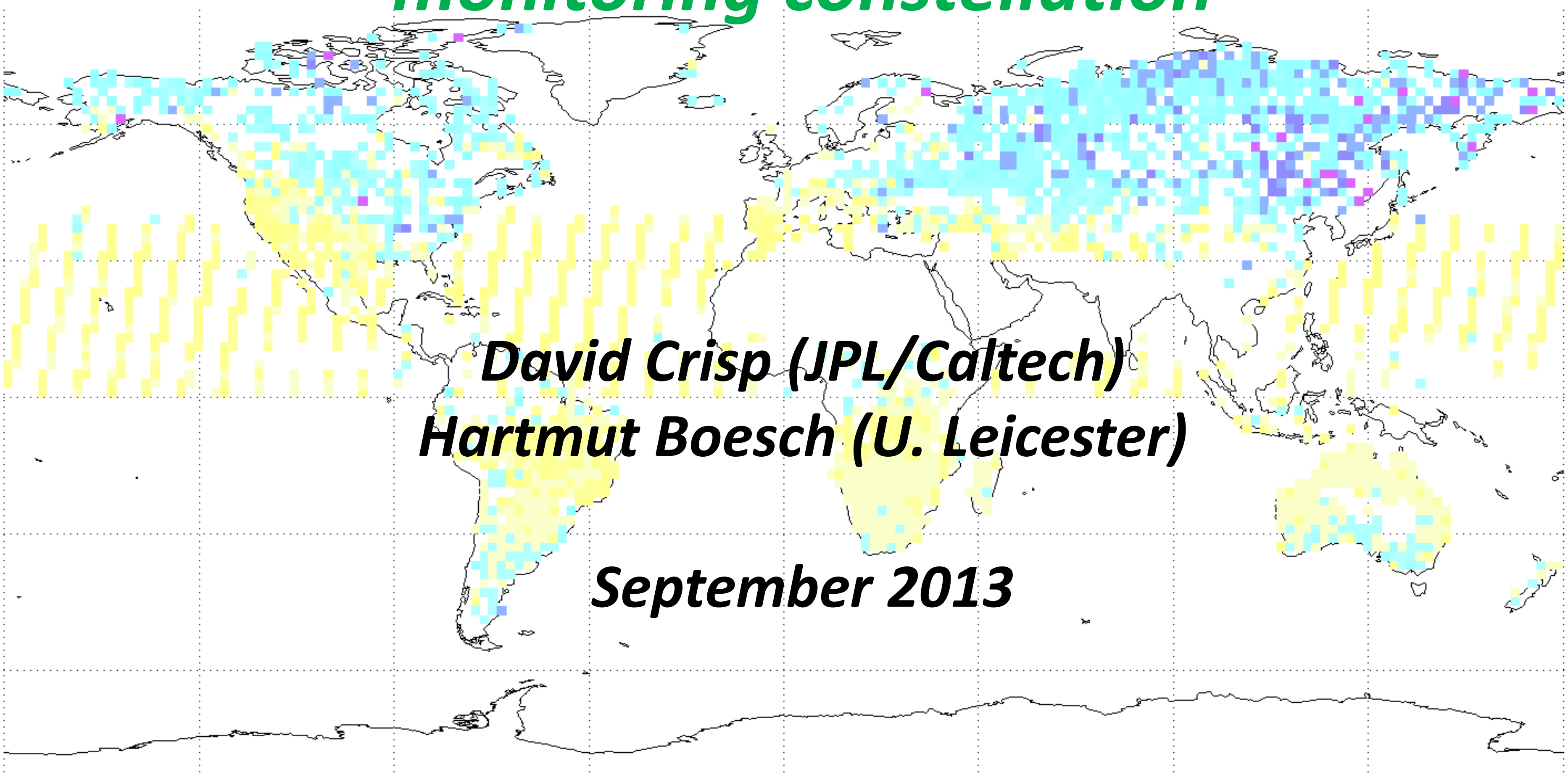
The evolving atmospheric carbon dioxide monitoring constellation

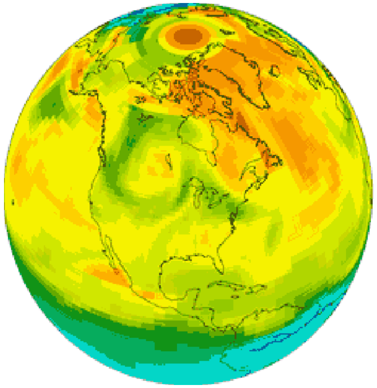


David Crisp (JPL/Caltech)

