# Spatial and Temporal Variability of Carbon Dioxide using Structure Functions in Urban Areas: Insights for Future Active Remote $CO_2$ Sensors

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*Atmospheric Vertical Observations of*

*AVOCET*

*CO2 in the Earth's Troposphere*

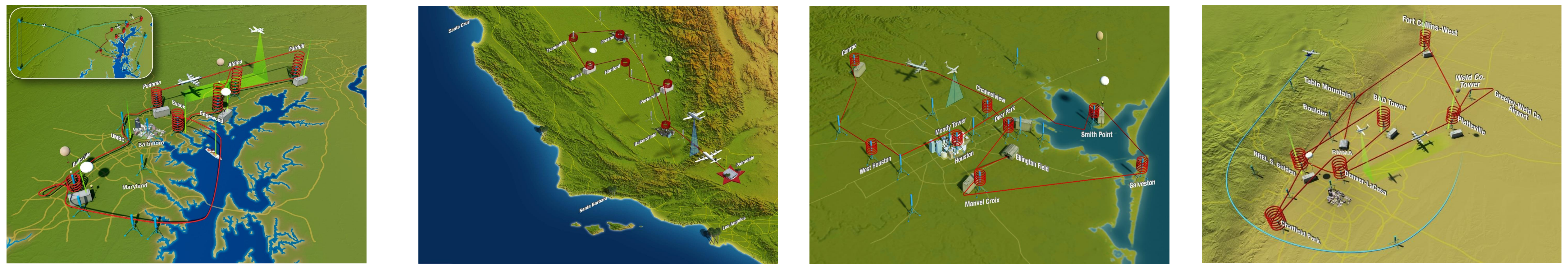
## Introduction

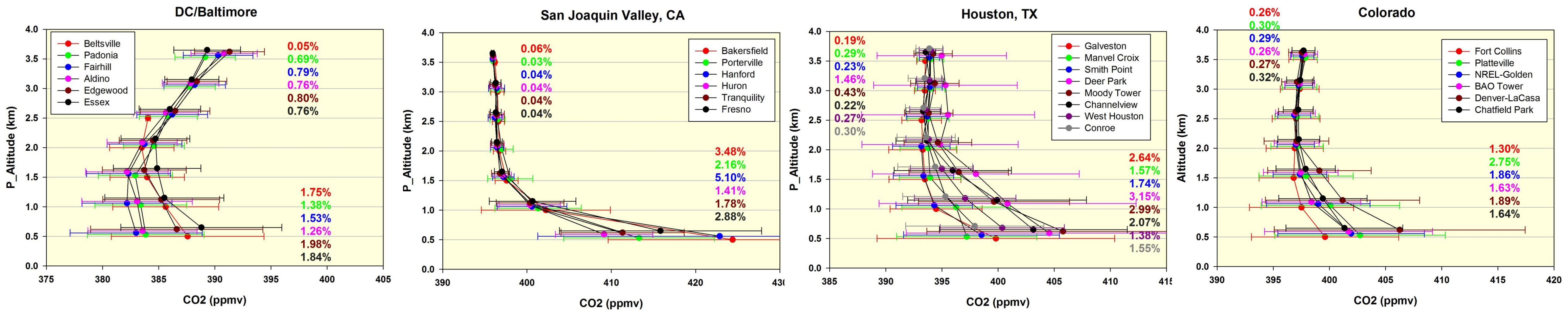
High resolution *in-situ* $CO_2$ measurements were recorded onboard the NASA P-3B during the DISCOVER-AQ (Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality) Field Campaigns during July 2011 over Washington DC/Baltimore, MD; January – February 2013 over the San Joaquin Valley, CA; September 2013 over Houston, TX; and July-August 2014 over Denver, CO. Each of these campaigns have approximately two hundred vertical soundings of $CO_2$ within the lower troposphere (surface to about 5 km) at 6-8 different sites in each of the urban area. In this study, we used structure function analysis, which are a useful way to quantify spatial and temporal variability, by displaying differences with average observations, to evaluate the variability of $CO_2$ in the 0-2 km range (representative of the planetary boundary layer). These results can then be used to provide guidance in the development of science requirements for the future ASCENDS (Active Sensing of $CO_2$ Emissions over Nights, Days, and Seasons) mission to measure near-surface $CO_2$ variability in different urban areas. We also compare the observed *in-situ* $CO_2$ variability with the variability of the $CO_2$ column-averaged optical depths in the 0-1 km and 0-3.5 km altitude ranges in the four geographically different urban areas, using vertical weighting functions for potential future ASCENDS lidar $CO_2$ sensors operating in the 1.57 and 2.05 µm measurement regions. In addition to determining the natural variability of $CO_2$ near the surface and in the column, radiocarbon method using continuous $CO_2$ and CO measurements are used to examine the variation of emission quantification between anthropogenic and biogenic sources in the DC/Maryland urban site.

### Sample Site – DISCOVER-AQ

To improve the interpretation of satellite observations in order to diagnose near surface conditions relating to air quality, low altitude in-situ measurements on the NASA P-3B aircraft were performed at four urban sites: DC/Baltimore (July 2011), San Joaquin Valley, CA (Jan-Feb 2013), Houston, TX (Sep., 2013), and Denver, CO (July – August, 2014).

