Observations of the Spatial Structure of Turbulence with Horizontal Arrays of In-Situ Sensors

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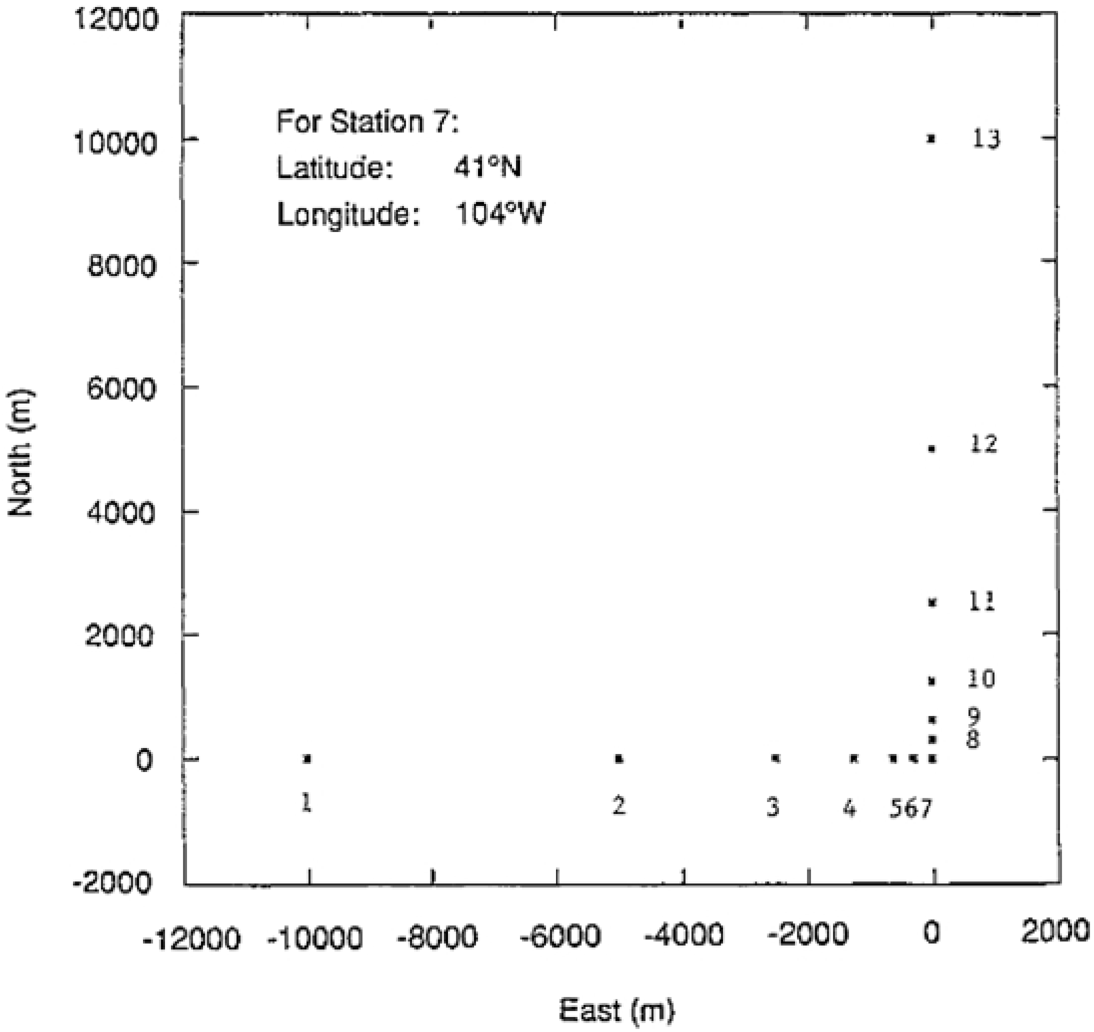
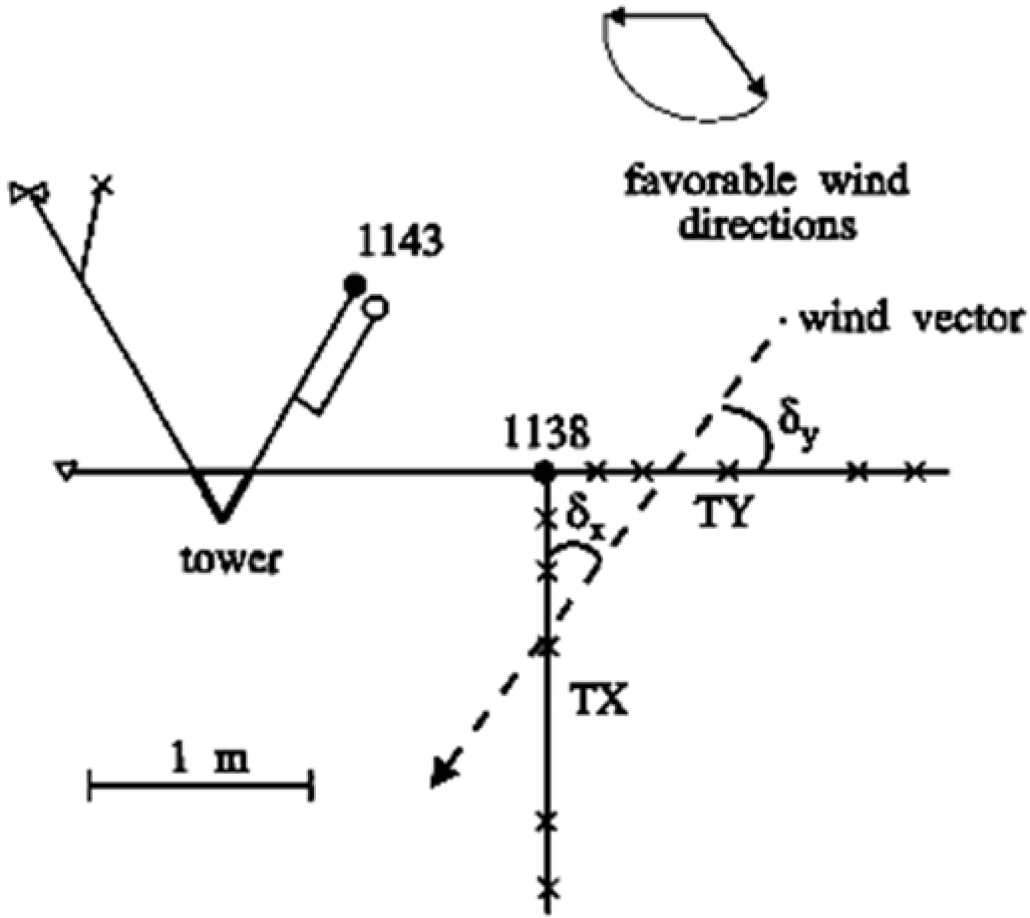
Hanna and Chang (1992)



