Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

NASA Science Definition and Planning Workshop Report

July 23-25, 2008
University of Michigan in Ann Arbor, Michigan

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Preface

In January 2007, the National Research Council released the first-ever decadal survey of Earth science, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. The study was sponsored by NASA, NOAA, and USGS in order to provide community consensus recommendations to guide the agencies' space-based Earth observation programs in the coming decade. The report recommended a set of 17 missions in three time phases to achieve the needed observations while providing for both scientific advances and societal benefit.

In 2008, NASA convened a series of workshops to further investigate each of the five missions recommended for second phase (2013-2016) implementation. Workshop participants were charged with defining core science investigations enabled by the recommended mission and identifying high-priority near-term activities required to further mature the mission concept towards readiness for a Phase A mission start. This report summarizes the community discussions, findings, and recommendations from the NASA Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission Workshop held July 23-25, 2008 at the University of Michigan in Ann Arbor, Michigan.

Executive Summary

A three day community workshop was held on July 23-25, 2008, to consider the NASA Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission recommended for mid-term (Launch Readiness 2013-2016) implementation by the 2007 Earth Science decadal survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. The purpose of the workshop was to refine the scientific goals, objectives, and requirements of the ASCENDS mission, and to identify and prioritize the near-term activities needed to mature the concept towards readiness for a Phase A mission start by 2010.

Participants from the anticipated ASCENDS science community were charged to:

1. Define the core science investigations to be addressed by ASCENDS
2. Identify and prioritize further studies and technology developments needed to advance the readiness of the ASCENDS mission

A fundamental scientific need for spaceborne active CO_2 measurements was reaffirmed by workshop participants. 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.

Priority areas for near-term investment to advance ASCENDS mission readiness include:

- ***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 CO_2 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.

This report reflects proceedings and findings from the workshop, outlining the state of the science and technology for active remote sensing of CO_2 and providing recommendations for further studies and technology development activities to ready ASCENDS for a Phase A mission start.

1. Introduction

The NASA Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission, recommended for launch in the second phase of missions (2013-2016) by the 2007 NRC Earth science decadal survey, is considered the technological next step following launch of the NASA Orbiting Carbon Observatory (OCO) in early 2009. Using an active laser measurement technique, ASCENDS will extend CO_2 remote sensing capability to include uninterrupted/all-season coverage of high-latitude regions and nighttime observations with sensitivity in the lower atmosphere, to enable investigations of the climate-sensitive southern ocean and permafrost regions, provide insight into the diurnal cycle and plant respiration processes, and provide useful new constraints to global carbon cycle models.

NASA held a three-day workshop in July 2008 to refine the scientific goals, objectives, and requirements of the ASCENDS mission and to identify priority near-term investments needed to further mature the concept towards readiness for a Phase A mission start.

This report documents ASCENDS workshop discussions and findings starting with a brief background on the decadal survey, its process, and ASCENDS mission recommendation, followed by a description of the ASCENDS workshop organization. An overview of existing CO_2 measurement sources is then provided as context for the ASCENDS active measurement. The science investigations enabled by and benefitting from the ASCENDS mission are then described, and near-term study priorities are identified to further refine measurement requirements. Several airborne CO_2 lidar measurement techniques which are currently being developed are then presented, followed by results of a mission concept study performed to examine mission feasibility. Challenges associated with validation of an active CO_2 measurement are then discussed, followed by a listing of recommended near-term technology and validation investment priorities. Finally, synergies with other current and future Earth science missions, including decadal survey missions, are presented.

1.1 The Decadal Survey

The National Research Council's decadal survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond,* was released in 2007 as the culmination of a two year study commissioned by NASA, NOAA, and USGS to provide consensus recommendations to guide the agencies' space-based Earth observation programs in the coming decade.

As described in the decadal survey report, the committee was organized into seven thematic panels and an executive committee. Community input was solicited via a Request for Information, and over 100 mission concepts were submitted by the community for consideration. The thematic panels evaluated submitted concepts based on eight prioritization criteria which were used to generate each panel's priority list:

1. Contribution to the most important scientific questions facing Earth sciences today (scientific merit, discovery, exploration)
2. Contribution to applications and policy making (societal benefits)
3. Contribution to long-term observational record of the Earth
4. Ability to complement other observational systems, including national and international plans
5. Affordability (cost considerations, either total cost for mission or cost per year)
6. Degree of readiness (technical, resources, people)
7. Risk mitigation and strategic redundancy (backup of other critical systems)
8. Significant contribution to more than one thematic application or scientific discipline

The panels then worked together to merge, combine, and condense the list of priorities into what is considered a "minimal yet robust" observing strategy. Ultimately, the report recommended a set of 17 missions in three time phases to achieve the needed observations while providing for both scientific advance and societal benefit.

The NRC report recommends the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) to produce global atmospheric column CO_2 measurements without seasonal, latitudinal, or diurnal bias, using simultaneous laser remote sensing of CO_2 and O_2, with the goal of enhancing understanding of the role of CO_2 in the global carbon cycle. Three science objectives are identified in the report:

1. *Quantify global spatial distribution of atmospheric CO_2 on scales of weather models in the 2010-2020 era,*
2. *Quantify current global spatial distribution of terrestrial and oceanic sources and sinks of CO_2 on 1-degree grids at weekly resolution; and*
3. *Provide a scientific basis for future projections of CO_2 sources and sinks through data driven enhancements of the Earth-system process modeling.*

The complete ASCENDS mission summary from the decadal survey is included as Appendix E.

1.2 ASCENDS Workshop

The ASCENDS workshop was held July 23-25, 2008, at the University of Michigan in Ann Arbor, Michigan. The workshop was open to all interested parties. Participants from the anticipated ASCENDS science community were invited to present plenary lectures and posters on key ASCENDS science topics. All workshop participants were encouraged to discuss and refine the science goals for active CO_2 measurements from space, discuss the merits and limitations of potential measurement strategies to achieve these science goals, define and refine the links between the science questions and measurement requirements, identify requirements for technological development to ensure mission success, identify and prioritize science requirements, summarize open questions, and recommend further studies needed to advance the readiness of the ASCENDS mission. Specifically, workshop participants were charged by NASA to:

1. Define the core science investigations to be addressed by ASCENDS
2. Identify and prioritize further studies and technology developments needed to advance the readiness of the ASCENDS mission

The workshop consisted of a blend of plenary presentations, poster sessions, and interactive breakout sessions. Presentations on day 1 focused on the scientific context for ASCENDS, including a discussion of current state-of-the-art measurements of CO_2 from ground, airborne, and space platforms. The second day focused on discussion of the ASCENDS mission, related instrument development activities, and other future and ongoing missions of interest to the carbon cycle community which might complement the ASCENDS mission. Sets of breakout sessions were held each afternoon (one on the fist day and two on the second day) to further discuss plenary topics and elaborate science measurement needs. Findings of each breakout session were presented in plenary session. The final day involved presentations and discussions related to ASCENDS validation needs and implications for coupled carbon cycle-climate models, as well as a synthesis of workshop findings and recommendations.

2. Science & Measurement Context

The modern atmospheric CO_2 measurement record began in 1957 with flask measurements taken atop Mauna Loa to provide samples of the global background concentration of atmospheric carbon dioxide. By design, the measurements were made far away from known sources and sinks, and thus have provided an unambiguous indication of the long-term trend of increasing atmospheric CO_2. Over the years, our understanding of the spatial and temporal variations in atmospheric CO_2 concentrations has improved via the establishment of additional ground measurement sites providing both surface and tower measurements, aircraft campaigns and routine airborne observations, and, most recently, contributions from space-based remote sensing. Yet, there remain significant gaps in our understanding, particularly related to the distribution and variability of terrestrial and oceanic sinks and the processes controlling this variability.

2.1 Science Context

Based on the difference between observed increases atmospheric CO_2 concentrations and anthropogenic CO_2 emissions, natural terrestrial and oceanic sinks have absorbed approximately 60% of the CO_2 generated by human activities; however, significant year-to-year variations are apparent (Figure 1). These variations are attributed to changes in the terrestrial and oceanic sinks, but the processes governing sink strengths and the relative partitioning of CO_2 between terrestrial, oceanic, and atmospheric reservoirs, are poorly understood (Figure 1). Errors in the representation of these processes in existing coupled carbon-climate models leads to large uncertainties in long-term climate projections. Improving our understanding carbon sink characteristics and processes is thus critical to improving projections of atmospheric CO_2 levels and, in turn, climate.

In order to address the gaps in our current understanding of atmospheric CO_2 and its relation to climate change, three overarching needs can be defined:

- Improved understanding of the current magnitude and distribution of terrestrial and oceanic sources and sinks, distinguishing between natural and anthropogenic sources and sinks.
- Improved understanding of the time varying behavior, and underlying processes of these natural sources and sinks, including processes that occur over short (e.g. diurnal) time scales, medium (seasonal/annual) time scales, and extended (climatological) time scales, including processes resulting from ecosystem/biosphere disturbances.
- Improved ability to predict/model long-term changes in the climate cycle based both on the understanding of the natural processes driving the variability of natural carbon sources and sinks, and on the transport of carbon through the atmosphere.

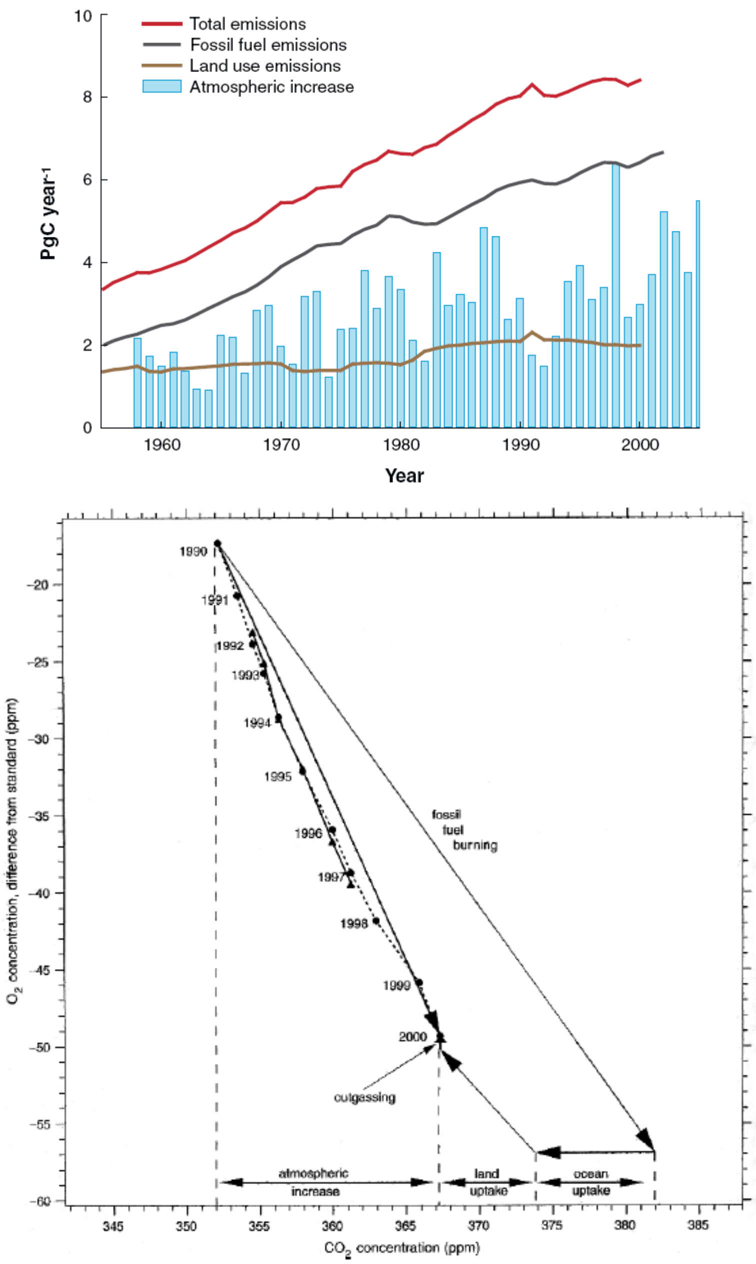


Figure 1: Annual variation in atmospheric CO_2 levels from 1958 until 2005, compared to emissions (top). Source: Houghton 2007; Partitioning between land and ocean sinks remains uncertain (bottom). Source: IPCC Third Assessment Report

2.2 Ground-based CO_2 Measurements

Ground-based measurements of atmospheric CO_2 mole fraction began in 1957 at Mauna Loa Observatory. This longest measurement record available for in situ CO_2 observations, begun by C. David Keeling of Scripps Institution of Oceanography, is continued today by the National Oceanic and Atmospheric Administration Earth System Research Laboratory (ESRL) Global Monitoring Division (Figure 2). ESRL manages four baseline observatories (located at Barrow, Alaska; Mauna Loa, Hawaii; American Samoa; and the South Pole, Antarctica) to detect long-term trends in several atmospheric gases. ESRL is the holder of the World Meteorological Organization (WMO) calibration standard gases, and leads on-going calibration and inter-comparison efforts to ensure measurements have the precision and accuracy required to detect long-term trends amidst short term variability.

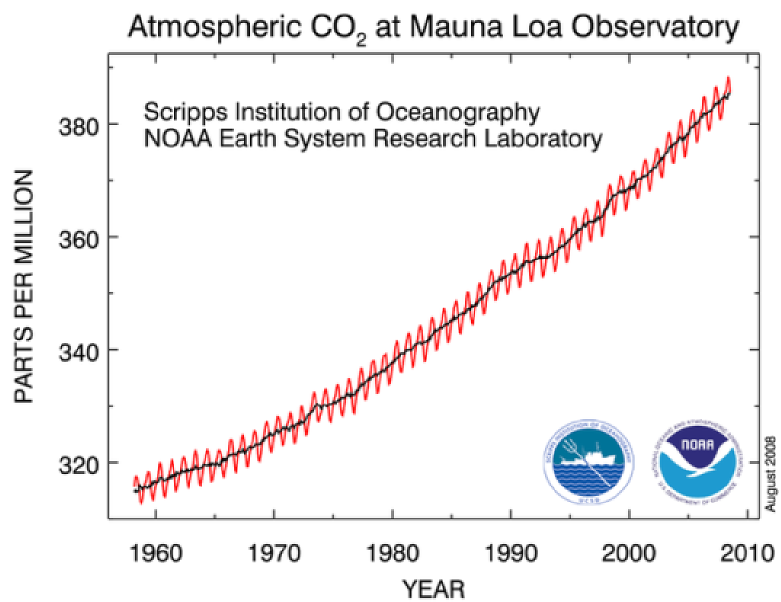


Figure 2: Atmospheric CO_2 at Mauna Loa Observatory showing an increase from approximately 315 ppm in 1958 to 385 ppm in 2008. Seasonal variability is clearly visible in the red curve. Source: P. Tans, NOAA/ESRL

NOAA ESRL also manages a global air sampling network of tall towers, surface, ship, and airborne assets to provide insight into the spatial variability of atmospheric CO_2 (Figure 3).

Adding to the set of available ground observations, the Total Carbon Column Observing Network (TCCON) was recently established. Currently consisting of ten of ground-based upward-looking Fourier Transform Spectrometers (FTS), TCCON records direct solar spectra in the near-infrared spectral region to provide accurate and precise column-averaged abundance of CO_2, and several other species (Figure 4). Column measurements from the Park Falls site have been traced directly to the WMO standard to provide the precision and accuracy required to allow for their use in the validation of spaceborne measurement (e.g., Washenfelder et al., 2006; Peters et al., 2007). TCCON will serve a key role in the validation of data from NASA's Orbiting Carbon Observatory.

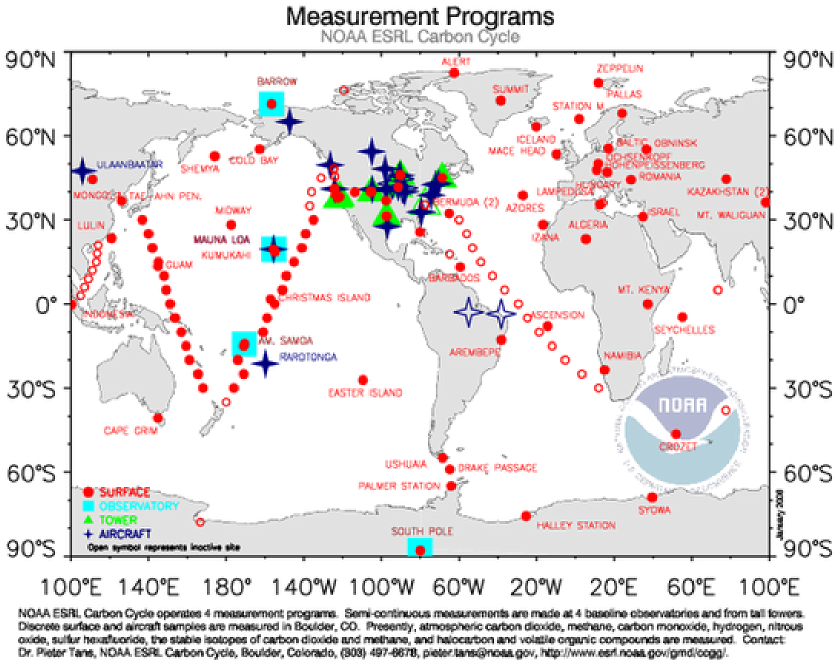


Figure 3: NOAA ESRL measurement programs. Red dots indicate surface measurements, cyan squares are observatories, green triangles are towers and blue crosses are aircraft. Source: http://esrl.noaa.gov/gmd/Photo_Gallery/GMD_Figures/ccgg_figures/tn/ccggmap.png.html

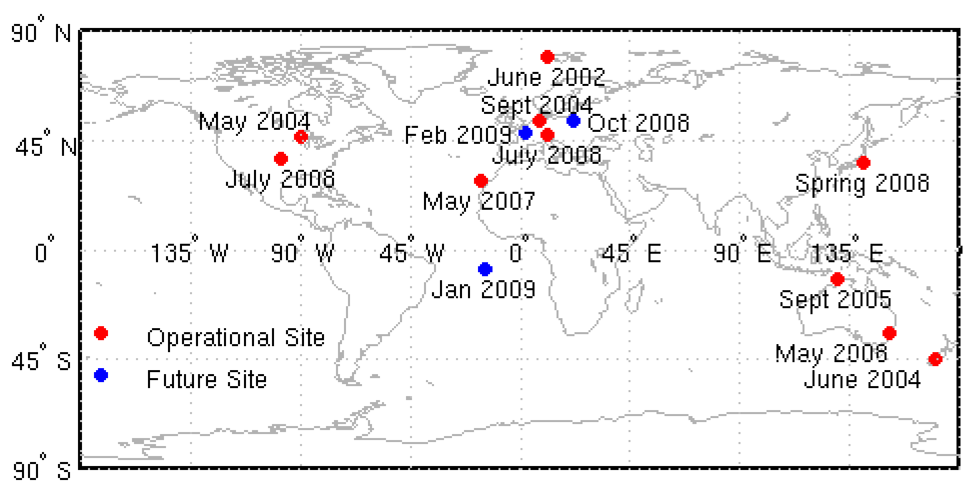


Figure 4: Current and future TCCON locations. Source: http://tccon.caltech.edu

While the existing observation network provides useful constraints for process and transport models, the sparseness of network's spatial coverage and scarcity of observations in the southern hemisphere are apparent.

