涡动相关技术的基本理论

CAMPBELL SCIENTIFIC®
WHEN MEASUREMENTS MATTER

理加联合科技有限公司

近地面层通量测定的理论要点与应用理解

周新华 **Campbell Scientific, Inc**

红外线 与 超声波

3D 风速 H₂O

CO₂

温度
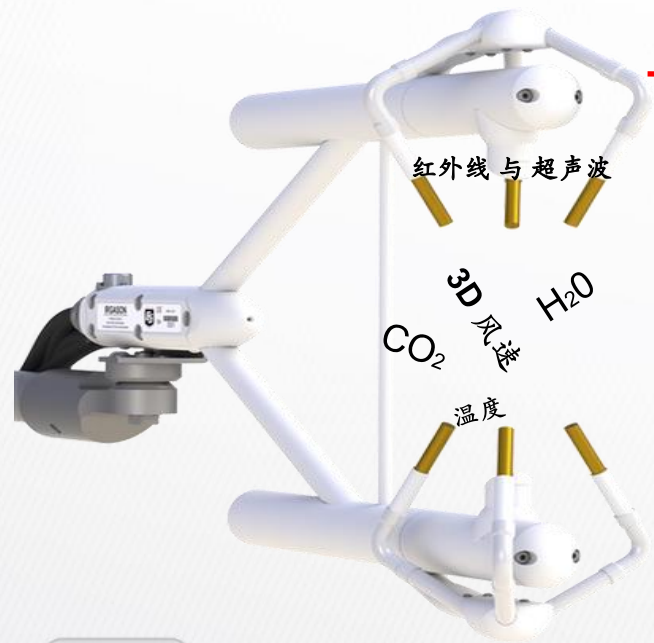
$$NEE_{CO2} \approx \overline{C_d} \left(\overline{w'X'_{CO2}}|_h + \int_0^h \overline{\frac{\partial X_{CO2}}{\partial t}} dz \right)$$

干空气   CO₂   通量测定高度下
密度   湍流通量   CO2 存储变化

Gu et al./Ag For Meteorol (2012)
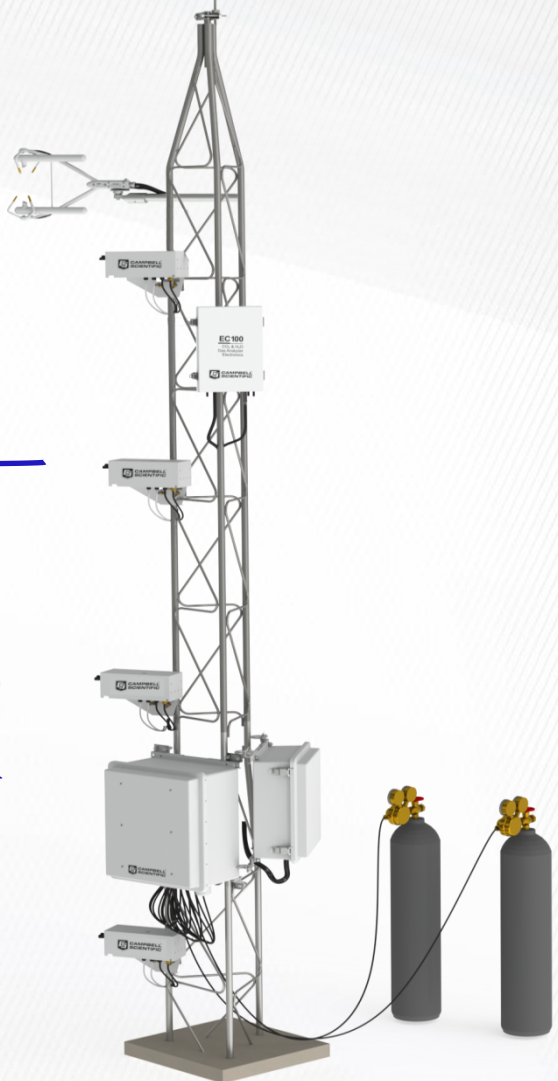
IRGASON
(红外超声碳水热通量集成观测仪)

AP200
（红外大气碳水热纵断面观测系统）

Acknowledgement

(综述于以下专家的讲座)

Campbell Scientific Inc.
Ryan Campbell, Benjamin Conrad, Sasha Ivans, Larry Jacobsen, Edward Swiatek, Bert Tanner

University of Nebraska
Shashi Verma

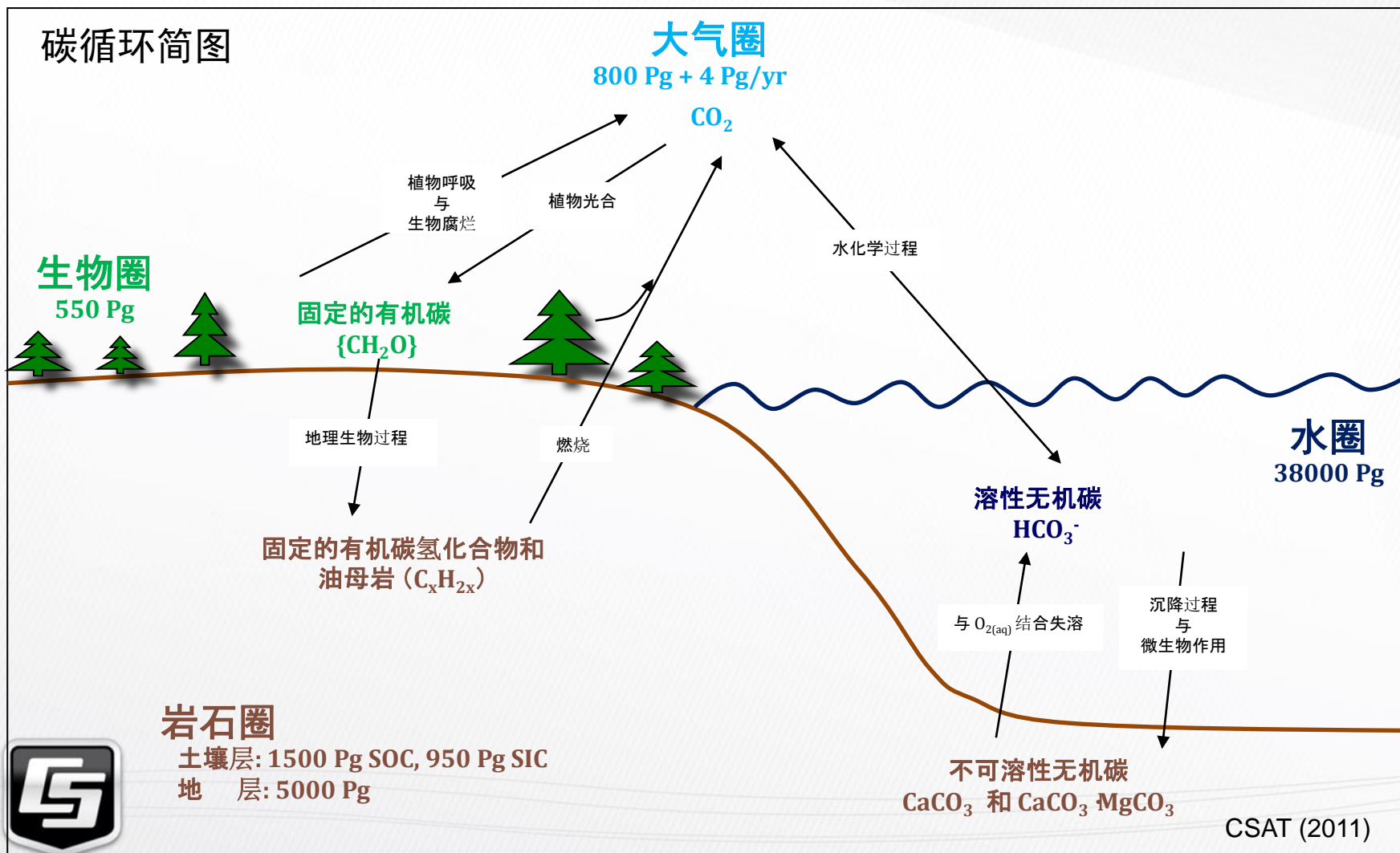**CSIRO Marine and Atmospheric Research**
Ray Leuning

全球关注

多

少

碳何从

碳何去

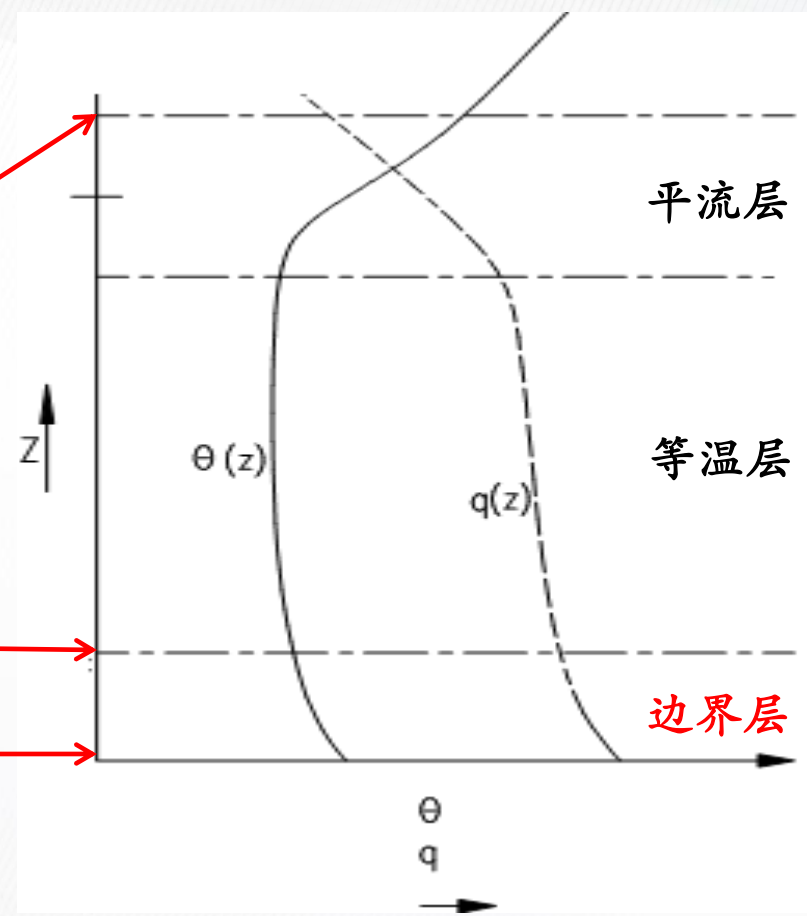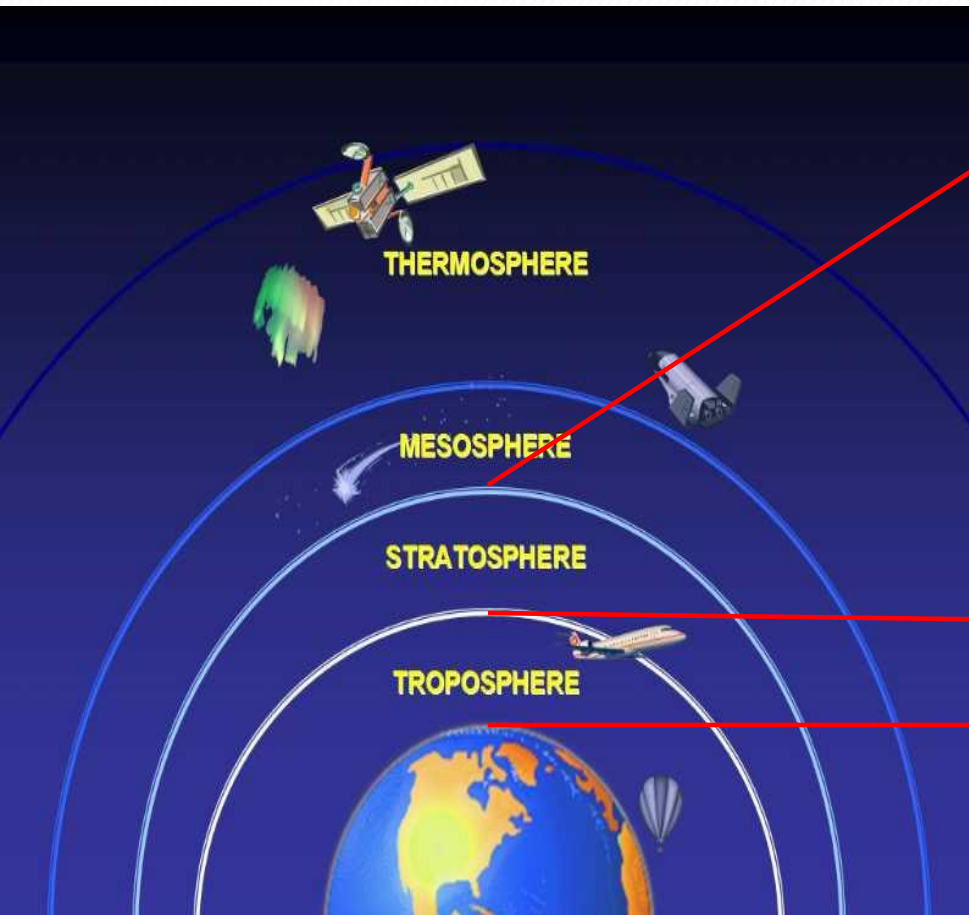研究目的: 1）更好地理解碳循环的自然机制
2）人类活动对这一自然机制的干扰程度
3）制定人类社会与经济发展策略使碳循环良性化

碳循环简图

大气圈
800 Pg + 4 Pg/yr
CO_2

植物呼吸
与
生物腐烂

植物光合

水化学过程

生物圈
550 Pg

固定的有机碳
{CH_2O}

地理生物过程

燃烧

水圈
38000 Pg

溶性无机碳
HCO_3^-

固定的有机碳氢化合物和
油母岩（C_xH_{2x}）

与 $O_{2(aq)}$ 结合失溶

沉降过程
与
微生物作用

岩石圈
土壤层: 1500 Pg SOC, 950 Pg SIC
地　层: 5000 Pg

不可溶性无机碳
$CaCO_3$ 和 $CaCO_3$ $MgCO_3$

CSAT (2011)

兴趣通量

$$Rn = LE + H + G \quad (W\, m^{-2}\, s^{-1})$$

净辐射　　潜热　　感热　　地表热

通量　　通量　　通量　　通量

Fc

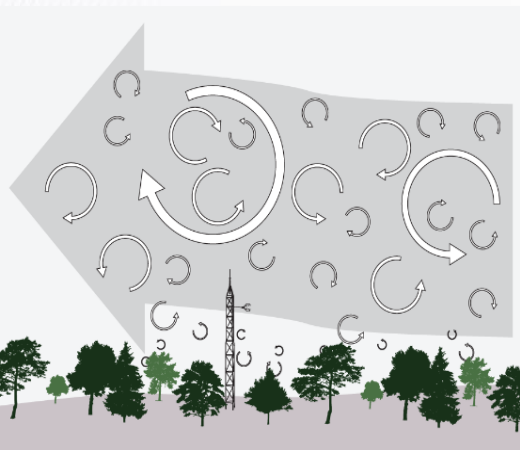二氧化碳通量

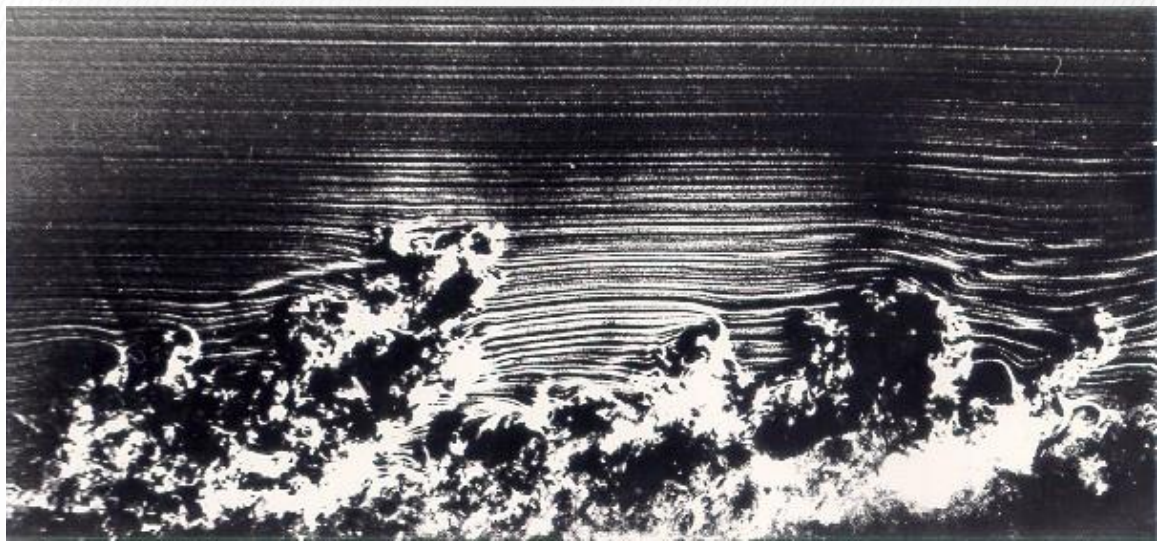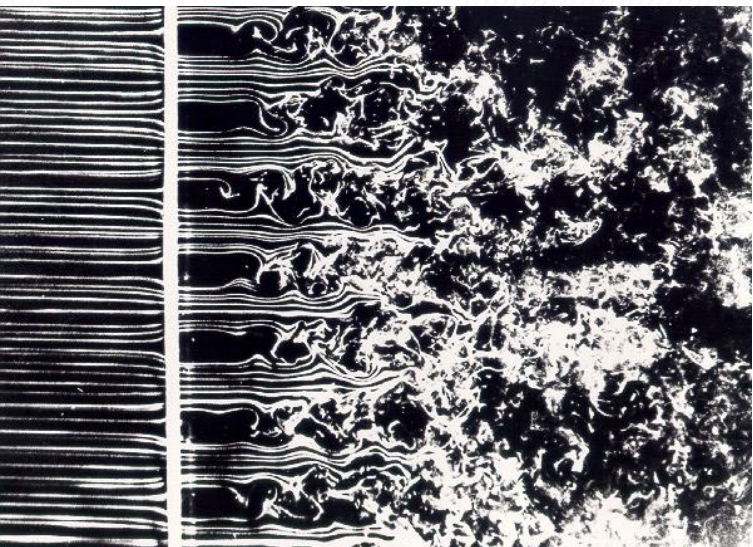$(mg\, m^{-2}\, s^{-1})$

平流层

等温层

边界层
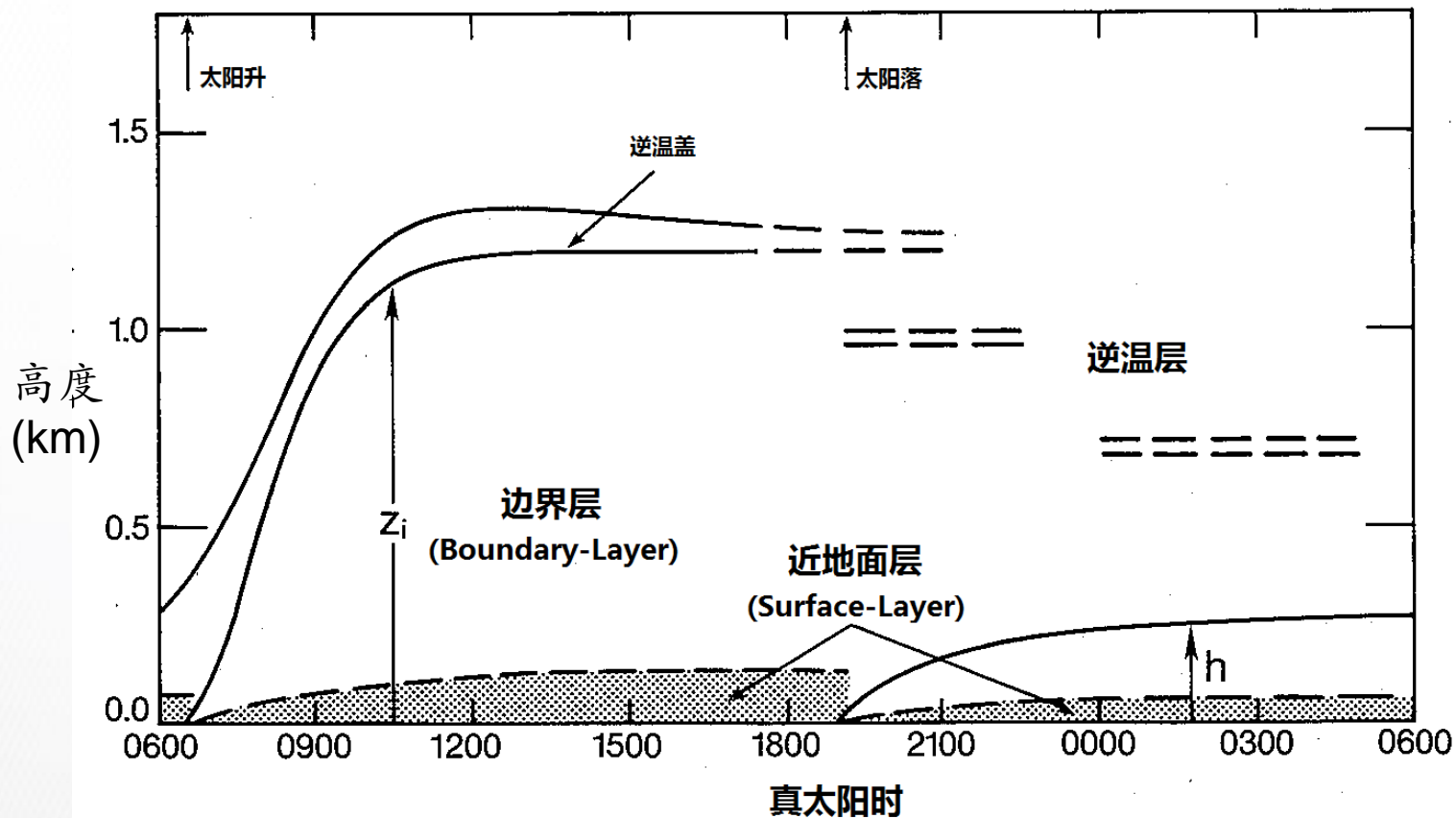
对流层：随太阳升起对地面加热而抬升活跃，随太阳降落与地面冷却而降低变稳 （Kaimal & Finnigan 1994)

近地面层的湍流

近地面层(Surface-Layer)
以水平流动为主的水气热空气湍流体。
　　其湍流产生于：
　　1. 与下垫面摩擦引发的水平风速梯度
　　2. 与下垫面热交换而改变密度所产生的空气浮力

内部特征
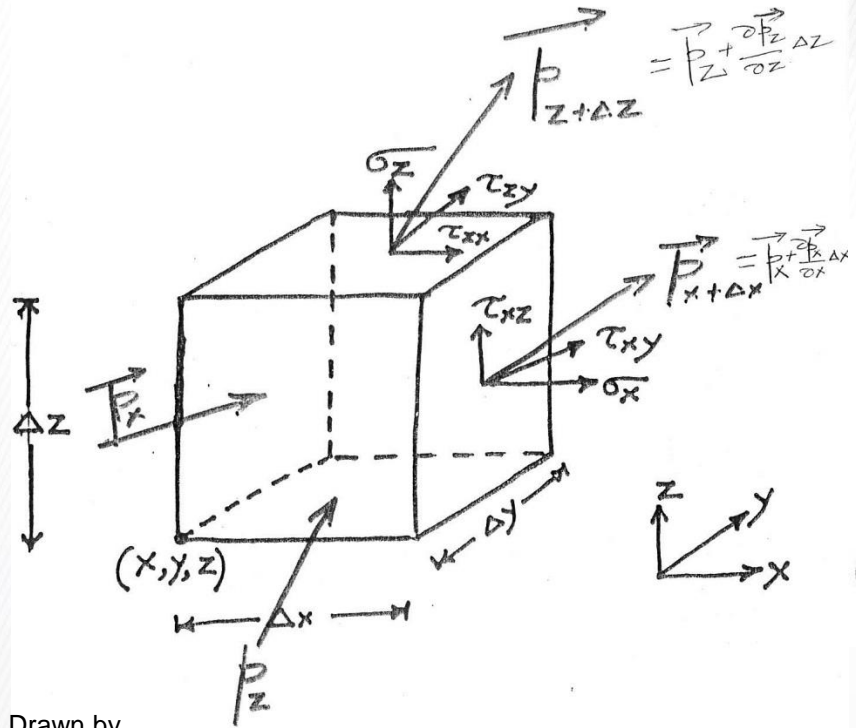　　1. 无序
　2. 三维无规则运动
　3. 各气体组分充分混合

了解近地面层湍流

1. 流体运动的数学物理描述

2. 湍流的产生与耗散及其综合描述原理

3. 湍流的结构
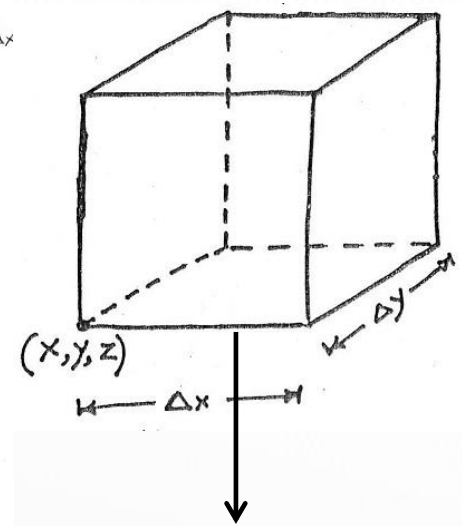
4. 湍流传输动量，热量，质量的规律

1. 流体运动的数学物理描述

压力（*P*）与应力（τ，σ）　　　重力　　　物质守恒

Drawn by
Dr. Shashi Verma

ρg∆*x*∆*y*∆*z*

空气　　重力
密度　　加速度
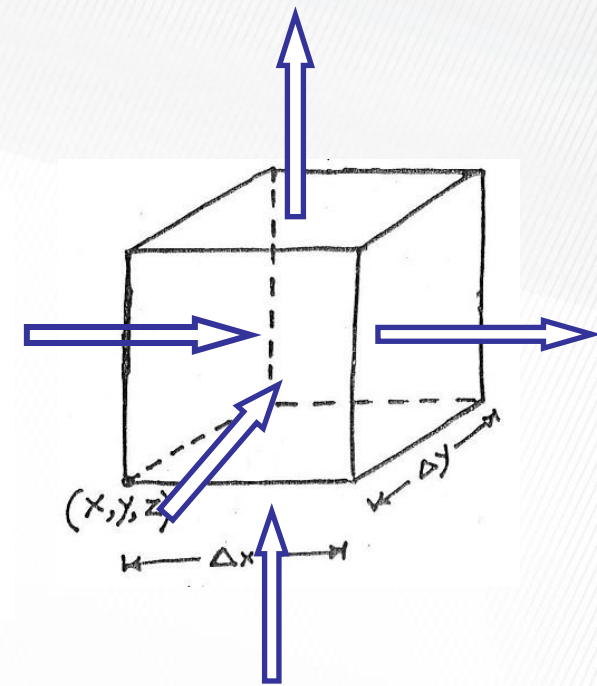
描述流体的基本方程

运动方程 (Navier-Stokes Equations)