Orthogonal grid of 13, logarithmically-spaced (312m-10km), anemometers at 10m height

Lee and Black (1994)



Orthogonal grid of 11 thermocouples with a sonic anemometer at the vertex to measure scalar flux attenuation caused by spatial displacement of the scalar sensor from the anemometer

Attenuation of Scalar Fluxes Measured with Horizontally-Displaced Sensors

Lee and Black (1994):

- $F_{wc}(r_x, r_y) = F_{wc}(0)\ \exp\left[-\alpha(\theta)\,\phi_h\phi_\epsilon^{1/3}\,(r/z)^{4/3}\right]$

  where $\quad r^2 = r_x^2 + r_y^2 \quad$ and $\quad \phi_h,\ \phi_\epsilon = f(z/L)$

- Functional dependence on z/L and $(r/z)^{4/3}$ is based on the assumption of inertial range scaling

- Dependence on wind direction is based on an empirical fit to observations

  $\alpha(\theta) = 1.18\,(\cos^2\theta + 2.4\sin^2\theta)^{2/3}$
  where $\quad \theta =$ wind direction w.r.t. $\vec{r}$

- Good agreement with observations for unstable stratification

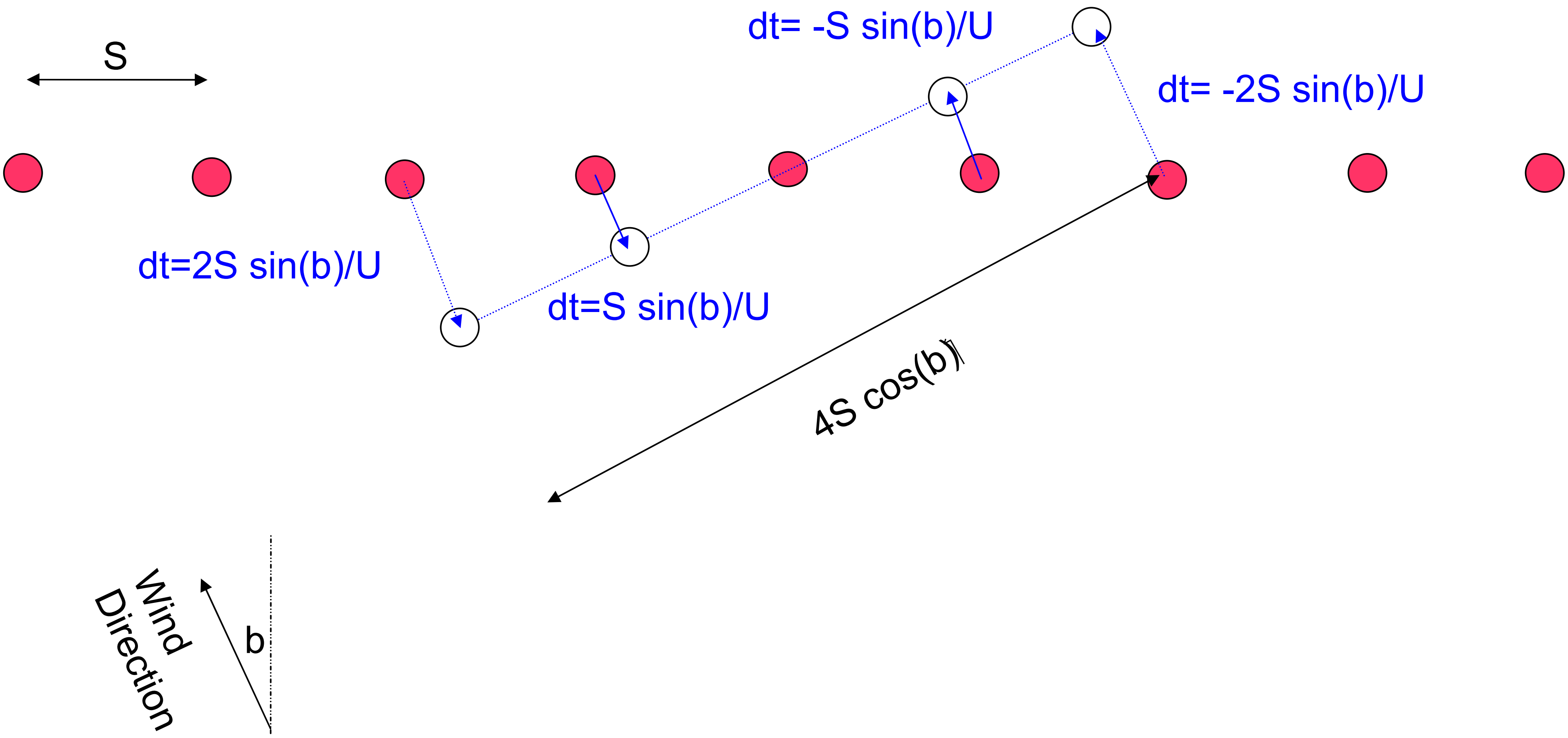
Lee and Black, 1994: Relating eddy correlation sensible heat flux to horizontal sensor separation in the unstable atmospheric surface layer. *J. Geophys. Res.*, **99**(D9), 18545–18553.

Tong, Wyngaard and Brasseur (1998)

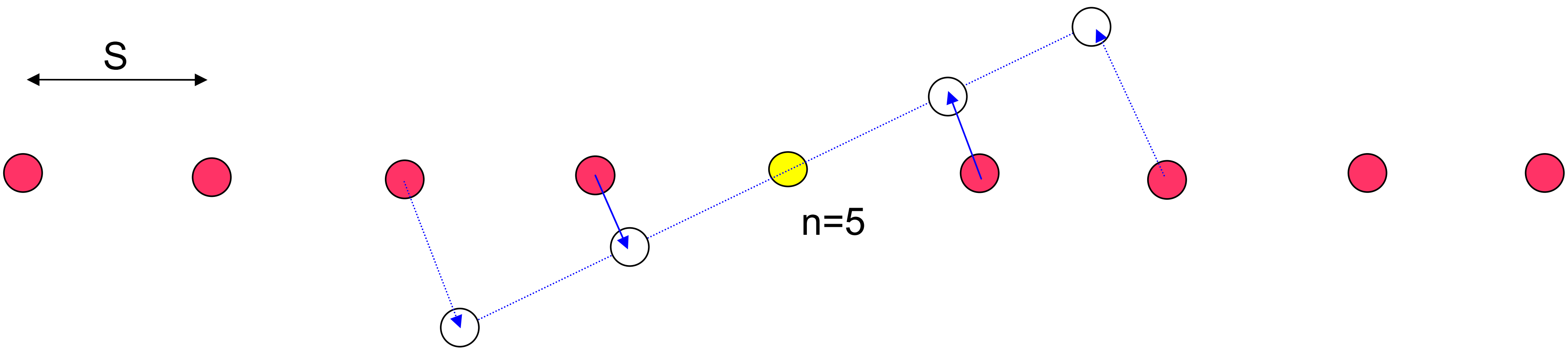
Observational investigation of LES sub-filter scale closure models

PSU Horizontal Array Technique: Measurement of 2D spatially-filtered turbulence using 9 sonic anemometers in a crosswind array along with Taylor's hypothesis in the streamwise direction.

