



Active Sensing of CO₂ Emissions over Nights, Days and Seasons

Study Activity/Plans

Ken Jucks, ASCENDS PS

Earth Science Decadal Survey Mission Symposium

Washington, DC

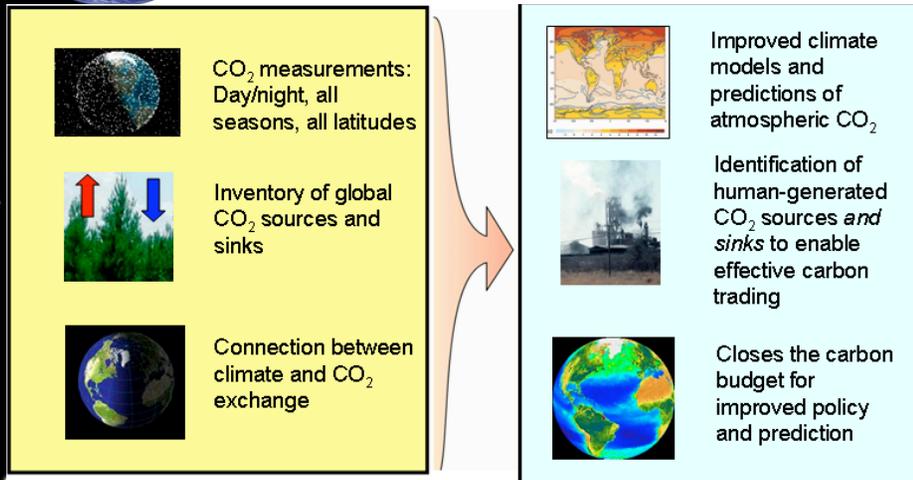
11-12 February, 2009



Active Sensing of CO₂ Emissions over Nights, Days and Seasons (ASCENDS)

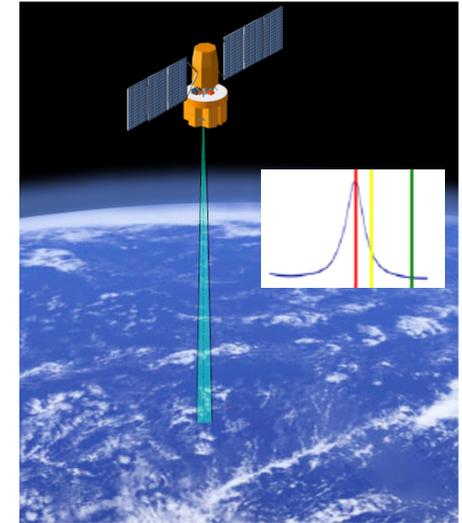


Mission Science



Mission Architecture/Structure

- **Laser-based differential absorption in the NIR for column CO₂ remote sensing at nights and at high latitudes during all seasons**
- **O₂ laser-based NIR differential absorption for surface pressure**
- **Passive CO sensor for improved source-sink interpretation**



Mission Implementation Challenges

- **Assess optimal CO₂ active sensing methodology**
- **Assess ancillary measurement requirements (path length, clouds, aerosols, CO, CH₄, surface pressure, temperature, etc.)**
- **Availability or lack of passive space-based CO₂ observations during ASCENDS operations impact Level 1 Requirements**

FY09 Objectives and Deliverables

- **Perform OSSEs to quantify ASCENDS science impact and define preliminary science measurement requirements**
- **Advance ASCENDS payload technology readiness through Conduct a field campaign with all 3 aircraft demonstrator instruments**
- **Sustain and augment the existing validation network to validate ASCENDS, especially night measurements**



Priority Investments to Advance ASCENDS Readiness



Workshop recommendations identified priority areas for near-term investment to advance ASCENDS mission readiness:

- **Studies of the end-to end ASCENDS system to improve traceability from science** questions to measurement requirements, maximizing science information content while accounting for realistic instrument and model performance. In particular, studies are desired to examine the variability in the column associated with surface gradients and to quantify the value of ancillary measurements (e.g., clouds, aerosols, CO, and atmospheric pressure, temperature, and moisture).
- **Acceleration of critical ASCENDS technology development, including active remote** sensing of surface pressure, as well as development of an end-to-end technology implementation path which considers space qualification of critical components, lifetime demonstrations of the science payload, and scaling of the power-aperture product needed for measurements from space. Demonstrations of the required measurement capabilities, preferably in conjunction with other measurement campaigns, are needed over a range of conditions.
- **Sustaining and enhancing the current CO₂ validation network to ensure validation** data continuity post-OCO and develop new capabilities to support validation of ASCENDS measurements. An airborne instrument simulator is considered a key part of the ASCENDS validation infrastructure