速度

$$\rho\left(\frac{\partial u_i}{\partial t} + u_J\frac{\partial u_i}{\partial x_J}\right) = -\frac{\partial P}{\partial x_i} + \mu\frac{\partial^2 u_i}{\partial x_J \partial x_J} - \rho g\delta_{3i}$$

时间
变量

空间
变量

粘度
系数

Kronecker
Delta

连续方程 (Continuity Equation)

$$\frac{\partial u_J}{\partial x_J} = 0$$

状态方程 (Equation of State)

$$P = \rho RT$$

压力   空气   气体   温度
        密度   常数

一般表达形式

运动方程

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \rho g$$

连续方程

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

宝思内思克近似 (Boussinesq Approximation)

1. 空气粘度系数不变（μ=constant）

2. 空气为不可压气体
   a. 在近地面层，压力(P)，温度(T) 和密度(ρ)与其
      各自基值(P_0, T_0, ρ_0)的差(P_1, T_1, ρ_1)与其基值比很小

   $$\left|\frac{P_1}{P_0}\right| \ll 1 \qquad \left|\frac{T_1}{T_0}\right| \approx \left|\frac{\rho_1}{\rho_0}\right| \ll 1$$

   b. 压力波动更小，空气密度波动主要由温度波动引起。

   $$\left|\frac{P_1}{P_0}\right| \ll \left|\frac{T_1}{T_0}\right| \approx \left|\frac{\rho_1}{\rho_0}\right|$$

   $$\rho\left(\frac{\partial u_i}{\partial t} + u_J \frac{\partial u_i}{\partial x_J}\right) = -\frac{\partial P}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_J \partial x_J} - \rho g \delta_{3i}$$

   $$\frac{\partial u_i}{\partial t} + u_J \frac{\partial u_i}{\partial x_J} = -\frac{\partial P_1}{\rho_0 \partial x_i} + \frac{\mu}{\rho_0} \frac{\partial^2 u_i}{\partial x_J \partial x_J} + \frac{T_1}{T_0} g \delta_{3i}$$

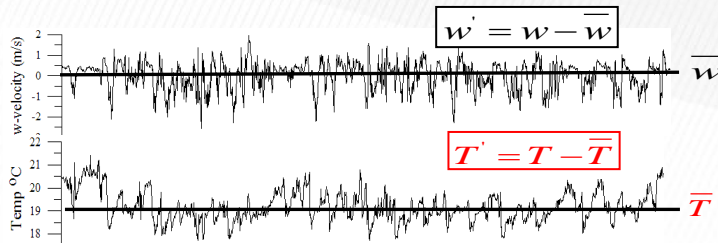   温度波动与重力偶联
   可有效地绕动气流

   运动方程的宝思内思克近似

雷诺(Reynolds)变量分解与平均规则

分解规则

$$u = \bar{u} + u'$$

$$w' = w - \overline{w}$$

$$\overline{w}$$

$$T' = T - \bar{T}$$

$$\bar{T}$$

平均规则

$$\overline{u'} = 0$$

$$\overline{\bar{u} + u'} = \bar{\bar{u}} + \overline{u'} = \bar{u}$$

宝思内思克近似运动方程

$$\overline{uw} = \overline{(\bar{u} + u')(\bar{w} + w')}$$

$$= \bar{u}\bar{w} + \overline{u'w'}$$

$$\frac{\partial u_i}{\partial t} + u_J \frac{\partial u_i}{\partial x_J} = -\frac{\partial p_1}{\rho_0 \partial x_i} + \frac{\mu}{\rho_0} \frac{\partial^2 u_i}{\partial x_J \partial x_J} + \frac{T_1}{T_0} g \delta_{3i}$$

$$\frac{\overline{\partial u}}{\partial x} = \frac{\partial \bar{u}}{\partial x} \qquad \frac{\overline{\partial u}}{\partial t} = \frac{\partial \bar{u}}{\partial t}$$

雷诺平均运动方程

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_J} \frac{\partial \overline{u_i}}{\partial x_J} = -\frac{\partial \overline{p_1}}{\rho_0 \partial x_i} + \frac{1}{\rho_0} \frac{\partial}{\partial x_J} \left(\mu \frac{\partial \overline{u_i}}{\partial x_J} - \rho_0 \overline{u'_i u'_J} \right) + \frac{\overline{T_1}}{T_0} g \delta_{3i}$$

2. 湍流的产生与耗散及其综合描述原理

湍流动能变化

$$\frac{\rho}{2}\frac{D\overline{\left(u'^2+v'^2+w'^2\right)}}{Dt} = -\rho\overline{(u'w')}\frac{\partial\bar{u}}{\partial z} + \rho\frac{g}{\bar{\theta}}\overline{(\theta'w')} + \frac{\partial\overline{(p'w')}}{\partial z} - \frac{\rho}{2}\frac{\partial\overline{(u'^2+v'^2+w'^2)w'}}{\partial z} - \rho\epsilon$$

动能变化 下垫面摩擦 气团沉浮 压力运输 湍流运输 粘度扩散

瑞查德数
Richard number

$$R_f = \frac{(g/\bar{T})\overline{T'w'}}{u'w'(\partial\bar{u}/\partial z)}$$

$$\frac{\text{气团浮力}}{\text{下垫面摩擦}}$$

奥布克瓦长度
Obukhov length

$$L = -\frac{u_*^3/k}{(g/\bar{T})\overline{(T'w')}_0}$$

描述整个大气近地面

近地面层
大气稳定度

$$\frac{z}{L} = -\frac{(g/\bar{\theta})\overline{\theta'w'}}{u_*^3/kz}$$

无量纲

近地面层稳定度

$$\frac{z}{L} = -\frac{g_0 / \overline{\theta}\left(\overline{w'\theta'}\right)_S}{u_*^3 / kz}$$

u_* 摩擦速度 (m s^{-1})

k von Karman 常数 (0.41)

g_0 海平面重力加速度 (9.81 m s^{-2})

θ 潜温 （K）

z 高度 （m）

$\dfrac{z}{L} < 0$ 非稳定近地面层

$\dfrac{z}{L} > 0$ 稳定近地面层

Rn> 0
LE> 0
H > 0
G < 0

Rn
LE
G
H

Rn< 0
LE ≤ 0
H < 0
G > 0

Rn
LE
G
H
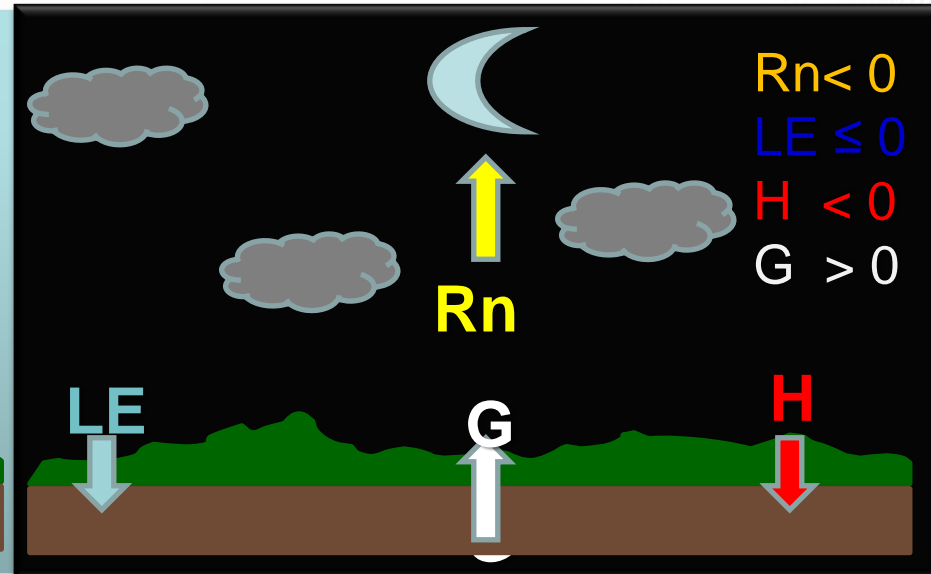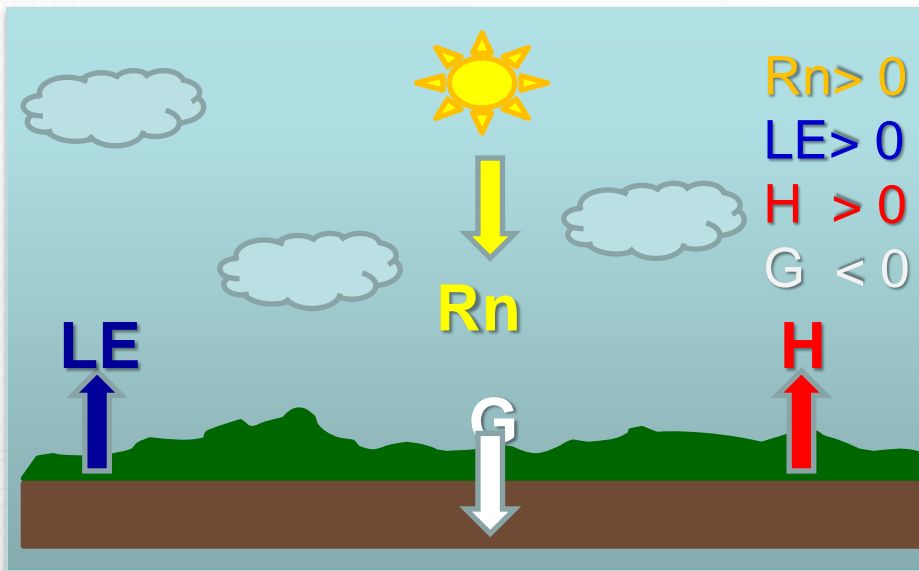
$$u_* = \left[-(\overline{u'w'})_0\right]^{1/2} \tag{1.25a}$$

$$T_* = \frac{-(\overline{w'\theta'})_0}{u_*}. \tag{1.25b}$$

Although defined strictly in terms of fluxes at the surface, u_* and T_* are evaluated, in practice, from measurements of the fluxes at some convenient height within the surface layer where their vertical variations can be assumed negligible with height, a reasonable assumption for $z \lesssim |L|$ (Haugen et al., 1971). The important nondimensional forms to emerge in the surface layer are

$$\phi_m = (kz/u_*)(\partial\overline{u}/\partial z) \quad \text{wind shear,} \tag{1.26}$$

$$\phi_h = (kz/T_*)(\partial\overline{\theta}/\partial z) \quad \text{thermal stratification,} \tag{1.27}$$

$$\phi_w = \sigma_w/u_* \qquad\qquad \text{variability in } w, \tag{1.28}$$

$$\phi_\theta = \sigma_\theta/|T_*| \qquad\qquad \text{variability in } \theta, \tag{1.29}$$

$$\phi_\epsilon = kz\epsilon/u_*^3 \qquad\qquad \text{dissipation of turbulent kinetic energy,} \tag{1.30}$$

where σ_w and σ_θ are the standard deviations of w and θ, and ϵ is the rate of dissipation of turbulent kinetic energy. We introduce ϵ here because of its relevance to discussions of the turbulent kinetic energy budget later in this chapter. Its relationship to velocity spectra will be discussed in Chapter 2.

All the above functions follow M-O scaling with surprisingly small scatter, as evident in the plots of the Kansas data (Businger et al., 1971; Wyngaard and Coté, 1971). The following formulations are essentially the Kansas results, reexamined and refined through comparison with other observations (Dyer, 1974; Högström, 1988):

$$\phi_m = \begin{cases} (1+16|z/L|)^{-1/4}, & -2 \le z/L \le 0 \\ (1+5\,z/L), & 0 \le z/L \le 1 \end{cases} \tag{1.31}$$

$$\phi_h = \begin{cases} (1+16|z/L|)^{-1/2}, & -2 \le z/L \le 0 \\ (1+5\,z/L), & 0 \le z/L \le 1 \end{cases} \tag{1.32}$$

$$\phi_w = \begin{cases} 1.25(1+3|z/L|)^{1/3}, & -2 \le z/L \le 0 \\ 1.25(1+0.2\,z/L), & 0 \le z/L \le 1 \end{cases} \tag{1.33}$$

$$\phi_\theta = \begin{cases} 2(1+9.5|z/L|)^{-1/3}, & -2 \le z/L \le 0 \\ 2(1+0.5\,z/L)^{-1}, & 0 \le z/L \le 1 \end{cases} \tag{1.34}$$

$$\phi_\epsilon = \begin{cases} (1+0.5|z/L|^{2/3})^{3/2}, & -2 \le z/L \le 0 \\ (1+5\,z/L), & 0 \le z/L \le 1. \end{cases} \tag{1.35}$$
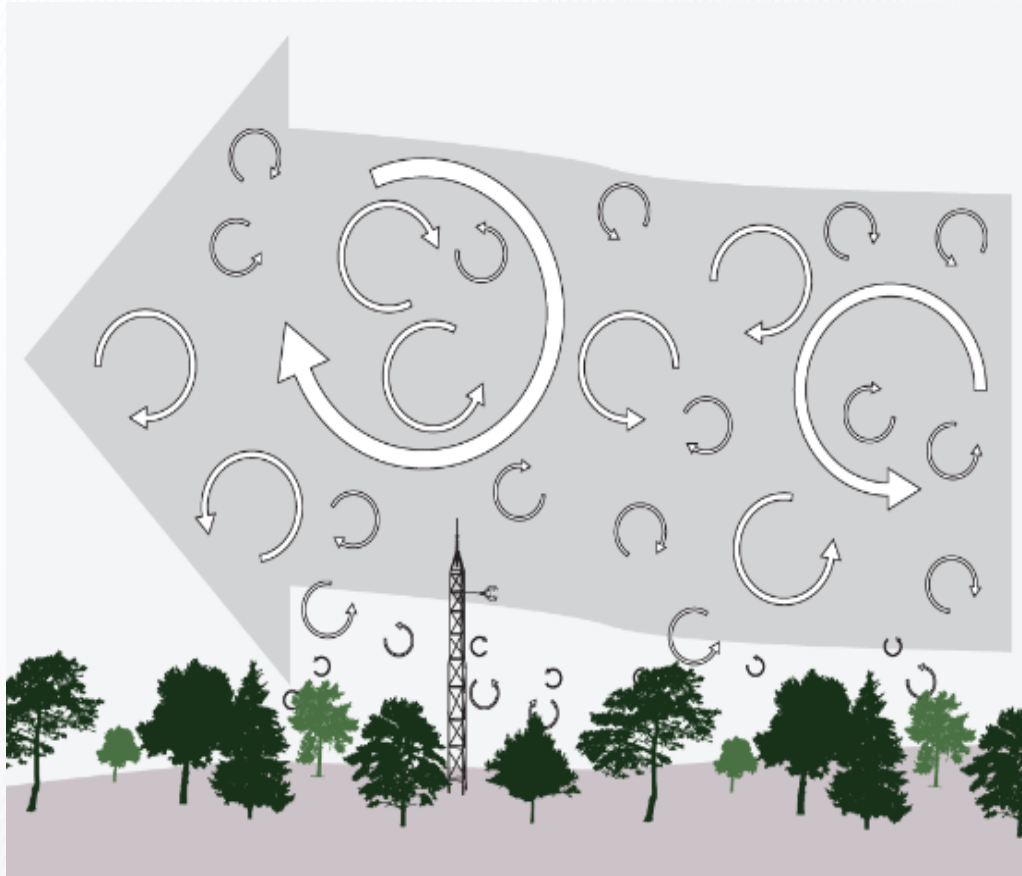
The forms of these functions, plotted in Fig. 1.7, cannot be predicted from
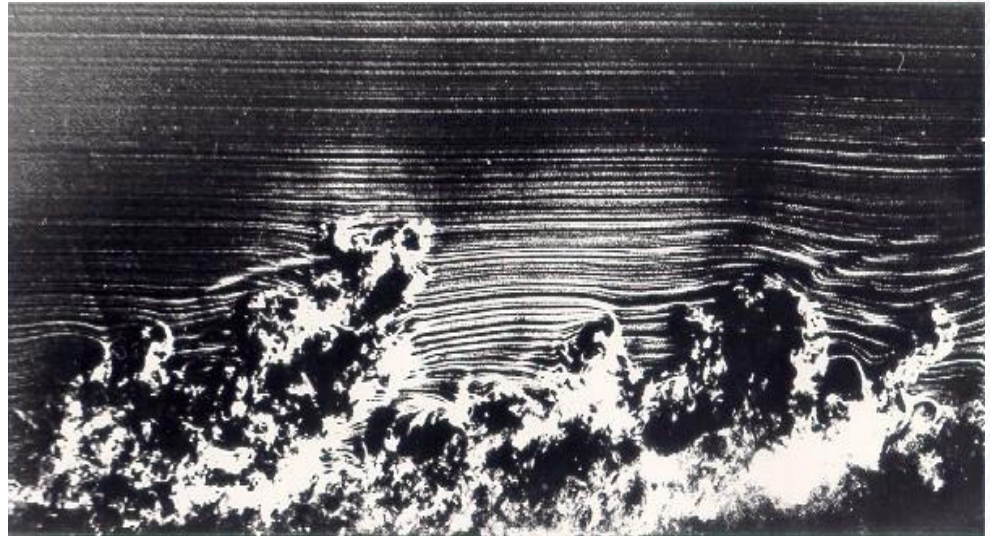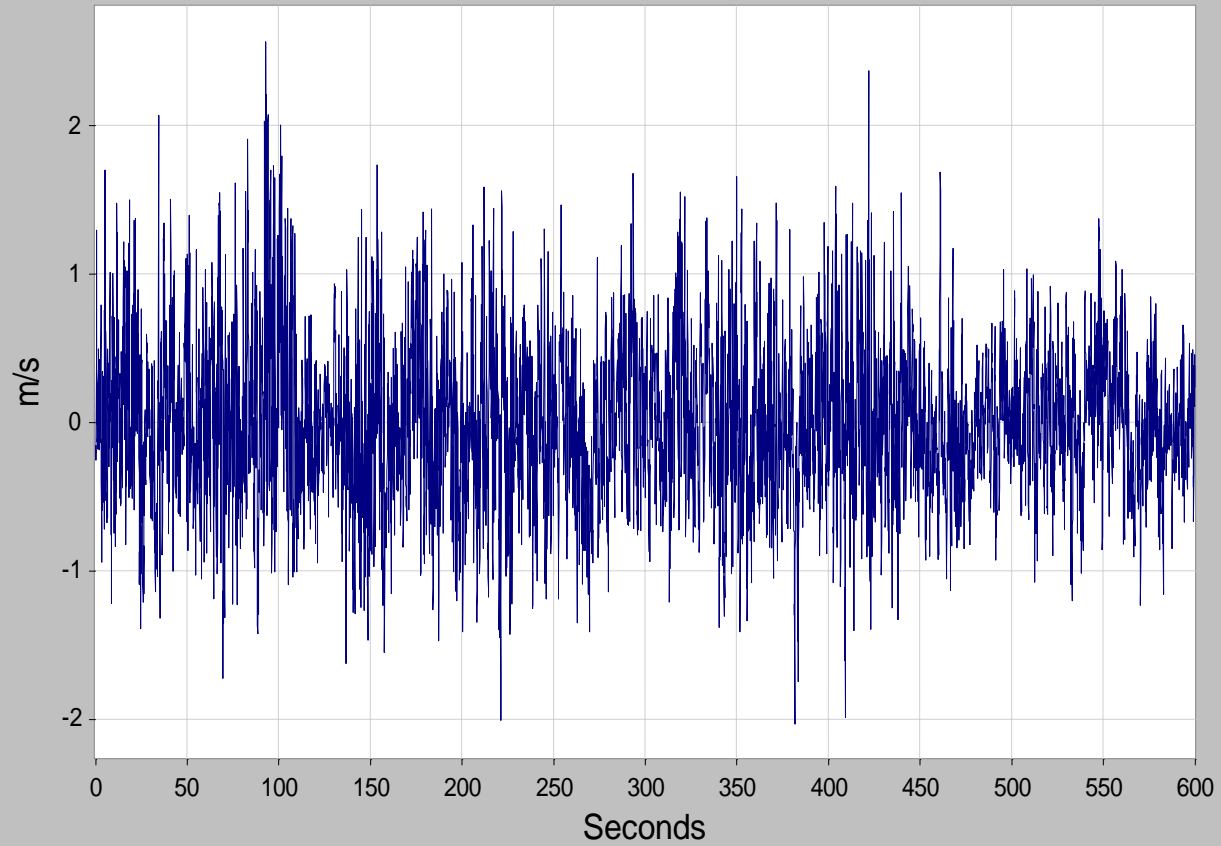
(Kaimal & Finnigan 1994)

3. 湍流的结构

时域上垂直风速

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垂直风速的湍流谱

ω − 角频率

t − 时间

$$w(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} w(t)\, e^{i\omega t} dt$$

$$w(t) = \int_{-\infty}^{\infty} w(\omega) e^{-i\omega t} d\omega$$

湍流谱的分解

任何信号均可以表达为三角玄函数级数之和，
即傅立叶级数（Fourier series）.