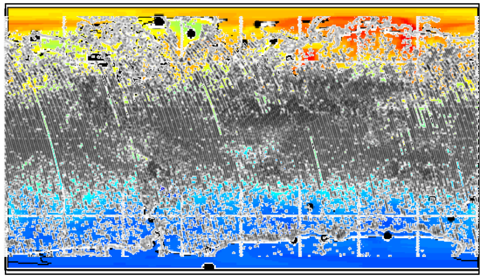
Hartmut Boesch (U. Leicester)

September 2013

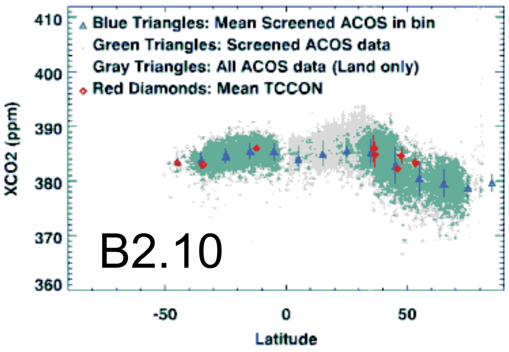
The Promise and Challenge for Space Based CO_2 Measurements



- Spatial coverage
  - Observations over both land and ocean
- Temporal resolution and sampling
  - Daily/Weekly sampling needed to resolve CO_2 weather
  - Monthly measurements required over > 1 year to resolve seasonal and inter-annual variability in CO_2



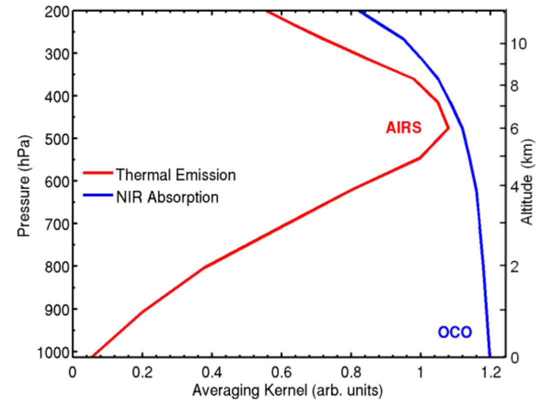
- Spatial resolution and sampling
  - Sensitivity to point sources scales with area of footprint
  - Small measurement footprints enhance sensitivity to point sources and reduce data losses due to clouds



- Primary Challenge: Precision and accuracy
  - High precision required to resolve small (0.2-0.3%) variations in CO_2 associated with sources and sinks
  - High accuracy essential to avoid regional-scale biases

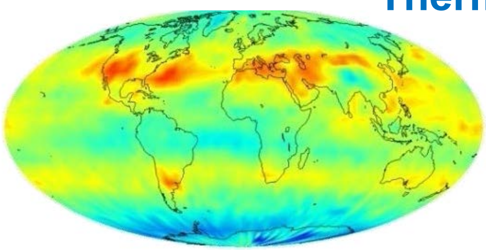
Solar Near IR and Thermal IR CO_2 Sounders

- Solar and thermal IR measurements of CO_2 AIRS,TES (NASA) and IASI (CNES) measure CO_2 above the mid-troposphere
    - Describe the vertical profile of CO_2 in the upper troposphere and lower stratosphere
    - Directly measure the greenhouse forcing by CO_2 in the present climate



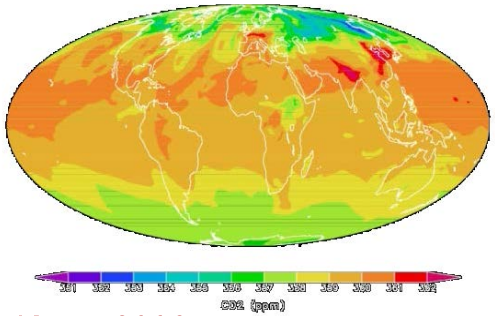
- Solar NIR instruments (SCIAMACHY, GOSAT, OCO) are most sensitive to CO_2 near the ground
    - Optimized for identifying and quantifying surface sources and sinks
    - Provides insight needed to predict future rates of CO_2 buildup and climate impacts
- Combining solar NIR and thermal IR measurements could provide insight into atmospheric transport

