Optical Remote Sensing with DIfferential Absorption Lidar (DIAL)

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http://www.etl.noaa.gov/et2

Guest lecture for ASEN-6519 Lidar Remote Sensing
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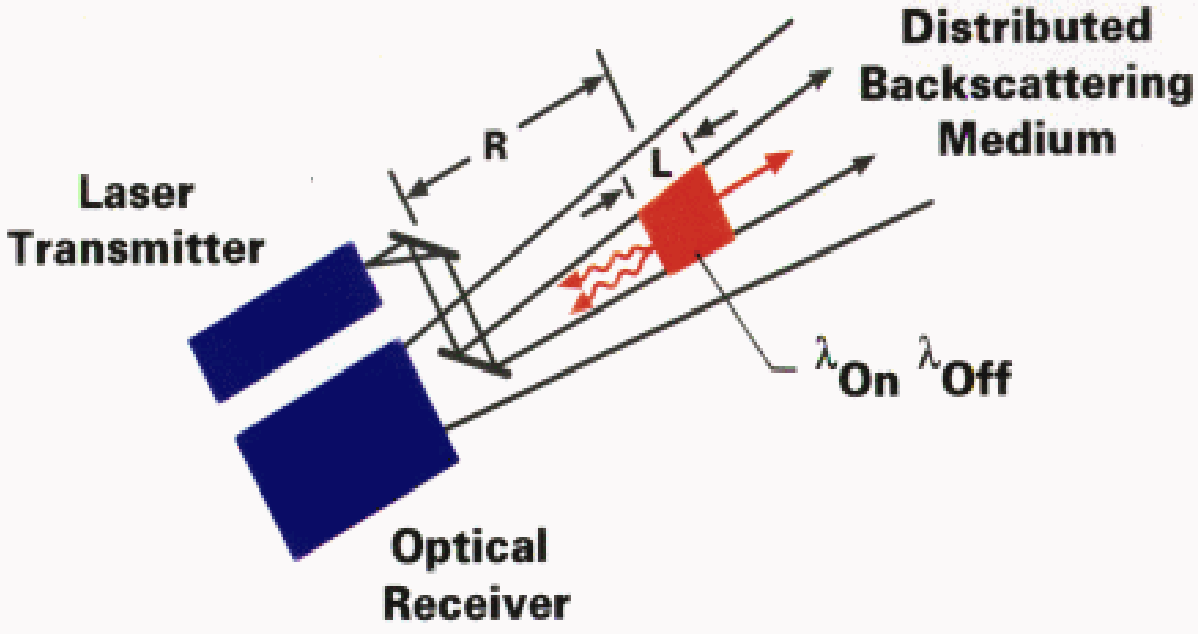
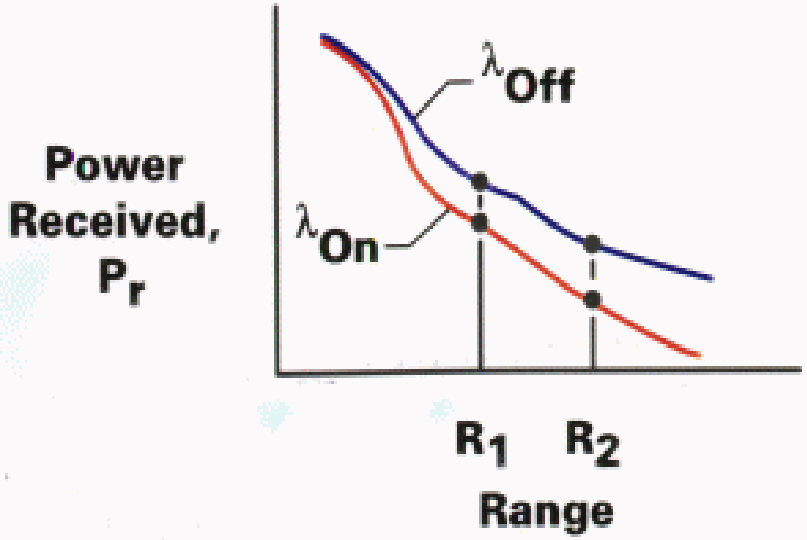
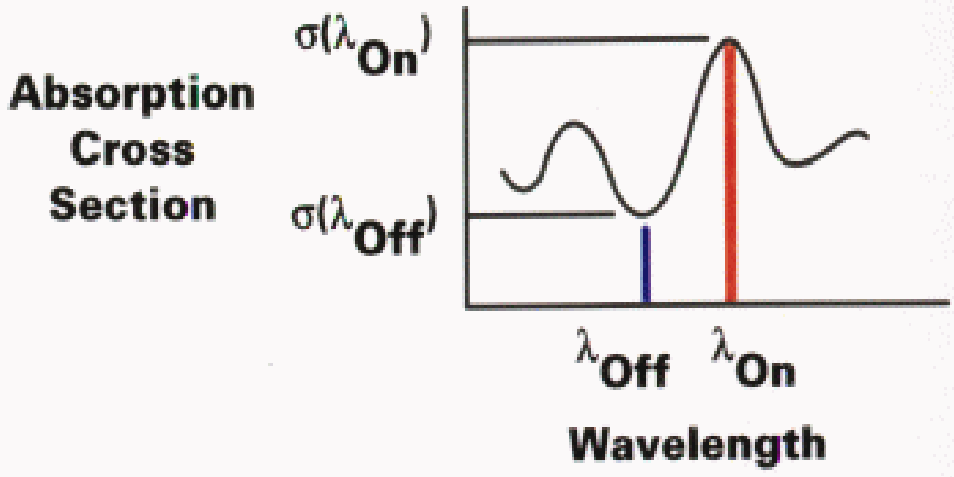
Outline

- DIAL concept
- A short history of DIAL
- DIAL equation, error analysis, and system components
- DIAL systems at NOAA/ESRL/CSD
- Multi-wavelength ozone DIAL
- Applications of airborne ozone DIAL

Differential Absorption Lidar (DIAL) Concept







Atmospheric gases measured with DIAL

- H_2O
- O_3
- SO_2
- NO_2, NO
- NH_3
- CH_4
- CO_2
- Hg
- VOCs (Volatile Organic Compounds)
- Toluene
- Benzene

First DIAL measurements

Richard M. Schotland ("The father of DIAL")

1964 – Measured vertical profiles of water vapor by thermally tuning a ruby laser on and off the water vapor absorption line at 694.38 nm.

Only 4 years after invention of ruby lidar!

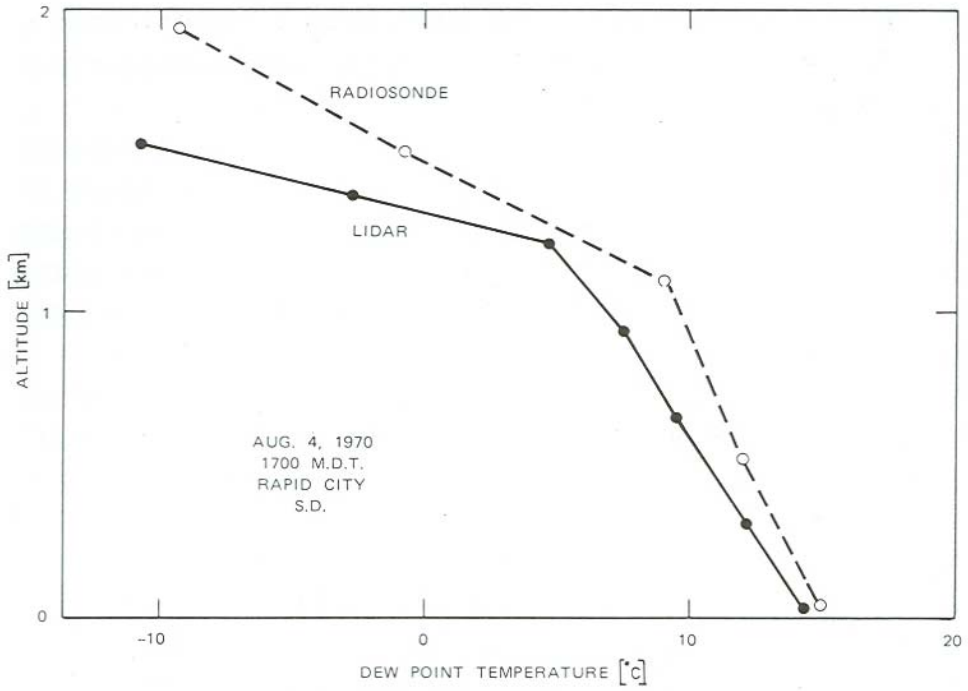
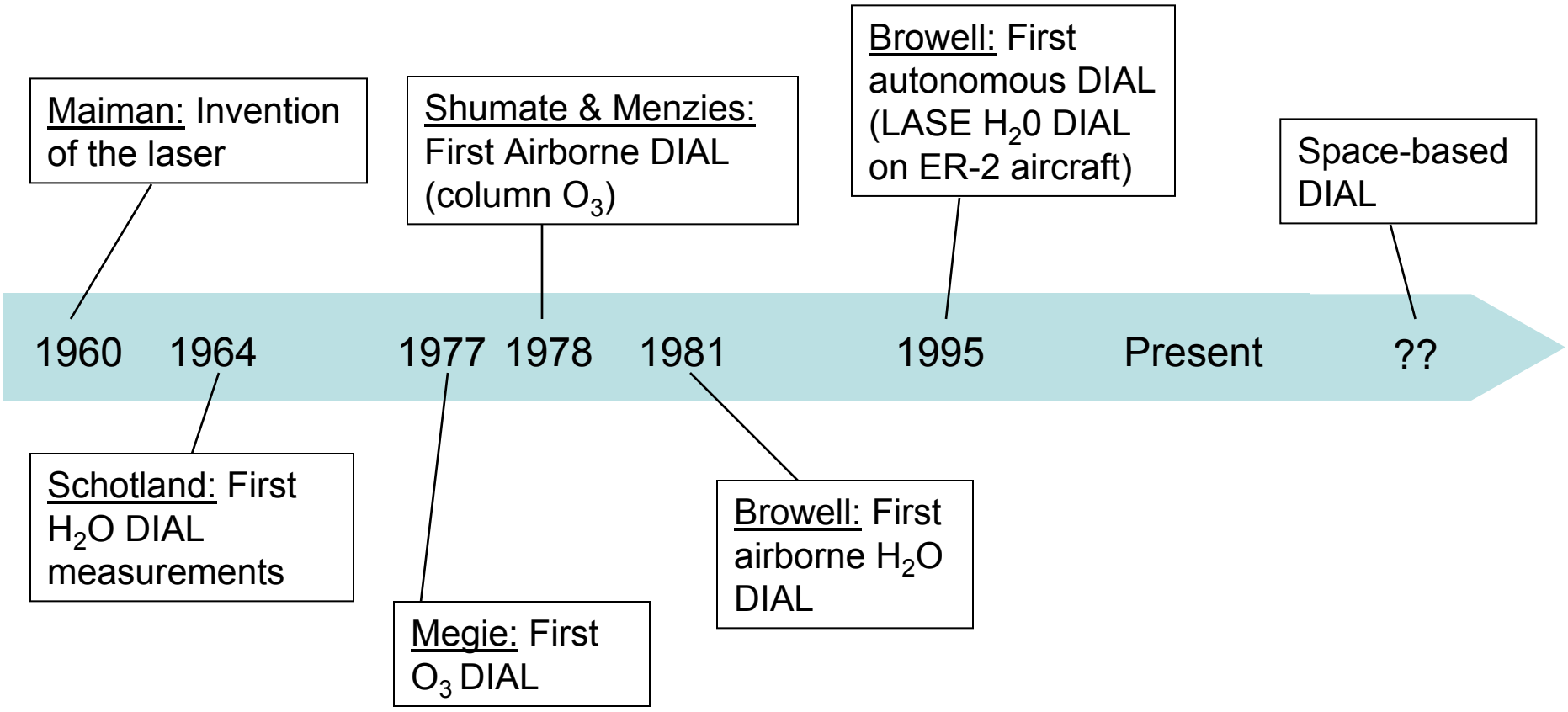


Fig. 4.20. Comparison of atmospheric water vapor vertical profiles (expressed as dew point temperature) measured by differential absorption lidar and radiosonde [4.82]

Major milestones in the history of DIAL



DIAL equation

Single scattering, elastic backscatter LIDAR equation:

$$N_S(\lambda,R) = N_L(\lambda)\left[\beta(\lambda,R)\Delta R\right]\frac{A}{R^2}\exp\left[-2\int_0^R \alpha(\lambda,r)\,dr\right]\left[\eta(\lambda)\,G(\lambda,R)\right]+N_B(\lambda)$$