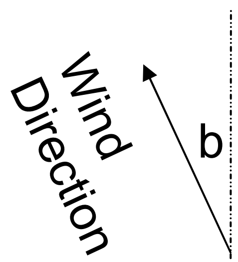
Project array onto crosswind direction



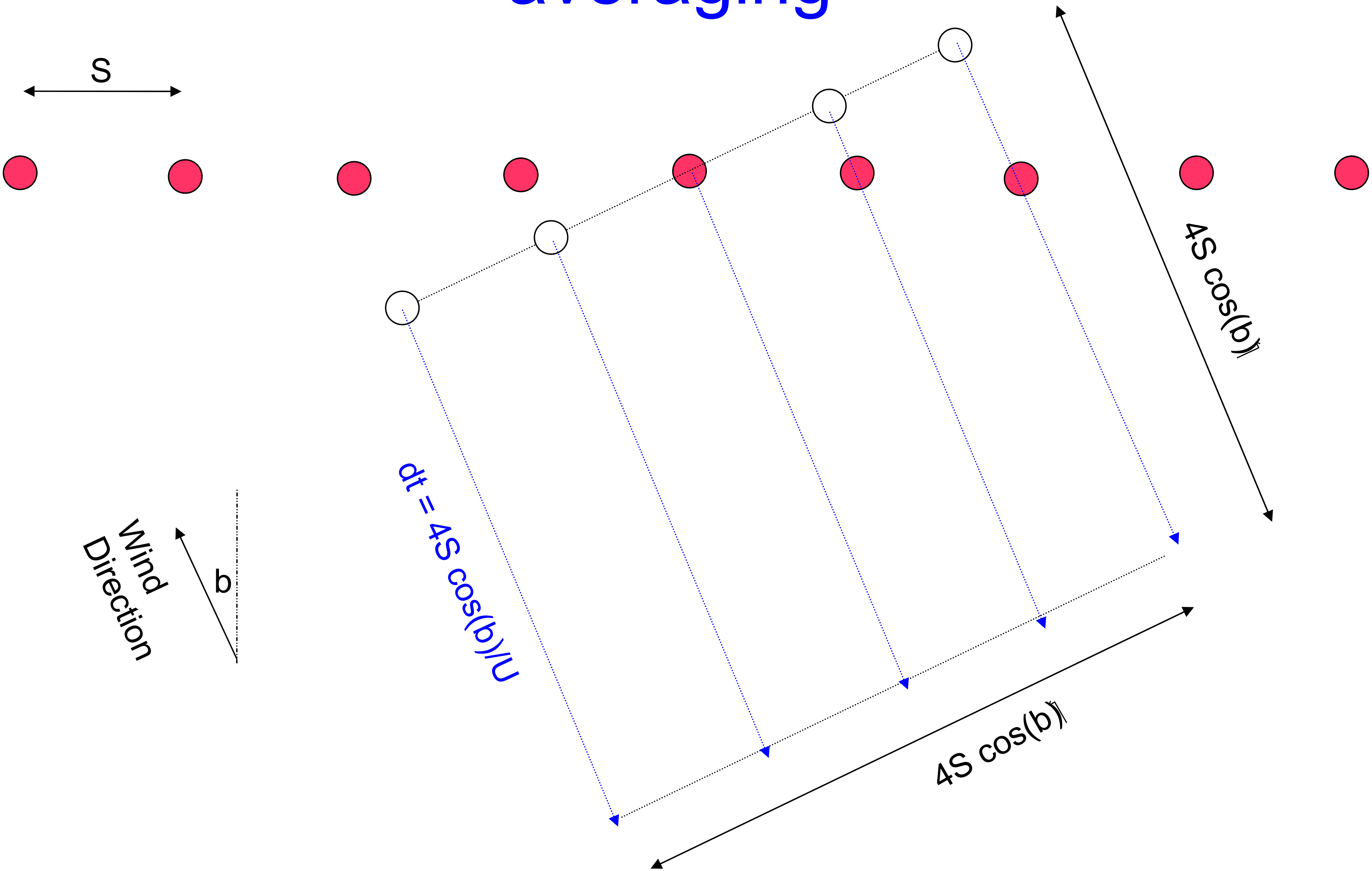
Project array onto crosswind direction



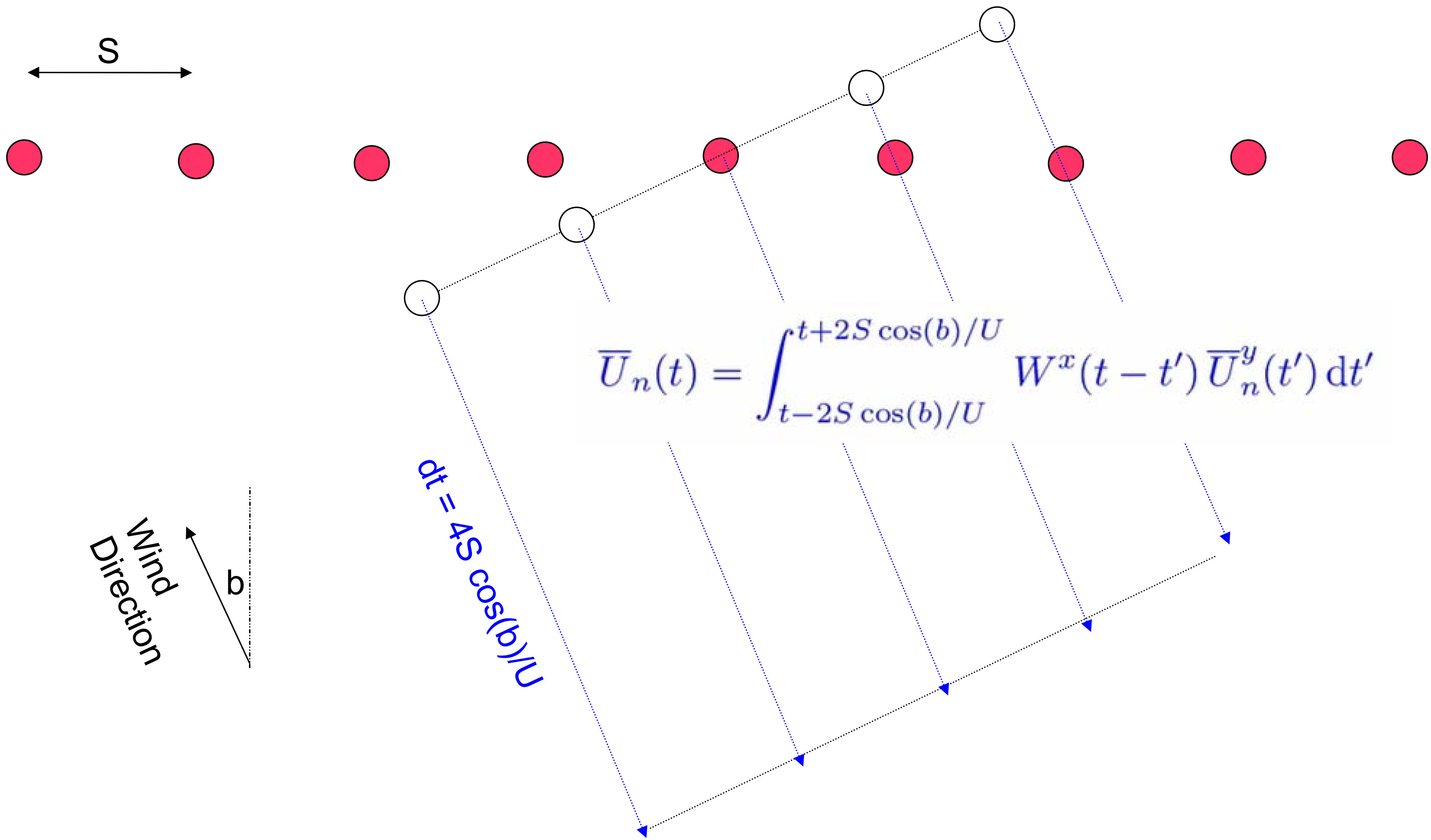
$$\overline{U}_n^y(t) = \sum_{m=-2}^{m=2} W_m^y \, U_{n+m}(t - mS\sin(b)/U)$$



