# Multi-layer retrievals of atmospheric $CO_2$ mixing ratio using multi-wavelength pulsed lidar measurements from aircraft

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# Going beyond column-averaged retrievals

- Column-averaged GHG measurements work well, but…
  - Boundary layer $CO_2$ (or $CH_4$) is most important
  - The need for BL $CO_2$ drives high-accuracy requirements on total column
  - Small biases can cause significant errors in carbon flux retrievals
- Measurements with even a few vertical layers can provide valuable $CO_2$ (or $CH_4$) profile information

# Vertical $CO_2$ information from lidar

- Unique capabilities of lidar
  - Measurement of atmospheric backscatter
  - Accurate ranging
  - High spectral resolution

- Two techniques for solving for two vertical layers
  1. Measurements from ground and clouds: **Cloud-slicing**
  2. Analysis of absorption line shape: **Multi-layer retrievals**

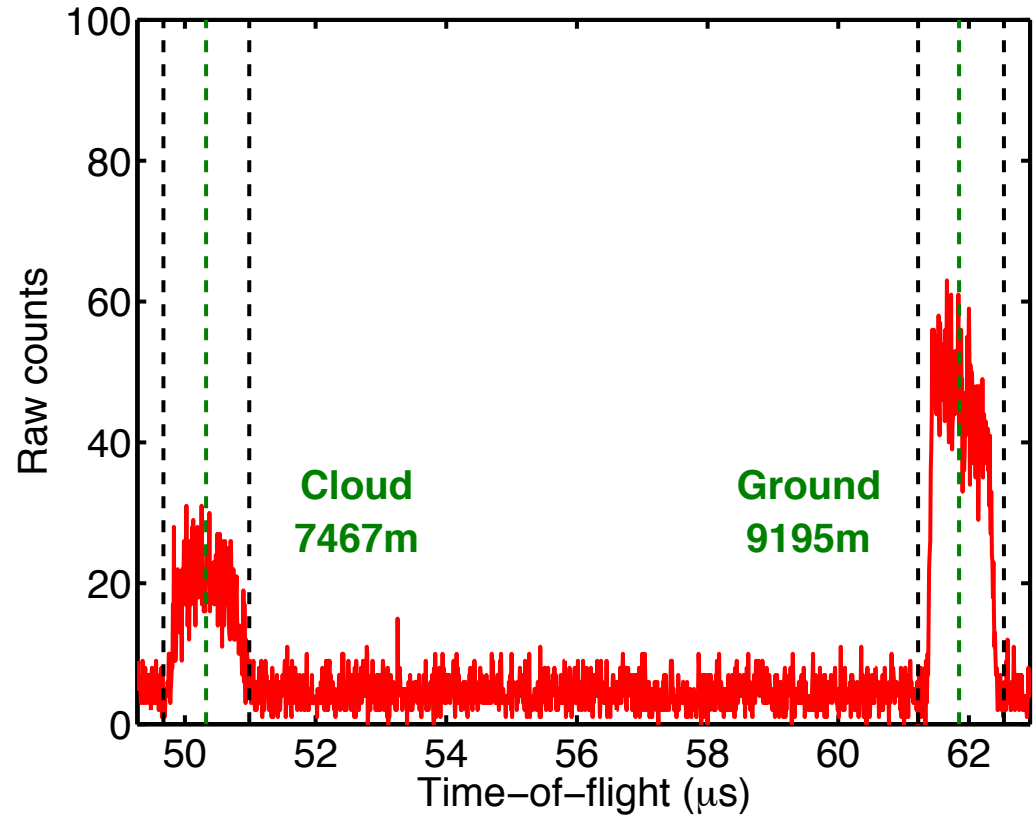
**Will show examples from airborne measurements using both techniques**