Ratio LIDAR equations for online and offline wavelengths λ_{on} and λ_{off} :

$$\frac{N_S(\lambda_{off},R)-N_B(\lambda_{off},R)}{N_S(\lambda_{on},R)-N_B(\lambda_{on},R)} = \frac{N_L(\lambda_{off})\,\eta(\lambda_{off})\,G(\lambda_{off},R)\,\beta(\lambda_{off},R)}{N_L(\lambda_{on})\,\eta(\lambda_{on})\,G(\lambda_{on},R)\,\beta(\lambda_{on},R)}$$

$$\times\exp\left[-2\int_0^R \alpha(\lambda_{off},r)-\alpha(\lambda_{on},r)\,dr\right]$$

$$\times\exp\left[-2\int_0^R \left(\sigma_C(\lambda_{off},r)-\sigma_C(\lambda_{on},r)\right)n_C(r)\,dr\right]$$

$$\times\exp\left[-2\int_0^R \sum_{i=1}^{m}\left[\left(\sigma_{X_i}(\lambda_{off},r)-\sigma_{X_i}(\lambda_{on},r)\right)n_{X_i}(r)\right]\,dr\right]$$

Number density of constituent C

DIAL equation (cont'd)

$$n_C = \frac{1}{2\,\Delta\sigma_C(R)}\frac{d}{dR}\ln\left[\frac{N_S(\lambda_{off},R)-N_B(\lambda_{off})}{N_S(\lambda_{on},R)-N_B(\lambda_{on})}\right]$$

$$-\frac{1}{2\,\Delta\sigma_C(R)}\frac{d}{dR}\ln\frac{G(\lambda_{off},R)}{G(\lambda_{on},R)} \qquad [G]$$

$$-\frac{1}{2\,\Delta\sigma_C(R)}\frac{d}{dR}\ln\frac{\beta(\lambda_{off},R)}{\beta(\lambda_{on},R)} \qquad [B]$$

$$-\frac{1}{\Delta\sigma_C(R)}\left[\alpha(\lambda_{on},R)-\alpha(\lambda_{off},R)\right] \qquad [E]$$

$$-\frac{1}{\Delta\sigma_C(R)}\sum_{i=1}^{m}\Delta\sigma_{X_i}(R)\,n_{X_i}(R) \qquad [X]$$

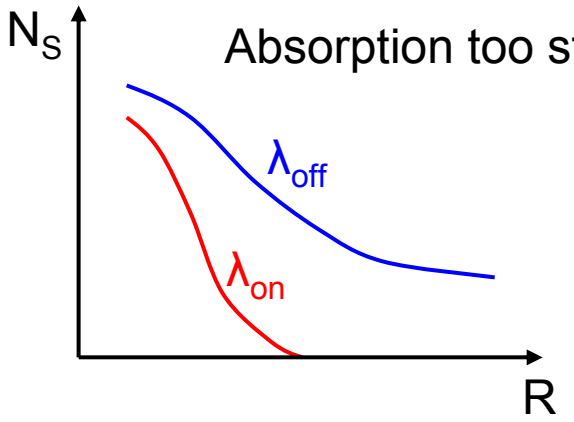
$$with \quad \Delta\sigma_C(R)=\sigma_C(\lambda_{on},R)-\sigma_C(\lambda_{off},R)$$

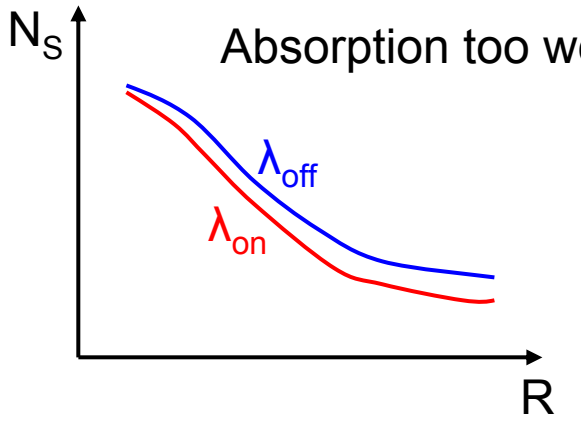
G = differential geometrical factor
B = differential backscatter
E = differential extinction
X = interfering constituents

How to choose an appropriate absorption line for DIAL

$$N_S(\lambda_{on}, R) \propto \exp\left[-2\int_0^R \sigma_C(\lambda_{on}, r)\, n_C(r)\, dr\right]$$

Extinction of online wavelength due to absorption by constituent C must be neither too small or too large.





Best precision in n_C when: $\tau(\lambda_{on}, R_{\max}) = \int_0^{R_{\max}} \sigma_C(\lambda_{on}, r)\, n_C(r)\, dr = 1.1$

Example: $mr_{O_3} = 80\,ppb \quad \Rightarrow \quad n_{O_3} = 2\times10^{18}\,m^{-3},\ R_{\max} = 3\,km$

$$\sigma_{O_3}(\lambda_{on})\, n_{O_3}\, R_{\max} = 1.1 \quad \Rightarrow \quad \sigma_{O_3}(\lambda_{on}) = 1.83\times10^{-22}\,m^2$$

Precision of DIAL measurements

Simple "back of the envelope" calculation:

$$n_C = \frac{1}{2\,\Delta\sigma_C(R)\,\Delta R}\,\ln\left[\frac{N(\lambda_{off}, R+\Delta R)\,N(\lambda_{on}, R)}{N(\lambda_{on}, R+\Delta R)\,N(\lambda_{off}, R)}\right] \quad with\ \ N = N_S - N_B$$

$$\delta n_C = \frac{1}{2\,\Delta\sigma_C(R)\,\Delta R}\sqrt{\sum_{i,j}\frac{\delta^2\left(N(\lambda_i, R_j)\right)}{\left(N(\lambda_i, R_j)\right)^2}} \approx \frac{1}{\Delta\sigma_C\,\Delta R}\,\frac{\delta N}{N} = \frac{1}{\Delta\sigma_C\,\Delta R\;SNR}$$

$$\frac{\delta n_C}{n_C} = \frac{1}{\tau_{\Delta R}\;SNR} \quad \Rightarrow \quad \boxed{SNR = \frac{1}{\tau_{\Delta R}\,\delta n_C / n_C}}$$

$$Example: \quad \tau_{\Delta R} = 0.05,\ \delta n_C / n_C = 5\% \quad \Rightarrow \quad \boxed{SNR = 400\,!}$$

Even modest precision of 5% requires high SNR. SNR can be increased by averaging on/offline signals time- and range-wise.

$$Poisson\ statistics: \quad \delta N = N^{0.5} \ \Rightarrow\ SNR = N^{0.5}$$

$$Since\ N \propto \Delta t\,\Delta R, \quad \boxed{SNR \propto \Delta t^{0.5}\Delta R^{0.5} \quad and \quad \delta n_C \propto \Delta t^{-0.5}\Delta R^{-1.5}}$$

Accuracy of DIAL measurements

$$n_C = \frac{1}{2\Delta\sigma_C(R)}\frac{d}{dR}\ln\left[\frac{N_S(\lambda_{off},R)-N_B(\lambda_{off})}{N_S(\lambda_{on},R)-N_B(\lambda_{on})}\right]$$

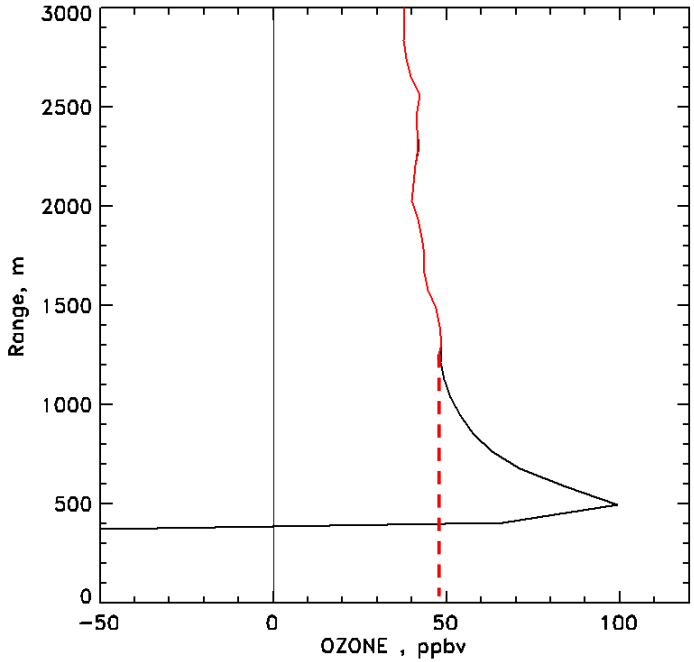
$$-\frac{1}{2\Delta\sigma_C(R)}\frac{d}{dR}\ln\frac{G(\lambda_{off},R)}{G(\lambda_{on},R)} \qquad [G]$$

$$-\frac{1}{2\Delta\sigma_C(R)}\frac{d}{dR}\ln\frac{\beta(\lambda_{off},R)}{\beta(\lambda_{on},R)} \qquad [B]$$

$$-\frac{1}{\Delta\sigma_C(R)}\left[\alpha(\lambda_{on},R)-\alpha(\lambda_{off},R)\right] \qquad [E]$$

$$-\frac{1}{\Delta\sigma_C(R)}\sum_{i=1}^{m}\Delta\sigma_{X_i}(R)\,n_{X_i}(R) \qquad [X]$$

Effect of differential geometrical factor on O_3 retrieval

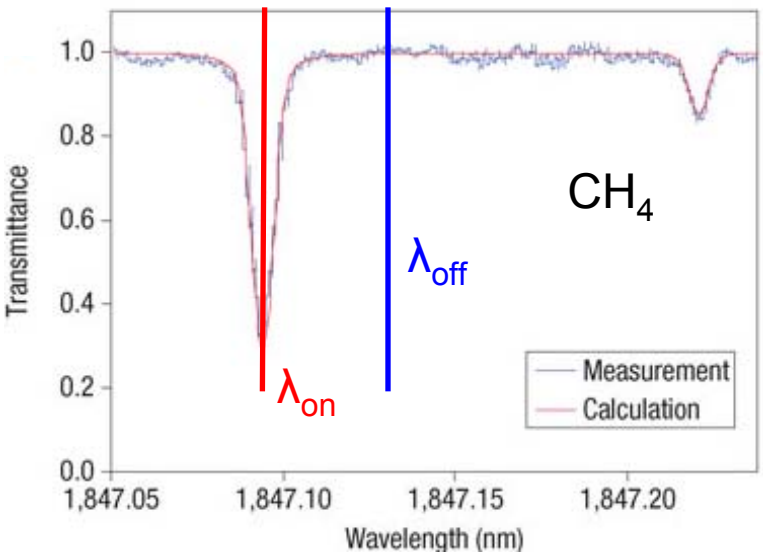


Accuracy affected by:

- How well is absorption cross section known?
- Improper correction of signal offsets, e.g. background light
- Geometrical factor different for λ_{on} and λ_{off}
- Differential backscatter & extinction not properly corrected
- Interfering species not taken into account

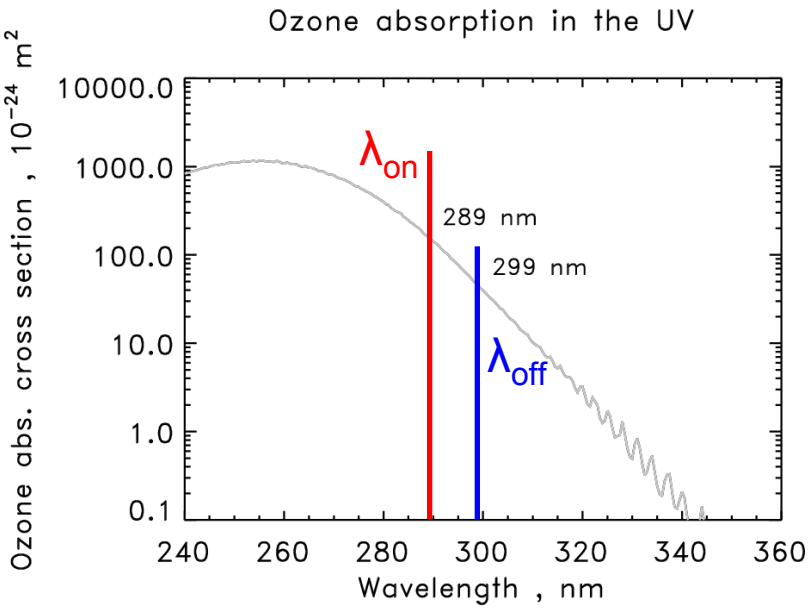
Narrow and broad absorption lines

Narrow absorption line



- $\Delta\lambda \approx 50$ pm
- No correction for differential backscatter or extinction needed
- Transmit laser needs to be tunable
- High frequency stability & spectral purity

