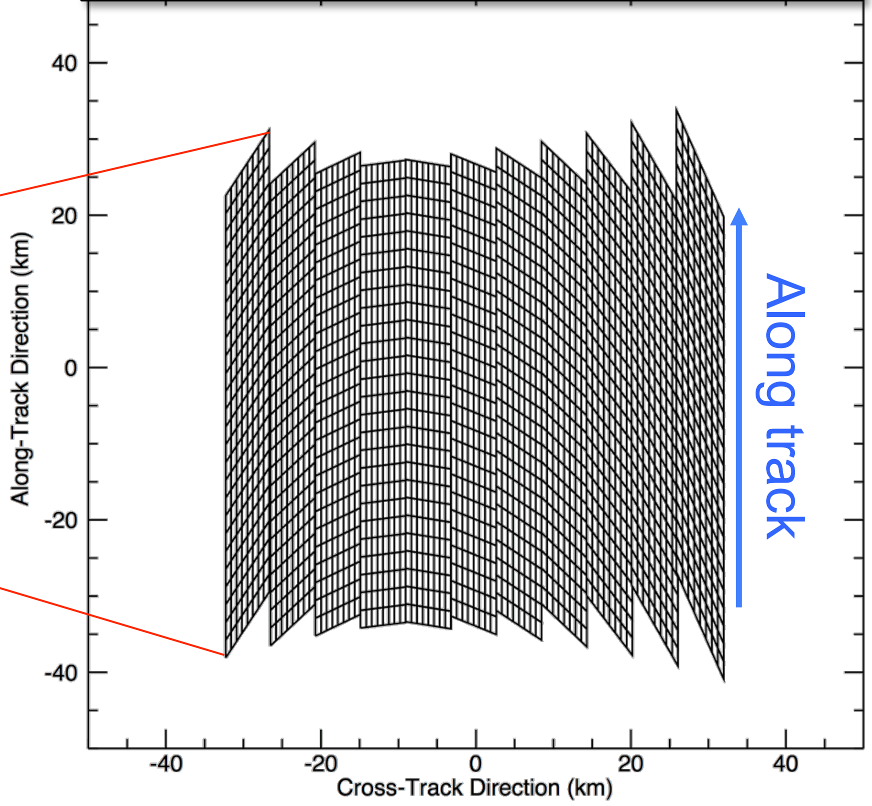
OCO-3* City Mode

- Scan starts when azimuth angle is ~50°
- PMA pointed to right of track and held steady for 8-9 seconds (50-60 km)
- PMA rotates quickly backwards and slightly left, waits 2 seconds to settle, then holds steady for 8-9 second scan
- Repeat until target is ~50° behind ISS

Best Case (ISS passes straight overhead) provides ~65 km x 65 km scan area
Typical will be 50 km to 60 km 'squares'