# Lidar Cloud Slicing

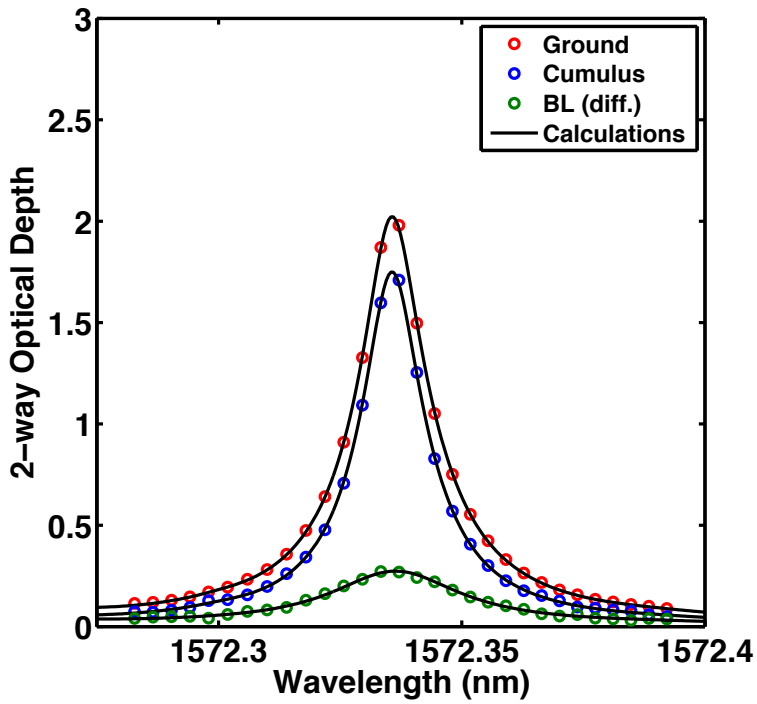
# Pulsed lidar returns

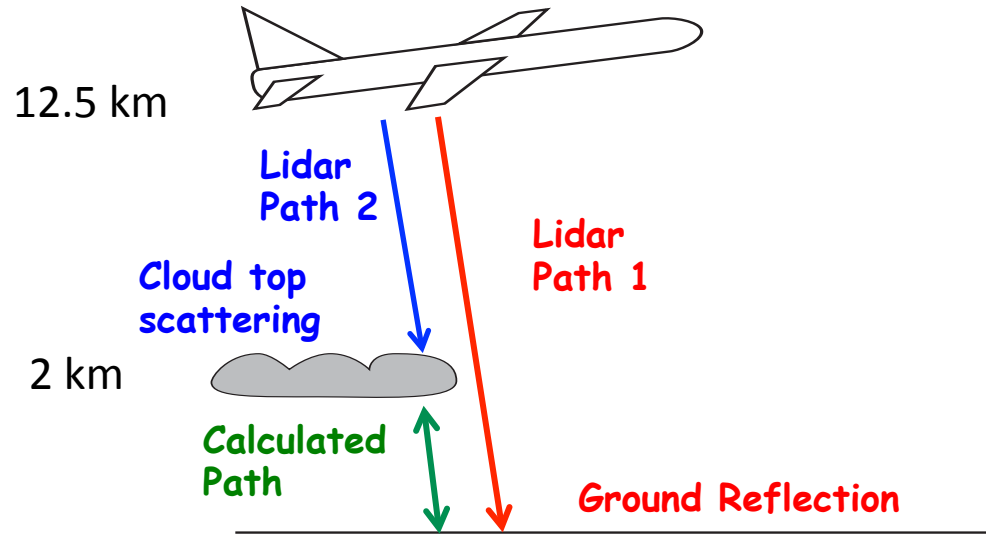
- Time-resolved lidar profiles completely sepearate echoes from different surfaces