$$s_a(t) = k_a + A_{a_1}\cos(\omega_{a_1}t + \phi_{a_1}) + A_{a_2}\cos(\omega_{a_2}t + \phi_{a_2}) + A_{a_3}\cos(\omega_{a_3}t + \phi_{a_3}) + ...$$
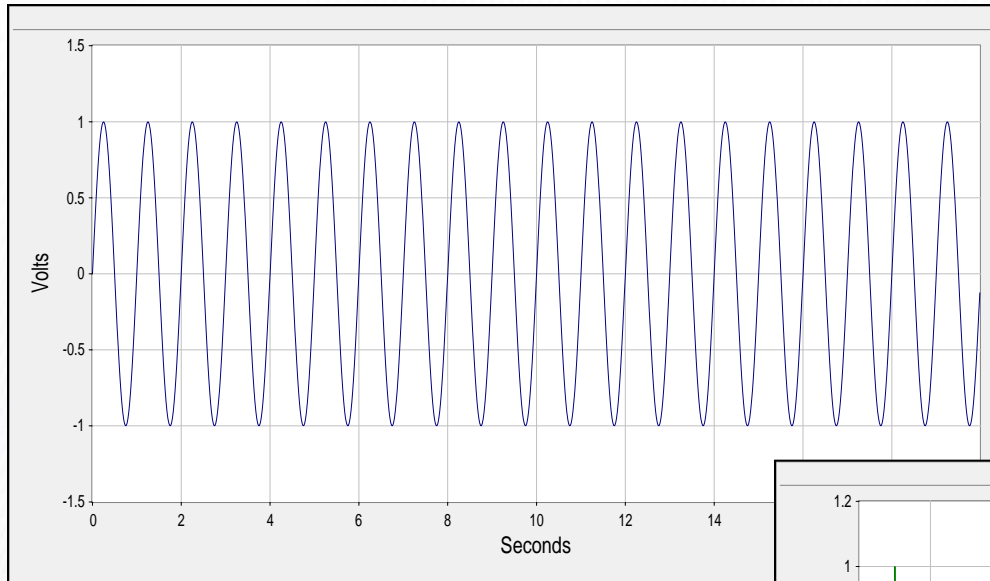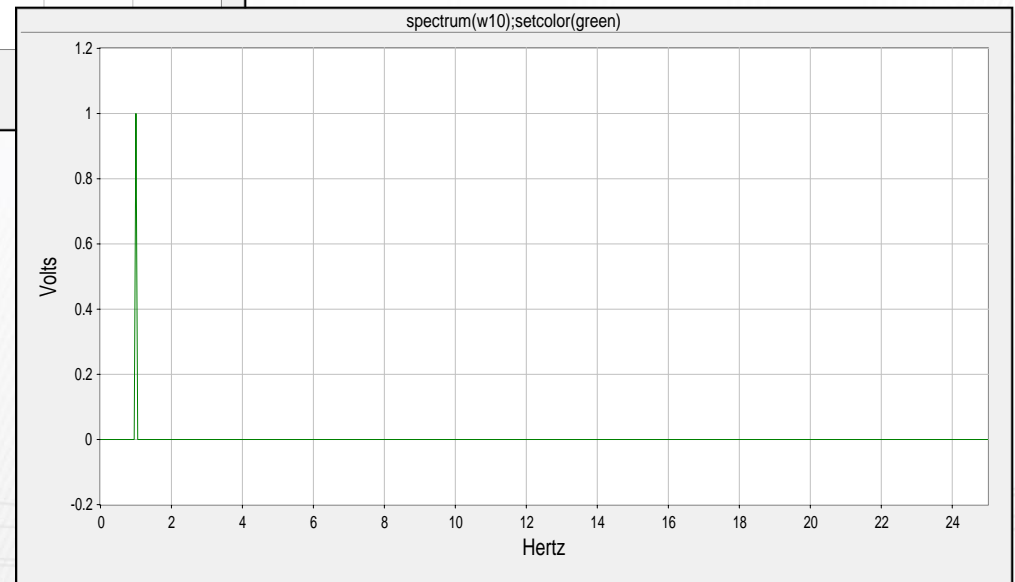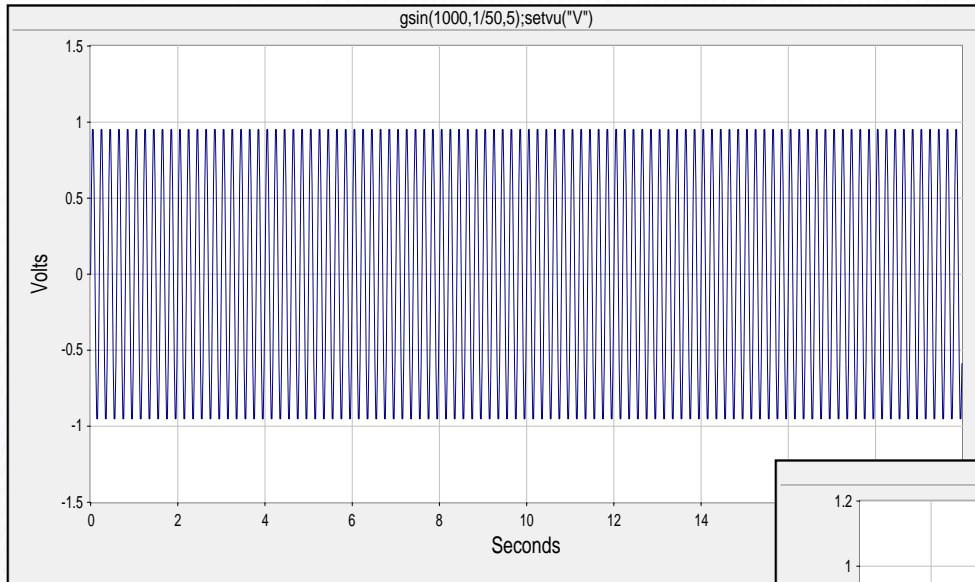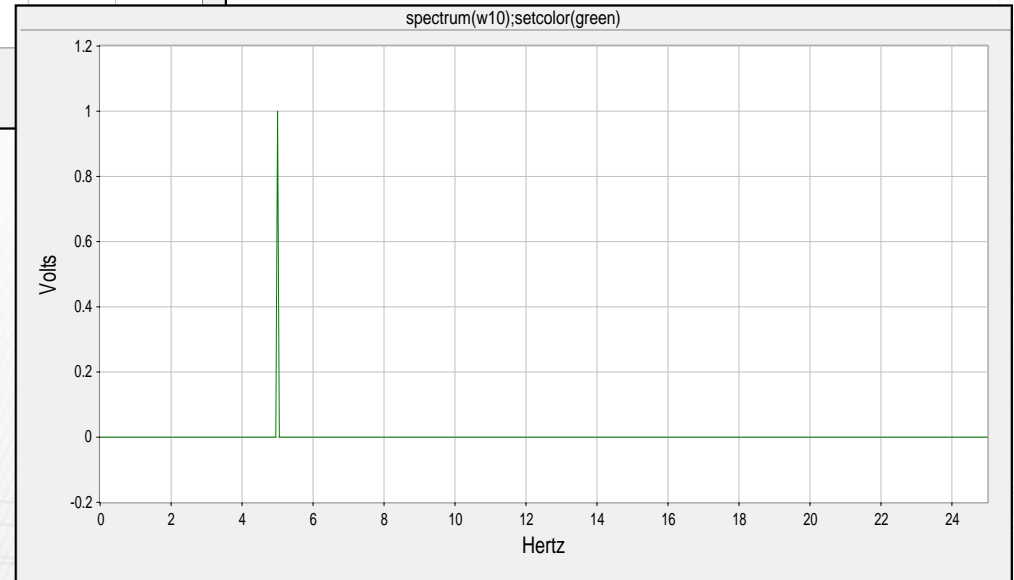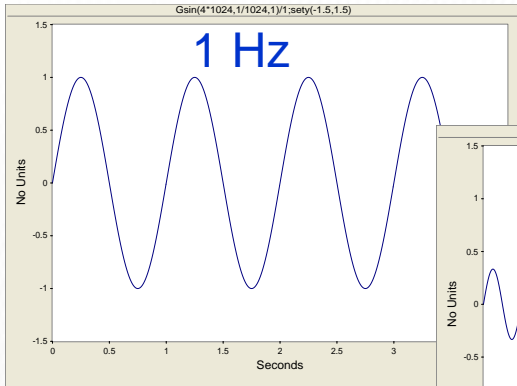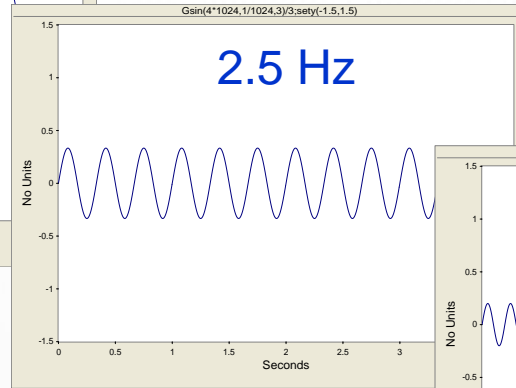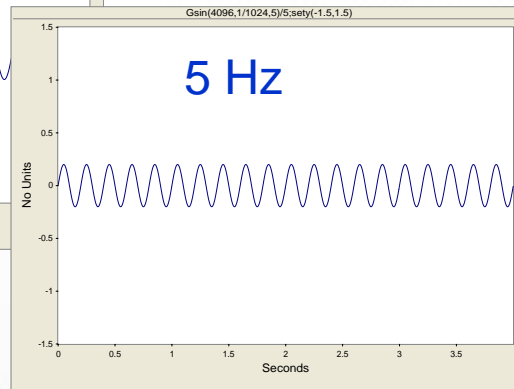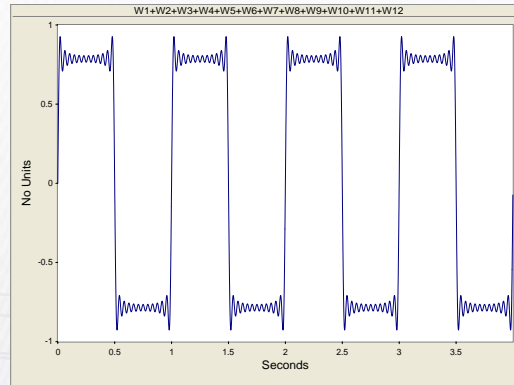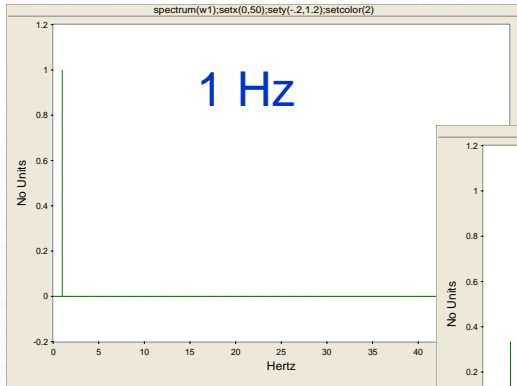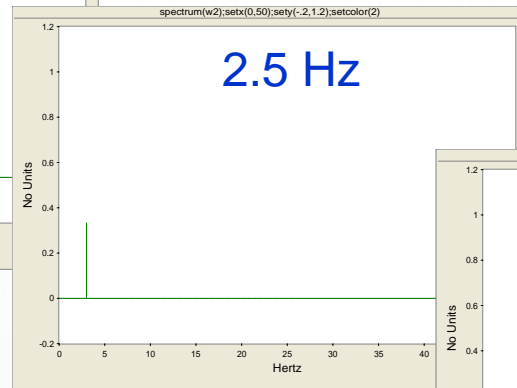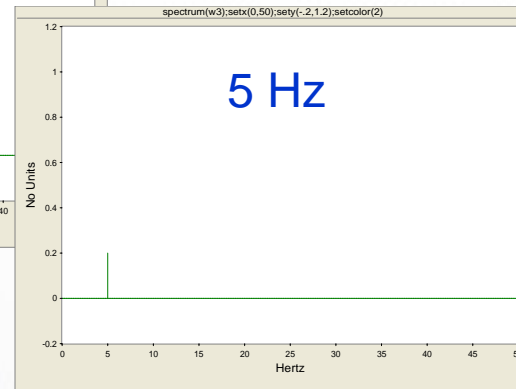
信号谱是将振幅 (A_{ai}) 和相位 (ϕ_{ai}) 表达为这些角频率 (ω_{ai}) 的函数

正弦波从时域到频域

$$s_a(t) = k_a + A_{a_1}\cos(\omega_{a_1}t + \phi_{a_1}) + A_{a_2}\cos(\omega_{a_2}t + \phi_{a_2}) + A_{a_3}\cos(\omega_{a_3}t + \phi_{a_3}) + \ldots$$

1-Hz 正弦时间函数

1-Hz 正弦时间函数在频域上的表达

正弦波从时域到频域

$$s_a(t) = k_a + A_{a_1}\cos(\omega_{a_1}t + \phi_{a_1}) + A_{a_2}\cos(\omega_{a_2}t + \phi_{a_2}) + A_{a_3}\cos(\omega_{a_3}t + \phi_{a_3}) + ...$$

5-Hz 正弦时间函数

5-Hz 正弦时间函数 在频域上的表达

多个正弦时间函数的叠加

$$s_a(t) = k_a + A_{a_1}\cos(\omega_{a_1}t + \phi_{a_1}) + A_{a_2}\cos(\omega_{a_2}t + \phi_{a_2}) + A_{a_3}\cos(\omega_{a_3}t + \phi_{a_3}) + \ldots$$

多个正弦时间函数叠加后
在频域上的表达
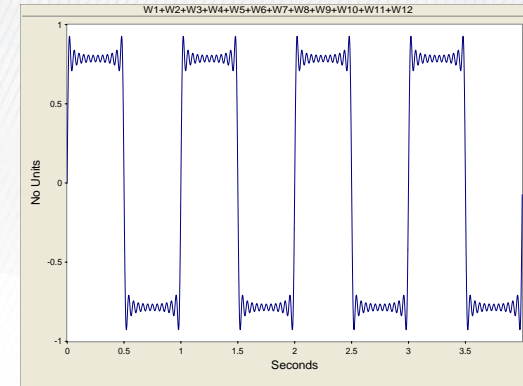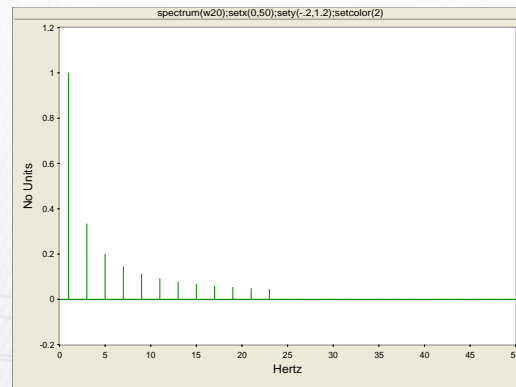
方差谱的分解

方差既可表达在时域上，也可表达在频域上（Parseval 定理）.

$$s_a(t) = k_a + A_{a_1}\cos(\omega_{a_1} t + \phi_{a_1}) + A_{a_2}\cos(\omega_{a_2} t + \phi_{a_2}) + A_{a_3}\cos(\omega_{a_3} t + \phi_{a_3}) + ...$$

$$\mathrm{var}(s_a) = \frac{A_{a_1}^2}{2} + \frac{A_{a_2}^2}{2} + \frac{A_{a_3}^2}{2} + ...$$

方差是对能量谱密度函数在频域上的积分

方差是对能量谱密度函数在频域上的积分

自相关定义

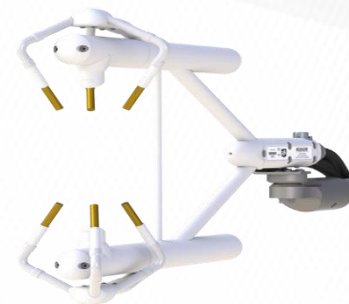$$R_{ww}(\tau) = \overline{w'(t)w'(t+\tau)} = \lim_{T_p \to \infty} \frac{1}{2T_p} \int_{-T_p}^{T_p} w'(t)w'(t+\tau)d\tau$$

傅立叶变换对

$$S_{ww}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R_{ww}(\tau)e^{i\omega\tau}d\tau$$

$$R_{ww}(\tau) = \int_{-\infty}^{\infty} S_{ww}(\omega)e^{-i\omega\tau}d\omega = \int_{-\infty}^{\infty} S_{ww}(\omega)d\omega = \overline{w'(t)w'(t+\tau)}$$

$$R_{ww}(0) = \int_{-\infty}^{\infty} S_{ww}(\omega)e^{-i\omega 0}d\omega = \int_{-\infty}^{\infty} S_{ww}(\omega)d\omega = \overline{w'(t)w'(t+0)} = \overline{w'^2}$$

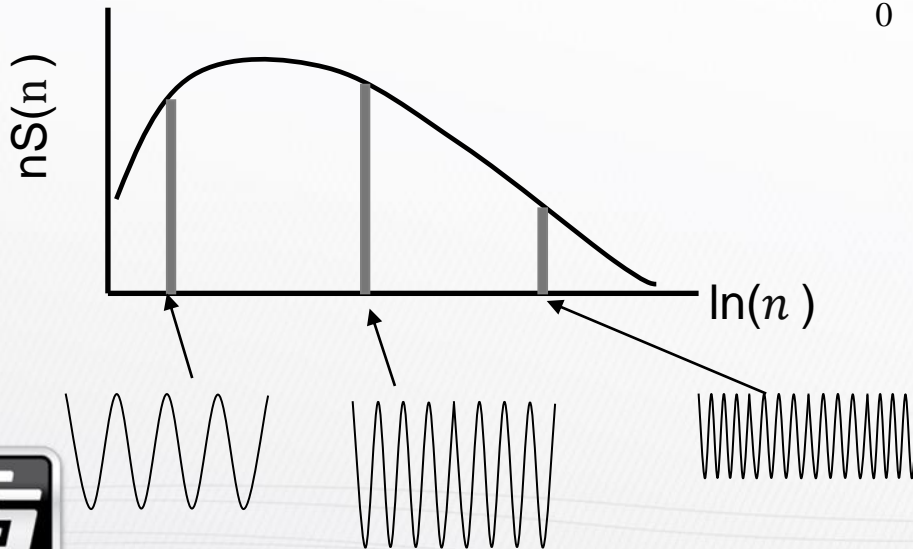$$\overline{w'^2} = \int_{-\infty}^{\infty} S_{ww}(\omega)d\omega$$

垂直风速

时域函数
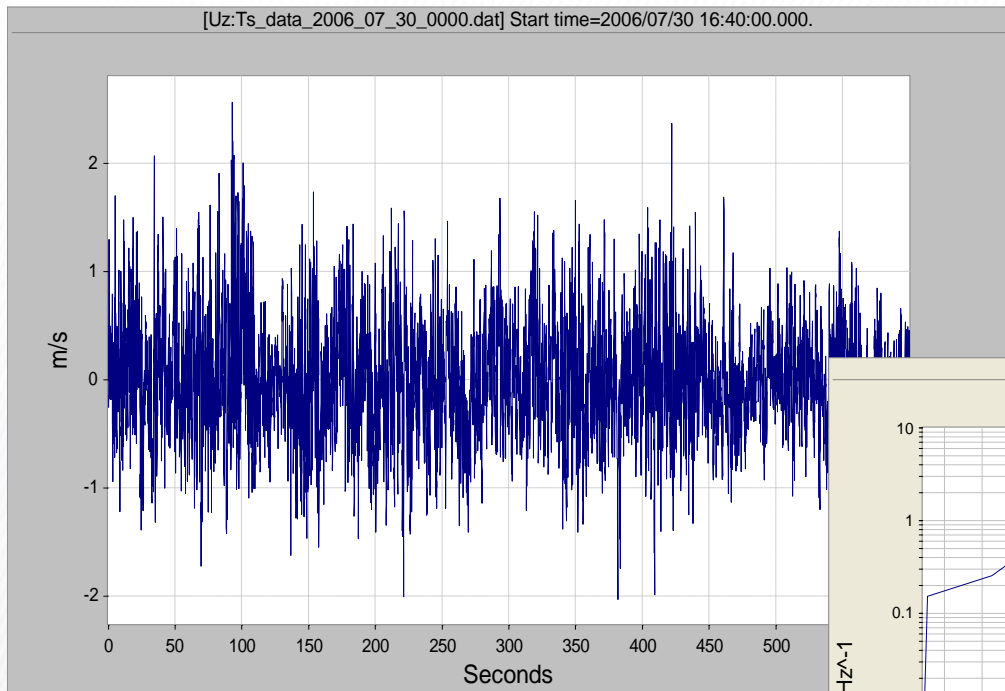
频域函数
(phase not shown)
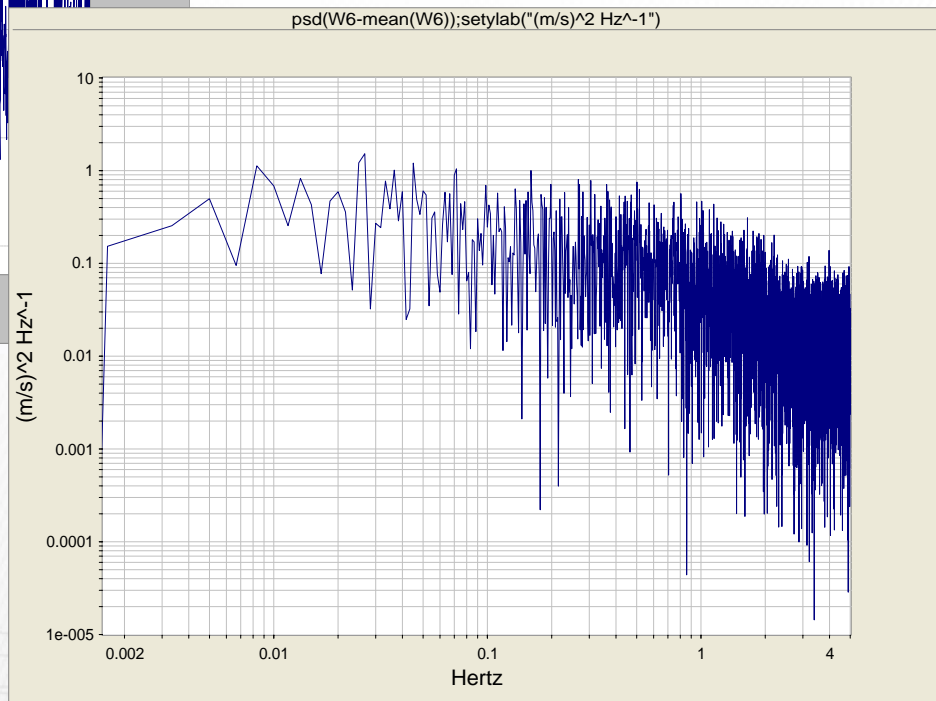
平滑的垂直风速能量谱

一般谱函数形状
Kaimal 谱

湍流能量谱的一般形式

频率 x 能量谱

−5/3
频率

湍流团的产生

湍流团破碎
（能量由大团传到小团）

湍流能量
由热形式扩散

频率（自然对数坐标）
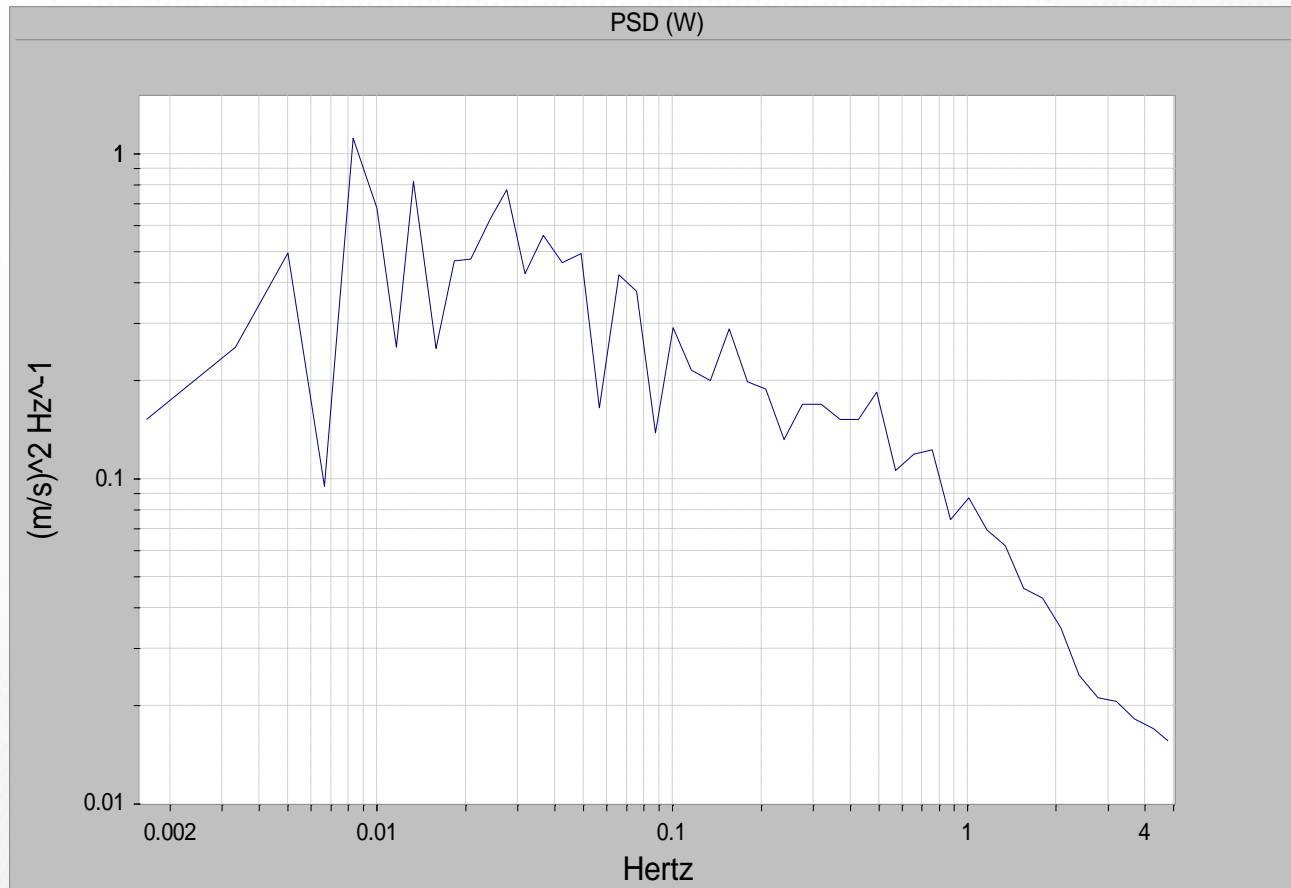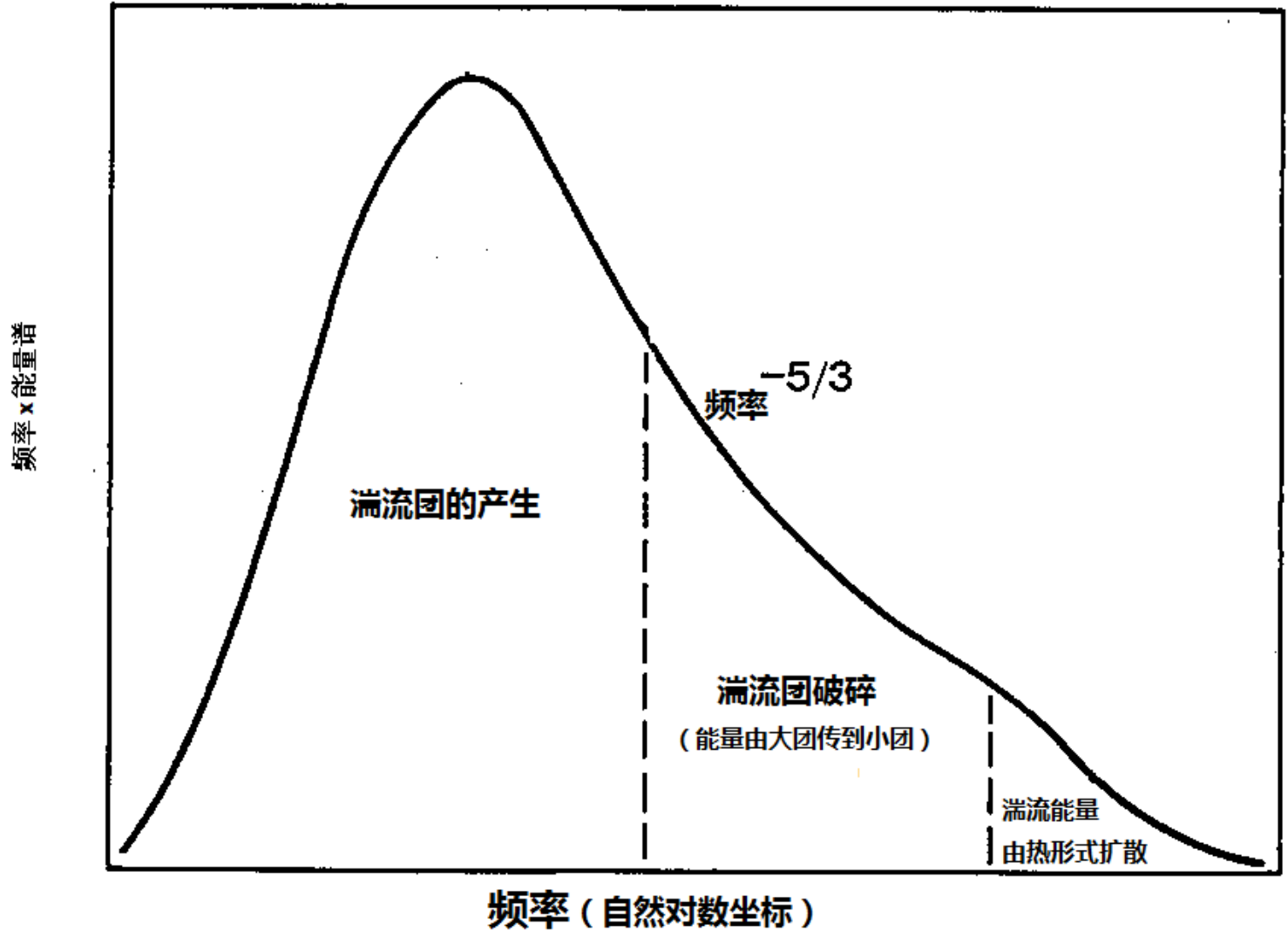
协方差也是对能量谱密度函数在频域上的积分

