# ACT-America: L2 Remotely Sensed Column-avg CO2 by Airborne Lidar, Lite, Eastern USA

Get Data

Documentation Revision Date: 2022-04-25

Dataset Version: 1

## Summary

This dataset provides a direct subset (i.e., the Lite version) of the Level 2 (L2) remotely sensed column-average carbon dioxide (CO2) concentrations measured during airborne campaigns in Summer 2016, Winter 2017, Fall 2017, and Spring 2018 conducted over central and eastern regions of the U.S. for the Atmospheric Carbon and Transport (ACT-America) project. Column-average CO2 concentrations were measured at a 0.1-second frequency during flights of the C-130 Hercules aircraft at altitudes up to 8 km with a Multi-functional Fiber Laser Lidar (MFLL; Harris Corporation). The MFLL is a set of Continuous-Wave (CW) lidar instruments consisting of an intensity-modulated multi-frequency single-beam synchronous-detection Laser Absorption Spectrometer (LAS) operating at 1571 nm for measuring the column amount of CO2 number density and range between the aircraft and the surface or to cloud tops, and surface reflectance and a Pseudo-random Noise (PN) altimeter at 1596 nm for measuring the path length from the aircraft to the scattering surface and/or cloud tops. The MFLL was onboard all ACT-America seasonal campaigns, except Summer 2019. Complete aircraft flight information, interpolated to the 0.1-second column CO2 reporting frequency, is included, but not limited to, latitude, longitude, altitude, and attitude.

This MFLL Lite product is intended for end-users of $CO_2$ observations. It is a direct subset of the ACT-America MFLL L2 product (Lin et al., 2018; Campbell et al., 2020). Variables in this Lite product include column-averaged $CO_2$ mole fraction, range at nadir, aircraft flight information, and data quality flags. Native measurements, processing parameters, and other ancillary data are excluded in this Lite product. Details about the full MFLL L2 product can be found in a related dataset (Lin et al., 2018). Since the nominal cruising speed of the ACT-America C-130 aircraft is about 250 knots, the equivalent spatial resolution of the 10 Hz data is approximately 13 m. All the reported values represent measurements along the nadir direction from the MFLL instrument to the main backscatters for the lidar.

ACT-America's overall mission spanned five years and included field campaigns covering all four seasons over central and eastern regions of the United States. ACT-America's objectives were to study the transport and fluxes of atmospheric CO2 and CH4. Two instrumented aircraft platforms, the NASA Langley Beechcraft B-200 King Air and the NASA Wallops Flight Facility's C-130 Hercules, were used to collect high-quality in situ measurements across a variety of continental surfaces and atmospheric conditions. At times they flew directly under Orbiting Carbon Observatory-2 (OCO-2) overpasses to evaluate the ability of OCO-2 to observe high-resolution atmospheric CO2 variations. The C-130 aircraft was also equipped with active remote sensing instruments for planetary boundary layer height detection and column greenhouse gas measurements.

There are 297 data files in netCDF (*.nc) format included in this dataset. Also included are two companion files in Portable Document Format (*.pdf).