**Image Credit: Tim Marvel (NASA LaRC/SSAI)**





Figures (above) show the spatial variation of in-situ $CO_2$ soundings with altitude at DC/Baltimore (left), CA (middle-left), TX (middle-right), and Denver, CO (right). Figures for each location were represented by the mean with standard deviation as a function of altitude at the various spiral points (252 spiral points at DC/Baltimore, 169 spirals at California, 180 spirals at Texas, and 223 spirals at Colorado). These plots shows that within a small geographical area emissions can vary by a lot, even at various locations within the same urban area. The color coded numbers seen in the top and bottom of the figures are the percentage variations from the mean for each site listed in the legend for the top and bottom of the spirals, respectively.

### Structure Function and Data Filtering

$$f(Z,y) \equiv \langle |Z(x+y) - Z(x)| \rangle$$

where, <> denotes taking the average for data pairs separated by distance y, Z is the variable of interest ($CO_2$ in this analysis) at a given location x, it represents the expected gradient (average difference) for a given resolution (distance y).

For the airborne data analysis here, the distance y is considered to represent satellite resolution and the average difference could represent the expected variability for given resolution.

### Data Filtration

High resolution 1 Hz data (roughly 100 m resolution), below 2km AGL, data pairs taken less than 60 minutes to minimize the differences by chemistry and transport, and data pairs with distance up to 100 km were used with the assumed well-mixed boundary layer.

