A Feasibility Assessment of Implementing the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) Mission

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Abstract

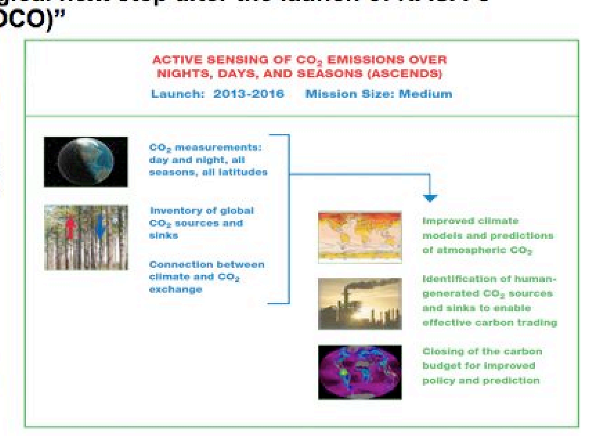
The decadal study report of the National Research Council (NRC), Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, recommends that NASA undertake development of the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) mission as the next step beyond the Orbiting Carbon Observatory (OCO) in enhancing the understanding of the role of carbon dioxide (CO_2) in the global carbon cycle. The NASA Science Mission Directorate sponsored an ASCENDS mission system study to assess the feasibility of implementing the decadal study recommendation. The ASCENDS mission concept would extend the observational capabilities of OCO by providing day/night, all-latitude, all-season column integrated measurements of CO_2 and the required ancillary measurements necessary for quantifying the global distribution of terrestrial and oceanic sources and sinks of CO_2. The purpose of this paper is to present the results of the ASCENDS mission study, including the key mission design constraints and assumptions, measurement performance goals, and assessments of the scientific and technical feasibility of the mission concept, with emphasis on the laser based measurements.

The Decadal Survey Recommendation

Mission Objectives

Goal: To significantly enhance the understanding of the role of CO_2 in the global carbon cycle and its impact on climate change by launching a "laser-based CO_2 mission" as "the logical next step after the launch of NASA's Orbiting Carbon Observatory (OCO)"

- Objective 1. Quantify global spatial distribution of atmospheric CO_2 on scales of weather models
- Objective 2. Quantify current global spatial distribution of terrestrial and oceanic sources and sinks of CO_2 on 1 degree grids at weekly resolution
- Objective 3. Provide a scientific basis for future projections of CO_2 sources and sinks through data-based process Earth System model enhancements



Mission and Payload

The ASCENDS mission should 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.

Primary Measurements

Simultaneous laser remote sensing of CO_2 and O_2, which is needed to convert CO_2 concentrations to mixing ratios. CO_2 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. To separate physiological fluxes from biomass burning and fossil-fuel use, 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.

CO_2 Measurements: 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.

O_2 Measurements: Concurrent on-board O_2 measurements are preferred to address atmospheric pressure and density effects on deriving the mixing ratio of CO_2 columns and can be based on measurements that use an O_2 absorption line in the 0.76- or 1.27-μm band.

Temperature: A concurrent passive measurement of temperature along the satellite ground track with an accuracy of better than 2 K is required to reduce residual temperature errors in the CO_2 measurement.

Orbit and Lifetime

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.

Cost and Schedule

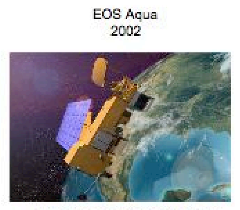
About $400 million. ASCENDS should be launched to overlap with OCO and hence in the 2013-2016 (the middle) time frame. Technology development must include extensive aircraft flights demonstrating not only the CO_2 measurement in a variety of surface and atmospheric conditions but also the O_2-based pressure measurement.

Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, NRC, 2007

Antecedent Missions

"A laser-based CO_2 mission is the logical next step after the launch of NASA's Orbiting Carbon Observatory (OCO)" [1]

EOS Aqua 2002



Atmospheric Infrared Sounder (AIRS) measures the concentration of carbon dioxide (CO_2) in the mid-troposphere.