用自相关定义两个不同变量的相关

$$R_{\alpha w}(r) = \overline{\alpha'(x)w'(x+r)} = \lim_{T_p \to \infty} \frac{1}{2T_p} \int_{-T_p}^{T_p} \alpha'(x)w'(x+r)dr$$

傅立叶变换对

$$S_{\alpha w}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R_{\alpha w}(r)e^{i\omega r}dr$$

$$R_{\alpha w}(\tau) = \int_{-\infty}^{\infty} S_{\alpha w}(\omega)e^{-i\omega\tau}d\omega = \int_{-\infty}^{\infty} S_{\alpha w}(\omega)d\omega = \overline{\alpha'(x)w'(x+\tau)}$$

$$R_{\alpha w}(0) = \int_{-\infty}^{\infty} S_{\alpha w}(\omega)e^{-i\omega 0}d\omega = \int_{-\infty}^{\infty} S_{\alpha w}(\omega)d\omega = \overline{\alpha'(x)w'(x+0)} = \overline{\alpha'w'}$$

$$\overline{\alpha'w'} = \int_{-\infty}^{\infty} S_{\alpha w}(\omega)d\omega$$

湍流谱和协湍流谱的一般形状

$$n = \frac{fz}{\bar{u}}, \quad f = \frac{\omega}{2\pi}$$

$$\text{variance} = \overline{T'^2} = \int_0^\infty n S_T(n) \, d\ln(n)$$

$$\text{covariance} = \overline{w'T'} = \int_0^\infty n C_{wT}(n) \, d\ln(n)$$

Larry Jacobsen, CSI

垂直风速与水平风速或温度
在近地面层不同稳定性下的协湍流谱

(Kaimal & Finnigan 1994)
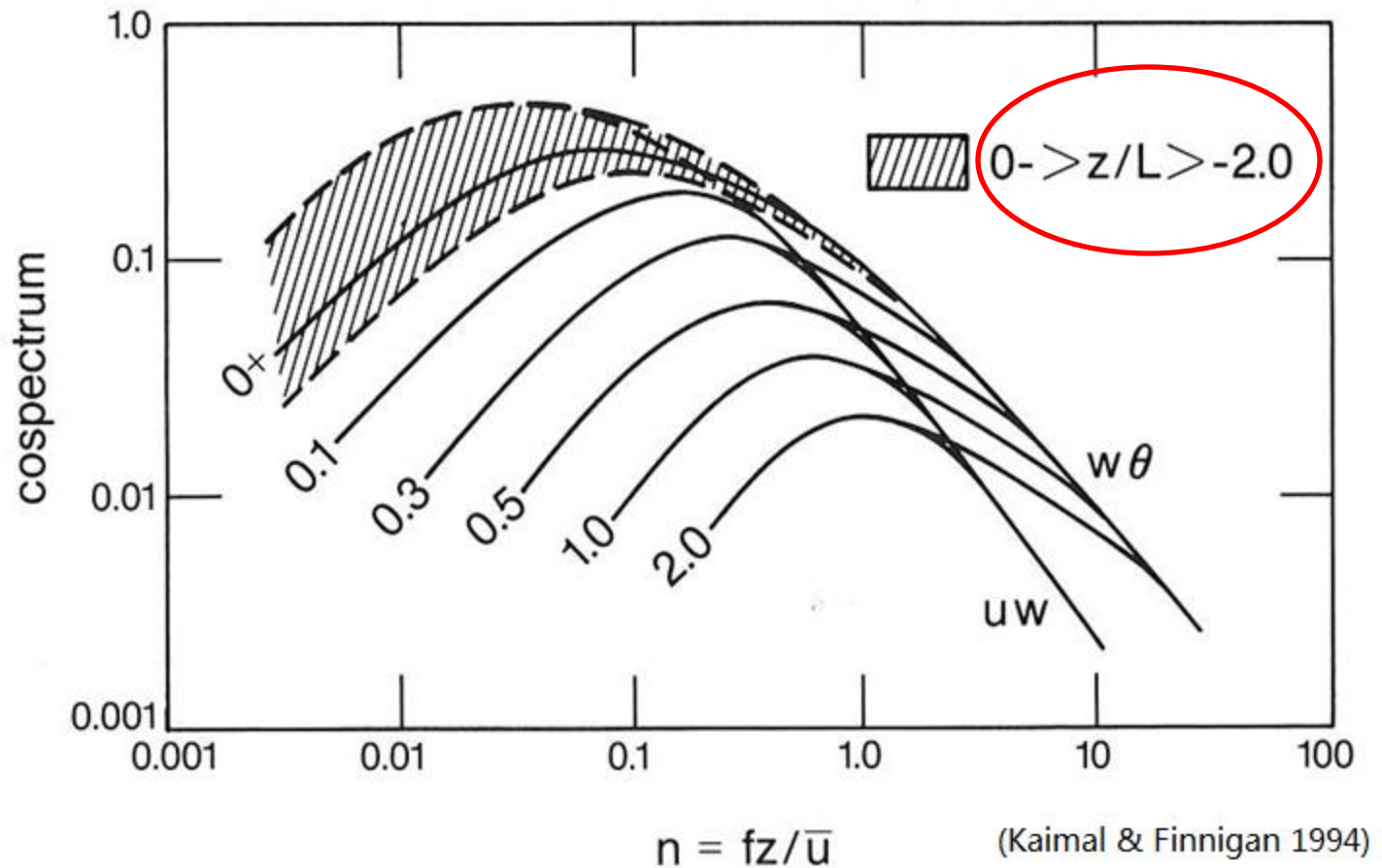
协湍流谱

$$\frac{Z}{L} > 0$$

水平风速与垂直风速

$$fS_{uw}(f) = \frac{fz/\overline{u}}{A_{uw} + B_{uw}\left(\dfrac{fz}{\overline{u}}\right)^{2.1}}$$

$$A_{uw} = 0.124\left(1 + 7.9\frac{z}{L}\right)^{0.75}$$

$$B_{uw} = 23.252\left(1 + 7.9\frac{z}{L}\right)^{-0.825}$$

气温与垂直风速

$$fS_{Tw}(f) = \frac{fz/\overline{u}}{A_{Tw} + B_{Tw}\left(\dfrac{fz}{\overline{u}}\right)^{2.1}}$$

$$A_{Tw} = 0.284\left(1 + 6.4\frac{z}{L}\right)^{0.75}$$

$$B_{Tw} = 9.3447\left(1 + 6.4\frac{z}{L}\right)^{-0.825}$$

4. 湍流传输动量，热量及质量的规律

三个假设

1. 等高空间上的一致性

$$\frac{\partial}{\partial x_1} = 0 \qquad \frac{\partial}{\partial x_2} = 0$$

2. 时域上的稳定性

$$\frac{\partial}{\partial t} = 0$$

3. 干空气物质守恒

$$\overline{u}_3 = 0$$

雷诺平均运动方程 (u_1 方向)

$$\frac{\partial \overline{u}_1}{\partial t} + \overline{u}_J \frac{\partial \overline{u}_1}{\partial x_J} = -\frac{\partial \overline{P}_1}{\rho_0 \partial x_1} + \frac{1}{\rho_0}\frac{\partial}{\partial x_J}\left(\mu\frac{\partial \overline{u}_1}{\partial x_J} - \rho_0 \overline{u'_1 u'_J}\right) + \frac{\overline{T}_1}{T_0} g \delta_{31}$$

$$\Downarrow$$

$$\frac{1}{\rho_0}\frac{\partial}{\partial x_3}\left(\mu\frac{\partial \overline{u}_1}{\partial x_3} - \rho_0 \overline{u'_1 u'_3}\right) = 0$$

$$\Downarrow$$

$$\mu\frac{\partial \overline{u}_1}{\partial x_3} - \rho_0 \overline{u'_1 u'_3} = \text{Constant}$$

$$\Downarrow$$

$$\rho_0 \overline{(u_1 - \overline{u}_1)(u_3 - \overline{u}_2)}$$

$$\frac{kg}{m^3} \qquad \frac{m}{s} \qquad \frac{m}{s}$$

$$\Downarrow$$

$$\frac{kg\,m/s}{m^2 s}$$
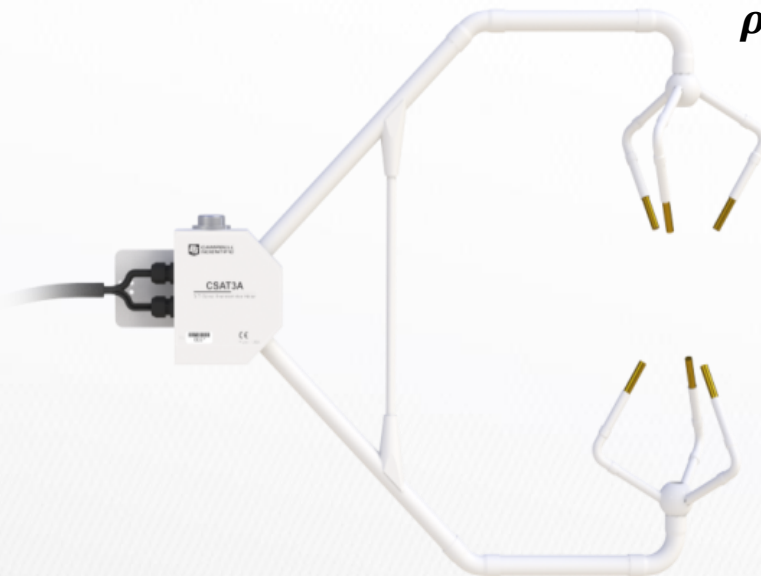
常通量结论

纵向CO₂，水，热通量是常量

$$\frac{\partial}{\partial w}\left(K_T \frac{\partial \overline{T}_1}{\partial w} - C_p \rho_0 \overline{w'T'}_1\right) = 0$$

$$\frac{J}{{}^oC\,kg} \frac{kg}{m^3} \frac{m}{s} {}^oC = \frac{J}{m^2 s}$$

$$\frac{\partial}{\partial w}\left(K_{co2} \frac{\partial \bar{\rho}_{Co2}}{\partial w} - \overline{w'\rho'}_{CO2}\right) = 0$$

$$\frac{m}{s} \frac{mg}{m^3} = \frac{mg}{m^2 s}$$

$$\frac{\partial}{\partial w}\left(K_{h2o} \frac{\partial \bar{\rho}_{h2o}}{\partial w} - \overline{w'\rho'}_{h2o}\right) = 0$$

$$\frac{m}{s} \frac{g}{m^3} = \frac{g}{m^2 s}$$

EC150
红外碳水开路分析仪

IRGASON
红外超声碳水热通量集成仪

EC155
红外碳水闭路分析仪

CSAT3
三维超声风速仪

z

$$\tau = \rho_0 \overline{w'u'}$$

$$H = C_p \rho_0 \overline{w'T'}$$

$$F_C = \overline{w'\rho'}_{co2}$$

$$E = \overline{w'\rho'}_{h2o}$$

$w' \downarrow$

$w' \uparrow$

CO_2

u

H_2O

T

R. Leuning, 2010

竖直风 m/s	U' m/s	T' ºC	ρ'_{CO2} mg/m³	ρ'_{h2o} g/m³
上 w'= 0.1	-1	1	-1	1
下 w'= - 0.1	1	-1	1	-1
通量	-0.2 $\frac{kg\,m/s}{m^2\,s}$	200 $\frac{w}{m^2}$	-0.2 $\frac{mg}{m^2\,s}$	0.2 $\frac{g}{m^2\,s}$
	动量	热	CO_2	H_2O

$$\rho_0 \approx 1 \, \frac{kg}{m^3}, \qquad C_p \approx 1000 \, \frac{J}{ºC\,kg}$$

$e.g \quad \Delta t = 0.5 \, s$

林下通量可逆梯度而行
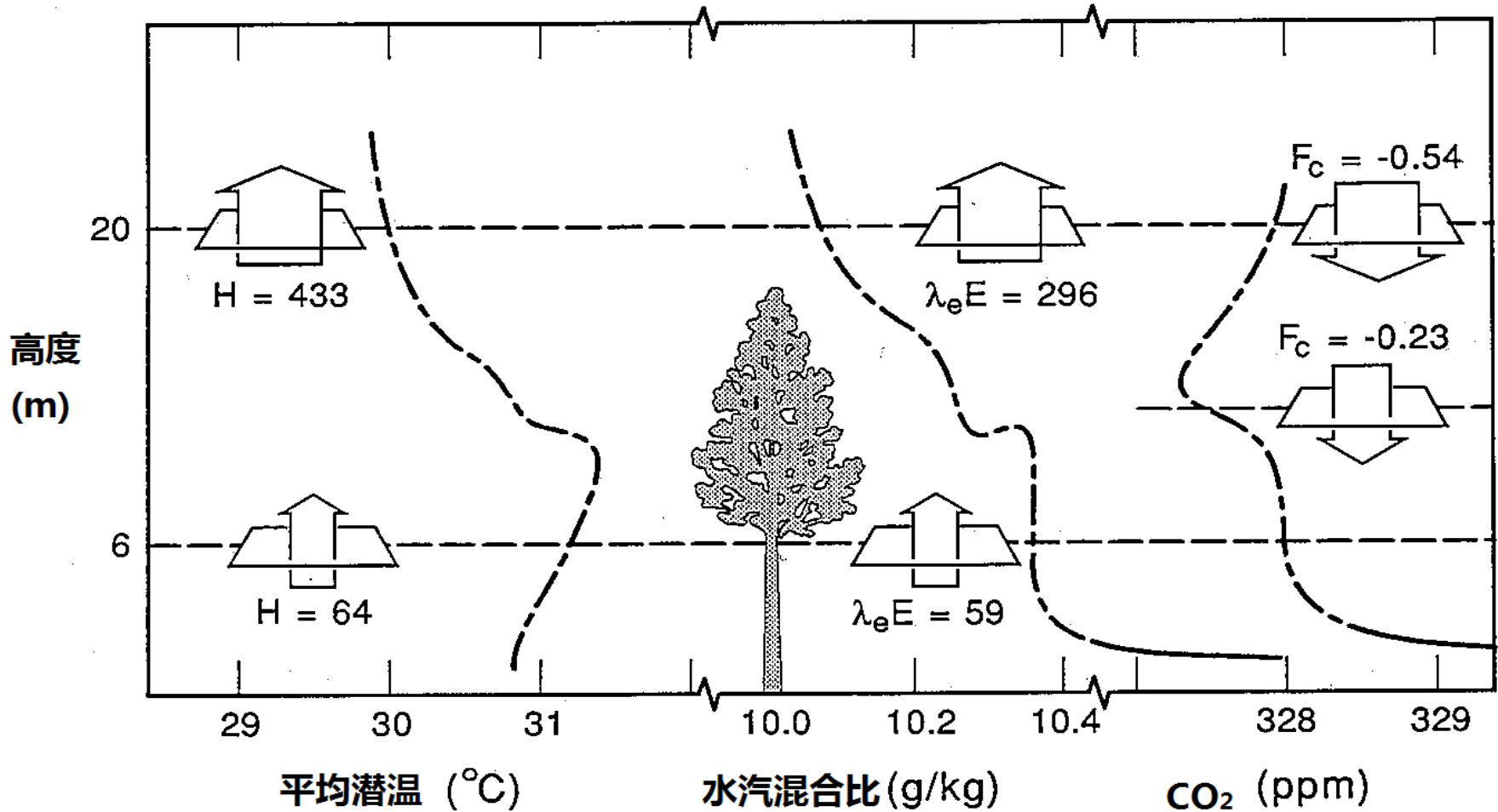
Denmead & Bradley 1985

林内的质能源汇使林内通量复杂化
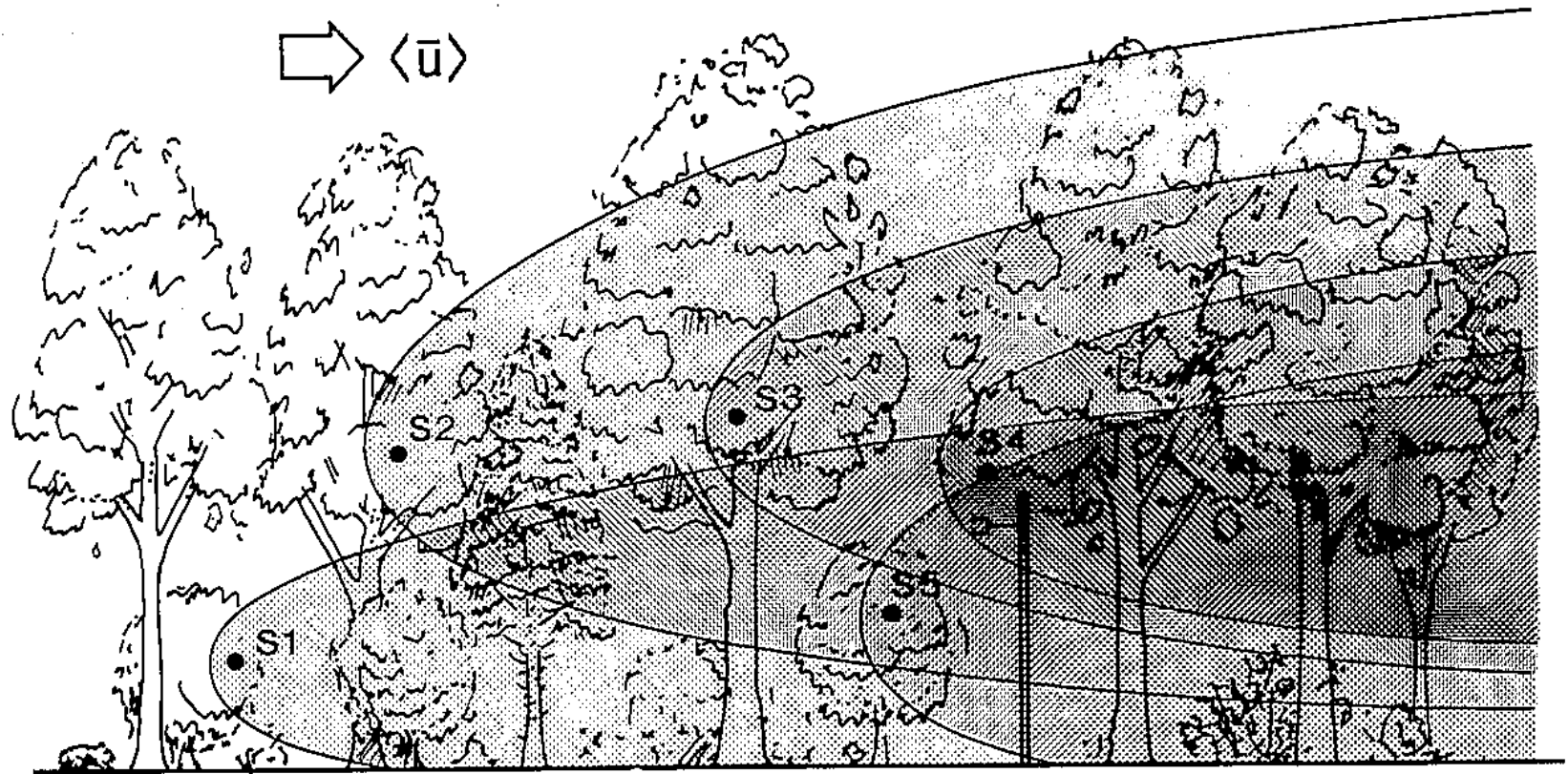
$$H = C_p \rho_0 \overline{w'T'}$$

$$F_{co2} = \overline{w'\rho'}_{co2}$$

$$E = \overline{w'\rho'}_{h2o}$$

严谨测定方法
依据：边界层流体物理学理论

1. 传感器的野外安装
a. 开阔域湍流场 (Fetch)
b. 传感器的感源分布 (Footprint)
c. 同时空测定
d. 坐标旋转

2. 传感器反应
a. 传感器的敏感度
b. 时间常数 **(Time constant)**
c. 传输函数 **(Transfer function)**
d. 测定路径和体积平均 (path length/volume averaging)
e. 平均时长 (**Low frequency issue**)

3. 测定频率 (Sampling frequency)
4. 高叠（"杂"）低现象 （Aliasing）
5. 超声感热通量订正 （**SND correction**）
6. 氧订正 （**Oxygen correction**）
7. 订正测定过程中空气密度的变化影响 （WPL correction）

1. 传感器的野外安装

空间异质性 (Spatial Heterogeneity)

Tsutomu WATANABE
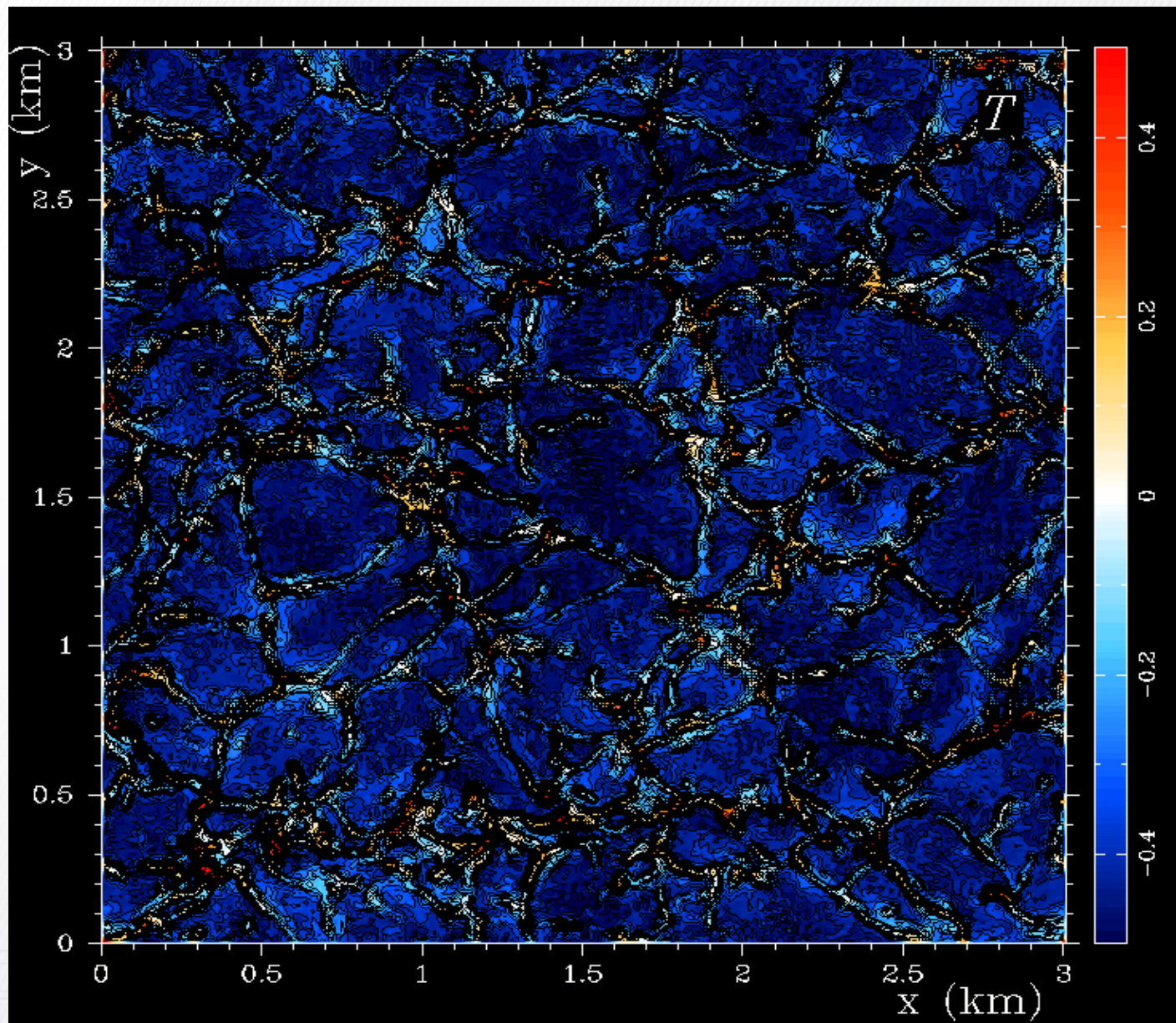
协方差与其能量谱

协方差定义

$$R_{\alpha w}(r) = \overline{\alpha'(x)w'(x+r)}$$

傅立叶变换对

$$S_{\alpha w}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R_{\alpha w}(r) e^{i\omega r} dr$$

$$R_{\alpha w}(0) = \int_{-\infty}^{\infty} S_{\alpha w}(\omega) e^{-i\omega 0} d\omega = \int_{-\infty}^{\infty} S_{\alpha w}(\omega) d\omega$$

$$R_{\alpha w}(0) = \overline{\alpha'(x)w'(x+0)} = \overline{\alpha' w'}$$

$$\overline{\alpha' w'} = \int_{-\infty}^{\infty} S_{\alpha w}(\omega) d\omega$$

同时空测定

异空测定

- *– loss of covariance*
- *- Samples eddies > ~2d*

最新工艺
IRGASON

d

Luning 2010

© 2011 Campbell Scientific
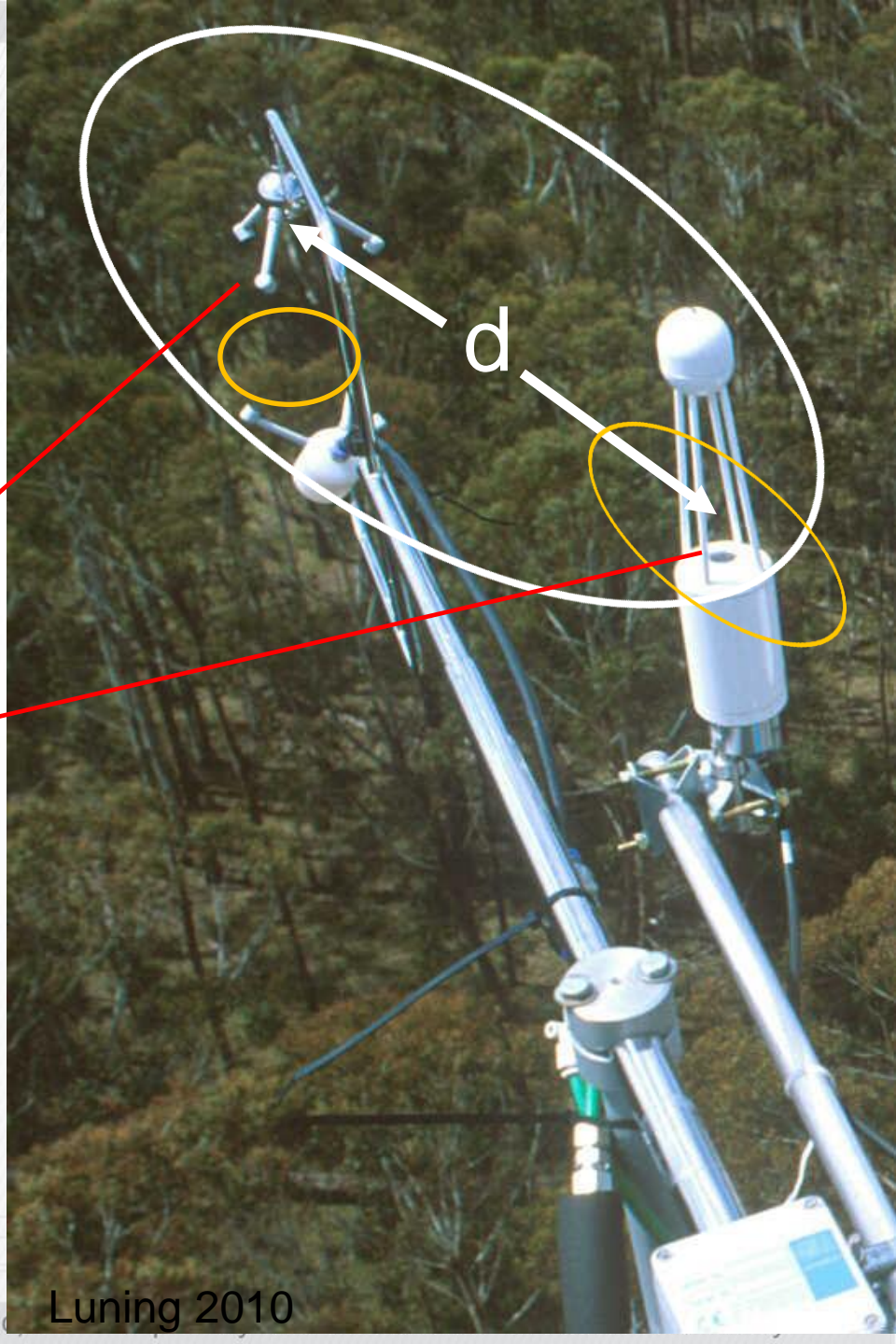
协方差与其能量谱

协方差定义
$$R_{\alpha w}(r) = \overline{\alpha'(x)w'(x+r)}$$

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$$S_{\alpha w}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R_{\alpha w}(r)e^{i\omega r}dr$$