Broad absorption feature



- $\Delta\lambda$ =10 nm
- Correction for differential backscatter or extinction necessary
- Fixed wavelength lasers OK
- High frequency stability & spectral purity not needed

DIAL system components

LIDAR transmitter

- High power (high pulse energy or lower pulse energy & high rep rate)
- Tunable laser or appropriate fixed frequencies

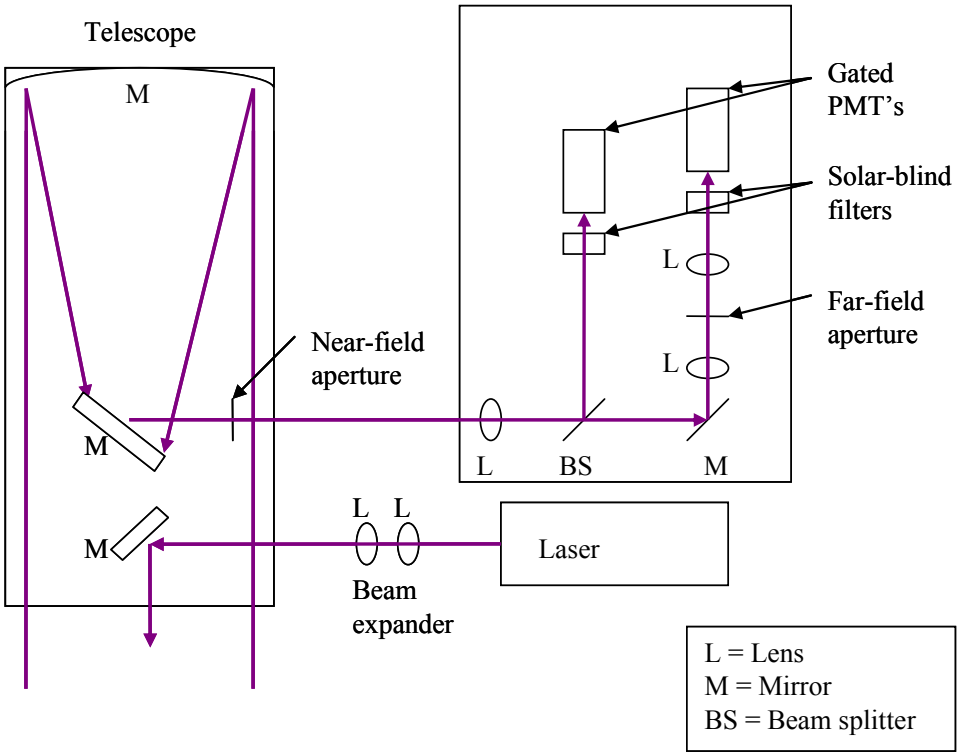
Species	Laser transmitter	Wavelengths
O_3	4x Nd:YAG / Excimer + Raman shift OPO, CeLiCAF, 3x Ti:Sapphire	Fixed: 266 – 359 nm Tunable: 280 – 320 nm
H_2O	Ti:Sapphire, Alexandrite, OPO, Fiber laser	720 – 940 nm, 1.5 μm
CH_4	OPO	1.67 μm, 3.3 μm
CO_2	Fiber laser, OPO, Tm:Ho:YLF	1.57 μm, 2.05 μm
VOCS	Dye lasers	Mid-IR @ several μm
NH_3	Dye laser, CO_2 laser	208 nm, 9 – 10 μm

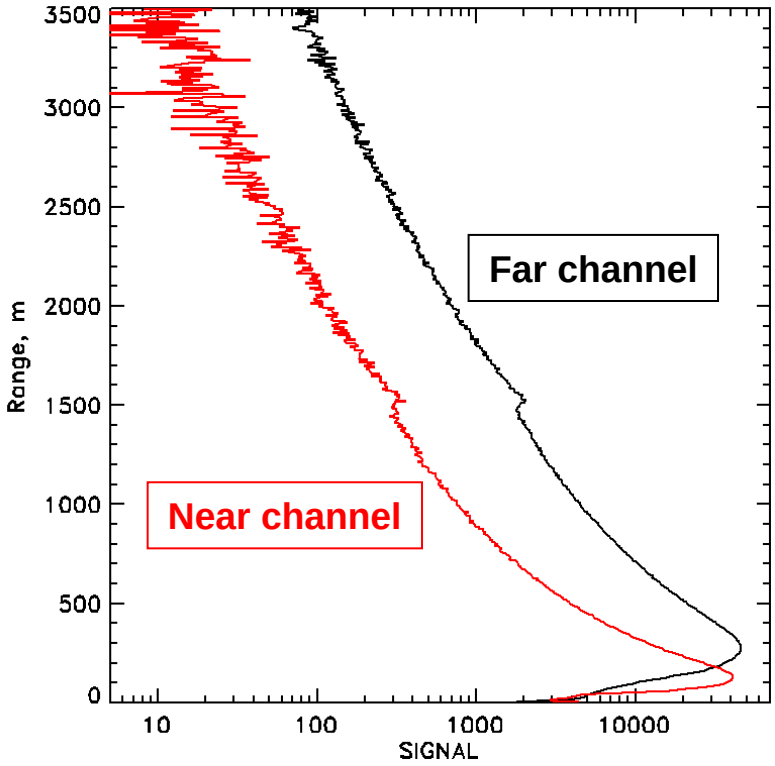
OPO = Optical Parametric Oscillator

DIAL system components (cont'd)

LIDAR receiver

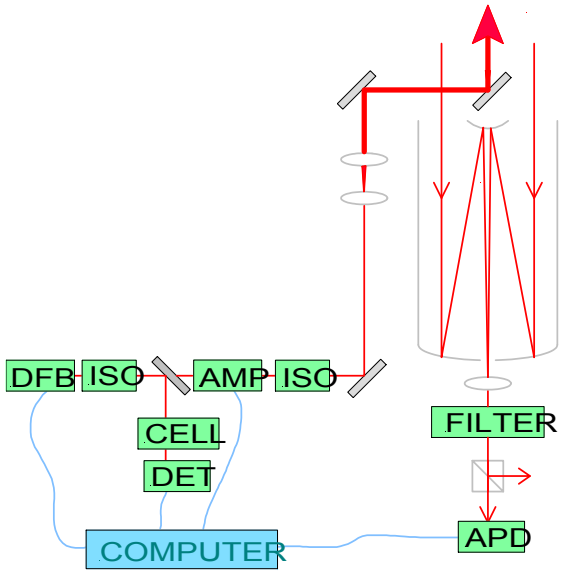
- large telescope
- combination of near and far channels to compress large dynamic range



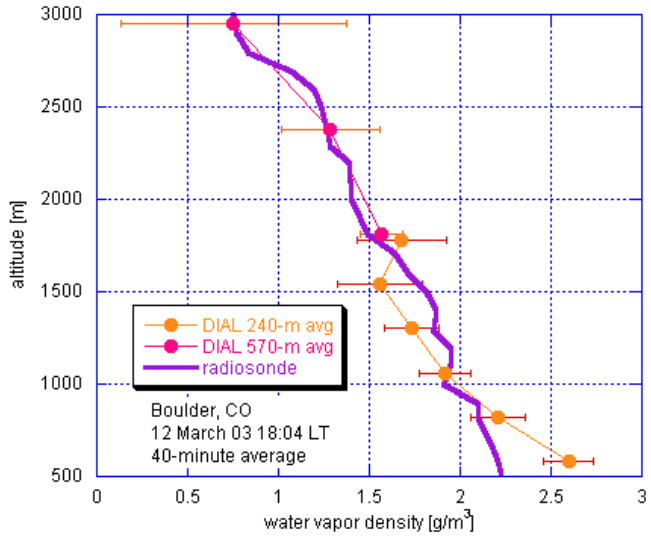


DIALs at NOAA/ESRL/CSD – Ground-based

CODI = COmpact DIAL (prototype of small, autonomous DIAL system)



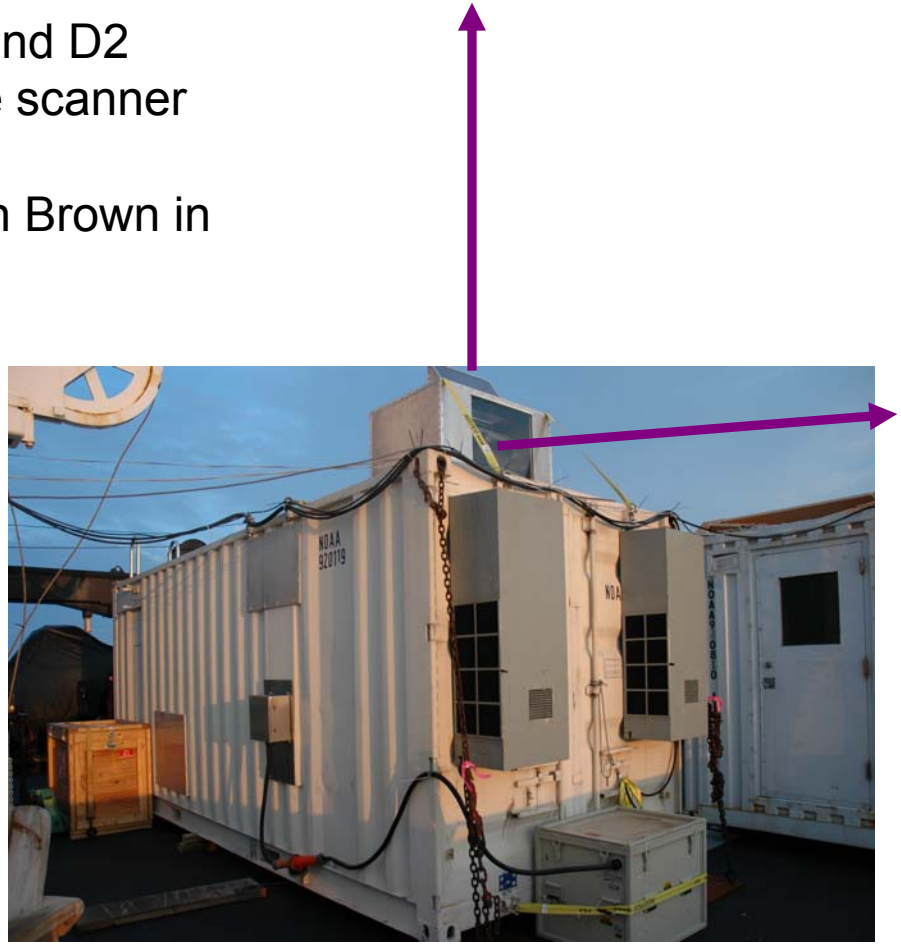
wavelength	823 nm
output pulse energy	~0.15 μJ
pulse duration	600 ns
pulse repetition freq.	8 – 10 kHz
telescope diameter	34 cm
field-of-view	180 μRad



DIALs at NOAA/ESRL/CSD - Shipborne

OPAL = Ozone Profiling Atmospheric Lidar (recently retired)

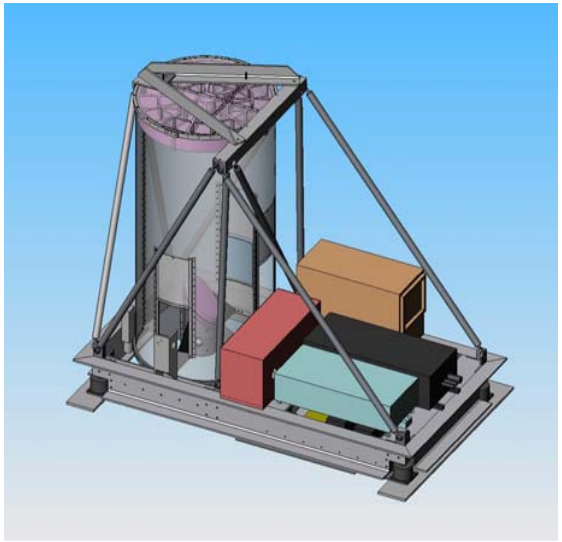
- Wavelengths: 266, 289, 299 nm
- 4x Nd:YAG + Raman-shifting in H2 and D2
- Motion-compensated elevation angle scanner from 0 – 90 deg
- Ship deployments on NOAA R/V Ron Brown in 2002 - 2006