### OPTICAL DEPTH CALCULATION

The 2-way optical depth $\tau$ of a gas is calculated as

$$\tau = 2\int_{z=b}^{z=t} \alpha \bullet n \bullet \delta z$$

Where

$\alpha$ = absorption cross section

n = number density of the gas

$\delta$z = vertical bin size

**ATMOSPHERIC COMPOSITION**

$CO_2$, T, P, WV AIRBORNE MEASUREMENTS

T, P AFGL 1986 US STANDARD ATMOSPHERE

**SPECTROSCOPIC PARAMETERS**

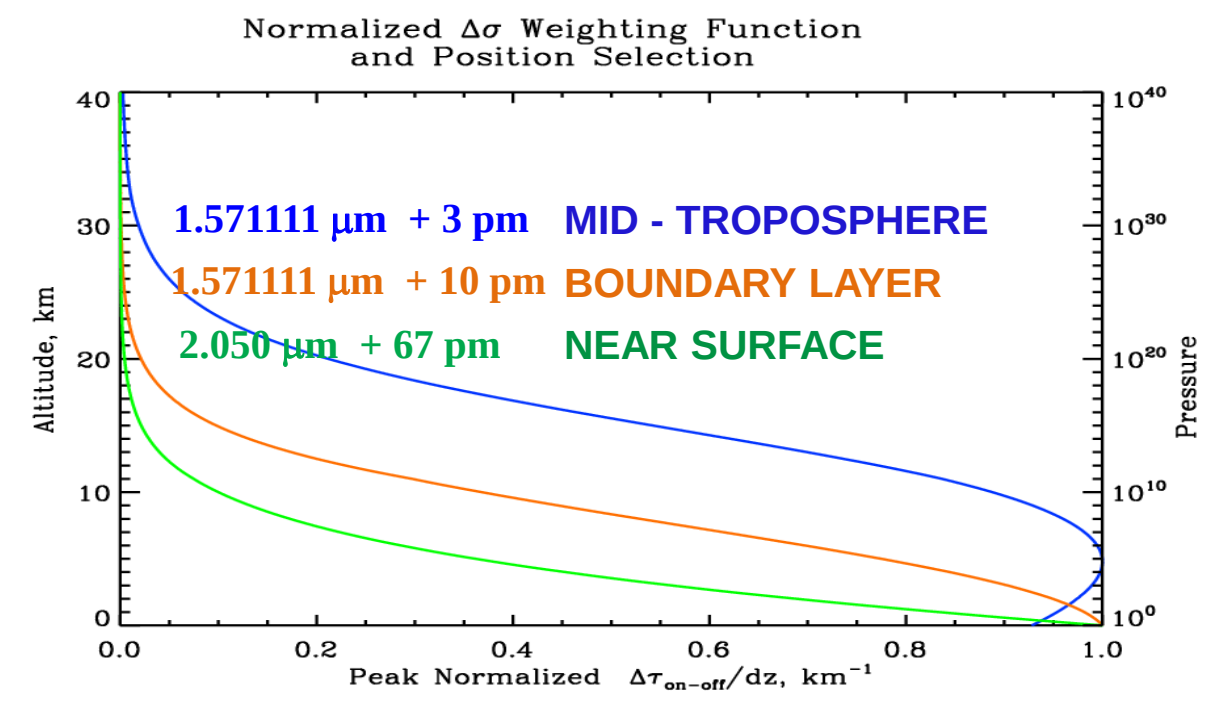
TRANSMITTED WAVELENGTHS

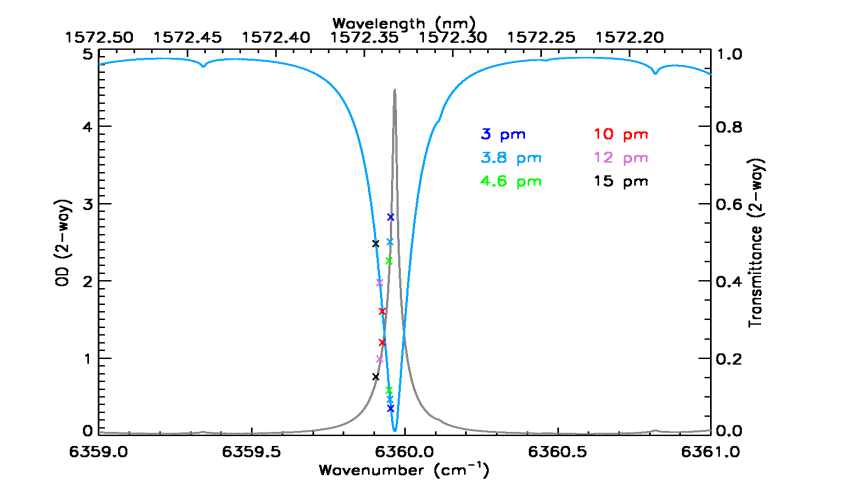
HITRAN 2008 LINE PARAMETERS

http://www.cfa.harvard.edu/hitran/

**PATH LENGTH**

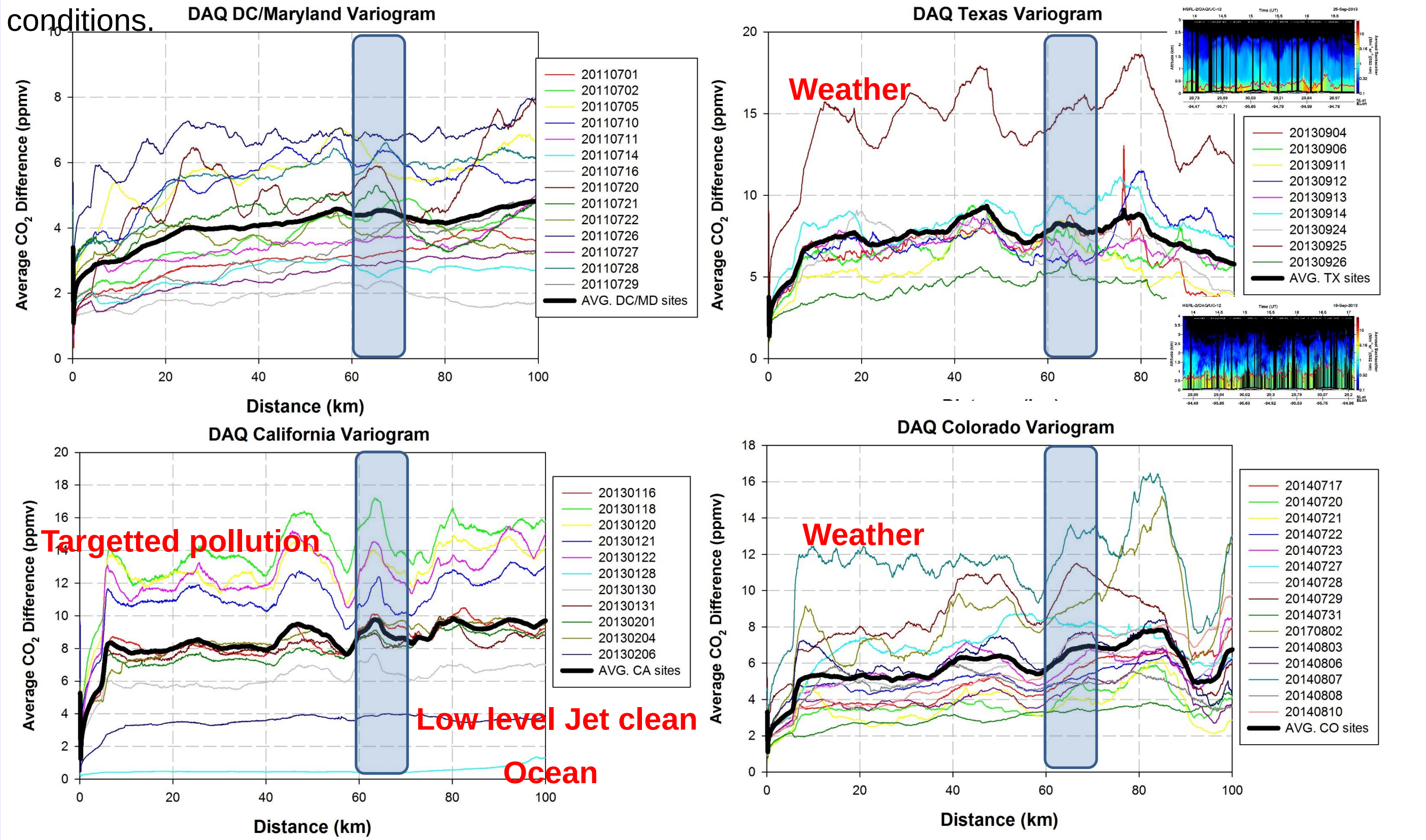
3.5 km FOR P-3 aircraft



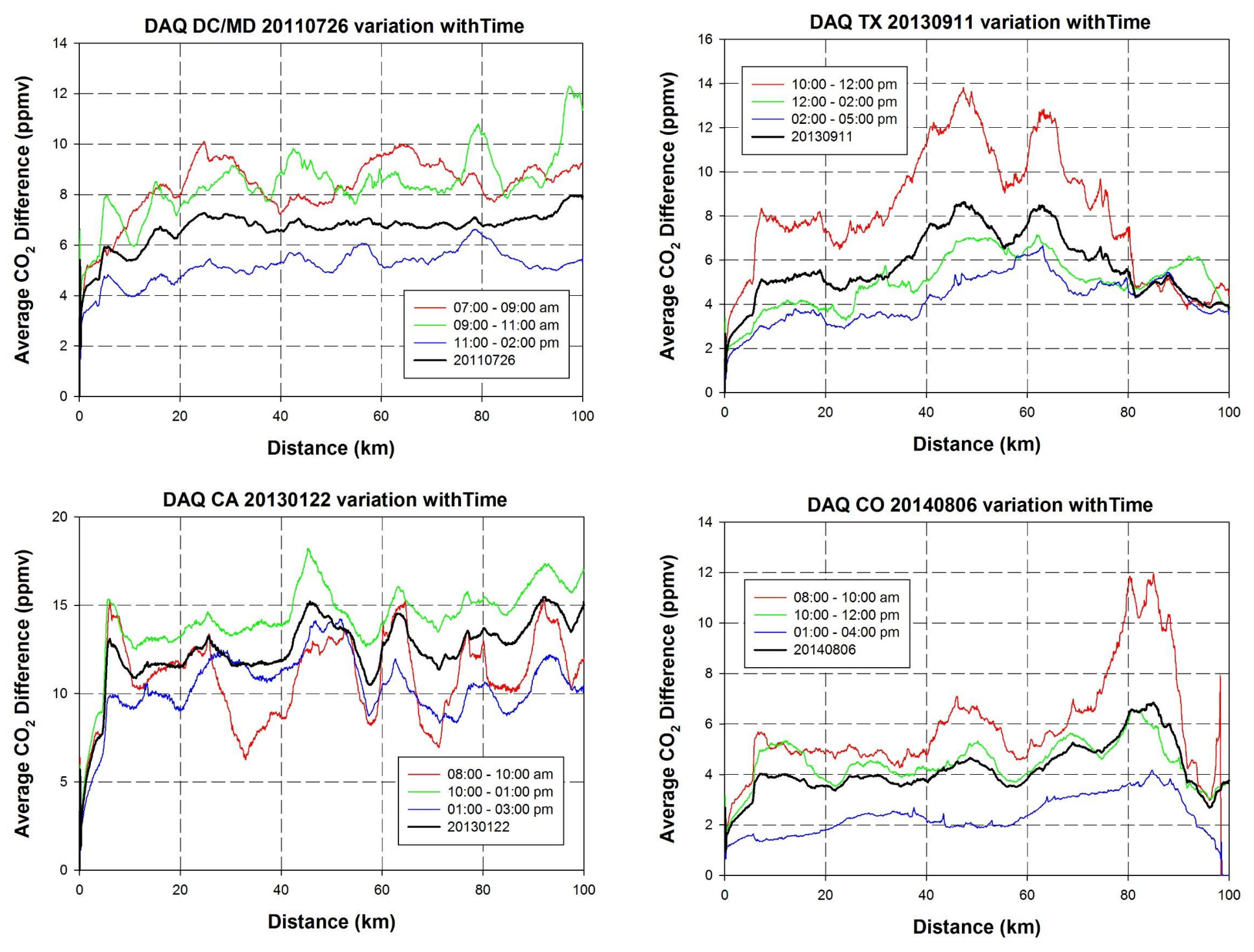


$CO_2$ Transmission and Optical Depth (from satellite to surface with candidate ASCENDS wavelength)

**Spatial Variability** using Structure Function. Figures below show the comparison of spatial variation observed during DISCOVER-AQ. Each color line indicates a different date and the thick black line is the average difference of targeted resolution in the sites. The shaded box shows the possible ASCENDS resolution to see the spatial variability for establishing measurements for future remote sensor. Some offset variabilities are shown by different weather or surface conditions.



Figures below show the spatial variability with different time resolutions. As the time is further away from the morning peak traffic time, the spatial variability decreases at most sites.



**Column and Surface Variability** using OD calculation**.** Tables the Column Optical Depth and Variability for 3 different weighting functions (1.57µ+3pm, 1.57µ+10pm, and 2.06µ) for Column (0-3.5 km) and Surface (0-1 km). *Equivalent Mixing Ratio (ppm) are compared with consistent 390 ppm at four different sites. The column variation shows 0.55–1.26 %(MD), 0.19–0.74 %(CA), 0.42–1.63(TX), and 0.64–0.88 %(CO) and surface variation range 0.66 – 2.05 % at sites.