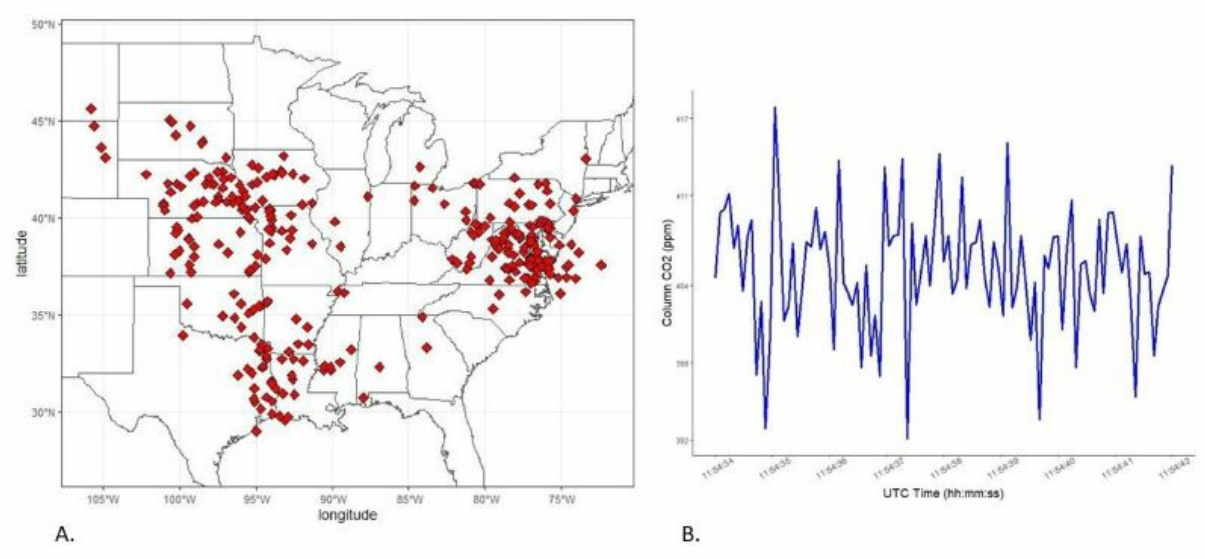


Figure 1. Locations of ACT-America flights collecting MFLL carbon dioxide (CO2) measurements over eastern and central U.S. in 2016-2018 (A). A sample of column CO2 concentrations retrieved on May 27, 2016, over eastern North Carolina. Source: ACTAmerica-MFLL-Lite-lev2_C130_2016-05-27T145325_R0.nc

## Citation

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## 1. Dataset Overview

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This MFLL Lite product is intended for end-users of $CO_2$ observations. It is a direct subset of the ACT-America MFLL L2 product (Lin et al., 2018; Campbell et al., 2020). Variables in this Lite product include column-averaged $CO_2$ mole fraction, range at nadir, aircraft flight information, and data quality flags. Native measurements, processing parameters, and other ancillary data are excluded in this Lite product. Details about the full MFLL L2 product can be found in a related dataset (Lin et al., 2018). Since the nominal cruising speed of the ACT-America C-130 aircraft is about 250 knots, the equivalent spatial resolution of the 10 Hz data is approximately 13 m. All the reported values represent measurements along the nadir direction from the MFLL instrument to the main backscatters for the lidar.

ACT-America's overall mission spanned five years and included field campaigns covering all four seasons over central and eastern regions of the United States. ACT-America's objectives were to study the transport and fluxes of atmospheric CO2 and CH4. Two instrumented aircraft platforms, the NASA Langley Beechcraft B-200 King Air and the NASA Wallops Flight Facility's C-130 Hercules, were used to collect high-quality in situ measurements across a variety of continental surfaces and atmospheric conditions. At times they flew directly under Orbiting Carbon Observatory-2 (OCO-2) overpasses to evaluate the ability of OCO-2 to observe high-resolution atmospheric CO2 variations. The C-130 aircraft was also equipped with active remote sensing instruments for planetary boundary layer height detection and column greenhouse gas measurements.

**Project:** Atmospheric Carbon and Transport - America

The Atmospheric Carbon and Transport - America (ACT-America) project is a NASA Earth Venture Suborbital-2 mission to study the transport and fluxes of atmospheric carbon dioxide and methane across three regions in the eastern United States. Flight campaigns measured transport of greenhouse gases by continental-scale weather systems. Ground-based measurements of greenhouse gases were also collected. Project goals include better estimates of greenhouse gas sources and sinks which are required for climate management and for prediction of future climate.

**Related Datasets**

Lin, B., J.F. Campbell, J. Dobler, E.V. Browell, S.A. Kooi, S. Pal, T. Fan, W. Erxleben, D. Mcgregor, M.D. Obland, and C. O'Dell. 2018. ACT-America: L2 Remotely Sensed Column-average CO2 by Airborne Lidar, Eastern USA. ORNL DAAC, Oak Ridge, Tennessee, USA.
https://doi.org/10.3334/ORNLDAAC/1649