Sample pulse return when flying over a thin cloud



# Two-level measurements via Cloud Slicing



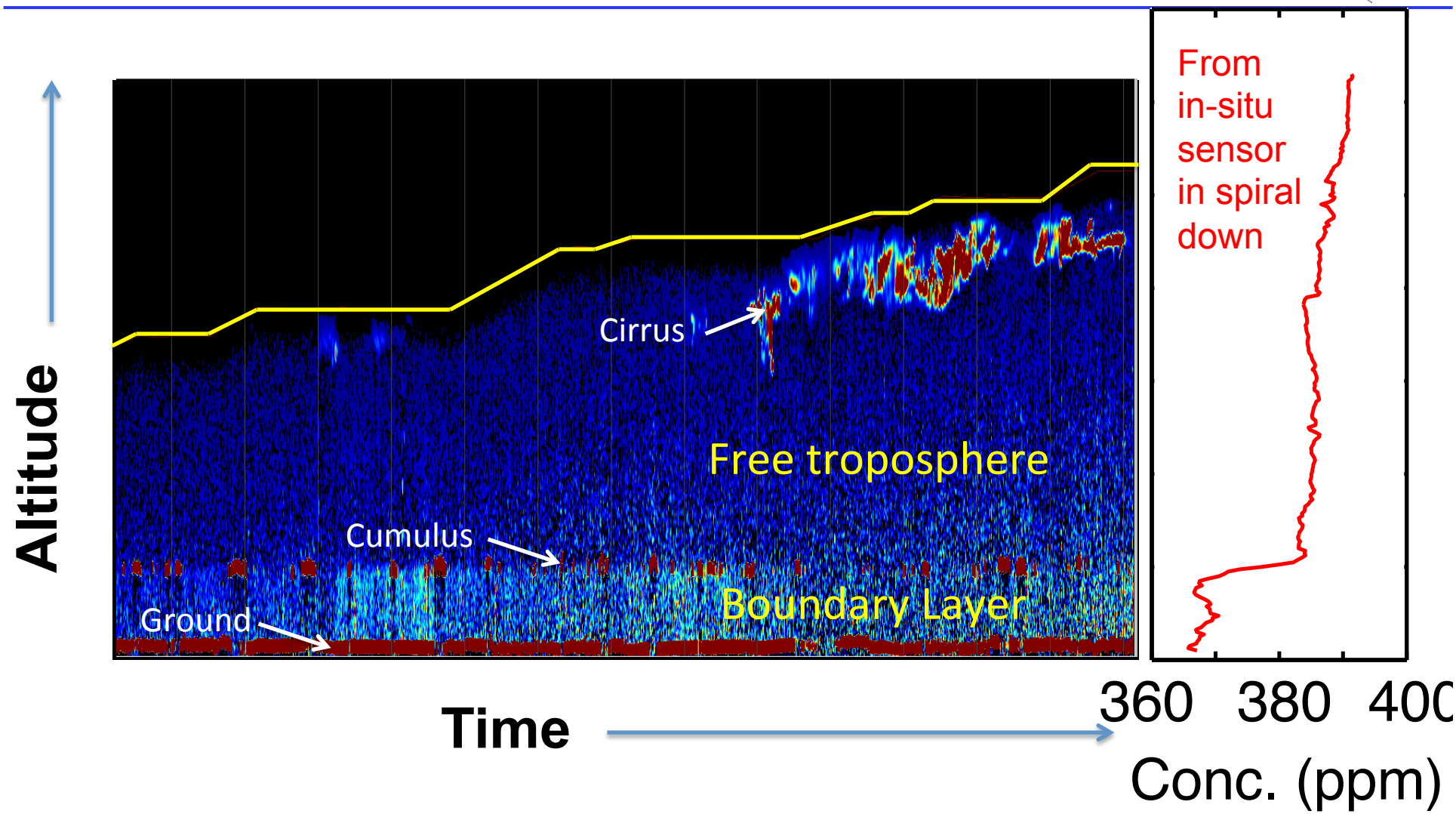

Upper layer = 387 ppm
Lower layer = 377 ppm

- Make column absorption & range measurements to ground and to cloud tops
- Difference the measurements to get bottom layer $CO_2$