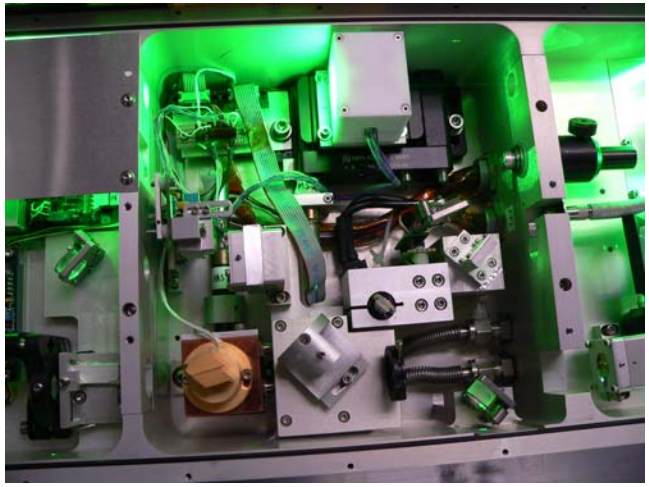
DIALs at NOAA/ESRL/CSD - Airborne

TOPAZ = Tunable Optical Profiler of Aerosol and oZone

- Tunable, all-solid state, compact airborne O_3 DIAL
- Replaced previous fixed-wavelength O_3 lidar in 2006
- Size & weight were reduced significantly



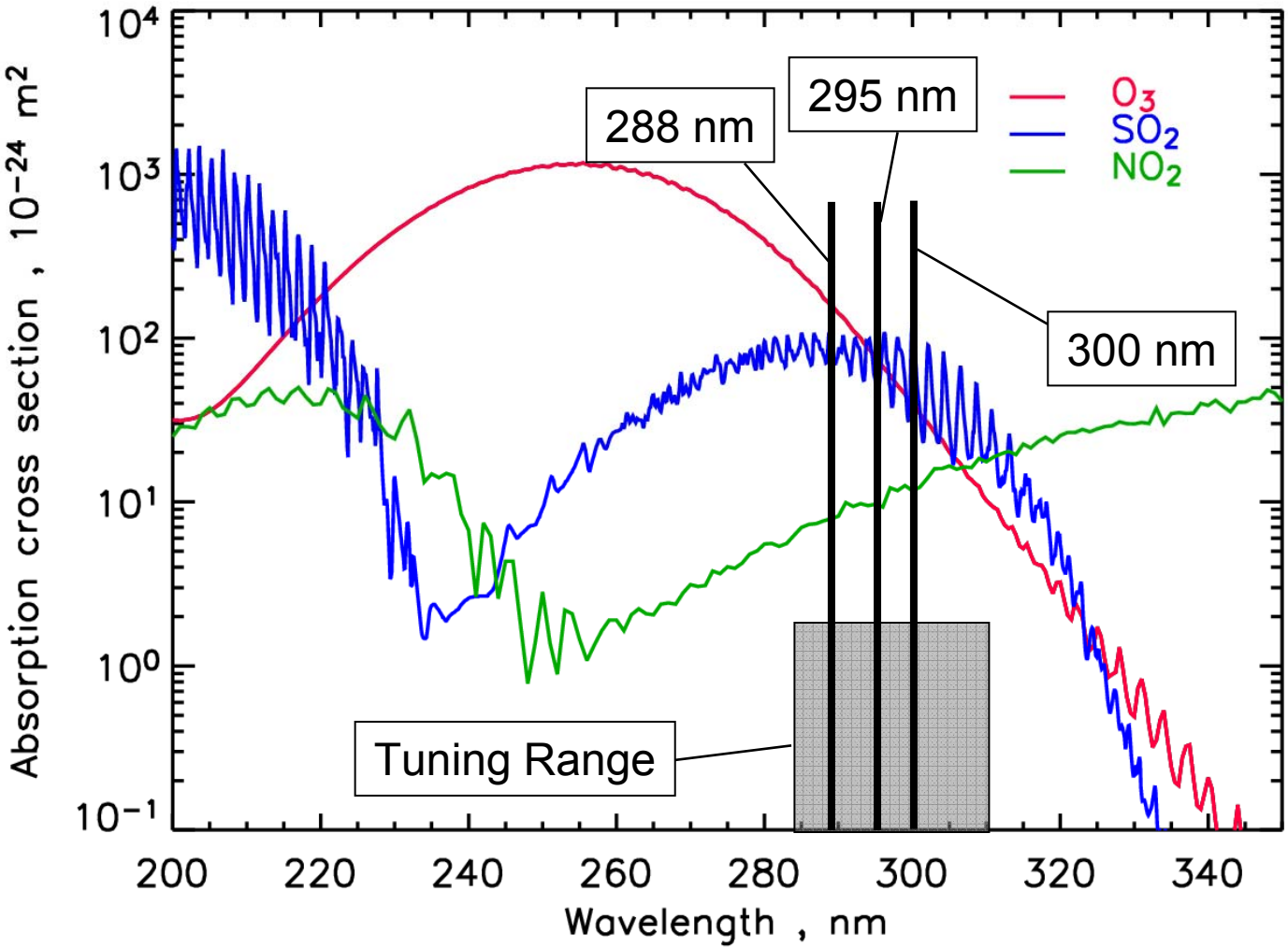
TOPAZ Specifications	
Wavelengths	3
Wavelength tuning range	285-310 nm
Pulse energy	0.2-0.8 mJ/pulse
Pulse rate	1 kHz with pulse-to-pulse tuning capability
Minimum/maximum range	0.3 km / 4 km
Eye-safe range	~150 m
System weight	~800 lbs (including chiller and control electronics)
Output	Ozone and aerosol backscatter profiles
Vertical/horizontal resolution	90 m / 600 m
Precision	3 - 15 ppb




TOPAZ


NOAA
AND ATMOSPHERIC ADMINISTRATION
DEPARTMENT OF COMMERCE

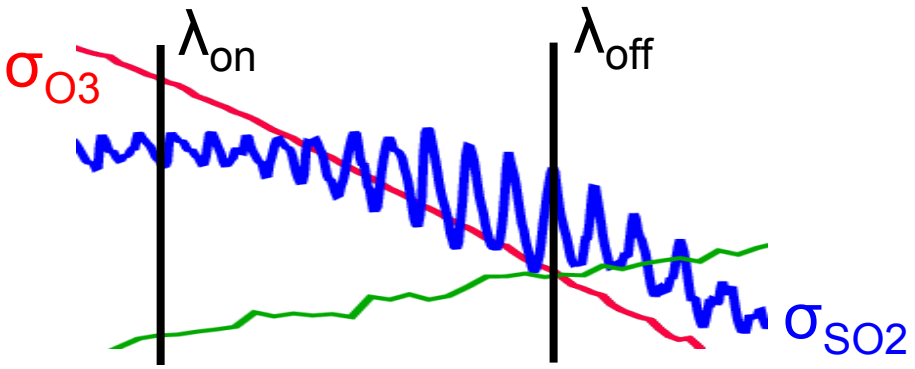
TOPAZ wavelengths & tuning range



TOPAZ is a tunable, multi-wavelength DIAL system

Advantages of tunability:

- Wavelengths can be optimized for given atmospheric ozone loading
- Minimize interference from other trace gases, e.g. SO_2



$$\Delta\sigma_{SO2} \approx 0$$

Advantages of multi-wavelength capability:

- Allows simultaneous measurement of 2 species (O_3 & SO_2)
- Dual-DIAL application to minimize uncertainties due to aerosol backscatter and extinction corrections

Dual-DIAL = 2 DIAL wavelength pairs, i.e. 288/295 nm & 295/300 nm

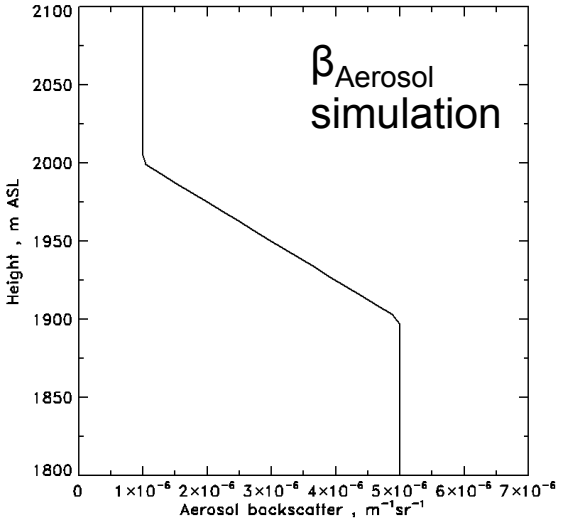
Back to single-DIAL ozone retrieval for a moment

$$n_C = \frac{1}{2\Delta\sigma_C(R)}\frac{d}{dR}\ln\left[\frac{N_S^*(\lambda_{off},R)}{N_S^*(\lambda_{on},R)}\right]$$

$$-\frac{1}{2\Delta\sigma_C(R)}\frac{d}{dR}\ln\frac{\beta(\lambda_{off},R)}{\beta(\lambda_{on},R)} \qquad [B]$$

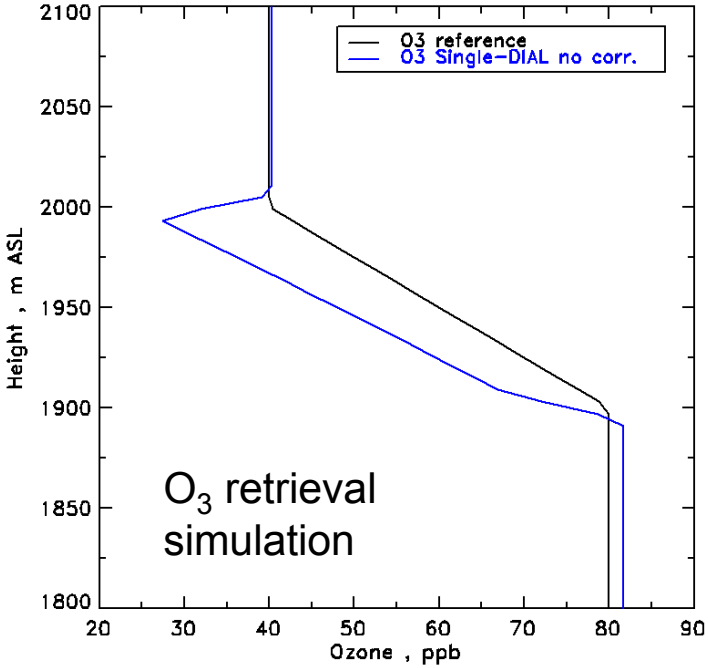
$$-\frac{1}{\Delta\sigma_C(R)}\left[\alpha(\lambda_{on},R)-\alpha(\lambda_{off},R)\right] \qquad [E]$$

$$\beta = \beta_{Rayleigh} + \beta_{Aerosol}\ , \quad \alpha = \alpha_{Rayleigh} + \alpha_{Aerosol}$$



$\beta_{Aerosol}$ and $\alpha_{Aerosol}$ have to be determined from offline signal data and wavelength dependence of β and α have to be guessed.

Lots of potential to introduce errors in O_3 retrieval!



