Title: Wyoming Cloud Lidar (WCL) Level-1 Data

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1.0 Data Set Description

- Summary: This dataset includes Wyoming Cloud Lidar data collected aboard the NSF/NCAR C-130 aircraft (tail number N130AR) during the CAESAR project. NetCDF files contain the corrected lidar data, total attenuated backscatter, signal to noise ratio, and depolarization ratio.
- Version: 0.1
- Release date: February 12, 2025
- Data Status: Preliminary
- Project: Cold Air Outbreak Experiment in the Sub-Arctic Region (CAESAR)
- Project base: Kiruna, Sweden
- Temporal coverage:
  - Begin datetime: 2024-02-09 19:06:25
  - End datetime: 2024-04-03 15:49:01
- Spatial coverage:
  - Maximum (North) Latitude: 82.00
  - Minimum (South) Latitude: 66.00
  - Minimum (West) Longitude: -14.00
  - Maximum (East) Longitude: 24.00
- Data Frequency: 2 seconds
- Data source: University of Wyoming
- Web address references: https://www.uwyo.edu/atsc/uwka/wcl.html
- Data set restrictions: Authorization required for 1 year following data collection

2.0 Instrument Description

The upward two Fields of View (2FOV) WCL is a dual polarization elastic backscatter lidar at 355nm in the ultraviolet. The lidar is zenith pointing.

An Ultra Pulsed Nd:YAG Laser from the Big Sky Laser Technologies Inc. providing a 20 Hz 16 mJ output at 355 nm is used for the WCL-I. Operating at 355 nm not only makes it easy to achieve eye-safe operation, it also provides a stronger molecular backscattering signal than a lidar operating at 532 or 1064 nm with the same laser energy. This is important for calibrating backscattering coefficients. The laser beam is expanded 5 times to a diameter of 15 mm before emittance into the atmosphere, making the system eye-safe beyond a distance of ~65 m. To improve lidar linear depolarization measurements, a 1/2 λ wave plate is placed after the beam expander and coupled with a cubic polarization beam splitter in the receiver path.

The receiver in the WCL-I is based on a 75mm refractive lens with a 12.5mm collimated beam that enters into the cubic polarization beam splitter. The field of view is controlled by a pinhole located at the focal plane of the receiving lens. The PMT packages include narrow band filters (0.3 nm), a focus lens, and a compact PMT. To provide the ruggedness and stability needed for the WCL to operate in a turbulent environment, the receiver is designed to share the same optical bench with the transmitter. The PMT's gain can easily be adjusted with bias control voltage. Signals from the PMTs are sent to the LICEL data acquisition system. The data system has a combined A/D and photon counting capability. To provide high-resolution spatial measurements, only strong signals digitized by A/D at 40 MHz are saved at single shot or averaging of number of shots. Thus, the WCL can provide measurements at ~4.5 m horizontal and 3.75 m vertical resolution from the UWKA, for an average cruise speed of ~90 m/s.

	Zenith Lidar CAESAR
Wavelength	355 nm
Pulse Energy	16 mj
Pulse Length	6 nm
Pulse Repetition Frequency	20 Hz
Laser Beam Divergence	1mrad
Receiver Diameter	75mm
Receiver Field of View	2 mrad narrow, 8 mrad wide
Receiving Channels	4 (2 FOV each with P and S polarization)
Detectors	PMT
Range Resolution	3.75m

Temporal Resolution	~1.5 s

3.0 Data Collection and Processing

WCL data were collected during all 10 research flights and during test flights 1, 2, 5, & 6.

The WCL transmitter-receiver alignment was performed in the lab at the university of Wyoming before installation on the aircraft.

The data acquisition range was changed by an operator mid flight to avoid saturation of the data acquisition system in clouds. Having a lower range increased the detector power signal resolution. The times where the range was changed mid flight appear as gaps in the data because the system could not collected data for a few seconds as the changed was performed.

3.1 Background noise Correction

Background noises due to the sunlight at 355 nm and the PMT noise are collected in addition to atmospheric backscatter signal, and they need to be subtracted. As the WCL is designed, pre-trigger values (data before the laser pulse is transmitted) are recorded for the average background noise correction. These data are subtracted from each time profile as a range independent factor.

3.2 Range-square correction

The PMT signal is range corrected based on the square of the range from the lidar. The noise residue or random noise is magnified in the range correction. Therefore, as the range increases, the noise residue in the signal also increases in the range-square correction, resulting in a decreasing signal-to-noise ratio (SNR) with range.