ASCENDS Study Overview



Science Justification and Requirements

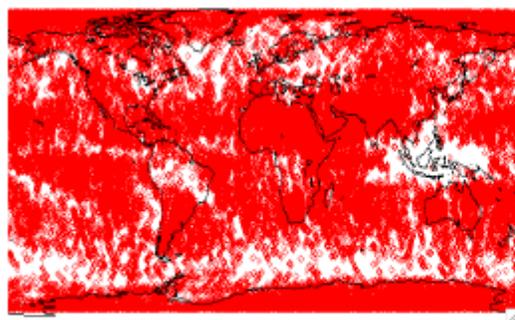
Core science themes addressed by ASCENDS include:

- Shifts in terrestrial carbon sources and sinks
- Identifying processes controlling biospheric carbon fluxes
- Understanding the evolving nature of oceanic carbon fluxes

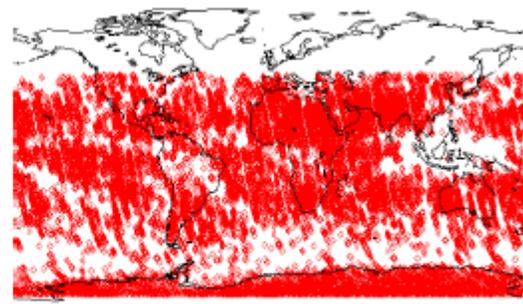
Workshop participants identified investigations in

- Changes in Northern High Latitude Sources and Sinks
- Southern Ocean Source/Sink Characteristics
- Respiration Processes

as core science investigations uniquely enabled by ASCENDS. These investigations directly leverage the ability of the ASCENDS lidar to obtain uninterrupted, all-season measurements at high latitudes and at night. The ASCENDS Baseline Mission would contribute to all three of these specific investigation areas, however participants noted that additional work is required before a minimum mission can be defined.



A-SCOPE



OCO

Figure 10: Spatial Sampling of a proposed active mission (A-SCOPE) versus a passive mission (OCO). Improved coverage at high latitudes and over ocean regions is apparent. Source: G. Ehret



ASCENDS Technology Readiness

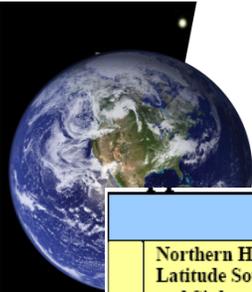


- 3 primary approaches have been developed to retrieve CO₂ from space.
 - LaRC/ITT approach uses space qualified CW 1.6 micron lasers at 2 wavelengths (partially on and off line) to infer CO₂ columns.
 - JPL/Lockheed approach uses CW 2.0 micron lasers using 2 wavelengths and heterodyne detection.
 - GSFC approach uses pulsed 1.6 micron lasers and 6 wavelengths.
- 2 primary approaches are being developed for O₂.
 - LaRC/ITT approach uses CW lasers in O₂ B band
 - GSFC approach uses pulsed lasers in the O₂ A band.
- Other countries approaches
 - ESA has A-SCOPE proposal that is in review for potential selection now.
 - JAXA is considering a GOSAT follow on that may involve active sensing.
- ASCENDS initial study leads include the primary instrument leads at the 3 centers (Abshire, Browell, Spiers), Berrien Moore, Chip Miller, and Anna Michalak

	JPL 2.06 μm Laser Absorption Spectrometer	GSFC 1.57 μm Dual Channel Laser Absorption Spectrometer	LaRC 1.57 μm Laser Absorption Spectrometer
CO₂ Absorption Wavelength	2.06 μm	1.57 μm	1.57 μm
Number of Discrete Lines Measured	2	8 or more for CO ₂ , 4 or more for O ₂	3 or more for CO ₂ , 3 or more for O ₂
Transmitter	CW laser	Tunable pulsed Erbium doped fiber lasers (CO ₂ and O ₂)	Tunable modulated Ytterbium-Erbium doped fiber lasers
Receiver	Single telescope Heterodyne detector	Single telescope Photon counting detectors (CO ₂ and O ₂)	Single or Multiple telescopes Near Single Photon Counting Avalanche Photodiode Detector for CO ₂ & O ₂ Single photon counting detector for altimetry & aerosols
Approach to Obtaining Needed Additional Measurements			
Altimetry	Not directly measured	Time distribution of pulsed laser echo signal	Time distribution of correlation of pseudo-random-modulated return echo
Surface Pressure	Not directly measured	Valley between two lines in the Oxygen A-band (near 765 nm)	Surface weighted LAS measurement of O ₂ absorption line near 1.27 μm
Aerosols	Not directly measured	Backscatter lidar	Time distribution of correlation of pseudo-random-modulated return echo

