Behavior of Buoyant Emissions in Urban Areas: Field and Laboratory Studies

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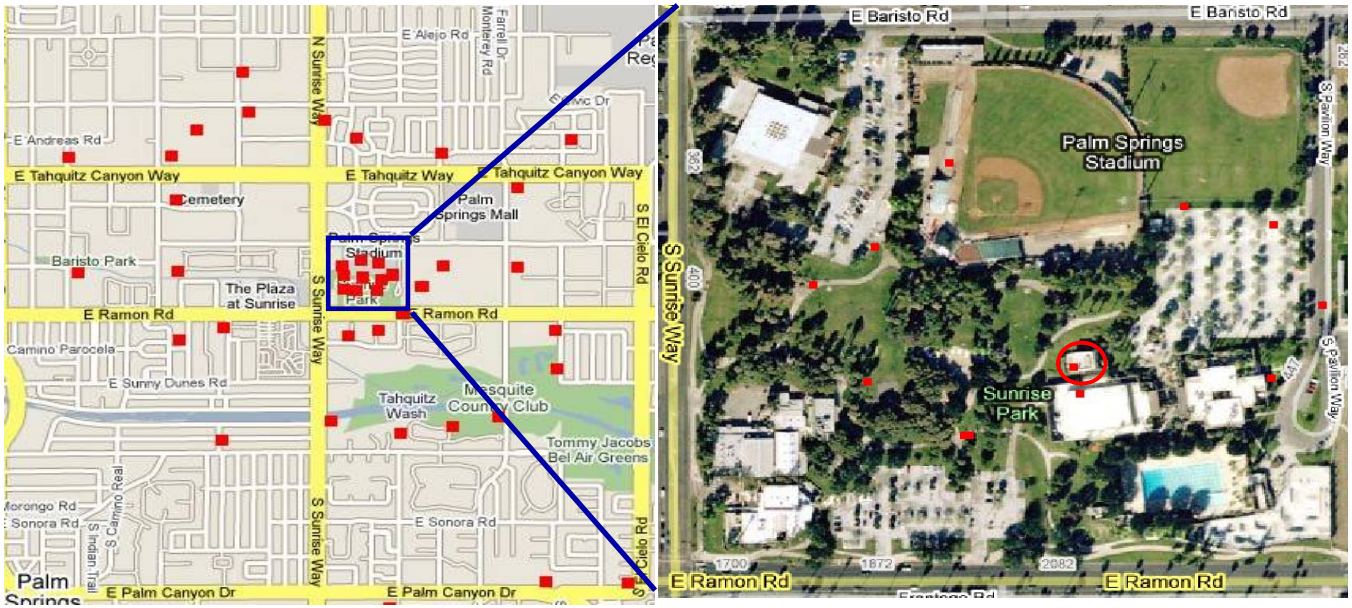
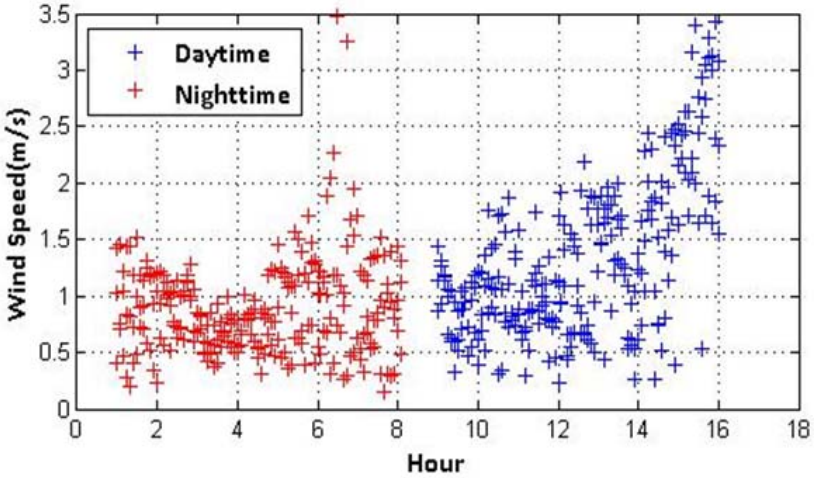
October 19, 2010

Ground Level Concentration Measurements

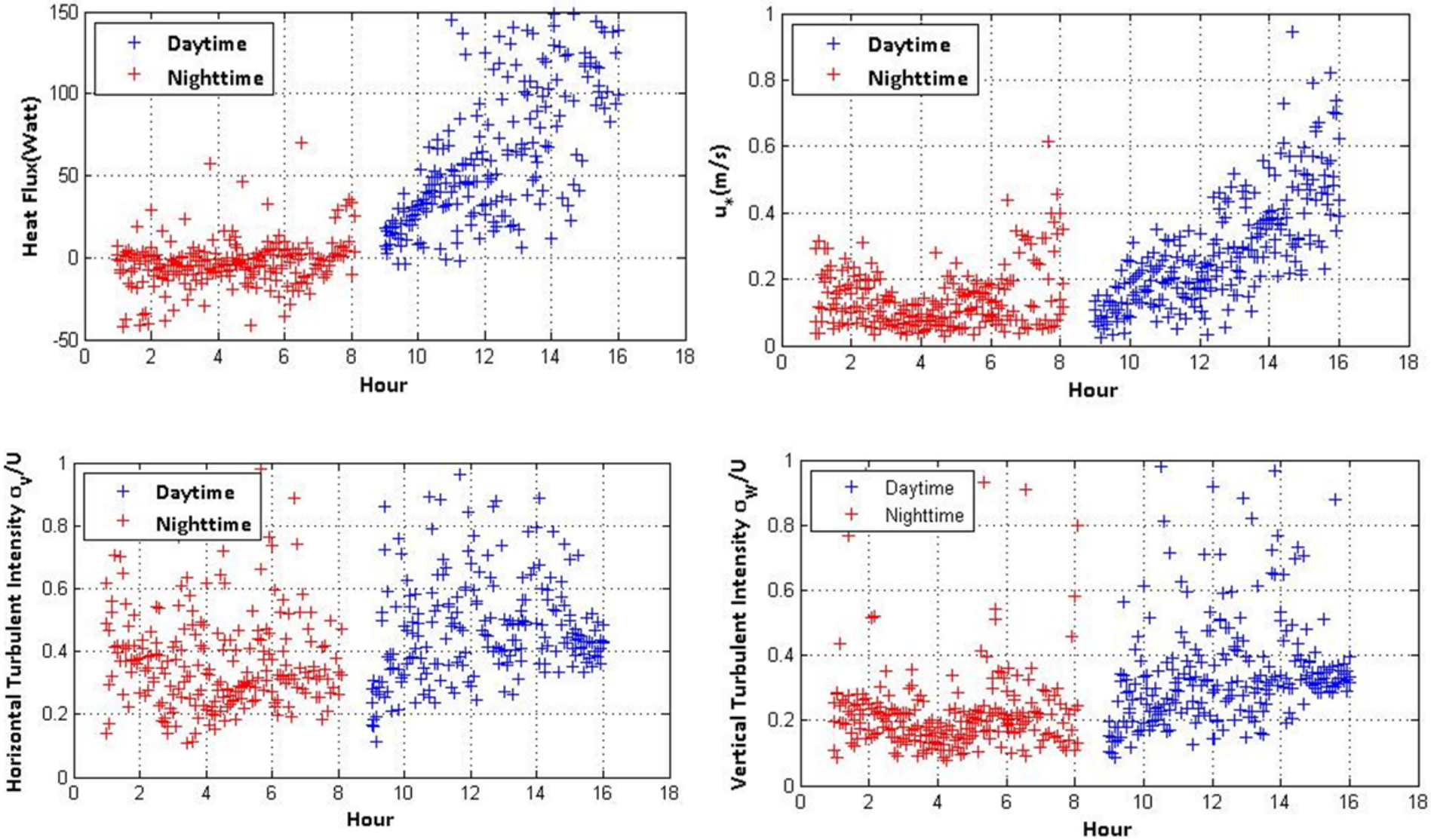


- Sampling stations were located at arcs of radii: 100 m, 400 m, 1 km, 2 km, and 4 km
- 650 kW plant. 3 daytime, 4 nighttime releases

Meteorological Measurements

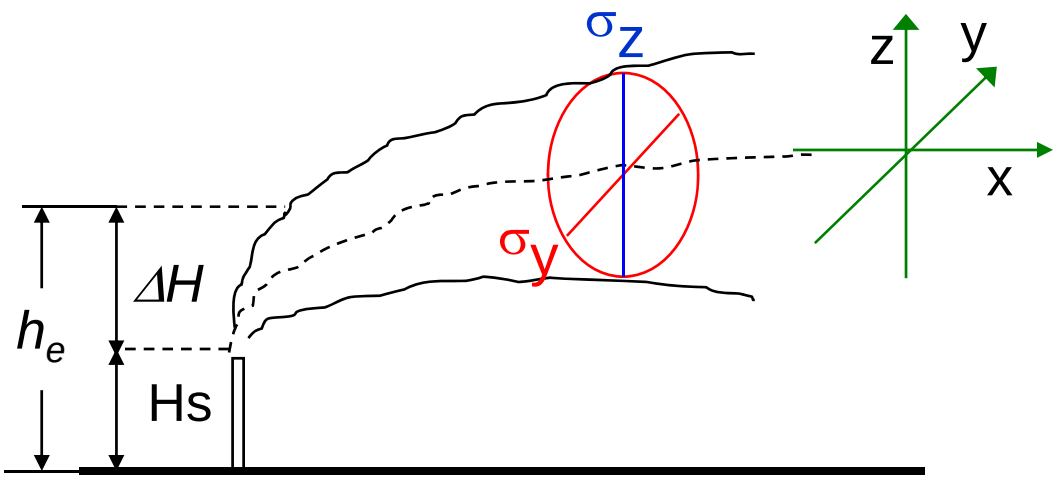


Meteorological Measurements



Plume Model Performance

$$\sigma_z = \min\left(\frac{\sigma_w x}{U}, \sqrt{\frac{2}{\pi}}\, Z_i\right)$$

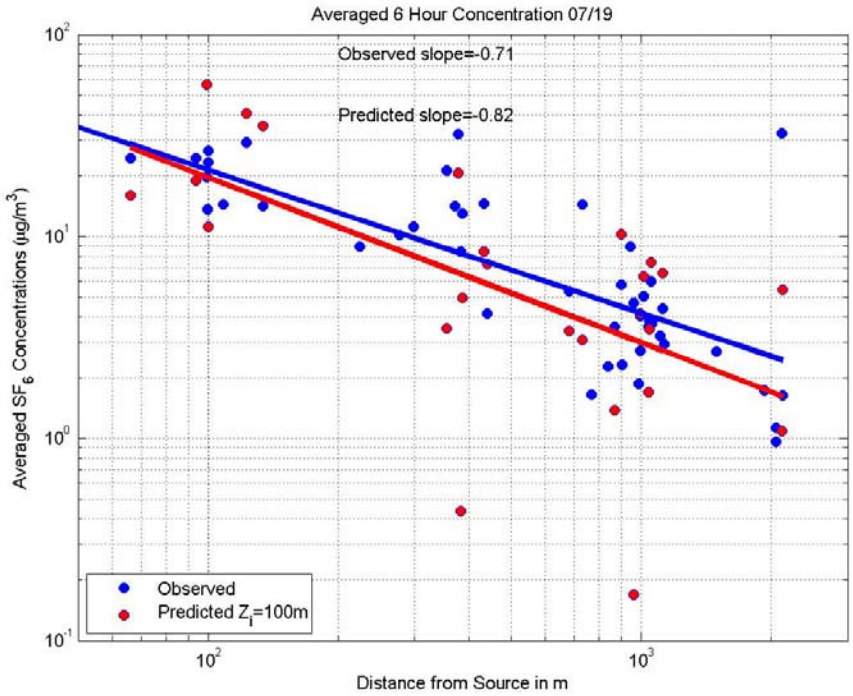


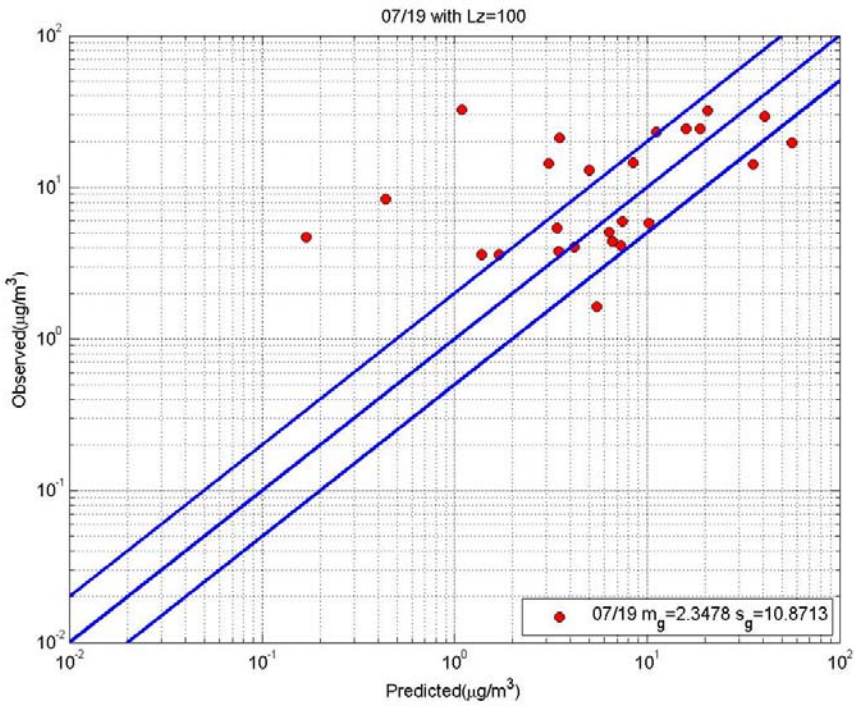
$$\sigma_y = \frac{\frac{\sigma_v X}{U}}{\left(1 + \frac{\sigma_v x}{L_z U}\right)}$$

$$C = \frac{1}{\pi U \sigma_z \sigma_y} \exp\left(-\frac{h_e^2}{2\sigma_z^2}\right) \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