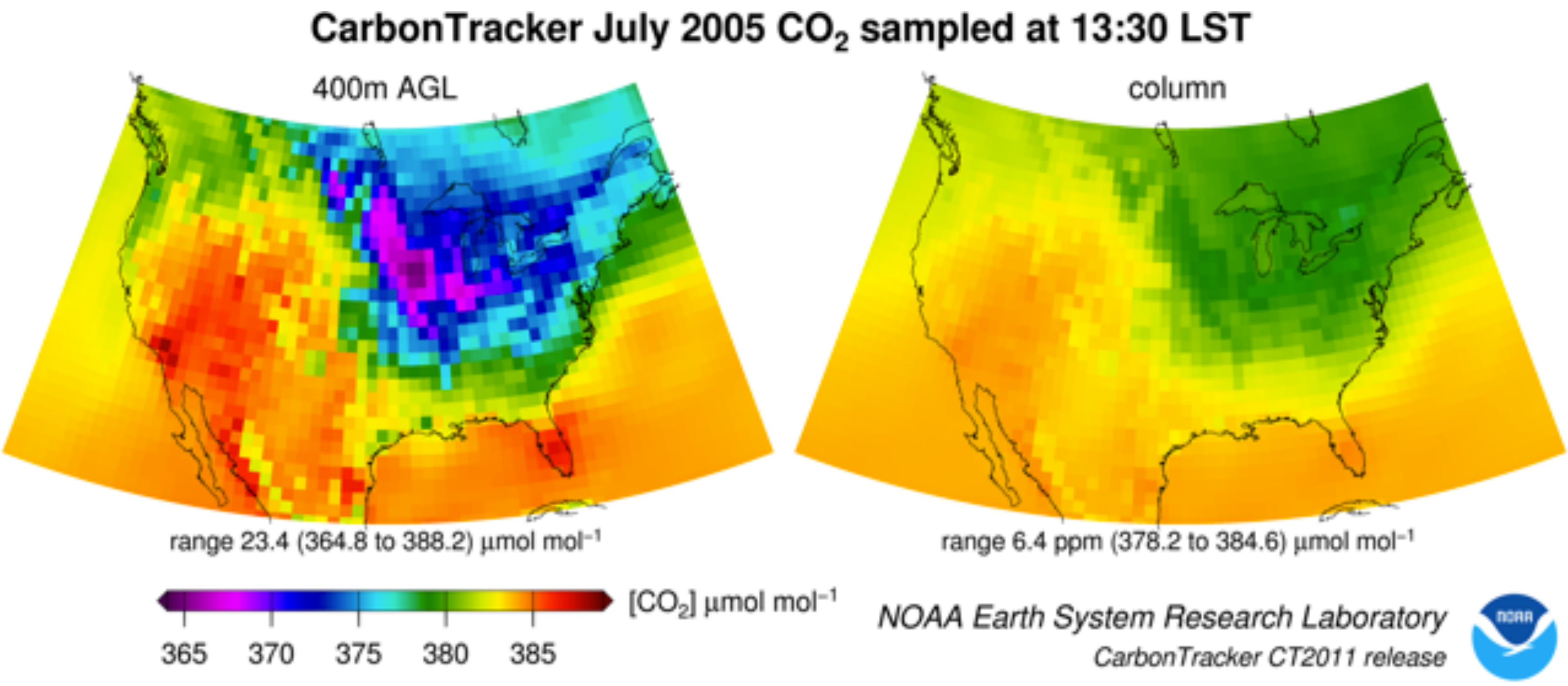
OCO-3 target mode raster-scan (~3600 samples per 3 minute pass in ~50km by ~50km region, several passes per month at different times of day