Use Taylor's hypothesis for streamwise averaging

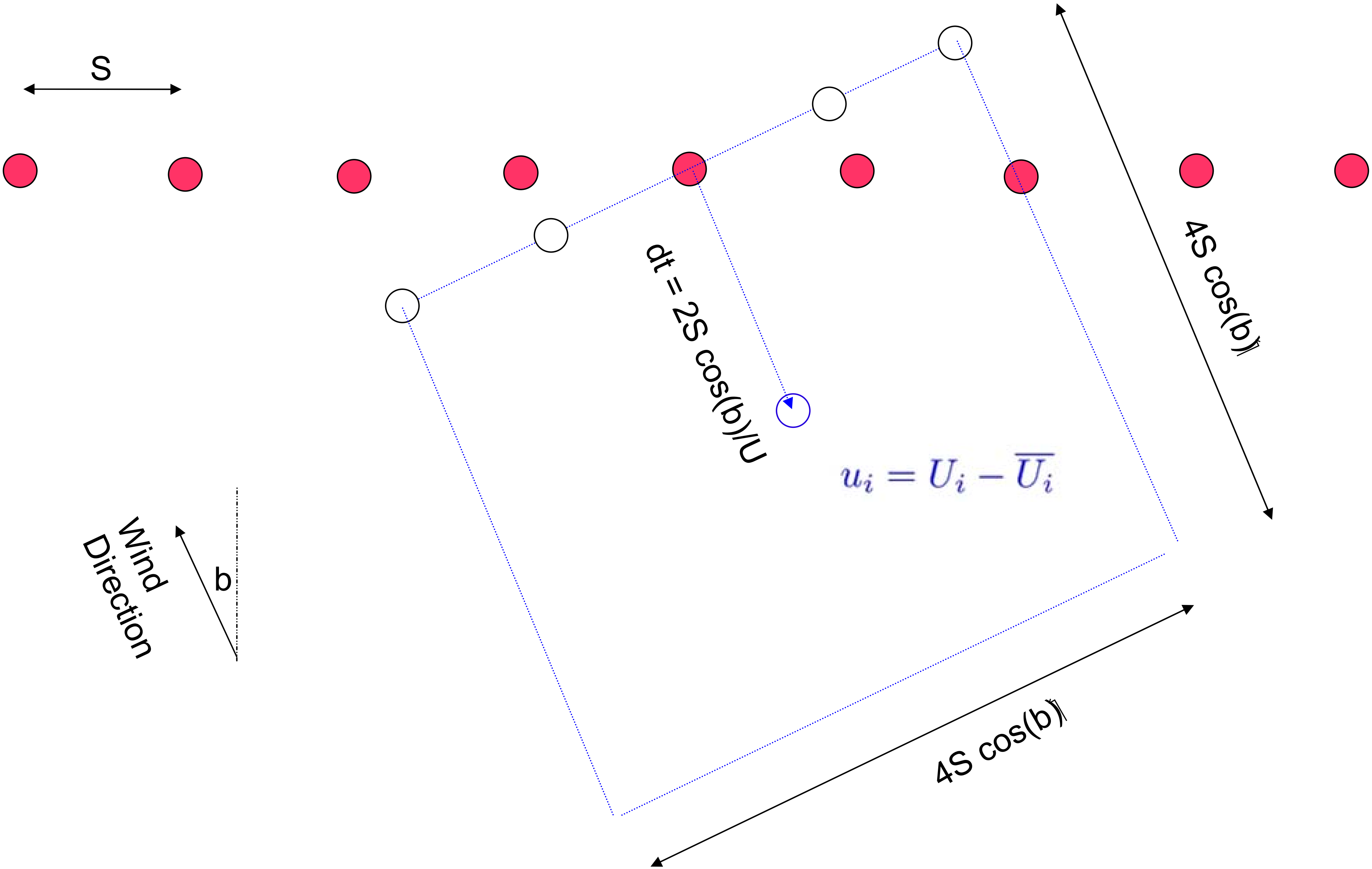


Use Taylor's hypothesis for streamwise averaging

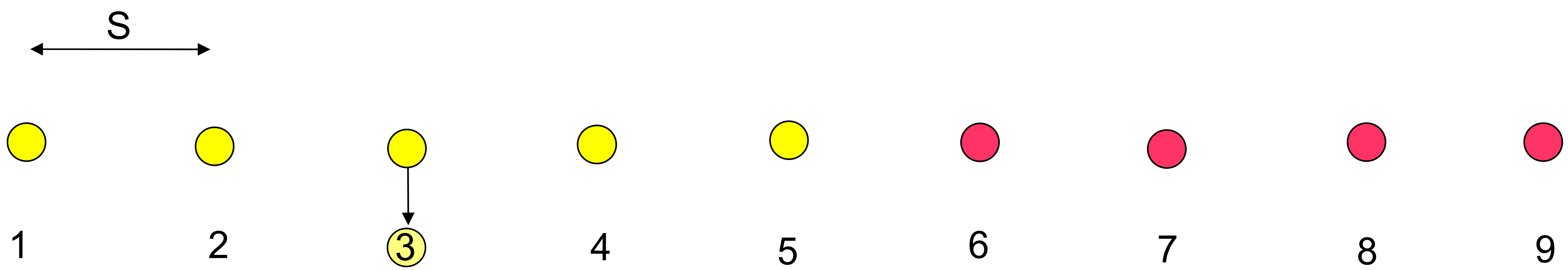


$$\overline{U}_n(t) = \int_{t-2S\cos(b)/U}^{t+2S\cos(b)/U} W^x(t-t')\,\overline{U}^y_n(t')\,\mathrm{d}t'$$