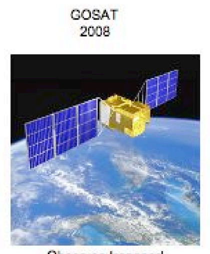
Envisat 2002

Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) provided first direct observation of the atmospheric CO_2 year-to-year increase from space

Orbiting Carbon Observatory 2008

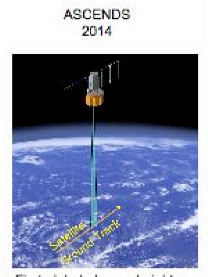
First space-based measurements of atmospheric CO_2 with the precision, resolution, and coverage needed to characterize the geographic distribution of sources and sinks

GOSAT 2008



Observes transport mechanisms of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4)

ASCENDS 2014



First global, day and night, observations of CO_2 at all latitudes

[1] *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, NRC, 2007

ASCENDS Science Questions

How is the Earth's carbon cycle changing?

What are the spatial and temporal patterns of exchange of CO_2 between the atmosphere and the surface, and how are these patterns affected by large scale modes in weather-climate, and how are these patterns affected by human actions?

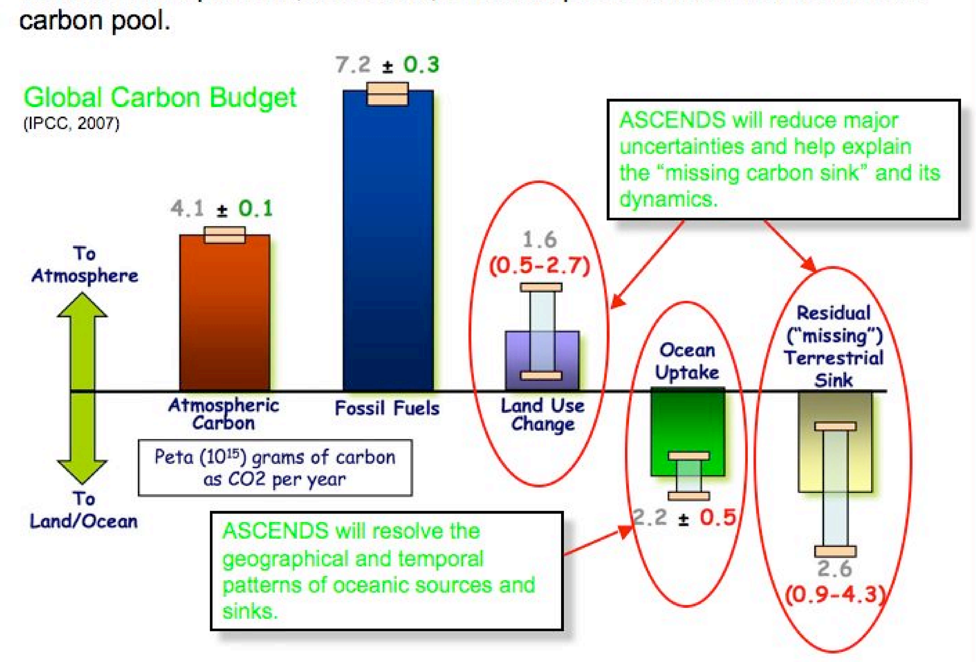
What are the feedbacks of climate on the carbon cycle, and what are the likely effects on the carbon cycle of these feedbacks in the future?

The ASCENDS mission will make measurements day and night at all latitudes in all seasons of total column mixing ratio of CO_2 with sufficient precision to allow accurate determination of spatial and temporal pattern of the sources and sinks of CO_2.

The CARBON CYCLE. Carbon in the atmosphere is a controlling factor on climate and hence on ecological productivity and the sustainability of life.

The Importance of the Science Questions

The largest uncertainties about the Earth's carbon budget are in its terrestrial components; moreover, land biosphere is the most vulnerable carbon pool.



Large uncertainties remain about the size of the oceanic sink. Recent evidence suggests that the Southern Ocean sink may be saturating. Oceanic uptake of CO_2 increases the acidity of the ocean with unknown ecological effects.