2.3 CO_2 Measurements from Airborne Platforms

Instruments aboard airborne platforms are capable of measuring CO_2 with uncertainties on the order of 0.1 – 0.2 ppm up to their allowable flight ceiling. Airborne measurements of CO_2 are obtained from field campaigns, routine sampling programs, and aircraft flights of opportunity.

NOAA ESRL provides regular airborne sampling near specific sites as indicated by the blue crosses in Figure 3. Many NASA-sponsored aircraft field campaigns have been conducted or are currently in progress including PEM-WEST (A: 1992 & B: 1994), PEM-Tropics (A: 1996 & B:1999), SPURT (2001-2003) TRACE-P (2000-2001), INTEX-NA (2004), INTEX-B (2006), TC-4 (2007), and ARCTAS (2008). The so-called CONTRAIL flask measurements by Matsueda, et al., provide another useful airborne data set based on observations taken by a science payload carried by the Japan Airlines (JAL), a commercial airline, on its routine flights between Japan and Australia, Europe, Asia, Hawaii and North America. The CONTRAIL payload conducts high-frequency measurements of CO_2 along the flight path with continuous sampling, augmented by a flask sampling system to provide isotopic ratios and measurements of other trace gas species.

Inter-comparisons with ground and spaceborne instruments are facilitated by establishing traceability to the NOAA-maintained WMO standard. The TCCON sites, for example, rely upon aircraft overflights with calibrated in situ instruments to tie FTS measurements to the WMO standard. Aircraft field campaigns also play a key role in the validation of spaceborne remote sensing instruments, such as the MOPITT, TES, OMI, HIRDLS, and CALIPSO.

2.4 CO_2 Measurements from Space Platforms

Spaceborne platforms are extending the atmospheric CO_2 record by providing high quality measurements with unprecedented coverage and density in space and time, augmenting local and regional measurements from ground and airborne sensors to provide a global context for existing measurements, and cover regions not readily accessible or instrumented by other means. The AIRS-TES-OCO series of NASA satellite CO_2 observations as well as observations from the SCIAMACHY (ESA) and GOSAT (JAXA-MOE-NIES) sensors were addressed in plenary presentations and breakout discussions, and are summarized here.

2.4.1 SCIAMACHY

The SCanning Imaging Absorption Spectrometer for Atmospheric CartograpHY (SCIAMACHY) launched in 2002 aboard ESA's ENVISAT spacecraft. SCIAMACHY is a multichannel diode array spectrometer covering the spectral range 240 – 2385 nm with moderate spectral resolution (0.2 – 1.6 nm) (Burrows et al., 1995). It measures spectra of scattered, reflected, and transmitted solar radiation in nadir, limb, and solar and lunar occultation viewing modes. Atmospheric CO_2 column amounts are retrieved from NIR nadir radiances in Channel 6 (1- 1.75 µm, resol 1.48 nm FWHM). For nadir observations, SCIAMACHY has a horizontal resolution of 30×60 km^2. Total column CO_2 is being retrieved using the Weighting Function Modified Differential Optical Absorption Spectroscopy (WFM-DOAS) algorithm (Buchwitz et al., 2007) (Figure 3). Comparisons of SCIAMACHY total column CO_2 with TCCON measurements over Park Falls, Wisconsin and over Bremen, Germany are yielding very encouraging results, suggesting a bias of ~2% in the satellite measurements (Bösch et al., 2007).

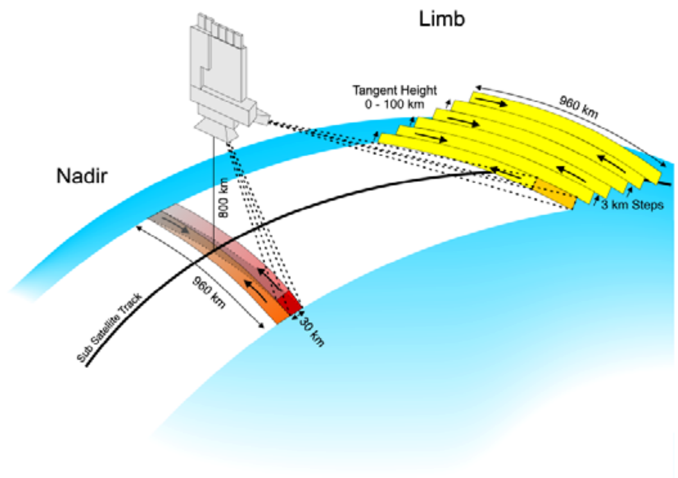


Figure 5: Observing methods of SCHIAMACHY. Source: H. Boesch

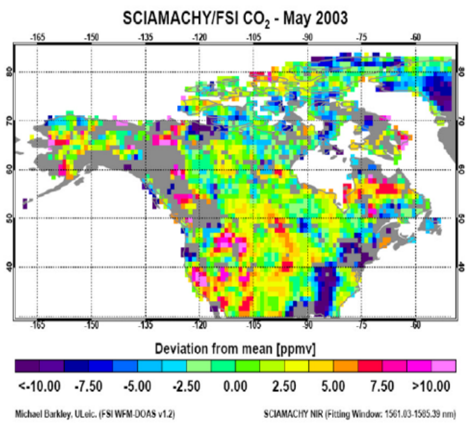


Figure 6: Column CO_2 retrieved from SCIAMACHY over North America in May 2003. Source: M. Barkley 2006

2.4.2 AIRS

The Atmospheric Infrared Sounder (AIRS) is one of six instruments on board the Aqua spacecraft as part of the Earth Observing System's Afternoon Constellation (Figure 7). With 2,378 spectral channels, AIRS has a spectral resolution more than 100 times greater than previous IR sounders and provides more accurate information on the vertical profiles of atmospheric temperature and moisture. AIRS can also measure trace greenhouse gases such as ozone, carbon monoxide, and methane. Data from AIRS have recently been used to produce global maps of CO_2 concentrations in the mid-troposphere (Chahine et al., 2005). These data provide important new constraints on the global distribution and transport of CO_2.

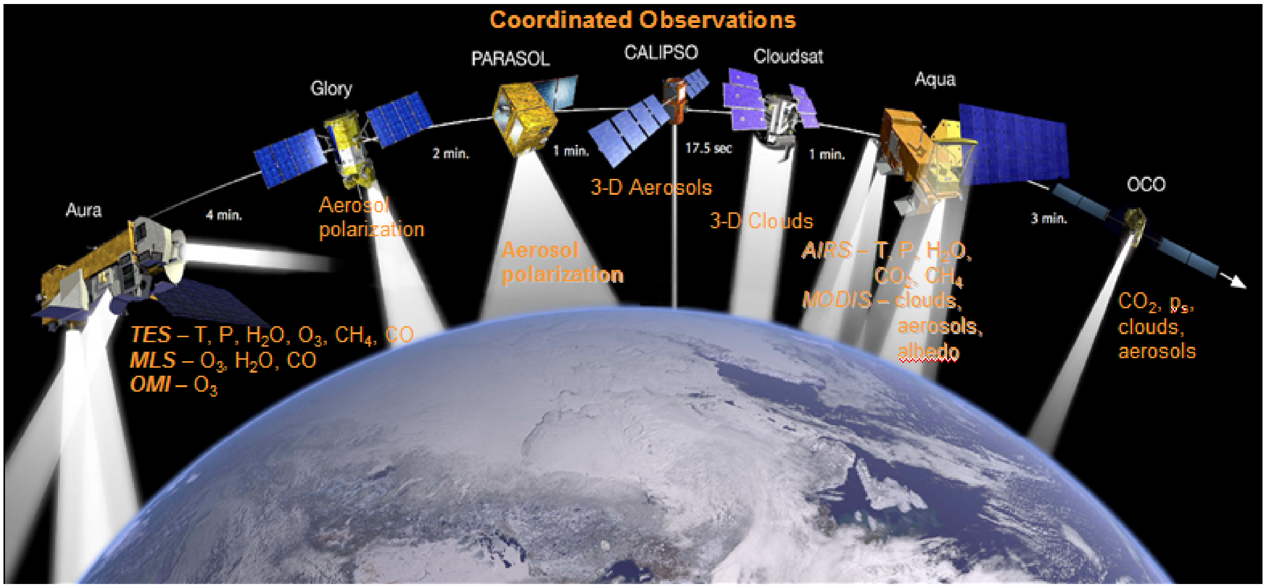


Figure 7: The Earth Observing System Afternoon Constellation ("A-train"). Source: NASA

2.4.3 TES

The Tropospheric Emission Spectrometer (TES) is a high resolution Fourier Transform Spectrometer aboard the Aura satellite, also in the A-train constellation. TES sensitivity peaks in the mid-troposphere. Current TES data products retrieved from nadir infrared emission spectra include tropospheric temperature, pressure, O_3, CO, H_2O, and CH_4. Tropospheric CO_2 retrieval is currently being developed and tested. Initial CO_2 retrievals have been demonstrated using the 1000 cm^{-1} spectral region (Kulawik 2008). Subsequent implementation of a TES retrieval algorithm using a combination of this region and the 700 cm^{-1} region is expected to result in further improvement (Kulawik 2008). Initial comparisons have been made with AIRS retrievals and aircraft flask CO_2 data. Near term activities include assimilation and inverse modeling of TES CO_2 measurements, using the chemical transport model GEOS-Chem.

2.4.4 OCO

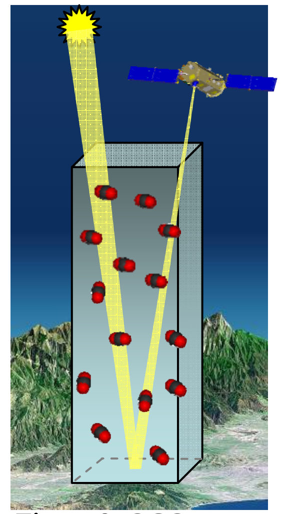


Figure 8: OCO measurement approach. Source: C. Miller

NASA's Orbiting Carbon Observatory (OCO) is scheduled to launch in February 2009. OCO measures CO_2 and O_2 spectral radiances via passive near infrared grating spectroscopy (Figure 8), to provide column-averaged CO_2 dry air mole fraction, X_{CO2}, with the precision, temporal and spatial resolution, and coverage needed to characterize the variability of CO_2 sources and sinks on regional spatial scales, and seasonal to interannual time scales. OCO carries a single instrument designed to make co-boresighted spectroscopic measurements of reflected sunlight in near-infrared CO_2 and molecular oxygen (O_2) bands, collecting 12 to 24 X_{CO2} soundings per second over the sunlit portion of the orbit, yielding 200 to 400 soundings per degree of latitude, or 7 to 14 million soundings for every 16 day orbit repeat cycle. Existing studies indicate that at least 10% of these soundings will be sufficiently cloud free to yield X_{CO2} estimates with accuracies of ~0.3 to 0.5% (1 to 2 ppm) on regional scales every month (Crisp et al., 2007). OCO will fly in loose formation with the A-train to enable correlation of Earth observations with instruments onboard other A-train satellites, particularly AIRS.

2.4.5 GOSAT

Japan's Greenhouse Gases Observing Satellite (GOSAT) is scheduled for launch in January 2009. GOSAT measures CO_2 and CH_4 spectral radiances via thermal and near infrared spectrometry to study the transport mechanisms of greenhouse gases with an emphasis on identification of CO_2 sources and sinks on sub-continental scales in support of the Kyoto protocol. Goals of the mission include producing more accurate estimates of the fluxes of greenhouse gases on a sub-continental basis (several thousand kilometers square) and accumulating new scientific knowledge on the global distribution of greenhouse gases, their temporal variations, and the mechanisms driving the global carbon cycle and its effect on climate.

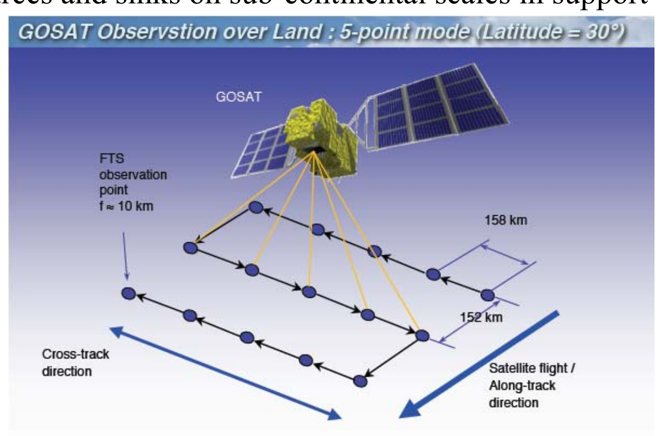


Figure 9: GOSAT Observation pattern over land. Source: T. Matasunga.

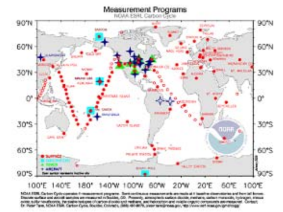
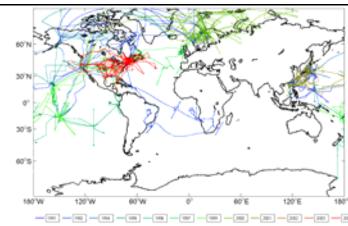
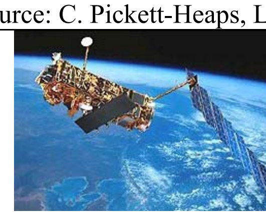
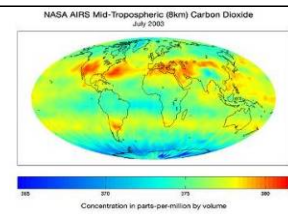
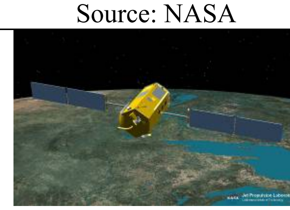
	Data Source	Characteristics	
Ground	Ground-Based Networks	Point measurements, sparse coverage Longest CO_2 record (continuous operation since 1957) Observations from surface to ~500 m High temporal resolution, accuracy, and precision	 Source: NOAA-ESRL
Airborne	CO_2 Aircraft Campaigns	Regional measurements Infrequent flights/operations Varying altitudes accessible Vertical profiles High accuracy and precision	 Source: C. Pickett-Heaps, LSCE
Space borne [current]	SCIAMACHY on EnviSat (Launched in 2002)	Global coverage Passive, 8 channel UV-Vis-NIR spectrometer Column CO_2 Moderate spectral resolution	 Source: ESA
	AIRS on Aqua (Launched in 2002)	Global coverage Passive, hyperspectral infrared sounder Monthly mid-tropospheric CO_2 Daytime/nighttime observations	 Source: NASA
	TES on Aura (Launched in 2004)	Global coverage Passive, high-resolution imaging infrared Fourier-transform spectrometer Tropospheric sensitivity	 Source: NASA
Space borne [near completion]	OCO (Launch early 2009)	Global coverage Passive, NIR spectrometers Highly accurate X_{CO2} Variability of CO_2 sources and sinks	 Source: NASA
	GOSAT (Launch early 2009)	Global coverage Passive, Fourier transform spectrometer Cloud-aerosol imager	 Source: JAXA

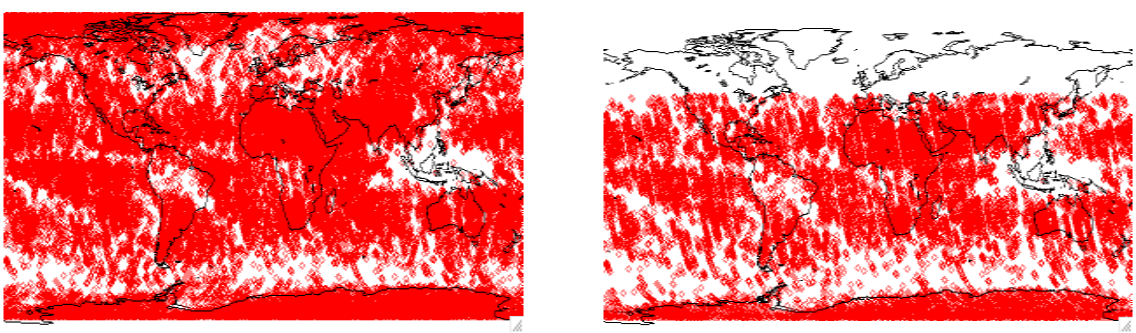
Table 1: Current/Near-Term Global CO_2 Observing Capabilities

2.5 Potential Benefits of an Active CO_2 Measurement

An active (lidar) CO_2 remote sensing mission is a logical next step in a global carbon cycle observing strategy. Spaceborne observations of CO_2 to date involve passive remote sensing techniques, and while their contributions to understanding the global carbon cycle are significant, passive measurement techniques have some inherent limitations.