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$$R_{\alpha w}(0) = \overline{\alpha'(x)w'(x+0)} = \overline{\alpha' w'}$$

$$\overline{\alpha' w'} = \int_{-\infty}^{\infty} S_{\alpha w}(\omega)d\omega$$

坐标旋转修正
为什么?
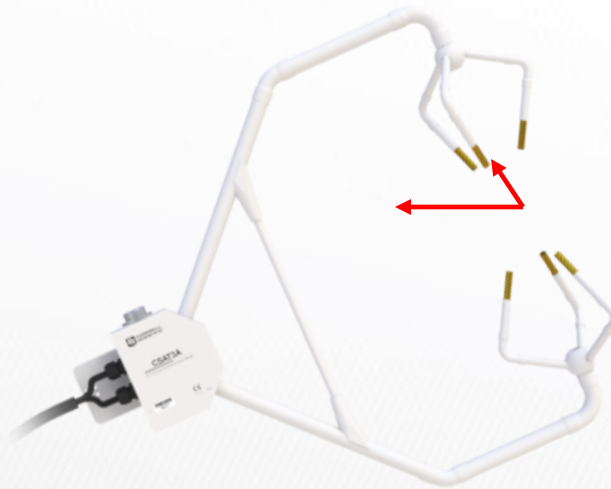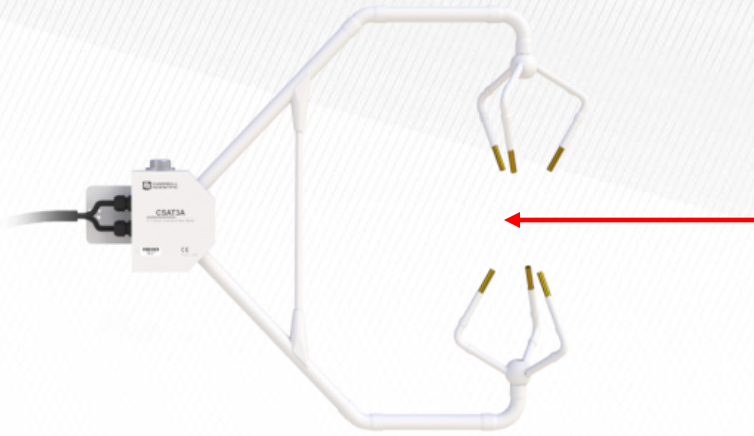
仪器与风场坐标系
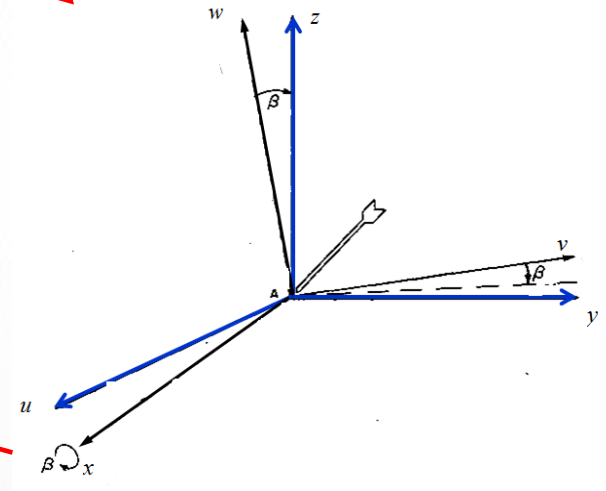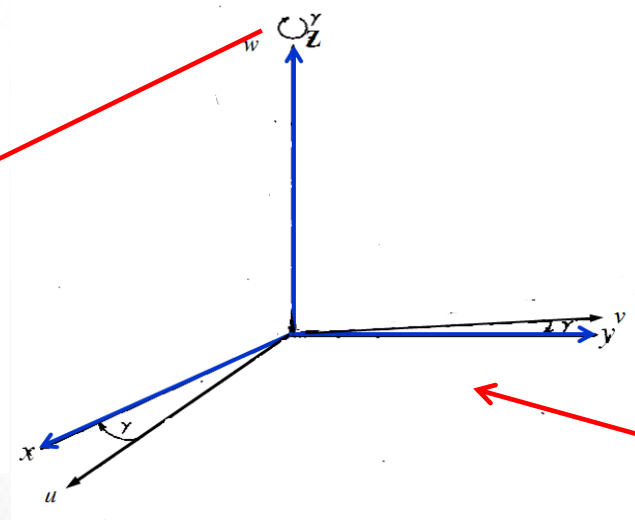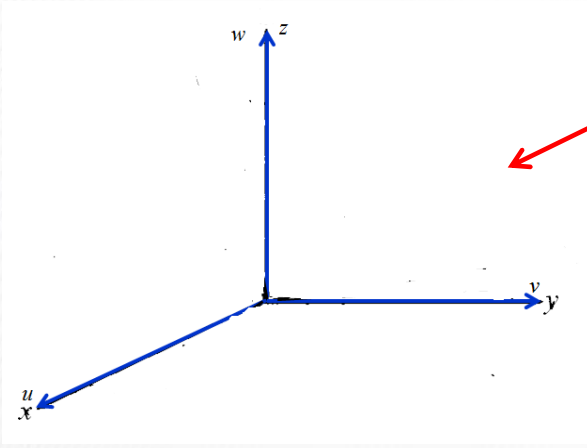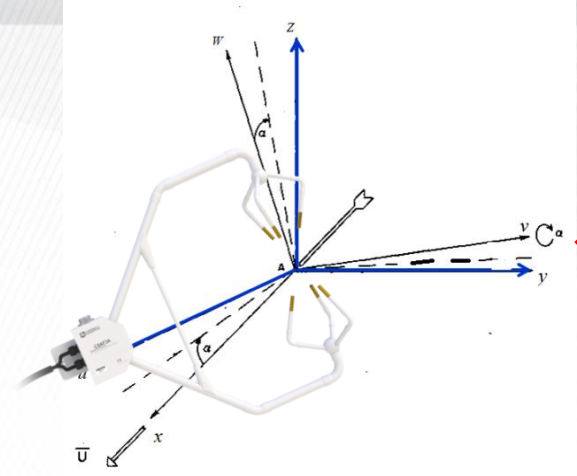
$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} u_m \\ v_m \\ w_m \end{bmatrix}$$
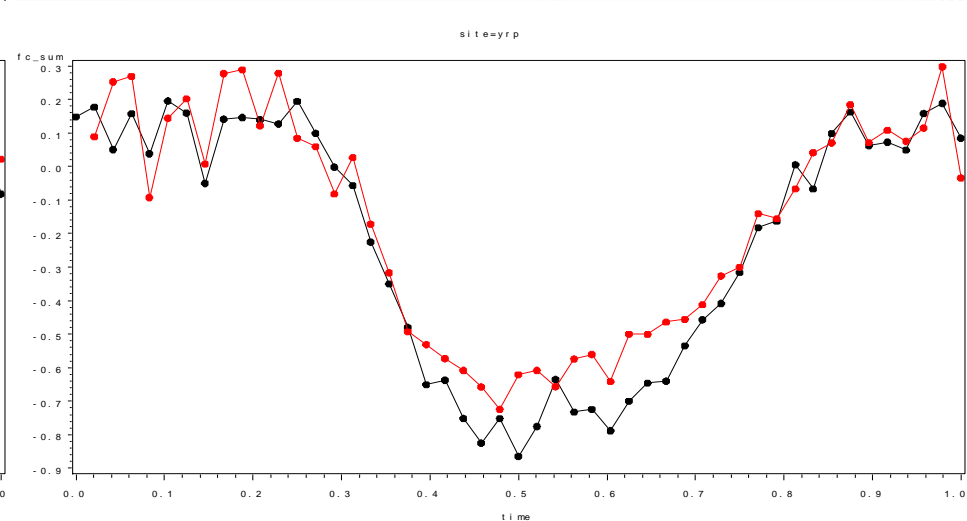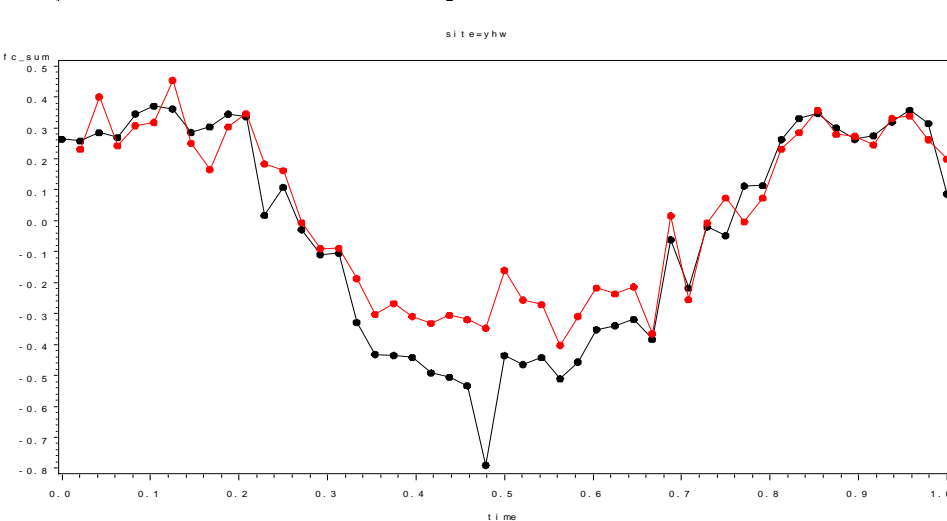
角度的计算

$$\gamma = \arctan\left(\frac{\overline{v}_m}{\overline{u}_m}\right)$$
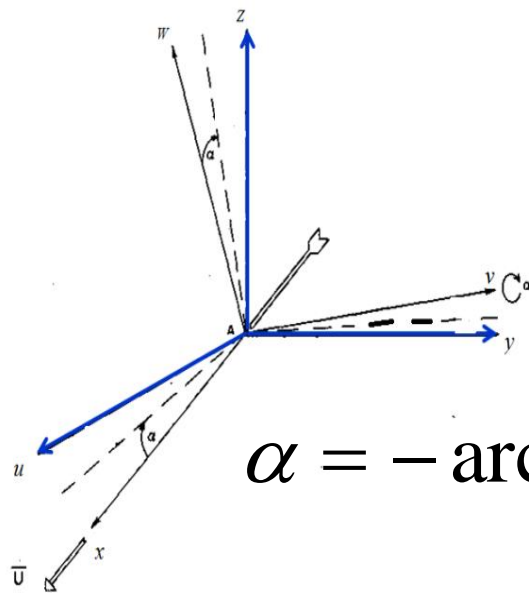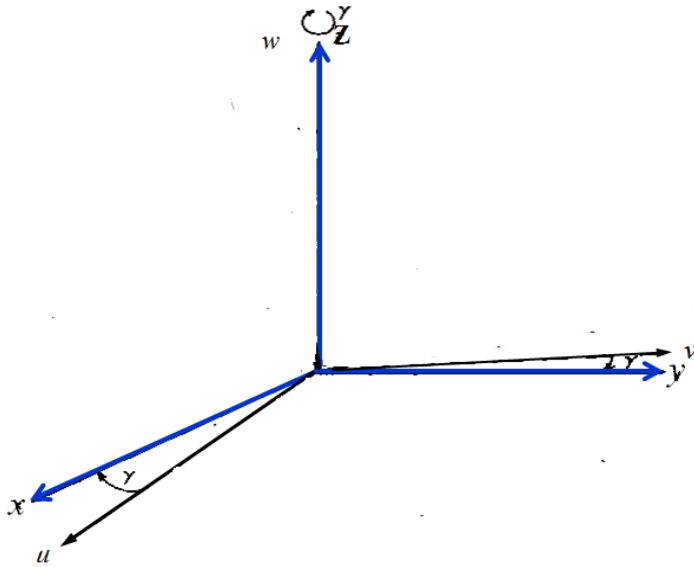
$$\alpha = -\arctan\frac{\overline{w}_1}{\overline{u}_1} = -\arctan\frac{\overline{w}_m}{\overline{u}_m\cos\gamma + \overline{v}_m\sin\gamma}$$

两次旋转

第一次旋转
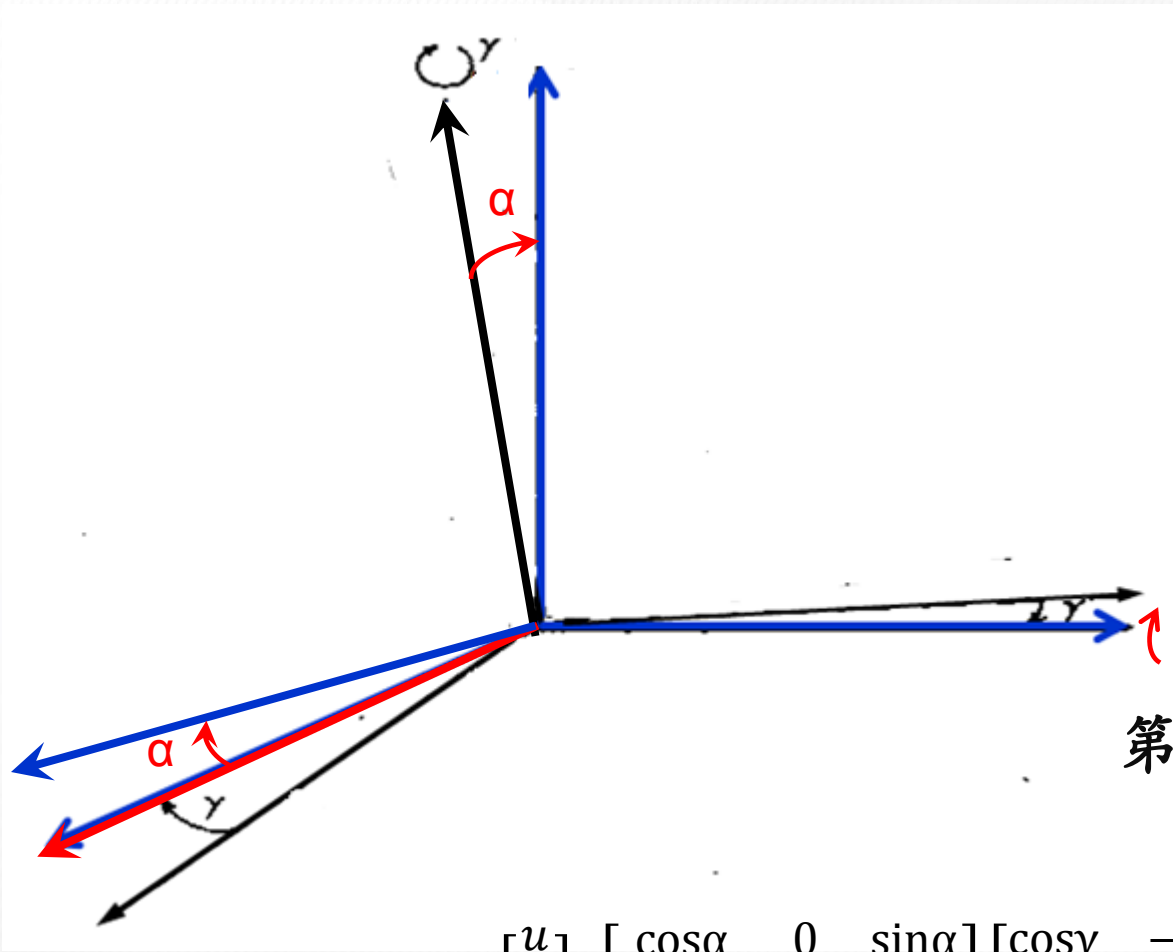
第二次旋转

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_m \\ v_m \\ w_m \end{bmatrix}$$

平面拟合坐标旋转角度计算
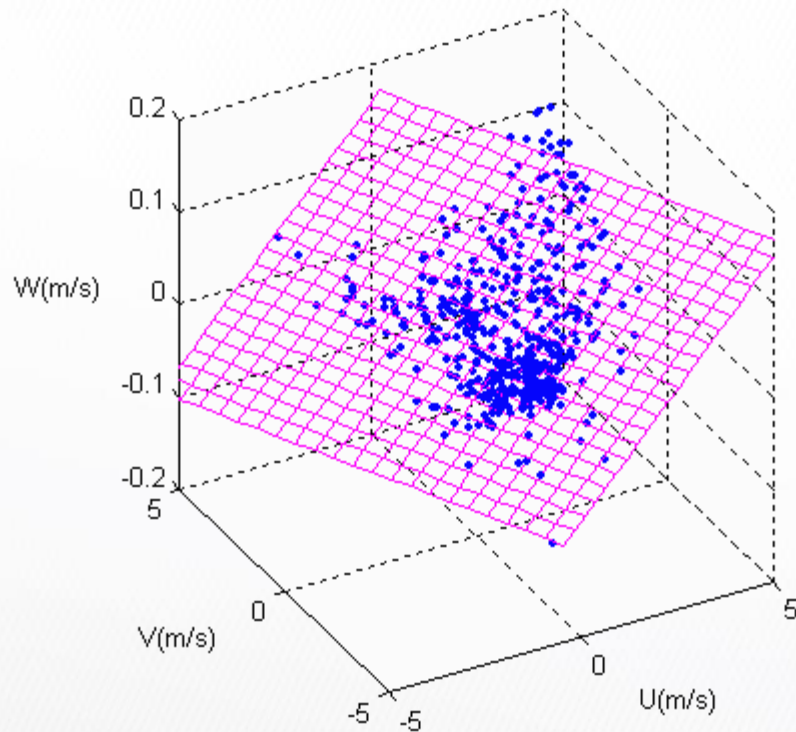
COORDINATE SYSTEM ROTATED ABOUT THIS PLANE

平面拟合
坐标旋转

第一次旋转

第二次旋转
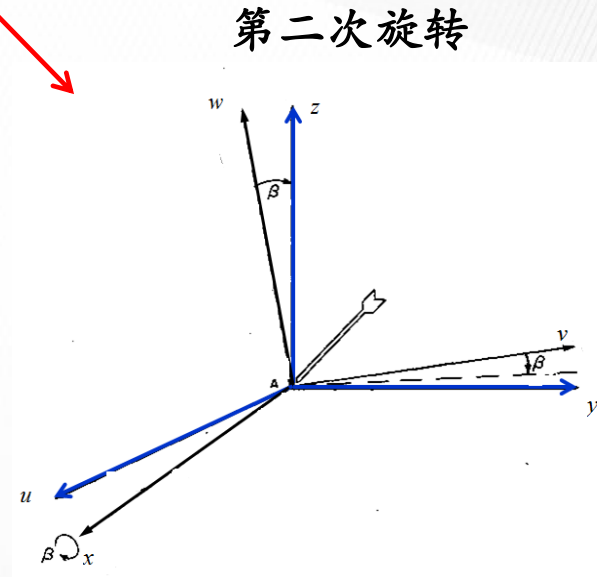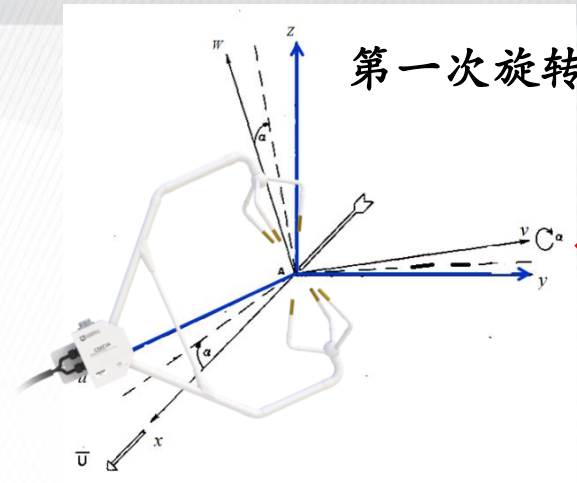
$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1 & 0 \\ -\sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} u_m \\ v_m \\ w_m \end{bmatrix}$$
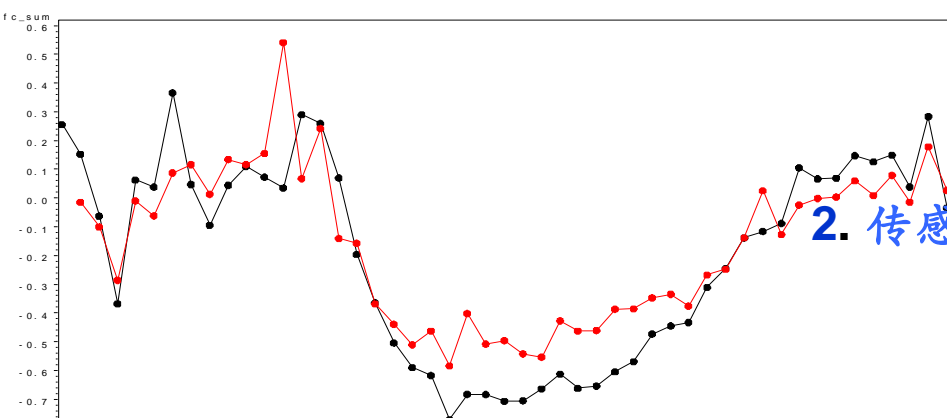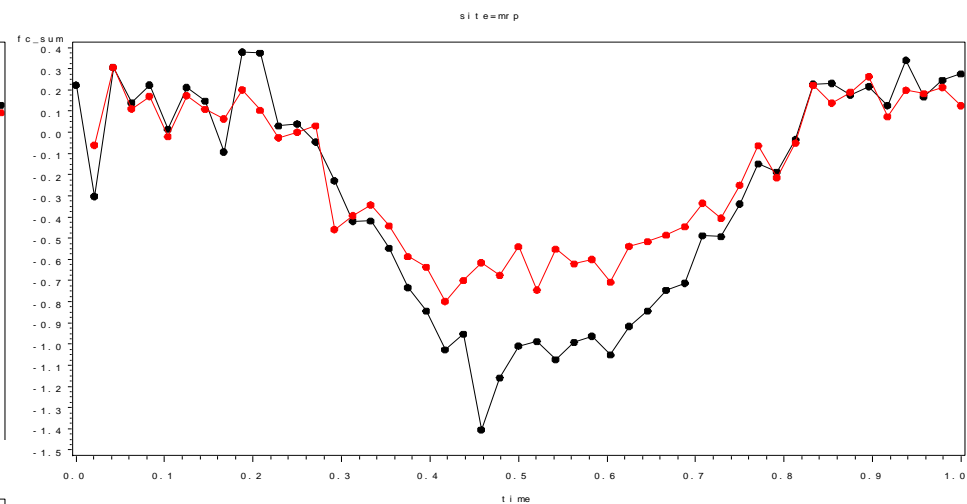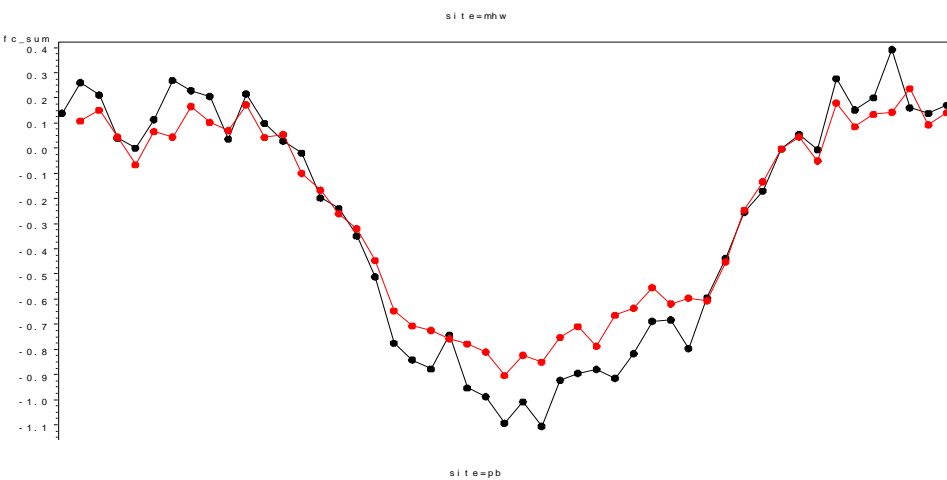
Fc+wpl+storage, July