Measurement Challenges

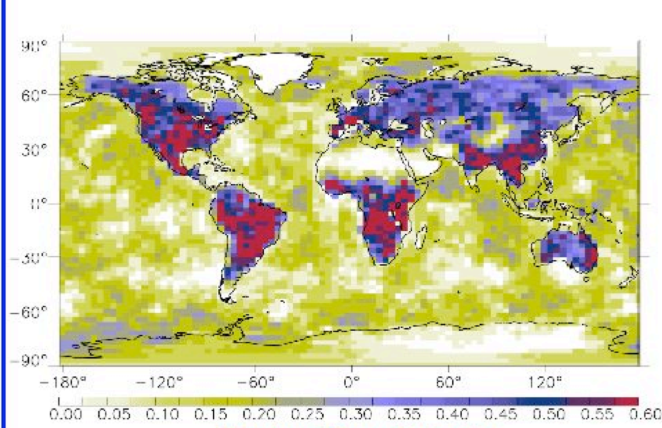
Inverting the casual relationship of surface sources and sinks to atmospheric concentrations requires precise measurement of the spatial temporal gradient of atmospheric CO_2 without biases. The presence of large seasonal and diurnal changes on the carbon cycle implies that the measurements must be day/night, all seasons at all latitudes which can only be accomplished with an active system.

Retrieval of column-integrated CO_2 concentrations must account for clouds, aerosols, heterogeneous surfaces, topographical changes, and changes in pressure.

The column-integrated nature of the measurement includes a significant portion of the atmosphere (above the troposphere) that is only weakly affected by the spatial and temporal pattern of sources and sinks. This implies that the measurement strategy must focus on the lower part of the atmosphere.

ASCENDS CO_2 Measurement Requirements derived from Observing System Simulation Experiments (OSSEs) conducted by Peter Rayner and Frédéric Chevallier, CEA-CNRS.

Assumed measurement precision for 100-km tropospheric CO_2 column measurement over land of 1.3 ppmv during day and 0.8 ppmv at night and over water of 4.2 ppmv during day and 2.1 during night.



Average Error Reduction
Land: 40%
Ocean: 13%
Total: 20%

ASCENDS will make major contribution to knowledge of CO_2 sources & sinks.

Alternative Instrument Concepts

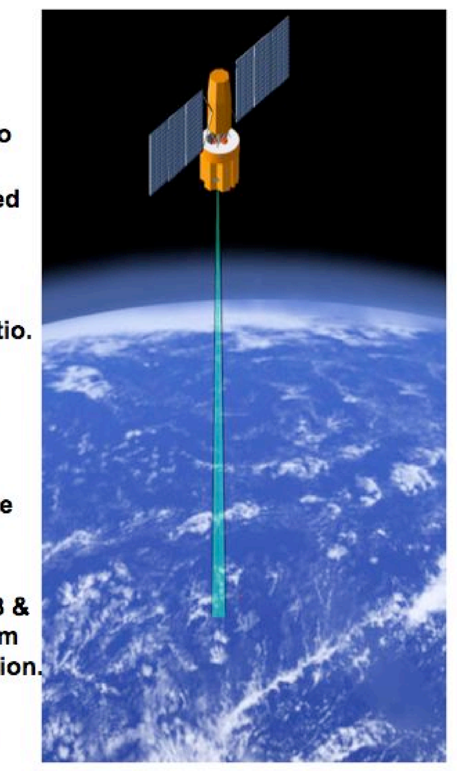
Instrument Type	Performance Goals: CO_2 mixing ratio (1 ppmv) Large Scale / Regional Scale	Diurnal Day / Night	Global Coverage: Land / Ocean	All Latitude	All Seasons Globally	Measurement Maturity / Readiness
High Spectral Resolution Sounder (i.e., AIRS)	Yes (but not near surface) / No	Yes / Yes	Yes / Yes	Yes	Yes	High
Solar Reflectance Spectrometer (i.e., OCO)	Yes / No	Yes / No	Yes (Nadir) / Yes ("Glint mode")	No	No	Medium-High
Laser Absorption Spectrometer*	Yes / Yes	Yes / Yes	Yes / Yes	Yes	Yes	Medium
Laser Profiler**	TBD / TBD	TBD / TBD	TBD / TBD	TBD	TBD	Low**

*Mature airborne measurement concept that lacks a space-proven implementation. Utilizes fiber-based laser transmitters and a large aperture telescope. **Key capabilities shown through analytical proof-of-concept and preliminary ground-based experiments. Empirical full performance over range of environmental conditions and design requirements for space instrumentation remain TBD.

ASCENDS Mission

ASCENDS Measurements

CO_2 column mixing ratio (XCO_2) measurement with Laser Absorption Spectrometer (LAS) technique requires the simultaneous measurement of the CO_2 column number density (CND); the O_2 column number density for converting the CND to XCO_2; and the path length of the measurement. A temperature profile measurement is also required to constrain the XCO_2 measurement. A column CO measurement over the same XCO_2 path is also recommended for interpreting sources and sinks of CO_2.