Dual-DIAL minimizes aerosol interference

$$n_C = \frac{1}{2\,\delta\sigma_C(R)}\frac{d}{dR}\left[\ln\frac{N_S^*(\lambda_{off\,1},R)}{N_S^*(\lambda_{on1},R)} - C\ln\frac{N_S^*(\lambda_{off\,2},R)}{N_S^*(\lambda_{on2},R)}\right]$$

$$-\frac{1}{2\,\delta\sigma_C(R)}\frac{d}{dR}\left[\ln\frac{\beta(\lambda_{off\,1},R)}{\beta(\lambda_{on1},R)} - C\ln\frac{\beta(\lambda_{off\,2},R)}{\beta(\lambda_{on2},R)}\right] \qquad [B']$$

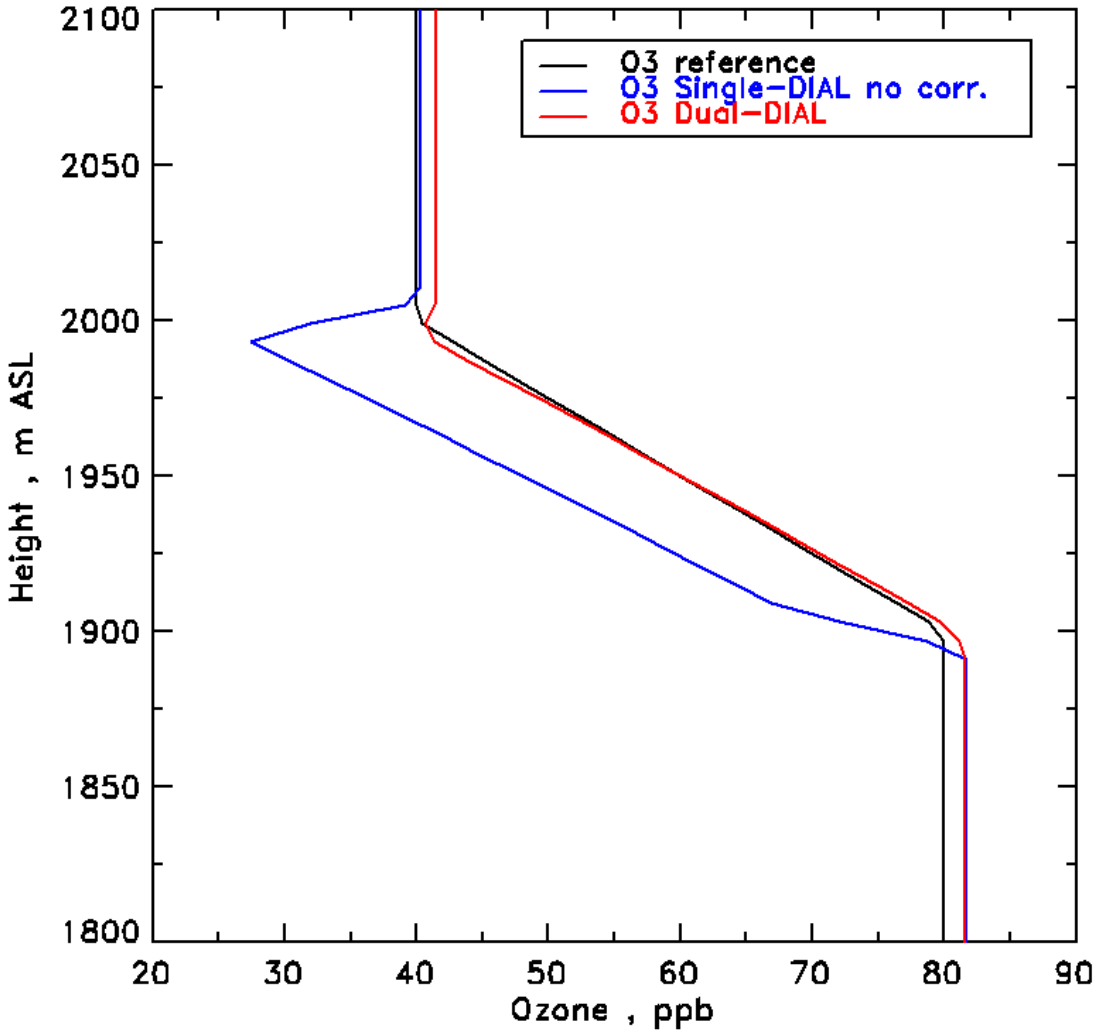
$$-\frac{1}{\delta\sigma_C(R)}\left[\alpha(\lambda_{on1},R)-\alpha(\lambda_{off\,1},R)-C\left(\alpha(\lambda_{on2},R)-\alpha(\lambda_{off\,2},R)\right)\right] \qquad [E']$$

$$with \quad \delta\sigma_C(R) = \Delta\sigma_{C1} - C\,\Delta\sigma_{C2}\,, \quad DIAL\ pair\,1 : \lambda_{on1}/\lambda_{off\,1}\,, \quad DIAL\ pair\,2 : \lambda_{on2}/\lambda_{off\,2}$$

$$B' = E' \approx 0 \quad for \quad C = \frac{\lambda_{on1}-\lambda_{off\,1}}{\lambda_{on2}-\lambda_{off\,2}}$$

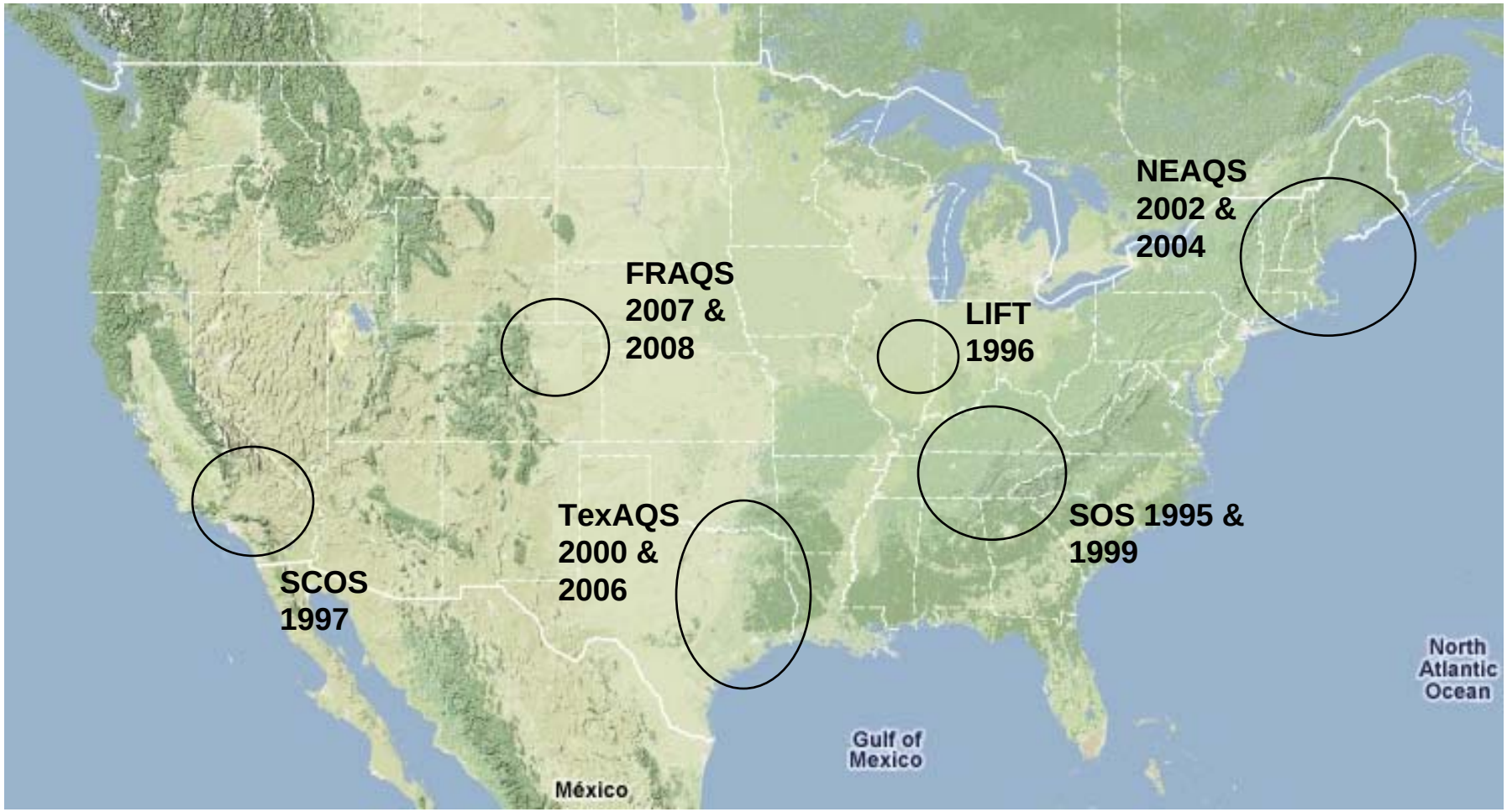
- No correction of differential aerosol effects needed and residual errors are small.
- However, precision of DIAL retrieval is degraded.

Dual-DIAL minimizes aerosol interference (cont'd)

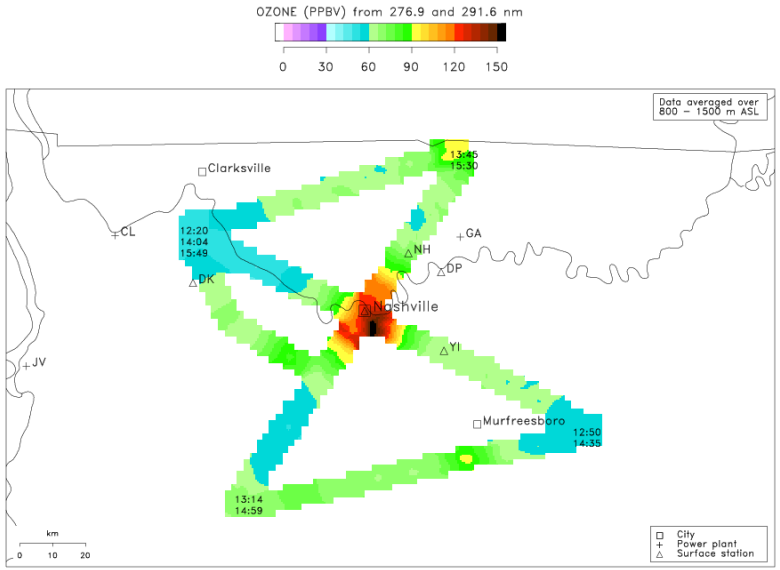


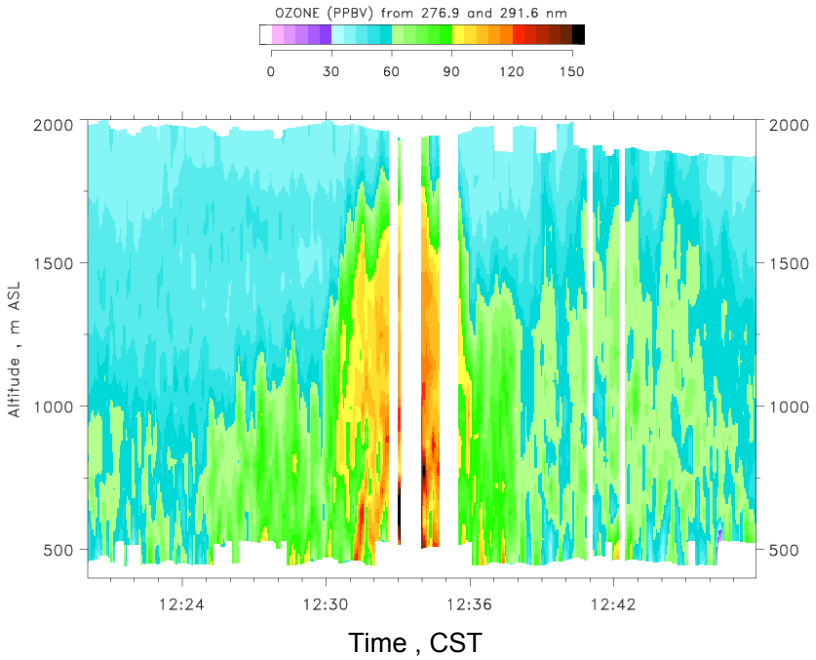
O_3 retrieval simulation

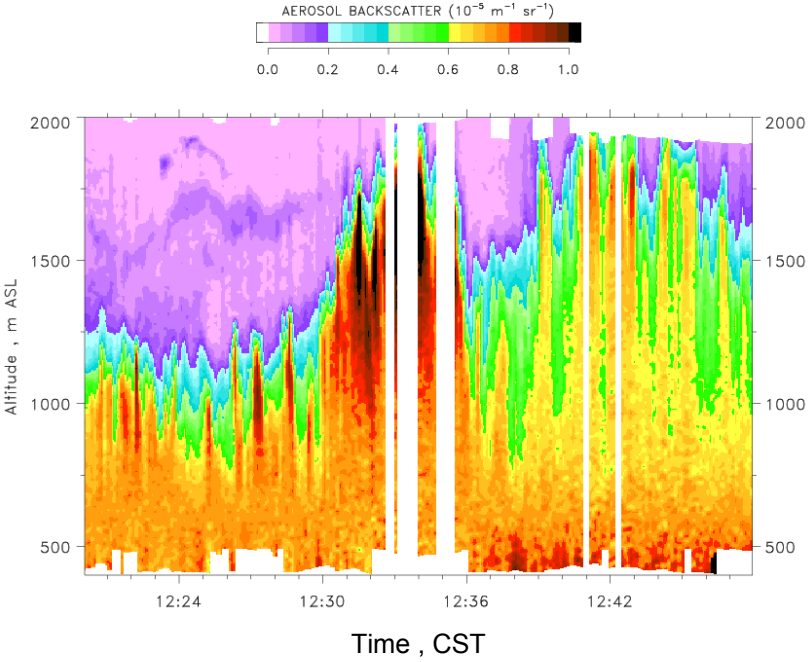
Ozone DIAL Application: Regional Air Quality