Lin, B., J.F. Campbell, J. Dobler, E.V. Browell, S.A. Kooi, S. Pal, T. Fan, W. Erxleben, D. Mcgregor, M.D. Obland, and C. O'Dell. 2020. ACT-America: L1 Remotely Sensed Column-average CO2 by Airborne Lidar, Eastern USA. ORNL DAAC, Oak Ridge, Tennessee, USA.
https://doi.org/10.3334/ORNLDAAC/1817

Lin, B., J.F. Campbell, J. Dobler, E.V. Browell, S.A. Kooi, S. Pal, T. Fan, W. Erxleben, D. Mcgregor, M.D. Obland, and C. O'Dell. 2021. ACT-America: L2 Weighting Functions for MFLL Column-avg CO2 measurements, 2016-2018. ORNL DAAC, Oak Ridge, Tennessee, USA.
https://doi.org/10.3334/ORNLDAAC/1891

**Acknowledgments**

This project was funded by NASA's ACT-America program (grant NNX15AG76G).

## 2. Data Characteristics

**Spatial Coverage:** flights over the eastern and central United States

**Spatial Resolution:** nominal 13 m, point measurements along C-130 flight tracks

**Temporal Coverage:** 2016-05-27 to 2018-05-20

**Temporal Resolution:** 0.1 second (10 Hz)

**Study Area:** Latitude and longitude are given in decimal degrees.

| Site | Westernmost Longitude | Easternmost Longitude | Northernmost Latitude | Southernmost Latitude |
|---|---|---|---|---|

| Site | Westernmost Longitude | Easternmost Longitude | Northernmost Latitude | Southernmost Latitude |
|---|---|---|---|---|
| eastern and central U.S. | -106.0535 | -71.9109 | 49.1083 | 27.2303 |

**Data File Information**

There are 297 data files in netCDF (*.nc) format included in this dataset. Also included are two companion files in Portable Document Format (*.pdf).

The files are named ACTAmerica-MFLL-Lite-lev2_C130_**YYYY-MM-DDTHHmmSS_R#**.nc (e.g., ACTAmerica-MFLL-Lite-lev2_C130_2016-05-27T145325_R0.nc), where **YYYY-MM-DDTHHmmSS** is the flight start date and time (UTC) and **R#** is the data revision number. A higher number indicates a more recent revision.

Table 1. File names and descriptions.

| File Name | Description |
|---|---|
| **Data Files** | |
| ACTAmerica-MFLL-Lite-lev2_C130_YYYY-MM-DDTHHmmSS_R#.nc | column-averaged $CO_2$ mole fraction measured in parts per million and have a single dimension measured by the *time* variable |
| **Companion Files** | |
| ACTAmerica-MFLL-Lite_C130_Readme_R0.pdf | details about MFLL instrument and methods for calculating XCO2 measurements |
| MFLL_XCO2_Range_10Hz.pdf | a PDF version of this user guide |

**Data File Details**

Missing values are represented by -9999. Locations are provided in geographic coordinates.

Table 2. Variables names and descriptions.

| Variable | Units | Description |
|---|---|---|
| Column_CO2 | $1e^{-6}$ | Mole fraction column $CO_2$, in parts per million, along nadir direction from the MFLL sensor to the backscatter |
| Range_nadir | m | The range from the instrument onboard the C-130 aircraft to the backscatter in the nadir direction |
| Latitude | degree_north | Latitude in decimal degrees |
| Longitude | degree_east | Longitude in decimal degrees |
| GPS_Altitude | m | Aircraft altitude measured by a global positioning system |
| time | s | Time in seconds since 1970-01-01 00:00:00 UTC |
| Data_quality_flag | 1 | See Table 2 |

Table 3. Data quality information encoded in the *Data_quality_flag* variable.

| Value | Signal strength | Pitch Angle <5 degrees & Roll Angle <5 degrees | Clear Sky? | Description |
|---|---|---|---|---|
| 1 | Good | Yes | Yes | Good data; clear column condition; normal retrieval |
| 2 | Good | Yes | Yes | Clear column condition; normal retrieval; use with caution |
| 3 | Good | Yes | No | Single-layer cloudy condition; normal retrieval; use with caution |
| 4 | Good | Yes | No | Multi-layer cloudy condition; normal retrieval; use with caution |
| 0 | Good | No | Yes/No | Normal retrieval under large pitch/roll angle and potential cloudy conditions; not suggested for use |
| -9999 | | | | Bad data |

**User Notes**

The *time* variable does not increase monotonically along the flight path. Gaps exist for segments of the flight when measurements were not being recorded. Refer to the *time* variable units "seconds since 1970-01-01 00:00:00 UTC".