2. 传感器反应 ● - w/o rotation

● - rotated

2. 传感器反应

订正测定中高频遗漏通量
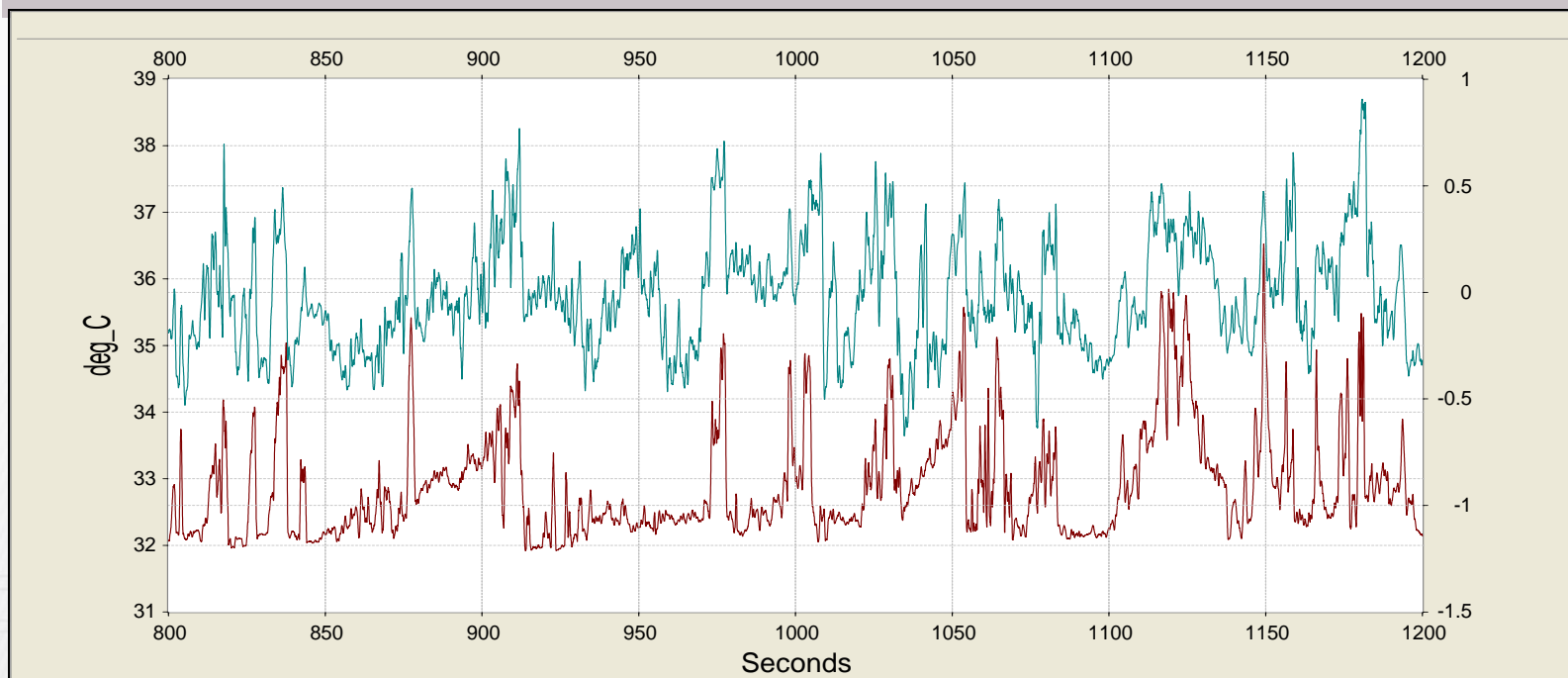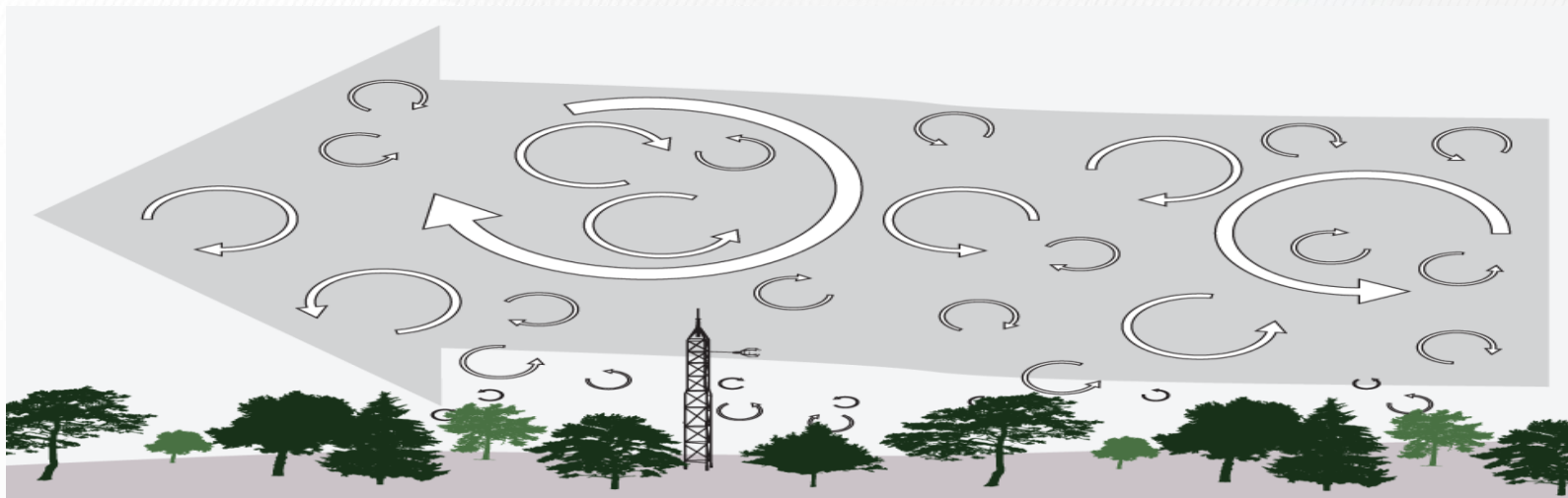
湍流团的大小与频率
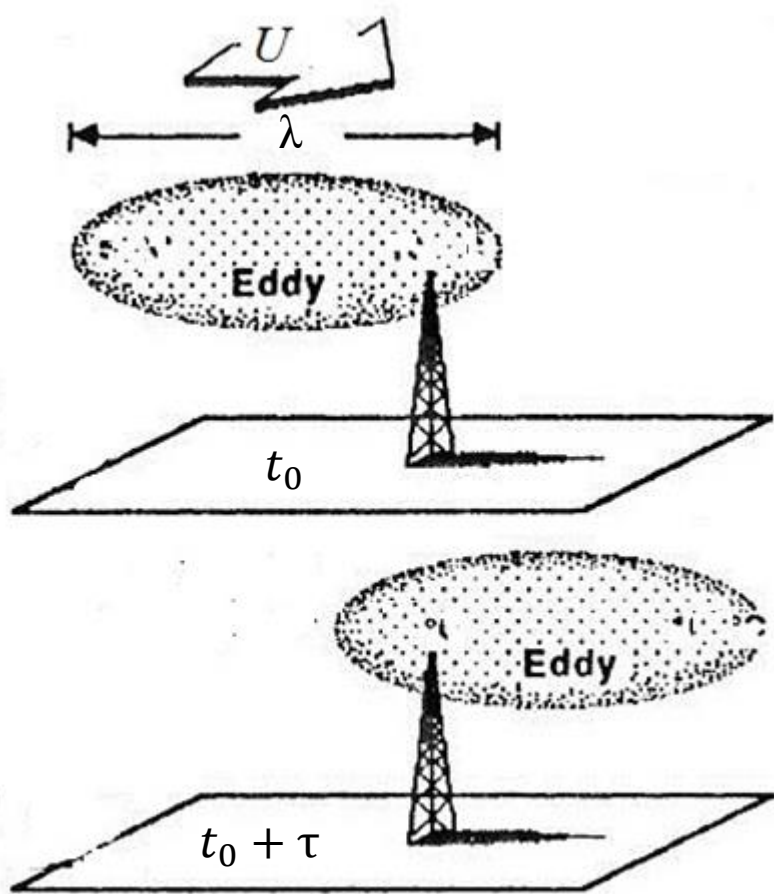
$$周期 (\tau) = \frac{波长 (\lambda)}{风速 (U)} = \frac{1}{频率 (f)}$$

$$f - 转动频率 \left(\frac{圈}{秒}\right)$$

$$k = \frac{2\pi f}{\bar{u}} \quad 波数 \left(\frac{圈}{米}\right)$$

$$\omega = 2\pi f \quad 角频率 \left(\frac{弧度}{秒}\right)$$

时间常数（τ）的定义
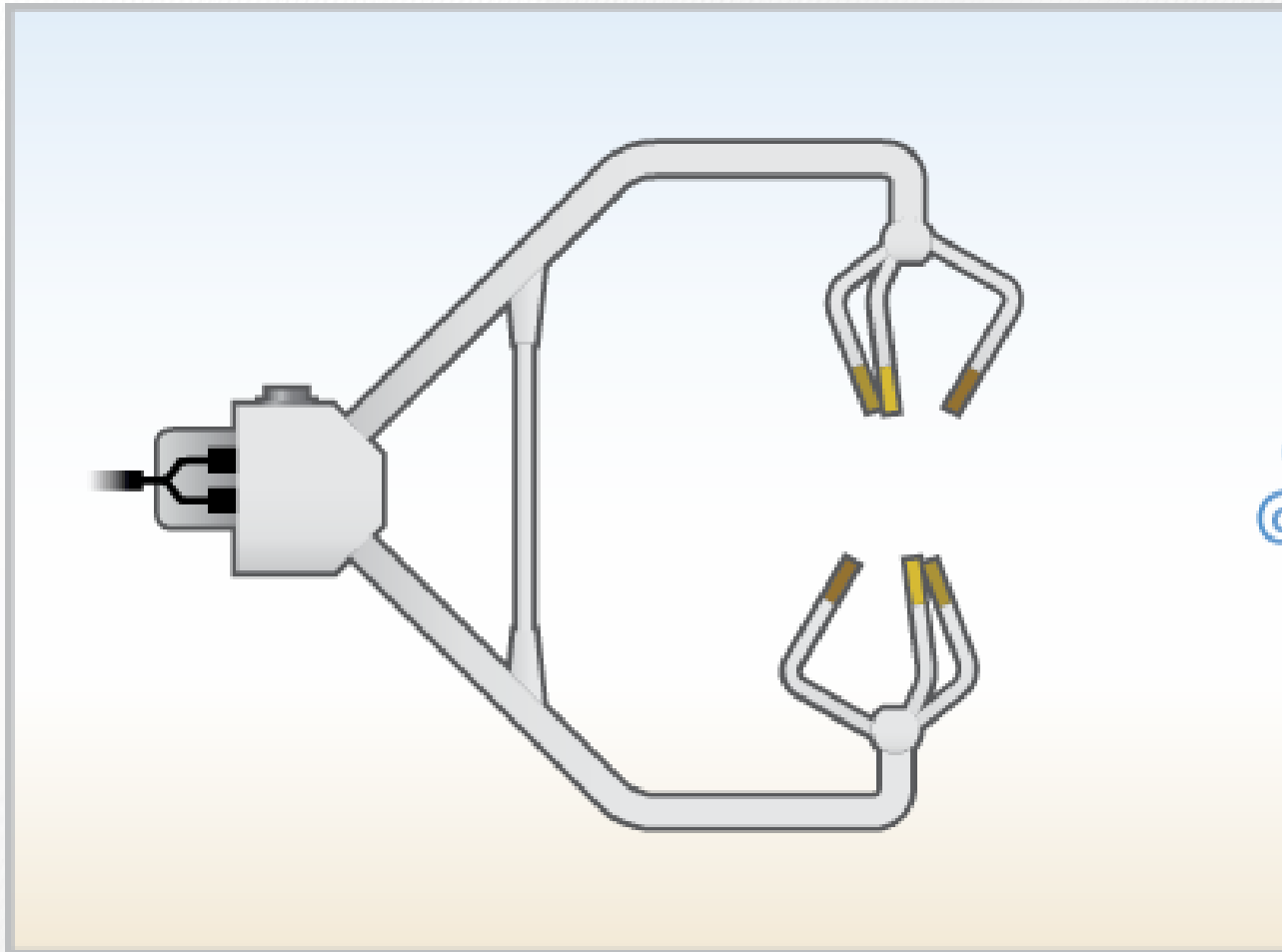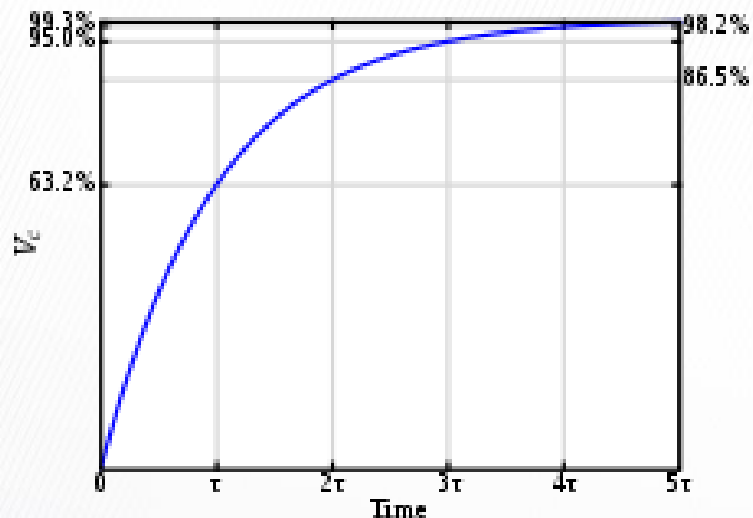
时间常数(τ_{FW})
　　传感器感应到63.2%被测物理量所需的时间。

$$\frac{dT_m(t)}{dt} = \frac{T(t) - T_m(t)}{\tau}$$

$T(t)$　时间t时的被测温度

$T_m(t)$ 时间t时传感器测得的温度

传感器反应速度与湍流团频率

$$\tau = 0.167 D^2 \frac{\rho_a C}{k_a \mathrm{Nu}}$$

D dimension

ρ_a material density of thermocouple

C specific heat of thermocouple materials

k_a thermal conductivity of air

Nu   Nusselt number

传输函数 （**Transfer function**）

—具有时间常数 τ 的传感器对不同频率信号（如温度）的相对反应。
是频率的函数。
函数值从1 到 0。1 是完全反映，0 没反应

$$\frac{dT_m(t)}{dt} = \frac{T(t) - T_m(t)}{\tau}$$

$T(t)$　时间t时的被测温度

$T_m(t)$　时间t时传感器测得的温度

基本例子：传输函数

对时间常数定义方程两端做傅立叶变换

$$\mathcal{F}\left(\frac{dT_m(t)}{dt}\right) = \mathcal{F}\left(\frac{T(t)-T_m(t)}{\tau}\right)$$

即

$$-j\omega T_m(\omega) = \frac{1}{\tau}[T(\omega) - T_m(\omega)]$$

ω - 频率， $j = \sqrt{-1}$.

整理得

$$\frac{T_m(\omega)}{T(\omega)} = \frac{1}{1-j\tau\omega}$$

$$T_{TT\_TC}(f, \tau_{FW}) = \frac{1}{1 + (2\pi f \tau_{FW})^2}$$
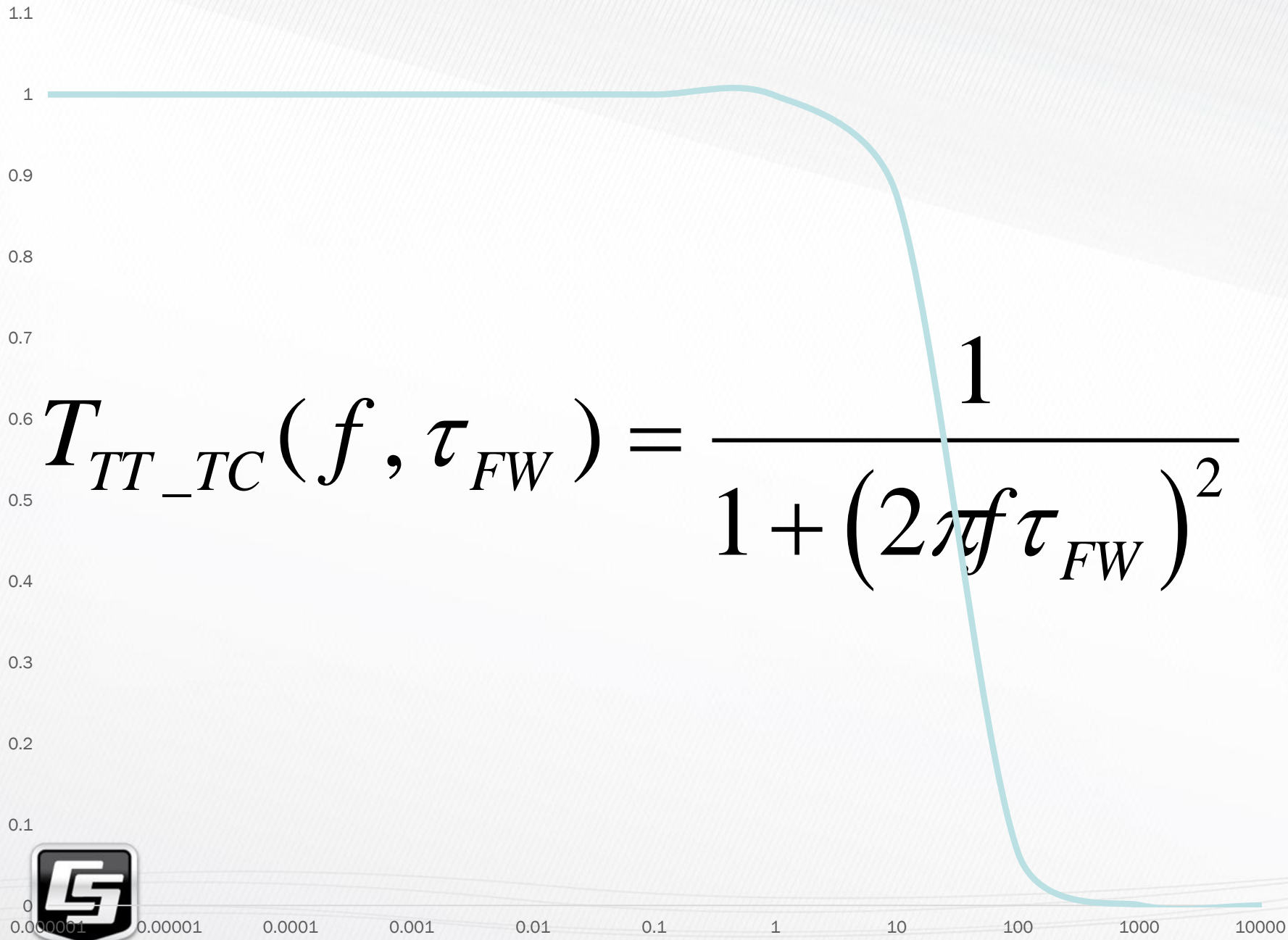
测定路径/体积平均

(path length/volume averaging)
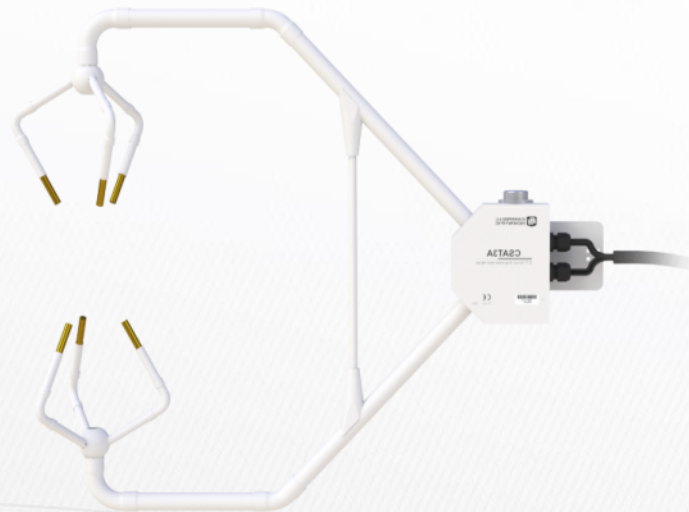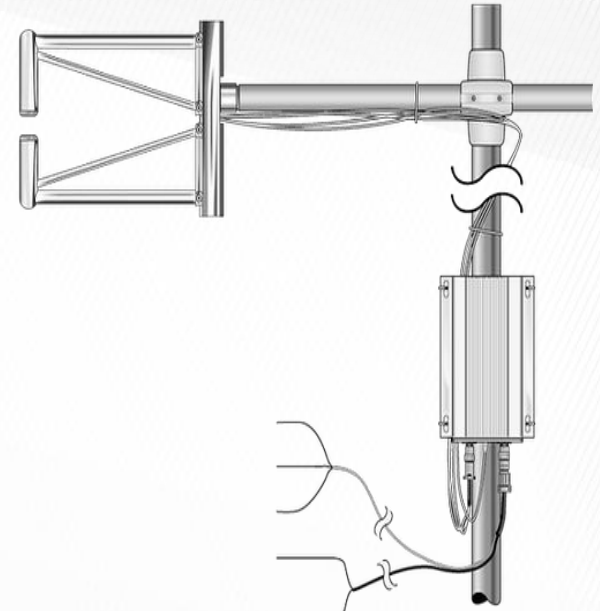
垂直风速路径平均频率反应近似函数

$$T_{ww\_LA}(f,p,u) = \frac{2}{\pi f p / u}\left(1 + \frac{\exp(-2\pi\frac{p}{u}f)}{2} - \frac{3\left[1-\exp(-2\pi\frac{p}{u}f)\right]}{4\pi f p / u}\right)$$