Preliminary

ASCENDS Science Traceability Matrix



	Spatial Scale	Temporal Scale	Mission Lifetime	Diurnal Preference	Acceptable Error/Bias	Additional Measurement Attributes	Ancillary Measurements Desired	Additional Studies Needed	
ASCENDS Core Science	Northern High Latitude Sources and Sinks	100 km x 100 km		≥ 1 year		Summertime is primary occurrence of permafrost melting; between cloud sampling; monthly to seasonal observations would further inform wintertime transition investigations	Methane, Radar freeze/thaw; boundary layer height	Examine radar freeze/thaw data to determine accuracy needed. Investigate balance between low altitude weighting and accuracy, as column changes from diurnal surface variations can be larger in the growing season.	
	Southern Ocean Source/Sink Characteristics	500 km x 500 km		≥ 4 years	Multiple times of day desired	<1 ppm	Looking for cumulative small temporal and spatial variations over a large scale, measurements at different times of day at the same location.	Coincident O ₂ /pressure measurements or knowledge. Need surface winds/wind stress, ocean color, salinity, sea surface temperature and sea state from other sources.	
	Respiration Processes	500 km x 500 km	Twice a day	Many seasons	Day & night; perhaps dawn/dusk	Low bias	High latitude and between cloud sampling	CO measurement over land, co-aligned, both day and night, to separate respiration from combustion sources	As day to night fluctuations in the full column are small compared to accuracies/precision thought to be practical for measurement, studies are needed to determine whether it is possible to detect sufficiently small gradients to quantify separation of photosynthesis and respiration from active remote sensing measurements. The value added by nocturnal CO measurements needs to be evaluated.
ASCENDS Enhanced Science	Ecosystem Behavior in Complex Terrains	On the order of 1 km		≥ 1 season		≤ 5 ppm	Relaxing accuracy may allow high spatial frequency characteristics. Low accuracy high spatial resolution may be preferable	Collocated O ₂ /pressure measurements key due to high spatial variability	
	Climate Variability as a Proxy for Climate Change	500 km x 500 km	Monthly to seasonal	≥ 4 years to observe ENSO cycle		~1 ppm	Coverage of southern oceans and polar regions, mid-latitude ocean during ENSO		Climate change simulations to determine mission lifetime needed to address long term (50+ yr) climate change
	Land/Sea & Air/Sea Flux	~25-50 km				Emphasis on low systematic errors	ΔPCO ₂ is the desired measurement, however it is unclear if it is directly measurable from space	Ocean color, salinity and temperature provide statistical estimators of ΔPCO ₂	Are tracer gas measurements required to distinguish terrestrial from oceanographic gases? Can ΔPCO ₂ be measured from space?
	Effects of Biospheric Disturbance on Carbon Flux Variability	"Few kilometer" (≤10 km) desired; Geolocation accuracy of measurement point: ~250 m.	Not a strong driver, 16 day repeat period desired	"long mission lifetime"		Accuracy <2 ppm in the lowest ~3 km; <0.5 ppm for "full column" (12 km).	Need: "full column" (integral constraint) up to tropopause (12 km) and partial column of lowest ~3 km.	Temperature, co-aligned CO with full column weighting and <10% precision to separate biomass. Co-aligned aerosol backscatter profile (~100 m vertical, 10 km horizontal, 10%). Context imaging desirable.	Determination of the required uniformity in full column weighting function and required CO ₂ accuracy in full & partial column
	Quantification of Anthropogenic CO ₂ Emissions	"City scale" 50 km (down-track) needed, 5 km desired	Weekly		Multiple times of day: minimum 2, every ~3 hr desired		Target capability desired to look at intense sources and reduce random error; coverage during polar winter and at high latitudes	CO, collocated, 3% uncertainty in column, day and night, lower tropospheric weighted sensitivity	Quantification of benefit of CO observation and what would be lost with day-only passive measurement