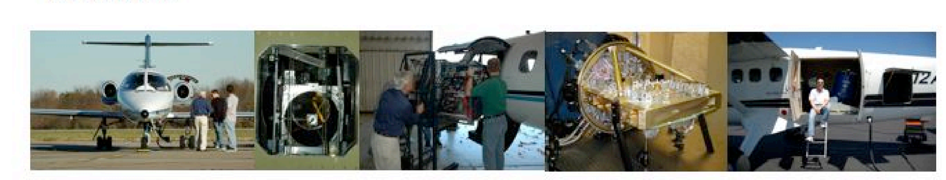


- CO_2 column measurement
  - CO_2 Laser Absorption Spectrometer to resolve (or weight) the CO_2 altitude distribution, particularly across the mid to lower troposphere.
  - 1.6-micron LAS only baseline or integrated 1.6-micron + 2.0-micron LAS option
- Surface pressure measurement
  - O_2 Laser Absorption Spectrometer to convert CO_2 number density to mixing ratio.
- Surface/cloud top altimeter
  - Laser altimeter to measure CO_2 column length.
- Temperature sounder
  - Six channel passive radiometer to provide temperature corrections.
- CO sensor
  - Gas Filter Correlation Radiometers (at 2.3 & 4.6 μm) to separate biogenic fluxes from biomass burning and fossil fuel combustion.
- Imager
  - To provide cloud clearing for soundings.

Technology for Active Remote Sensing of CO_2

ASCENDS CO_2 Measurements

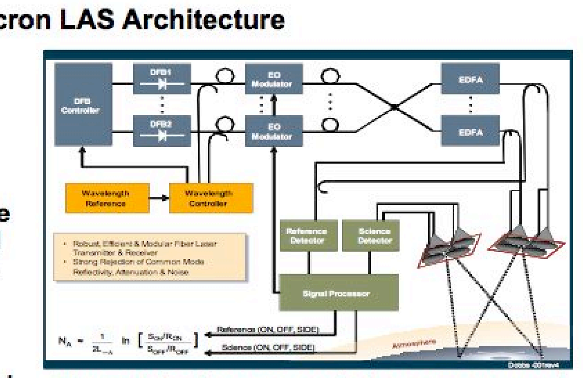
- CO_2 absorption lines available in the 1.57 μm and 2.06 μm
  - Minimize the effects of temperature errors
  - Have some ability to resolve (or weight) the altitude distribution of the CO2 column measurement, particularly across the mid to lower troposphere
- CO_2 absorption lines at 1.57 μm are recommended by the Decadal Survey
  - Good insensitivity to temperature errors
  - Relatively free from interfering water vapor bands
  - Good weighting functions for column measurements across the lower troposphere
  - High technology readiness of telecom lasers in this wavelength region
- Mature airborne instrument concepts for obtaining high precision CO_2 measurements have been demonstrated for both CO_2 absorption lines
  - Instrument use simultaneous, continuous wave (CW) transmission of multiple laser wavelengths
  - Engineering development units (EDUs) demonstrates high SNR CO_2 measurements with excellent correlation to in-situ measurements
  - Measurements have been conducted under a wide range of environmental conditions



The 1.57-micron LAS Architecture

The 1.57 micron LAS architecture

1. simultaneously transmits online and offline wavelengths reducing noise from the atmosphere, target and sensor into a common-mode term which is readily removed,
2. is independent of the system wavelength, and
3. supports N+M redundancy.



The architecture supports the measurement of multiple species (i.e., CO_2 and O_2) simultaneously.