# Clouds in the measurement

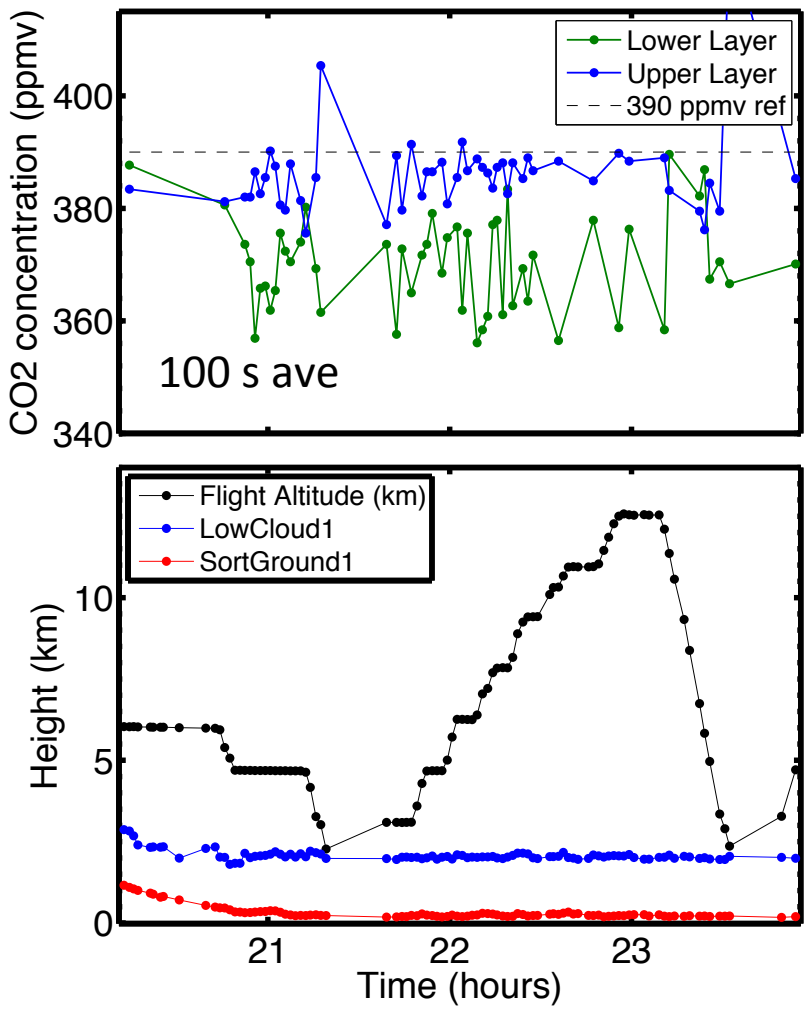
Near Iowa City, Iowa, Aug 10th 2011

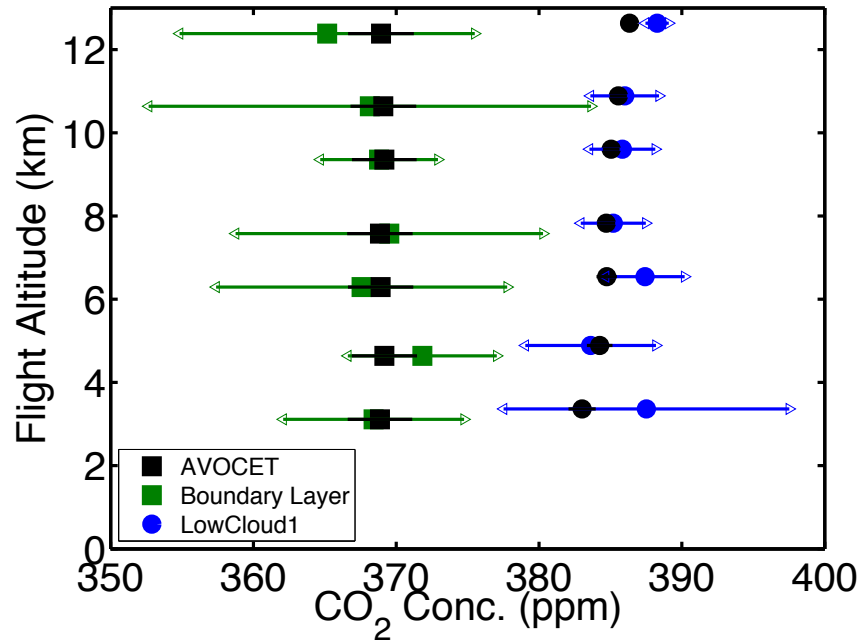
# Backscatter Profile History




- Backscatter reveals cloud layers

# Using cloud slicing to cumulus cloud tops to measure boundary layer $CO_2$

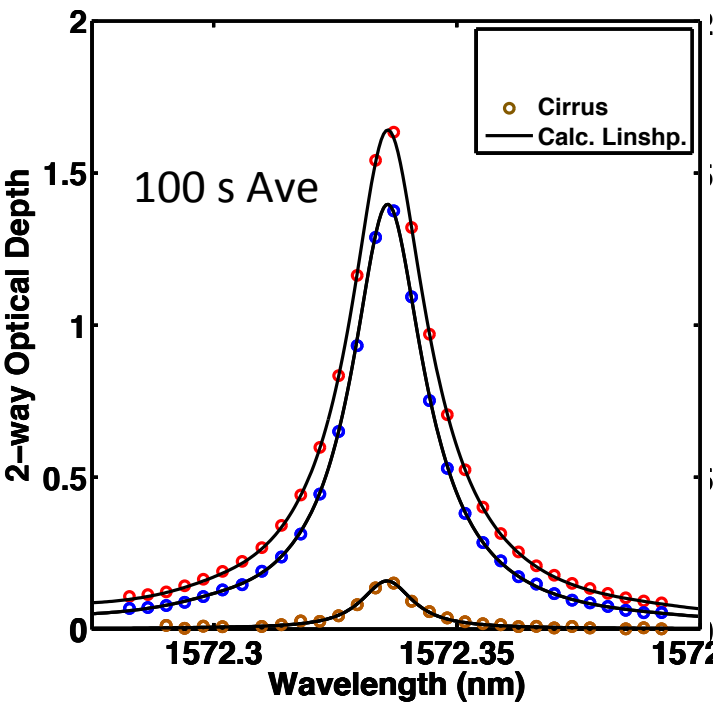


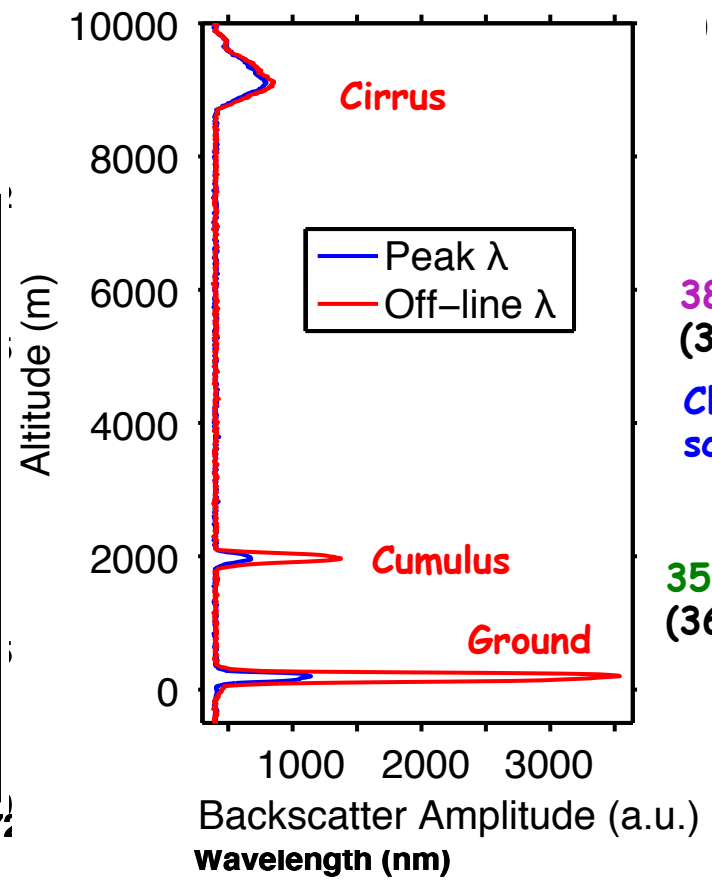



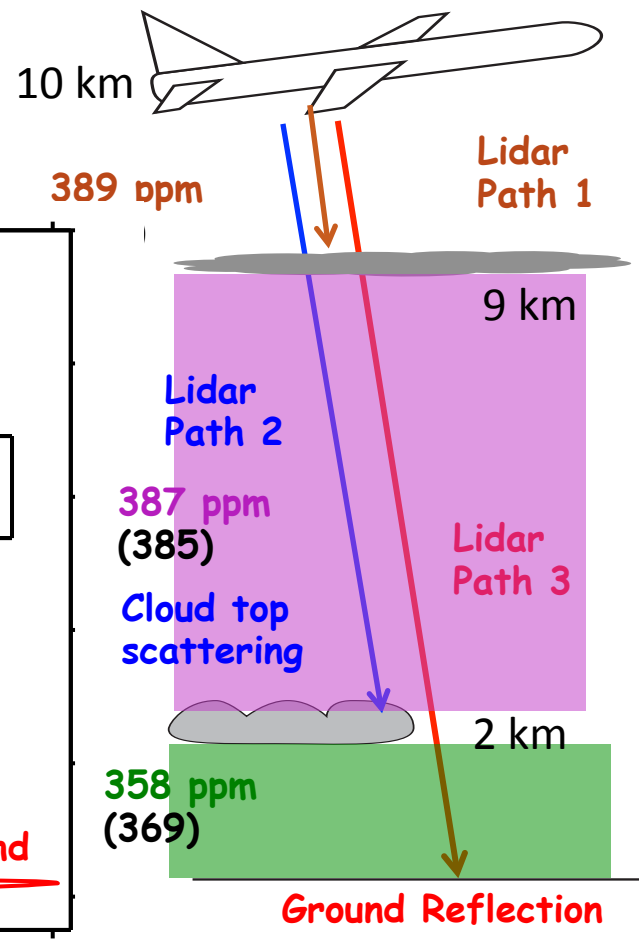

- Differential measurement -> more scatter (10 ppm)
- Measurements in agreement with in situ data (<5 ppm)