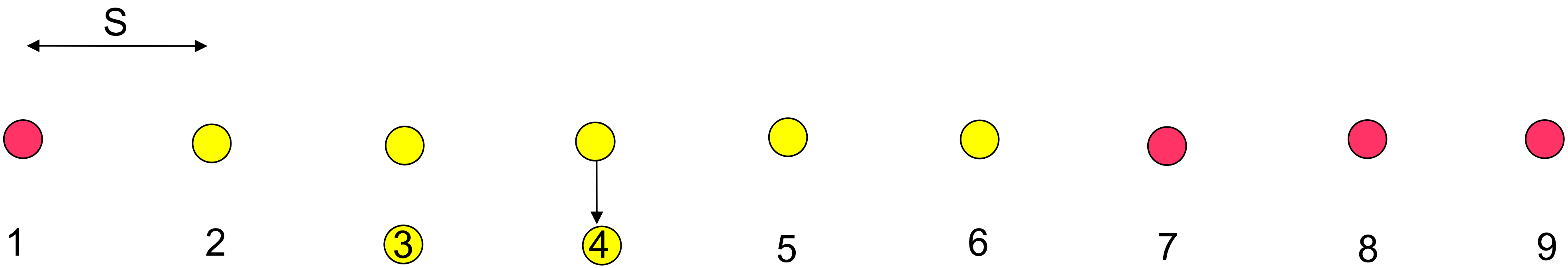
Calculate Sub-Filter-Scale Variables



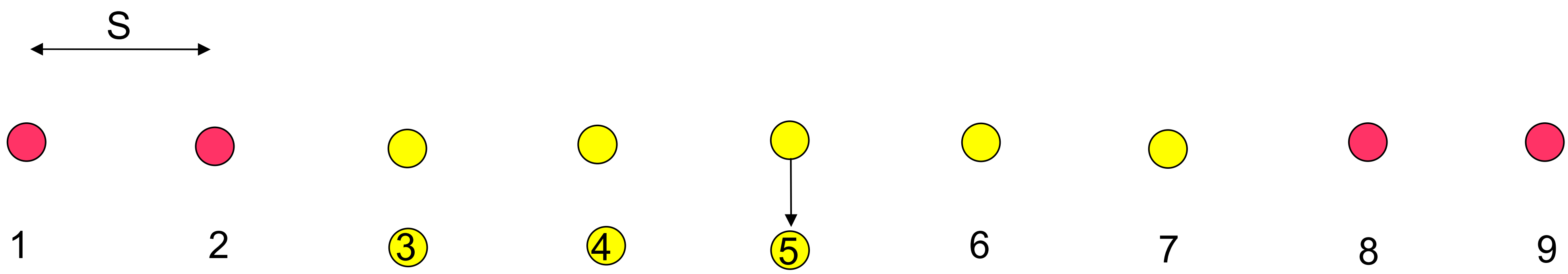
Tong et al. Horizontal Array Technique



Tong et al. Horizontal Array Technique



Tong et al. Horizontal Array Technique



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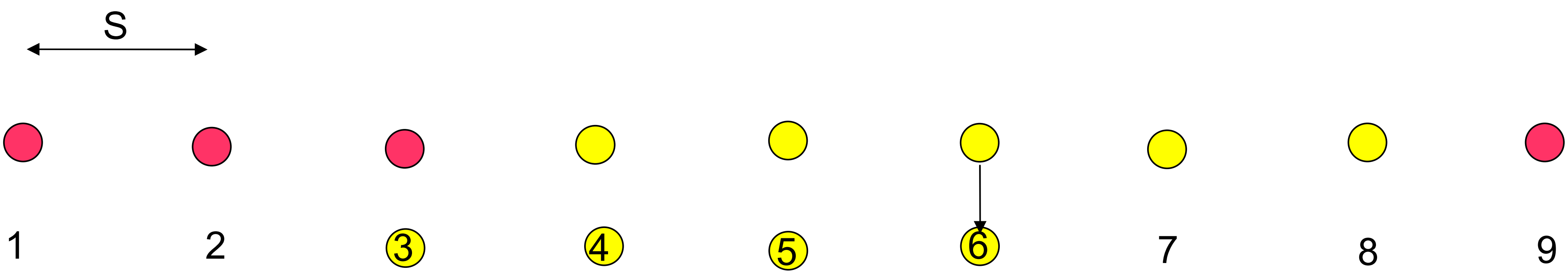

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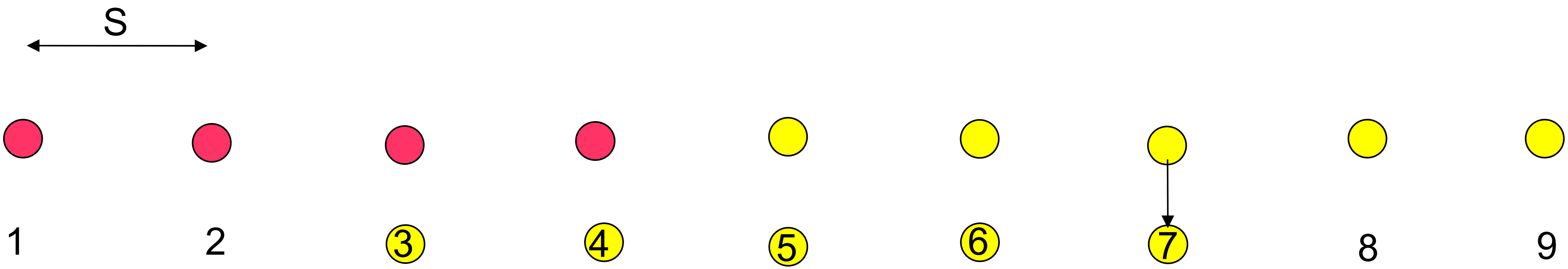