At high latitudes, passive systems which rely on reflected sunlight are limited by variable sensitivity at different solar illumination angles and an inability to observe high-latitude targets during the local winter. Over oceans, reflected sunlight passive systems may be limited to observations in areas of solar specular reflections (so called "glint" regions) due to very low surface reflectivity of ocean water in the near infrared, and hence low observation signal-to-noise characteristics. Thermal infrared emission sounders are capable of making global day-night observations independent of solar illumination; however, their measurements are most sensitive to CO_2 in the mid- to upper-troposphere (Engelen and McNally 2005; Maddy et al., 2008).

In contrast, an active remote sensing mission allows measurements to be taken day and night, over ocean and land surfaces, and at all times of year. It involves a simpler observational geometry, with a common illumination and observation path, and is less susceptible to errors from atmospheric scattering. Active CO_2 remote sensing enables enhanced sensitivity to CO_2 in the lower troposphere, where its atmospheric concentration shows the most response to surface fluxes. Over oceans, a lidar system enables more frequent observations of the southern ocean specifically, especially in the wintertime, where dark oceans are virtually inaccessible to passive systems (Figure 10).



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

The ability of active CO_2 sensors to measure during day and night provides for at least twice the diurnal coverage of passive systems which rely on reflected sunlight. Nocturnal measurements with lower-atmospheric weighting are desired for investigations of respiration. Since lidar can make effective measurements regardless of local observation time, various non-Sun synchronous orbits (SSO) can be considered to provide additional information to separate diurnal cycles from seasonal or other cycles, though increased mission, science, and validation complexity might impact costs.

Depending on the approach chosen, there are other possible benefits from lidar measurements. Higher spatial sampling, for example, would allow detection of strong, localized gradients in CO_2 concentration to facilitate investigations in complex terrain where local climate variability is used as a proxy for climate change, or in regions with broken cloud coverage. It could also enable measurements through smaller gaps in clouds or to cloud tops, significantly reducing errors caused by atmospheric scattering.

3. ASCENDS Science

Workshop participants identified numerous scientific investigations that can benefit from active CO_2 remote sensing measurements. These were classified into 'core' and 'enhanced' science categories based on plenary discussions at the workshop. Core science areas are defined as those high priority exploratory science objectives which are uniquely enabled by ASCENDS, and are considered to be part of the science floor. Enhanced science opportunities remain dependent upon mission implementation decisions. Preliminary measurement needs were identified, and quantified as feasible; however, ***further studies are needed before the measurement and mission requirements for ASCENDS can be rigorously quantified***.

3.1 Core Science Enabled by ASCENDS

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.

During breakout sessions, participants discussed the measurement needs associated with each investigation.

3.1.1 Changes in Northern High Latitude Sources and Sinks

Permafrost covers about 20% of the Earth's land mass (UNEP 2007). Climate models predict that northern high latitudes will experience accelerated surface temperature increases during the next century (IPCC 2007), exposing Northern Hemisphere permafrost regions to thaw and releasing sequestered organic carbon. Some areas are expected to thaw completely, while others may experience seasonal freeze-thaw cycles. The secular release of CO_2, possibly coincident with other trace gasses such as methane (CH_4) from permafrost melting in the northern tundra is an important element of future climate change scenarios (Hansen et al., 2007). Identifying the onset of atmospheric CO_2 release from permafrost thaw and understanding the magnitude and variability of CO_2 release rates from this growing carbon source is critical to predicting its role in global climate change.

Numerous models attempt to capture the seasonal variation in northern boreal forest CO_2 uptake, but the models exhibit large variation amongst themselves. Globally consistent, inter-seasonal, and unbiased measurements of atmospheric CO_2 concentrations above these high-latitude forests are necessary to understand and constrain the behavior of these conflicting models to reduce the uncertainty in resulting climate projections.

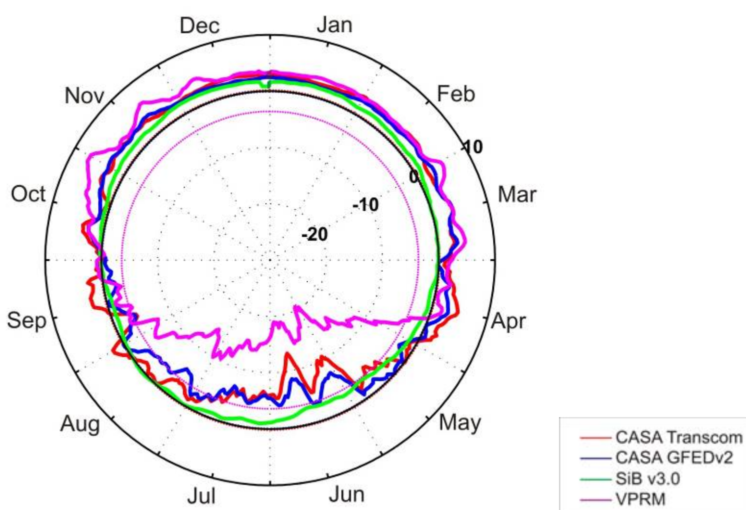


Figure 11: Variability in the predicted carbon (CO_2) flux of deciduous broad-leaf forests from different modeling techniques. Source: D. Huntzinger

Participants in one workshop breakout session discussed the measurement attributes needed from ASCENDS (Table 2) to provide meaningful information about northern high latitude sources and sinks. Observations with spatial resolution on the order of about 100 km by 100 km will allow permafrost regions to be resolved. A one year observation record (minimum time needed) would reveal a "fossil fuel" level signal, which could inform the long term melting rates. A longer mission lifetime is preferred to constrain the long term trends. Monthly to seasonal measurements are desired as they would provide further information on wintertime transition. A high-inclination (e.g., polar or sun-synchronous) orbit will provide a large number of samples at high-latitudes in clear areas, though persistent cloud cover and low snow/ice reflectivity (resulting in low signal-to noise) in the Northern high-latitudes is a key limitation. The ability to measure between breaks in high-latitude clouds would improve the number of available measurement opportunities. The accuracy needed for these measurements can perhaps be determined through analysis of radar freeze/thaw data. A trade study between a lower altitude weighting function (laser wavelength) and the measurement accuracy required should be considered. Ancillary measurements including methane, radar freeze/thaw, and boundary layer height, if available, would allow for a more complete understanding of permafrost melting. Workshop participants noted the possibility of strong scientific synergies with radar freeze/thaw measurements anticipated from the NASA SMAP mission, should the two missions fly concurrently. An ASCENDS launch readiness date in the 2013-2014 period will maximize the opportunity for concurrent ASCENDS and SMAP observations.

Changes in Northern High Latitude Sources and Sinks	
Goal	Understand the effect of changes in northern high latitude sources and sinks (e.g., permafrost melting) on the global CO_2 balance
Spatial Scale	Observations on the order of 100 km x 100 km
Temporal Scale	
Mission Lifetime	≥ 1 year
Diurnal Preference	
Acceptable Error/ Bias	
Additional Measurement Attributes	Summertime is the primary occurrence of permafrost melting; between cloud sampling; monthly to seasonal observations would further inform wintertime transition investigations
Ancillary Measurements Desired	Methane, Radar freeze/thaw, boundary layer height
Additional Studies Needed	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.

Table 2: Measurement Needs for Investigations of Changes in Northern High Latitude Sources and Sinks

3.1.2 Southern Ocean Source/Sink Characteristics

ASCENDS will enable investigations of the seasonal variability in the southern ocean CO_2 flux. The southern ocean is poorly sampled by existing ground, airborne, and space observations even though it is considered an important large-scale sink of atmospheric CO_2. Temporal and spatial variability of the southern ocean sink is thus poorly understood, though there are indications the sink's strength is weakening. Model estimates of the southern ocean sink show large disagreements, however uncertainty due to lack of measurement data is large.

The southern high latitude region poses many challenges for any atmospheric CO_2 observing system. Compared to the instrument ground networks of the northern hemisphere, developing a ground network for consistent and continuous observations of CO_2 concentration in the southern hemisphere is difficult because a substantial fraction of surface is ocean. Passive spaceborne remote sensors have difficulty observing high-latitude and oceanic targets due to low surface albedo, which results in low signal-to-noise for sensors reliant upon reflected sunlight. The southern ocean is often too dark and/or cloud-covered to be observed by passive systems. Further, CO_2 flux between the ocean and atmosphere is highly dependent on the local weather and sea surface conditions, and thus requires access to ancillary data sets, such as sea surface temperature (SST), surface winds (i.e., surface roughness), and salinity in addition to atmospheric CO_2 measurement.

The measurement characteristics needed to enable study of the southern ocean CO_2 sink were discussed in breakout session. The fundamental science measurement requirement is to observe temporal and spatial variations in atmospheric CO_2 with a cumulative value on the order of 1 ppm over large distances. Measurements aggregated over a spatial scale of 500 km by 500 km are thought to be sufficient. The southern ocean's source/sink characteristics vary depending on season and mixing from both meteorological (e.g., rough seas provide higher albedo) and diurnal processes (e.g., natural sources and sinks are active at dusk/dawn), therefore measurements at different times of day are desirable. Determining the optimal observing time(s) requires further study, however the benefits of certain times of day were noted (i.e., the 10 pm timeframe represents a well mixed case and nighttime observations add insight to the near-to-surface boundary layer). Coincident surface pressure knowledge or measurement is required and additional information needs (likely from other platforms) include wind stress, ocean color, and sea state, salinity, surface winds, and temperature. To understand seasonal variations in source/sink characteristics and constrain long-term trends, a mission lifetime of at least 4 years is necessary.

Southern Ocean Source/Sink Characteristics	
Goal	Understanding southern ocean sources and sinks.
Spatial Scale	On the order of 500 km x 500 km
Temporal Scale	
Mission Lifetime	$\geq$ 4 years
Diurnal Preference	Multiple times of day desired, sampling day and night
Acceptable Error/ Bias	On the order of 1 ppm
Additional Measurement Attributes	Looking for cumulative small temporal and spatial variations over a large scale, measurements at different times of day at the same location.
Ancillary Measurements Desired	Coincident surface pressure knowledge or measurement is required. Surface winds/wind stress, ocean color, salinity, sea surface temperature and sea state will be obtained from other sources
Additional Studies Needed	Determination of optimal observing time

Table 3: Measurement Needs for Southern Ocean Investigations

3.1.3 Respiration Processes

The magnitude of the nightly release of CO_2 by plants during metabolism has never been quantified on a global scale and respiration is thought to decrease the net uptake of CO_2 by plants by a factor of two. Plant respiration rates tend to increase with temperature, as is evident in tropical regions, and therefore could increase further as global temperatures rise. On the other hand, increasing atmospheric CO_2 is likely to result in increased photosynthesis rates (i.e., the so-called “fertilization effect”) which might counterbalance the increased respiration. Whether increasing atmospheric CO_2 results in a net increase or decrease in terrestrial uptake is thus uncertain.

Terrestrial biosphere flux studies are often process based, using bottom-up models. However, this requires assumptions about the physical processes involved and models vary dramatically in terms of complexity. Models agree at continental scales, as current atmospheric monitoring provides adequate constraints at a large scale, however on the scale of biomes, (e.g., grasslands, forests) the models do not agree on seasonality or flux.

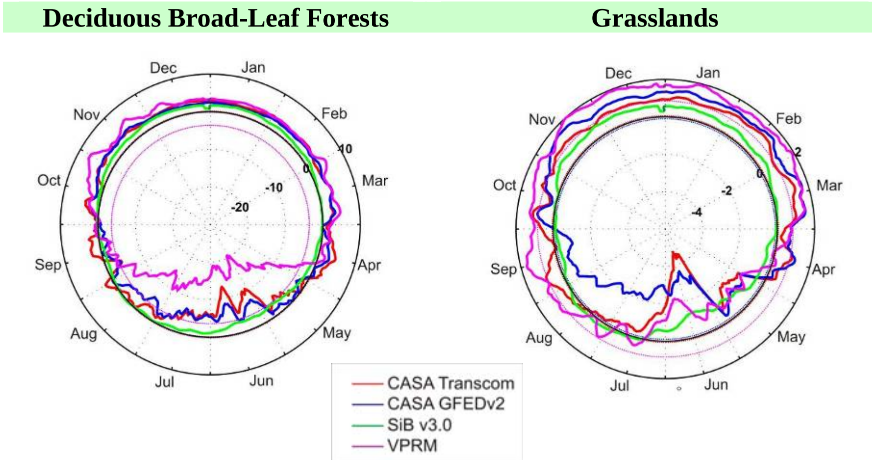


Figure 12: Variability in the bottom-up models for seasonally varying terrestrial source/sink processes. Source: D. Huntzinger

An ability to make nocturnal measurements of CO_2, will allow for study of plant respiration processes.

Participants noted that nighttime active spaceborne CO_2 measurements alone are insufficient to separate photosynthesis and respiration. Isotopic measurements (e.g., C12/13 and oxygen 16/17/18 isotopes) are needed. Presumably these measurements would be provided by ground-based systems, as measurements of isotopic ratios from space would require accuracies which are thought to be quite challenging using existing technologies. However, nighttime remote sensing measurements from space were seen to have substantial benefit for interpreting changes seen in daytime measurements, reducing the possibility of diurnal changes being aliased into long term sink changes, though night respiration insight does not directly correspond to day respiration process insight.

In order to better constrain model estimates of photosynthesis and respiration rates to improve understanding of the CO_2 fertilization effect, breakout group participants discussed ASCENDS measurement needs. Regional spatial coverage on the order of 500 km by 500 km is considered sufficient. Both day and night measurements are needed, though there is some flexibility in time of observation. Measurements over all seasons and latitudes are required. Further study is needed to quantify the acceptable error to ensure sufficiently small gradients can be detected in order to separate photosynthesis from respiration, as diurnal fluctuations in the full column are small compared to accuracies/precision thought to be practical for an active measurement. A co-aligned CO measurement over land during both the day and night was suggested as a means to distinguish respiration from combustion and fossil fuel burning, though further study is warranted to determine whether this is required and whether it is technically feasible.

Photosynthesis/Respiration Rates from CO_2	
Goal	Estimate the photosynthesis and respiration rates from CO_2 concentrations and improve understanding of fertilization effecting order to improve models.
Spatial Scale	On the order of 500 km x 500 km
Temporal Scale	Twice a day
Mission Lifetime	Many seasons
Diurnal Preference	Day & night; perhaps dawn/dusk
Acceptable Error/ Bias	Low bias
Additional Measurement Attributes	High latitude & between cloud sampling
Ancillary Measurements Desired	CO measurement over land, co-aligned, both day and night, to separate respiration from combustion sources
Additional Studies Needed	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 lidar measurements. The value added and technical feasibility of nocturnal CO measurements needs to be evaluated.

Table 4: Measurement Needs for Respiration Investigations

3.2 Opportunities for Enhanced Science

The science investigations covered here involve non-core science investigations which will benefit from the ASCENDS mission. The degree to which each is enabled or benefitted will depend in large part on the particular implementation approach selected. While all are desirable, workshop participants agreed they should not be considered drivers for determining ASCENDS mission measurement requirements.

3.2.1 Ecosystem Behavior in Complex Terrains

Since the major contributor to column CO_2 variability is due to the CO_2 within the planetary boundary layer, the spatial variation of the column CO_2 can be strongly influenced by topography and surface heterogeneity. Complex terrains vary on small spatial scales (e.g., steep mountains) and thus large spatial and diurnal variations in column CO_2 are expected. An active system with high spatial resolution would provide a unique opportunity to study complex terrains on scales small enough such that the measurements would be representative of the areas being observed. For example, the regional circulation associated with mountain ecosystems in highland areas located below the subalpine is unique and predictable for CO_2 transport over heterogeneous terrain both day and night, but atmospheric boundary layer mixing due to flow induced by topography and surface heterogeneity differs significantly from boundary layer mixing over flat terrain. Nighttime CO_2 can be drained to low altitudes and forms CO_2 "lakes." During daytime, the convective mixing of CO_2 can be delayed or shifted in regions surrounded by mountains as a result of mountain shading. Similarly, CO_2 transport caused by surface heterogeneity and gentle terrain can occur over "flat" land. Active CO_2 measurements at sufficiently small spatial scales could provide unique evidence of large spatial and diurnal variations of CO_2 accumulation over complex terrain and the roles of surface heterogeneity over "flat" land, and therefore, unique opportunities to investigate the role of complex terrain in regional and global CO_2 budget.

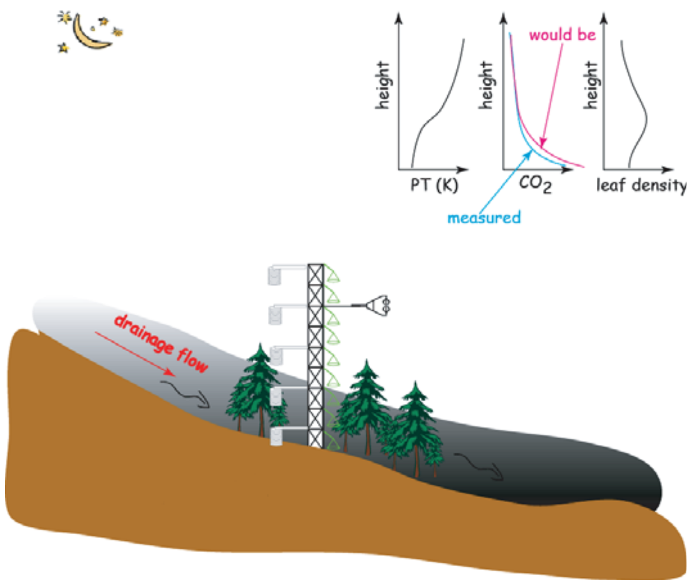


Figure 13: Nocturnal accumulation of CO_2 at low elevations. Source: J. Sun

In order to understand the role of complex terrain in the regional and global CO_2 budget without over-constraining ASCENDS measurement requirements, breakout group participants suggested that relaxed accuracy needs might allow collection of higher spatial resolution data with the same observing system envisioned to satisfy core requirements (e.g., through reduced along-track averaging). To characterize the spatial variations in CO_2 in complex terrain, measurements are needed with a spatial resolution on the order of 1 km and collocated surface pressure measurement. Further study could demonstrate the benefits low accuracy high spatial resolution measurements.