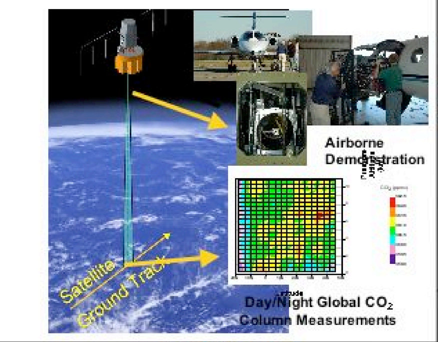
- Principal of Operation
  - Transmitter
    - Consists of a Distributed Feedback Diode (DFB) and Electro Optical (EO) Modulator for each wavelength, 1 to n. Modulated outputs are combined into a single fiber, which is input to several multi-watt Erbium Doped Fiber Amplifiers (EDFAs), whose outputs are NOT coupled and which remain independent.
    - The transmitter is 100% fiber (no discrete optical elements until the output lens). The fiber amplifiers are very efficient and compact, producing 5-10 watts per 8 x 10 x 1 inch module, at 10% total electrical to optical efficiency.
  - Receiver
    - Consists of a telescope, an optical bandpass filter, APD detector fabricated in HgCdTe and low noise amplifier. Each wavelength, 1 to n, is readily separated by the electrical subcarriers and avoids complex optical filters and etalons.
    - Signal processing subsystem contains a multi-channel lock-in amplifier that provides the modulation signal to the modulators and performs the lock-in process on the received signal.
  - See poster by Dobbs, et al

The 2 μm Laser Absorption Spectrometer

- The instrument was developed under the IIP program in collaboration with Coherent Technologies Inc. (now Lockheed Martin Coherent Technologies) and is based on a prior ozone measuring instrument developed at JPL in the 1970s.
- Principal of Operation
  - Two wavelengths are transmitted simultaneously and reflected from the surface. The wavelengths are selected [Menzies, 2004] such that one is more heavily attenuated by CO_2 in the atmosphere than the other – the ratio of the return signal strengths provides the column integrated CO_2 once corrections for other variables are made.
  - The laser transmitter technology is derived from the local oscillator technology developed during the SPARCLE EO-2 mission development. These lasers are now used as local oscillators in commercial operational systems installed at several airports as a real time wind turbulence and shear detection system.
  - The receiver uses heterodyne detection. This permits effectively perfect signal isolation against optical noise from both external sources (solar and thermal radiation) and internal scatter from the transmitter sources while permitting the transmit and receive signals to share a common aperture. Sensitivity of the heterodyne detection technique leads to a low transmitter power requirement (5W/channel). A single 750 mm class telescope is required.
  - See poster paper (Gary Spiers / Bob Menzies)

ASCENDS Mission Concept - Option #1

1.6 um LAS plus ancillary measurements



Features

- Integrated active & passive instrument on single spacecraft
  - N+1 redundancy in active instrument
- Sun synchronous 450 km orbit
- Selective redundant avionics
- Blowdown monopropellant hydrazine for orbit maintenance
- ACS: momentum bias; earth pointing
  - Reaction wheels; magnetic torquers
- Comm: Redundant S-Band T&C
- Designed for uncontrolled reentry (demise)

Performance

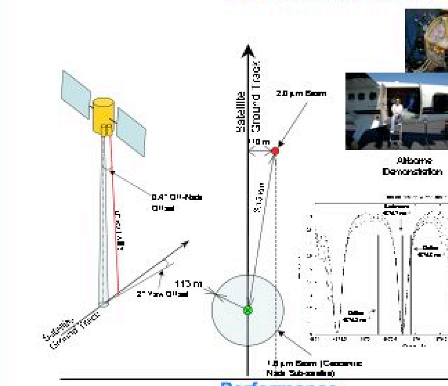
- Orbit average power (w contingency) 850 W
- Observatory wet mass (w contingency) 841 kg
- Launch vehicle capacity used 98% (lower performance
  - Taurus is feasible
- Daily data volume 1.2 Gbits

Technology Development

- No spacecraft technology development required.
- Advanced telecom laser technology in 1.57 mm region generates three laser wavelengths across a CO_2 and two wavelengths across a O_2 absorption lines.
- Advanced laser absorption spectrometer (LAS) technique, including a modulated transmitter and detector technique, obtains high precision measurements.

ASCENDS Mission Concept - Option #2

1.6 um and 2.0 um LAS plus ancillary measurements



Features

- Both instruments on same spacecraft
  - Share central telescope
  - Overlapped FOV
- Redundant avionics
- Monoprop: orbit maintenance
- ACS: momentum bias; earth pointing
  - Reaction wheels; magnetic torquers
- Comm: Redundant S-Band plus X-Band
- Power: Dual, 4 panel solar arrays
- Designed for uncontrolled reentry (demise)