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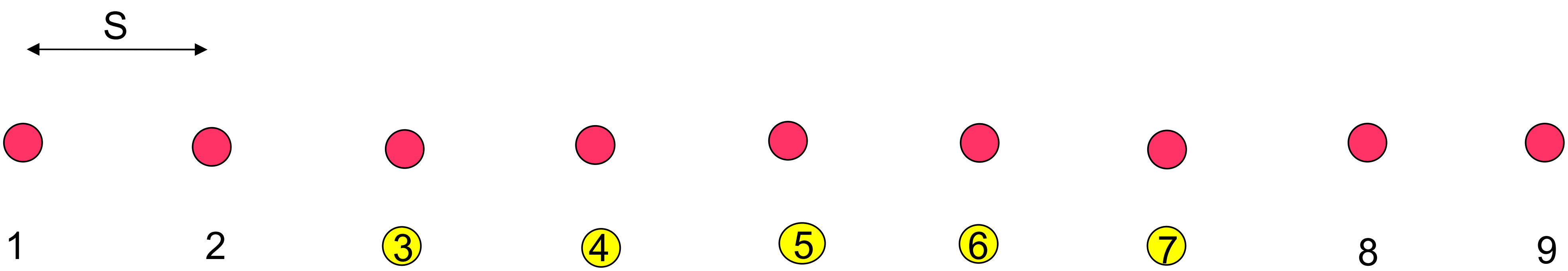


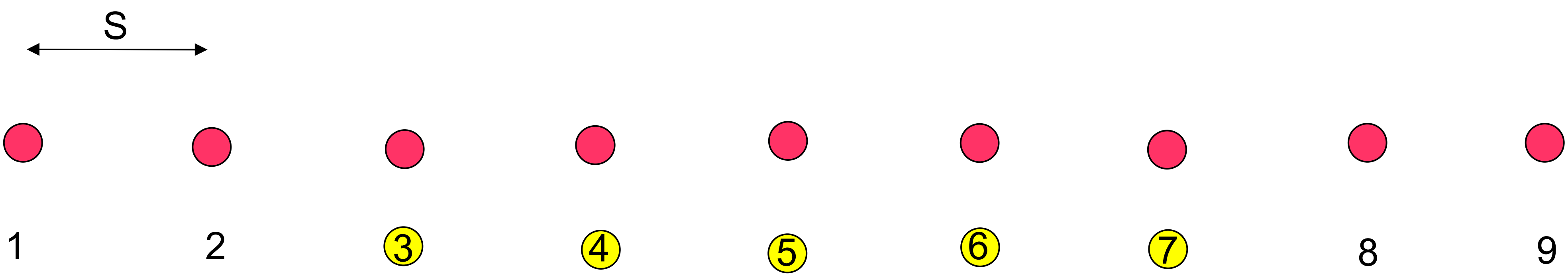
Crosswind gradient

$$\frac{d\overline{U}_5(t)}{dy} = \frac{-\overline{U}_7(t-2\delta t)+8\overline{U}_6(t-\delta t)-8\overline{U}_4(t-\delta t)+\overline{U}_3(t-2\delta t)}{12S\cos(b)}$$

where

$$\delta t = S\sin(b)/U$$

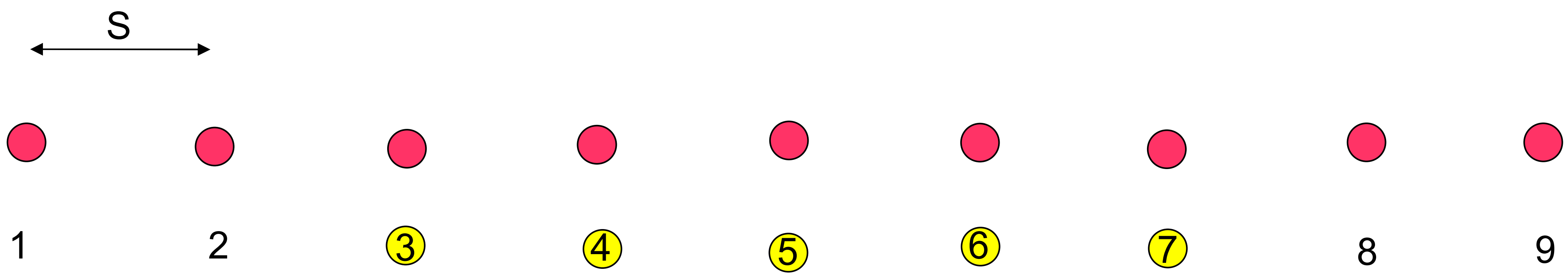
Tong et al. Horizontal Array Technique



Double Filtering

$$\overline{\overline{U}}_5(t) = \int_{t-2S\cos(b)/U}^{t+2S\cos(b)/U} W^x(t-t') \sum_{m=-2}^{m=2} W^y_m\, \overline{U}_{5+m}(t' - mS\sin(b)/U)\,\mathrm{d}t'$$

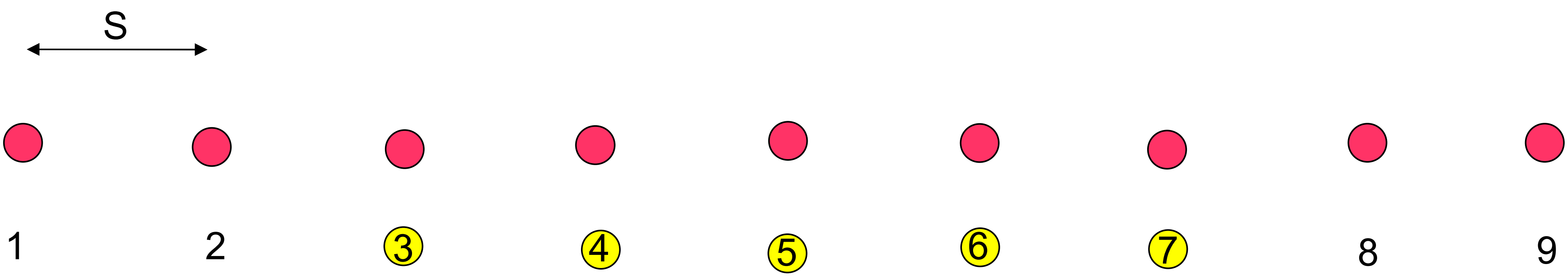
Tong et al. Horizontal Array Technique



Germano-Leonard decomposition

$$\tau_{ij} = \overline{U_i U_j} - \overline{U}_i \overline{U}_j \qquad \Leftarrow \qquad U_i = \overline{U}_i + u_i$$

Tong et al. Horizontal Array Technique



Germano-Leonard decomposition

$$\tau_{ij} = \overline{U_i U_j} - \overline{U_i}\,\overline{U_j} \equiv L_{ij} + C_{ij} + R_{ij}$$

$$L_{ij} = \overline{\overline{U_i}\,\overline{U_j}} - \overline{\overline{U_i}}\,\overline{\overline{U_j}} \quad , \qquad \text{modified} - \text{Leonard term}$$

$$C_{ij} = \overline{\overline{U_i} u_j} + \overline{u_i \overline{U_j}} - \overline{\overline{U_i}}\,\overline{u_j} - \overline{u_i}\,\overline{\overline{U_j}} \quad , \qquad \text{cross term}$$

$$R_{ij} = \overline{u_i u_j} - \overline{u_i}\,\overline{u_j} \quad , \qquad \text{SFS Reynolds flux}$$

Horizontal Array Turbulence Study (HATS)