Plume Model Performance

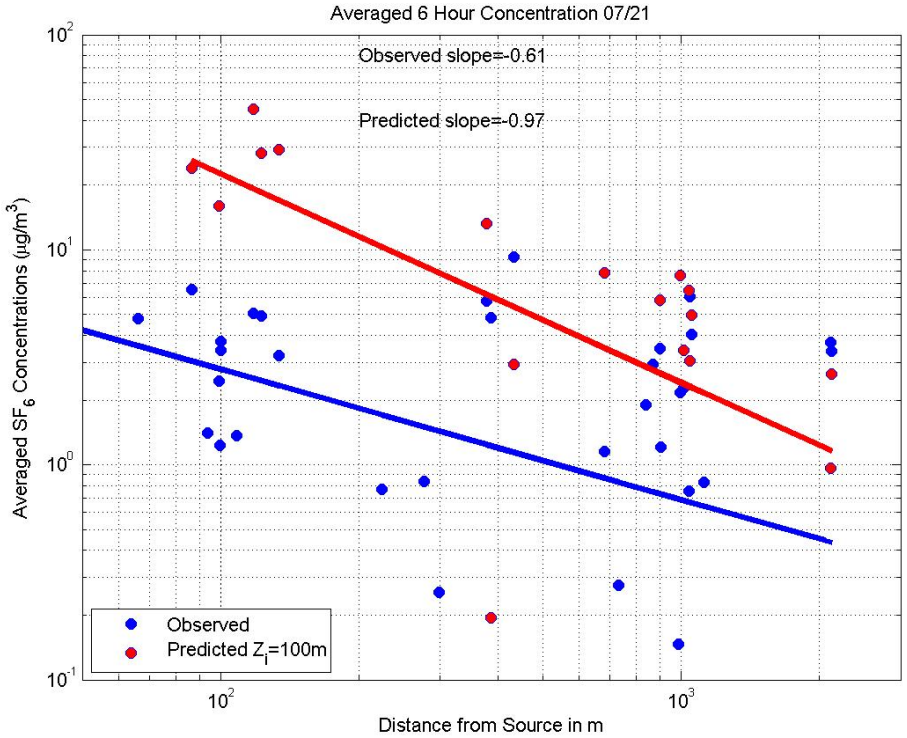
07/19

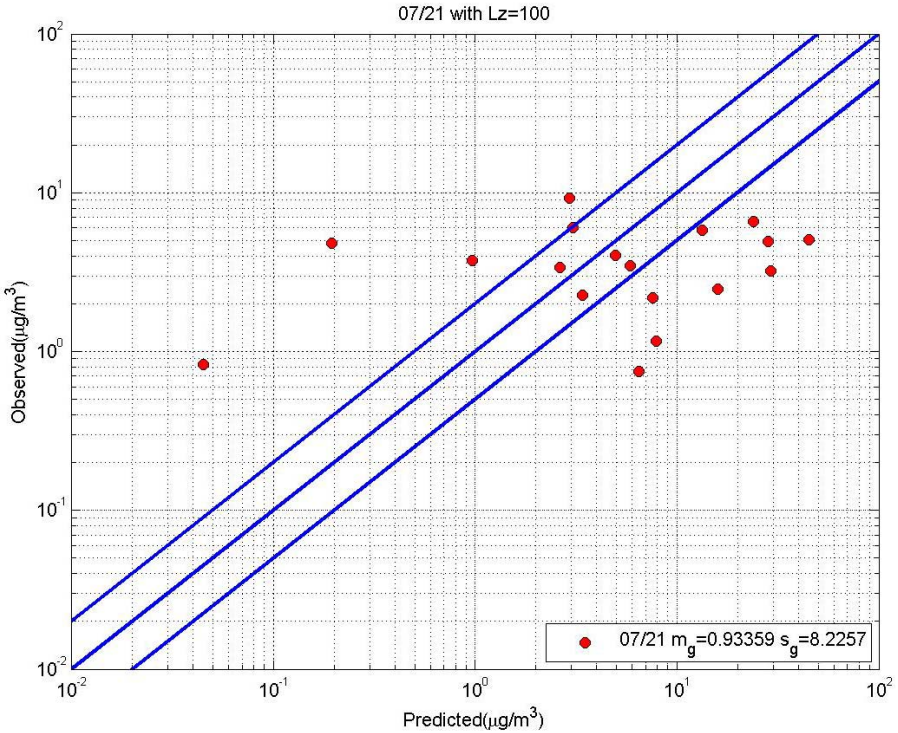




Plume Model Performance

07/21

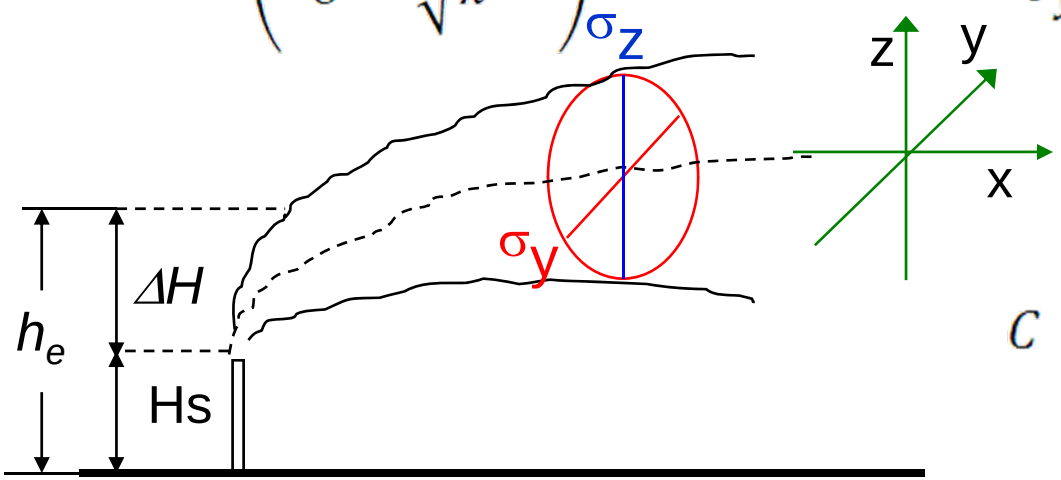




Plume Model Performance with Meandering

$$\sigma_z = \min\left(\frac{\sigma_w x}{U}, \sqrt{\frac{2}{\pi}}\, Z_i\right)$$

$$\sigma_y = \frac{\frac{\sigma_v X}{U}}{\left(1 + \frac{\sigma_v x}{L_z U}\right)}$$



$$C = \frac{2}{\sqrt{2\pi}\, U \sigma_z} \exp\left(-\frac{h_e^2}{2\sigma_z^2}\right) H(x,y)$$

$$H(x,y) = f_p H_p(x,y) + (1 - f_p) H_r(x,y)$$

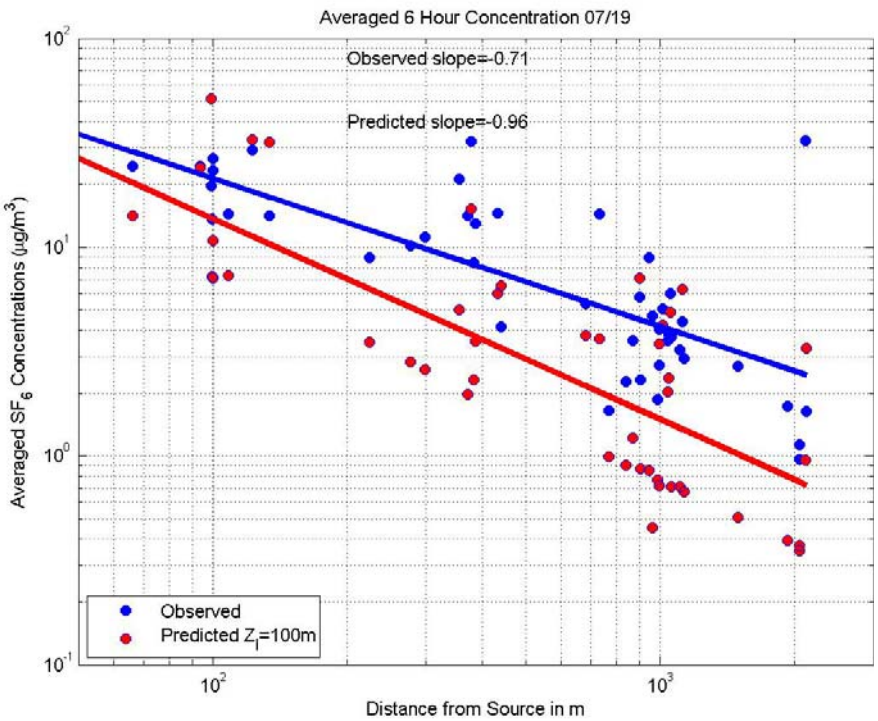
$$H_p(x,y) = \frac{1}{\sqrt{2\pi}\, \sigma_y} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

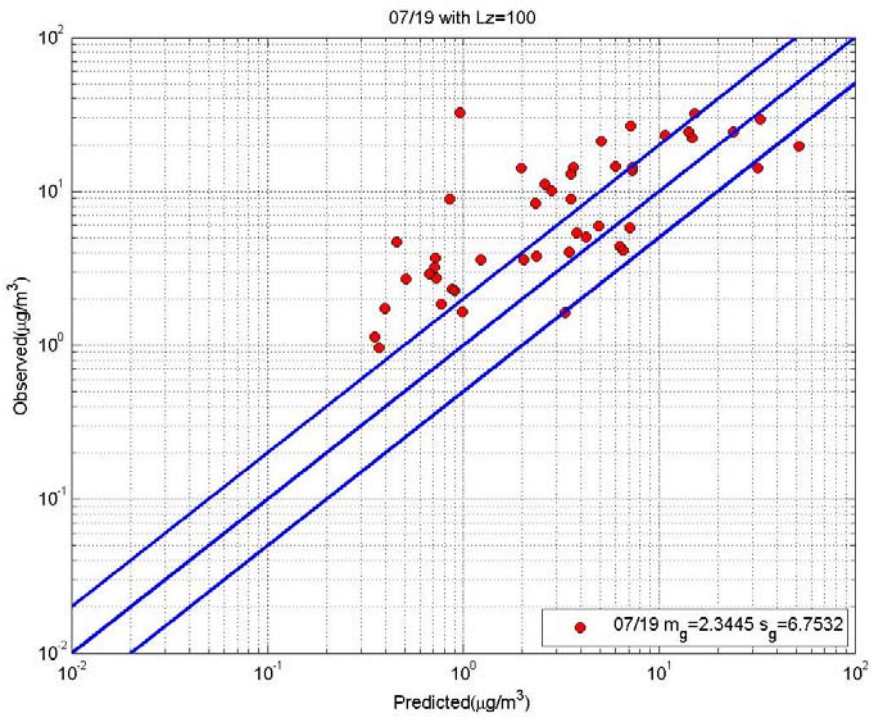
$$H_r(x,y) = \frac{1}{2\pi (x^2 + y^2)^{0.5}}$$

$$f_p = \frac{u}{(u^2 + 2\sigma_v^2)^{0.5}}$$

Plume Model Performance with Meandering

07/19





Plume Model Performance with Meandering

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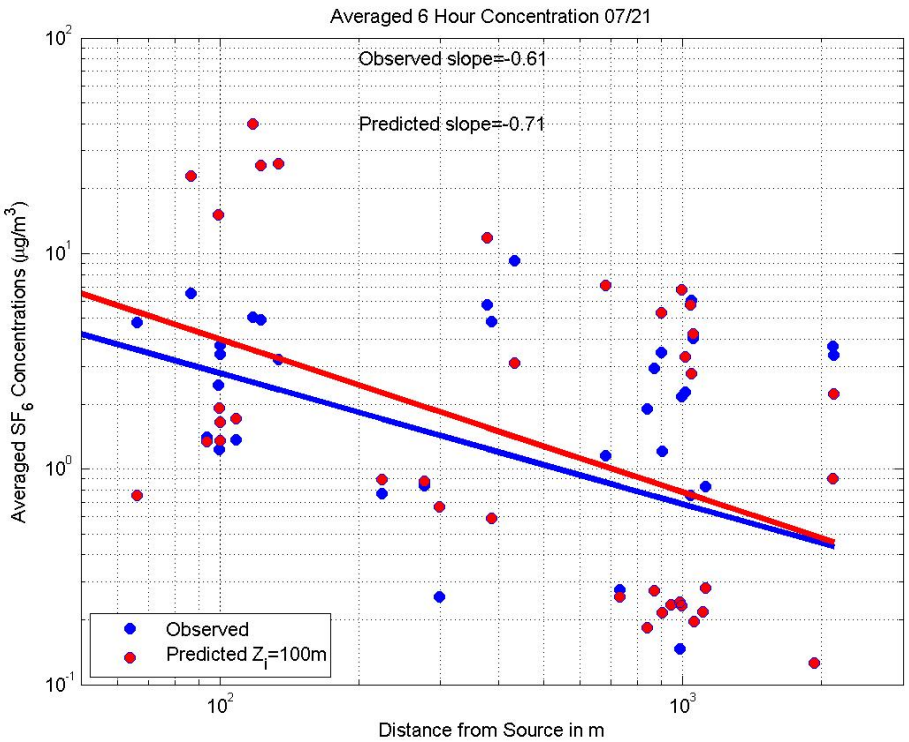
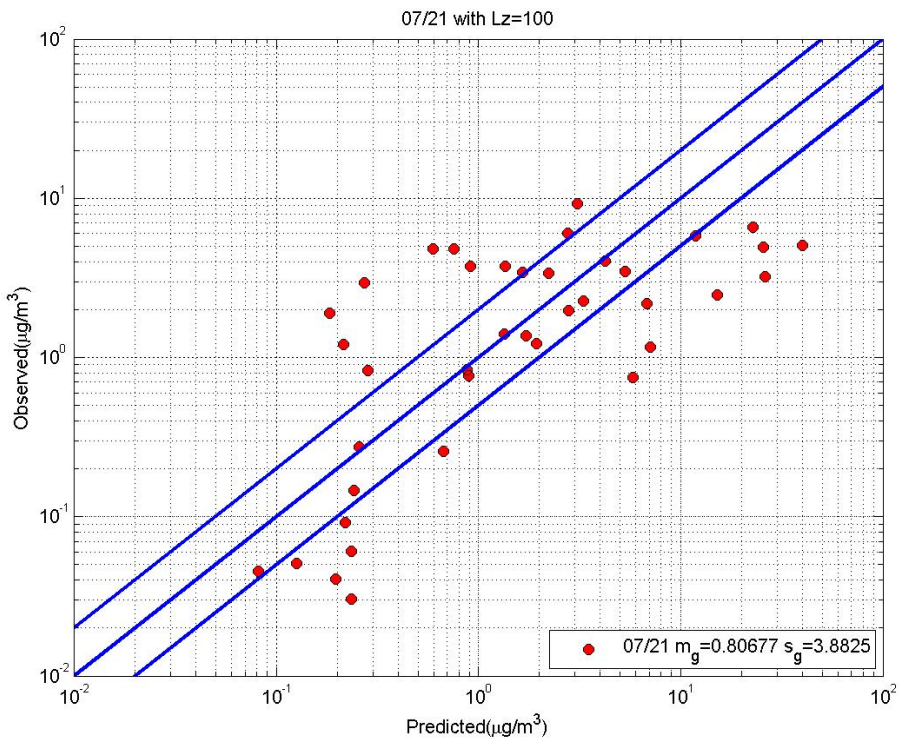
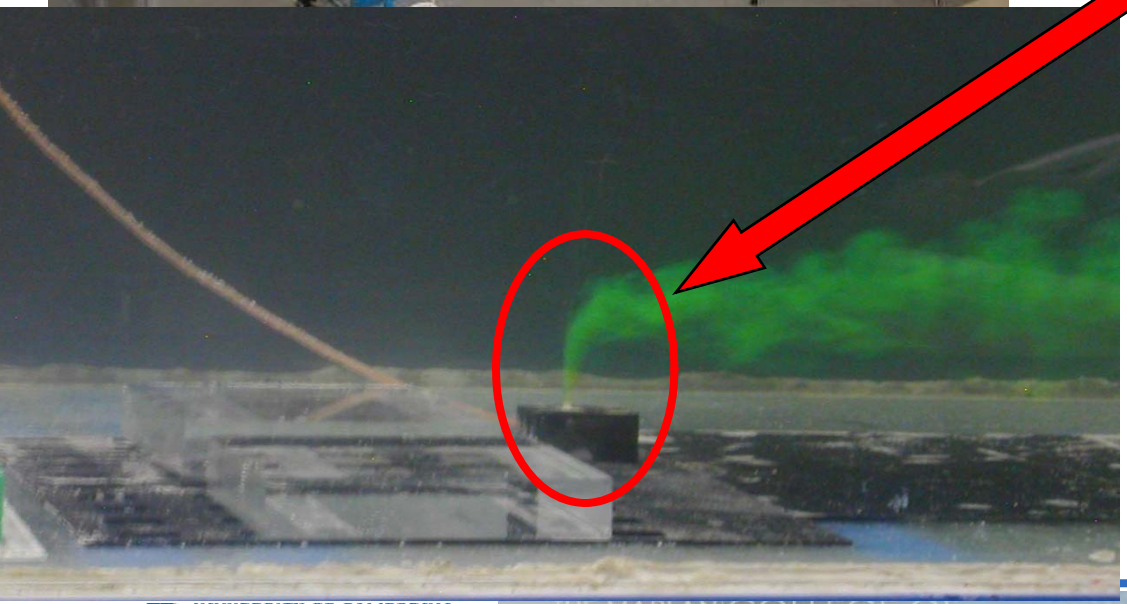