Complex Terrains	
Goal	Understand the role of complex terrain in regional and global CO_2 budget.
Spatial Scale	On the order of 1 km
Temporal Scale	
Mission Lifetime	≥ 1 season
Diurnal Preference	
Acceptable Error/ Bias	<~5 ppm
Additional Measurement Attributes	Relaxing accuracy may allow high spatial frequency characteristics. Low accuracy high spatial resolution may be preferable for this investigation
Ancillary Measurements Desired	Collocated O_2/pressure measurements key due to high spatial variability
Additional Studies Needed	

Table 5: Measurement Needs for Investigations of Complex Terrains

3.2.2 Climate Variability as a Proxy for Climate Change

Long-term climate trend investigations can be informed by shorter-term observations of interannual change. The El Niño Southern Oscillation (ESNO), for example, is both a major contributor to the interannual changes in CO_2 atmospheric growth rate (Figure 14) and an important climate-scale process. Observations of the variability of CO_2 associated with the El Niño cycle can thus inform long-term climate change investigations.

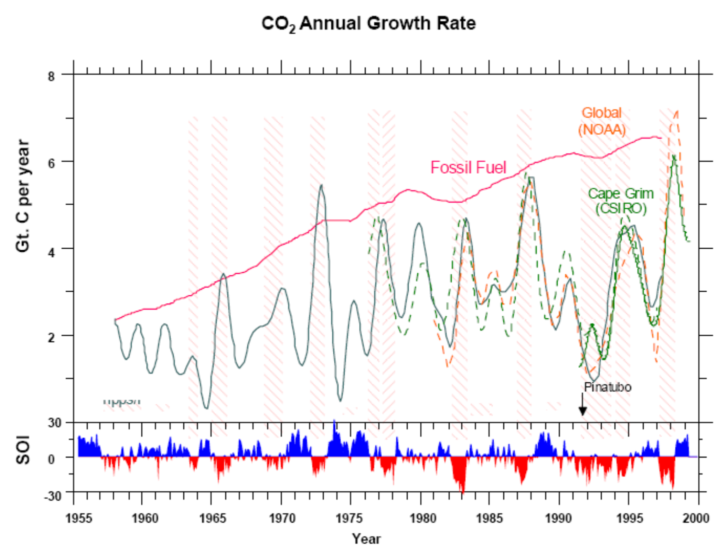


Figure 14: CO_2 Annual Growth Rate and its connection with the ENSO. ENSO cycles can last from between 2-11 years, making longer missions more likely to observe this key system process. Source: R. Francey

To use observed climate variability to inform climate change investigations, acceptable measurement errors are on the order of 1 ppm. Monthly to seasonal observations are needed with spatial resolution on the order of 500 km x 500 km. Most ENSO-related variability is expected the mid-latitude oceans, however coverage of the southern oceans and polar regions is also desired to capture other climate-relevant processes. A minimum mission duration of 4 years is required to cover at least one full ENSO cycle, though climate change simulations should be utilized to determine the ideal mission lifetime needed to most effectively address long term climate change via observations of climate variability.

Climate Variability as a Proxy for Climate Change	
Goal	Understand contributions to the inter-annual changes in CO_2 atmospheric growth rate due to variations in climate (e.g., ENSO)
Spatial Scale	On the order of 500 km x 500 km
Temporal Scale	Monthly to seasonal
Mission Lifetime	$\geq$ 4 years to observe ENSO cycle
Diurnal Preference	
Acceptable Error/ Bias	~1 ppm
Additional Measurement Attributes	Coverage of southern oceans and polar regions, mid-latitude ocean during ENSO
Ancillary Measurements Desired	
Additional Studies Needed	Climate change simulations to determine mission lifetime needed to address long term (50+ yr) climate change

Table 6: Measurement Needs for Investigations Involving Climate Variability as a Proxy for Climate Change

3.2.3 Land/Sea & Air/Sea Flux

Exchange of CO_2 between the land, air, and sea plays an important role in the carbon cycle. The amount of CO_2 exchanged between the land, atmosphere, and ocean depends on many variables, particularly boundary conditions such as wind speed and surface roughness. CO_2 cycling at oceanic margins is poorly understood. Coastal regions are under-sampled to the point that it is unknown whether most regions are a net source or sink.

Diurnal land-sea-air exchange in coastal regions can cause dramatic and sometimes extremely localized CO_2 concentration variation (e.g., on the scale if 10-100 km). Models of CO_2 fluxes in coastal regions would benefit from improved understanding of CO_2 uptake variability, particularly in relation to climate-sensitive processes (e.g., river run-off, severe storms, algal blooms).

Coastal and ocean flux studies require low systematic errors, however further study is required to quantify the acceptable measurement bias. High spatial variability in coastal regions suggests spatial resolution of ~25-50 km is appropriate; however open ocean flux measurements remain valuable at larger scales. The desired measurement is ultimately ΔPCO_2, however, it is not readily apparent that this measurement can be made from space. Measurements of ocean color, salinity and temperature can provide statistical estimations of ΔPCO_2; therefore, it may be possible to obtain this information from another source and it is unclear what value is added by a column atmospheric CO_2 measurement.

Land/Sea & Air/Sea Flux	
Goal	Understand coastal land/sea and air/sea flux in order to better characterize oceanic sinks
Spatial Scale	~25-50 km
Temporal Scale	
Mission Lifetime	
Diurnal Preference	
Acceptable Error/ Bias	Emphasis on low systematic errors
Additional Measurement Attributes	ΔPCO_2 is the desired measurement, however it is unclear whether it is directly measurable from space
Ancillary Measurements Desired	Ocean color, salinity and temperature provide statistical estimations of ΔPCO_2
Additional Studies Needed	Are tracer gas measurements required to distinguish terrestrial from oceanographic gases? Can ΔPCO_2 be measured from space?

Table 7: Measurement Needs for Land/Sea & Air/Sea Flux Investigations

3.2.4 Effects of Biospheric Disturbance on Carbon Flux Variability

The value of atmospheric CO_2 measurements in measuring biospheric disturbances was discussed during breakout session. Investigations of disturbances due to forest fires, land use and land cover changes (e.g., harvest), infestations (e.g., pine beetles in British Columbia), droughts/floods (e.g., Amazon River basin, agricultural flooding), climate/weather conditions (e.g., ENSO events, hurricanes, ice storms, and frost), volcanic eruptions, dust trans-ocean transport (i.e., variation of aerosols), and algal blooms might benefit from active CO_2 measurements, however the extent to which each is enabled or enhanced depends on the particular sampling strategy implemented (Table 8). As many disturbance investigations require global mapping capability, biospheric disturbance studies enabled by ASCENDS are likely limited to opportunistic case studies. Thus, the breakout group suggested that emphasis be put on characterizing the response of ecosystems to natural climate variability (i.e., temperature, moisture, etc.) in order to reach a better understanding of the large observed inter-annual variations in carbon uptake and to quantify the effects due to disturbances to enable the detection and understanding of underlying trends from which key similarities and differences between types of disturbances can be identified.

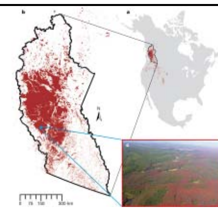
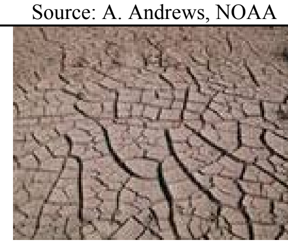
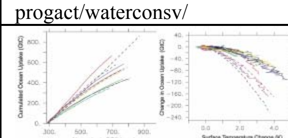
Disturbance Type	Characteristics			
	Spatial	Temporal	Other	
Fires	Localized, rapid spread, km scale	Fast release, days to weeks (source), slow recovery (sink)	Possible relation to trace CO emissions	 Source: NASA
Pine Beetle (Insect) Infestation	Regional, slow spread, 10-100kms scale	Slow release (source), slow regrowth (sink)	Possibly related to climate change (new habitats	 Source: W. Kurz 2008
Land Use Change	Localized to Regional scales	Rapid change of sink (logging, deforestation → crop planting, urban encroachment)	Readily correlated with imagery and land observations	 Source: http://www.usgcrp.gov/
Flooding	Localized, km scales	Rapid removal of sink, slow recovery over 1 or more annual cycles	Related to seasons and climate change	 Source: A. Andrews, NOAA
Drought	Regional, 10s-100km scales	Rapid removal of sink, slow recovery of 1 or more annual cycles	Related to seasons and climate change	 Source: http://www.usbr.gov/uc/progact/waterconsv/
Ocean Uptake	Regional - Global	Rapid changes in flux	Related to seasons and climate change; Processes not well understood	 Source: Fung et al, 2005; Friedlingstein et al, 2006

Table 8: Characteristics of Various Disturbance Types

Forest fires were recognized to be a challenging disturbance to measure and therefore, were used to quantify measurement needs. While fires produce a large increase in CO levels, only a small increase in CO_2 is observed in column measurements, therefore, high sensitivity and near-surface is required to observe the changes in CO_2. Measurements of the vertical profile were considered to be necessary, to avoid relying solely on model transport for lofted plumes. The full column should be resolved through the troposphere (i.e., the integral constraint needs to be defined to about 12-15 km altitude in the tropical tropopause) and weighted in the lowest 3 km. CO_2 accuracy should be better than 2 ppm in the lowest 3 km, and 0.5 ppm from 12-15 km. However, random errors can be larger with suitable data compositing. Ancillary measurements including pressure and temperature are also necessary. To meet the science goal of characterizing the response of ecosystems to natural climate variability, measurements need to be performed over extended periods so recovery from disturbances can be tracked. Synergistic measurements (e.g., from MODIS and CALIPSO) were considered to be complementary in determining the magnitude and spatial extent of a disturbance (e.g., burned area, active fire regions, burn intensity). Therefore, an A-train type orbit would add scientific value, though it is perhaps impractical for an active system. Nominally, a 16-day repeat orbit was considered sufficient sampling strategy for investigating most disturbances. Useful ancillary data includes co-aligned aerosol backscatter profile with resolution on the order of 100 m vertical and 10 km horizontal and uncertainty of less than 10%. Co-aligned CO data with full column weighting and <10% uncertainty can reveal fire plume extent.

Disturbances	
Goals	Characterize the response of ecosystems to natural climate variability (i.e., temperature, moisture, etc.) to understand the large observed inter-annual variations of carbon uptake and quantify the effect of disturbances. Identify key similarities and differences between types of disturbances
Spatial Scale	"Few kilometer" (≤10 km) desired; Geolocation accuracy of measurement point: ~250 m.
Temporal Scale	Not a strong driver, 16 day repeat period desired
Mission Lifetime	“long mission lifetime”
Diurnal Preference	
Acceptable Error/ Bias	Accuracy < 2 ppm in the lowest ~3 km; < 0.5 ppm for “full column” (12 km).
Additional Measurement Attributes	Need: “full column” (integral constraint) up to tropopause (12 km) and partial column of lowest ~ 3km.
Ancillary Measurements Desired	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.
Additional Studies Needed	Determination of the required uniformity in full column weighting function and required CO_2 accuracy in full & partial column

Table 9: Measurement Needs for Disturbance Investigations

3.2.5 Top Down Assessment of Anthropogenic CO_2 Emissions

The quantification of anthropogenic CO_2 emissions was not considered to be a core exploratory science objective by the research community, despite its emphasis in the decadal survey description of ASCENDS. The ASCENDS mission’s main contribution to determining emissions is likely to be through results obtained from models it informs. Additionally, ASCENDS data could assist in disentangling terrestrial fluxes and serve as a top down assessment for CO_2 emissions estimated from fossil fuel inventories. ASCENDS has unique capabilities that will complement detailed ground-based observations (e.g. Project Vulcan in the U.S.) to determine anthropogenic CO_2 emissions.

Anthropogenic emissions remain the largest perturbation in the global carbon budget. Figure 15 depicts the rapid increase in fossil fuel emissions over the last 40 years. ASCENDS will enable continued investigations of anthropogenic emissions (from fossil fuel use or land use changes) using a top-down approach, constraining the emissions determined by the current bottom-up inventory approach. At present, these inventories are known to have large errors, especially in developing regions of the world. However, since uncertainties in biospheric sources and sinks are much larger than uncertainties in anthropogenic sources, constraining the anthropogenic sources is partially dependent on successfully characterizing and constraining biospheric sources and sinks.

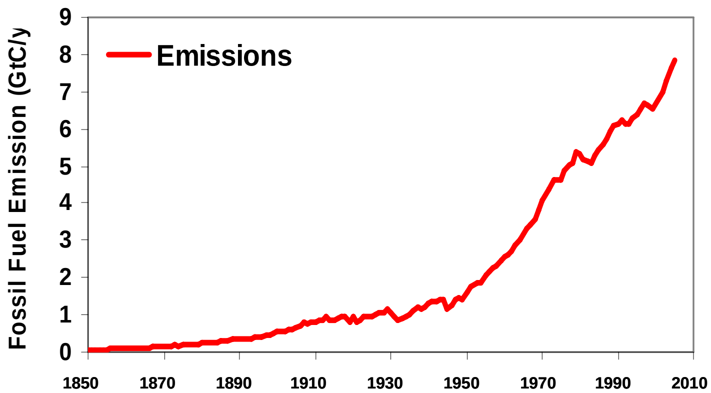


Figure 15: Anthropogenic Carbon Emissions: Fossil Fuel emissions from 1990-1999 increased about 1.3% per year. From 2000-2006 emissions increased to 3.3% per year. Source: G. Marland

The breakout session participants discussed the resolution and acceptable error needed to quantify anthropogenic emissions, though detailed measurement requirements must be determined through a series of Observing System Simulation Experiments (OSSEs).

High spatial resolution is particularly important for the study of anthropogenic sources, which tend to be intense and have small horizontal scales. A down-track spatial resolution of approximately 50 km or less (assuming 100 m wide swath) is needed for detailed studies on the scale of a city. Larger scales would add significant aggregation error to the measurement since a densely populated area would be averaged with suburban or rural areas. Higher spatial resolution is desirable, (e.g., a 5 km down-track length) to resolve emissions from different parts of a metropolitan area and see between clouds, if this were technically feasible. A capability to perform enhanced precision measurements for given targets (similar to OCO target mode) is desired to aid in both validation and addressing site-specific science questions.

CO measurements with boundary layer sensitivity are strongly desired, if not required, to distinguish between anthropogenic CO_2 sources and natural emissions by analysis of CO/CO_2 correlations. Participants felt the accuracy and precision of the CO measurements should improve upon the precision of the current suite of nadir CO sounders (e.g., MOPITT, TES, AIRS, IASI, SCIAMACHY) with an aim of 3% uncertainty in single target column values, but with accuracy requirements are not as strict as for CO_2 since CO has a much larger range of variability. These CO measurements are most useful if they are spatially and temporally (day and night) collocated with the CO_2 measurements, although it is recognized that night-time CO measurements may require an active approach (i.e. CO lidar), which lacks the technological readiness to be implemented in the timeframe proposed for ASCENDS. A study should be undertaken to assess the necessity of nighttime CO measurements.

Anthropogenic Emissions	
Goals	Distinguish natural from anthropogenic sources Top down assessment of anthropogenic CO_2 emissions
Spatial Scale	"City scale" 50 km (down-track) needed, 5 km desired
Temporal Scale	Weekly
Mission Lifetime	
Diurnal Preference	Multiple times of day: minimum 2, every ~3 hr desired
Acceptable Error/ Bias	
Additional Measurement Attributes	Target capability desired to look at intense sources and reduce random error; coverage during polar winter and at high latitudes
Ancillary Measurements Desired	CO, collocated, 3% uncertainty in column, day and night, lower tropospheric weighted sensitivity
Additional Studies Needed	Quantification of benefit of CO observation and what would be lost with day-only passive measurement

Table 10: Measurement Needs for Investigations of Anthropogenic Emissions

3.3 Summary of ASCENDS Measurement Needs

Additional studies are required to quantify science measurement requirements for ASCENDS; however, some likely measurement requirements can be inferred through examination of the measurement needs described in the previous sections. A preliminary science traceability matrix was prepared based on breakout discussions to facilitate such analysis (Appendix F). The measurement needs of core science objectives are expected to drive ASCENDS mission design, though the measurement needs for enhanced science investigations were also captured for further consideration during implementation trade studies. A high-level comparison of measurement needs suggests the following ASCENDS mission attributes:

- *Orbits* - All investigations appear compatible with a polar orbit, and some (but not all) with sun-synchronous "dawn-dusk type" equator crossing times. A mission design trade study is required to determine optimal crossing time. Precessing orbits should be considered for the variable diurnal sampling they provide, however the increased complexity of validating time varying observations must be acknowledged.

- *Mission lifetime* – For many investigations, participants suggested ≥ 4 year measurement lifetime as a target, with sub-seasonal temporal resolution. Trade studies must balance the desire for extended mission lifetime with engineering consideration of the requirements this places on the entire flight system, particularly the science payload.
- *Surface pressure measurements* – Most investigations stated the need for surface pressure knowledge along the same optical path as the CO_2 measurement (e.g., through direct measurement of O_2 column, dry air column, or dry air pressure). Several participants asserted that the currently available surface pressure forecasts and/or reanalyses from numerical weather models were insufficiently accurate, especially over sparsely observed areas, to relax the need for concurrent measurement of pressure. Additional studies are warranted to explore the accuracy of required surface pressure knowledge and mechanisms by which it can be obtained in the ASCENDS time frame (e.g., direct measurement, models)
- *Spatial scales for observations (and/or final analysis)* – Desired spatial scales ranged from ~500 x 500 km (oceans) down to ~10 x 10 km (plumes from fires). Trade studies are needed to consider the signal-to-noise levels and integration times required to achieve acceptable measurement errors as a function of investigation.
- *Concentration bias & uncertainty* - Participants representing most science areas stated a need to keep bias errors "low" (<1 ppm) over a range of spatial scales. Participants frequently asserted the need for "a continuous cal/val" capability to allow monitoring of space measurement quality and errors and to maximize the confidence in the space mission results. Studies are needed to more rigorously define bias and uncertainty requirements as a function of investigation.
- *Type of column measurement* – Several times participants noted the need for <u>both</u> lower tropospheric and full column (to ~12 km) measurements for an investigation. Concentrations in the lower tropospheric column are more sensitive to fluxes, while full column concentrations are more sensitive to transport. Observations of both are needed to constrain the models and determine the most accurate flux estimates. However, additional studies are needed to quantify the benefit associated with providing both measurements.
- *Carbon Monoxide* – Several science investigations need collocated CO measurements, at least in the daytime. In several cases, there is also desire for nighttime CO measurements. However, laser approaches for nighttime measurements are presently only conceptual, and the need for them should be better quantified.
- *Aerosol profile/boundary layer height* - Some science investigation areas desire determination of mixed layer/boundary layer height (e.g., from backscatter lidar) to better localize "plumes" from fires/emissions, etc. Further investigation is required to determine which methods exist to provide height estimation of the atmospheric mixed layer depth.
- "*Target mode" capability* – The capability to shift the pointing angle cross-track is desirable over land to enable observing intense sources (such as fires) more

frequently than allowed by a fixed nadir viewing geometry and to enable site-specific science investigations.