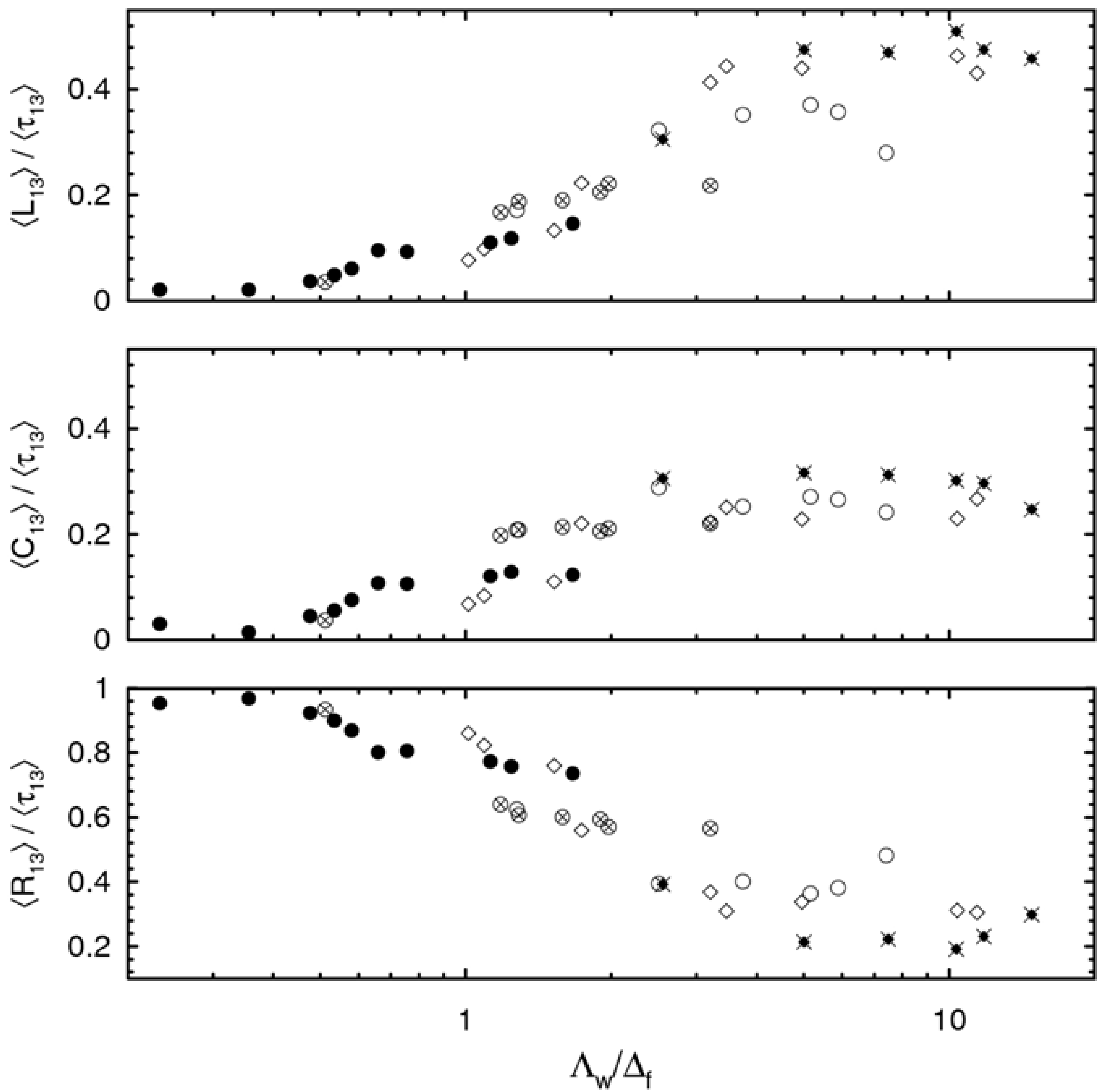


Figure 12: Decomposition of τ_{13} flux into modified-Leonard, cross, and Reynolds terms.

Cerutti and Meneveau (2000)

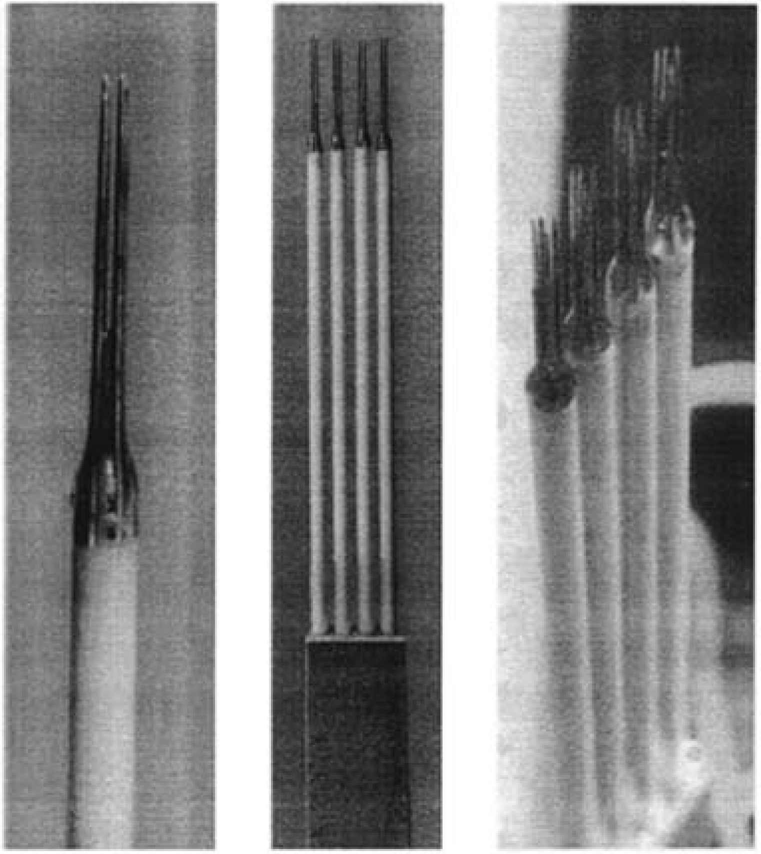
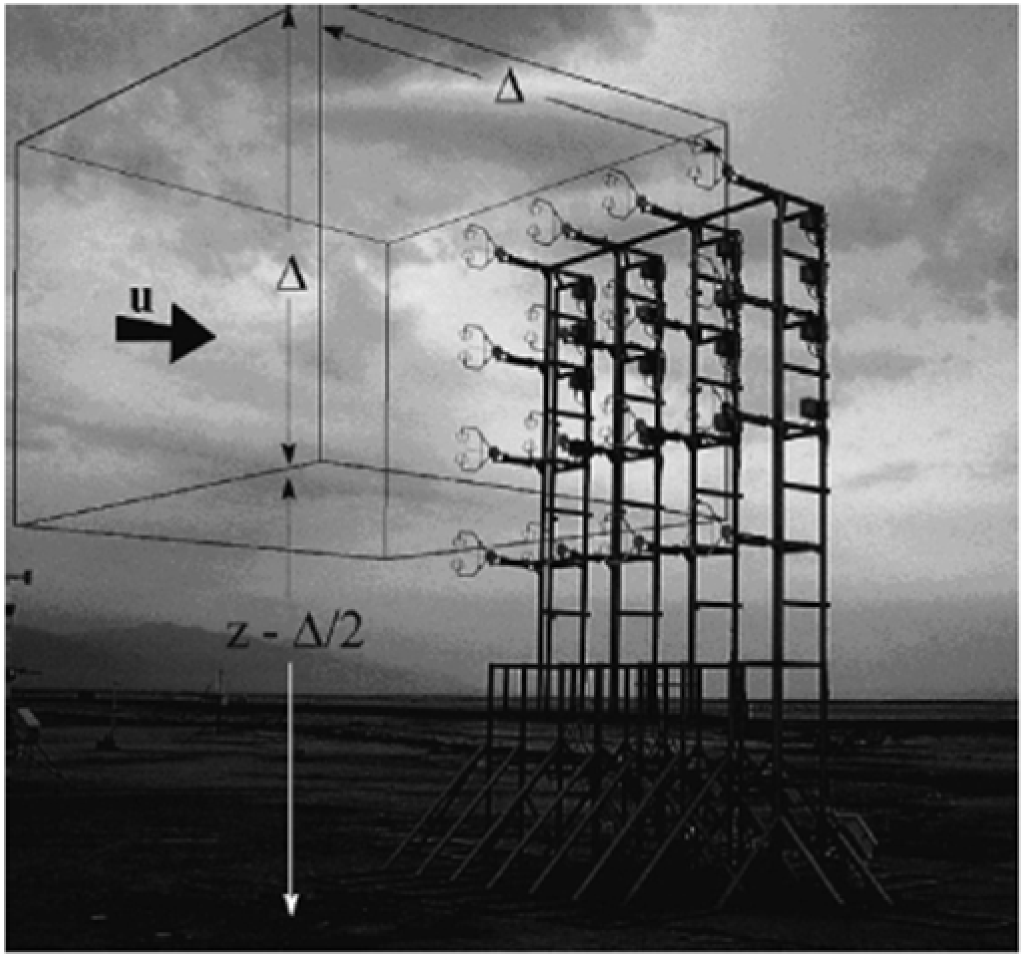