City Mode is an expanded case of Target Mode

*Proposed Mission

THE GLOBAL GREENHOUSE GAS REFERENCE NETWORK IN THE 2000s

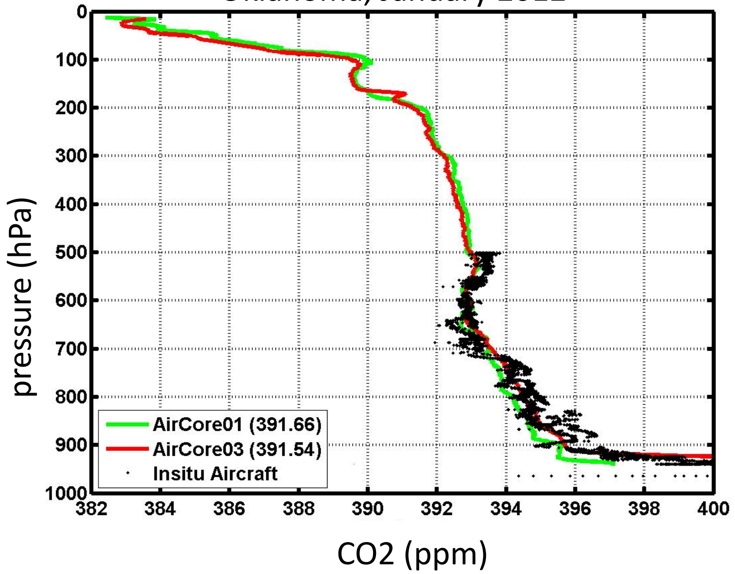


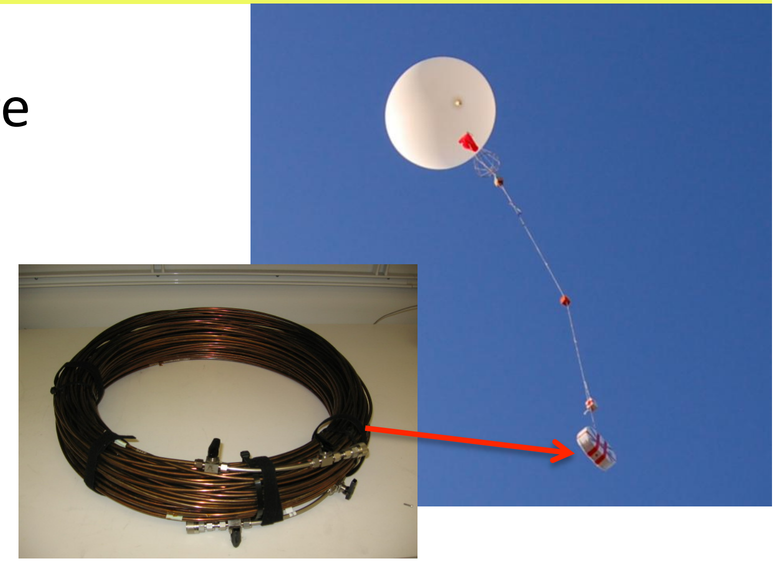
CarbonTracker July 2005 CO_2 sampled at 13:30 LST

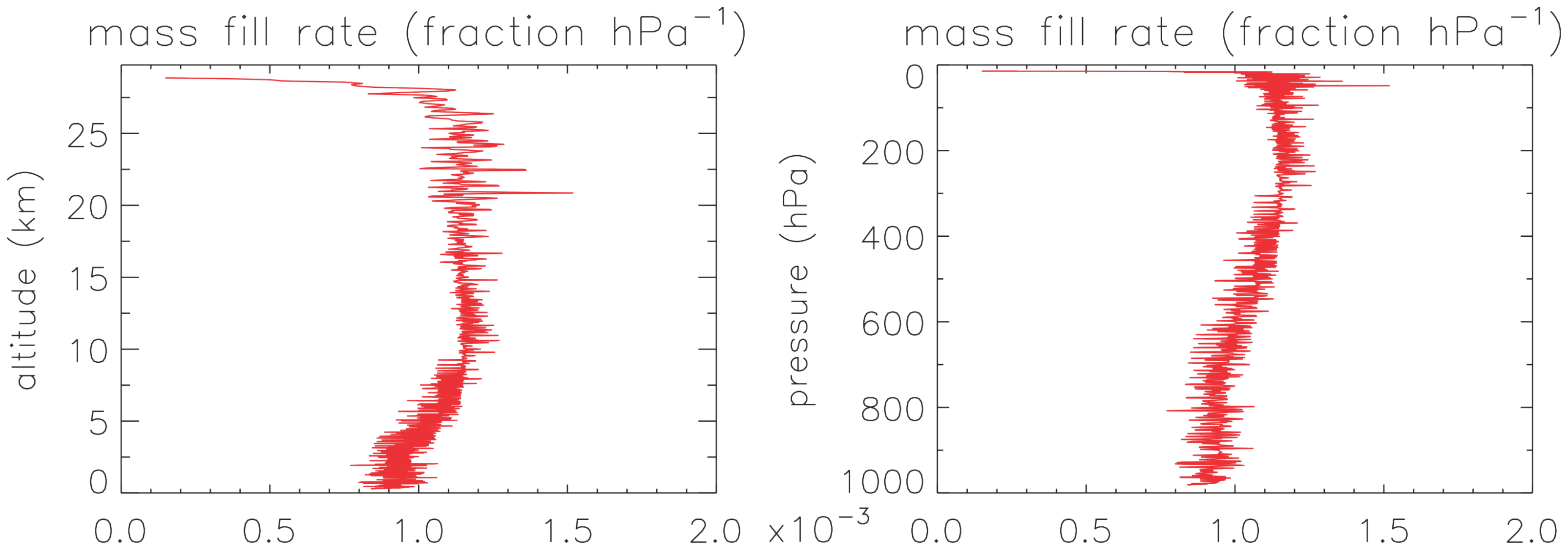
Mass balance estimate:
1 PgC/year source of CO_2 in the USA causes the total column average to increase by ~0.5 ppm on average.