ASCENDS Synergies with Other DS Missions



Decadal Survey Mission	Science	Possible Areas of Science Overlap with ASCENDS	Possible Complementary Measurements or Contributions to ASCENDS	
Launch: 2010-2013	CLARREO	Solar and Earth radiation, spectrally resolved forcing and response of climate system	Northern High Latitude Sources and Sinks, Disturbances (land-use change)	Cloud properties
	SMAP	Soil moisture and freeze-thaw for weather and water cycle processes	Northern High Latitude Sources and Sinks, Respiration, Air/Sea & Land/Sea Flux	Freeze/thaw measurement
	ICESat-II	Ice sheet height changes for climate change diagnosis	Northern High Latitude Sources and Sinks, Complex Terrain, Air/Sea & Land/Sea Flux, Disturbances (land use change)	
	DESDynI	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	Northern High Latitude Sources and Sinks, Respiration, Disturbances (land-use change)	
	GPSRO	High accuracy, all-weather temperature, water vapor, and electron density profiles for weather, climate and space weather		Provision of temperature and water vapor profiles
Launch: 2013-2016	HypIRI	Land surface composition for agricultural and mineral characterization; vegetation types for ecosystem health	Disturbances (land-use change)	Measurements of ecosystem health
	SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	Northern High Latitude Sources and Sinks, Southern Ocean, Land/Sea & Air/Sea Flux	
	GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	Southern Ocean, Land/Sea & Air/Sea Flux, Disturbances, Respiration; Anthropogenic Emissions	Regional CO measurements with high temporal resolution
	ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biochemistry	Southern Ocean, Land/Sea & Air/Sea Flux, Disturbances	Cloud and aerosol properties
	XOVWM	Sea-surface wind vectors for weather and ocean ecosystems	Southern Ocean, Land/Sea & Air/Sea Flux	Improved transport models



ASCENDS Study FY08/09 Budgets



2008 Budget and Spending

- ASCENDS workshop:
 - infrastructure for the workshop,
 - travel for some key invited participants,
 - CS workforce to support workshop at JPL, LaRC, and GSFC

2009 Budget and Spending

•\$2M budget for FY09

- This plan is being finalized now.
- Development and execution of an aircraft field campaign to test and assess the state of the current technological approaches in relationship to the science priorities.
- CS time to further support development of science traceability and analyze the field data.
- CS and contractor (and university) time for OSSE related work to augment both the science traceability and in relationship enhance any field campaign.
- Schedule a workshop near the end of FY09 to assess the state of the science definition
- This work will be distributed amongst JPL, LaRC, and GSFC at roughly the \$500K-700K level to perform the above tasks.



Other ASCENDS related investments



- ◆ ESTO IIP funding
 - *GSFC activities, current*
 - *JPL activity, past*
- ◆ ESTO ACT
 - *Lockheed-Martin 2.0 micron source development (with JPL), current*
 - *ITT, O2 development*
 - *ITT, telescope investment*
- ◆ AITT call
 - *Joint LaRC/JPL airborne conversion investment.*

- ◆ JPL, GSFC, and LaRC have all invested internal funds into ASCENDS related technology development.



ASCENDS Study Results: FY08 - Present



- Primary activity WAS the workshop, development of the initial science traceability matrix, and the resulting report.
- The report is now final, after significant feedback from the workshop attendees.
- It is available on the ASCENDS workshop web site to the public.
 - <http://cce.nasa.gov/ascends/>
- This report contains the primary recommendations on which the FY09 plans are based.
- Prioritizes tasks for achieving ASCENDS science objectives and KDP/A preparedness
- The initial discussions at the workshop and with the community provided information that was used for feedback with ESTO for their ACT selections, so that their selections related to ASCENDS went toward highest priority investments.