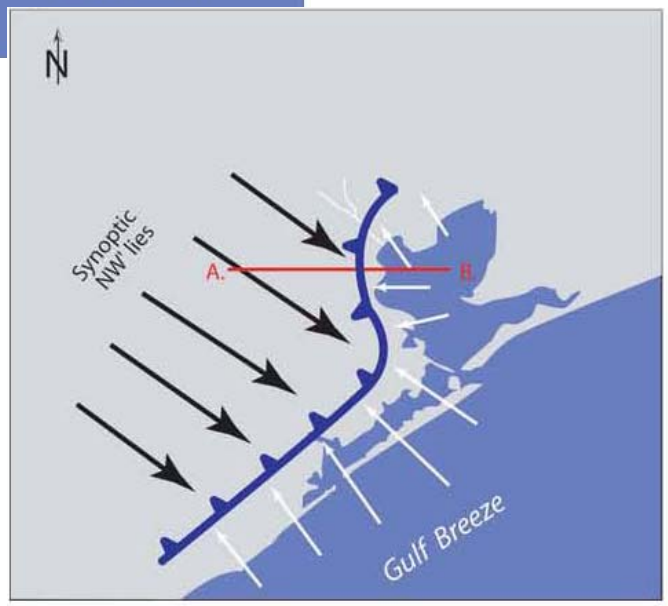
Nashville urban plume

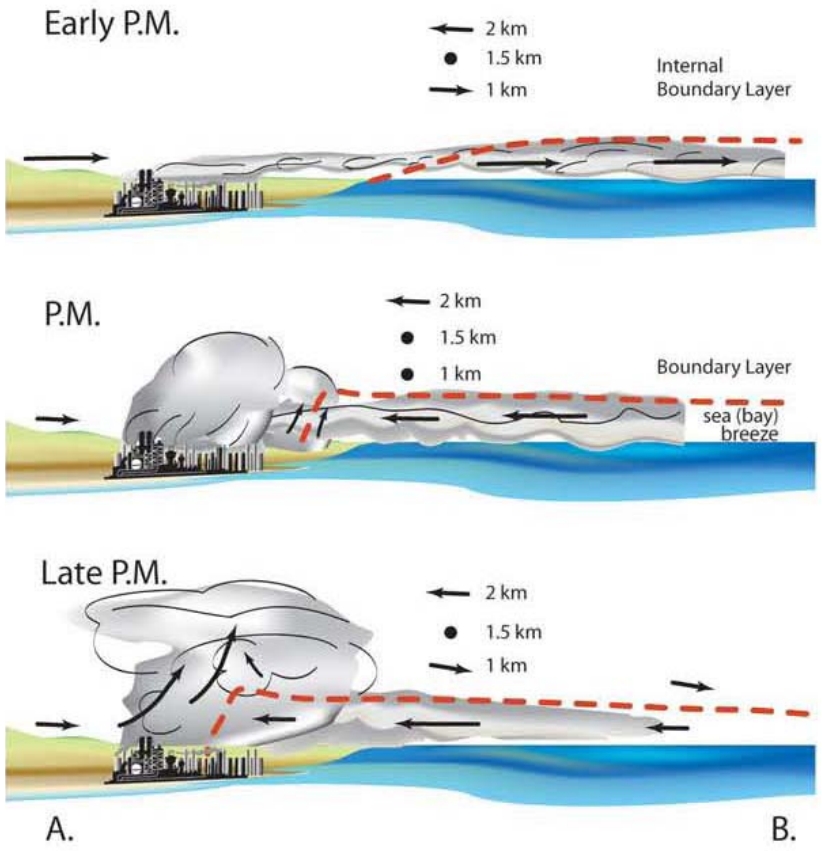




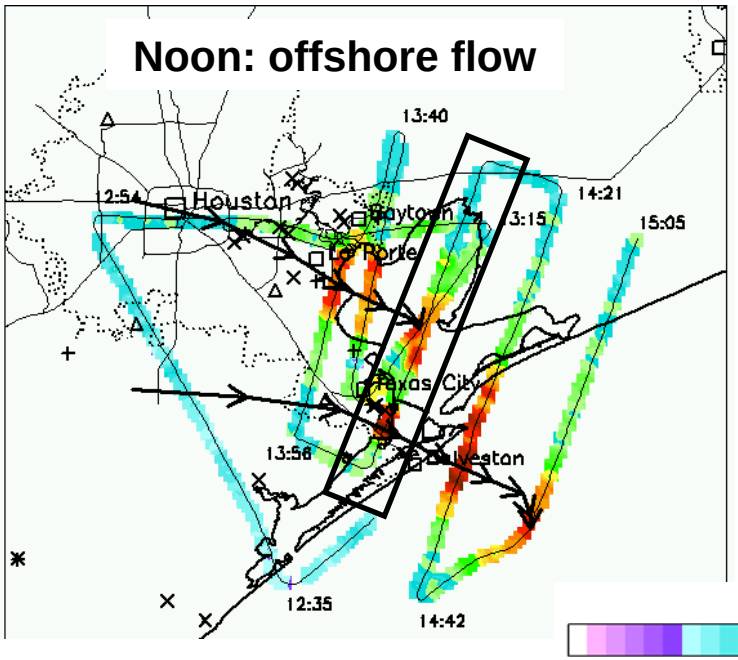


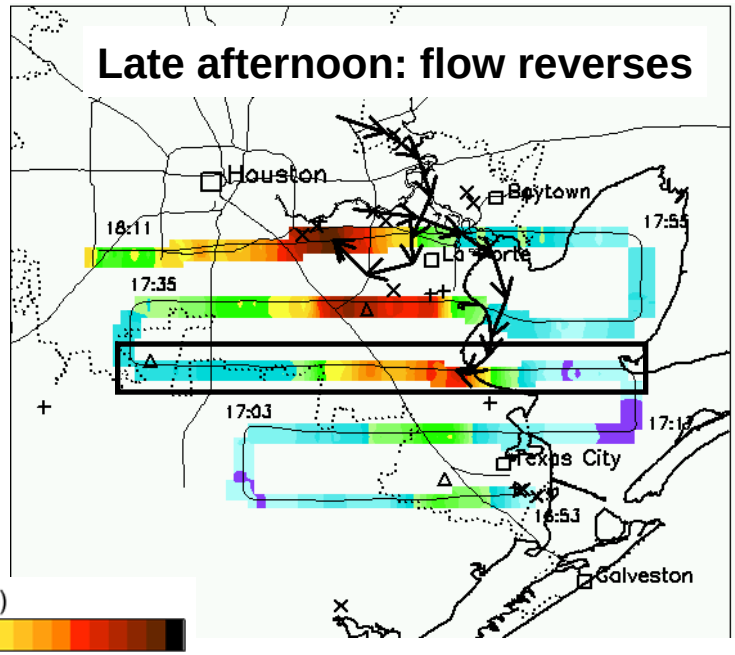
Houston, TX: High ozone event due to sea-breeze re-circulation of pollutants

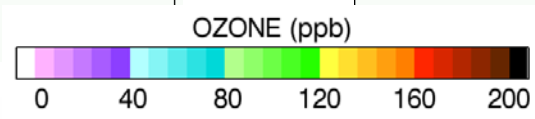


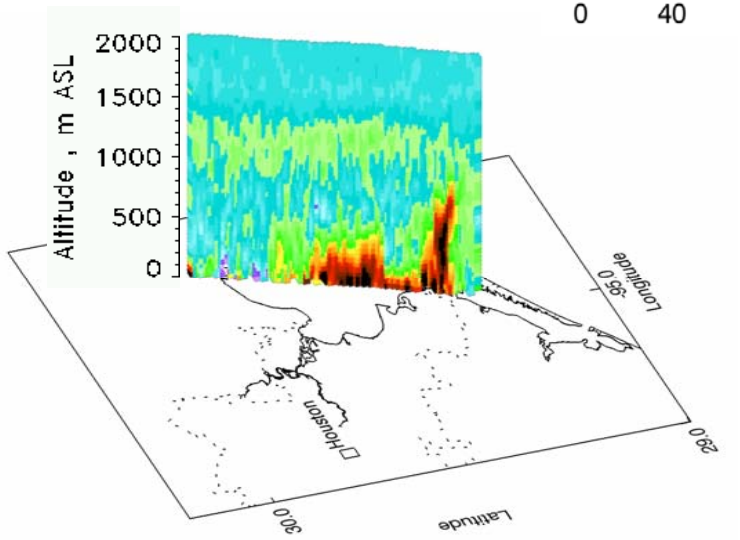


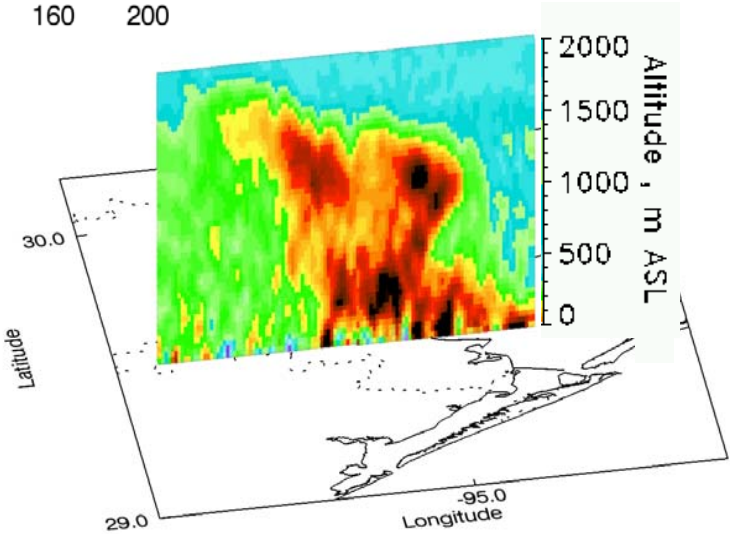
Local Transport:
Houston land-sea breeze recirculation