Thermal



M. Chahine 2008

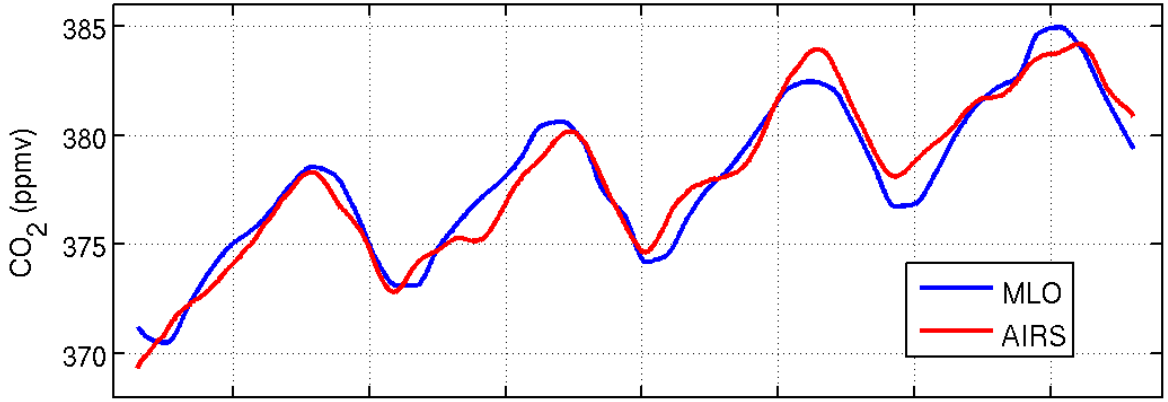
NIR



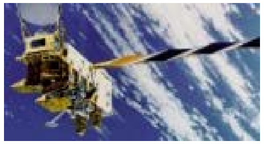
R. Kawa 2008

Thermal Infrared Observations of CO_2

- Thermal IR observations (AIRS, TES, IASI, CriS) measure CO_2 in the middle troposphere
  - Provide global maps of CO_2 at altitudes where it is most effective as a greenhouse gas
  - Provide limited information about surface sources and sinks of CO_2

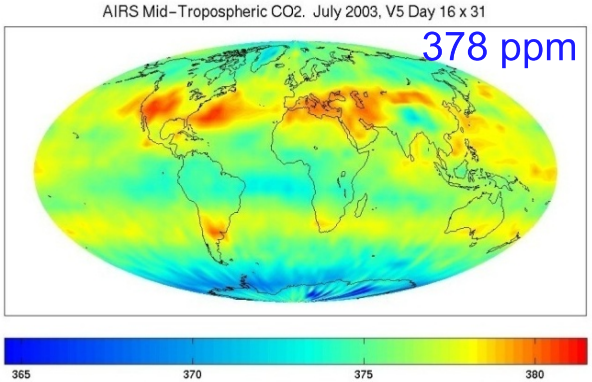


Aqua AIRS

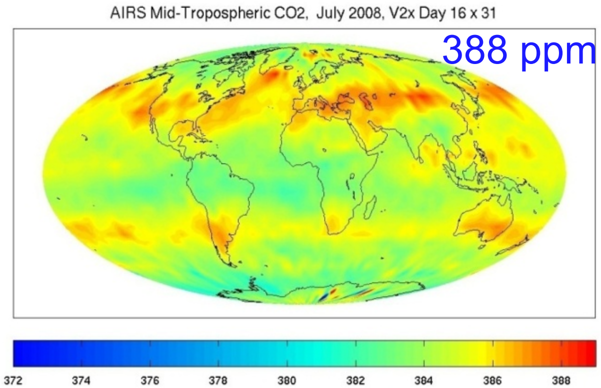


Metop IASI

AIRS July 2003 CO2

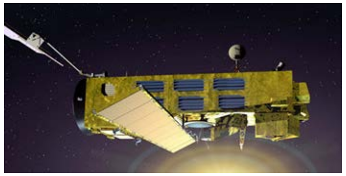


AIRS JULY 2008 CO2



Remote Sensing of CO_2 using Reflected Sunlight: The Pioneers

- **SCIAMACHY (2002 - 2012)** – first NIR/SWIR CO_2 / CH_4 sensor
  - Provided regional-scale maps of CO_2 and CH_4 over continents on seasonal time scales
  - Low spectral resolution limited precision (3-6 ppm), while large footprint (18,000 km^2) and lack of ocean glint pointing limits coverage