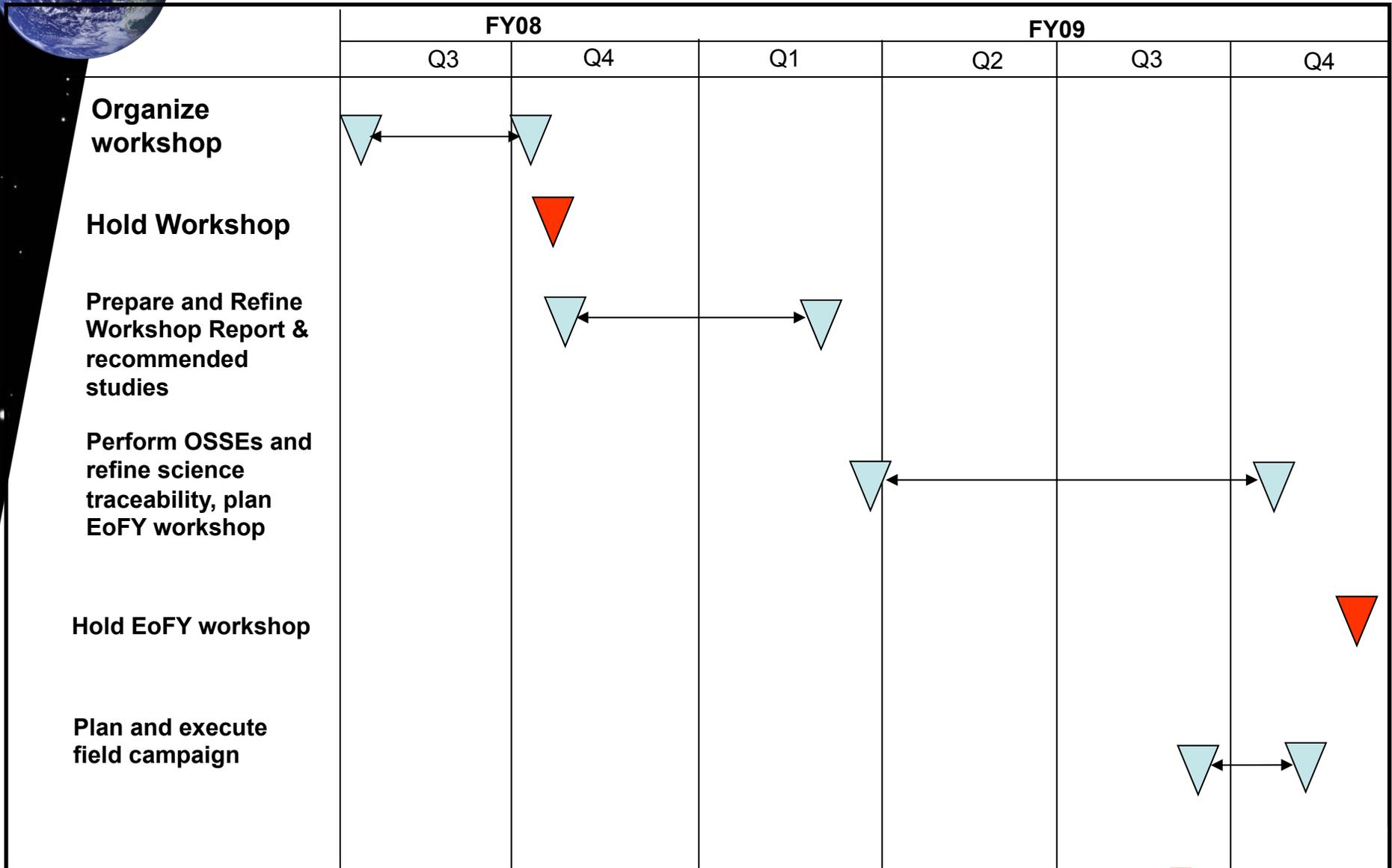
ASCENDS FY09/10 Plans



- Further refinement of the Science and Measurement requirements will occur
 - This will be done primarily through the working group and a few directed individuals.
- Directed studies to clarify the types of sampling issues, cloud issues, and potential benefit of obtaining altitude information. (both working group and directed tasks). These are OSSE-like studies.
- Aircraft flights to further develop and inter-compare the current technology capabilities from the various center based groups.
 - This will initially be done with multiple planes to avoid the costs and time associated with retrofitting all the instruments onto one plane.
- Further smaller workshop to discuss the status and prepare to get the mission closer to a KDP-A level.
- Plan to KDP/A



ASCENDS Development Schedule FY08-10





ASCENDS Issues and Challenges (1/3)



◆ Challenge:

- ◆ Assess optimal CO₂ active sensing methodology

◆ Current status

- *NASA airborne demo units address 3 of 4 potential measurement methodologies*
- *NASA and ESA have developed ground-based demonstration units to cover the remaining measurement methodology*

	1.6 μm	2.0 μm
CW		
Pulsed		ESA & LaRC (ground)

◆ Path forward:

- *Trade study to evaluate science knowledge gain for each measurement methodology*
- *Leverage ESA ASCOPE study results and capabilities to accelerate measurement methodology trade study*