标量路径平均频率反应近似函数

$$T_{ss\_LA}(n, p, u) = \frac{1}{2\pi fp/u}\left(3 + \exp(-2\pi\frac{p}{u}f) - \frac{4\left[1 - \exp(-2\pi\frac{p}{u}f)\right]}{2\pi fp/u}\right)$$
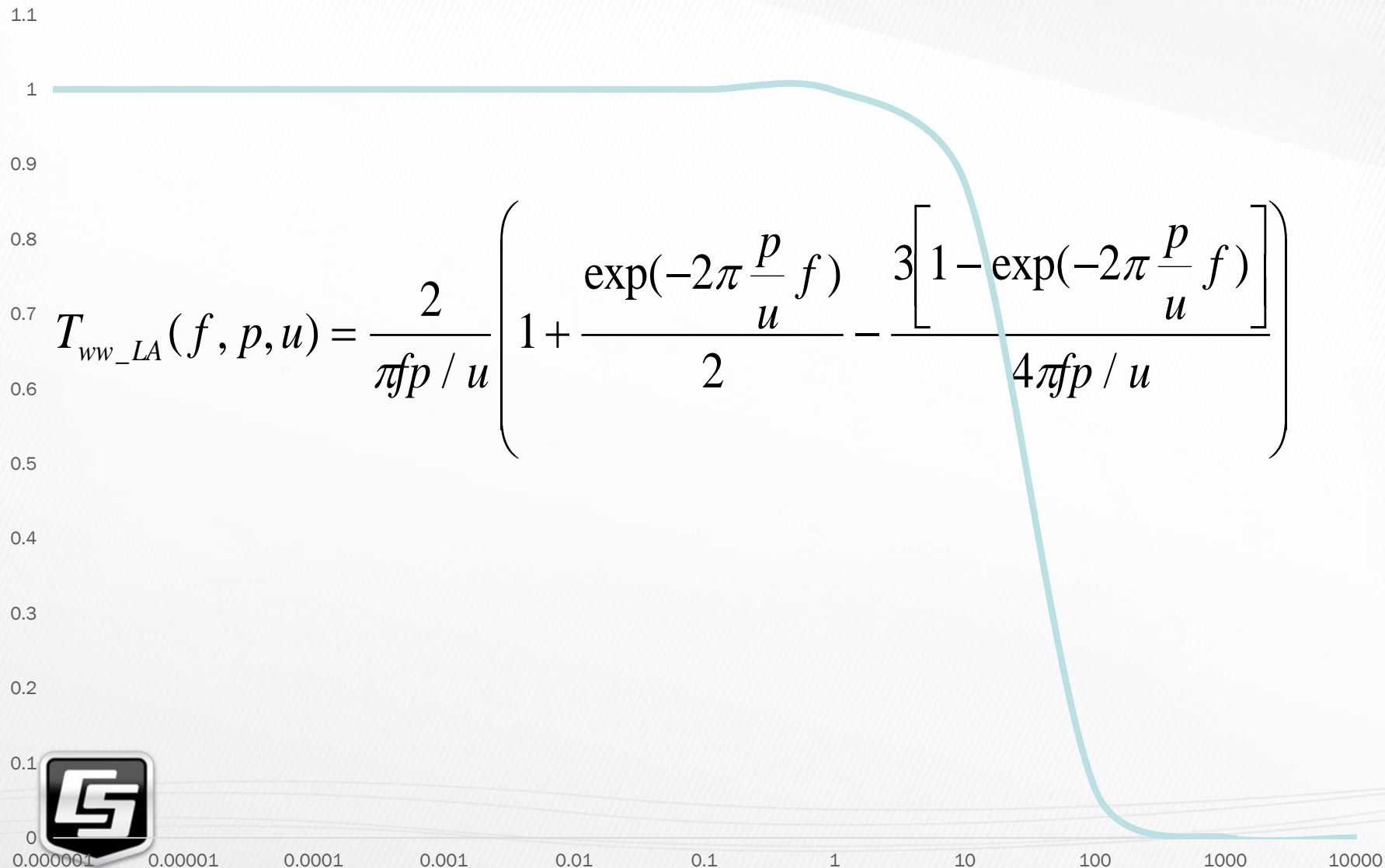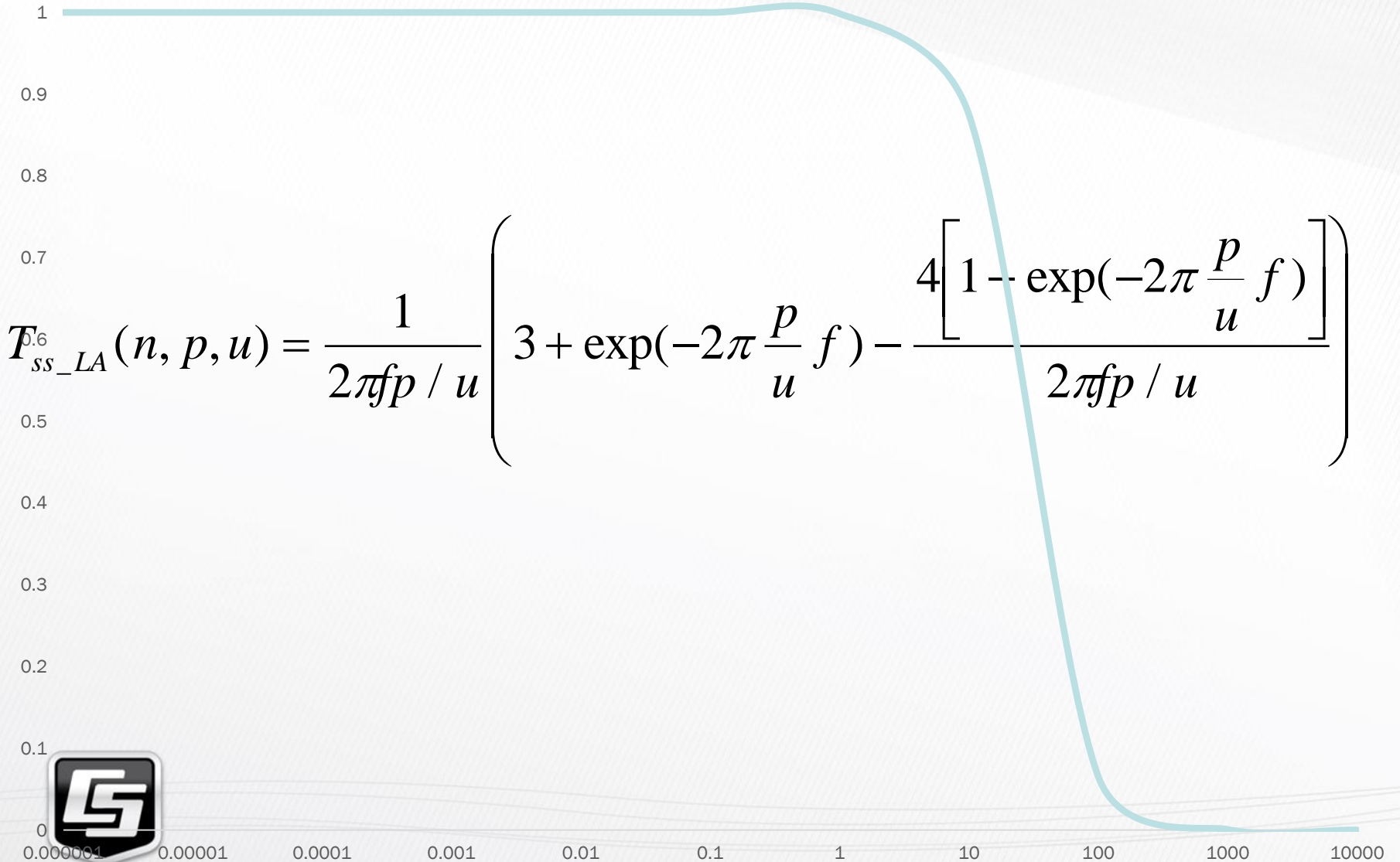
CSAT超声热通量路径平均频率反应函数 Dijk （2002）

$$T(k) = \frac{1}{\beta z \overline{w} \overline{S}(|k|z)^{-7/3}} \int_0^\infty \int_0^{2\pi} KA \frac{k^2 + K^2 \sin^2\theta}{\sqrt{k^2 + K^2}} \times \frac{1}{3} \left[\sin\mathbf{c}\left(\frac{\mathbf{k} \cdot \mathbf{I_a}}{\mathbf{2}}\right) + \sin\mathbf{c}\left(\frac{\mathbf{k} \cdot \mathbf{I_b}}{\mathbf{2}}\right) + \sin\mathbf{c}\left(\frac{\mathbf{k} \cdot \mathbf{I_c}}{\mathbf{2}}\right) \right] d\theta dK$$

传感器分离频率反应函数

$$T_{Tw\_S}(f, s, u) = \exp\left[-9.9\left(\frac{f \times \text{Separation distance}}{u}\right)^{1.5}\right]$$

高频被滤(high-cut filter)的湍流谱
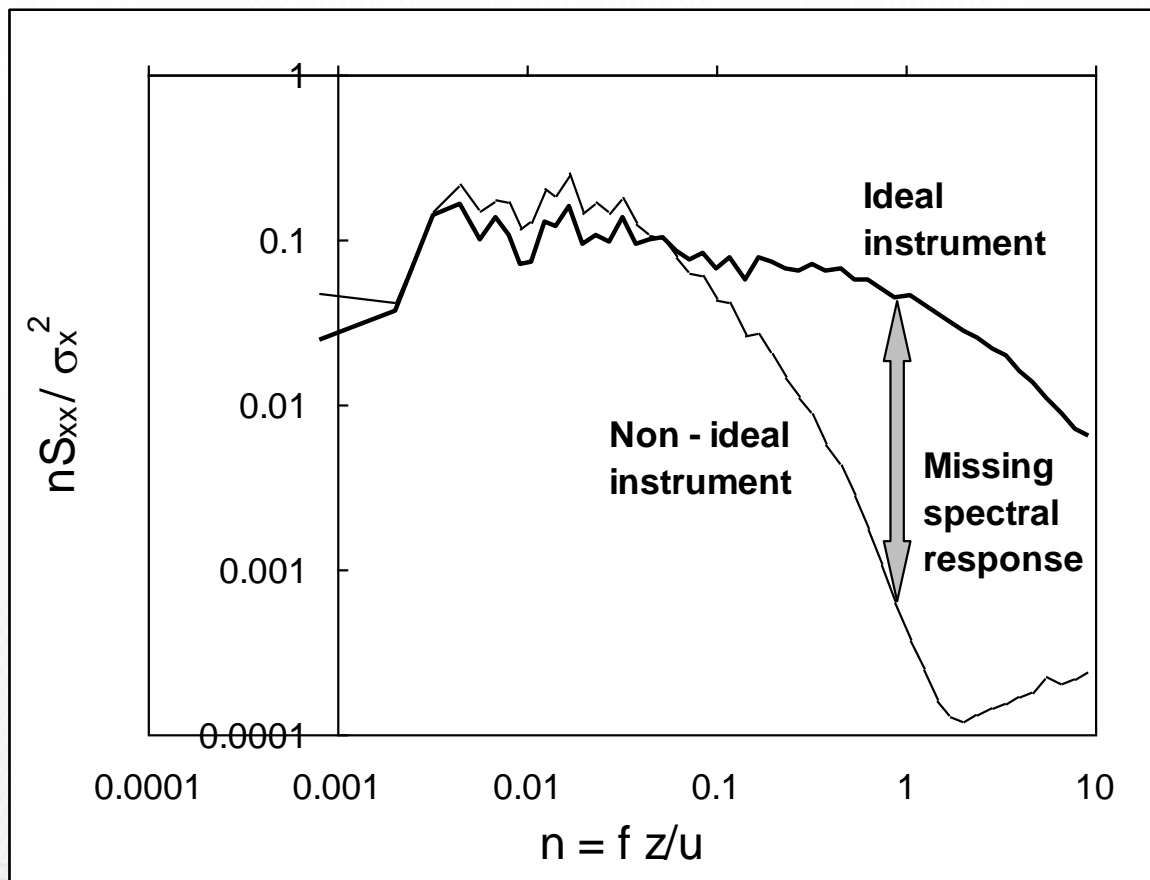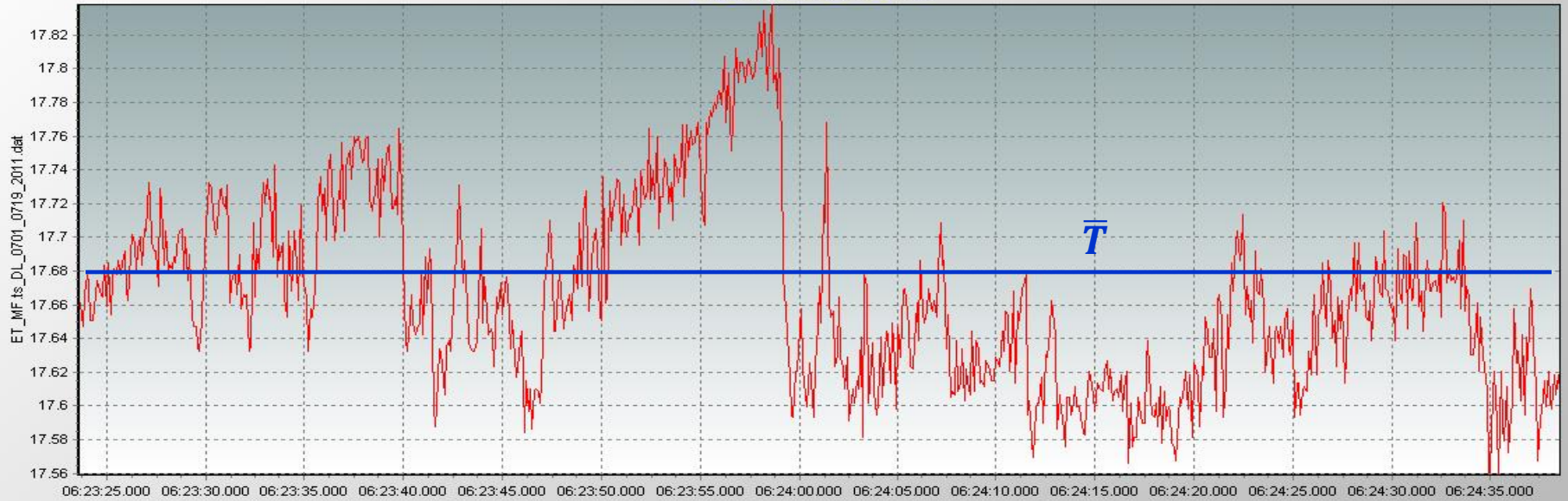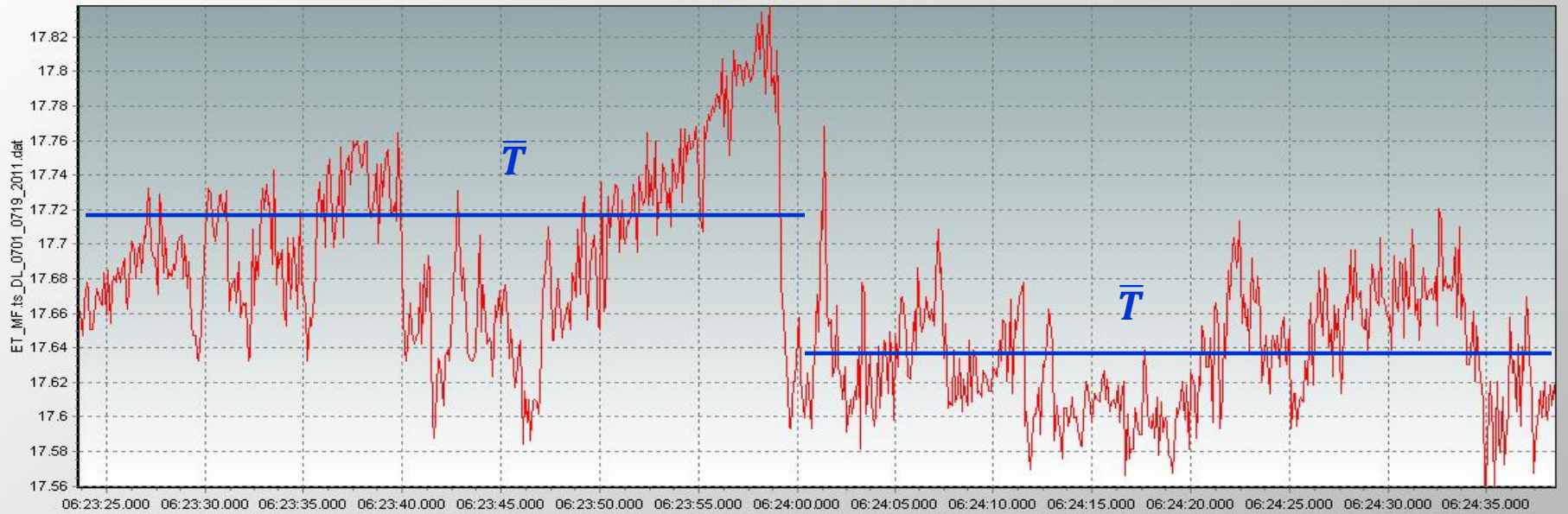
一般平均时长是30分钟

这个时长在一些情况下较短，可能丢失通量

- 在Manaus 热带雨林，平均时长短于180 分钟有通量丢失.

Finnigan et al., (2001)

Y轴: % (EB closure H+LE/Rn-G)

X轴: averaging period *T* minutes

平均方法 **(平均时长)**

$$T_{BA}(f,T_b) = 1 - \frac{\sin^2(\pi f T_b)}{(\pi f T_b)^2}$$
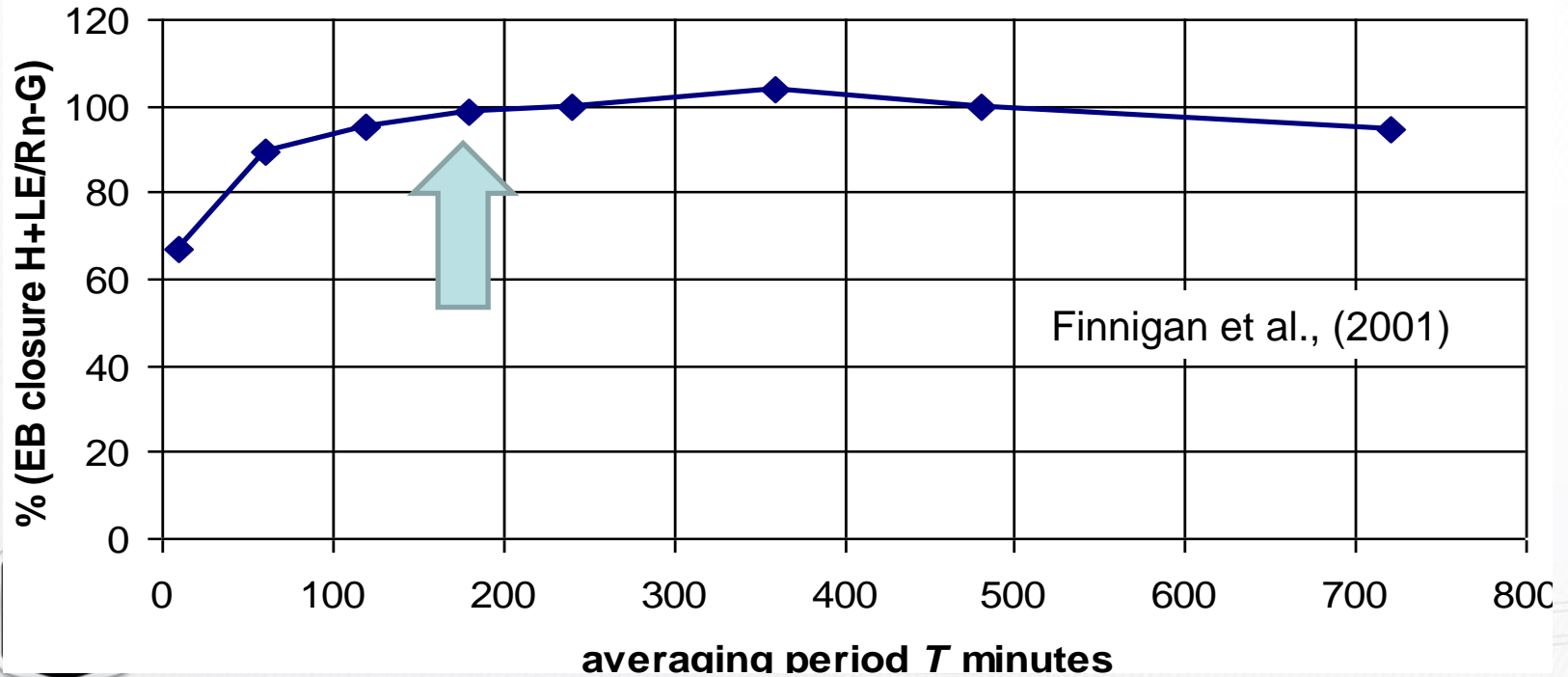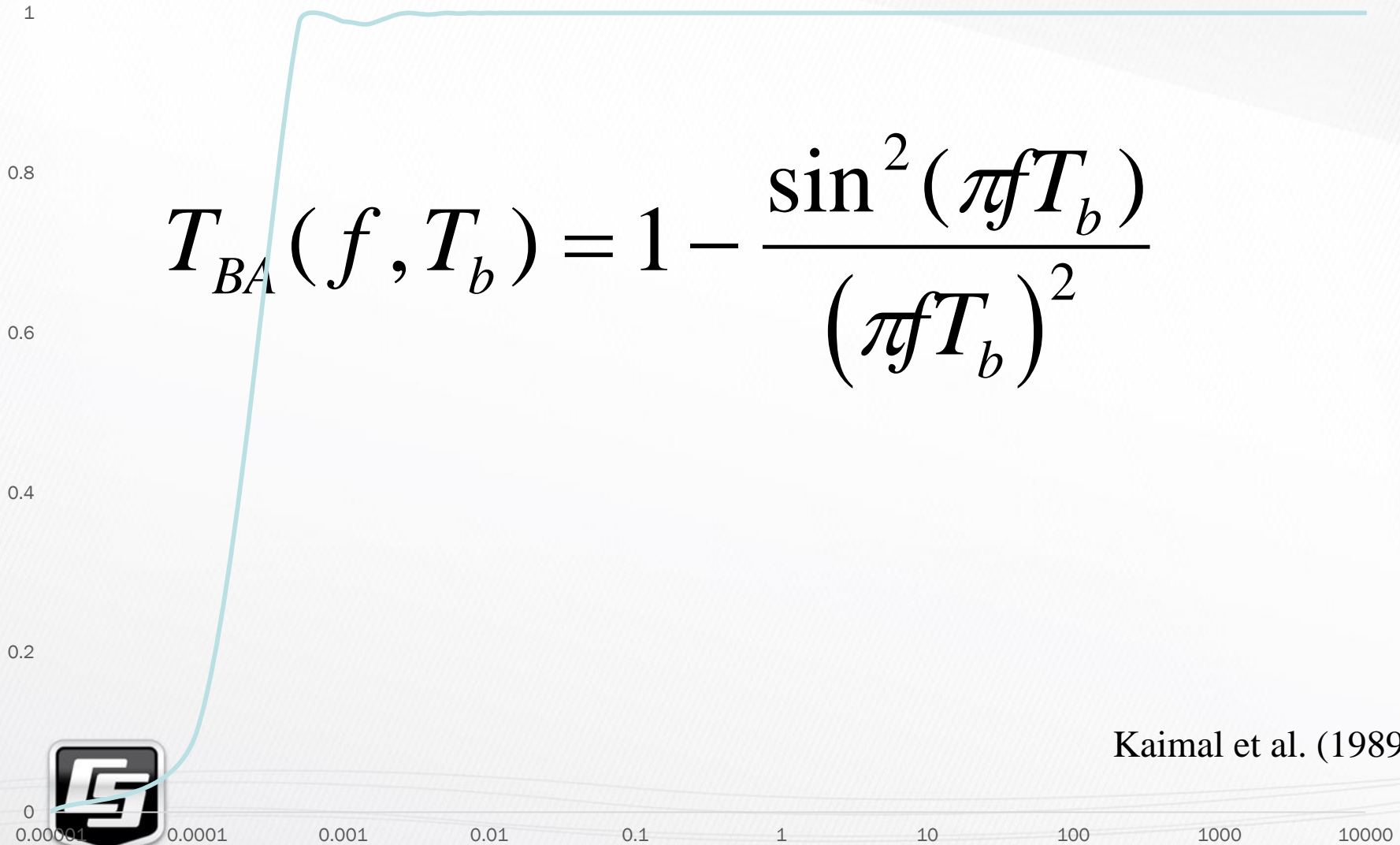
Kaimal et al. (1989)

频率修正

'真'协谱

$$\overline{\alpha'w'} = \left(\overline{\alpha'w'}\right)_m \left\{ \frac{\int_0^\infty S_{\alpha w}(f)df}{\int_0^\infty T_{\alpha w}(f)S_{\alpha w}(f)df} \right\}$$
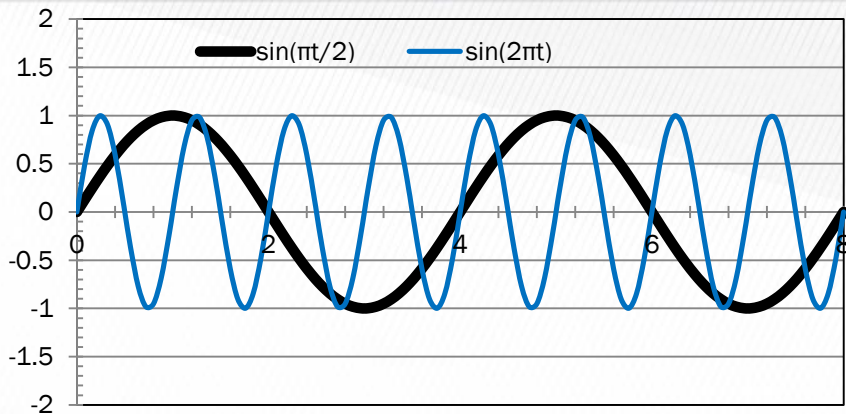
测得的
协方差

频率反应
函数

(Stable condition, Z/L=1 and wind=0.5 m)
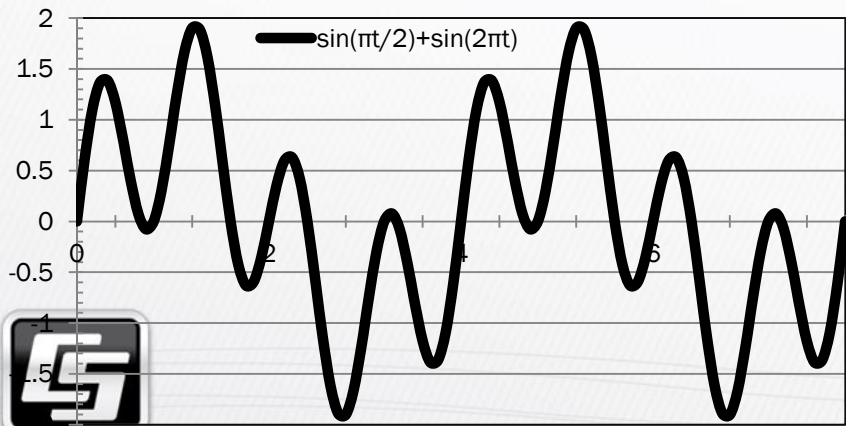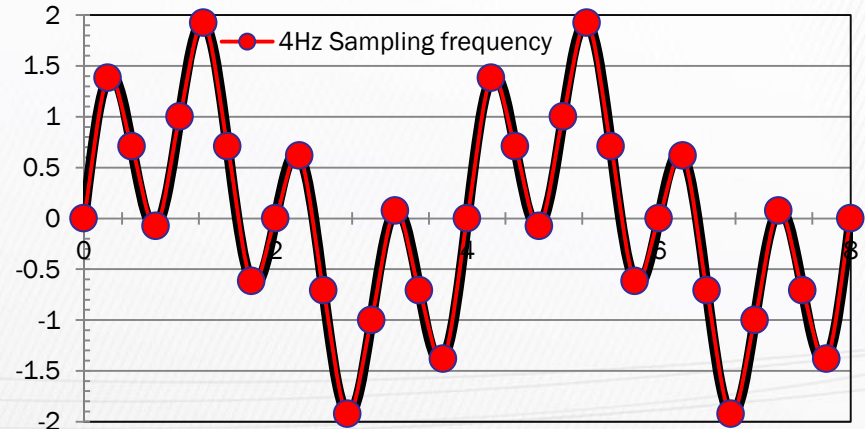
- Block averaging
- Cospectra
- Line_volume averaging
- Separation