CALIBRATED MEASUREMENTS ARE THE BASIS OF OBSERVING SYSTEMS

AirCore


Oklahoma, January 2012





Consistent validation of GOSAT, SCIAMACHY, and CarbonTracker using TCCON

Susan Kulawik[1], Debra Wunch[2], Christian Frankenberg[1], Chris O'Dell[3], Tom Oda[3], Andy Jacobson[4], Joyce Wolf[1], Max Reuter[5], Michael Buchwitz[5], Paul Wennberg[2], David Griffith[6], David Baker[3], Gregory Osterman[1], Edward Olsen[1], And TCCON data providers

[1] Jet Propulsion Laboratory Caltech
[2] Caltech
[3] Colorado State University
[4] University of Colorado
[5] IUP Bremen
[6] U. Wollongong

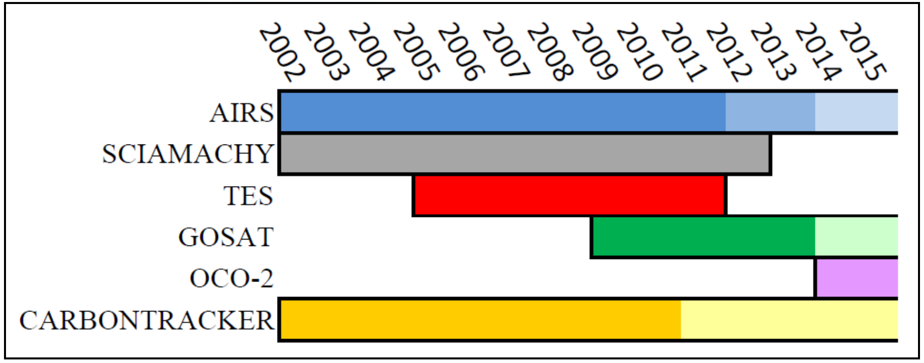
Consistent validation of GOSAT, SCIAMACHY, and CarbonTracker using TCCON

ROSES 2010: Estimation of biases and errors of CO_2 satellite observations from AIRS, GOSAT, SCIAMACHY, TES, and OCO-2

Goals of our project

- Apply rigorous methodology to unify space-based CO_2 observations
- Prequel for developing an Earth Science Data Record (ESDR) product for CO_2

- **Traditional bias and precision analyses do not capture key metrics**: defined methods and implemented testing for, e.g. seasonal cycle amplitude and phase, error as a function of averaging, etc