Laboratory Modeling



$$\frac{\Delta h_f}{H_f} = \frac{\Delta h_l}{H_l}$$

$$\Delta h = 1.8 \frac{F}{U \sigma_w^2}$$

$$F_f = \frac{gVD^2}{4} \frac{T_s - T_a}{T_s}$$

$$F_l = \frac{gVD^2}{4} \frac{\rho_a - \rho_s}{\rho_a}$$

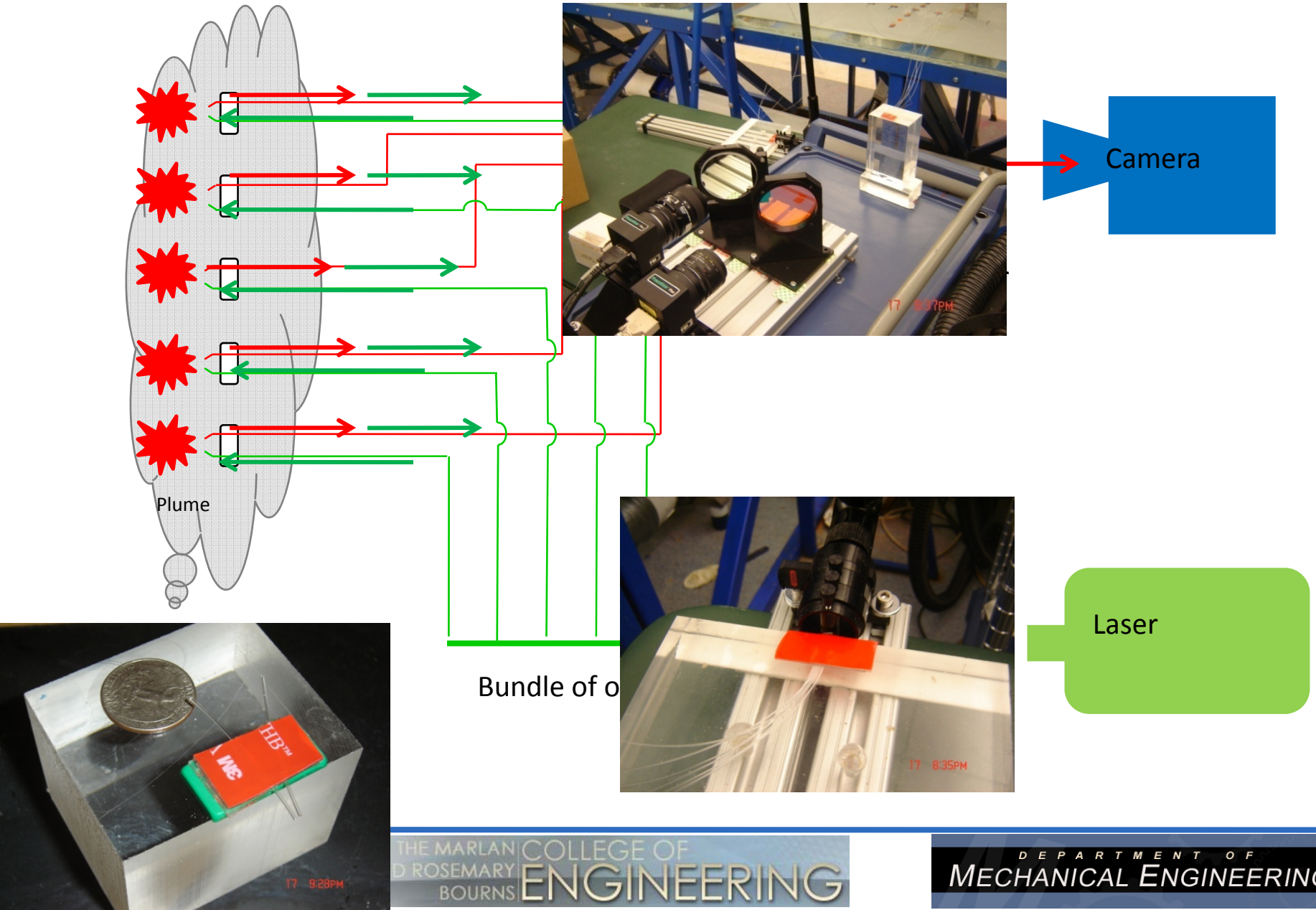
$$d = \frac{C}{C_0 \dot{Q}} = \frac{C}{C_0 V \left(\frac{\pi}{4} D^2\right)}$$

$$\frac{C}{C_0} = dV \left(\frac{\pi}{4} D^2\right)$$

$$\left[\frac{C}{C_0}\right]_f = \left[\frac{C}{C_0}\right]_l$$

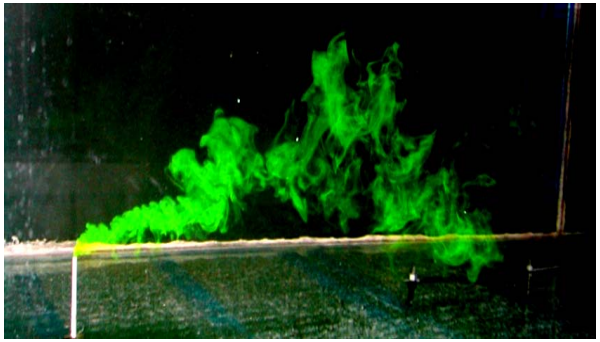
$$d_f = d_l \frac{V_l}{V_f} \left(\frac{D_l}{D_f}\right)^2$$

Precise concentration measurements

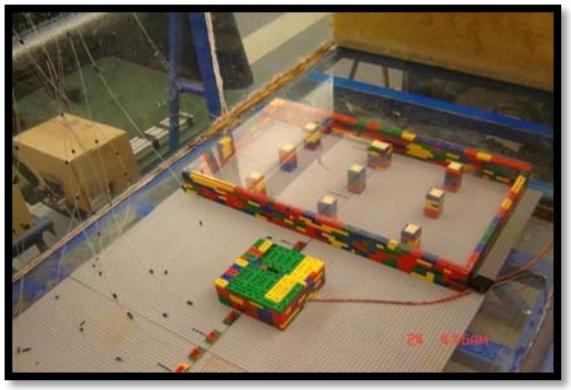


Laboratory Modeling

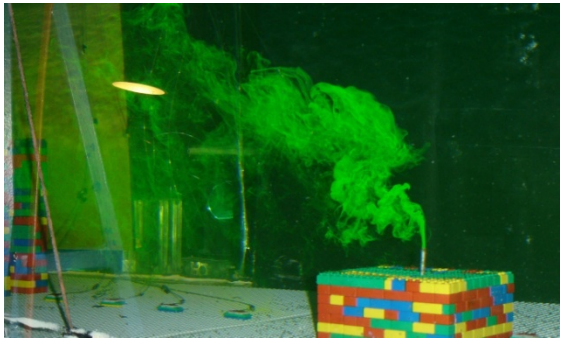
1. Dispersion of Pollutants from Single Stack

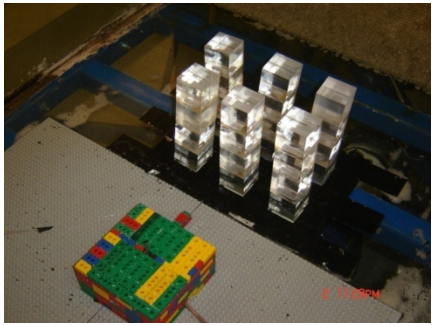


2. Palm Springs Field study simulation

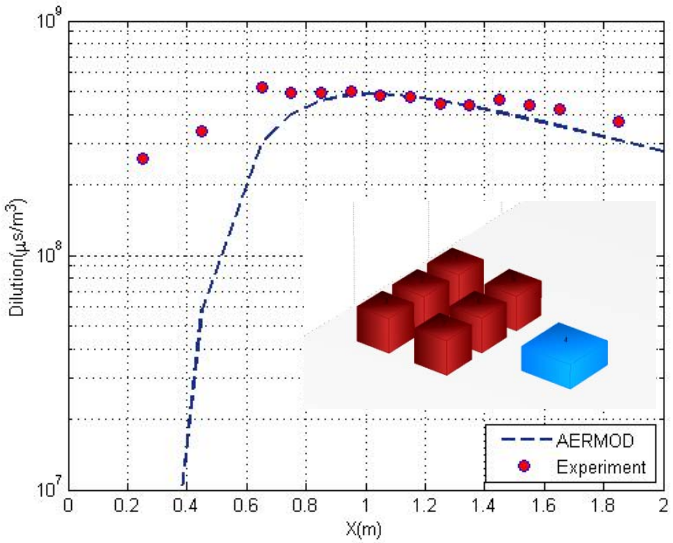


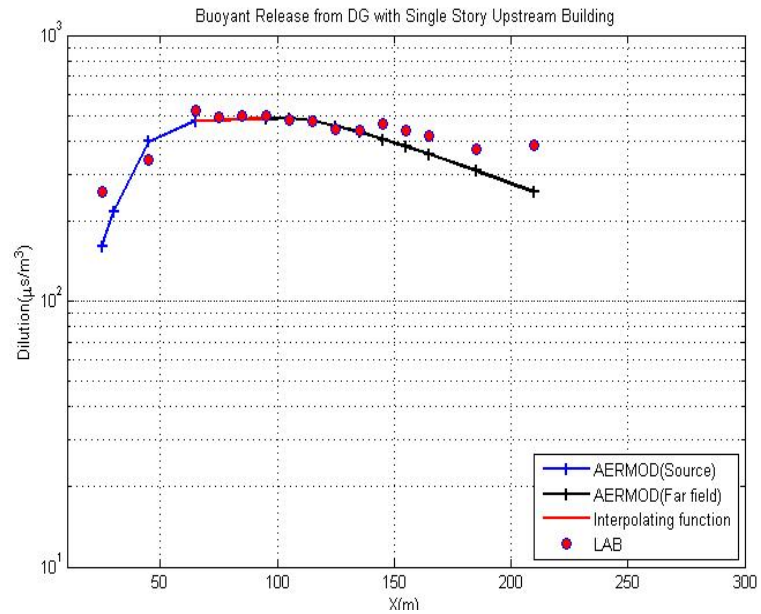
3. Urban Dispersion measurements in Complex Geometries