- *Launch Readiness Date* – Participants noted multiple scientific drivers for a launch in the 2013-2015 time frame, including the importance of maximizing overlap with OCO measurement record and leveraging freeze/thaw measurements from SMAP.

3.4 Near-Term ASCENDS Study Priorities

Each breakout group was charged with identifying near-term studies and activities to advance understanding of the ASCENDS measurement requirements towards readiness for a Phase A mission start. Because it was recognized that ASCENDS' measurement capability is to a large extent dependent upon the ultimate measurement strategy employed, most recommended studies focused on methods to quantify the measurement requirements needed to enable core science objectives. ***In plenary session it was agreed that studies of the end-to-end ASCENDS system were of highest priority.*** These studies are needed 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 of clouds, aerosols, CO, and atmospheric temperature, pressure, and moisture.

Additional desired near-term activities discussed in breakout sessions include:

- Simulations to determine precision requirements for column measurements to enable detection of surface fluxes, particularly those due to photosynthesis and respiration, including its dependence on weighting function, time of day, atmospheric conditions, and transport (transport model error). Simulations are required to support quantification of CO_2 bias as well as the accuracy requirements as a function of investigation.
- Quantification of the impact that clouds and aerosols will have on ASCENDS measurements and their distributions. This includes determining accurate cloud and atmospheric scattering statistics in terms of their optical depth, backscatter coefficients, cloud attenuation and backscatter statistics based on CALIPSO and ICESat/GLAS data, and development of realistic cloud and aerosol distributions for use in OSSE studies. The value of broken cloud and partial column measurement should be evaluated, as it may drive spatial resolution requirements.
- Simulations to determine the measurements needed to effectively separate natural from anthropogenic emissions. The value of a CO measurement needs to be quantified with respect to measurement characteristics (e.g., column vs. profile, day only vs. nighttime observations) and weighed against other potential tracers.
- Simulations to determine the science value of vertical column retrievals versus vertical column plus lower tropospheric column. The desire for more than one piece of vertical information was expressed; however the actual heights desired are yet to be determined. Ultimately, this is expected to depend on the lowest

partial column that can be resolved by the instrument and the lowest that will be useful based on model capability. There is a trade-off between information content and ability to inform transport models (surface sensitivity vs. total column constraint) which needs to be examined in more detail.

- Establishment of an OCO reference case, which can be updated when data allows, for the refinement of carbon flux error estimates in relation to 'current' capability.
- Assessment of the impact of transport model error on fluxes inferred from ASCENDS data through consideration of multiple transport models in measurement simulations (e.g., via Transcom community involvement)
- Analysis of the correlation of expected errors
- Simulations to enable optimization of orbit selection, including consideration of optimal orbit crossing time for sun-synchronous options and consideration of precessing orbits to detect time-varying processes. Orbit selection trade studies should also consider potential synergies with other sensors planned for the 2015 time frame (e.g., EarthCare, ACE, ASCOPE) and whether ASCENDS science and measurement requirements may be best achieved flying in formation with other platforms.
- Examination of the trade-off between absolute accuracy and high spatial resolution for complex terrain studies
- Analysis of the modes of variability in long climate runs with embedded carbon-cycle models to quantify mission duration requirements
- Forward calculations with regional models at fine spatial scale (i.e., ~15 km scale) to determine instrument specifications needed to detect a particular signal (e.g., due to a fossil fuel emission source). This is in contrast to traditional OSSE studies which generally address the error reduction possible with a particular observing strategy.
- Field studies to characterize the variability in column-integrated CO
- Improving the spectroscopic knowledge of candidate absorption lines in the CO_2 and O_2 bands

4. Technical Feasibility

Plenary presentations covered the basic principles behind active CO_2 measurement techniques and three ongoing aircraft instrument development efforts.

4.1 Lidar Measurement Techniques

Lasers have been used in Differential Absorption Lidar (DIAL) systems since the mid-1960s for the remote sensing of atmospheric trace gas concentrations. This technique was first applied for water vapor (Schotland, 1965) and since then it has been used to measure many naturally occurring and pollutant atmospheric gases including ozone, sulfur dioxide, nitrogen dioxide, ammonia, mercury, carbon monoxide, and carbon dioxide. Recent reviews by Calpini and Simeonov (2005) and Browell (2005) summarize the state of the art for ground-based and airborne DIAL measurements, respectively.

The basic DIAL technique samples the absorption feature of interest at two laser wavelengths: the “online” wavelength near the absorption maximum, and the “offline” wavelength which is chosen in the far wing where there is minimal absorption. Using the Beer-Lambert law for an absorbing gas, the average gas absorption, or optical depth, between two ranges on the lidar profile can be determined by subtracting the log of the ratio of the on-line and off-line lidar returns. The average gas concentration is determined from this ratio and accurate knowledge of the online and offline absorption cross sections. For trace gases such as water vapor and ozone with highly variable concentrations, the DIAL technique can be used to provide vertical profiles along the lidar line-of-sight with a precision in the 1-5% range through use of pulsed lasers.

To achieve the precision required for ASCENDS CO_2 measurement, a variation of the DIAL technique, termed “Integrated Path Differential Absorption,” is being considered in which the absorption of the on-line laser wavelength is integrated over the entire transmission-reflection-reception path between the lidar and surface (land, ocean, or cloud top). With IPDA a direct CO_2 profile cannot be obtained, however some altitude-dependent CO_2 information can be obtained by selecting the particular on-line laser wavelength location (or locations) with respect to the center of the CO_2 absorption line (Menzies and Chahine 1974).

The atmospheric weighting function of an IPDA measurement is determined by the particular absorption line(s) selected and the relative position of the online wavelength(s) with respect to absorption line center(s). Figure 16 shows the impact of atmospheric pressure and online position (relative to center) on the relative contribution of CO_2 absorption as a function of altitude. Moving away from line center, an increasingly smaller fraction is contributed from the upper atmosphere, as higher pressure at lower altitudes results in absorption line broadening. The highest sensitivity to tropospheric absorption is seen for on-line positions farthest offset from line center. Instrument design trade studies are typically performed to select the optimal line positions and offsets used.

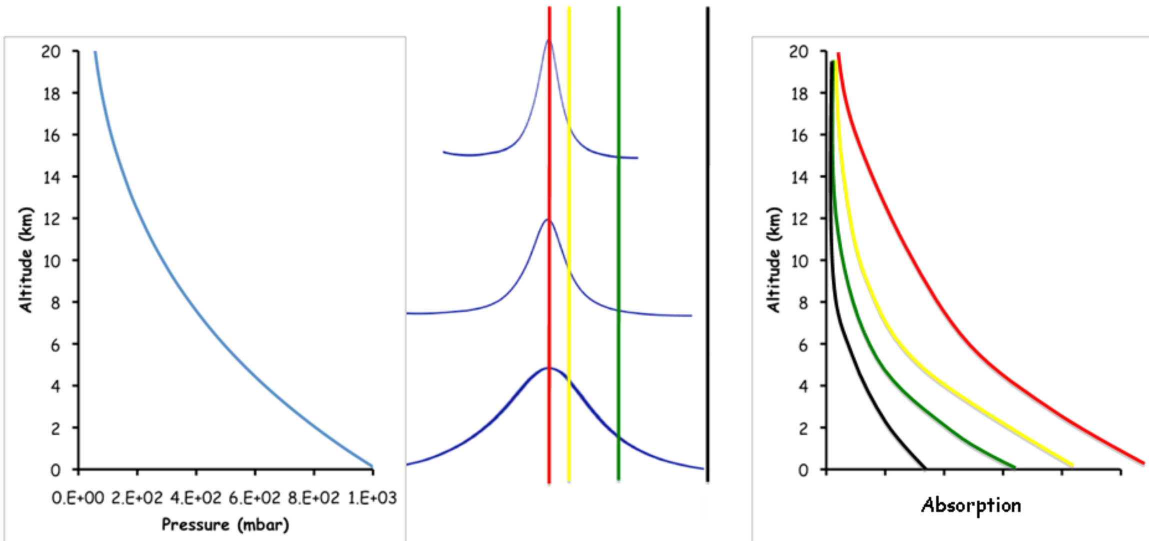


Figure 16: Sketch illustrating the general dependence of the atmospheric weighting function on the distance from the centerline. Source: Gary Spiers

Menzies and Tratt (2003) reported the first sensitivity analysis for space-based CO_2 lidar measurements. They identified CO_2 transitions in the 1.57 and 2.0 μm absorption bands suitable for making global measurements of CO_2. Line strengths for transitions in the 2.0 μm band are stronger (by a factor of ten or more) than the corresponding transitions in the 1.57 μm band, which allows selection of an online wavelength further from line center (maximum absorption) in the 2.0 μm band to achieve the same differential absorption signal. This has the advantage of increasing the weighting function near the surface where CO_2 sources and sinks have the largest impact on CO_2 concentrations (Figure 17). The advantages and disadvantages of making CO_2 measurements in these two regions have been discussed by Menzies and Tratt (2003) and Ehret et al. (2008). It should be noted that spectroscopy is only part of the consideration in any system implementation, as other factors such as available laser power, receiver aperture, and detector sensitivity in each of these wavelength regions must also be taken into account in determining the optimum system performance for ASCENDS.

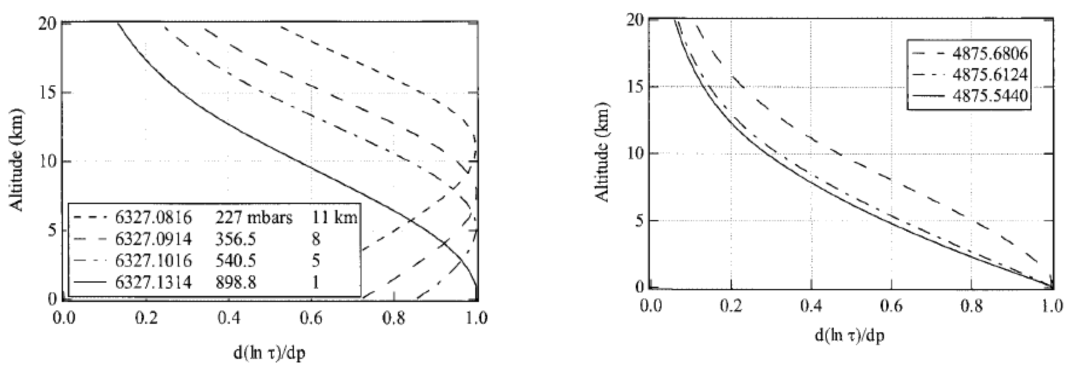


Figure 17: Weighting functions for frequencies offset from 1.57 μm (left) and 2.06 μm (right). Source: Menzies & Tratt.

4.2 Existing Proof of Concept Instruments

Several lidar-based techniques have been proposed to provide space-based active measurements of CO_2. These include various combinations of continuous-wave (CW) and pulsed lasers with direct and heterodyne detection (see, for example, Ehret et al., 2008). The particular absorption line used, distance from line-center chosen, and even number of line positions measured around an absorption line varies according to measurement approach. The techniques also vary in their proposed mechanisms for obtaining required additional parameters, such as altitude, temperature, humidity, and cloud and aerosol content of the atmosphere, needed to unambiguously determine path length in the presence of scattering sources and line shape changes due to atmospheric conditions.

Three CO_2 lidar airborne demonstrators have been developed with support from the NASA Earth Science Technology Office Instrument Incubator Program and various internal and external research and development activities. Results from all three efforts were presented in plenary session.[1] Together, they showed the feasibility of measuring CO_2 concentrations under a variety of atmospheric and surface conditions via lidar-based measurement techniques. These and other measurement techniques will be considered during ASCENDS mission development to determine the optimal approach to meeting the mission's science objectives.

4.2.1 LaRC CO_2 (1.57 μm) and O_2 (1.27 μm) Instrument

A team from NASA LaRC and ITT presented details of a multi-frequency, single-beam, 1.57 μm laser absorption spectrometer (LaRC 1.57 μm LAS) developed as a precursor for space-based measurements of CO_2 in the troposphere (Dobbs et al, 2007; Dobbs et al., 2008). The system, which takes advantage of fiber laser technology developed for the communications industry, uses a modulated continuous-wave fiber transmitter that simultaneously emits multiple wavelengths across a CO_2 absorption line. The airborne demonstrator uses three wavelengths to provide total column measurements of CO_2 (line center) and weighted column measurements in the lower troposphere (on the side of the line). Using modeled optical depths for the selected line positions yields a signal-to-noise requirement of 174 at line center and 822 on the side line to achieve a ~1 ppm uncertainty in XCO_2. In space, this SNR would require a measurement integration time of 10 s, which corresponds to a horizontal distance of about 70 km. An integrated pseudo-random-noise modulated laser ranging system is also used to provide ranging to the surface or cloud tops and information on thin clouds and aerosol scattering along the path of the CO_2 measurement.

[1] The sections below capture instrument status as presented at the workshop, and have not been updated to report post-workshop progress.

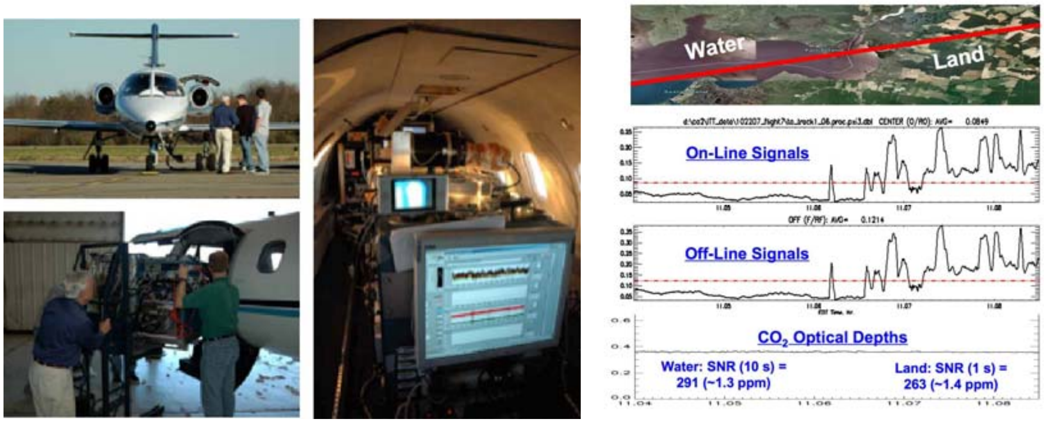


Figure 18. LaRC 1.57 µm Laser Absorption Spectrometer in the Lear-25 for test flights (left) and on-line and off-line signals and CO_2 optical depth for LAS flight over water and land on October 22, 2007 (right).

Key attributes of the measurement technique are provided in Table 11. Additional details of the measurement approach are reported in (Dobbs et al., 2007).

LaRC 1.57 µm Laser Absorption Spectrometer	
CO_2 Absorption Wavelength	1.57 µm
Number of Discrete Wavelengths Measured	3 or more for CO_2, 3 or more for O_2
Transmitter	Tunable modulated Ytterbium-Erbium doped fiber lasers
Receiver	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	Time distribution of correlation of pseudo-random-modulated return echo
Surface Pressure	Surface weighted LAS measurement of O_2 absorption line near 1.27 µm
Aerosols	Time distribution of correlation of pseudo-random-modulated return echo

Table 11: LaRC 1.57 µm Laser Absorption Spectrometer Measurement Technique Attributes

A demonstration aircraft instrument suite and physics-based simulation model have been constructed and validated through several years of ground, field and airborne testing (Dobbs et al., 2007 and 2008, Browell et al., 2008). Five separate LAS flight campaigns have been conducted over the last three years (Browell et al., 2008, Figure 18). Each flight campaign was designed to permit 1.57 µm LAS validation tests under a number of measurement conditions. Flights were conducted both during the day and at night, over a wide range of surface conditions (land and water), and in clear and scattered-cloud conditions.

In test flights up to 7 km in altitude, CO_2 column measurements with high signal-to-noise ratios in excess of 250 (<0.4% or about 1.5 ppm of CO_2) were obtained for 1 second averages over land and for 10 second averages over water (Figure 18). At the same time, the signal-to-noise of the ratio of two offline signals was found to be over 700, which indicates the underlying performance of this system can be scaled to space. The absolute accuracy of the remote CO_2 column measurements were found to be within 1.5% of the *in situ* measured CO_2 column under the flight track. Additional details of the flight test results are reported in (Browell et al., 2008).

The instrument suite has recently been extended to include the collection of column pressure via an LAS O_2 measurement and the precision measurement of range to surface and clouds (Dobler et al., 2008). The combined CO_2 and O_2 LaRC LAS system is being integrated into the NASA Langley UC-12 aircraft for initial flight tests of the O_2 measurements at low power in September 2008.