3.3 Overlap

The lidar overlap function is a function of range where the transmitted laser beam and the receiver view overlap. The overlap function is a unitless factor multiplied by the received signal as a function of range and ranges from 0 to 1. The overlap function starts at 0 at 0m in range and increases to 1 at about 100-200m in range. After that point, the overlap function stays at 1 for the remainder of the lidar range and does not need to be considered. The overlap function is calibrated by choosing a section of flight with purely molecular (Rayleigh) scattering. Purely molecular scattering is found above the boundary layer (typically >2000m agl). The lidar returns can then be fitted to a theoretical calculation of Rayleigh scattering based on temperature and pressure estimations as a function of range. The lidar overlap function is the fitted theoretical returns divided by the actual pure molecular scattering lidar returns. The lidar overlap function can then be applied to the entire dataset as long as the transmitter-receiver alignment is not changed.

3.4 Depolarization ratio

The Lidar depolarization calibration was performed in the lab at the University of Wyoming after the flights. The lidar includes a half-waveplate for rotating the transmitter polarization. The half-waveplate is used to set the correct polarization and to calibrate the polarization measurements. The lidar polarization is calibrated by taking several measurements at different half-waveplate angles to find a gain ratio between the S and P polarization channels.

3.5 Total Attenuated backscatter coefficient

The total attenuated backscatter is based on the lidar overlap function, receiver area, receiver optical transmission (including optical port), detector gain, and transmitter power. The overlap function, receiver area, receiver transmission, and detector gain can be measured and estimated and stays consistent. The external optical port or window may be affected by condensation or dust and can be variable. The transmitter optical power can have a shot to shot energy stability of 6%.

The total attenuated backscatter coefficient can be normalized to clear sky Raleigh scattering. This is used to find the correct power*efficiency coefficient. This technique can also be used to find the correct coefficient for ice/condensation on the lidar optical window causing lower output power. The molecular extinction coefficient is

$$\sigma_m(z,\lambda) = \frac{N_A P(z)}{R_a T(z)} \frac{24\pi^3 (n_s^2(\lambda) - 1)^2}{\lambda^4 N_s^2 (n_s^2(\lambda) + 2)^2} \frac{(3 + 6\delta_m(\lambda))}{(3 - 4\delta_m(\lambda))}$$

Where λ is the lidar wavelength, n_s and N_s are the refractive index and molecular number density of standard air respectively. δ_m is the molecular depolarization ratio. $T(z)$ and $P(z)$ are the atmospheric temperature and pressure at range z. N_A is Avogadro's number and R_a is the gas constant.

$$\beta_m(z,\lambda) = \frac{\sigma_m(z,\lambda)}{\left(8\pi/3\right) k_{bw}(\lambda)}$$

The time periods with condensation/icing are identified by the ratio of the lidar signal at zero range with the signal at full overlap. If the lidar signal at zero range is higher than the signal at full overlap the time period is classified at reduced output power.

3.5 Signal to Noise Ratio

The signal to noise ratio is primarily due to the photomultiplier detectors and background light. The signal to noise ratio is calculated from

$$SNR = real\left(\frac{I_s}{\sqrt{2e(I_s + 2(I_{bg} + I_d)GFB}}\right)$$

Where I_s is the detected signal current, e is the charge of an electron, I_{bg} and I_d are the background detected current and dark current respectively. G is the PMT gain, F is the PMT noise factor, and B is the detector electrical bandwidth. The data acquisition card measures voltage from the current signal across two 50Ω resistors so $I = V/25$.

The PMT detector gain is 6.4e5 for the high gain channels and 7e4 for the low gain channels. The electrical bandwidth is 125 MHz. The noise factor for the PMT is estimated as 1.2.

4.0 Data Format

Processed lidar data are stored in NetCDF-4 files. File naming starts with the date span (yyyymmdd_hhmmss_to_ yyyymmdd_hhmmss), the instrument (WCL), the data level (L1), the project (CAESAR24), and the lidar pointing direction (UP).

Examples:

“.20240311_121000_to_20240311_121959_WCL_L1_CAESAR24.UP.nc”

“20240311_121000_to_20240311_121959_WCL_L1_CAESAR24.UP.png”

Example File variables:

```
>> ncdisp('20240316_095000_to_20240316_100000_WCL_L1_CAESAR24.UP.nc')
Source:
    \20240316\20240316_095000_to_20240316_100000_WCL_L1_CAESAR24.UP.nc
Format:
    netcdf4
Global Attributes:
    Source              = 'University of Wyoming, Department of Atmospheric Science'
    Address             = '1000 E. University Ave., Laramie, WY 82071'
    Phone               = '307-766-3245'
    ProcessAuthor       = 'Owen Cruikshank'
    Email               = 'owen.cruikshank@uwyo.edu'
    Version             = 'L1 - Preliminary'
    ProjectName         = 'CAESAR'
    Platform            = 'N130AR'
    WCL_Aperture_Diameter = '75 mm'
    WCL_Beam_Divergence   = '1 mrad'
    WCL_Narrow_FOV        = '2 mrad'
```