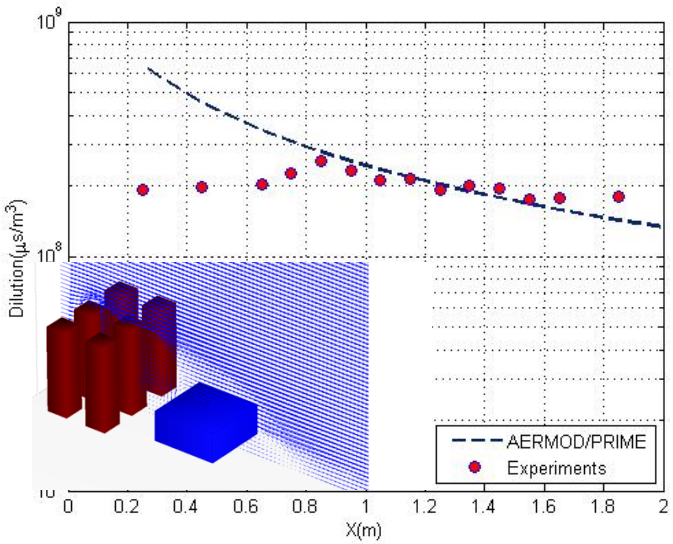


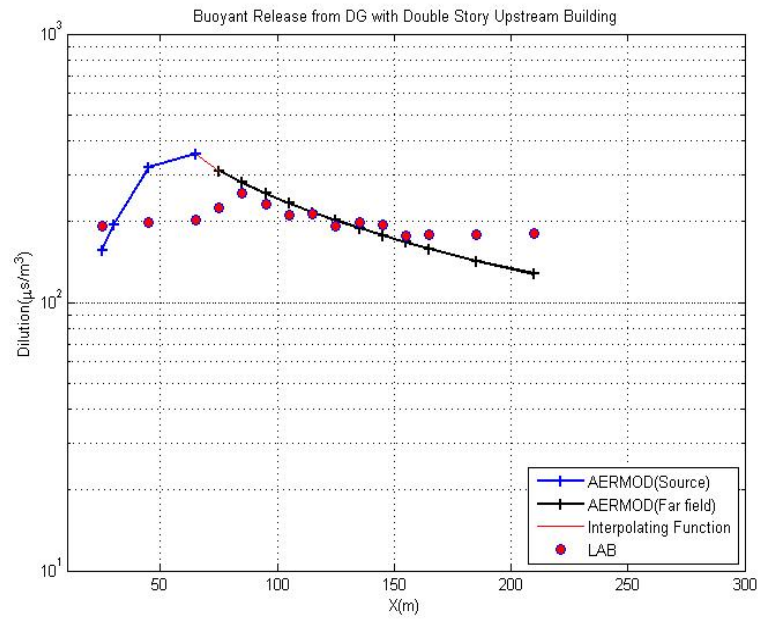


Laboratory Results and AERMOD



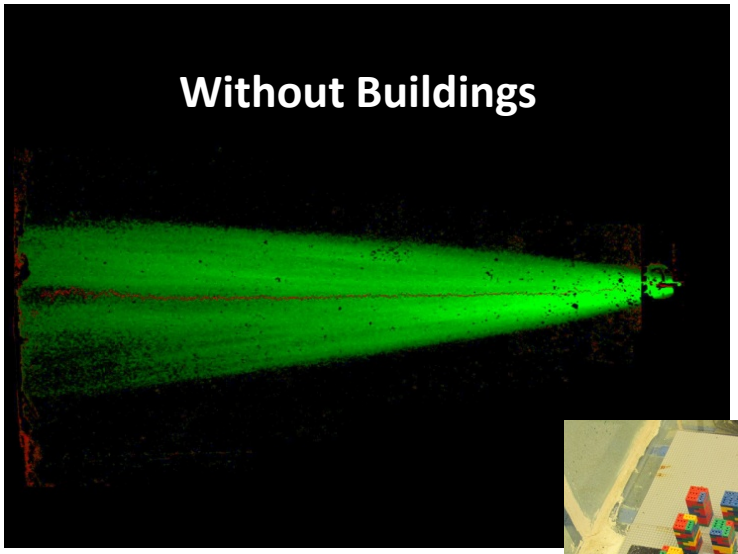


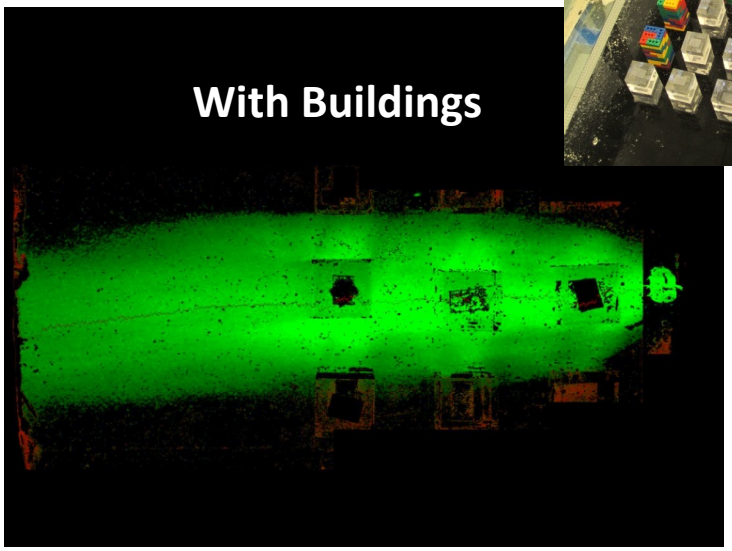


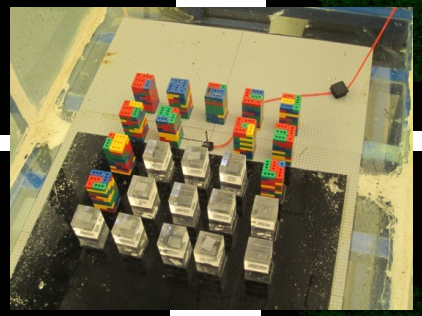


Horizontal Plume Spread

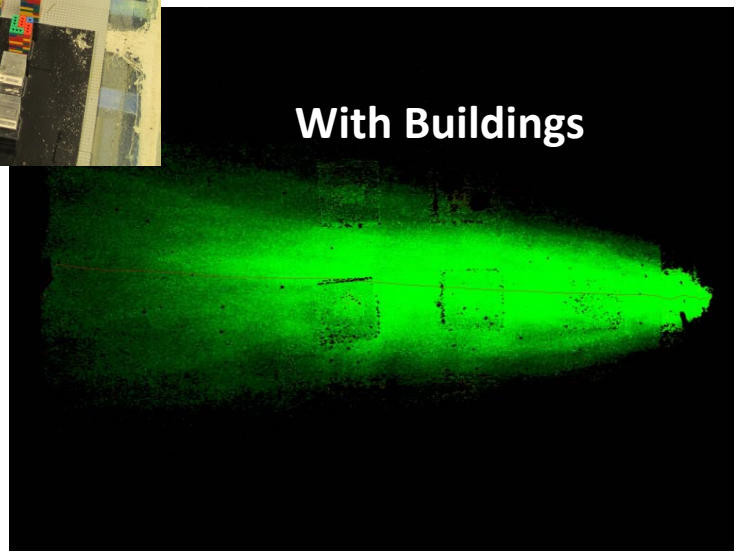
Without Flow Meandering





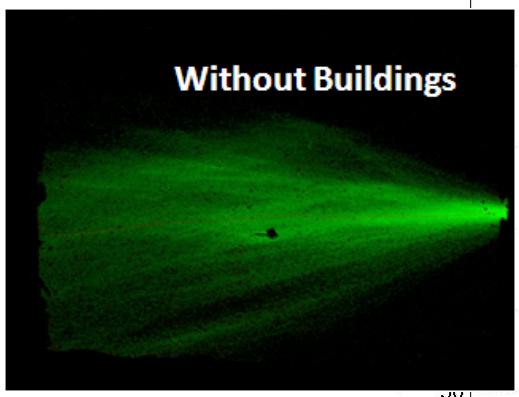


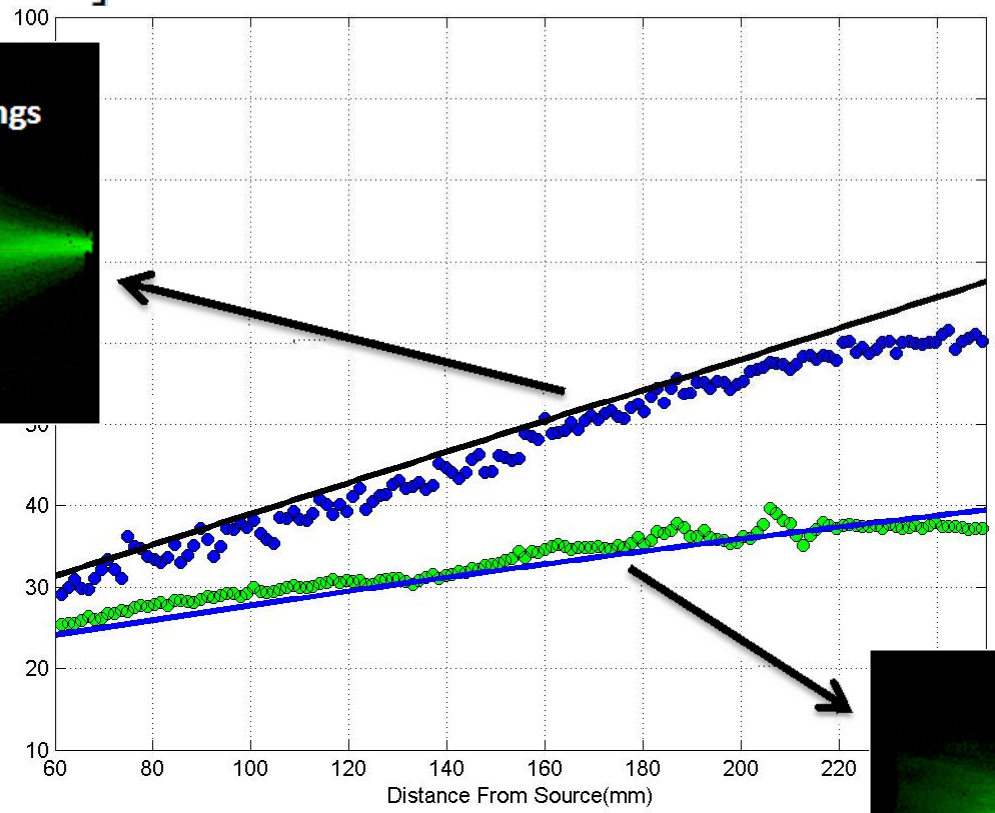
With Flow Meandering



Horizontal Plume Spread

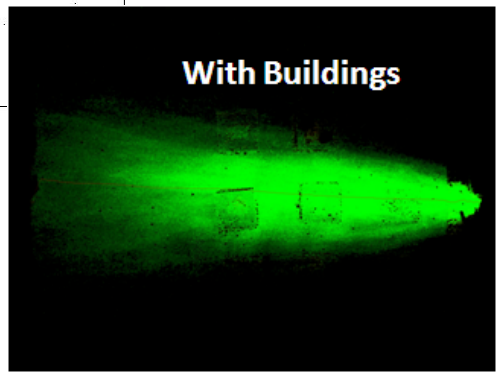
$$\sigma_y = \left[\left(\frac{\sigma_v X}{U}\right)^2 + \sigma_{y0}^2\right]^{0.5}$$



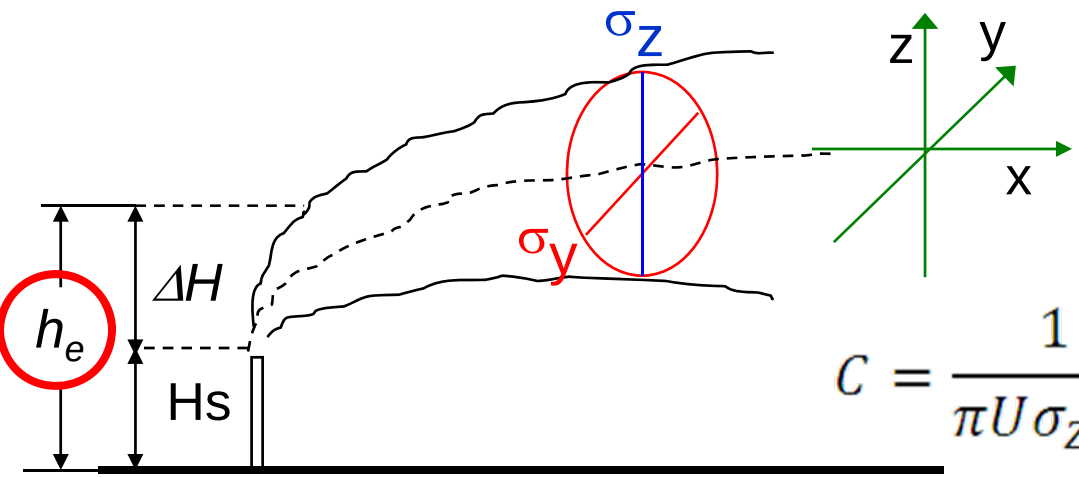


$$\sigma_{y0} = \frac{W_b}{\sqrt{2\pi}}$$

$$\sigma_y = \left[\left(\frac{\frac{\sigma_v x}{U}}{\left(1 + \frac{x}{W_b}\right)^{0.5}}\right)^2 + \sigma_{y0}^2\right]^{0.5}$$



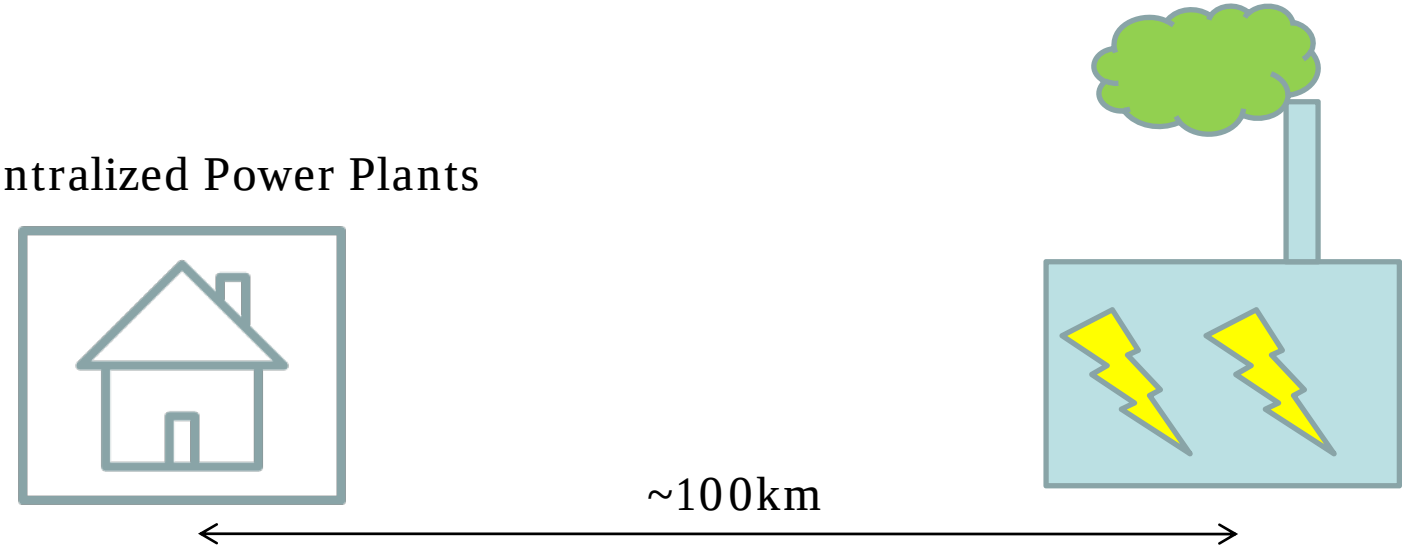
Plume Rise



$$C = \frac{1}{\pi U \sigma_z \sigma_y} \exp\left(-\frac{h_e^2}{2\sigma_z^2}\right) \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

DGs

Centralized Power Plants



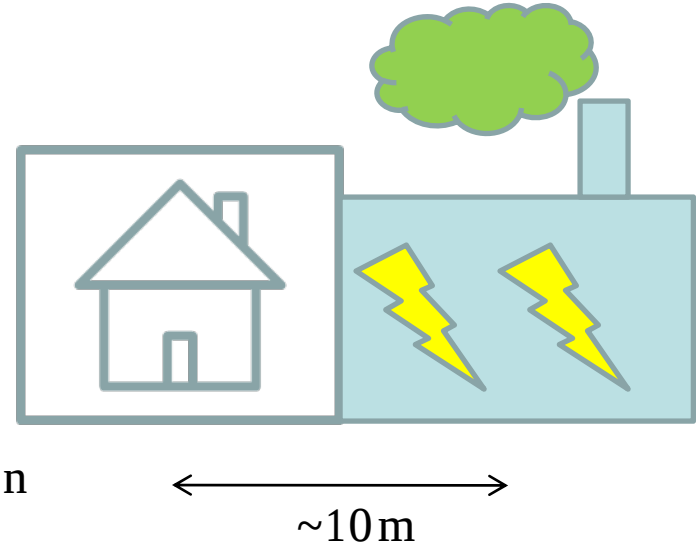
Distributed Generators

Heat recovery

=> Lower plume buoyancy

=> Lower plume rise

=> Higher ground level concentration



Plume Rise

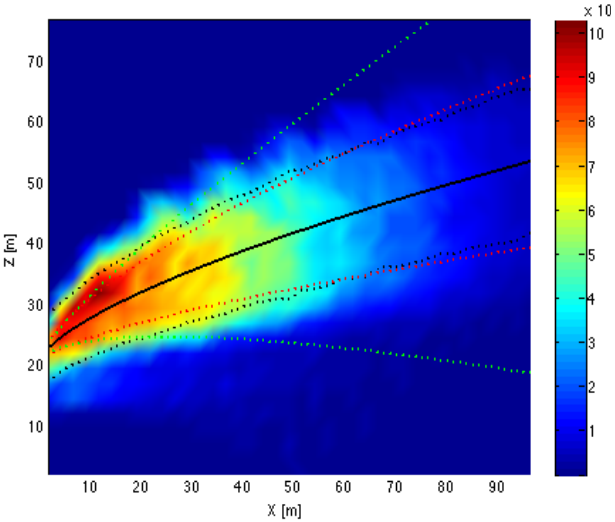
Briggs's theory

Buoyant Plume, Neutral Atmosphere, no obstacles:

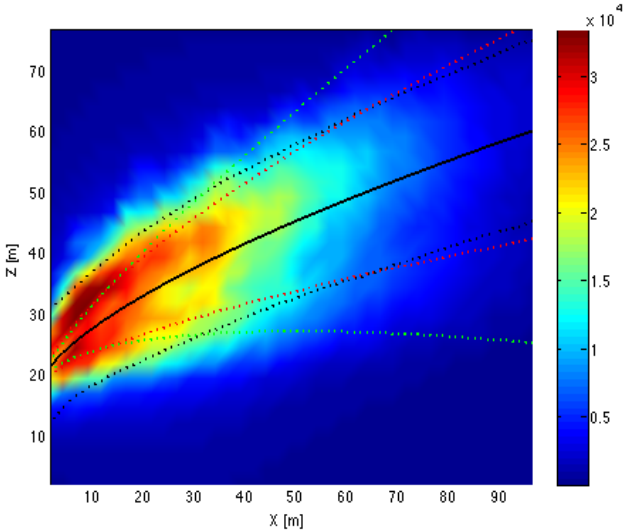
$$F_b = \frac{gV_s D^2}{4}\frac{\rho_a - \rho_s}{\rho_a} = \frac{gV_s D^2}{4}\frac{T_s - T_a}{T_s}$$

$$\Delta H(x) = 1.6\frac{F_b^{1/3}x^{2/3}}{U}$$

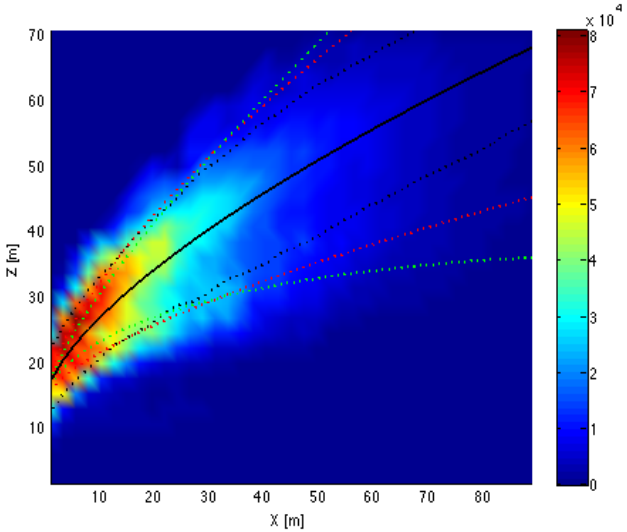
$$\Delta H_{final} = 1.8\frac{F_b}{U\sigma_w^2}$$



Field scaled buoyancy



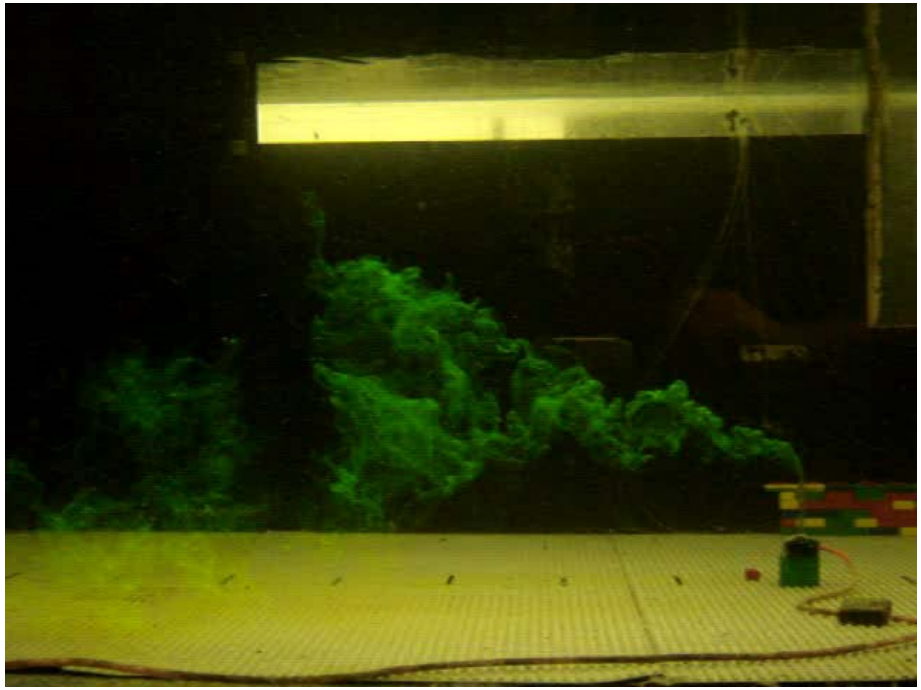
Double buoyancy

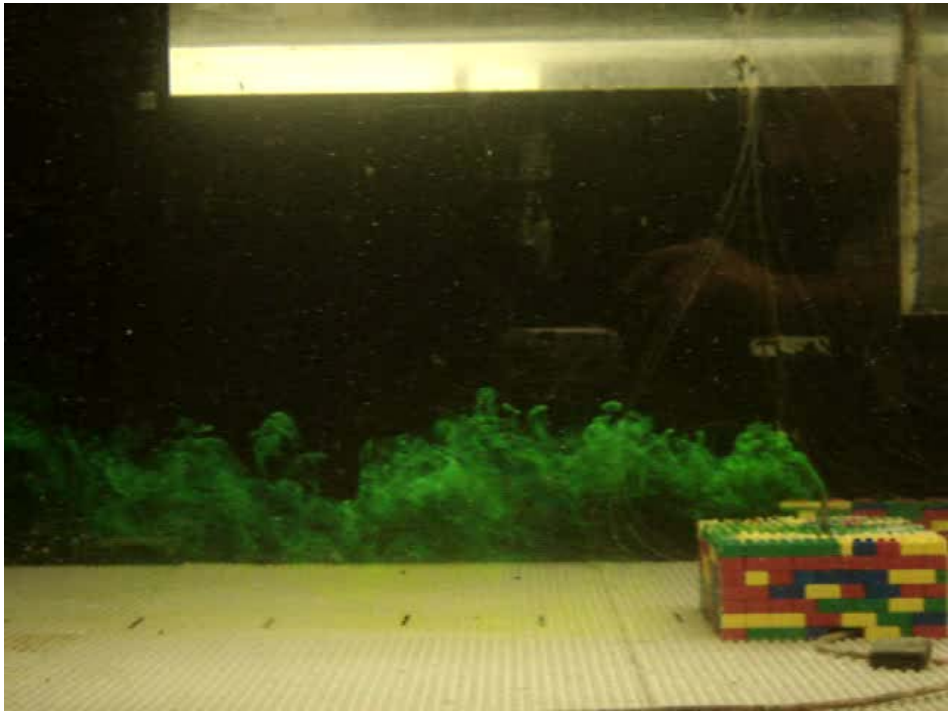


5 times of buoyancy

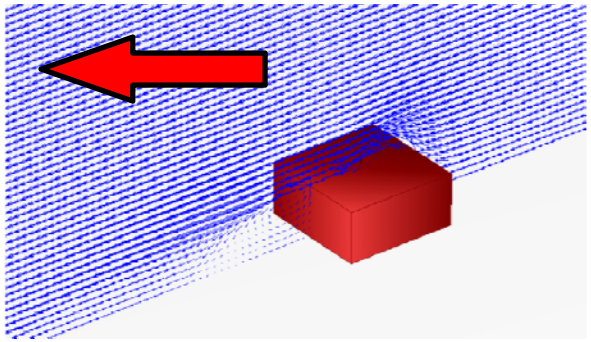
Presence of buildings and low wind conditions present a major problem!