Use the *Data_quality_flag* variable to select measurements that meet desired standards.

## 3. Application and Derivation

ACT-America, or Atmospheric Carbon and Transport - America, conducted five airborne campaigns across three regions in the eastern United States to study the transport and fluxes of atmospheric carbon. The eastern half of the United States is a region that includes a highly productive biosphere, vigorous agricultural activity, extensive gas and oil extraction and consumption, dynamic, seasonally varying weather patterns and the most extensive carbon cycle and meteorological observing networks on Earth, serves as an ideal setting for the mission.

Each 6-week campaign accurately and precisely quantified anomalies in atmospheric carbon, also known as carbon flux. Accurate carbon flux data is necessary to address all terrestrial carbon cycle science questions. ACT-America addressed the three primary sources of uncertainty in atmospheric inversions—transport error, prior flux uncertainty, and limited data density.

ACT-America advances society's ability to predict and manage future climate change by enabling policy-relevant quantification of the carbon cycle. Sources and sinks of atmospheric carbon dioxide (CO2) and methane (CH4) are poorly known at regional to continental scales. ACT-America enables and demonstrates a new generation of atmospheric inversion systems for quantifying CO2 and CH4 sources and sinks.

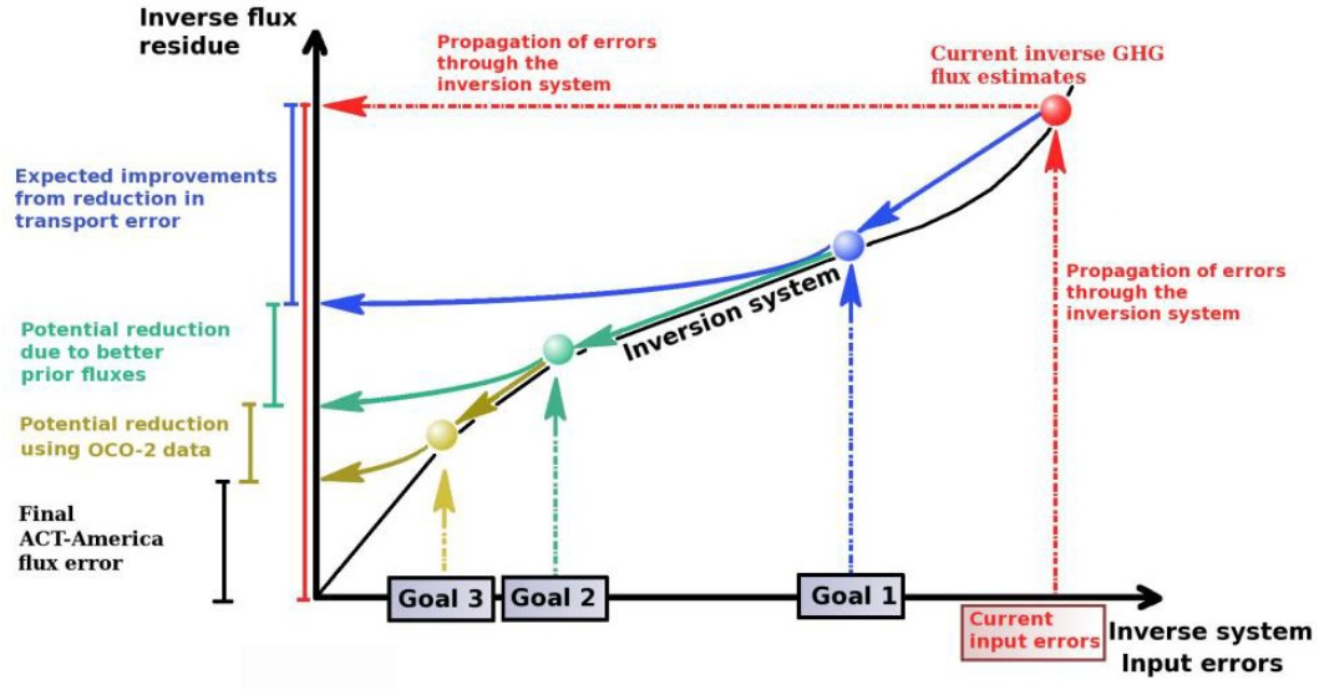


Figure 2. A schematic showing ACT-America mission goals.