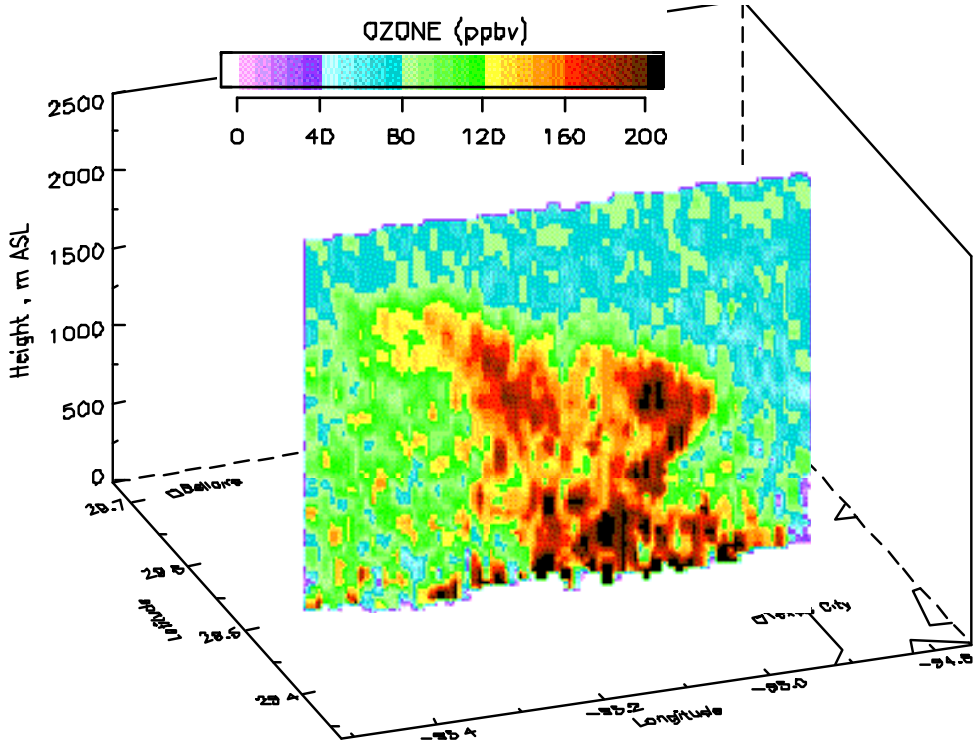


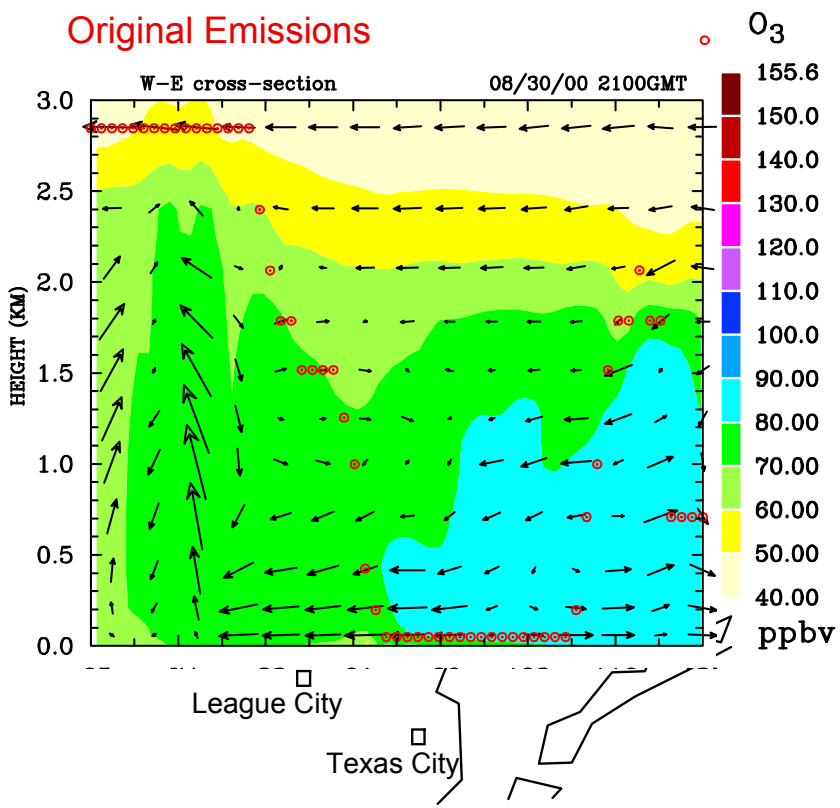




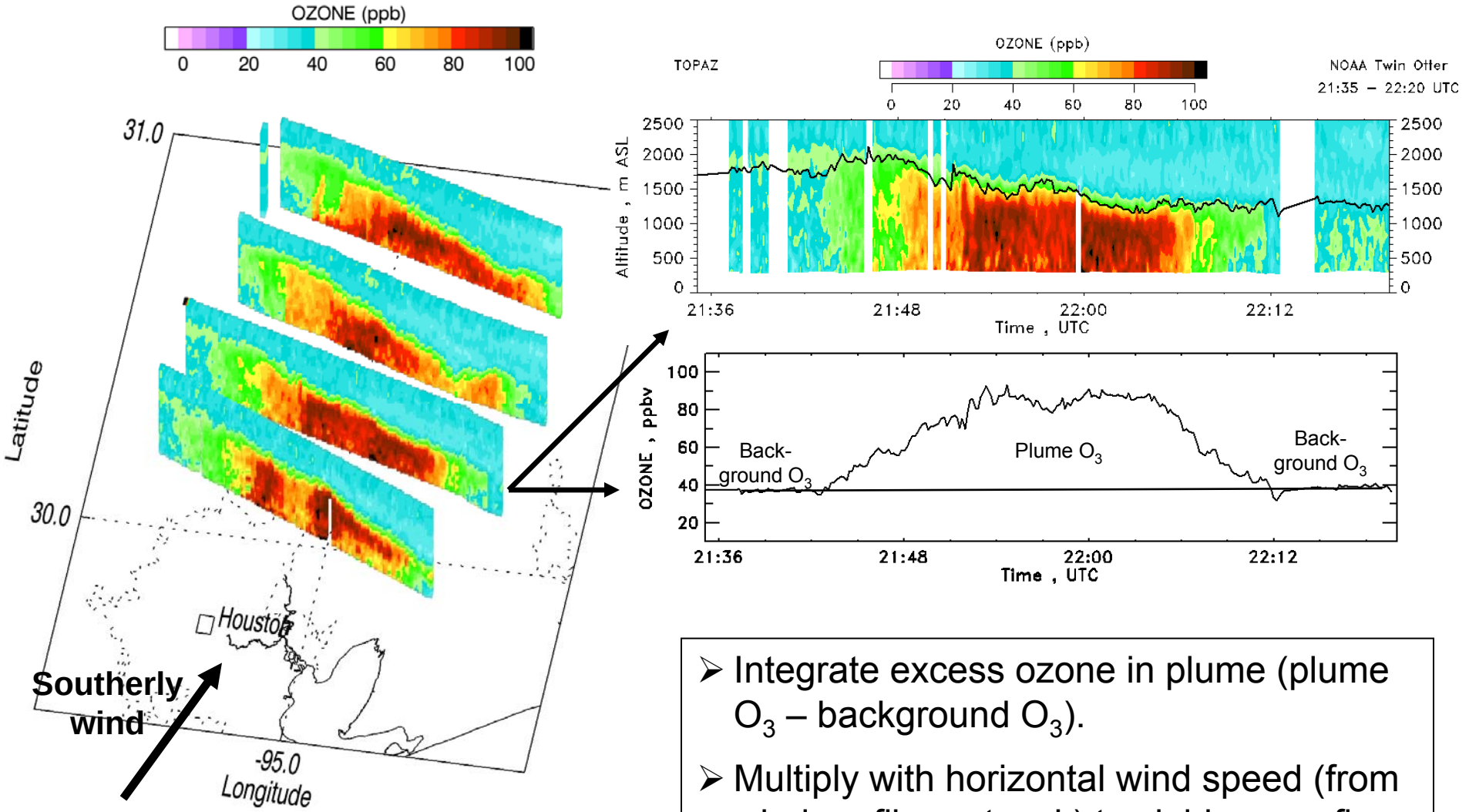


AQ forecast model comparison with lidar



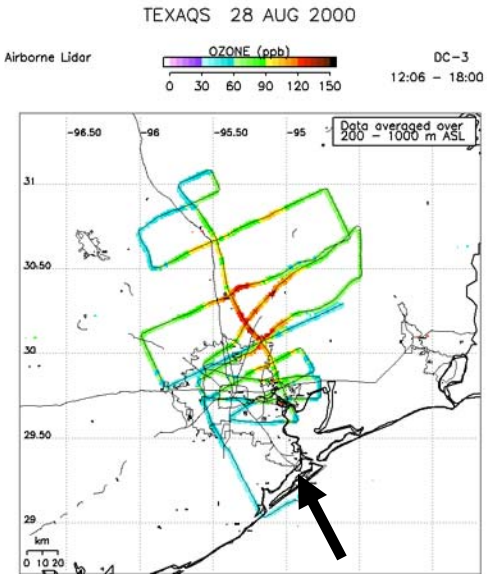


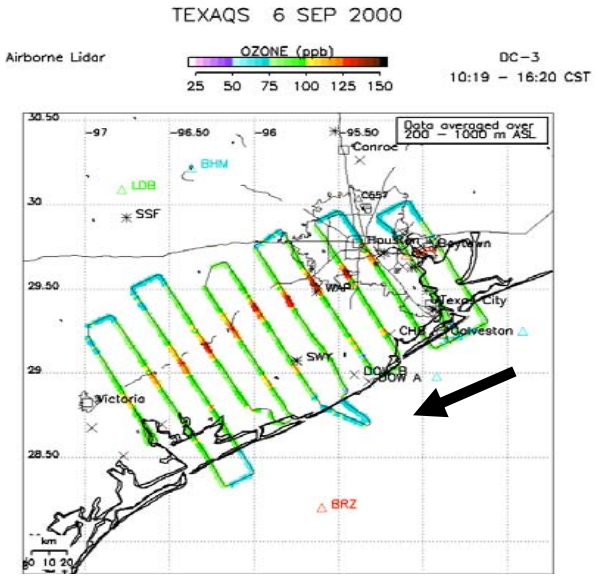
Regional Transport:
Estimating ozone exported from Houston

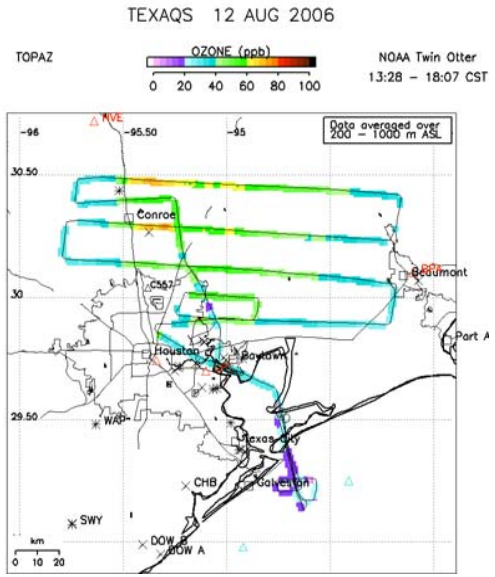


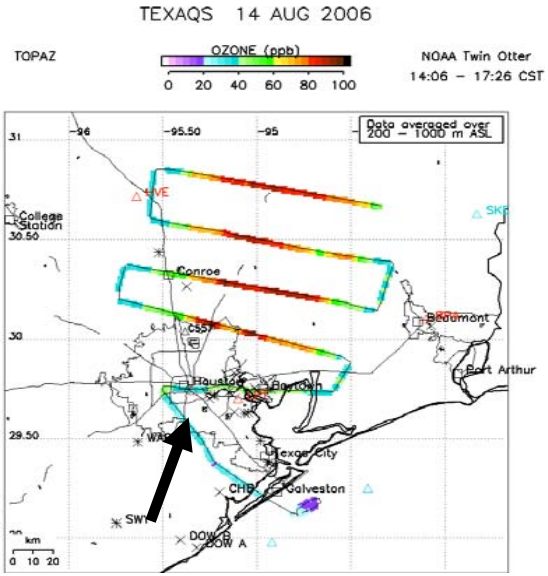
- Integrate excess ozone in plume (plume O_3 – background O_3).
- Multiply with horizontal wind speed (from wind profiler network) to yield ozone flux for each transect.

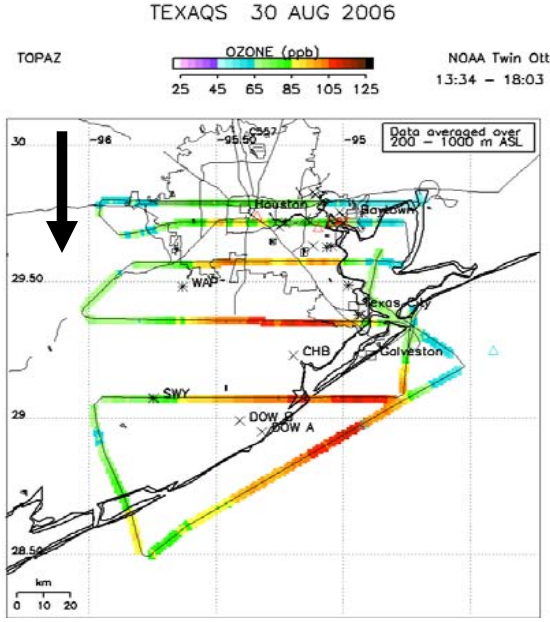
Six Houston/Dallas ozone export cases studied