| | Beltsville | | | | Padonia | | | | Fairhill | | | | Aldino | | | | Edgewood | | | | Essex | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Column (0-3.5 km) | | | Surface | Column (0-3.5 km) | | | Surface | Column (0-3.5 km) | | | Surface | Column (0-3.5 km) | | | Surface | Column (0-3.5 km) | | | Surface | Column (0-3.5 km) | | | Surface |
| Weighting Fn. | 1.57µ (3pm) | 1.57µ (10pm) | 2.05 µ | | 1.57µ (3pm) | 1.57µ (10pm) | 2.05 µ | | 1.57µ (3pm) | 1.57µ (10pm) | 2.05 µ | | 1.57µ (3pm) | 1.57µ (10pm) | 2.05 µ | | 1.57µ (3pm) | 1.57µ (10pm) | 2.05 µ | | 1.57µ (3pm) | 1.57µ (10pm) | 2.05 µ | |
| Colm.Avg.(ppm)* | 386.81 | 386.82 | 386.87 | 387.80 | 385.17 | 385.07 | 384.80 | 382.32 | 384.79 | 384.64 | 384.27 | 383.35 | 384.92 | 384.81 | 384.52 | 386.32 | 386.18 | 386.11 | 385.96 | 387.41 | 386.48 | 386.46 | 386.45 | 388.61 |
| Variability (%) | 1.24 | 1.25 | 1.26 | 1.88 | 0.55 | 0.56 | 0.60 | 1.13 | 0.67 | 0.67 | 0.70 | 1.22 | 0.70 | 0.71 | 0.76 | 1.38 | 0.74 | 0.75 | 0.79 | 1.66 | 0.75 | 0.76 | 0.81 | 0.69 |

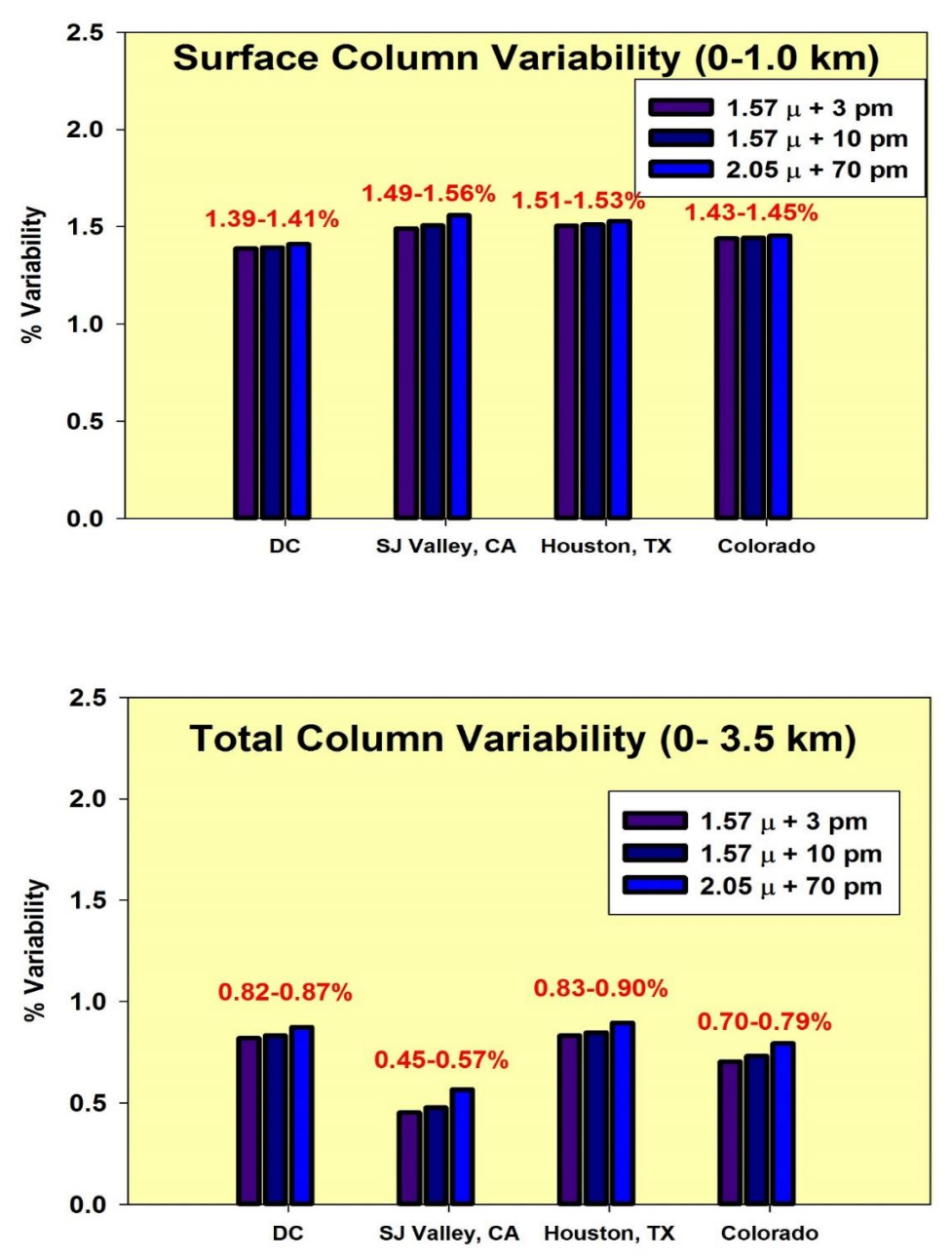
| | Bakersfield | | | | Porterville | | | | Hanford | | | | Huron | | | | Tranquility | | | | Fresno | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Colm.Avg.(ppm)* | 401.90 | 402.24 | 403.32 | 413.01 | 399.96 | 400.21 | 401.00 | 407.72 | 400.64 | 400.97 | 402.03 | 410.88 | 399.08 | 399.26 | 399.84 | 405.02 | 399.36 | 399.58 | 400.28 | 406.55 | 399.38 | 400.04 | 405.89 | 388.61 |
| Variability (%) | 0.63 | 0.65 | 0.74 | 2.05 | 0.28 | 0.30 | 0.38 | 1.18 | 0.39 | 0.42 | 0.55 | 1.49 | 0.23 | 0.23 | 0.26 | 0.66 | 0.19 | 0.21 | 0.28 | 0.92 | 0.41 | 0.43 | 0.51 | 1.32 |