# Cloud Slicing using both Cirrus & Cumulus Clouds

- With 2 cloud layers, can get 3-level $CO_2$ information !



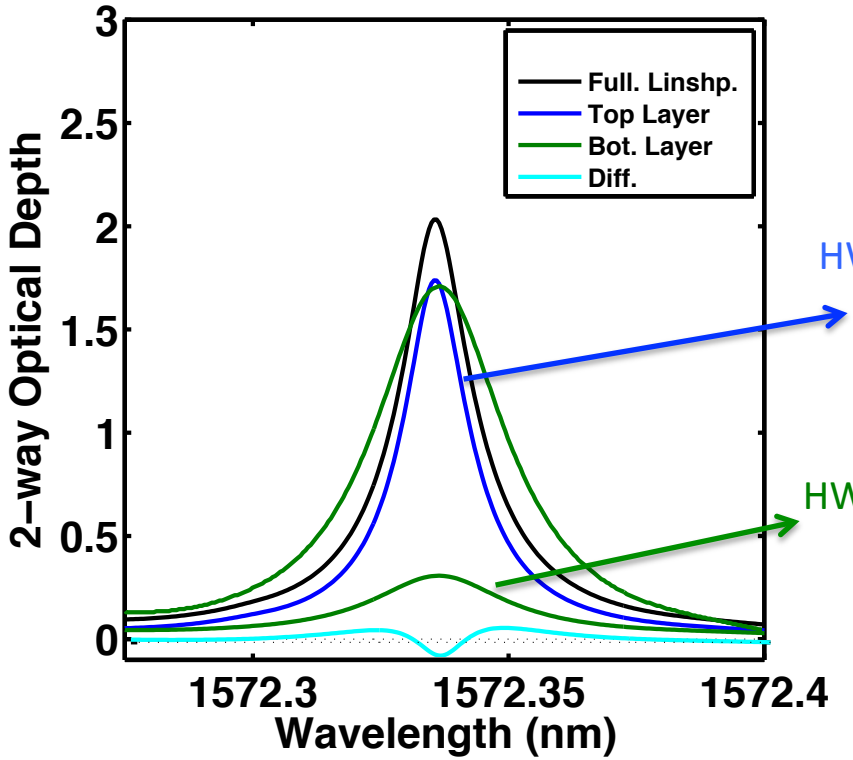



# Features of lidar cloud-slicing retrievals

- Works for many types of thin or broken cloud
  - Need enough backscatter to fit the lineshape
- Uses photons that are otherwise discarded
- No *a priori* information needed (initial - uniform fixed $XCO_2$)
- Shot-noise limited measurement.
  - Noise from cloud & ground reflections
  - Depends on transmittance of cloud layer
- Robust, low-bias measurement
  - Independent of upper air modeling