4.2.2 GSFC CO_2 (1.57 μm) and O_2 (0.78 μm) Instrument

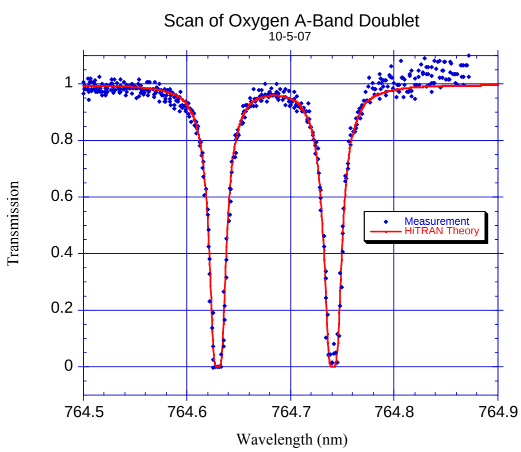
The NASA GSFC 1.57 μm Dual Channel Laser Absorption Spectrometer approach uses a single line in the 1.57 μm CO_2 band, a line pair in the 0.78 μm O_2 band, and a pulsed LAS technique. It uses several tunable fiber laser transmitters allowing simultaneous measurement of the absorption from a CO_2 absorption line in the 1.57 μm band, O_2 extinction in the oxygen A-band, as well as surface height and aerosol backscatter profile in the same measurement path. It directs the narrow co-aligned laser beams toward nadir, and measures the energy of the pulsed laser echoes reflected from land and water surfaces, as well as from cloud tops. During the measurement, the lasers are tuned across a selected CO_2 line and a region between two O_2 lines near 765 nm. The lasers have spectral widths much narrower than the gas absorption lines and are wavelength tuned across the line(s) at kHz rates. The gas extinction and column densities for the CO_2 and O_2 gases are estimated from the ratio of the on- and off-line signals via the differential optical absorption technique. Time gating is used to exclude potential errors from scattering from partially transmitting clouds and aerosols in the path. Signal-to-noise ratios and measurement stabilities of greater than 700:1 are needed to allow CO_2 mixing ratio estimates at the few ppm level.

Key attributes of the measurement technique are provided in Table 12. Additional details of the measurement approach are reported in (Abshire 2008).

Breadboard horizontal field testing of CO_2 and O_2 measurements have been demonstrated (Figure 19). These will be followed in the fall of 2008 by an airborne CO_2 measurement demonstration and a kick-off to a recently-funded Instrument Incubator Program activity in November 2008.

GSFC 1.57 µm Dual Channel Laser Absorption Spectrometer	
CO_2 Absorption Wavelength	1.57 µm
Number of Discrete Wavelengths Measured	8 or more for CO_2, 4 or more for O_2
Transmitter	Tunable pulsed Erbium doped fiber lasers (CO_2 and O_2)
Receiver	Single telescope Photon counting detectors (CO_2 and O_2)
Approach to Obtaining Needed Additional Measurements	
Altimetry	Time distribution of pulsed laser echo signal
Surface Pressure	Valley between two lines in the Oxygen A-band (near 765 nm)
Aerosols	Backscatter lidar

Table 12: GSFC 1.57 µm Dual Channel Laser Absorption Spectrometer Measurement Technique Attributes



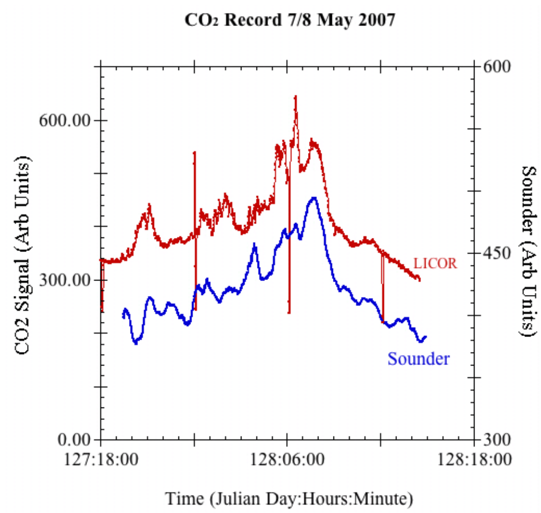


Figure 19: (top left) Measurements of O_2 line pair using the breadboard O_2 sensor in the lab (in blue) over a 220 m horizontal path compared to the calculated O_2 line shapes from HITRAN (in red).

(top right) Measured series of CO_2 absorption with breadboard sensor from the GSFC lab over a 405 m horizontal path and 24 hr time span in May 2007, compared to end-point CO_2 measurements made at top of the GSFC laboratory building with an in situ sensor (LICOR).

(bottom) Instrument during field tests from van over horizontal paths during October 2007.

Source: J. Abshire

4.2.3 JPL CO_2 (2.06 μm) Instrument

NASA JPL has developed an aircraft based heterodyne detection Integrated Path Differential Absorption Spectrometer at 2.06 μm for evaluation purposes. The instrument was developed under the IIP program in collaboration with Coherent Technologies Inc. (now Lockheed Martin Coherent Technologies) and is based on ozone measurement instruments developed at JPL in the 1970s. It operates by simultaneously transmitting two continuous wave laser beams down to the earth's surface where the beams are reflected back to the instrument and detected. Based on analyses conducted by Menzies and Tratt (2003) the instrument is designed to operate at 2 μm in order to maximize the sensitivity to carbon dioxide sources near the surface. This approach is complementary to the 1.6 μm wavelength approaches which have a weaker weighting function to the surface, and combining the 1.6 μm and 2 μm instruments would enable basic information about the structure of the CO_2 column to be obtained. Unlike the other proposed instrument concepts this instrument uses heterodyne detection. Heterodyne detection effectively makes the detection system insensitive to external noise sources and their fluctuation but requires integration of the signals to reduce speckle fluctuations.

In assessing a space based implementation of this concept focus has currently rested on the instrument required to make the differential CO_2 measurement. Additional parameters are required to retrieve the CO_2 and there is considerable discussion within the community about the advantages and disadvantages of various retrieval methods. Methods to retrieve these additional parameters either already exist or are being developed elsewhere. The aircraft instrument includes sensors for each of these parameters. The JPL group completed initial airborne demonstration and validation campaigns in 2006 (Figure 20); additionally, they flew a joint campaign in 2007 with the LaRC/ITT group. With the limited aircraft data collected to date, comparison of the post processed data with the in-situ data collected has shown a precision (2%), consistent with the amount of speckle averaging being conducted, while the absolute value exhibits a bias that is being investigated.

Figure 20: JPL Twin-Otter Airborne Platform for 2 micron CO_2 LAS instrument. Source: G. Spiers.

Key attributes of the measurement technique are provided in Table 13. Additional details of the measurement approach are reported in (Spiers 2007).

JPL 2.06 µm Laser Absorption Spectrometer	
CO_2 Absorption Wavelength	2.06 µm
Number of Discrete Wavelengths Measured	2
Transmitter	CW laser
Receiver	Single telescope Heterodyne detector
Approach to Obtaining Needed Additional Measurements	
Altimetry	Not directly measured
Surface Pressure	Not directly measured
Aerosols	Not directly measured

Table 13: JPL 2.06 µm Laser Absorption Spectrometer Measurement Technique Attributes

4.3 Active CO_2 Mission Concept Study

An active CO_2 mission concept study was conducted by LaRC and JPL for NASA Headquarters to assess the scientific and technical feasibility of space-based lidar CO_2 measurement. The feasibility study considered two mission point designs to achieve the mission objectives set forth in the 2007 Earth Science decadal survey, which recommends ASCENDS for launch in the 2013-2016 timeframe with a rough cost target of $400 million. The mission point design was heavily constrained by the NRC cost and schedule recommendations.

The study considered a class B mission with a launch readiness date of August 2013. The mission architecture consisted of a single spacecraft with a nominal three-year mission design lifetime and four years of consumables to allow for extended mission operation. To maximize synergy with the European Space Agency's Cloud and Aerosol

Mission (EarthCare), the study baselined a sun-synchronous, 10:30 AM ascending node, 450 km, 97.2° inclination orbit.

For both point design options, the payload architecture consists of a nadir-viewing LAS system and a passive sounder suite. The LAS system is comprised of a CO_2 and O_2 LAS integrated with a pseudo noise encoded altimeter sharing a common telescope. This system provides simultaneous measurements of column CO_2 and O_2. A passive sounder suite provides temperature profiles, CO column and profile measurement, and visible imagery to enable cloud detection. For both options, the payload is considered to be entirely self-contained and thermally isolated from the spacecraft bus.

Specific payload instrument designs were then considered to meet the science objectives set forth in the decadal survey. As discussed in the previous sections, instrument concepts for active remote sensing of CO_2 in the 1.57 and 2.06 μm bands have been demonstrated. For the purposes of the feasibility study, the 1.57 μm band was chosen for the first point design because of its insensitivity to temperature errors, relative freedom from interfering water vapor bands, good weighting function for column measurements in the lower troposphere, and high technology readiness of CW lasers in this wavelength region. A second point design considered augmentation of the 1.57 μm system with a 2.06 μm band to provide improved determination of CO_2 vertical distribution. Both mission point designs also included:

- *Concurrent on-board O_2 measurements using lines at 1.27 μm* to allow for the best relative compensation for aerosol scattering along the line-of-sight of the CO_2 and O_2 measurements. The particular O_2 band was chosen so that the surface and atmospheric scattering characteristics from aerosols and thin clouds would be nearly the same as for the measurement of CO_2 at 1.57 μm.
- *An on-board laser altimeter* to measure column length to the surface or cloud tops and the vertical profiles of optically thin clouds and aerosols.
- *A six channel passive radiometer* to further reduce residual temperature errors by concurrently measuring temperature along the laser line of sight.
- *A Gas Filter Correlation Radiometer* to provide measurements of CO to enable attribution of sources and sinks to natural or anthropogenic sources.

For both point design options, payload accommodation requirements (summarized in Table 14) are readily met using existing spacecraft technologies and require only modest improvements to readily available commercial buses contained in the Rapid Spacecraft Development Office (RSDO) catalog. These changes include an upgraded power system (e.g., addition of solar panels, associated electronics and support structure) and redundancy to support a three-year nominal mission design life.

	Option 1 (1.57 µm LAS system)	***Option 2 (combined 1.57 & 2.06 µm LAS system)***
Payload Mass	351 kg	501 kg
Payload Power	850 W	1550 W
Average Data Volume	1.2 Gb/day	12 Gb/day
Downlink	S-band	X-band
SC bus changes	Add solar array panels, supporting structure, ACS & Telecom redundancy (+) Replace X-band system with S-band (-)	Add solar array panels, supporting structure, additional battery capacity, ACS & Telecom redundancy (+)
Spacecraft Wet Mass	957 kg	1322 kg
Launch Vehicle	Small to Medium	Medium

Table 14: Active CO_2 Mission Point Design Comparison

For both point designs, the observatories can be readily launched using existing small or medium class expendable launch vehicle options. The first option requires a small to medium launch vehicle with large fairing (aperture driven) and, with reasonable attention to further mass reduction, can likely be accommodated by the Taurus 3210 (delivers 860 kg to 450 km sun-synchronous). The second (augmented) point design option requires a medium class launcher (i.e., Delta-II 2320-10 delivers 1565 kg to 450 km sun-synchronous).

The cost estimate for the first point design option aligns well with the decadal survey rough cost estimate. Cost for the second point design (enhanced) option exceeds the target; however optimal configurations for the combined system have not been explored. Areas suggested for additional study include the refinement of ancillary data requirements and optimization of orbit/power/aperture and configuration for combined 1.57 & 2.06 µm system. Additional details of this study are reported in Harrison et al. (2008).

4.4 ASCENDS Validation Strategy

Breakout discussion participants discussed the challenges associated with validation of an active CO_2 remote sensing measurement and outlined key elements of an ASCENDS validation strategy. The recommended strategy relies heavily on existing validation infrastructure, and requires both sustaining the CO_2 validation network established by OCO and GOSAT to ensure continutity of validation data, and expanding the capabilities of the network to support ASCENDS high-latitude and nighttime measurement validation.

A combination of ground-based lidar, airborne lidar, and Fourier transform spectrometer measurements are required for ASCENDS validation. CO_2 column and profile measurements as well as O_2 lidar field measurements are considered essential, and a number of supporting measurements are likely required (e.g., profiles of pressure, temperature, water vapor data, surface pressure and surface reflectance). Depending on mission implementation approach, ancillary measurements of CH_4 column and profiles, aerosol backscatter data, boundary layer height, and CO might also be required.

The ASCENDS validation strategy will benefit considerably from the TCCON network developed in support of OCO validation, which enables traceability of space-based remote sensing measurements to the WMO CO_2 standard. Participants noted the value of such traceability, and recommended the ASCENDS validation strategy retain this key aspect of the OCO approach. However, due to differences in measurement technique and weighting function, this will require development of a new mechanism to cross-calibrate the ASCENDS active meaurements with the TCCON upward-looking Fourier Transfer Spectrometers. The TCCON network will also need to be extended to include additional stations at high-latitudes, and individual sites will need to be augmented to support nighttime measurement validation through provision of additional measurements (e.g., boundary layer height).

An airborne instrument simulator is considered an essential part of the ASCENDS validation infrastructure. Instrument simulator flights are desired over a range of latitudes and environmental conditions (i.e., variety of topography, cloud, and aerosol conditions) to validate retrieval algorithms. Airborne field campaigns will be required at high northern and southern latitudes to support ASCENDS validation. Overflights of the ground network sites with the airborne instrument simulator will be key in establishing traceability to the WMO CO_2 standard.

Cross-calibration between ASCENDS and other CO_2 remote sensing missions (e.g., OCO, GOSAT) is highly desirable and would enable numerous opportunities for enhanced science. Though OCO and GOSAT will be past their design lifetimes by the time ASCENDS launches, workshop participants strongly recommended at least one ASCENDS ground-based lidar experiment and several airborne demonstrations be conducted during the OCO validation period.

Development of a measurement error budget was seen as key to further development of the ASCENDS validation strategy, as it could drive the need for improved spectroscopy, algorithm development, or additional field campaigns/ground measurements.

4.5 Near-term Technology and Validation Investment Priorities

Workshop participants recognized that ASCENDS technology development and validation needs are to a large extent dependent upon the ultimate measurement strategy selected. In plenary session, the following near-term technology and validation investment needs were identified as those with the highest priority to enable ASCENDS progress towards Phase A mission start:

- *Development of detailed end-to-end roadmaps of instrument evolution, from current state to launch, for each of the proposed concepts*, including definition of

the technology readiness level (TRL) of all key instrument components and plans to advance their TRL to 6 or above. These plans are needed to provide a basis for the scheduling of key instrument decision points and investment priorities for ASCENDS.
- *Development of active oxygen remote sensing techniques to measure surface pressure* via oxygen absorption, which is considered a cross-cutting need. The need for oxygen measurement should further be clarified vis-à-vis A-SCOPE study findings.
- *End-to-end system demonstrations of measurement capability*, preferably in coordination with other campaigns and over a range of conditions. As ASCENDS advances towards Phase A and implementation decisions are made, an airborne simulator is considered essential to achieving the intended science.
- *Sustaining and enhancing the current CO_2 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.

During the technology-focused breakout session, a variety of additional activities were identified to advance each of the measurement technologies towards flight readiness, including:

- *Demonstration of 1.57 µm fiber amplifier(s)* with total power and efficiency at the desired bandwidths, to meet on-orbit requirements (multiple CW amplifier demonstration for LaRC 1.57 µm LAS and pulsed amplifier development for GSFC 1.57 µm LAS)
- *Lifetime demonstrations of the lidar systems* to show that they can be continuously operated over a 3-4 year mission duration
- *Scaling 2.06 µm CO_2 laser transmitter to 5W optical power*, which would bring the 2.06 µm laser source to a similar readiness for space fight as the 1.57 µm architectures (JPL 2.06 µm LAS)
- *Pursuit of techniques to increase power levels* of pressure-sensing oxygen lidar transmitters for high-altitude airborne and space O_2 measurements (LaRC 1.57 µm LAS and GSFC 1.57 µm LAS)
- *Improved configuration for combined 1.57 & 2.06 µm system*
- *Continuation of segmented telescope development*, with the goal of cost reduction for ASCENDS and future missions. This will result in a reduction in cost and risk in procuring large monolithic telescopes for ASCENDS and other Decadal Survey missions (LaRC 1.57 µm LAS)
- *Development of altimetry capability*
- *Signal processing hardware* to reduce the signal bandwidth relative to the current aircraft instrument (JPL 2.06 µm LAS)

5. Potential Space Mission Synergies

The ASCENDS mission will enable exploratory investigations of nighttime CO_2 processes and high-latitude sources and sinks. Currently available, planned, and future remote sensing missions and concepts provide additional opportunities for enhanced science through provision of complementary measurements.

5.1 Current Missions

Opportunities for synergy between ASCENDS and OCO and GOSAT include extension of the space-based CO_2 measurement record and improved understanding of the spatial representativeness of the narrow lidar measurement swath. Direct ASCENDS team involvement in these missions, particularly validation campaign participation, would improve ASCENDS science return. Participants recognized that OCO and GOSAT will likely be beyond their mission design lifetime upon ASCENDS launch, however the strong synergy between passive and active remote sensing CO_2 techniques prompted calls for an operational or sustained follow-on mission to continue the passive CO_2 record. Partnerships with international space agencies (e.g., ESA and JAXA) as well as NOAA were suggested as a mechanism to maintain passive observations.

Possible synergies with AIRS (for comparison of ASCENDS CO_2 distribution at the surface with AIRS mid-troposphere measurements) and TES (for provision of CO measurements) were also suggested. A study was recommended to determine whether TES CO measurements might provide insight as to the necessity of collocated CO_2 and CO measurements for enhanced science opportunities.

5.2 Planned Missions & Future Concepts

Potential ASCENDS synergies were identified for international and decadal survey future mission concepts. The extent to which the missions are complementary ultimately will depend on how the missions are implemented and whether they overlap with ASCENDS.

5.2.1 Synergies with International Missions

Both the ESA and Japan are currently evaluating CO_2 remote sensing missions. Like ASCENDS, the objective of these missions is to monitor the spatial and temporal gradients of atmospheric CO_2 with a precision and accuracy sufficient to constrain the natural carbon fluxes (sources and sinks).

ESA's Advanced Space Carbon and Climate Observation of Planet Earth (A-SCOPE) mission concept aims to observe total column carbon dioxide via a nadir-looking pulsed IPDA measurement technique. A-SCOPE also plans to provide cloud and aerosol information to increase the precision of the data. The simultaneous measurements of CO_2, aerosols, and clouds from this mission will provide key observations that can be assimilated into future operational environmental monitoring systems such as the Global Environmental Measurement System (GEMS). Should A-SCOPE launch in the ASCENDS timeframe, increased spatial and diurnal coverage might be achieved if the two observatories are launched into different orbits.