Consistent validation of GOSAT, SCIAMACHY, and CarbonTracker using TCCON

Project Team

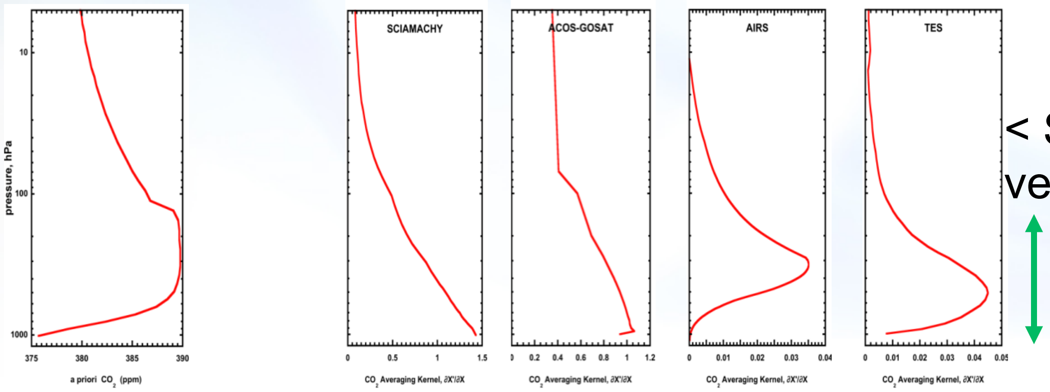
Name	Organization	Role	Contribution
Dr. Susan Kulawik	JPL	PI	TES, analysis, PI
Dr. Edward Olsen	JPL	Co-I	AIRS
Dr. Gregory Osterman	JPL	Co-I	GOSAT
Dr. Andy Jacobson	U. Colorado	Co-I	CT2011
Dr. Christian Frankenberg	JPL	Co-I	GOSAT
Joyce Wolf	JPL	Progr.	Dataset generation
Dr. Debra Wunch	Caltech	Co-I	TCCON
Dr. Steve Wofsy	Harvard	Co-I	HIPPO & aircraft
Dr. Michael Buchwitz	U. Bremen	Collab.	SCIAMACHY
Dr. Marc Fischer	LBNL	Collab.	SGP
Prof. David Griffith	U. Wollongong	Collab.	TCCON
Dr. Brian Kahn	JPL	Collab.	MODIS/clouds
Dr. Fredrick Irion	JPL	Collab.	AIRS
Dr. Charles Miller	JPL	Collab.	OCO-2
Prof. Dr. Justus Notholt	U. Bremen	Collab.	TCCON
Prof. Ross Salawitch	U. Maryland	Collab.	CO_2 datasets
Prof. Paul Wennberg	Caltech	Collab.	TCCON

Other key participants are **David Baker** (modeler @Colorado State University), **Chris O'Dell** (ACOS-GOSAT, CSU), **Tom Oda** (CT2011, CSU), **Max Reuter** (SCIAMACHY, IUP Bremen), **Mathias Schreier** (MODIS, JPL)

Consistent validation of GOSAT, SCIAMACHY, and CarbonTracker using TCCON

Challenges of consistent validation for remote sensed observations:

Each satellite has unique vertical sensitivity, observation strategy, and averaging requirements



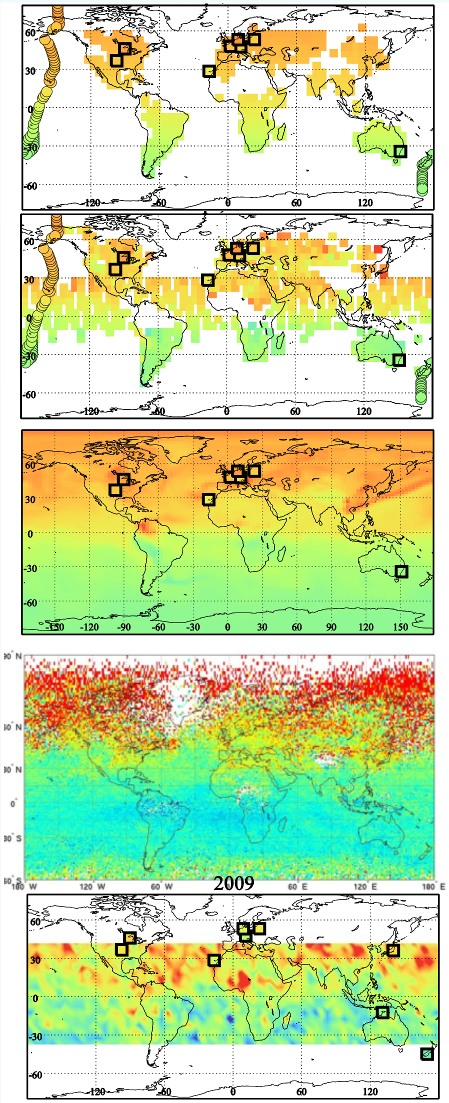
CO_2 profile **SCIA.** **GOSAT** **AIRS** **TES**