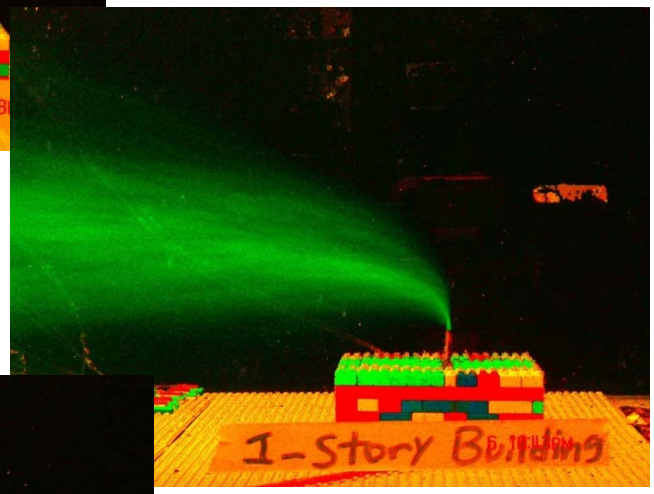
Plume Rise - Presence of Buildings

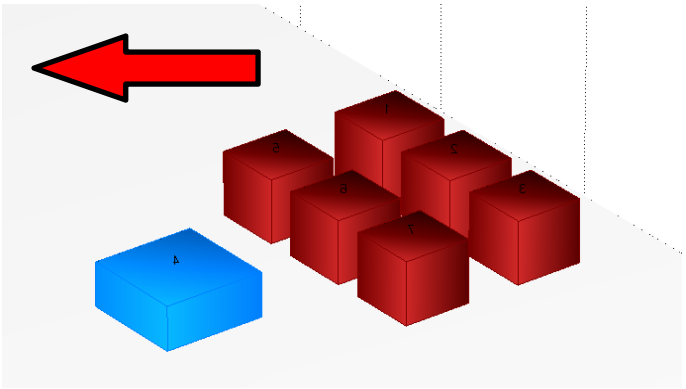


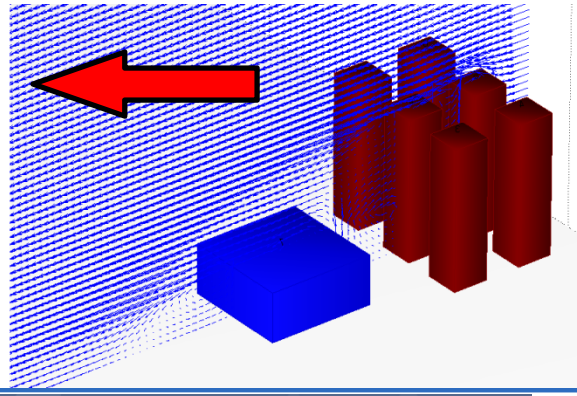


Plume Rise - Laboratory





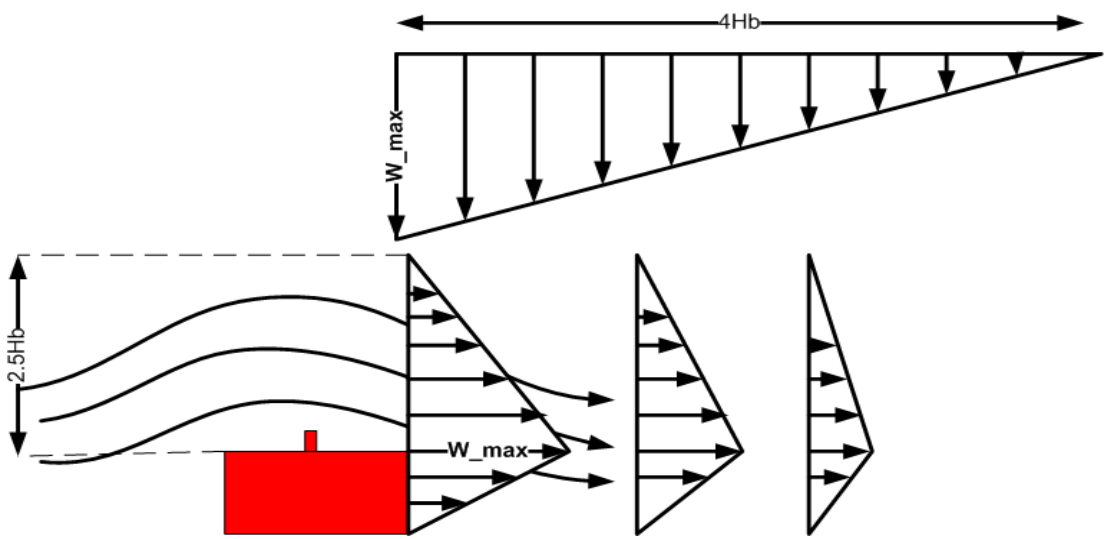




Plume Rise - Laboratory

Turbulence increase by buildings affects plume spread

$$C = \frac{1}{\pi U \sigma_z \sigma_y} \exp\left(-\frac{h_e^2}{2\sigma_z^2}\right) \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$



Flow modifications by building affects plume rise

$$\Delta H(x) = 1.6 \frac{F_b^{1/3} x^{2/3}}{U}$$

Numerical Plume Rise

$$\cancel{\Delta H(x) = 1.6\frac{F_b^{1/3}x^{2/3}}{U}}$$

Conservation of Mass

$$\frac{d}{ds}(U_{sc}r^2) = E \qquad \textit{where } E \textit{ is entrainment equal to } E = 2r\beta w$$

Conservation of Horizontal Momentum

$$\frac{d}{ds}(U_{sc}r^2(u - U_a)) = -r^2 w\frac{dU_a}{dz}$$

Conservation of vertical Momentum

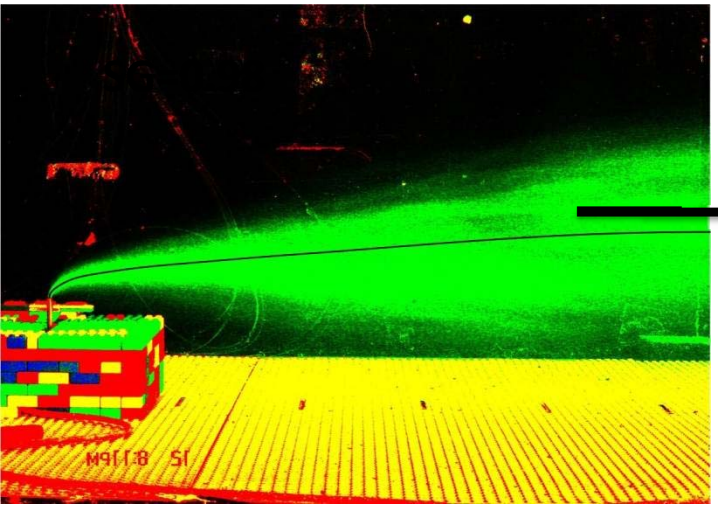
$$\frac{d}{ds}(U_{sc}r^2 w) = gr^2\frac{\Delta\rho}{\rho}$$

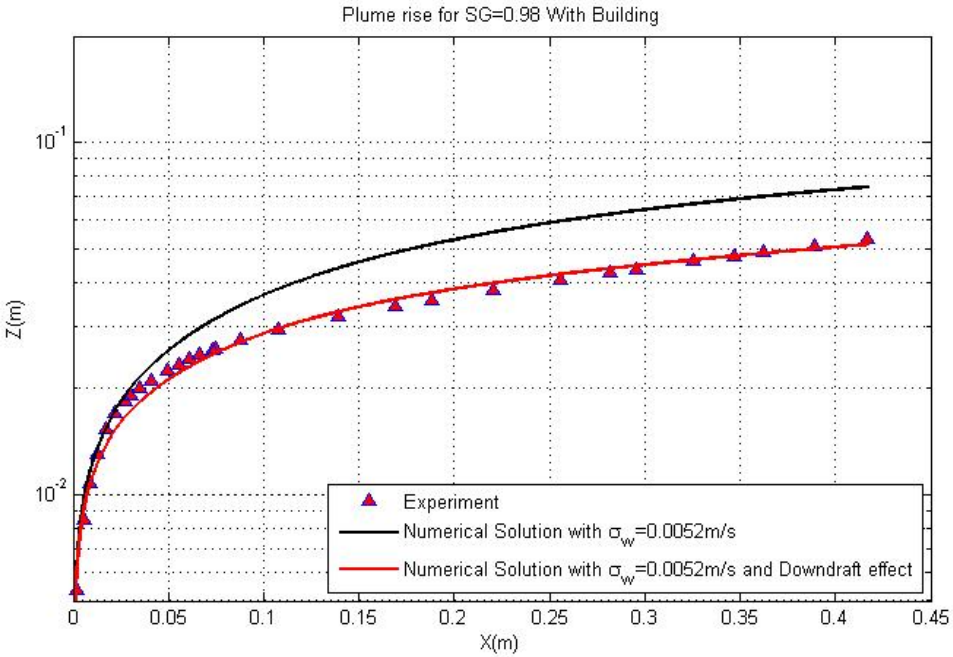
From measurements

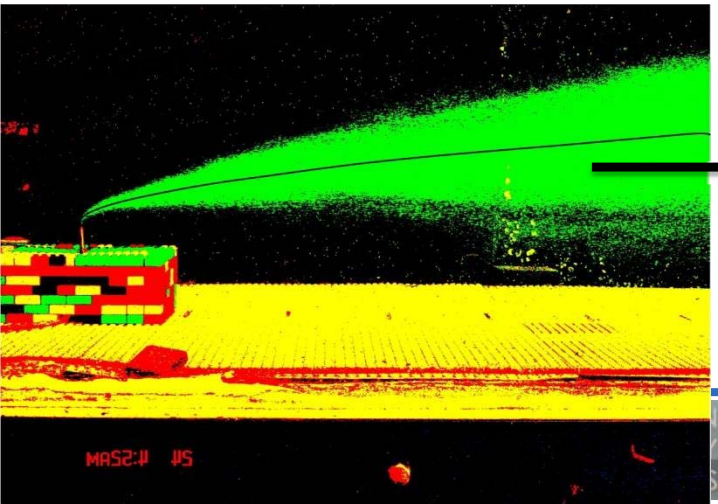
Conservation of Energy

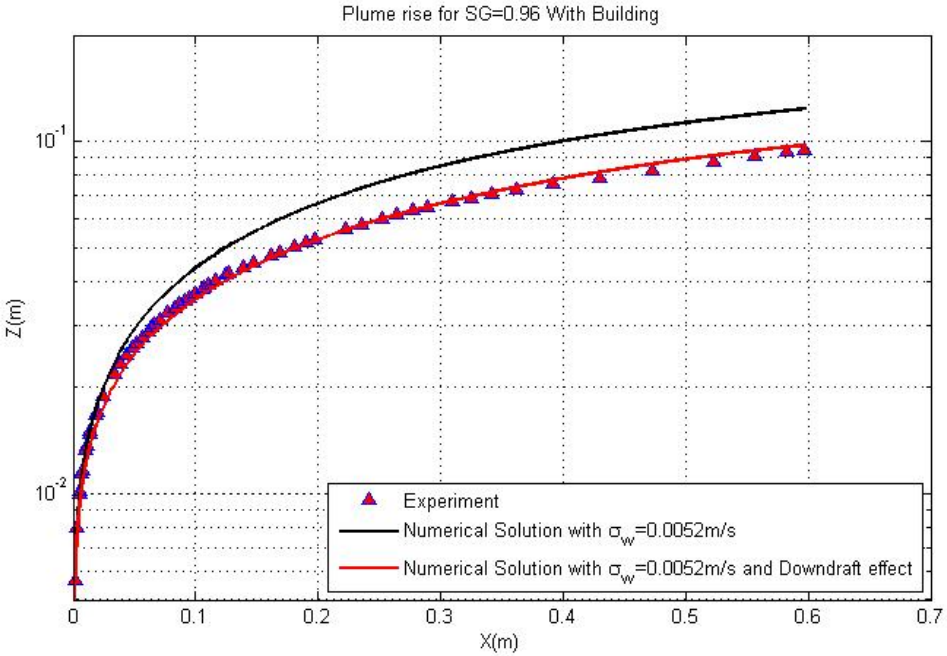
$$\frac{d}{ds}[\rho U_{sc}r^2(T - T_a)] = -\frac{d\theta}{dz}\rho w r^2 - R_p r(T^4 - T_a^4)$$