**ACT-America Goals**

1. To quantify and reduce atmospheric transport uncertainties.
2. To improve regional-scale, seasonal prior estimates of C)2 and CH4 fluxes.
3. To evaluate the sensitivity of Orbiting Carbon Observatory (OCO-2) column measurements to regional variability in tropospheric CO2.

ACT-America achieved these goals by deploying airborne and ground-based platforms to obtain data that were combined with data from existing measurement networks and integrated with an ensemble of atmospheric inversion systems. Aircraft instrumented with remote and in situ sensors observed how mid-latitude weather systems interact with CO2 and CH4 sources and sinks to create atmospheric CO2/CH4 distributions. A model ensemble consisting of a mesoscale atmospheric transport model with multiple physics and resolutions options nested within global inversion models and surface CO2/CH4 flux ensembles was used to predict atmospheric CO2 and CH4 distributions.

Beyond the conclusion of the mission, the application of knowledge gained from this mission will improve diagnoses of the carbon cycle across the globe for decades.

## 4. Quality Assessment

The evaluation of ACT-America field campaign data (Campbell et al., 2020) has shown that the lidar $CO_2$ measurements are consistent from season to season and have an absolute calibration uncertainty (i.e., standard deviation) of 0.80 ppm. The $CO_2$ measurement precision for 0.1 s, 1 s, 10 s, and 60 s averages was found to be 3.4 ppm, 1.2 ppm, 0.43 ppm, and 0.26 ppm, respectively, and the drift in XCO2 over one-hour of flight time was very small and below 0.1 ppm. Because of the unprecedented high stability, accuracy, and precision, the ACT-America MFLL data have been used for many analyses (e.g., Bell et al., 2020).

## 5. Data Acquisition, Materials, and Methods

The intensity-modulated continuous-wave (IM-CW) $CO_2$ lidar (MFLL) has been a crucial instrument in measuring column $CO_2$. This lidar was jointly developed for remote $CO_2$ column measurements by the NASA Langley Research Center and the Harris Space and Intelligence Systems Corp (Dobler et al., 2013; Lin et al., 2013; Lin et al., 2015). These MFLL data were collected during the first four ACT-America field campaigns: Summer 2016, Winter 2017, Fall 2017, and Spring 2018.

The MFLL lidar system transmits online and offline wavelengths simultaneously on the 1.57 μm $CO_2$ absorption line. The online wavelength is positioned on the $CO_2$ absorption line center at 1571.112 nm, and the two offline wavelengths are set to be ±50 pm on either side of the absorption line. Each wavelength is modulated with a unique orthogonal waveform before being combined for simultaneous transmission through the atmosphere (Campbell 2013; Campbell et al., 2014a; Campbell et al., 2014b). The individual wavelengths are then separated from the combined received signal by cross-correlating the received signal by each orthogonal waveform. The result of this cross-correlation allows the determination of a backscatter profile for each wavelength, and the range to a scattering surface and signal amplitude is determined.

The MFLL instrument used orthogonal linear swept-frequency waveforms (Campbell, 2013). Differential Absorption Optical Depth (DAOD) values were estimated from the combined online and offline measurements using the Integrated Path Differential Absorption (IPDA) approach (Dobler et al., 2013; Lin et al., 2013; Lin et al., 2015; Campbell et al., 2020). The DAOD measurements were calibrated through an experimental series including ground short-path instrument calibration and spiral flight testing with in-situ $CO_2$ and meteorological profiling. The calibrated DAOD values were converted to XCO2 values assuming a vertically uniform 400 ppm $CO_2$ profile under the pressure, temperature, and humidity at the measurement time and location (Campbell et al.,

2020). The meteorological data were obtained from the Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA−2) weather product of the NASA Goddard Space Flight Center (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). $CO_2$ measurements along the vertical profile were averaged (Lin et al., 2021) to create the column-average $CO_2$ estimates provided in this dataset.