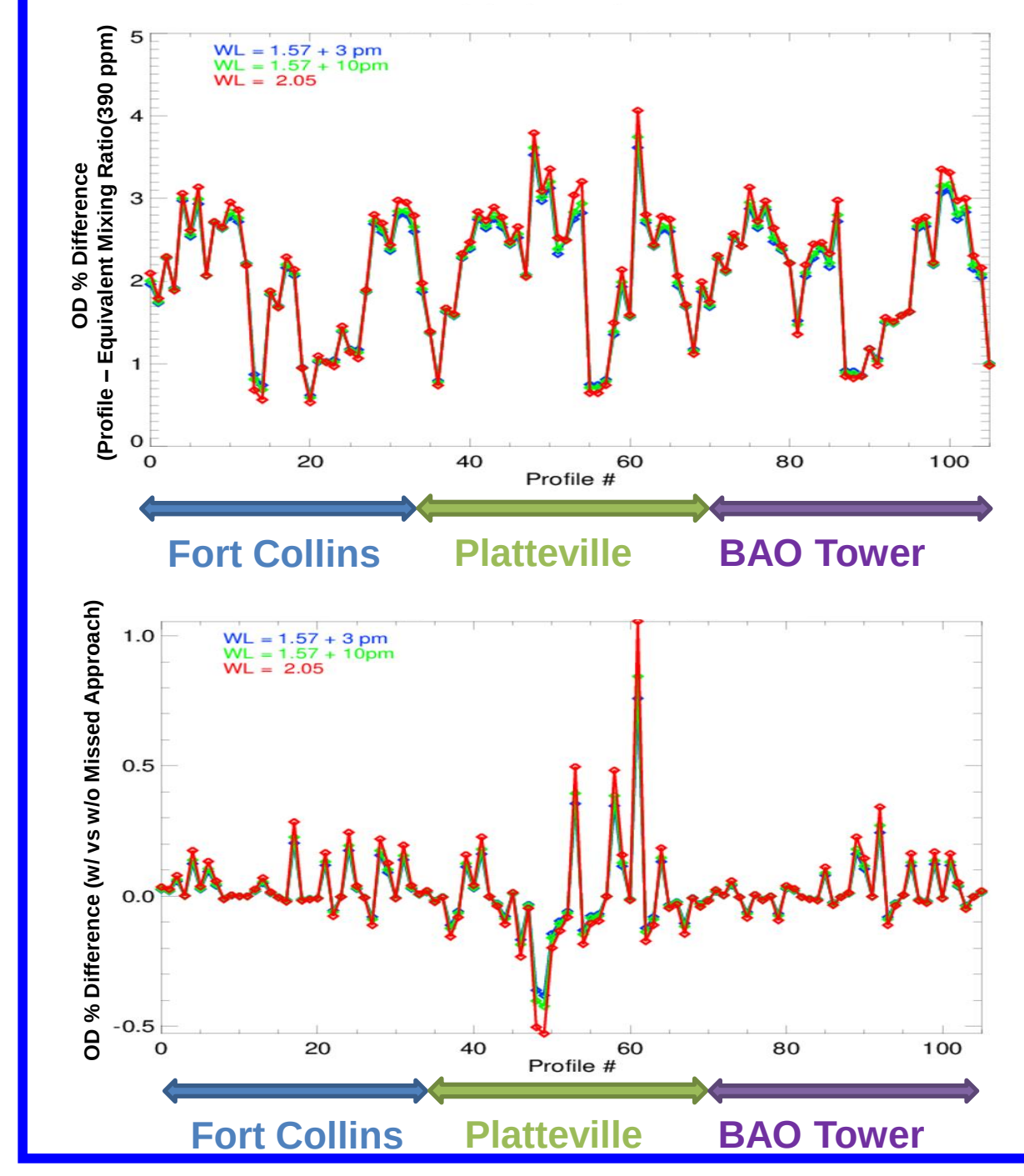
| | Galveston | | | | Manvel Croix | | | | Smith Point | | | | Deer Park | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Colm.Avg.(ppm)* | 394.33 | 394.41 | 394.65 | 396.83 | 394.66 | 394.72 | 394.93 | 396.90 | 394.27 | 394.31 | 394.44 | 395.71 | 398.44 | 398.59 | 399.04 | 402.94 |
| Variability (%) | 0.57 | 0.59 | 0.64 | 1.06 | 0.45 | 0.47 | 0.53 | 1.17 | 0.42 | 0.43 | 0.46 | 0.74 | 1.63 | 1.63 | 1.61 | 1.86 |