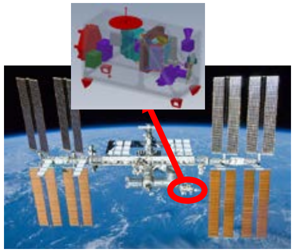
- **GOSAT (2009 - ?)** - Optimized for spectral coverage and fast repeat cycle
  - Combination of high spectral resolution over broad spectral range yields high sensitivity to CO_2, CH_4, and chlorophyll fluorescence
  - Limitations: Number of cloud free soundings (1000/day) and lack of ocean glint at high latitudes limits spatial resolution and coverage

- **OCO/OCO-2 (2014)** - Optimized for X_{CO2} sensitivity and spatial resolution
  - Optically fast, high resolution spectrometer with agile pointing (glint, nadir, target), small (3 km^2) footprint and rapid sampling (10^6 samples/day) expected to yield high substantial improvements in spatial resolution and coverage
  - OCO lost due to launch vehicle malfunction, OCO-2 delayed by launch vehicle availability

*Remote Sensing of CO_2 using Reflected Sunlight: The Next Generation**

- **TanSat (2015)** - First Chinese greenhouse gas satellite
  - Uses same O_2 and CO_2 bands and similar orbit as OCO-2
  - Cloud and Aerosol Imager: 0.38, 0.67, 0.87, 1.38 and 1.61μm channels

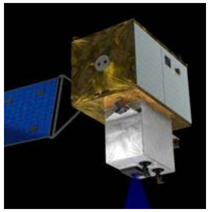
- **OCO-3 (2017)** - OCO-2 spare instrument, to be deployed on ISS
  - First solar CO_2 instrument to fly in a low inclination, precessing orbit



- **GOSAT-2 (2018)** – High precision CO_2, CH_4, CO, and NO_2
  - Improved precision (0.5 ppm), spatial resolution, and range of ocean glint spot expected to improve coverage
  - Exploring additions of an FTIR channel to measure CO, a wider NIR channel for chlorophyll fluorescence, and a UV channel for NO_2

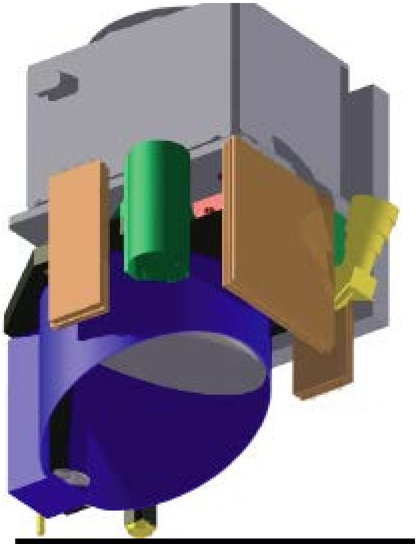
- **CNES MicroCarb (2019)** – high sensitivity at low cost
  - Flies in the A-Train, providing data continuity for OCO-2
  - ~1/2 to 1/3 of the size (and cost) of OCO-2, with similar sensitivity.
    - Enables constellations of low-cost CO_2 monitoring satellites

- **ESA CarbonSat (2022)** – CO_2 and CH_4 at high resolution over a broad swath
  - Combines a high precision target (1 ppm) over a broad swath (160 to 500 km) to yield complete coverage of sunlit hemisphere at high resolution (2 km x 2 km) on 6-12 day time scales



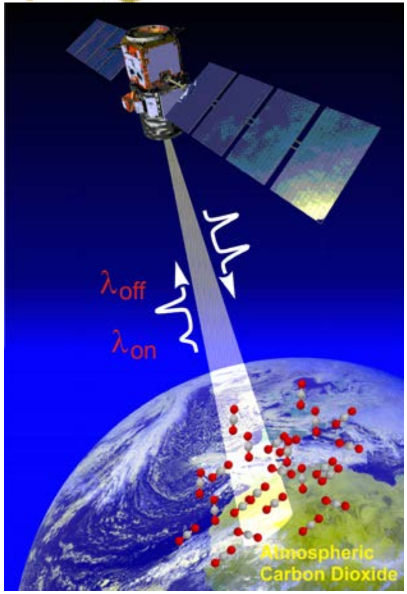
Planned Active Greenhouse Gas Missions*

Allow full-column greenhouse gas measurements day and night and at high latitudes.