< Sensitivity versus altitude

aircraft

	Launch	Spectral region	Peak sens.	Day/ night	Land/ ocean	Latitude	Cloud OD	Obs/ day	Averaging	Precis (ppm)
AIRS	2002	IR	6–9 km	Both	Both	60° S–90° N	All	~ 15 000	≥ 9 targets	2
SCIAMACHY	2002	UV-VIS-IR	Column (col)	Day	Land	80° S–80° N	~ 0	< 10 000	5° × 2 month	~ 1.4
TES	2004	IR	5 km	Both	Both	40° S–40° N	< 0.5	~ 500	15° × 1 month	~ 1.2
IASI	2006	IR	11–13 km	Both	Both	20° S–20° N	Clear		5° × 1 month	2.0
GOSAT	2009	Near IR	Col.	Day	Both	80° S–80° N	< 0.2	~ 2000	None	2
OCO-2	2013	Near IR	Col.	Day	Both	80° S–80° N	< 0.2	~ 200 000	None	< 2

Consistent validation of GOSAT, SCIAMACHY, and CarbonTracker using TCCON



SCIAMACHY XCO$_2$ (IEP-BESD v2)

GOSAT XCO$_2$ (ACOS b2.10 5x5 degree monthly)

CT2011

AIRS CO$_2$ v6

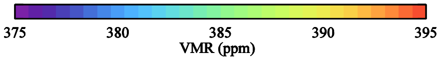
TES CO$_2$ v5 5x5 degree monthly, 2009

Also OCO-2 CO$_2$

< Datasets characterized

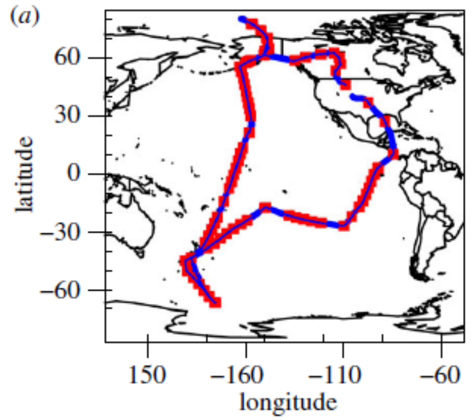
Validation datasets and methods:

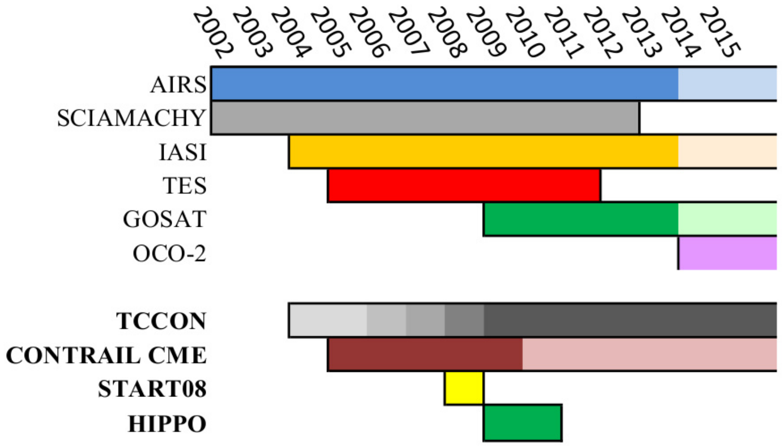
- **Column measurements: TCCON** (Total Carbon Column Observing Network) at 14 worldwide sites
- Aircraft profile data: **HIPPO, START08, ARCTAS**, and **CONTRAIL CME**, accounting for instrument vertical sensitivity
- **CarbonTracker** model assesses co-location and **MODIS** assesses performance in clouds
- Analysis based on **retrieval sensitivity and predicted errors**



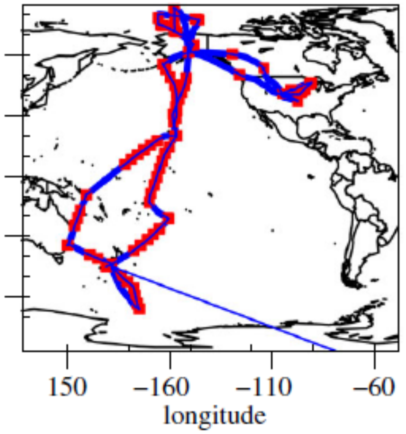
Consistent validation of GOSAT, SCIAMACHY, and CarbonTracker using TCCON