Plume Rise – Numerical

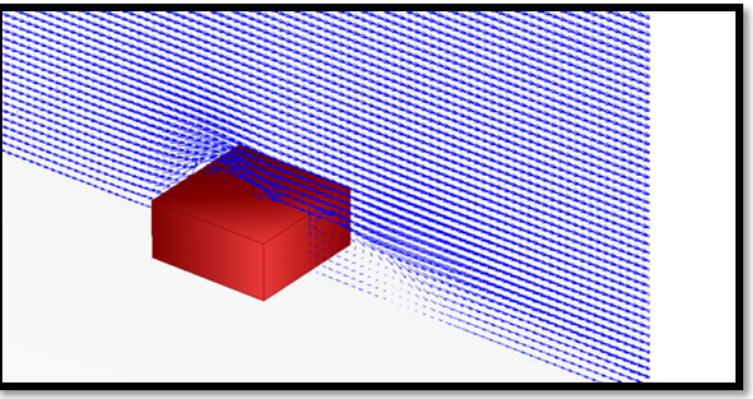


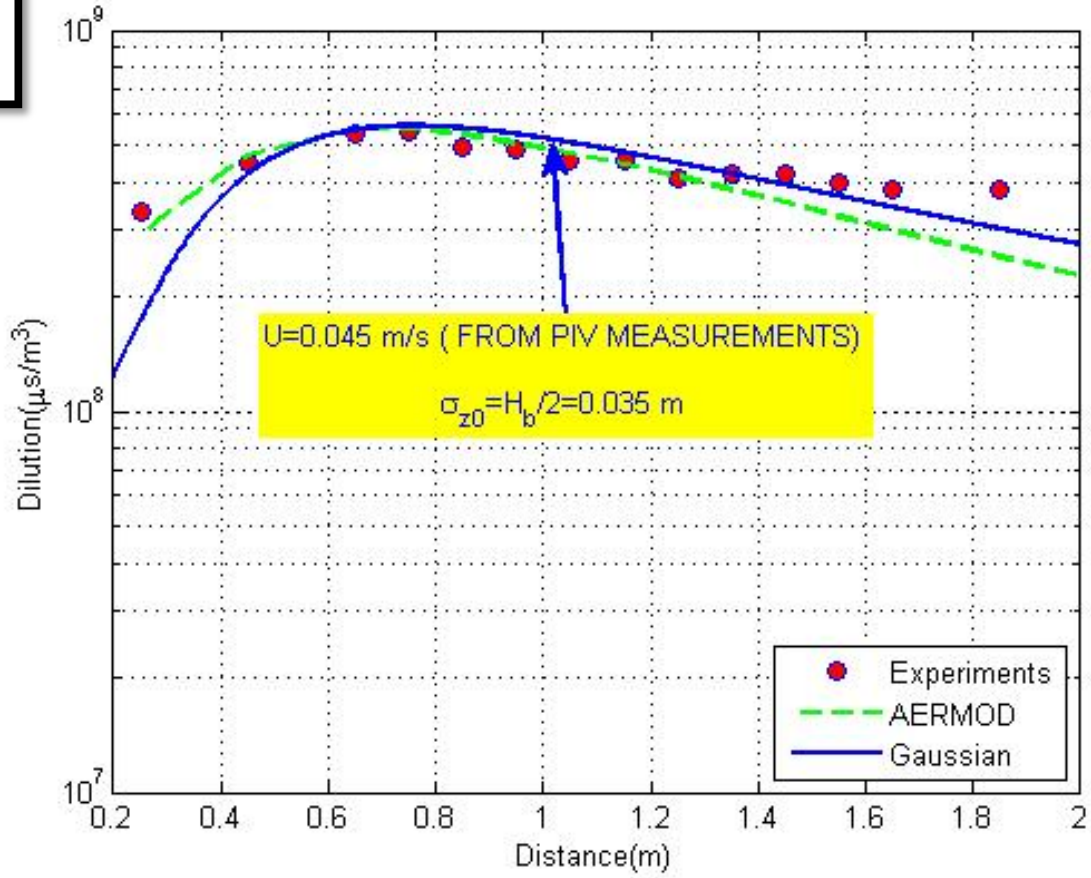




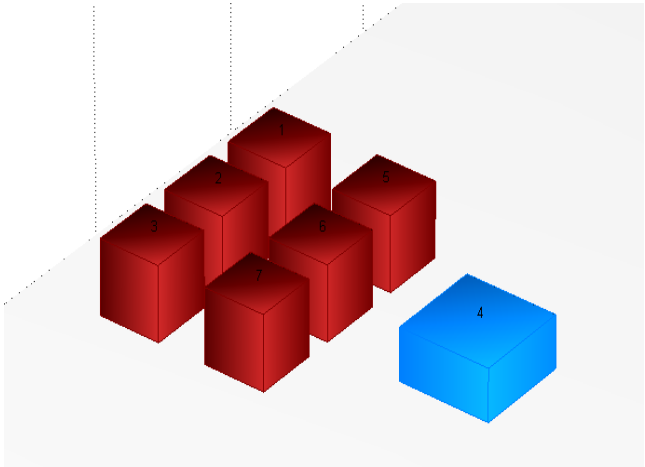


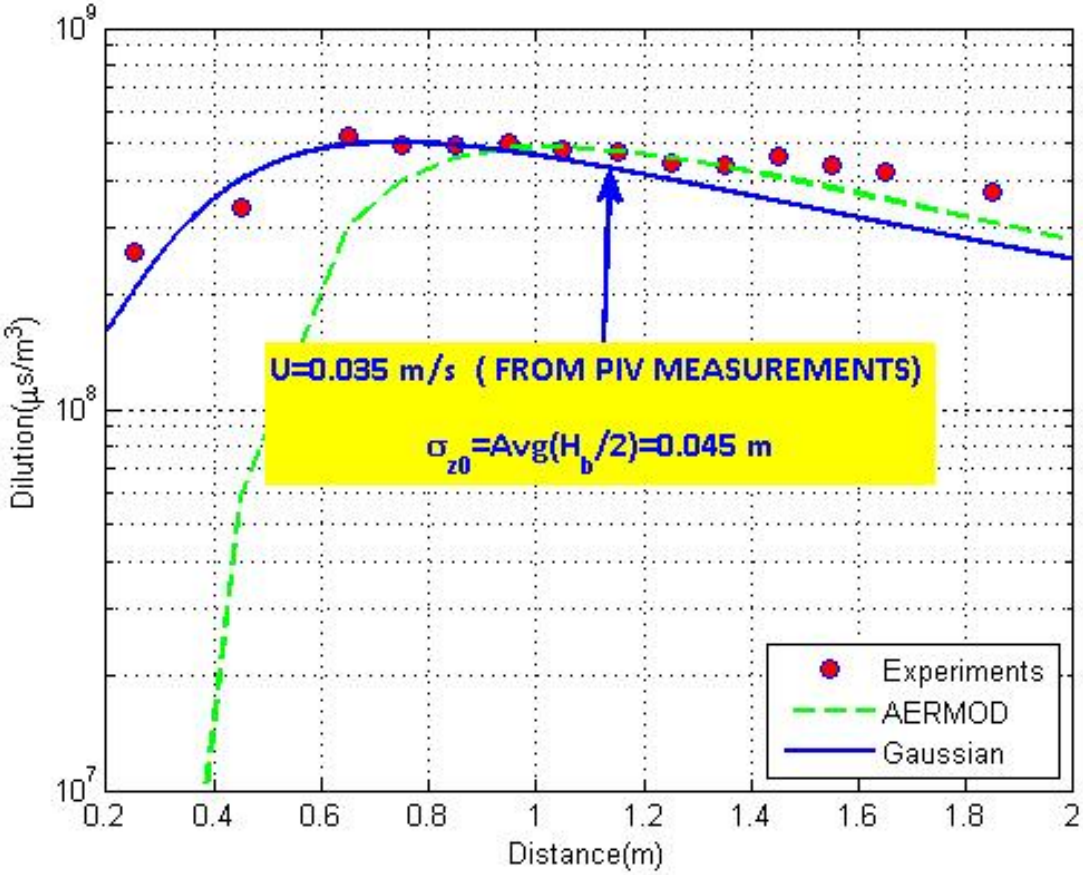
Laboratory vs. Model



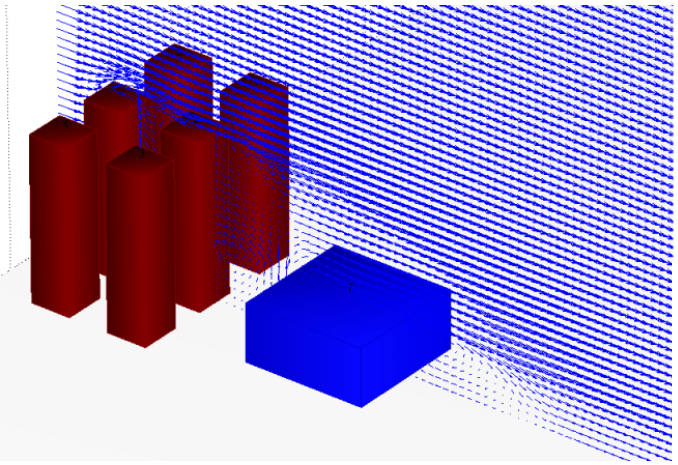


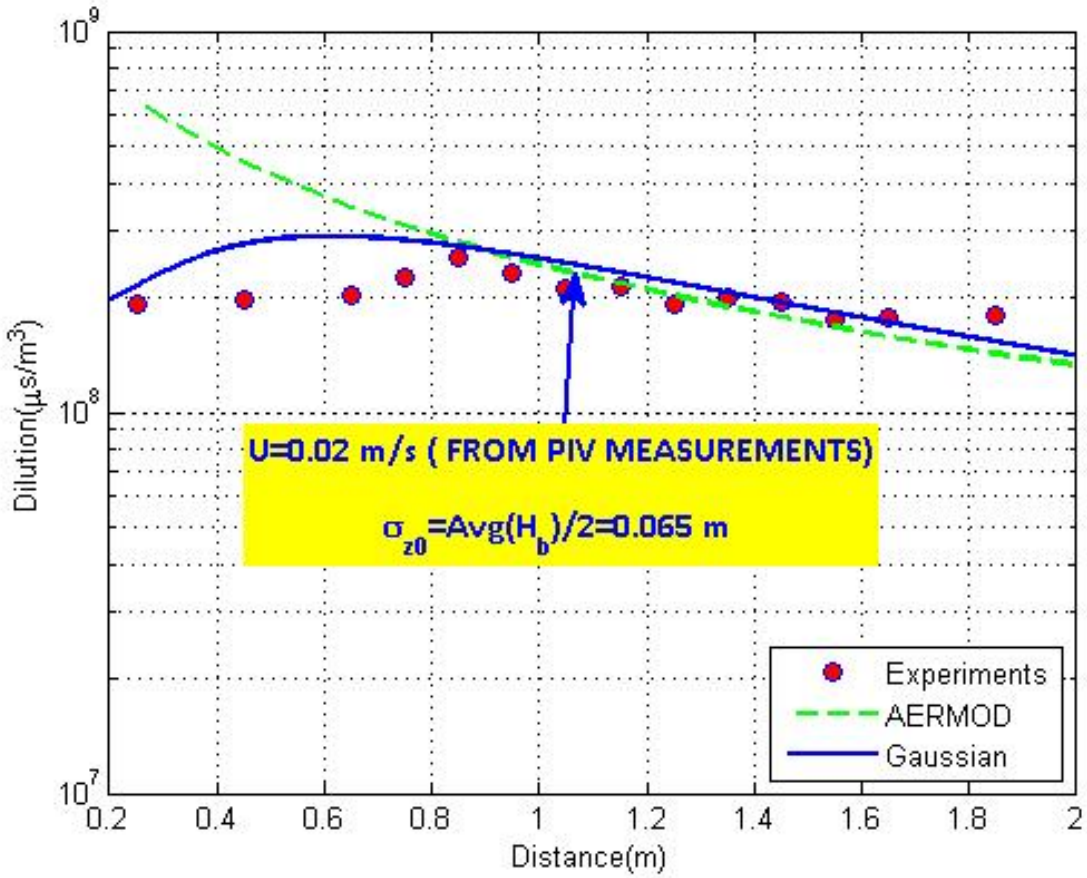
Laboratory vs. Model





Laboratory vs. Model



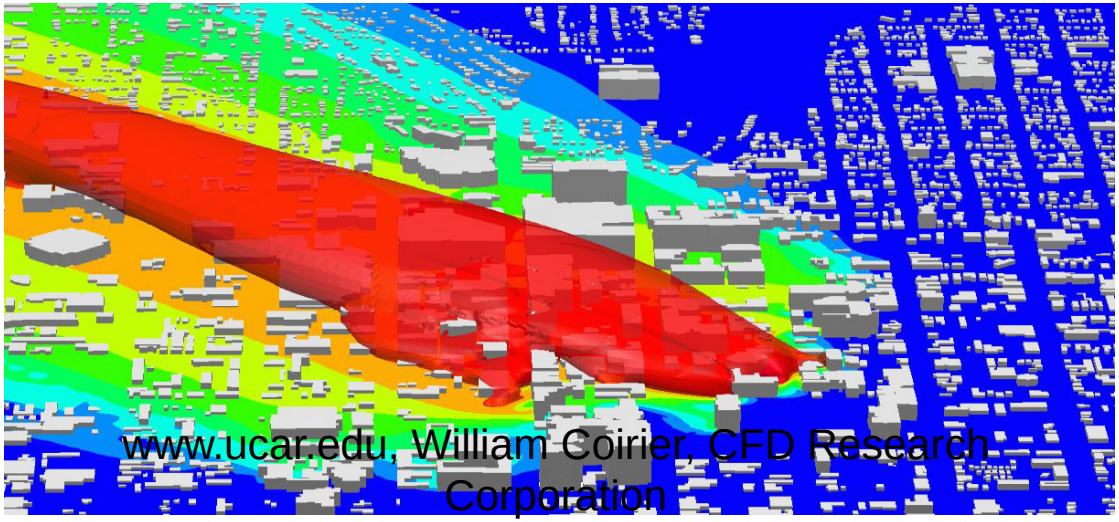


Plume Rise Measurements in the Field

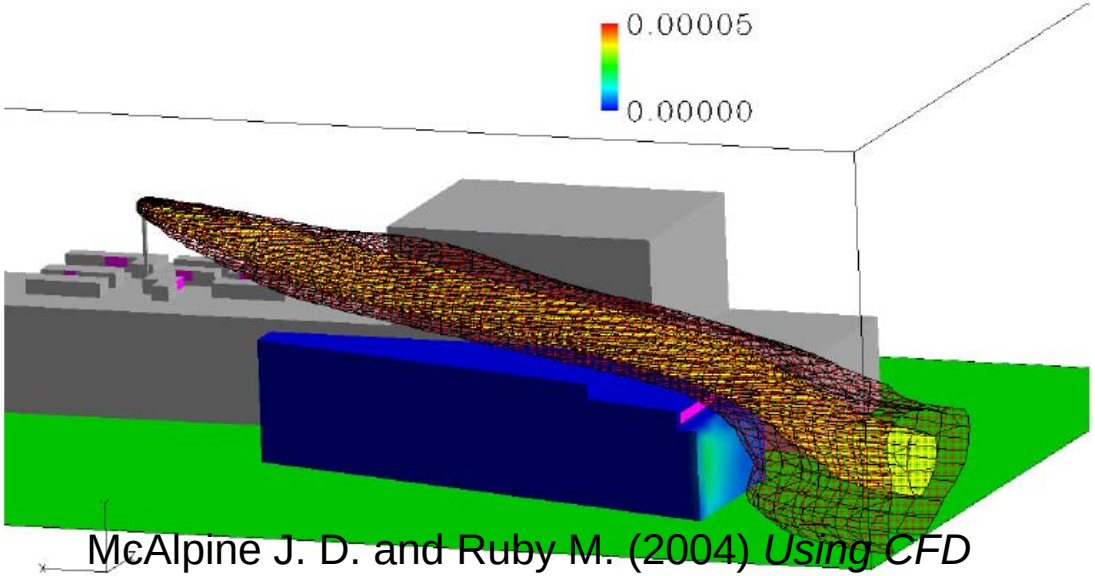
~~DG in Palm Springs – plume visualization~~

Fire Burns at Verizon Building in Palm Springs

CFD Plume



www.ucar.edu, William Coirier, CFD Research Corporation

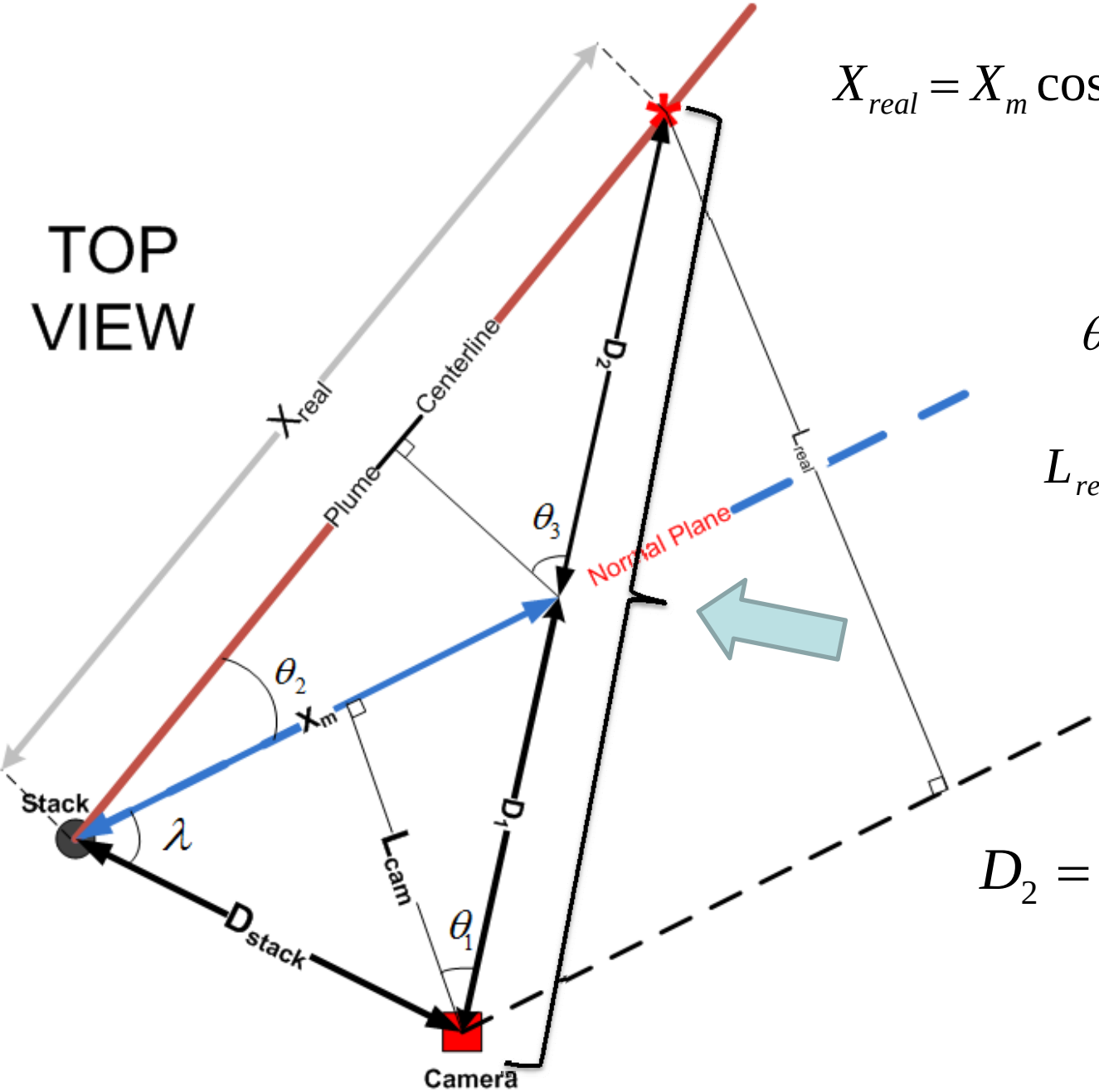


McAlpine J. D. and Ruby M. (2004) *Using CFD to Study Air Quality in Urban Microenvironments.*