Performance

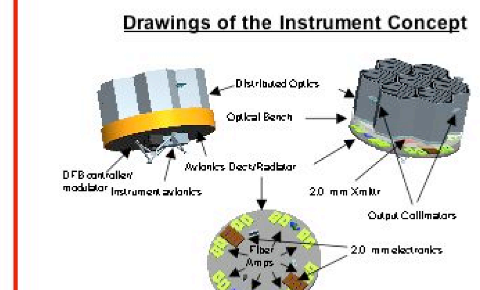
- Orbit average power (w contingency) 1550 W
- Observatory wet mass (w contingency) 1056 kg
- Launch vehicle (Delta II) capacity used 63%
- Daily data volume 12 Gbits

Technology Development

- No spacecraft technology development required.
- The instrument senses at the online and offline wavelengths.
- Reference laser is locked to a CO2 cell [not transmitted].
- Online and offline lasers are frequency offset locked from the reference laser.

ASCENDS Instrument Concept

Drawings of the Instrument Concept



Features of the Instrument Concept

- Nadir-pointed Multi-Beam Lidar
  - Co-aligned beams imaged in the far field
  - 113m (1.6mm laser), 230 m (passive) footprints
- Instrument is not redundant
- Expected Laser Lifetime = 8+ years
  - Based on commercial telecom standards
- Distributed receive aperture on composite bench
- 2.0 um transmitter tightly-coupled to optical bench
- Primary mirror segment diameters:
  - Option 1: 650 mm; Option 2: 750 mm

Performance Data

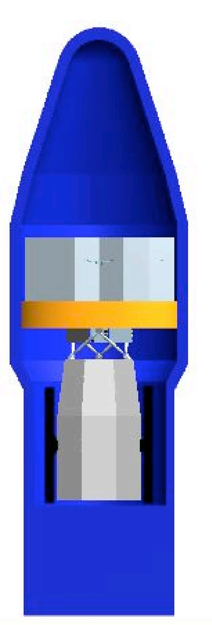
	Option 1	Option 2
Mass	351 kg	501 kg
Power (peak)	850 W	1550 W
Power (standby)	225 W	280 W
Power (avg)	850 W	1550 W
Data Rate (peak)	2 Mbps	20 Mbps
Compression	None	None
Duty Cycle	85%	85%

Technology Development Needs

- CO_2 laser transmitter is currently at TRL 5
  - All components space qualified (TRL 6 or higher)
- O_2 laser transmitter is currently at TRL4
  - Ground test and airborne EDU under development by NASA IPP
- Telescope technology is currently at TRL 5
  - Joint development effort between GSFC and ITT expected to raise TRL to 6 in CY07
- Transmitter life test is is key need.
- R&A investment in measurement validation can offer significant risk mitigation.
  - Participation in OCO Cal/Val will be proposed.

Launch Options

- Option #1 (1.6 μm LAS + Passive Sounder)
  - Observatory wet mass: 841 kg (with contingency)
    - Observatory wet mass 957 kg (with contingency) at time of Team X study
  - Requires small launch vehicle with large fairing (aperture driven)
  - Taurus 3210 (delivers 860 kg to 450 km Sun-Synchronous)
  - Minotaur IV (delivers 1115 kg to 450 km Sun-Synchronous)
  - Point Design: Taurus 3210
- Option #2 (1.6 um and 2.0 um LAS + Passive Sounder)
  - Observatory wet mass: 1056 kg (with contingency)
    - Observatory wet mass 1322 kg (with contingency) at time of Team X study
  - Delta-II 2320-10 (delivers 1565 kg to 450 km Sun-Synchronous)
  - If a Delta-II is not available, other launch vehicles have larger capabilities. Can consider dual-payload launch if desired.
  - Point Design: Delta-II
- With identified mass reductions, both options can launch on a Minotaur IV



Study Conclusions

An ASCENDS mission has been defined that can meet the science objectives defined in the NRC decadal survey.

- CO_2 column mixing ratios over day/night, all latitudes, all seasons with high precision.
- Global coverage to surface/cloud tops and to surface between broken clouds.
- Mission data will permit significant improvements in source/sink estimates on regional scales.

The ASCENDS mission approach utilizes mature instrument technologies supporting the recommended LRD.

- Architecture based on advanced telecom technologies mitigates risk associated with early launch option.
- Mission design utilizes mature SC and launch vehicle capabilities.

Baseline ASCENDS mission cost is aligned with decadal survey estimate.

- Cost for enhanced science options evaluated.

The ASCENDS mission includes the complete set of required measurements.

- Minimizes risk from dependencies on other missions and external data sets.

Acknowledgements

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