## 6. Data Access

These data are available through the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC).

ACT-America: L2 Remotely Sensed Column-avg CO2 by Airborne Lidar, Lite, Eastern USA

Contact for Data Center Access Information:

- E-mail: uso@daac.ornl.gov
- Telephone: +1 (865) 241-3952

## 7. References


Bell, E., C. O'Dell, K. Davis, S. Pal, B. Lin, S. Kooi, T. Fan, J. Campbell, E. Browell, J. Dobler, W. Erxleben, B. Weir, and S. Denning. 2020. Evaluation of OCO-2 XCO2 variability at local and synoptic scales using lidar and in situ observations from the ACT-America Campaign. Journal of Geophysical Research: Atmospheres 125:e2019JD031400. https://doi.org/10.1029/2019JD031400.

Campbell, J.F. 2013. Nonlinear swept frequency technique for CO2 measurements using a CW laser system. Applied Optics 52:3100-3107. https://doi.org/10.1364/AO.52.003100.

Campbell, J., B. Lin, A. Nehrir, F.W. Harrison, and M. Obland. 2014a. Super-resolution technique for CW lidar using Fourier transform reordering and Richardson–Lucy deconvolution. Optics Letters 39:6981-6984. https://doi.org/10.1364/OL.39.006981.

Campbell, J.F., B. Lin, A.R. Nehrir, F.W. Harrison, and M.D. Obland. 2014b. Binary phase shift keying on orthogonal carriers for multi-channel CO2 absorption measurements in the presence of thin clouds. Optics Express 22:A1634-A1640. https://doi.org/10.1364/OE.22.0A1634.

Campbell, J., B. Lin, E. Browell, M. Obland, J. Dobler, W. Erxleben, D. McGregor, C. O'Dell, E. Bell, S. Pal, B. Weir, T. Fan, S. Kooi, A. Corbett, K. Davis, I. Gordon, R. Kochanov. 2020. Field evaluation of column CO2 retrievals from intensity-modulated continuous-wave differential absorption lidar measurements during ACT-America. Earth and Space Science 7:e2019EA000847. https://doi.org/10.1029/2019EA000847.

Dobler, Jeremy T., F.W. Harrison, E.V. Browell, B. Lin, D. McGregor, S. Kooi, Y. Choi, and S. Ismail. 2013. Atmospheric CO2 column measurements with an airborne intensity-modulated continuous wave 1.57 μm fiber laser lidar. Applied Optics 52:2874-2892. https://doi.org/10.1364/AO.52.002874.

Lin, B., S. Ismail, F.W. Harrison, E.V. Browell, A.R. Nehrir, J. Dobler, B. Moore, T. Refaat, and S.A. Kooi. 2013. Modeling of intensity-modulated continuous-wave laser absorption spectrometer systems for atmospheric CO2 column measurements. Applied Optics 52:7062-7077. https://doi.org/10.1364/AO.52.007062.

Lin, B., A.R. Nehrir, F.W. Harrison, E.V. Browell, S. Ismail, M.D. Obland, J.l Campbell, J. Dobler, B. Meadows, T. Fan, and S. Kooi. 2015. Atmospheric CO2 column measurements in cloudy conditions using intensity-modulated continuous-wave lidar at 1.57 micron. Optics Express 23:A582-A593. https://doi.org/10.1364/OE.23.00A582.

Lin, B., J.F. Campbell, J. Dobler, E.V. Browell, S.A. Kooi, S. Pal, T. Fan, W. Erxleben, D. Mcgregor, M.D. Obland, and C. O'Dell. 2018. ACT-America: L2 Remotely Sensed Column-average CO2 by Airborne Lidar, Eastern USA. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1649.

Lin, B., J.F. Campbell, J. Dobler, E.V. Browell, S.A. Kooi, S. Pal, T. Fan, W. Erxleben, D. Mcgregor, M.D. Obland, and C. O'Dell. 2021. ACT-America: L2 Weighting Functions for MFLL Column-avg CO2 measurements, 2016-2018. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1891.