WCL_Wide_FOV = '8 mrad'

WCL_Pulse_Width = '8 ns'

WCL_Wavelength = '355 nm'

WCL_Pulse_Energy = '16 mJ'

LidarDataSource = 'WCL_2FOVUP'

AcquisitionDate = '20240316'

DateProcessed = '12-Feb-2025 16:13:05(UTC)'

Dimensions:

range = 10624

profile = 401

vector3 = 3

Variables:

Time

Size: 401x1

Dimensions: profile

Datatype: double

Attributes:

long_name = 'Profile acquisition time'

units = 'seconds since 2024-03-16 00:00:00 +0000'

strptime_format = 'seconds since %F %T %z'

time

Size: 401x1

Dimensions: profile

Datatype: double

Attributes:

long_name = 'Profile acquisition time'

units = 'seconds since 1970-01-01 00:00:00 +0000'

strptime_format = 'seconds since %F %T %z'

Navg

Size: 401x1

Dimensions: profile

Datatype: int16

Attributes:

long_name = 'Number of indidual lidar profiles averaged in time dimension'

Range

Size: 10624x1

Dimensions: range

Datatype: single

Attributes:

long_name = 'Range from Aircraft to the center of lidar range gates'

units = 'meters'

TotalAttenuatedBackscatterCoefficient

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Backscatter Pr2 from the parallel channel of High gain'

status = 'range corrected, mean noise subtracted, overlap corrected, no attenuation correction, backscatter correction'

units = 'm^-1 sr^-1'

TotalAttenuatedBackscatterCoefficient_DataFlag

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Flag where icing/condencation caused the need for attenuated backscatter correction'

status = '1 = further correction, 0 = no further correction'

units = 'none'

CopolPowerR2H

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Backscatter Pr2 from the parallel channel of High gain'

status = 'range corrected, mean noise subtracted, overlap corrected, no attenuation correction'

units = 'unitless'

CrossPowerR2H

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Backscatter Pr2 from the perpendicular channel of High gain'

status = 'range corrected, mean noise subtracted, overlap corrected, no attenuation correction'

units = 'unitless'

CopolPowerR2L

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Backscatter Pr2 from the parallel channel of Low gain'

status = 'range corrected, mean noise subtracted, overlap corrected, no attenuation correction'

units = 'unitless'

CrossPowerR2L

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Backscatter Pr2 from the perpendicular channel of Low gain'

status = 'range corrected, mean noise subtracted, overlap corrected, no attenuation correction'

units = 'unitless'

DepolarizationRatioH

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Depolarization Ratio from the high gain channel, CopolPowerR2H and CrossPowerR2H'

status = 'Uncalibrated'

units = 'Unitless'

DepolarizationRatioL

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Depolarization Ratio from the low gain channel, CopolPowerR2L and CrossPowerR2L'

status = 'Uncalibrated'

units = 'Unitless'

CopolPowerH_org

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Original Signal power from the parallel channel of High gain'

status = 'no correction'

units = 'unitless'

CrossPowerH_org

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Original Signal power from the perpendicular channel of High gain'

status = 'no correction'

units = 'unitless'

CoPolPowerL_org

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Original Signal power from the parallel channel of Low gain'

status = 'no correction'

units = 'unitless'

CrossPowerL_org

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Original Signal power from the perpendicular channel of Low gain'

status = 'no correction'

units = 'unitless'

CopolOverlapH

Size: 10624x1

Dimensions: range

Datatype: single

Attributes:

long_name = 'The overlap factor of parallel channel of High gain'

CrossOverlapH

Size: 10624x1

Dimensions: range

Datatype: single

Attributes:

long_name = 'The overlap factor of perpendicular channel of High gain'

CopolOverlapL

Size: 10624x1

Dimensions: range

Datatype: single

Attributes:

long_name = 'The overlap factor of parallel channel of Low gain'

CrossOverlapL

Size: 10624x1

Dimensions: range

Datatype: single

Attributes:

long_name = 'The overlap factor of perpendicular channel of Low gain'

CoPolHiSNR

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Signal to noise ratio'

CrossHiSNR

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Signal to noise ratio'

CoPolLoSNR

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Signal to noise ratio'

CrossLoSNR

Size: 401x10624

Dimensions: profile,range

Datatype: single

Attributes:

long_name = 'Signal to noise ratio'