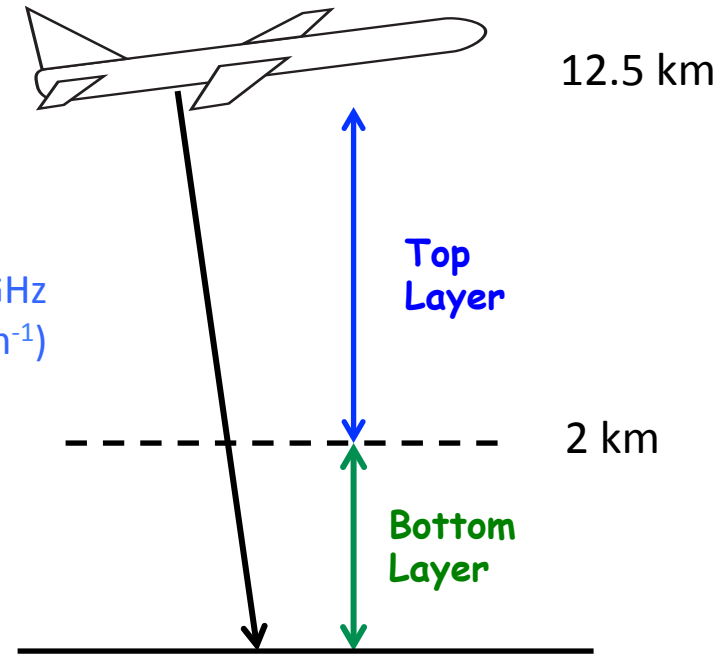
# Multi-layer retrievals

# Analyzing the line shape: 2-Level measurements via *multi-layer* retrievals




HWHM≈1.2 GHz
(0.04 $cm^{-1}$)

HWHM≈2 GHz
(0.06 $cm^{-1}$)