FIG. 1. Side, front, and perspective view of the probe array.

Cerutti and Meneveau applied the horizontal array technique in the wind tunnel with 4 X-probes placed transverse to the flow direction to study filtered velocity statistics in grid and wake turbulence.

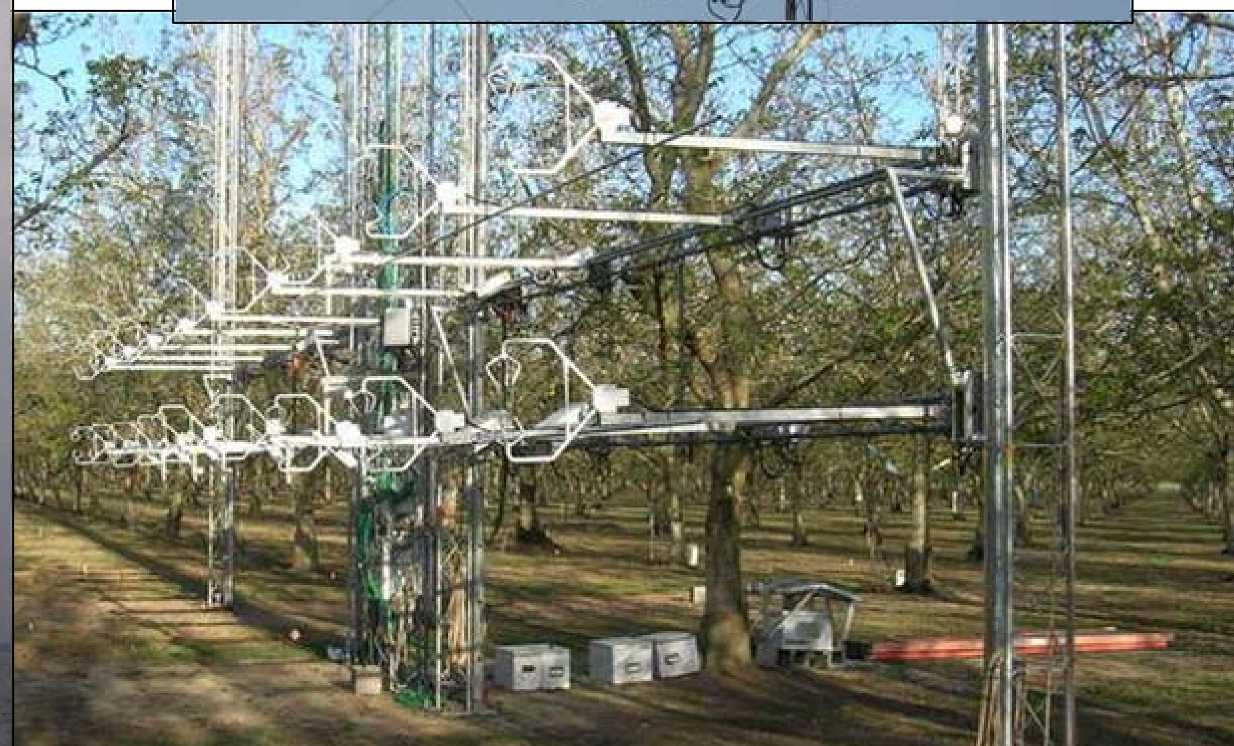
Higgins et al. (2007)



16 sonics were deployed in a 4x4 planar grid to enable 3D turbulence filtering. PDF's and spectra of the stresses were found to collapse by reducing the 3D filter scale as $L_{3D} = 0.84\ L_{2D}$.

HATS

OHATS



CHATS

HATS SCALAR FLUX ATTENUATION MODEL

$$A_x = F(r_x)/F_o = \int_{-\infty}^{\infty} Co_{wc}(\kappa) \cos\left[2\pi n_{mx}(z/L)\kappa\, r_x/z\right] \mathrm{d}\kappa$$

where $\kappa = k/k_m$

$$A_y = F(r_y)/F_o = \exp\left[-2\pi n_{my}(z/L)\, r_y/z\right]$$

$$F(r_x, r_y) = F_o \exp\left[-\left(\ln^2 A_x + \ln^2 A_y\right)^{1/2}\right]$$

$$A_z = F(z, z')/F_o = \exp\left[-2\pi n_{mz}(z/z', z/L)\, r_z/z\right]$$

where $r_z = |z - z'|$