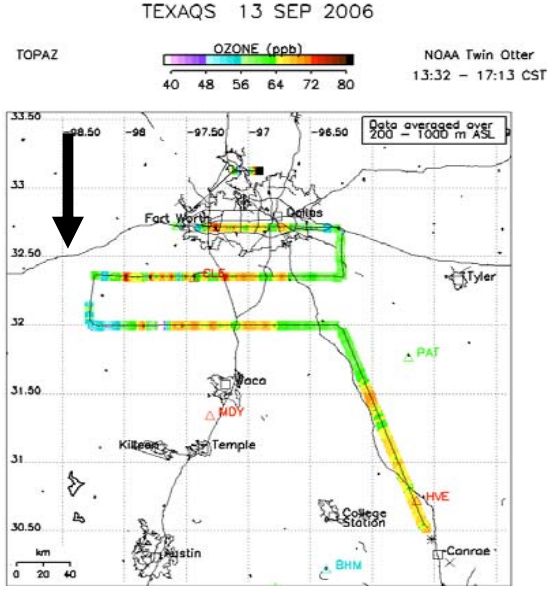






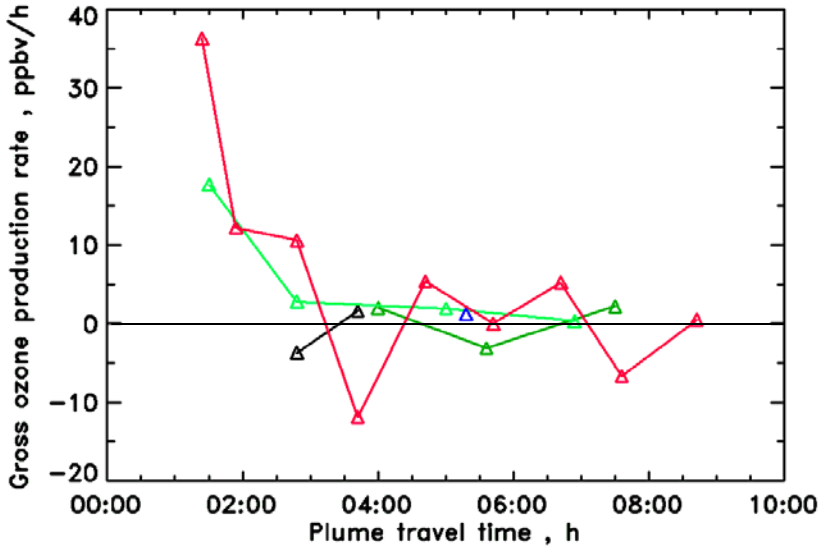


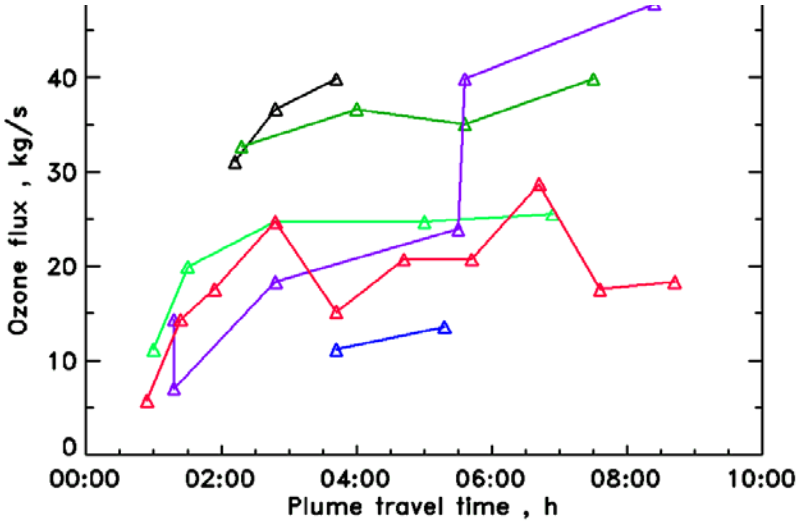


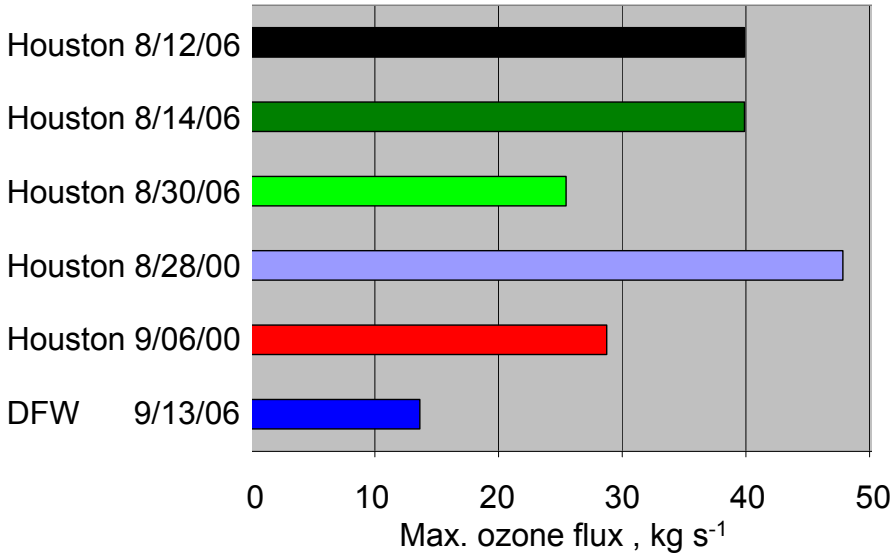


Horizontal ozone flux and ozone production

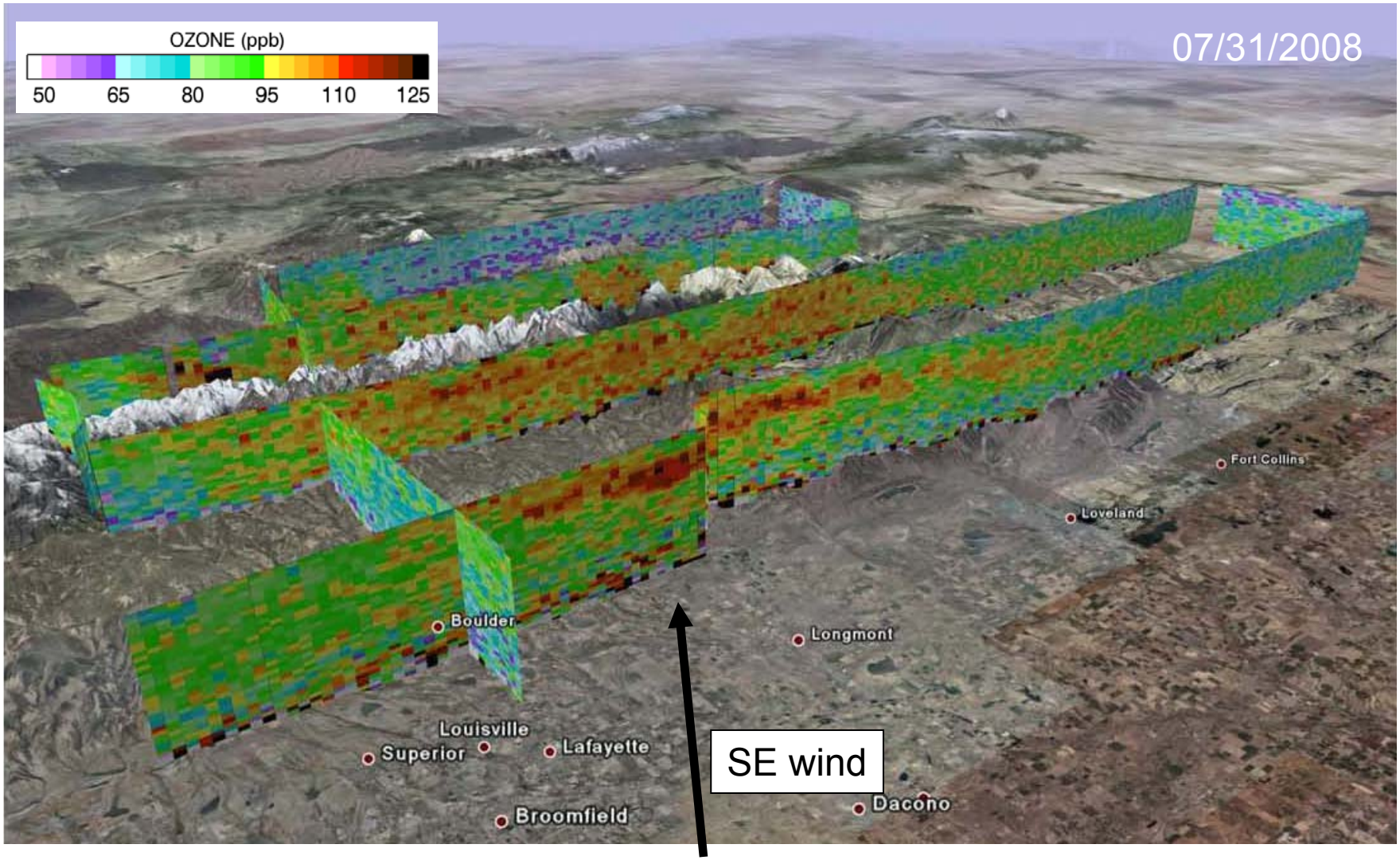
A flux of 35 kg O_3 / s (average of all Houston cases) emitted over a day (8 hours) is equivalent to a 10-ppb increase in ozone over an approx. 10,000 square mile area, assuming a 2-km deep mixed layer.



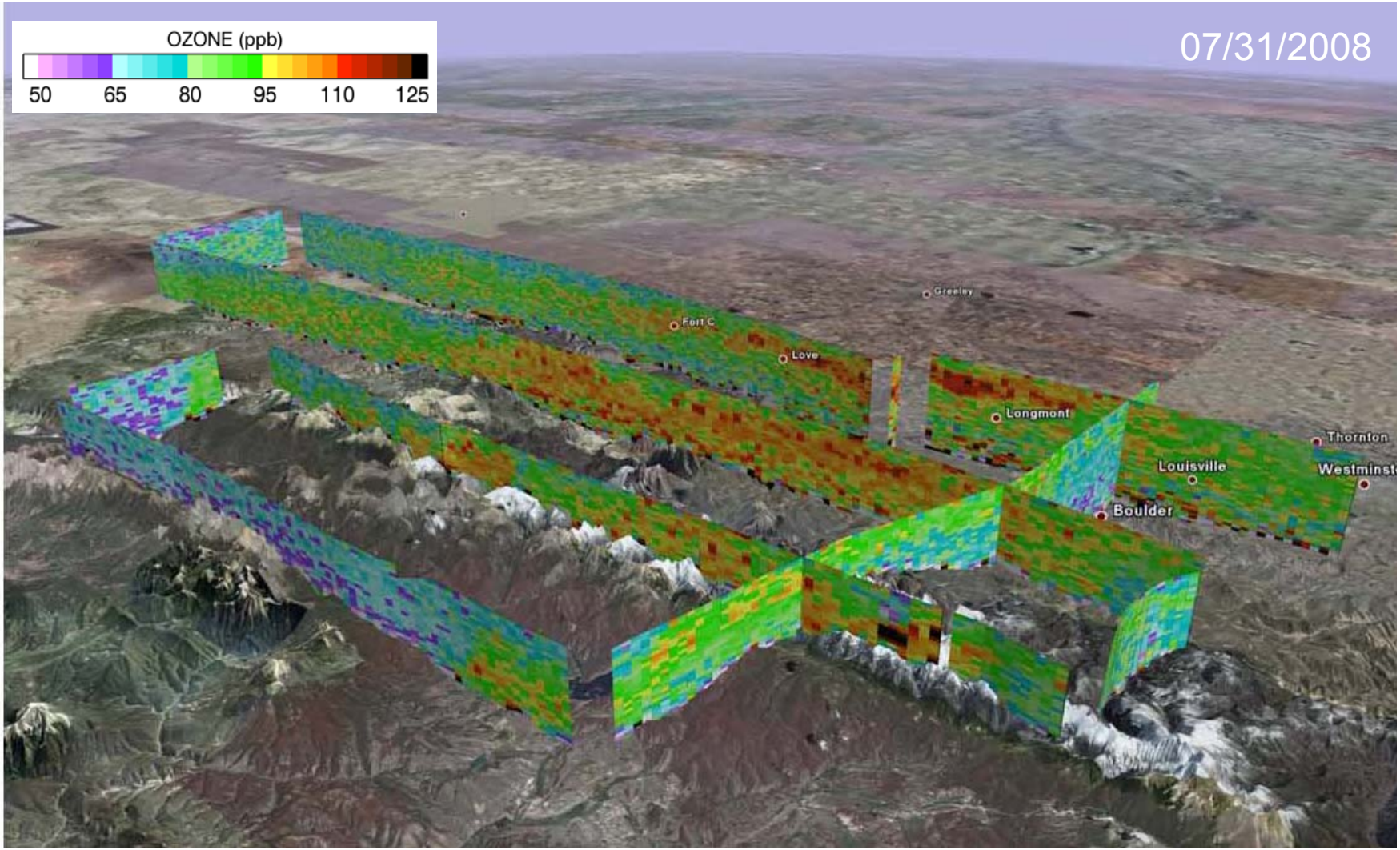




Front Range Air Quality Study 2008: Transport of O_3 into and over the mountains



Front Range Air Quality Study 2008: Transport of O_3 into and over the mountains (cont'd)



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Aerosol correction & DUAL-DIAL (slides 21 - 22)

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