CopolHBG_far

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Mean background noise of parallel channel in far range of High gain'

units   = 'unitless'

CrossHBG_far

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Mean background noise of perpendicular channel in far range of High gain'

units   = 'unitless'

CopolLBG_far

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Mean background noise of parallel channel in far range of Low gain'

units   = 'unitless'

CrossLBG_far

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Mean background noise of perpendicular channel in far range of Low gain'

units   = 'unitless'

CopolHBGSTD

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Std. Dev. of background noise power in parallel channel of High gain'

units   = 'unitless'

CrossHBGSTD

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Std. Dev. of background noise power in perpendicular channel of High gain'

units   = 'unitless'

CopolLBGSTD

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Std. Dev. of background noise power in parallel channel of Low gain'

units   = 'unitless'

CrossLBGSTD

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Std. Dev. of background noise power in perpendicular channel of Low gain'

units = 'unitless'

CopolHSatur

Size: 401x10624

Dimensions: profile,range

Datatype: int16

Attributes:

long_name = 'data saturated flags for the parallel channel of High gain'

status = '1 - saturated data point, 0 - unsaturated data point'

CrossHSatur

Size: 401x10624

Dimensions: profile,range

Datatype: int16

Attributes:

long_name = 'data saturated flags for the perpendicular channel of High gain'

status = '1 - saturated data point, 0 - unsaturated data point'

CopolLSatur

Size: 401x10624

Dimensions: profile,range

Datatype: int16

Attributes:

long_name = 'data saturated flags for the parallel channel of Low gain'

status = '1 - saturated data point, 0 - unsaturated data point'

CrossLSatur

Size: 401x10624

Dimensions: profile,range

Datatype: int16

Attributes:

long_name = 'data saturated flags for the cross channel of Low gain'

status = '1 - saturated data point, 0 - unsaturated data point'

ALT

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Lidar platform Altitude above MSL'

units = 'meters'

source = 'N130AR, GPS altitude (MSL), GGALT'

Ralt

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Lidar platform Altitude above ground'

units = 'meters'

source = 'N130AR, Radar altimeter altitude (AGL)'

Pitch

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'IRS Aircraft Pitch Angle'

units = 'degree'

source = 'N130AR'

Roll

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'IRS Aircraft Roll Angle'

units = 'degree'

source = 'N130AR'

LON

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'GPS-Corrected Inertial Longitude'

units = 'degree_E'

source = 'N130AR'

LAT

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'GPS-Corrected Inertial Latitude'

units = 'degree_N'

source = 'N130AR'

trf

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Ambient Temperature'

units = 'degree_C'

source = 'N130AR'

pmb

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Static Pressure, Corrected'

units = 'mb'

source = 'N130AR'

Zenith

Size: 401x1

Dimensions: profile

Datatype: single

Attributes:

long_name = 'Laser beam Zenith Angle'

units = 'degree'

BeamVector

Size: 3x401

Dimensions: vector3,profile

Datatype: single

Attributes:

long_name = '(East,North,Up) lidar beam unit vectors'

units = ' '

dependencies = 'N130AR IRS variable'

Prof_qc_flag

Size: 401x1

Dimensions: profile

Datatype: int16

Attributes:

long_name = 'quality control check flag'

status = '1 - good profile, 0 - bad profile or no data'

5.0 Data Remarks

The lidar was turned on and collecting data shortly after takeoff. The lidar transmission and data collection were stopped over restriction zones.

For many flights there was a high lidar return at low ranges. This is most likely due to condensation on the optical window. This may lower the total lidar transmitter signal. Later flights appear to have fixed this issue.

The Attenuated backscatter includes a correction to counteract the icing/condensation on the optical window.

6.0 References

- Zhien Wang, Perry Wechsler, William Kuestner, Jeffrey French, Alfred Rodi, Brent Glover, Matthew Burkhart, and Donal Lukens, "Wyoming Cloud Lidar: instrument description and applications," Opt. Express 17, 13576-13587 (2009)

- Deng, M., Wang, Z., Volkamer, R., Snider, J. R., Oolman, L., Plummer, D. M., Kille, N., Zarzana, K. J., Lee, C. F., Campos, T., Mahon, N. R., Glover, B., Burkhart, M. D., & Morgan, A. (2022). Wildfire Smoke Observations in the Western United States from the Airborne Wyoming Cloud Lidar during the BB-FLUX Project. Part I: Data Description and Methodology, Journal of Atmospheric and Oceanic Technology, 39(5), 545-558.

7.0 Appendix

Keywords: Lidar, depolarization, Cloud Properties