Validation with TCCON and aircraft data





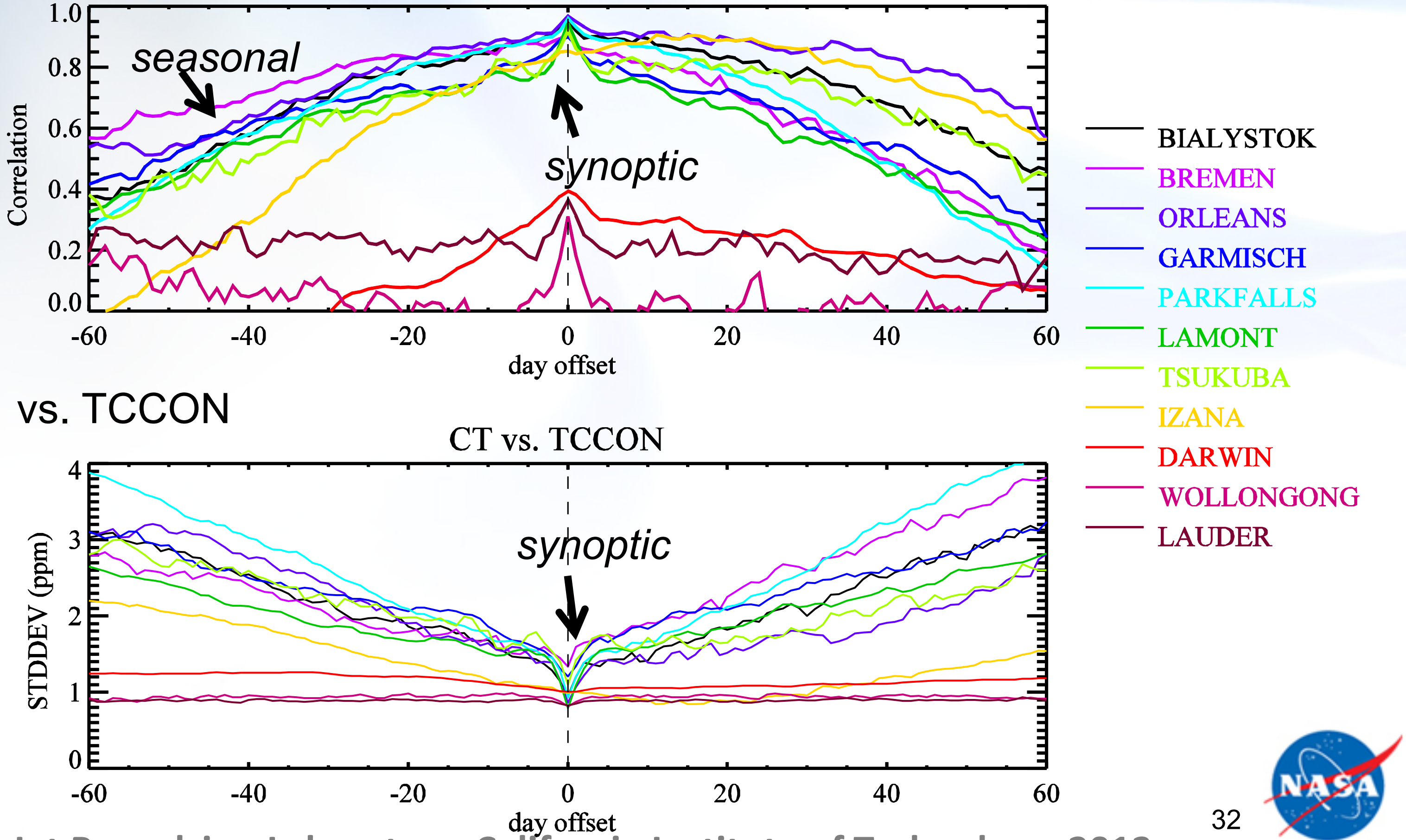
Each validation dataset covers different times, altitudes, and locations



Estimation of biases and errors of CO_2 satellite observations from AIRS, GOSAT, SCIAMACHY, TES, and OCO-2

How to test seasonal cycle phase and synoptic variability?