Japan is currently planning a GOSAT-2 mission to continue space-based global CO_2 observations after GOSAT reaches its five year design life. The current conceptual design for GOSAT-2 calls for a passive FTS payload and improved cloud and aerosol imager, though other options are being considered which involve a CO_2 DIAL or backscatter lidar, an ultraviolet spectrometer, and/or addition of an infrared channel to the cloud and aerosol imager. To ensure there are no gaps in data between GOSAT and GOSAT-2 a target launch date has been set for January 2014, which overlaps with the desired ASCENDS launch timeframe. Active or passive GOSAT-2 measurements are highly desirable for enabling ASCENDS enhanced science opportunities through increased spatial and/or diurnal coverage. Passive measurements would also enhance ASCENDS validation efforts, as noted above.

		Carbon Cycle Science	ASCENDS Synergy Opportunity
International Space-borne Missions	**A-SCOPE**	ESA Earth explorer mission; total column with a nadir-looking IPDA.	Active CO_2 mission
	GOSAT II	Main mission instrument: FTS to continue observations of GOSAT, other candidates include:CO_2 DIAL or backscatter lidar, Ultraviolet Spectrometer, and improved Cloud Aerosol Imager	Passive CO_2 mission

Table 15: International Carbon Cycle Missions

5.2.2 Synergies with Decadal Survey Missions

Opportunities for synergy between ASCENDS and the other 16 missions recommended in the NRC decadal survey were examined to determine which provided complementary measurements or enabled enhanced science investigations (Table 16). SMAP freeze/thaw data was of particular interest to participants for its direct application to the ASCENDS northern high latitude sources and sinks science objectives.

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	**HyspIRI**	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

Launch: 2016-2020	**LIST**	Land surface topography for landslide hazards and water runoff	Northern High Latitude Sources and Sinks, Disturbances, Air/Sea & Land/Sea Flux, Complex Terrain	Improved topography
	PATH	High frequency, all weather temperature and humidity sounding for weather forecasting and sea-surface temperature	Northern High Latitude Sources and Sinks, Southern Ocean, Climate Variability, Land/Sea & Air/Sea Flux, Disturbances	Temperature and water vapor profiles; Boundary layer processes
	GRACE-II	High temporal resolution gravity fields for tracking large scale water movement	Northern High Latitude Sources and Sinks	
	SCLP	Snow accumulation for freshwater availability	Northern High Latitude Sources and Sinks, Complex Terrain	
	GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	Respiration, Land/Sea & Air/Sea, Disturbances, Anthropogenic Emissions	Improved chemical transport models; Provision of trace gas measurements; global CO measurements
	3D-Winds	Tropospheric winds for weather forecasting and pollution transport	Southern Ocean, Land/Sea & Air/Sea Flux	Improved Transport Models

Table 16: Decadal Survey Missions - Possible Areas of Science Overlap with ASCENDS

6. Conclusion

A fundamental scientific need for spaceborne active CO_2 measurements was reaffirmed by workshop participants. 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

The science investigations enabled by and benefitting from active CO_2 remote sensing measurements are found to be compelling and are considered achievable with modest technology advances. Priority areas for near-term investment to advance ASCENDS mission readiness include:

- ***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 CO_2 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.

Appendices

Appendix A: Acronyms

ACE – Aerosol-Cloud-Ecosystems

AOT – Aerosol Optical Thickness

APD – Avalanche Photodiode Detector

AIRS – Atmospheric Infrared Sounder

ARCTAS – Arctic Research of the Composition of the Troposphere from Aircraft and Satellites

A-train – Earth Observing System's Afternoon Constellation

ASCENDS – Active Sensing of CO_2 Emissions over Nights, Days, and Seasons

CALIPSO – Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation

CLARREO – Climate Absolute Radiance and Refractivity Observatory

CSIRO – Commonwealth Scientific and Industrial Research Organisation (Austrailia)

DESDynI – Deformation, Ecosystem Structure, and Dynamics of Ice

EDFA - Erbium-Doped Fiber Amplifier

ENSO – El Niño Southern Oscillation

ENVISAT – Environmental Satellite (ESA mission)

EOS – Earth Observing System

ESA – European Space Agency

ESRL – Earth System Research Laboratory

FTS –Fourier Transform Spectrometer

GACM – Global Atmospheric Composition

GEMS - Global and regional Earth-System (atmosphere) Monitoring using Satellite and in-situ data

GEO – Geostationary orbit

GEO-CAPE – Geostationary Coastal and Air Pollution Events

GOSAT – Greenhouse Gas Observing Satellite

GRACE-II – Gravity Recovery and Climate Experiment II

GSFC – Goddard Space Flight Center (NASA)

HyspIRI – Hyperspectral Infrared Imager

ICESat - Ice, Cloud, and land Elevation Satellite

IFOV – Instantaneous Field of View

INTEX – Intercontinental Chemical Transport Experiment

IPDA – Integrated Path Differential Absorption

IIP – Instrument Incubator Program

IR – Infrared

JAXA - Japan Aerospace Exploration Agency

JAL – Japan Airlines

JPL – Jet Propulsion Laboratory (NASA/Caltech)

LaRC – Langley Research Center (NASA)

LAS – Laser Absorption Spectrometer

LCSE - Laboratoire des Sciences du Climat et de l'Environneme

LEO – Low Earth Orbit

LIDAR – Light Detection and Ranging

LIST – Lidar Surface Topography

MODIS – Moderate Resolution Imaging Spectroradiometer

MOE – Ministry of Environment, Japan

NAS – National Academy of Science

NASA – National Aeronautics and Space Administration

NIES – National Institute for Environmental Studies, Japan

NOAA – National Oceanic and Atmospheric Administration

NRC – National Research Council

NWP – Numerical Weather Prediction

OCO – Orbiting Carbon Observatory (NASA)

OD – Optical Depth

OSSE – Observing System Simulation Experiment

PATH - Precipitation and All-Weather Temperature and Humidity

PEM – Pacific Exploratory Mission

ppm – part per million

ppmv – part per million volume

RSDO – Rapid Spacecraft Development Office

SCIAMACHY – SCanning Imaging Absorption Spectrometer for Atmospheric CartograpHY

SCLP – Snow and Cold Land Processes

SI – Systeme Internationale

SMAP – Soil Moisture Active-Passive Mission

SNR – Signal to Noise Ratio

SSO – Sun Synchronous Orbit

SST – Sea Surface Temperature

SWOT – Surface Water and Ocean Topography

TCCON – Total Carbon Column Observing Network

TES – Tropospheric Emission Spectrometer

TOPS – Terrestrial Observation and Prediction System

TRACE-P – TRAnsport & Chemical Evolution over the Pacific

TRL – Technology Readiness Level

USGS – United States Geological Survey

WFM-DOAS – Weighting Function Modified Differential Optical Absorption Spectroscopy

WMO – World Meteorological Organization

X_{CO2} – Column-Averaged CO_2 Dry Air Mole Fraction

XOVWM – Extended Ocean Vector Winds

3D-Winds – Three Dimensional Tropospheric Winds from Space-Based Lidar

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Appendix C: Agenda

Wednesday, July 23, 2008			
7:30 AM	Atrium	Registration	
8:00 AM	Atrium	Continental Breakfast	
8:30 AM	Rm 1040	**Welcome**	**Ken Jucks,** NASA Headquarters
8:40 AM		**NASA Headquarters Welcome and Workshop Charge**	**Ken Jucks and Bill Emanuel,** NASA Headquarters
9:00 AM		**NRC Decadal Survey and the ASCENDS Concept**	**Berrien Moore,** Climate Central
9:20 AM		**Decadal Survey Mission Planning**	**Steve Neeck**, NASA Headquarters
9:45 AM		**Questions and Discussions**	
10:00 AM		Break	
10:30 AM	Rm 1040	**Atmospheric CO_2 and ASCENDS Science Background**	**Anna Michalak,** University of Michigan
11:00 AM		**Atmospheric Inverse Model Analysis for Carbon Sources and Sinks**	**Scott Denning,** Colorado State University
11:30 AM		**Carbon Data Assimilation: State-of-the-Art**	**Richard Engelen,** European Centre for Medium-Range Weather Forecasts (ECMWF)
12:00 PM	Michigan League Ballroom	Group Lunch: **Carbon Data Assimilation in the ASCENDS Era**	**Eugenia Kalnay,** University of Maryland
1:30 PM	Rm 1040	**Quantification of Fossil Fuel Emissions and Related Human Activities**	**Greg Marland,** Oak Ridge National Laboratory (ORNL)
2:00 PM		**Ecosystems, Disturbance, and Land Use**	**Natasha Miles,** Penn State University
2:30 PM		**Systematic CO_2 Measurements and ASCENDS Validation**	**Pieter Tans,** NOAA Earth System Research Laboratory (ESRL)
3:00 PM		**Charge to Breakout Sessions**	
3:10 PM		Break	
3:30 PM	Rm 1040, 1046, 1024	**Breakout Session I - ASCENDS Scientific Goals & Requirements / Key Investigations**	
5:00 PM	Atrium	Break - Optional Walking Tour of the University of Michigan Central Campus	
6:00 PM	Atrium	**Poster Session and Reception**	
7:30 PM		Adjourn	

Thursday, July 24, 2008			
7:30 AM	Atrium	Registration	
8:00 AM	Atrium	Continental Breakfast	
8:30 AM	Rm 1040	**Breakout Session Reports**	
9:10 AM		**AIRS Overview**	**Edward Olsen,** Jet Propulsion Laboratory (JPL)
9:30 AM		**SCIAMACHY Overview**	**Hartmut Boesch,** University of Leicester
9:50 AM		**Orbiting Carbon Observatory Overview**	**Charles Miller,** Jet Propulsion Laboratory (JPL)
10:10 AM		Break	
10:30 AM	Rm 1040	**Greenhouse Gases Observing Satellite (GOSAT) Overview**	**Tsuneo Matsunaga,** National Institute for Environmental Studies (NIES), Japan
10:50 AM		**Active CO_2 Mission Concepts**	**Wallace Harrison,** NASA Langley
11:10 AM		**ASCENDS Instrument Concepts**	**Ed Browell,** NASA Langley; **Gary Spiers,** Jet Propulsion Laboratory (JPL); **James Abshire,** NASA Goddard Space Flight Center (GSFC)
12:00 PM	Atrium	Box Lunch	
1:00 PM	Rm 1040	**Advanced Space Carbon and Climate Observation of Planet Earth (A-SCOPE)**	**Gerhard Ehret,** German Aerospace Center
1:30 PM		**Charge to Breakout Sessions**	
1:40 PM	Rm 1040 1046, 1024	**Breakout Session II - Measurement Requirements**	
3:15 PM		Break	
3:30 PM	Rm 1040	**Breakout Session Reports**	
4:00 PM	Rm 1046 1024, 1040, 1028	**Breakout Session III- Traceability Matrix, Short-term Studies, Next Steps**	
5:30 PM		**Adjourn**	

Friday, July 25, 2008			
8:00 AM	Atrium	Continental Breakfast	
8:30 AM	Rm 1040	**Breakout Session Reports**	
9:00 AM		**Plenary Discussion Session**	
10:15 AM		Break	
10:30 AM	Rm 1040	**Validation Strategies**	**Steve Wofsy** (Harvard University)
11:00 AM		**Implications for Coupled Climate and Carbon Cycle Models and Analyses**	**Peter Rayner,** Laboratoire des Sciences du Climat et de L'Environnement (LSCE), France
11:30 AM		**Plenary Discussion of Workshop Findings and Recommendations**	
12:00 PM		Adjourn	

Appendix D: Poster Agenda

Group 1:

- Estimation of Net Ecosystem Carbon Exchange for the Conterminous United States by Combining MODIS and AmeriFlux Data
  - Jingfeng Xiao, Purdue University**,**
  - Qianlai Zhuang, Purdue University (presenting)**,**
  - Other 40 AmeriFlux, Principal Investigators
- Equifinality in Parameterization of Process-Based Biogeochemistry Models: A Significant Uncertainty Source to Estimation of Regional Carbon Dynamics
  - Jinyun Tang, Purdue University
  - Qianlai Zhuang, Purdue University (presenting)
- Ensemble modeling of carbon and water fluxes using the Terrestrial Observation and Prediction System (TOPS)
  - Weile Wang, Oak Ridge Associated Universities & NASA Ames Research Center (presenting)
  - Andrew Michaelis, California State University Monterey Bay & NASA Ames Research Center
  - Jennifer Dungan, NASA Ames Research Center
  - Ramakrishna Nemani, NASA Ames Research Center
- Influences of spatial and temporal resolutions of CO_2 concentration on carbon budget estimation: Implications for ASCENDS
  - Lianhong Gu, ORNL (presenting)
  - Mac Post, ORNL
  - Dan Ricciuto, ORNL
- The role of remote sensing in quantifying emissions from wildland fires in North America
  - Nancy HF French, Michigan Tech Research Institute (presenting)
  - Eric S Kasischke, University of Maryland
  - Laura L Bourgeau-Chavez, Michigan Tech Research Institute
  - Merritt R Turetsky, University of Guelph

Group 2:

- Status of Regional Transport Modeling in Support of Achieving ASCENDS Science Objectives and Defining Measurement Concepts
  - Janusz Eluszkiewicz, AER, Inc. (presenting)
  - Hilary E. Snell, AER, Inc.
  - T. Scott Zaccheo, AER, Inc.
  - Michael Dobbs, ITT
- Diurnal and Synoptic Variability of Simulated Atmospheric CO_2 along Satellite Orbits: results obtained with TransCom Satellite Experiment
  - Ryu Saito, National Institute for Environmental Studies (presenting)
  - Dmitry Belikov, National Institute for Environmental Studies
  - Prabir K Patra, Frontier Research Center for Global Change
  - Ravi Lokupitiya, Colorado State University
  - Sander Houweling, SRON Netherlands Institute for Space Research

  - Shamil Maksyutov, National Institute for Environmental Studies
- The impact of convective parameter sensitivity on simulated atmospheric CO_2 distributions
  - Lesley Ott, Global Modeling and Assimilation Office, NASA GSFC (presenting)
  - Steven Pawson, Global Modeling and Assimilation Office, NASA GSFC
  - Julio Bacmeister, Global Modeling and Assimilation Office, NASA GSFC
- Carbon Cycle Data Assimilation Using Local Ensemble Transform Kalman Filter
  - Ji-Sun Kang, University of Maryland, College Park (presenting)
  - Eugenia Kalnay, University of Maryland, College Park
  - Junjie Liu, University of California, Berkeley
  - Inez Fung, University of California, Berkeley
- CO_2 Transport Over Mountains and Heterogeneous 'Flat' Terrain
  - Jielun Sun, National Center for Atmospheric Research (presenting)

Group 3:

- Retrieval and Assimilation of Tropospheric Emission Spectrometer (TES) CO_2
  - Susan Sund Kulawik, NASA Jet Propulsion Laboratory, California Institute of Technology
  - Fredrick W. Irion, NASA Jet Propulsion Laboratory, California Institute of Technology
  - Kevin W. Bowman, NASA Jet Propulsion Laboratory, California Institute of Technology
  - Ray Nassar, Centre for Global Change Science, University of Toronto (presenting)
  - Dylan B. Jones, Department of Physics, University of Toronto
- Current Status and Future Plan of GOSAT Project at National Institute for Environmental Studies (NIES)
  - Tsuneo Matsunaga, National Institute for Environmental Studies, Japan (presenting)
  - Hiroshi Watanabe, National Institute for Environmental Studies, Japan
  - Tatsuya Yokota, National Institute for Environmental Studies, Japan
  - Osamu Uchino, National Institute for Environmental Studies
  - Isamu Morino, National Institute for Environmental Studies
  - Shamil Maksyutov, National Institute for Environmental Studies
- Validated Observations of CO_2 Dry Mole Fraction from the Airborne Platform
  - James R Smith, Atmospheric Observing Systems, Inc. (presenting)
  - Michael P Hahn, Atmospheric Observing Systems, Inc.
  - Michael Jacox, Atmospheric Observing Systems, Inc. (presenting)
  - Stephen Stearns, NaCaPe Design, Inc.
  - Todd Bernatsky, Atmospheric Observing Systems, Inc.
  - Drew Elam, Atmospheric Observing Systems, Inc.
  - Nicholas Sato, Atmospheric Observing Systems, Inc.
  - Eric Kinne, Atmospheric Observing Systems, Inc.
  - Jena Lane, Atmospheric Observing Systems, Inc.
  - Margaret Torn, DOE / Lawrence Berkeley National Laboratory

    - Sebastian Biraud, DOE / Lawrence Berkeley National Laboratory
- Carbon Source/Sink Information Provided by Column CO_2 Measurements from the Orbital Carbon Observatory
    - David F. Baker, CIRA/CSU (presenting)
    - Hartmut Boesch, University of Leicester
    - Scott C. Doney, Woods Hole Oceanographic Institution
- TIMS Instrumentation to Characterize OCO and Spatial CO_2 Distributions in the ASCENDS Era
    - Robert B Chatfield, NASA Ames R.C. (presenting)
    - John Kumer, Lockheed Martin ATC
    - Aidan Roche, Lockheed Martin ATC
    - Jack Doolittle, Lockheed Martin ATC
    - Matthew Fladeland, NASA Ames R.C.