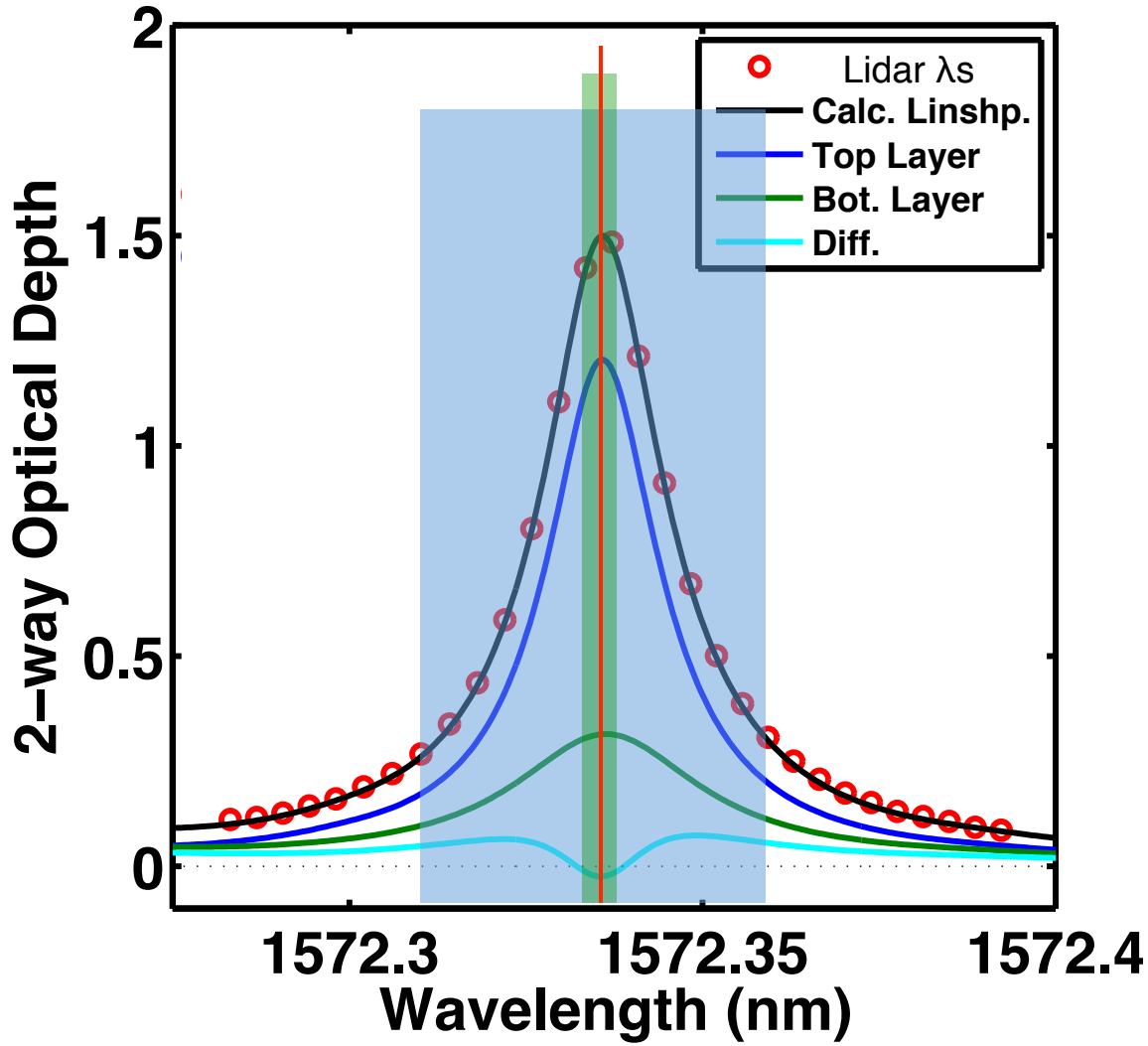



**Exploits varying pressure broadening vs altitude to resolve concentration in two layers**

- Use vertical slicing point (here 2 km) from backscatter profiles
- Solve for top & bottom $CO_2$ concentrations via a 2-parameter fit to absorption line shape
- Parameters are independent and unconstrained

# Lidar's high Spectral Resolution enables line shape analysis

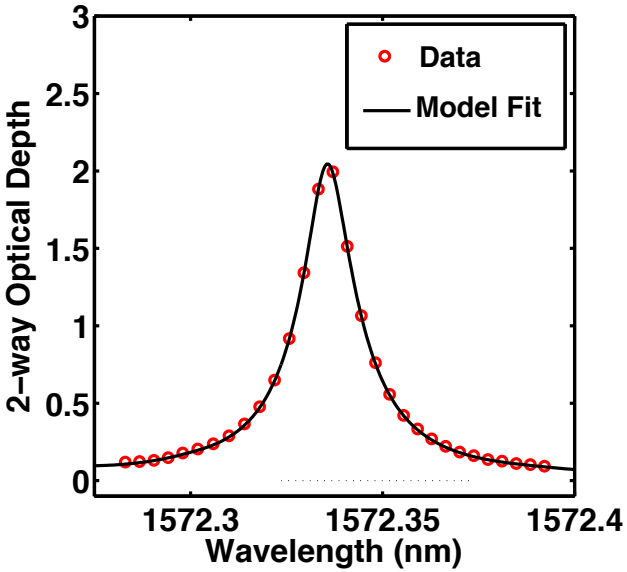
- Layer linewidth
  - Top = 1200 MHz
  - Bot. = 2000 MHz
- Current instrument spectral resolutions:
  - GOSAT: ~ 6000 MHz
  - TCCON: ~ 600 MHz
  - Sounder: ~ 5 MHz
- $CO_2$ sounder has the requisite spectral resolution

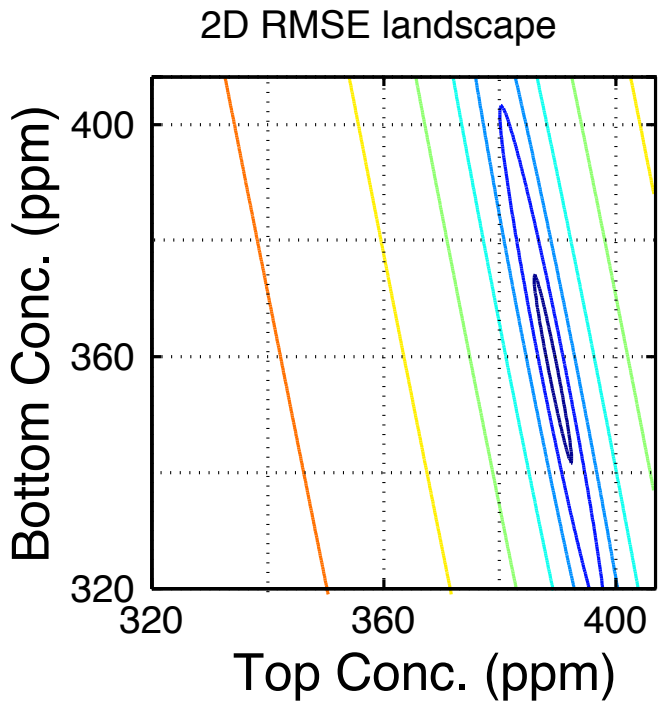


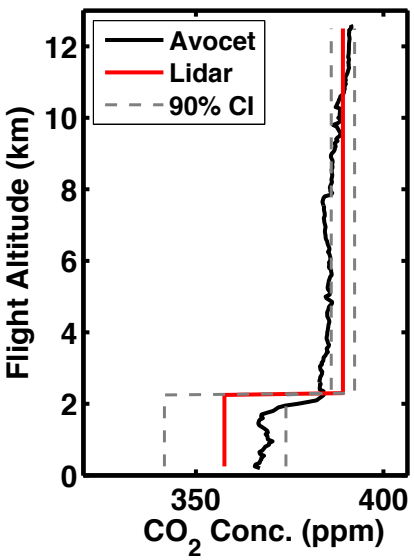
# Example of Multi-layer retrieval line fit

100 s average

Flight at 12.5 km alt.