- Datasets offset by -60 to +60 days.

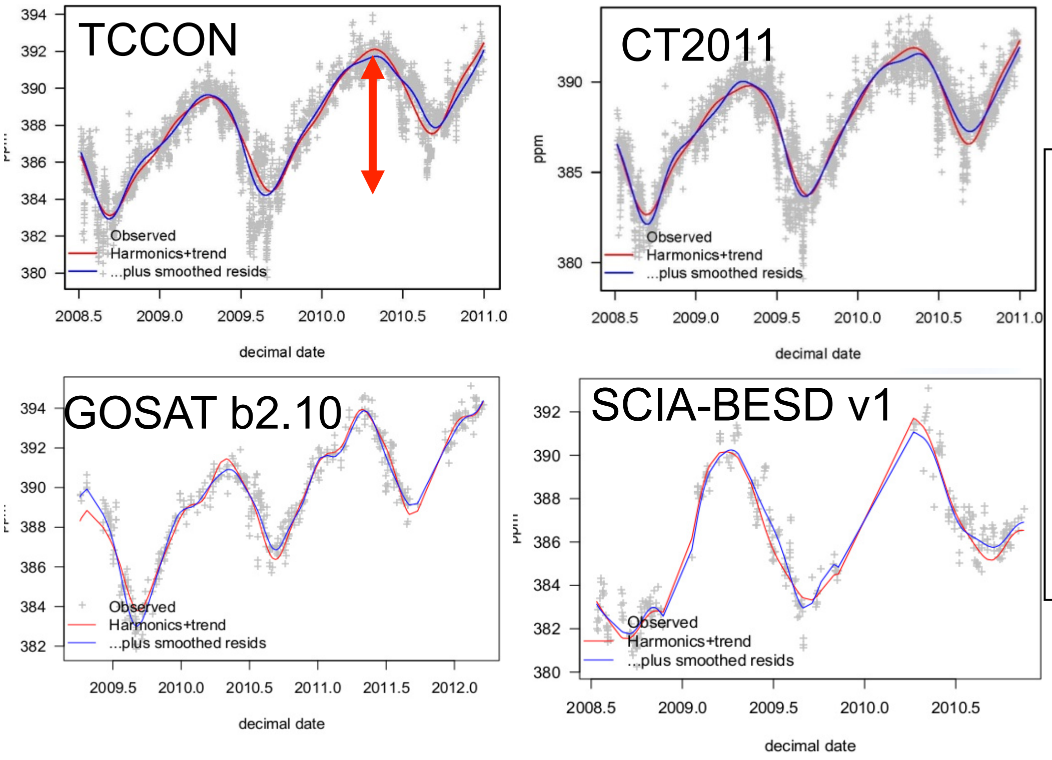


CT2011 vs. TCCON

Consistent validation of GOSAT, SCIAMACHY, and CarbonTracker using TCCON

Key results (year 1-2)

- **Seasonal Cycle amplitude**



Comparison	Region	Seasonal amp. TCCON (ppm)	Seasonal amp. Difference (ppm)
CT2011	NH polar	8.48	-0.42
	NH midlat	6.73	-0.95
	SH	1.32	-0.05
GOSAT B2.9	NH polar	7.94	-0.74
	NH midlat	6.10	-0.10
	SH	1.82	0.03
SCIAMACHY BESD-V2	NH Polar	8.25	-0.34
	NH Midlat	7.37	1.22
	SH	1.40	-0.91

Consistent validation of GOSAT, SCIAMACHY, and CarbonTracker using TCCON

Summary

Team consensus on approach and results for comparisons to TCCON. Results evaluating biases and errors, effects of averaging, seasonal cycle amplitude and phase.

Future directions

- Incorporating future validation data (particularly AirCore) and future missions (e.g. OCO-3, ASCENDS, IASI)
- Similar methodology would apply to other gasses, e.g. CH_4
- Our work moves towards an Earth Science Data Record for CO_2