Group 4:

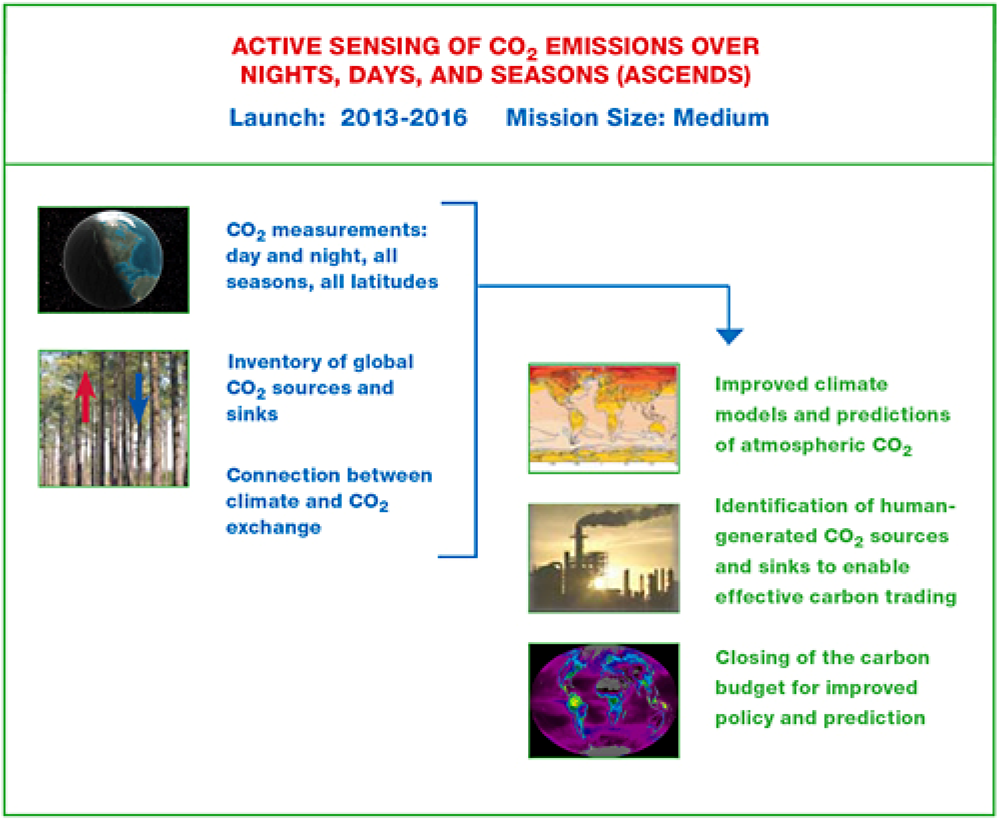
- Development of 2 micron Coherent Differential Absorption Lidar with Conductive-cooled Laser
    - Kohei Mizutani, National Institute of Information and Communications Technology (presenting)
    - Shoken Ishii, National Institute of Information and Communications Technology
    - Toshikazu Itabe, National Institute of Information and Communications Technology
    - Tetsuo Aoki, National Institute of Information and Communications Technology
    - Philippe Baron, National Institute of Information and Communications Technology
    - Jana Mendrok, National Institute of Information and Communications Technology
    - Kazuhiro Asai, Tohoku Institute of Technology
    - Atsush Sato, Tohoku Institute of Technology
- Development and Initial Testing of a High Sensitivity DIAL System For Profiling Atmospheric CO_2
    - Syed Ismail, NASA Langley Research Center (presenting)
    - Grady J Koch, NASA Langley
    - Tamer Refaat, Old Dominion University
    - Ken Davis, Pennsylvania State University
    - Nurul Abedin, NASA Langley Research Center
    - Jirong Yu, NASA Langley Research Center
    - Charles Miller, Jet Propulsion Laboratory
    - Upendra Singh, NASA Langley Research Center
- Development of a DIAL model for atmospheric CO_2
    - James Lawrence, Physics and Astronomy department, University of Leicester (presenting)
    - Roland Leigh, Physics and Astronomy department, University of Leicester
    - Paul Monks, Chemistry department, University of Leicester,

    - John Remedios, Physics and Astronomy department, University of Leicester
- An Instrument for the ASCENDS Mission Enabling Identification of Anthropogenic CO_2 Emissions Using Concurrent CO Measurements
    - William B. Cook, NASA Langley Research Center (presenting)
    - James H. Crawford, NASA Langley Research Center
    - Glenn S. Diskin, NASA Langley Research Center
    - Larry L. Gordley, GATS, Inc.
    - Manuel A. Rubio, NASA Langley Research Center
    - Glen W. Sachse, National Institute of Aerospace
- Laser Sounder for Measuring Atmospheric CO_2 Concentrations for the ASCENDS Mission – Progress
    - James B. Abshire, NASA-Goddard, Code 690 (presenting)
    - Haris Riris, NASA-Goddard, Code 694
    - S. Randy Kawa, NASA-Goddard, Code 613
    - Jianping Mao, SSAI
    - Graham R. Allan, Sigma Space
    - Xiaoli Sun, NASA- Goddard, Code 694
    - Mark A. Stephen, NASA-Goddard, Code 554
    - Michael A. Krainak, NASA-Goddard, Code 554
    - Emiliy Wilson, NASA-Goddard, Code 554
- Laser Sounder for the ASCENDS Mission - Space Instrument Study
    - James B. Abshire, NASA-Goddard (presenting)
    - Xiaoli Sun, NASA-Goddard
    - Mark A. Stephen, NASA-Goddard
    - Jeffrey Chen, NASA-Goddard
    - Emily Wilson, NASA-Goddard
    - Luis Ramos-Izquierdo, NASA-Goddard
    - Haris Riris, NASA-Goddard
- Development of a CO_2 DIAL Lidar at 1570 nm
    - John Burris, NASA/Goddard (presenting)
- A Modulated CW Fiber Laser-Lidar Suite for the ASCENDS Mission
    - Michael Dobbs, ITT Space Systems Division (presenting)
    - Jeremy Dobler, ITT Space Systems Division
    - Berrien Moore III, Climate Central, Princeton, NJ & University of New Hampshire (Emeritus)
    - Edward Browell, NASA Langley Research Center
    - T. Scott Zaccheo, Atmospheric and Environmental Research, Inc.
- Refinements in the Calculation of Model Optical Depth for Comparison with DIAL CO_2 Optical Depth Measurements
    - Susan A. Kooi, SSAI Hampton, VA 23666 (presenting)
    - Edward V. Browell, NASA LaRC, Hampton, VA 23681
    - Syed Ismail, NASA LaRC, Hampton, VA 23681
    - Yonghoon Choi, NIA Hampton, VA 23666
    - Marta A. Fenn, SSAI Hampton, VA 23666
- Simple, Robust, CO_2 Sounder employing a Broadband Laser Source.
    - William S Heaps, NASA Goddard Space Flight Center (presenting)

- Emily L Wilson, NASA Goddard Space Flight Center
    - Elena Georgieva, University of Maryland Baltimore County
- Assessment of Aircraft-based CO2 Measurements and the Extension to Space-based Missions
    - T Scott Zaccheo, Atmospheric and Environmental Research, Inc. (presenting)
    - Hillary E Snell, Atmospheric and Environmental Research, Inc.
    - Michael Dobbs, ITT Space Systems Division
    - Jeremy Dobler, ITT Space Systems Division
    - Edward Browell, NASA Langley Research Center
    - Berrien Moore III, Climate Central, Princeton NJ & University of New Hampshire (Emeritus)
- An Assessment of the Feasibility of Implementing the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission
    - Fenton W Harrison, NASA Langley Research Center (presenting)
    - Edward V Browell, NASA Langley Research Center
    - Stacey W Boland, Jet Propulsion Laboratory (presenting)
    - Gary D Spiers, Jet Propulsion Laboratory
- Laser Sounding Instrument using Oxygen A-Band for Atmospheric Pressure Sensing
    - Mark A Stephen, NASA-GSFC
    - James B Abshire, NASA-GSFC (presenting)
    - Jian-ping Moa, RSIS, Inc.
    - S. Randy Kawa, NASA-GSFC
- Airborne Demonstration of 1.57-Micron Laser Absorption Spectrometer for Atmospheric CO2 Measurements
    - Edward V. Browell, NASA LaRC (presenting)
    - Michael E. Dobbs, ITT Corp.
    - Jeremy Dobler, ITT Corp.
    - Susan A. Kooi, NASA LaRC
    - Yonghoon Choi, NASA LaRC
    - F. Wallace Harrison, NASA LaRC
    - Berrien Moore, Climate Central
    - T. Scott Zaccheo, AER
- An Airborne 2 micron Laser Absorption Spectrometer for the Remote Measurement of Atmospheric Carbon Dioxide
    - Gary D. Spiers, Jet Propulsion Laboratory (presenting)
    - Robert T. Menzies, Jet Propulsion Laboratory
    - Luke Chen, Jet Propulsion Laboratory
    - Mark W. Phillips, Lockheed Martin Coherent Technologies
- Sensitivity Studies for a Space-based CO2 Laser Sounder
    - Jianping Mao, NASA GSFC/SSAI
    - Stephan R. Kawa, NASA GSFC
    - James B. Abshire, NASA GSFC (presenting)
    - Haris Riris, NASA GSFC
- Airborne In Situ CO2 Measurements Used in Validation of Remote Sensing Measurements
    - Stephanie A. Vay, NASA LaRC

- Yonghoon Choi, NASA LaRC
- Edward V. Browell, NASA LaRC (presenting)
- F. Wallace Harrison, NASA LaRC
- Susan A. Kooi, NASA LaRC

Appendix E: Decadal Survey Excerpt



ACTIVE SENSING OF CO_2 EMISSIONS OVER NIGHTS, DAYS, AND SEASONS (ASCENDS) MISSION

The primary human activities contributing to the nearly 40 percent rise in atmospheric CO_2 since the middle of the 20th century are fossil-fuel combustion and land-use change, primarily the clearing of forests for agricultural land. More than 50 percent of the CO_2 from fossil-fuel combustion and land-use change has remained in the atmosphere; land and oceans have sequestered the nonairborne fraction in roughly equal proportions. However, the balance between land and oceans varies in time and space. The current state of the science cannot account with confidence for the growth rate and interannual variations of atmospheric CO_2. The variability in the rate of increase in the concentration of CO_2 in the atmosphere cannot be explained by the variability in fossil-fuel use; rather, it appears to reflect primarily changes in terrestrial ecosystems that are connected with large-scale weather and climate modes. The overall pattern is important and is not understood. The geographic distribution of the land and ocean sources and sinks of CO_2 has likewise remained elusive, an uncertainty that is also important. As nations seek to develop strategies to manage their carbon emissions and sequestration, the capacity to quantify current *regional* carbon sources and sinks and to understand the underlying mechanisms is central to prediction of future levels of CO_2 and therefore to informed policy decisions, sequestration monitoring, and carbon trading (Dilling et al., 2003; IGBP, 2003; CCSP, 2003, 2004).

Background: Direct oceanic and terrestrial measurements of carbon and of the flux of CO_2 are important but are resource-intensive and hence sparse and are difficult to extrapolate in space and time. Space-based measurements of primary production and biomass are valuable and needed, and the problem of source-sink determination of CO_2 will be aided greatly by such measurements and studies, but it will not be resolved by this approach. There is, however, a different complementary approach. The atmosphere is a fast but incomplete mixer and integrator of spatially and temporally varying surface fluxes, and so the geographic distribution (such as spatial gradient) and temporal evolution of CO_2 in the atmosphere can be used to quantify surface fluxes (Tans et al., 1990; Plummer et al., 2005). The current set of direct in situ atmospheric observations is far too sparse for this determination; however, long-term accurate measurements of atmospheric CO_2 columns with global coverage would allow the determination and localization of CO_2 fluxes in time and space (Baker et al., 2006; Crisp et al., 2004). What is needed for space-based measurements is a highly precise global data set for atmospheric CO_2-column measurements without seasonal, latitudinal, or diurnal bias, and it is possible with current technology to acquire such a data set with a sensor that uses multiwavelength laser-absorption spectroscopy.

The first step in inferring ecosystem processes from atmospheric data is to separate photosynthesis and respiration; this requires diurnal sampling to observe nighttime concentrations resulting from respiration. Analyses of flux data show that there is a vast difference in the process information obtained from one measurement per day versus two (i.e., one measurement per day plus one per night), with a much smaller gain attributable to many observations per day (Sacks et al., 2007). It is also essential to separate physiological fluxes from biomass burning and fossil-fuel use, a distinction that requires simultaneous measurement of an additional tracer, ideally carbon monoxide (CO).
A laser-based CO_2 mission—the logical next step after the launch of NASA's Orbiting Carbon Observatory (OCO)[2], which uses reflected sunlight—will benefit directly from the data-assimilation procedures and calibration and validation infrastructure that will handle OCO data. In addition, because it will be important to overlap the new measurements with those made by OCO, the ASCENDS mission should be launched in the 2013–2016 time frame at the latest.

Science Objectives: The goal of the ASCENDS mission is to enhance understanding of the role of CO_2 in the global carbon cycle. The three science objectives are to (1) quantify global spatial distribution of atmospheric CO_2 on scales of weather models in the 2010–2020 era, (2) quantify current global spatial distribution of terrestrial and oceanic sources and sinks of CO_2 on 1-degree grids at weekly resolution; and (3) provide a scientific basis for future projections of CO_2 sources and sinks through data-driven enhancements of Earth-system process modeling.

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[2] The Orbiting Carbon Observatory (OCO) is a NASA Earth System Science Pathfinder (ESSP) project mission designed to make precise, time-dependent global measurements of atmospheric CO_2 from an Earth-orbiting satellite. OCO should begin operations in 2009. See description at http://oco.jpl.nasa.gov/.

Mission and Payload: The ASCENDS mission consists of simultaneous laser remote sensing of CO_2 and O_2, which is needed to convert CO_2 concentrations to mixing ratios. The mixing ratio needs to be measured to a precision of 0.5 percent of background (slightly less than 2 ppm) at 100-km horizontal length scale over land and at 200-km scale over open oceans. Such a mission can provide full seasonal sampling to high latitudes, day-night sampling, and some ability to resolve (or weight) the altitude distribution of the CO_2-column measurement, particularly across the middle to lower troposphere. CO_2 lines are available in the 1.57- and 2.06-μm bands, which minimize the effects of temperature errors. Lines near 1.57 μm are identified as potential candidates because of their relative insensitivity to temperature errors, relative freedom from interfering water-vapor bands, good weighting functions for column measurements across the lower troposphere, and the high technology readiness of lasers. To further reduce residual temperature errors in the CO_2 measurement, a concurrent passive measurement of temperature along the satellite ground track with an accuracy of better than 2 K is required. Atmospheric pressure and density effects on deriving the mixing ratio of CO_2 columns can be addressed with a combination of simultaneous CO_2 and O_2 column density measurements at the surface or cloud tops, or possibly with surface-cloud-top altimetry measurements from a lidar in conjunction with advanced meteorological analysis for determining the atmospheric-pressure profile across the measured CO_2 density column. The concurrent on-board O_2 measurements are preferred and can be based on measurements that use an O_2 absorption line in the 0.76- or 1.27-μm band. The mission requires a Sun-synchronous polar orbit at an altitude of about 450 km and with a lifetime of at least 3 years. The mission does not have strict requirements for specific temporal revisit or map revisit times, because the data will be assimilated on each pass and the large-scale nature of the surface sources and sinks will emerge from the geographic gradients of the column integrals. The important coverage is day and night measurements at nearly all latitudes and surfaces to separate the effects of photosynthesis and respiration. The maximal power required would be about 500 W, with a 100 percent duty cycle. Swath size would be about 200 m.

Ideally, a CO sensor should complement the lidar CO_2 measurement. The two measurements are highly synergistic and should be coordinated for time and space sampling, with the minimal requirement that the two experiments be launched close together in time to sample the same area.

Cost: About $400 million.

Schedule: ASCENDS should be launched to overlap with OCO and hence in the 2013–2016 (the middle) time frame. Technology development must include extensive aircraft flights demonstrating not only the CO_2 measurement in a variety of surface and atmospheric conditions but also the O_2-based pressure measurement.

Further Discussion: See in Chapter 7 the section "Carbon Budget Mission (CO_2 and CO)."

Related Responses to Committee's RFI: 4 and 20.

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Appendix F: Preliminary ASCENDS 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

Appendix G: ASCENDS Workshop Steering Committee Membership

Anna Michalak, University of Michigan, Co-Chair and Local Host
Charles Miller, NASA Jet Propulsion Laboratory, Co-Chair
Ed Browell, NASA Langley Research Center
Berrien Moore, Climate Central
Jim Abshire, NASA Goddard Space Flight Center
Gary Spiers, NASA Jet Propulsion Laboratory

NASA Headquarters Leads:
Ken Jucks, ASCENDS Program Scientist
Bill Emanuel

Appendix H: Participant List
(103 Registrants)

Name	Organization
Abshire, James (Jim)	NASA GSFC
Alkhaled, Alanood	University of Michigan
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Baize, Rosemary	SD
Baldauf, Brian	Northrop Grumman
Boesch, Hartmut	University Leicester
Boland, Stacey	JPL
Bourgeau-Chavez, Laura	Michigan Tech Research Institute
Braverman, Amy	JPL
Breckheimer, Eric	The Aerospace Corporation
Browell, Edward (Ed)	NASA Langley Research Center
Burris, John	Goddard Space Flight Center
Case, Kelley	JPL
Chandler, Ashley	JPL
Chatfield, Robert (Bob)	NASA Ames
Chatterjee, Abhishek	University of Michigan, Ann Arbor
Chen, Songsheng	SSAI at LaRC
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Cressie, Noel	The Ohio State University
Crisp, David	JPL
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Denning, Scott	Colorado State University
Di, Liping	George Mason University
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Dobler, Jeremy	ITT Space Systems Division
Drewry, Darren	University of Illinois
Dybdahl, Art	Northrop Grumman
Ehret, Gerhard	German Aerospace Center
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French, Nancy	Michigan Tech Research Institute
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Hammerling, Dorit	University of Michigan
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Heymann, Roger	NOAA NESDIS (National Environmental Satellite

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Howard, Regan	Orbital Sciences Corporation
Hu, Yongxiang (Yong)	NASA LaRC
Huntzinger, Deborah	University of Michigan
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Kalnay, Eugenia	University of Maryland
Kampe, Thomas	Neon Inc.
Kang, Ji-Sun	University of Maryland, College Park
Kawa, Stephan (Randy)	NASA Goddard Space Flight Center
Kooi, Susan	SSAI/NASA LaRC
Lawrence, James	University of Leicester
Liu, Hongyu	NIA / NASA Langley Research Center
Loverro, Adam	JPL
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Matsunaga, Tsuneo (Mat)	National Institute for Environmental Studies
Mcguire, James	NASA/IPO
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Miles, Natasha (Tasha)	Penn State University
Miller, Charles	JPL
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Polonsky, Igor	CSU
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Spiers, Gary	JPL
Sun, Jielun	UCAR
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Zaccheo, T Scott	AER, Inc
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