Field - Low Wind Speed

Plume height from 2D image

Plume height from 2D image



$$X_{real} = X_m \cos(\theta_2) + X_m \sin(\theta_2)\tan(\theta_3)$$

$$\theta_3 = \theta_1 + \theta_2$$

$$\theta_1 = \tan^{-1}\left(\frac{X_m - X_{center}}{L_{cam}}\right)$$

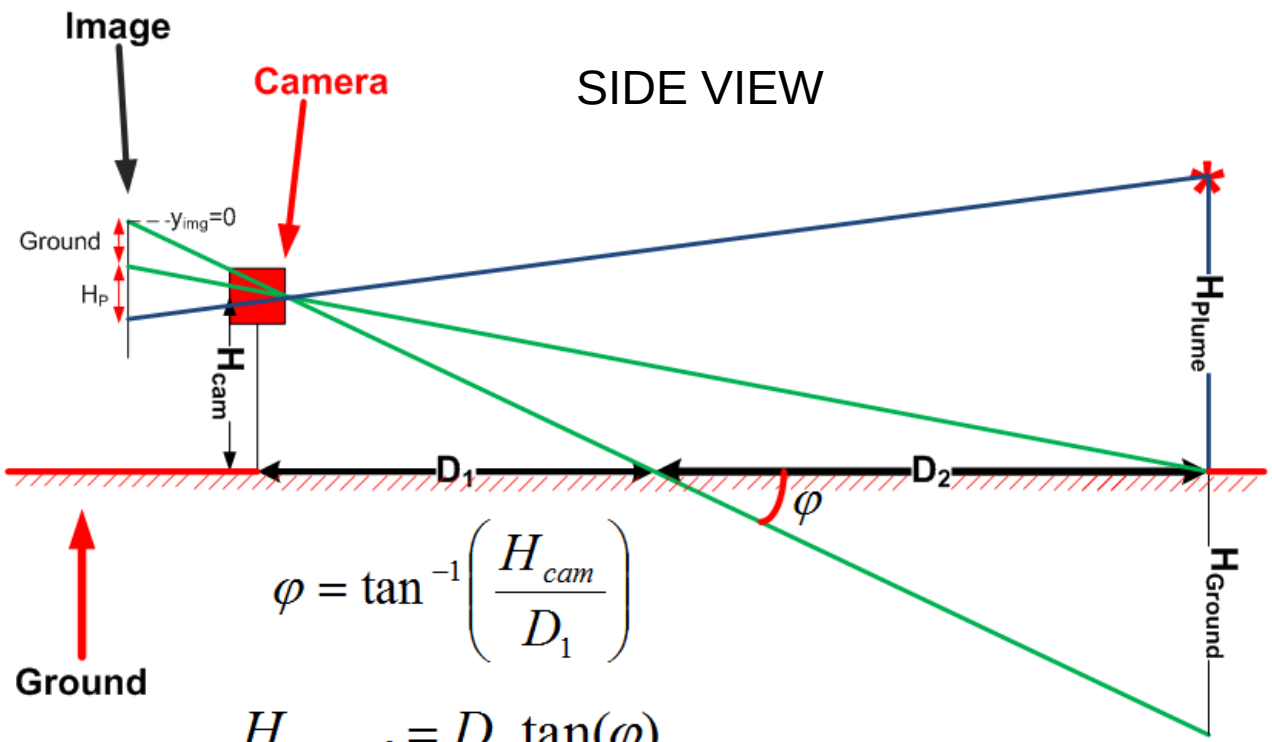
$$L_{real} = L_{cam} + X_{real} \times \sin(\theta_2)$$

$$L_{cam} = D_{stack} \sin(\lambda)$$

$$D_1 = L_{cam} / \cos(\theta_1)$$

$$D_2 = X_m \sin(\theta_2) / \cos(\theta_3)$$

Plume height from 2D image



$$\varphi = \tan^{-1}\left(\frac{H_{cam}}{D_1}\right)$$

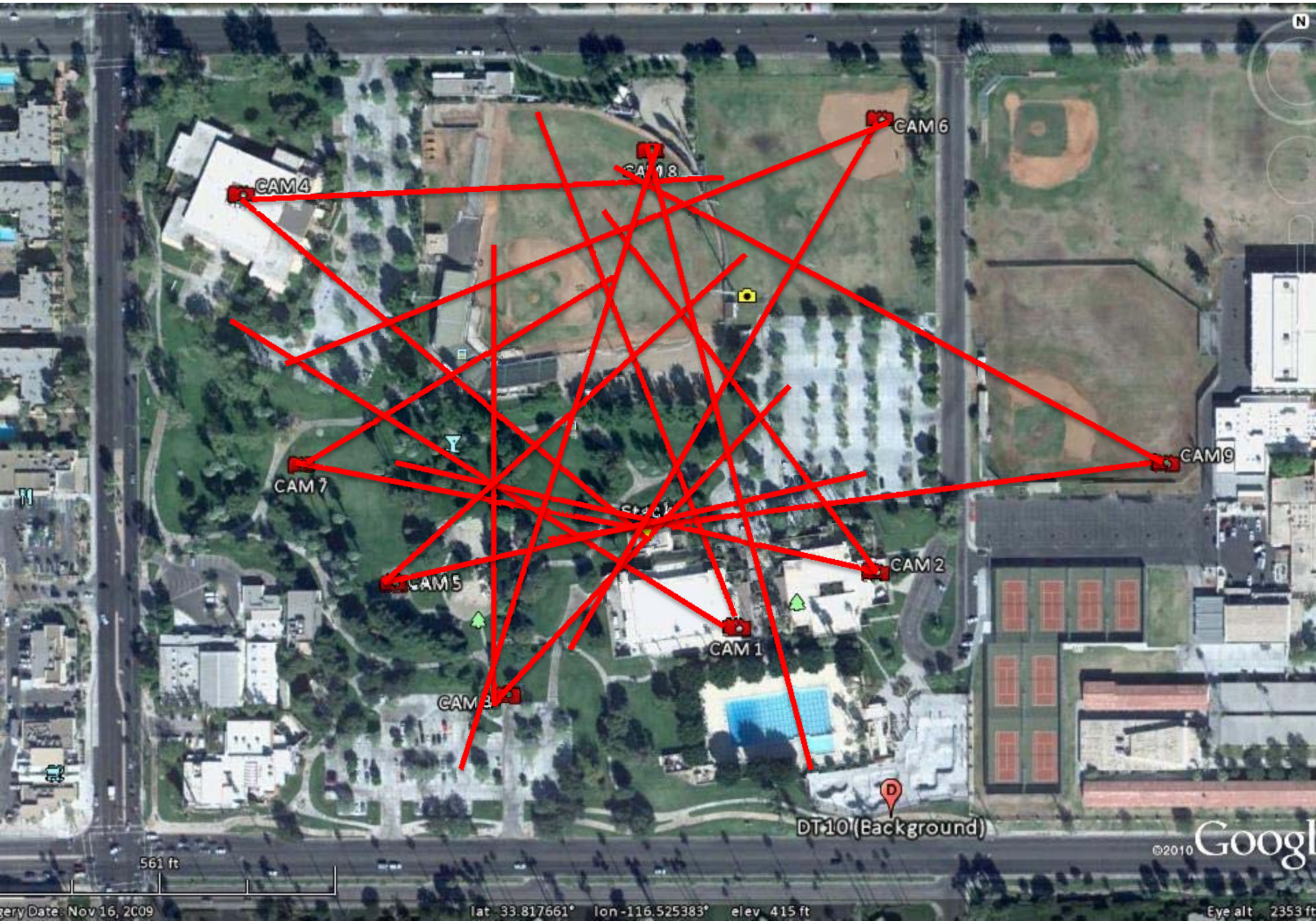
$$H_{Ground} = D_2 \tan(\varphi)$$

$$Z_1 = Z_{img} \times \frac{H_{s-real}}{H_{s-img}}$$

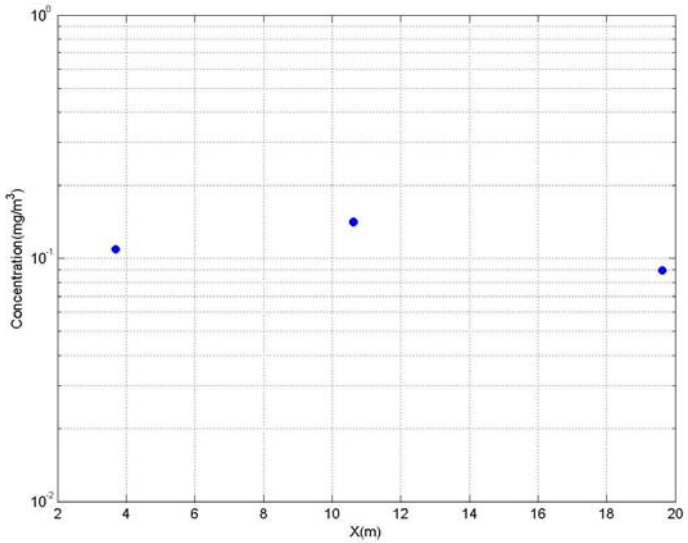
$$Z_2 = Z_1 \times \left(1 + \frac{X_{real}\sin(\theta_2)}{L_{cam}}\right)$$

$$H_{Plume} = Z_2 - H_{Ground}$$

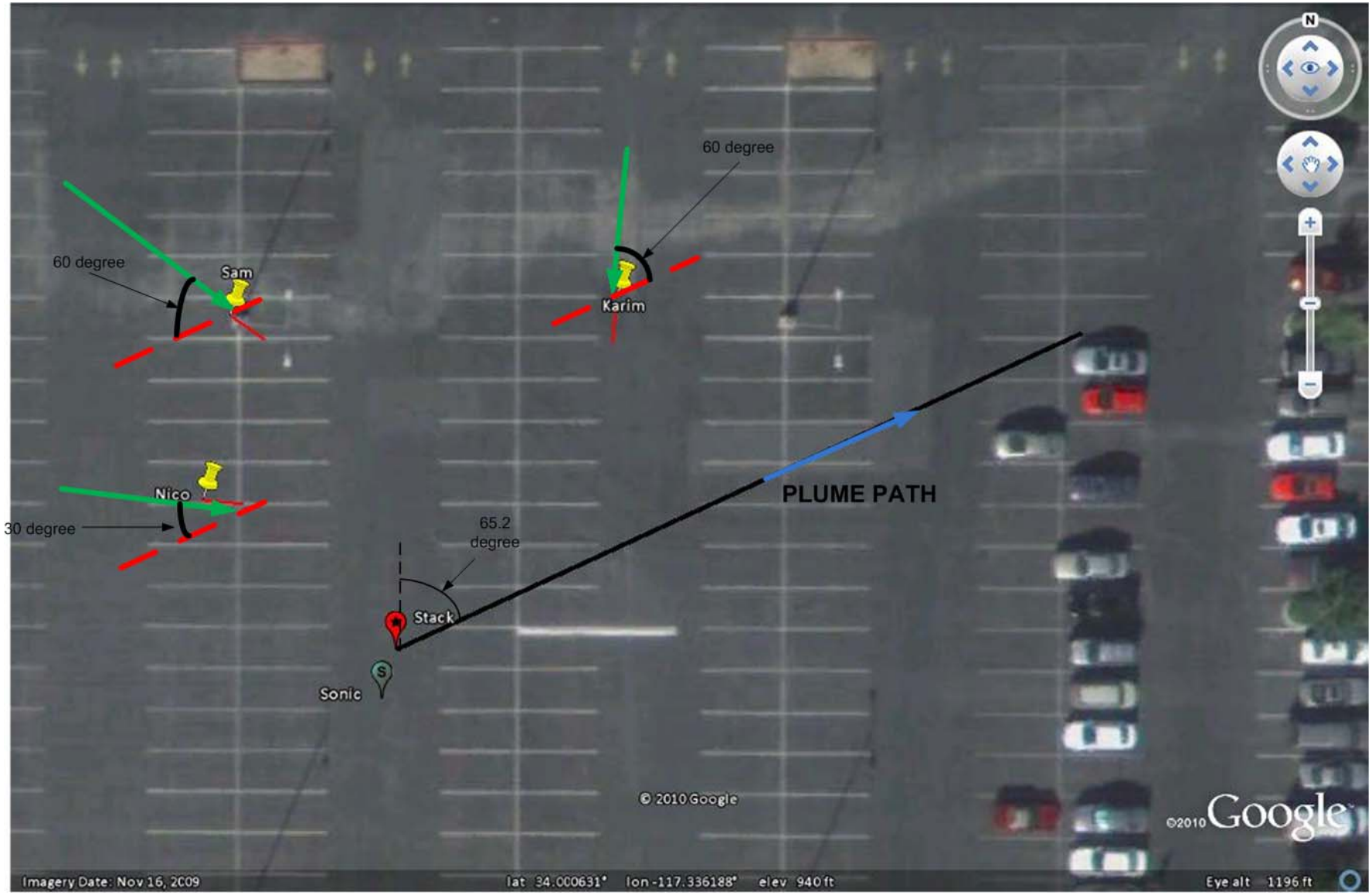
Field Plan


CAM 6
CAM 4
CAM 9
CAM 7
CAM 2
CAM 5
CAM 1
DT10 (Background)
561 ft
©2010 Google
lat 33.817661° lon -116.525383° elev 415 ft
Eye alt 2353 ft