| | Moody Tower | | | | Channelview | | | | West Houston | | | | Conroe | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Colm.Avg.(ppm)* | 397.13 | 397.32 | 397.91 | 403.03 | 396.53 | 396.72 | 397.30 | 402.59 | 395.35 | 395.46 | 395.81 | 398.94 | 394.42 | 394.48 | 394.67 | 396.42 |
| Variability (%) | 0.70 | 0.72 | 0.80 | 1.76 | 0.73 | 0.76 | 0.86 | 1.74 | 0.43 | 0.44 | 0.49 | 0.99 | 0.47 | 0.48 | 0.51 | 0.87 |

| | Fort Collins | | | | Platteville | | | | NREL Golden | | | | BAO Tower | | | | Denver-LaCasa | | | | Chatfield | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Colm.Avg.(ppm)* | 397.36 | 397.38 | 397.46 | 398.24 | 398.75 | 398.88 | 399.17 | 401.89 | 398.14 | 398.23 | 398.44 | 400.55 | 398.05 | 398.13 | 398.31 | 400.04 | 399.75 | 399.94 | 400.35 | 404.31 | 398.61 | 398.69 | 398.88 | 400.72 |
| Variability (%) | 0.71 | 0.74 | 0.79 | 1.28 | 0.73 | 0.76 | 0.83 | 1.43 | 0.56 | 0.59 | 0.65 | 1.25 | 0.64 | 0.66 | 0.72 | 1.26 | 0.80 | 0.83 | 0.88 | 1.62 | 0.62 | 0.64 | 0.69 | 1.23 |

Figure (Right) shows the sensitivity of 3 different weighting functions at all urban spiral sites. Houston, DC, and Denver sites show similar column variability in range from 0.70 to 0.90 %, and San Joaquin site shows least variability in at 3.5 km column. The surface column variability (0-1.0 km) was similar at all four sites with 1.39 – 1.53 % variation. The 2 µ weighting function shows a little more sensitivity than others at below 3.5km column and surface.





### Missed Approach Analysis for Column Variability

Figures (Left) When compared with usual aircraft profile (missing in low altitude), Missed approach profiles give a chance to calculate the column values precisely. Here, Colorado Missed Approach profiles were used to derive OD % difference from a constant 390 ppm OD (1st figure). They show $CO_2$ enhancements varied from 0.6 – 3.6 % OD, or equivalent column mixing ratios of 2.4 – 14.1 ppmv at Colorado profiles. The same profiles were used to evaluate the impact of extending short profiles to the surface before calculating OD (2nd Figure). Assuming these profiles stopped 300 m above the surface, our extension technique introduced maximum errors of 0.8 % (3.1 ppm) at Colorado. Without missed approach, Galveston at Texas (which is not shown here), and Platteville at Colorado show biggest errors in column OD.

### Quantification of Fossil Fuel $CO_2$ using continuous $CO_2$ and CO measurement with Radiocarbon

➢ **Basic Concept**

$$\boxed{CO_{2\,ff}} = (CO_{obs} - CO_{bg})/\boxed{R_{CO}}$$

Use Emission Inventory of MD NEI 2008 value (19.1)

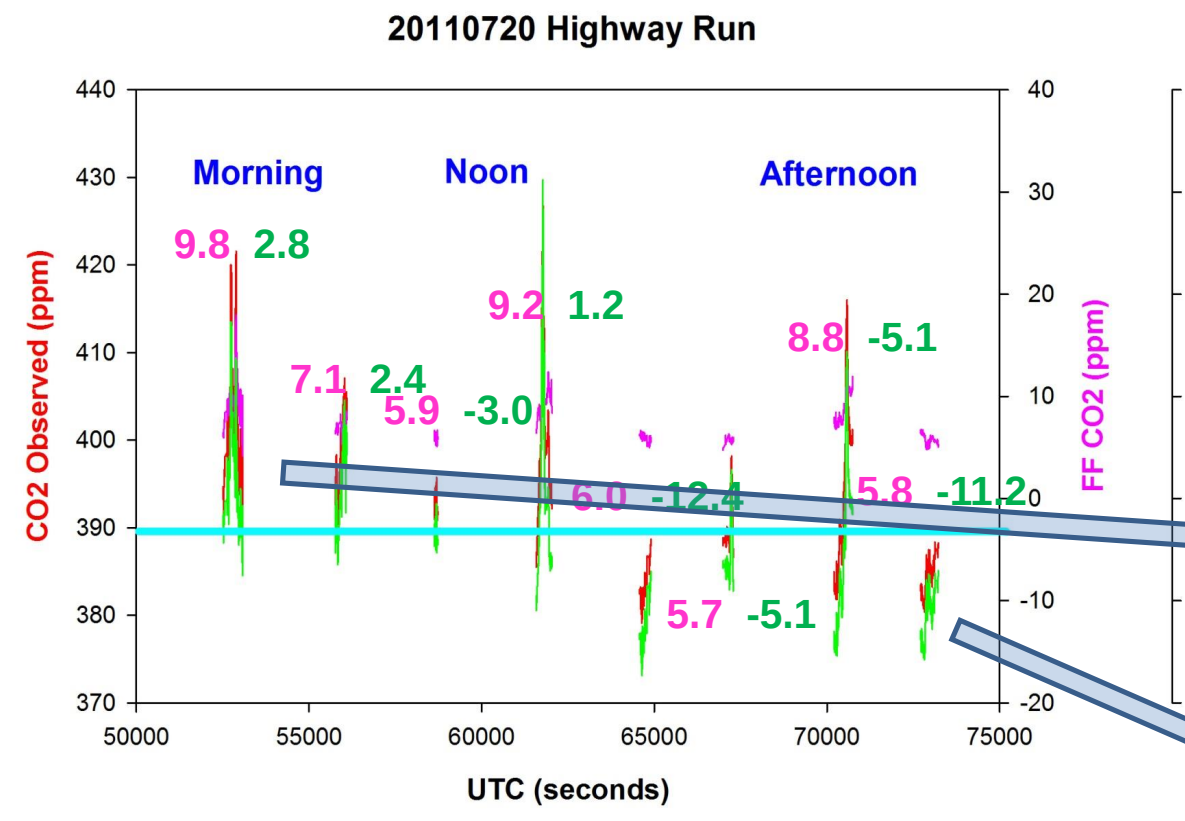
$$\boxed{R_{CO} = \frac{CO}{CO_{2\,ff}}}$$