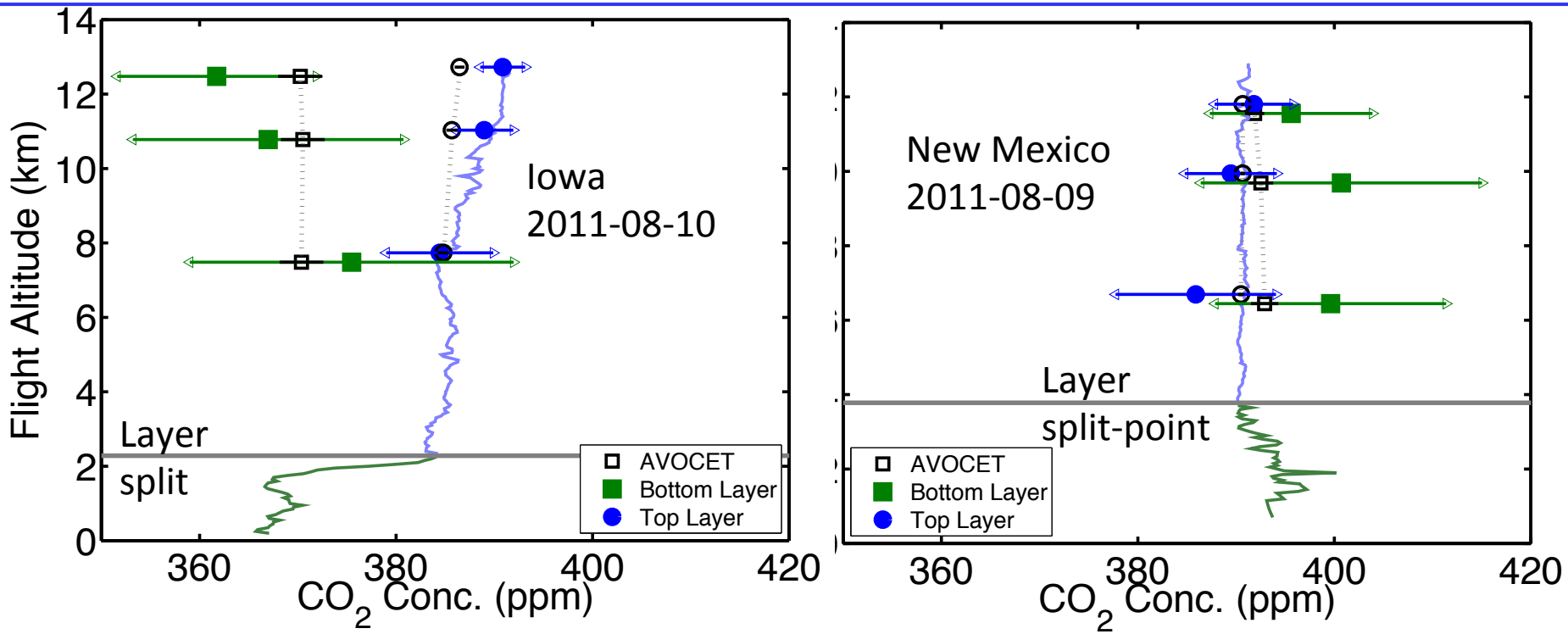




Bottom layer CI= ±15 ppm

- Lidar profile matches in situ data
- Error contour is highly elliptical
  - Aspect ratio ≈ 20:1
  - Due to similarity in top and bottom lineshapes.

# Boundary Layer $CO_2$ using multi-layer retrievals




- Lidar gives a measure of the BL $CO_2$
- Bias <5 ppm for top layer, <9 ppm for BL
- **Measurement quality limited by 0.4 pm (5 MHz, $2x10^{-4}$ $cm^{-1}$) wavelength calibration accuracy**
- Wavelength accuracy will be improved to <1 MHz for 2014 ASCENDS campaign

# Conclusions

- $CO_2$ Sounder approach measures both range and line shape
- Allow solving for vertically-resolved column concentrations
- Using airborne measurements, have demonstrated *two-level measurements* column using both:
  - Lidar cloud slicing
  - Multi-layer retrievals using abs. lineshape
- No *a priori* information or constraints used
- Both approaches require longer averaging times
- Optimization of techniques is ongoing
- Both techniques should work globally work from space as well