Test experiments at CE-CERT parking lot

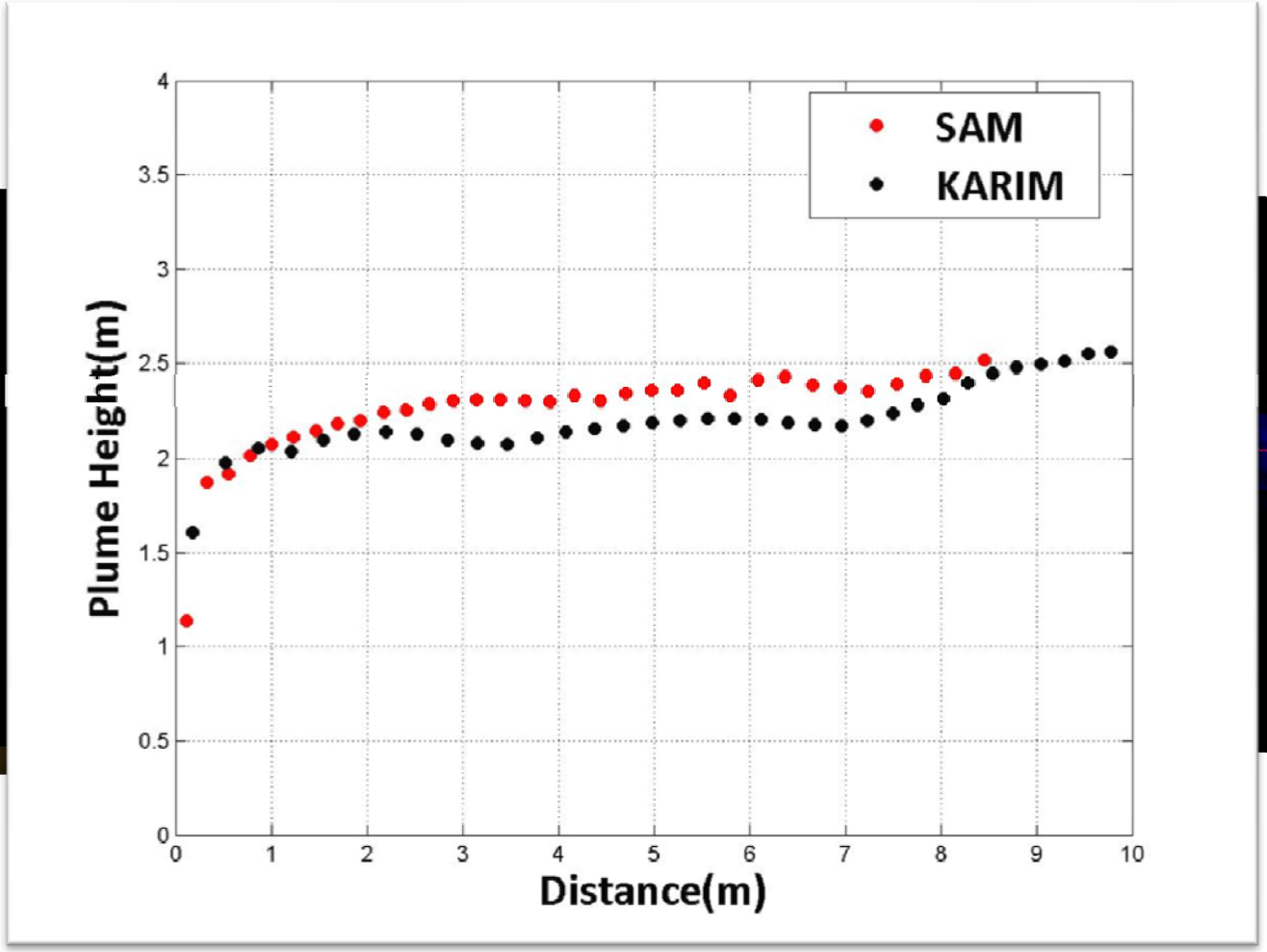


Test experiments at CE-CERT parking lot

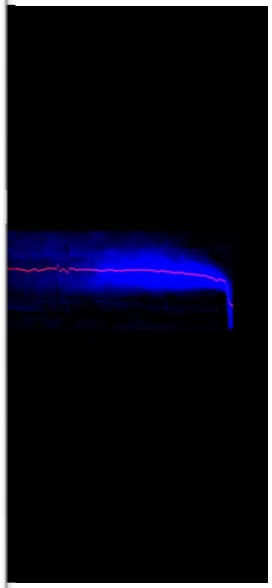


Test experiments at CE-CERT parking lot

KARIM



SAM

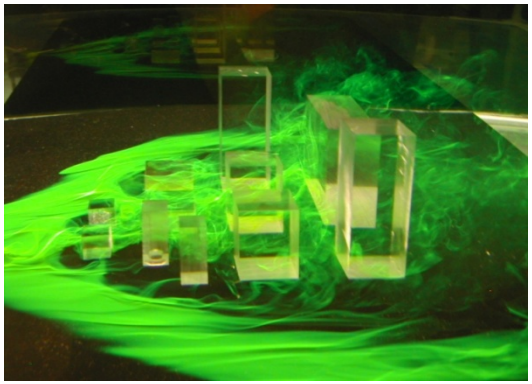


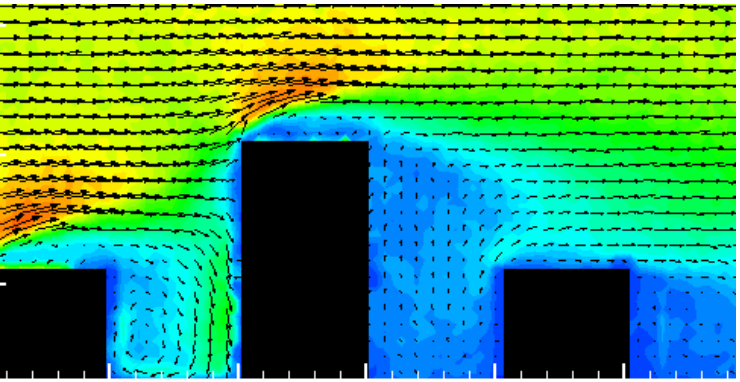
Ready for Palm Springs Measurements

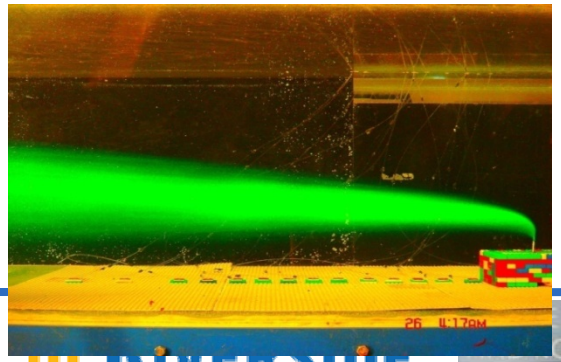
Summary

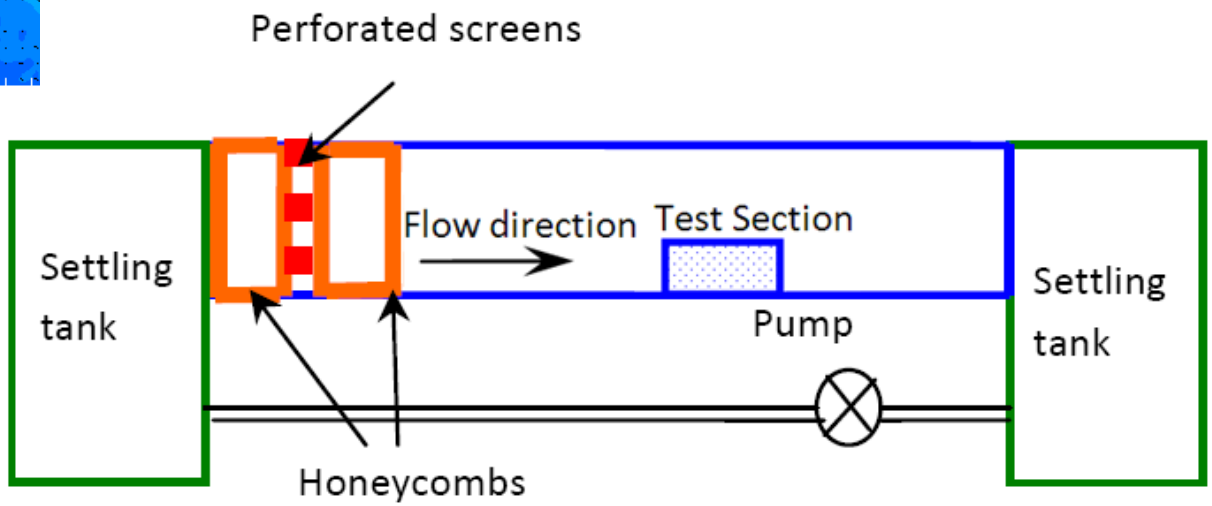
- Dispersion experiments conducted in the field and laboratory
- Building influence on plume rise and plume spread explained
- Urban areas – low wind speed – wind meandering is very important
- AERMOD tested and recommendations suggested
- Developed and tested methods for field plume rise measurements
- Ongoing plume rise field study in Palm Springs

Laboratory Setup







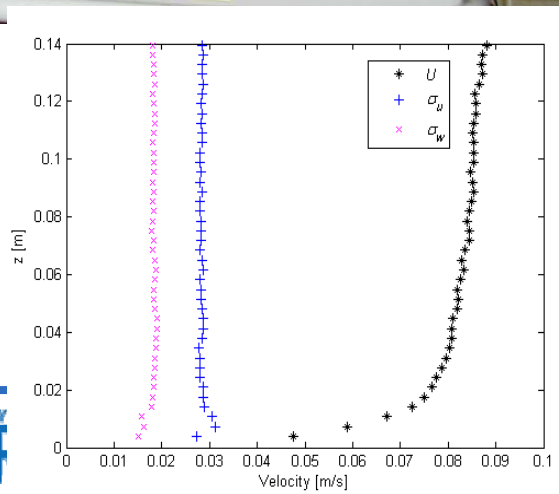


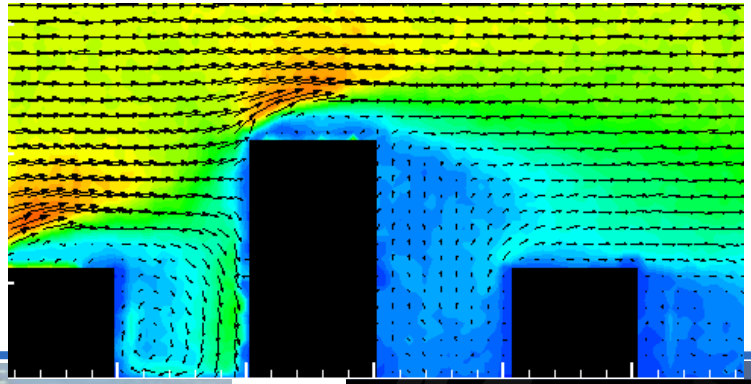
Velocity Measurements

Flow Field is measured using Particle Image Velocimetry (PIV) system

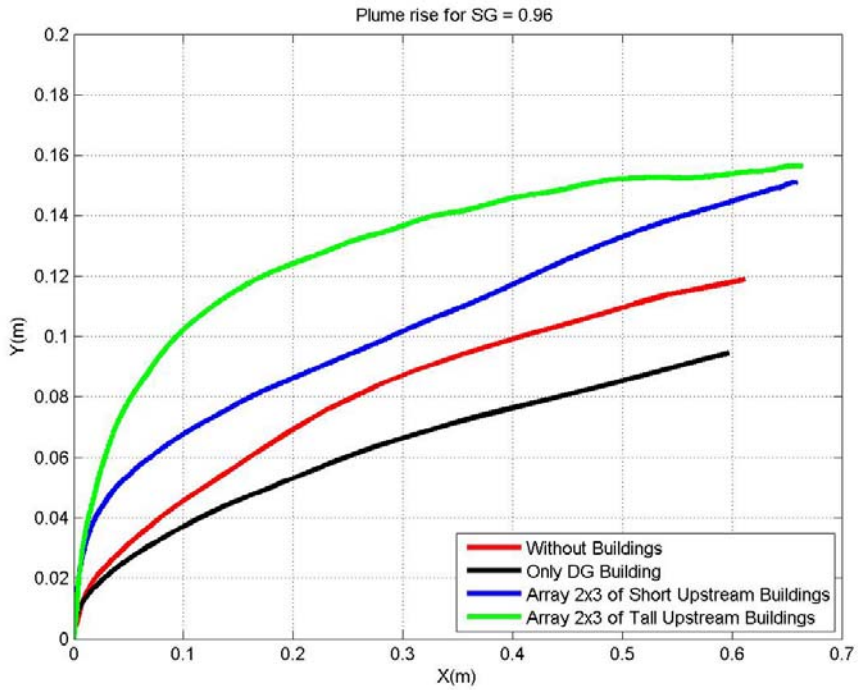
400 mJ Nd-YAG Laser

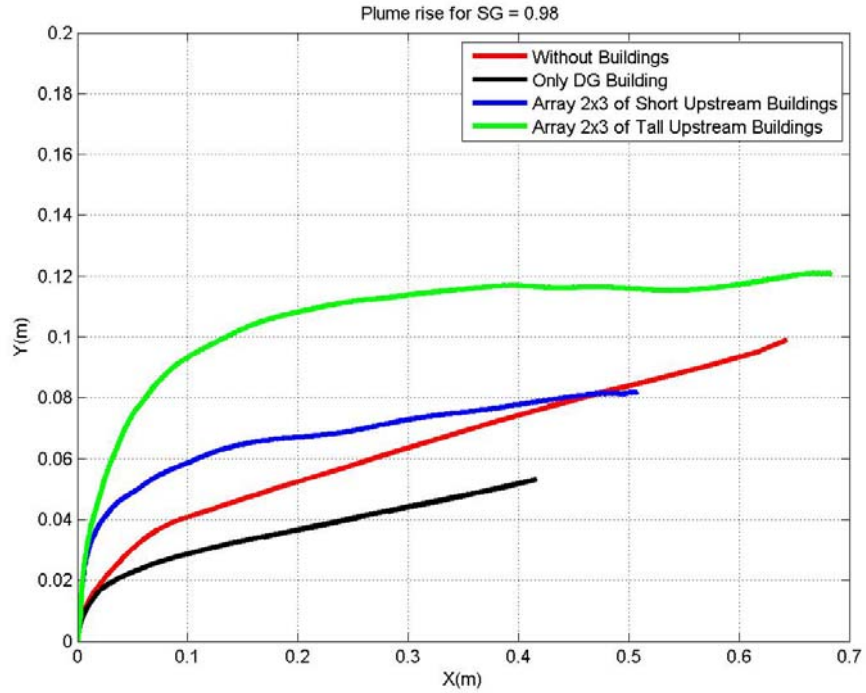
POWERVIEW 11M CCD camera



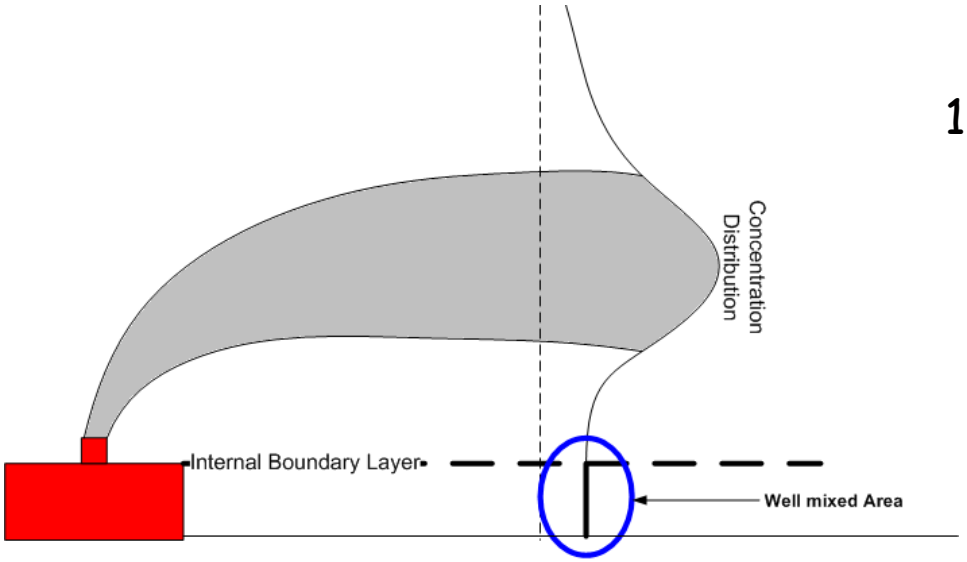


Plume rise Measurements



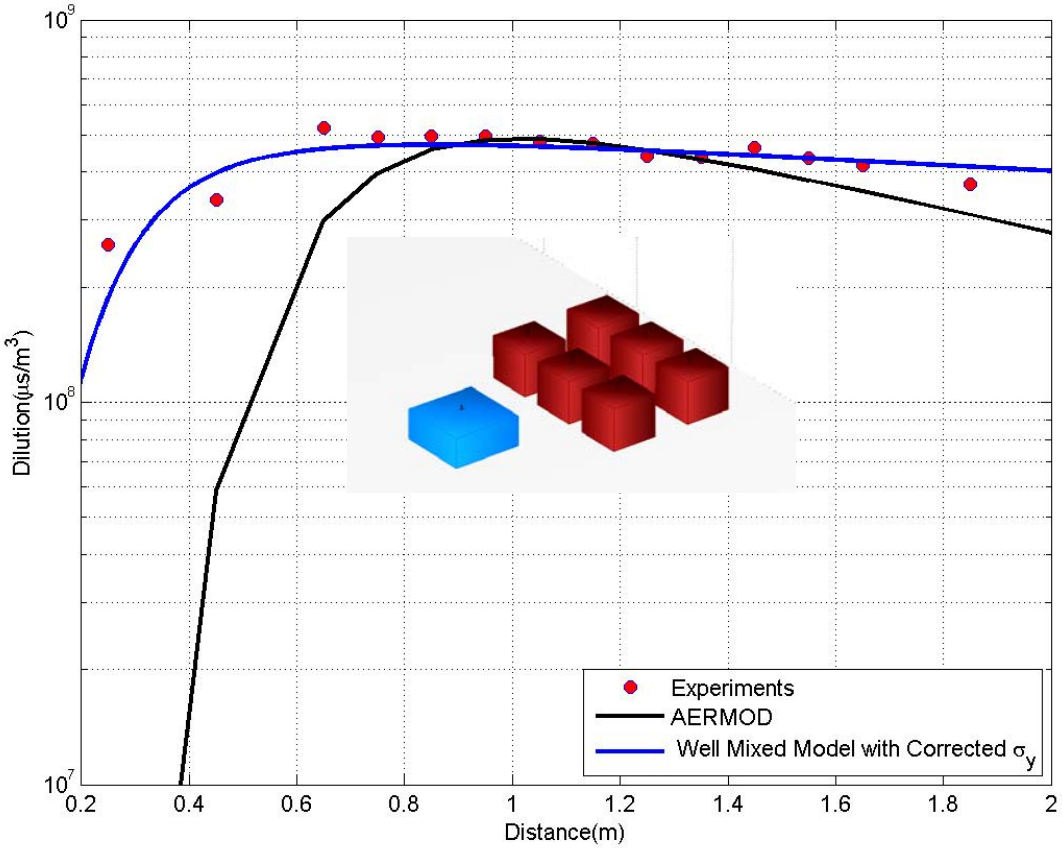


Near Source Model



1. Rapid vertical mixing below canopy
2. Rapid initial mixing in the horizontal
3. Horizontal length scale set by building geometry

$$C(x,y,0) = \frac{1}{2\sqrt{2\pi}\sigma_y U h_c}\left[\mathrm{erf}\left(\frac{h_e + h_c}{\sqrt{2}\sigma_z}\right) - \mathrm{erf}\left(\frac{h_e - h_c}{\sqrt{2}\sigma_z}\right)\right]\exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

$$\sigma_y = \left[\left(\frac{\frac{\sigma_v x}{U}}{\left(1 + \frac{x}{W_b}\right)^{0.5}}\right)^2 + \sigma_{y0}^2\right]^{0.5} \qquad \sigma_{y0} = \frac{W_b}{\sqrt{2\pi}}$$

Laboratory Results