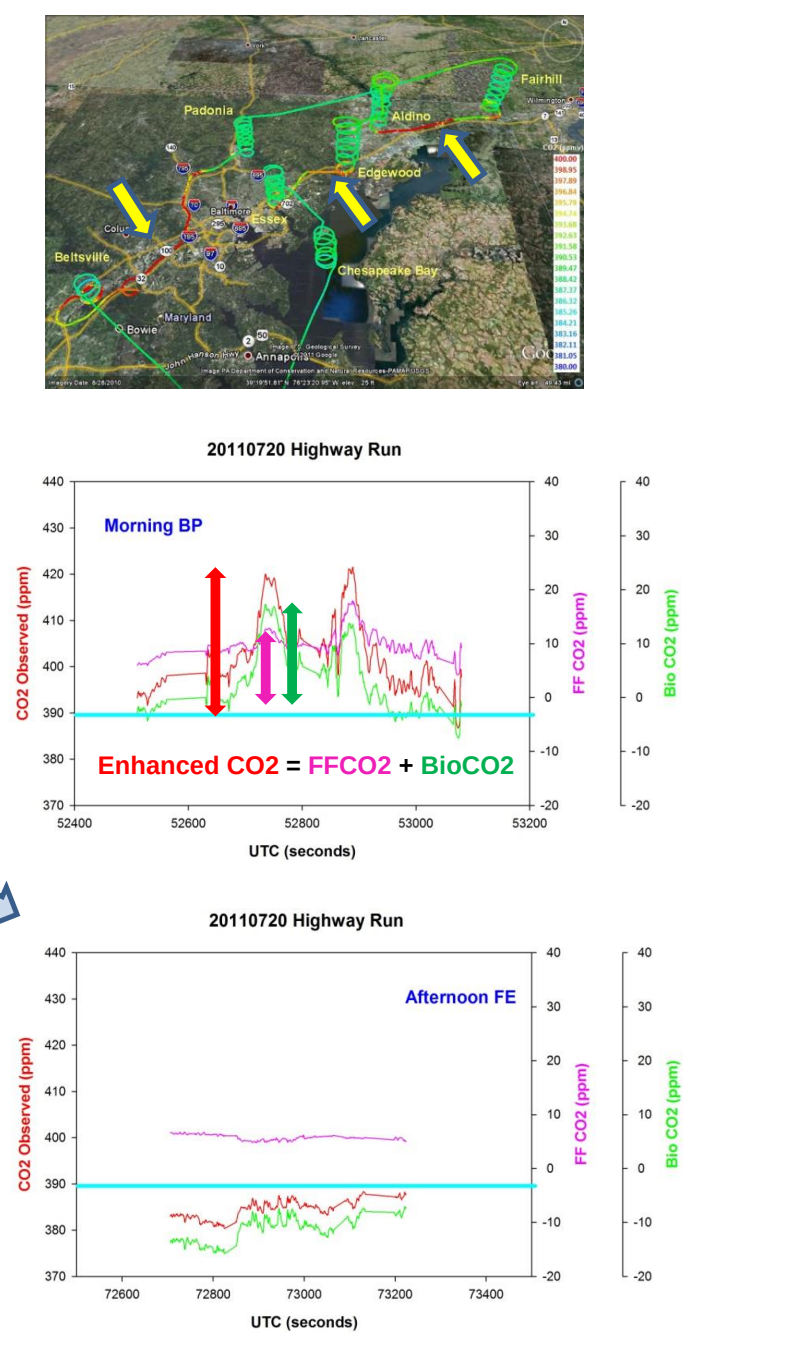
C-14 unavailable for DAQ

$$\xcancel{CO_{2\,ff} = \frac{CO_{2\,obs}(\Delta_{obs} - \Delta_{bg})}{\Delta_{ff} - \Delta_{bg}} - \frac{CO_{2\,oter}(\Delta_{oter} - \Delta_{bg})}{\Delta_{ff} - \Delta_{bg}}}$$

$$CO_{2\,obs} = \boxed{CO_{2\,bio}} + \boxed{CO_{2\,ff}} + CO_{2\,bg}$$

($CO_2$ bg = 390 ppm)





During the highway run, the observed $CO_2$ values are shown with higher than background values at Morning and Noon, but it's lower than background value at Afternoon.

FF $CO_2$ are almost consistent at 3 different time period, but the biogenic uptake signal, which is shown much lower during afternoon, result in the lower observed $CO_2$ even in the highway.

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