- MERLIN (2017): First CH_4 LIDAR (IPDA)
  - Science focus: Precise (1-2%) X_{CH4} retrievals for studies of wetland emissions, inter-hemispheric gradients and continental scale annual CH_4 budgets
  - Orbit: 6AM/6PM, 28-day repeat

- ASCENDS* (2022+): First CO_2 LIDAR
  - Precise (0.3%) global measurements of X_{CO2}, over days, nights, including winter high latitude regions to quantify continental and oceanic CO_2 sources and sinks
  - Should provide many useful soundings in partially cloudy regions because of near vertical sounding



The Evolving GHG Mission Timeline

Satellite, Instrument (Agencies)	CO_2	CH_4	FOV	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
ENVISAT SCIAMACHY (ESA)	•	•	30x60 km^2														
GOSAT TANSO-FTS (JAXA-NIES-MOE)	•	•	10.5 km (d)			?											
OCO-2 (NASA)	•		1.25x2.26 km^2														
TanSat (CAS-MOST-CMA)	•		1x2 km^2														
Sentinel-5P TROPOMI (ESA)		•	7x7 km^2														
MERLIN (DLR-CNES)		•	0.135 km (w)														
OCO-3 (NASA)	•		~3 km^2							ISS							
GOSAT-2 TANSO-FTS (JAXA-NIES-MOE)	•	•	3-4 km (d)														
MicroCarb (CNES)	•		~25 km^2														
PCW-PHEOS-FTS (CSA)	?	•	10x10 km^2									HEO continuous ~50-90°N only					
MetOpSG Sentinel-5 (ESA-EUMETSAT)		•	7x7 km^2														
CarbonSat (ESA)	•	•	2x2 km^2														
*ASCENDS (NASA)	•		0.100 km (w)														
*GEO-CAPE (NASA)		•	4x4 km^2													GEO 100°W	

Based on information from various sources

d = diameter
w = width of a narrow strip along orbit track

Operating | Planned | Considered | Potential Extension

*Proposed Mission - Pre-decisional - for Planning and Discussion Purposes Only

Exploiting the Benefits of Multiple Missions

- Space-based remote sensing observations hold substantial promise for future long-term monitoring of CO_2 and other greenhouse gases
  - These measurements will complement existing ground-based data with increased spatial coverage and sampling density
- Over the next decade, a succession of missions with a range of CO_2 and CH_4 measurement capabilities will be deployed in low Earth orbit
  - Include near polar, sun synchronous orbits with morning and afternoon mean local times, and low inclination, precessing orbits (OCO-3/ISS)
  - Because there is little overlap between the missions, Each one is a critical link in a chain that must be successfully deployed to ensure a continuous climate data record.
- Measurements from Geosynchronous obit (GEO) would also be valuable for studying the diurnal cycles of CO_2 and CH_4
  - There are no plans to collect precise CO_2 measurements from GEO
- Much greater benefits could be realized if these missions could be coordinated and their data products can be combined

Examples of Collaborative Cal/Val Activities

Pre Launch:

- Cross calibration of pre-launch radiometric standards
- Exchange of gas absorption coefficient and solar databases
- Algorithm development/intercomparison
- Validation system development (TCCON + Tsukuba FTS?)
- Dual/multi-Satellite OSSE's – what do you gain with truly coordinated observations

Post Launch:

- Cross calibration of solar/lunar/Earth(vicarious: RRV+?) observations
  - Including exchange of solar and lunar (ROLO) standards
- Cross validation: TCCON (possibly adding a validation campaign or two)
- Algorithm implementation/intercomparison
- Intercomparisons of flux inversions

Acknowledgements and Apologies

- Most of the images, and much of the information about these missions was gleaned from other presentations by the SCIAMACHY, GOSAT, GOSAT-2, TanSat, MicroCarb, CarbonSat, and ASCENDS* Teams

- Because many of these missions are still in the planning stages, some of his information is likely to change