ASCENDS Issues and Challenges (2/3)



◆ Challenge:

- *Assess ancillary measurement requirements (path length, clouds, aerosols, CO, CH₄, surface pressure, temperature, etc.)*

◆ Current status

- *NASA developing airborne demo units for 2 potential active O₂ measurement methodologies (surface pressure, path length)*
- *Investigating passive remote sensing solutions for other ancillary variables based on existing technologies*

◆ Path forward:

- *Trade study to evaluate ancillary measurement requirements*
- *Final ancillary measurement requirements will depend heavily on the selected active CO₂ measurement methodology and Level 1 Requirements*



ASCENDS Issues and Challenges (3/3)



- ◆ Issue:
 - ◆ Availability or lack of passive space-based CO₂ observations during ASCENDS operations impact Level 1 Requirements
 - *ASCENDS is intended to be an exploratory observation, “the logical technological follow-on to OCO”*
 - *With simultaneous passive CO₂ observations*
 - ◆ ASCENDS requirements could focus on exploratory science objectives, eg high latitude change, day/night, etc.
 - *Lack of simultaneous passive CO₂ observations*
 - ◆ Overconstrains ASCENDS measurement requirements to continue and improve upon OCO science return in addition to exploratory science objectives
- ◆ Current status
 - *DS recommends overlap of ASCENDS and OCO observations (2013-2016 LRD for ASCENDS)*
 - *ASCENDS LRD before 2016 unlikely given current resource profile and priority of Tier I missions*
 - *OCO single-string design supports a 2 year lifetime*
 - *OCO extended mission lifetime uncertain*



Potential Overguide (Stimulus) Efforts to Accelerate ASCENDS Readiness



- ◆ Adapt existing efforts to more autonomous airborne demonstrators for ASCENDS technology. More work would be required for the O₂ sensors than the CO₂ sensors.
- ◆ Develop a combination OCO/CO/CH₄ airborne simulator. Efforts at LaRC, ARC/L-M, and JPL could be used for this development.
- ◆ Execute a follow-on single plane (DC-8) campaign in FY10 to take advantage of lessons learned from FY09 joint campaign. This would serve to validate OCO as well. (Spring FY10)
- ◆ Perform a more complete mission architecture study, based on what was learned from the various instrumentation development and data requirement studies (some time in mid to late FY10).



Backup/Old Charts





Current Global CO₂ Observing Capabilities



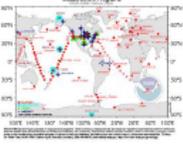
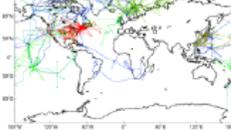
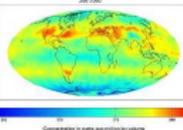
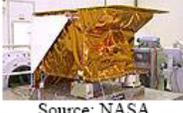
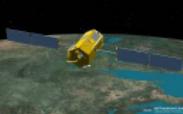
	Data Source	Characteristics	
Ground	Ground-Based Networks	Point measurements, sparse coverage Longest CO ₂ record (continuous operation since 1957) Observations from surface to ~500 m High temporal resolution, accuracy, and precision	 <p>Source: NOAA-ESRL</p>
	CO ₂ Aircraft Campaigns	Regional measurements Infrequent flights/operations Varying altitudes accessible Vertical profiles High accuracy and precision	 <p>Source: C. Pickett-Heaps, LSCE</p>
Space borne (current)	SCIAMACHY on EnviSat (Launched in 2002)	Global coverage Passive, 8 channel UV-Vis-NIR spectrometer Column CO ₂ Moderate spectral resolution	 <p>Source: ESA</p>
	AIRS on Aqua (Launched in 2002)	Global coverage Passive, hyperspectral infrared sounder Monthly mid-tropospheric CO ₂ Daytime/nighttime observations	 <p>Source: NASA</p>
	TES on Aura (Launched in 2004)	Global coverage Passive, high-resolution imaging infrared Fourier-transform spectrometer Tropospheric sensitivity	 <p>Source: NASA</p>
Space borne (near completion)	OCO (Launch early 2009)	Global coverage Passive, NIR spectrometers Highly accurate X _{CO2} Variability of CO ₂ sources and sinks	 <p>Source: NASA</p>
	GOSAT (Launch early 2009)	Global coverage Passive, Fourier transform spectrometer Cloud-aerosol imager	 <p>Source: JAXA</p>

Table 1: Current/Near-Term Global CO₂ Observing Capabilities