CAST3 path length: 0.11547 m
KH20 path length: 0.01295 m
Separation: 0.165 m
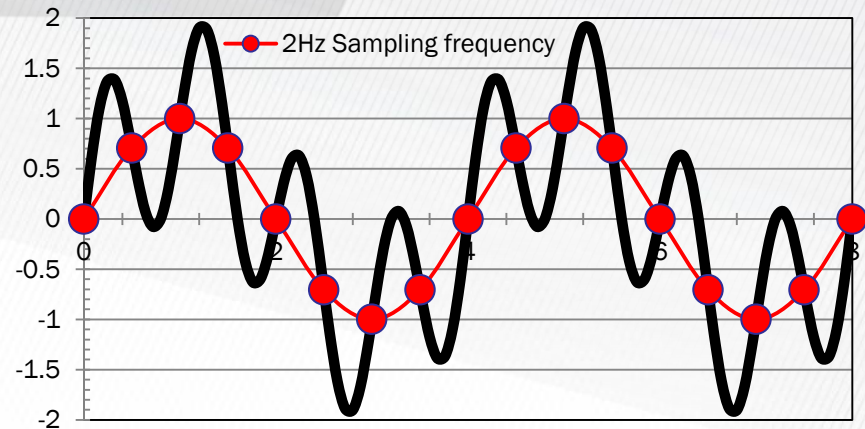Block Averaging: 30 min
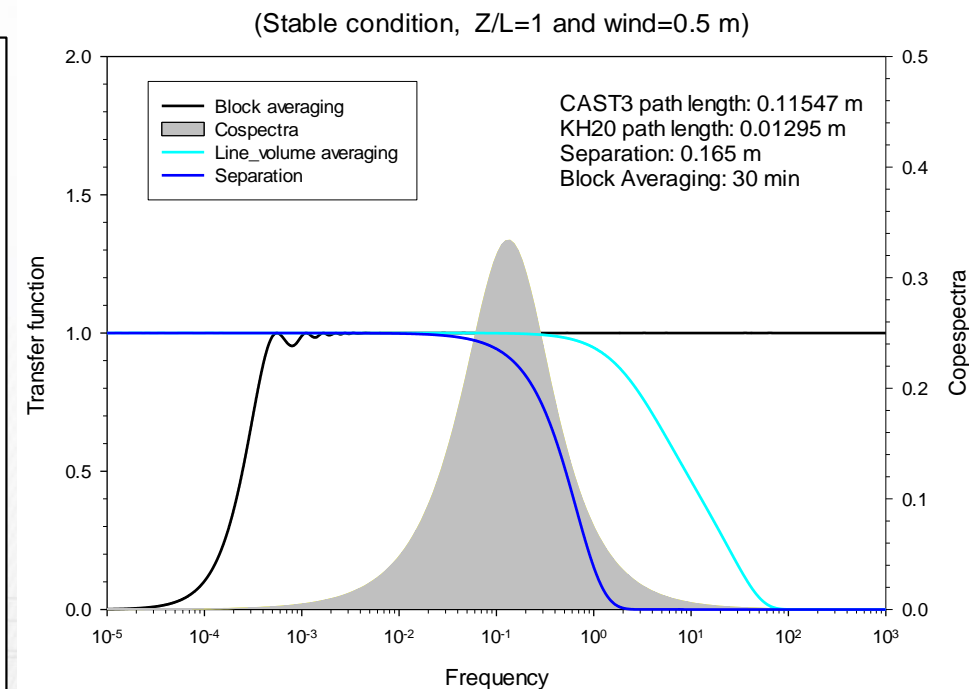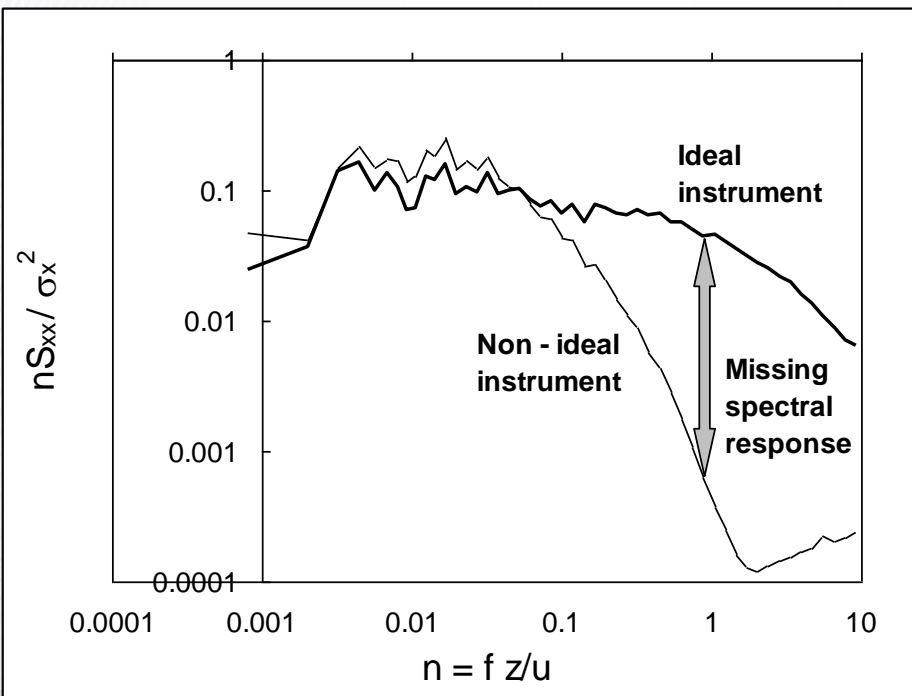
4. 测定频率

(Sampling frequency)
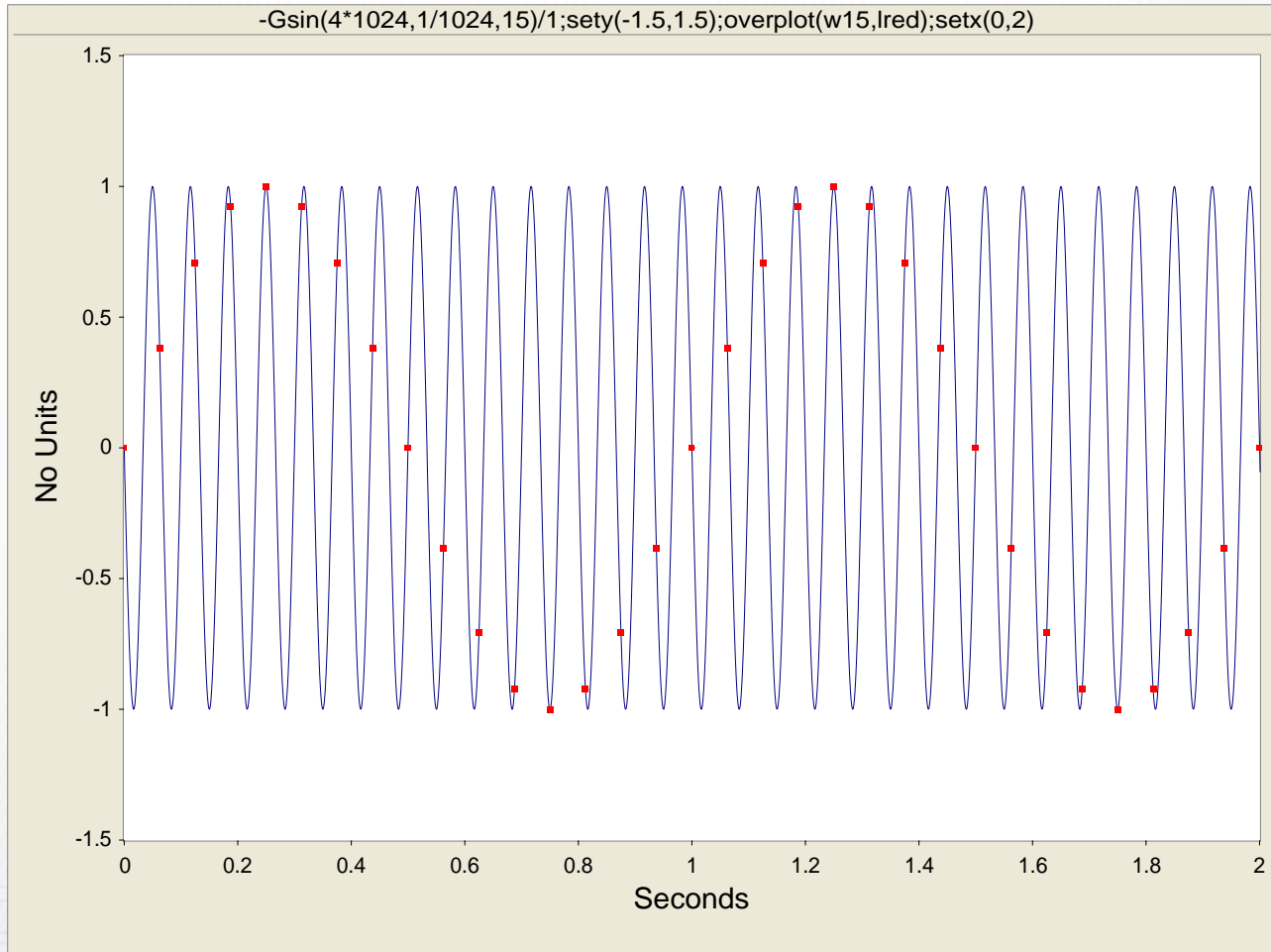
测定频率与湍流信号频率

香农定理 (Shannon Theorem)

测定频率最低应是
被测信号最高频率的二倍。
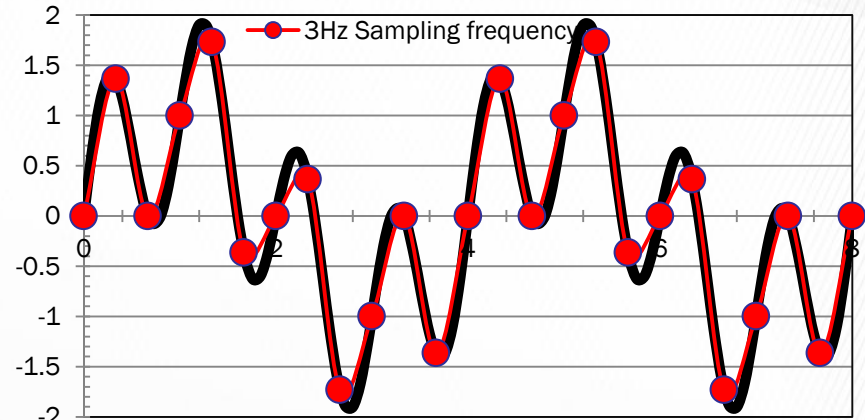
非连续性样本

原信号?

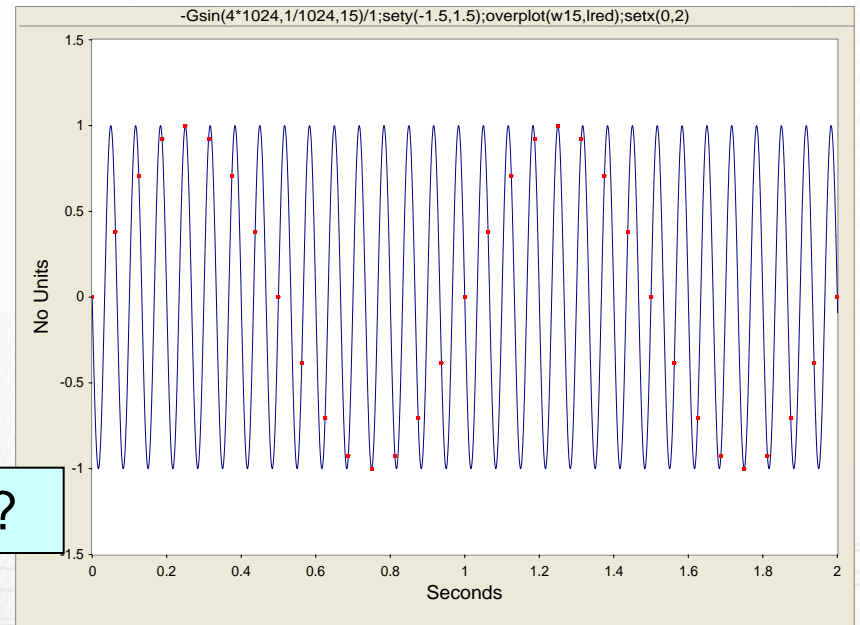# 另一可能?

失真信号的统计描述

Variance = ???

Variance = ???
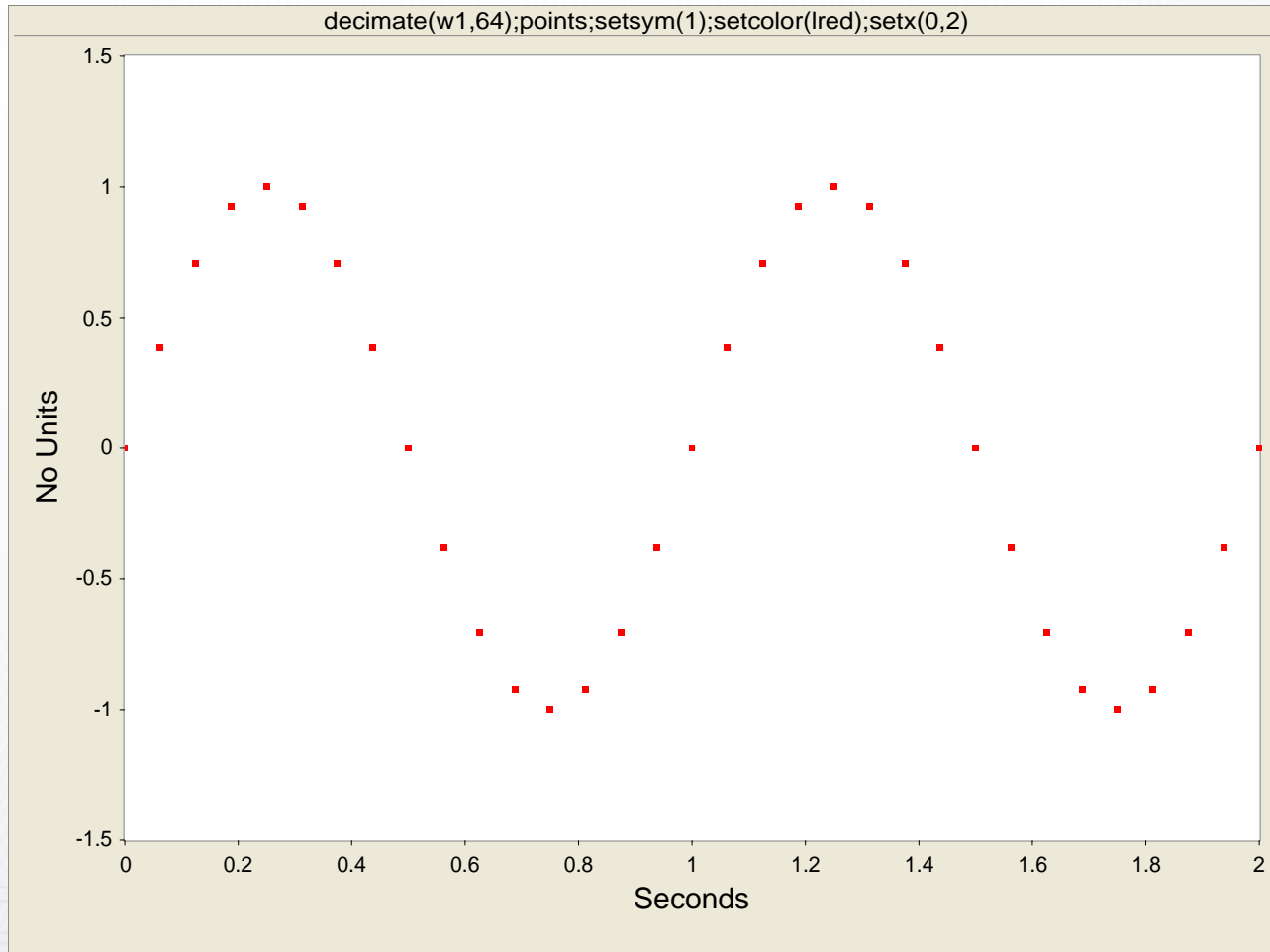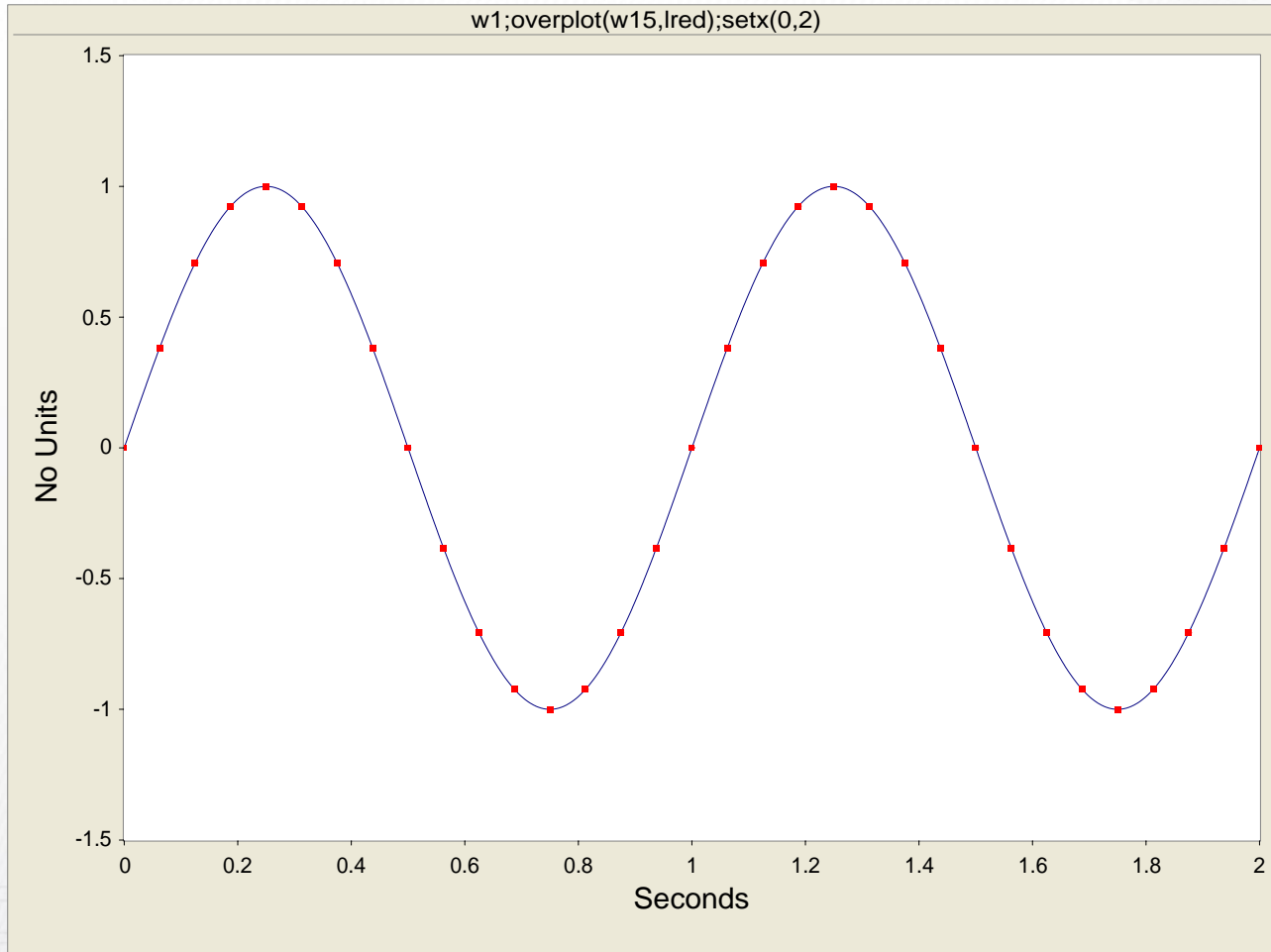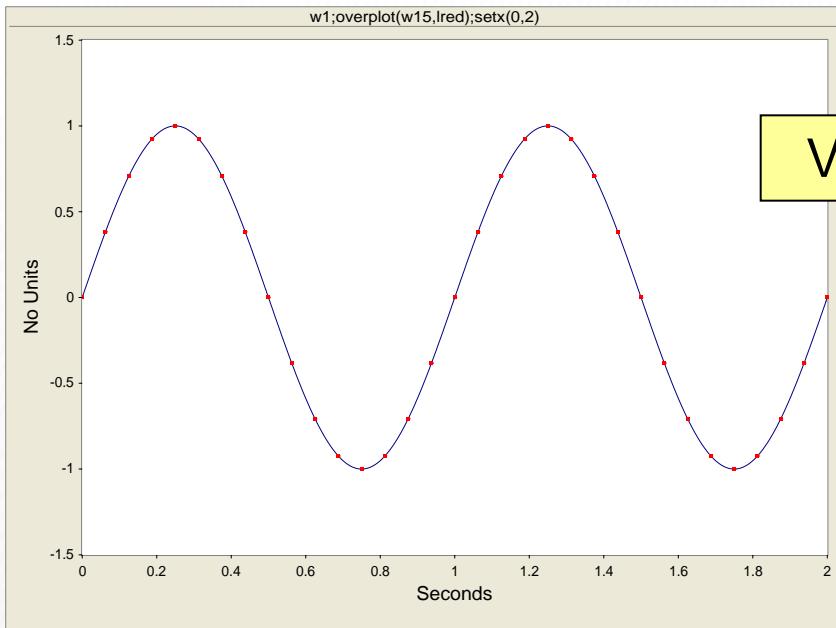
样本信号的奈奎思特（**Nyquist**）频率
Sine Waves

gsin(1000,1/50,5);setvu("V")
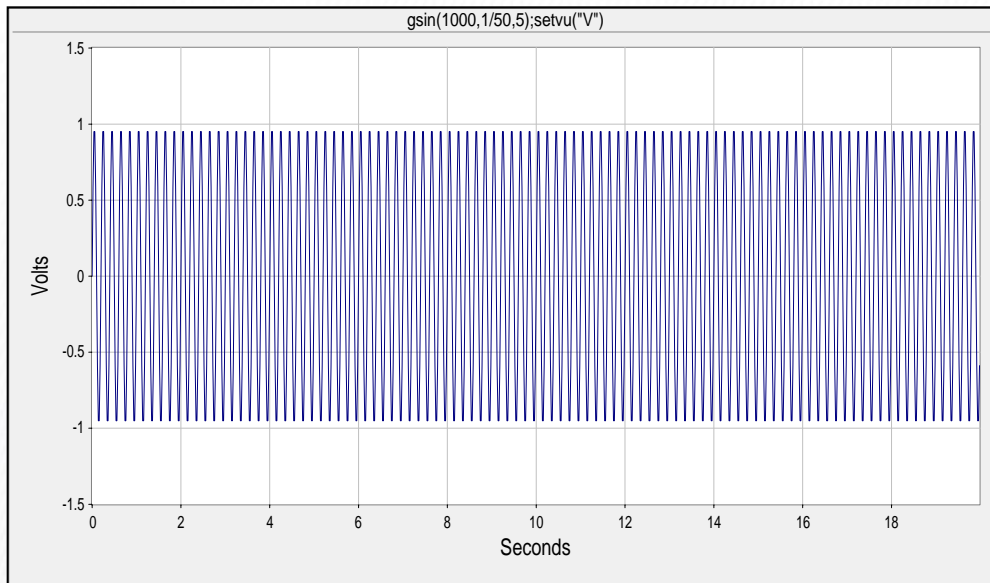
5-Hz 时间正玄函数
50 Hz 采样频率

Nyquist Frequency =
f_sample/2 =25 Hz

5-Hz 频率正玄函数
50 Hz 采样频率

spectrum(w10);setcolor(green)
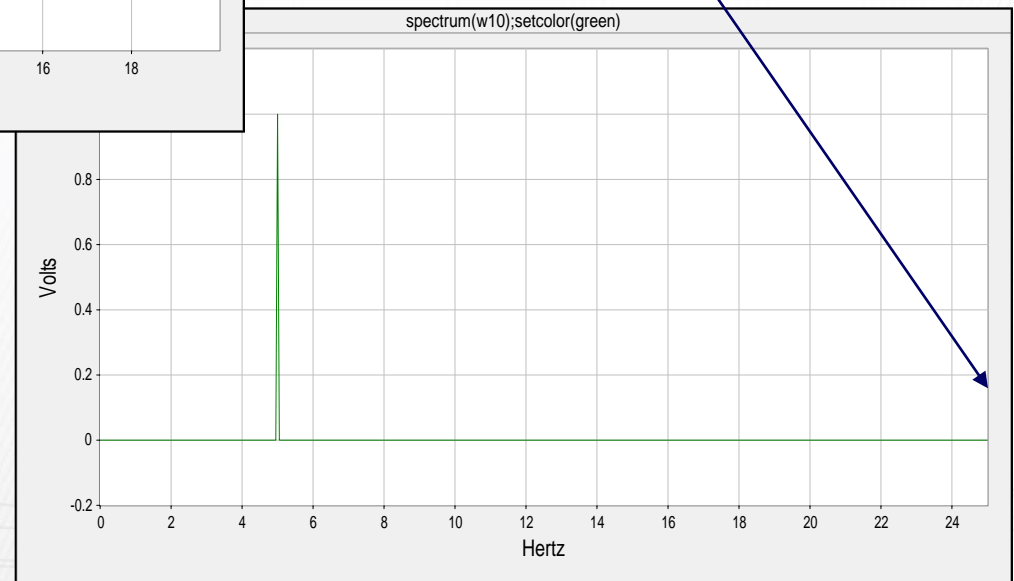
测定频率(f_s)的确定
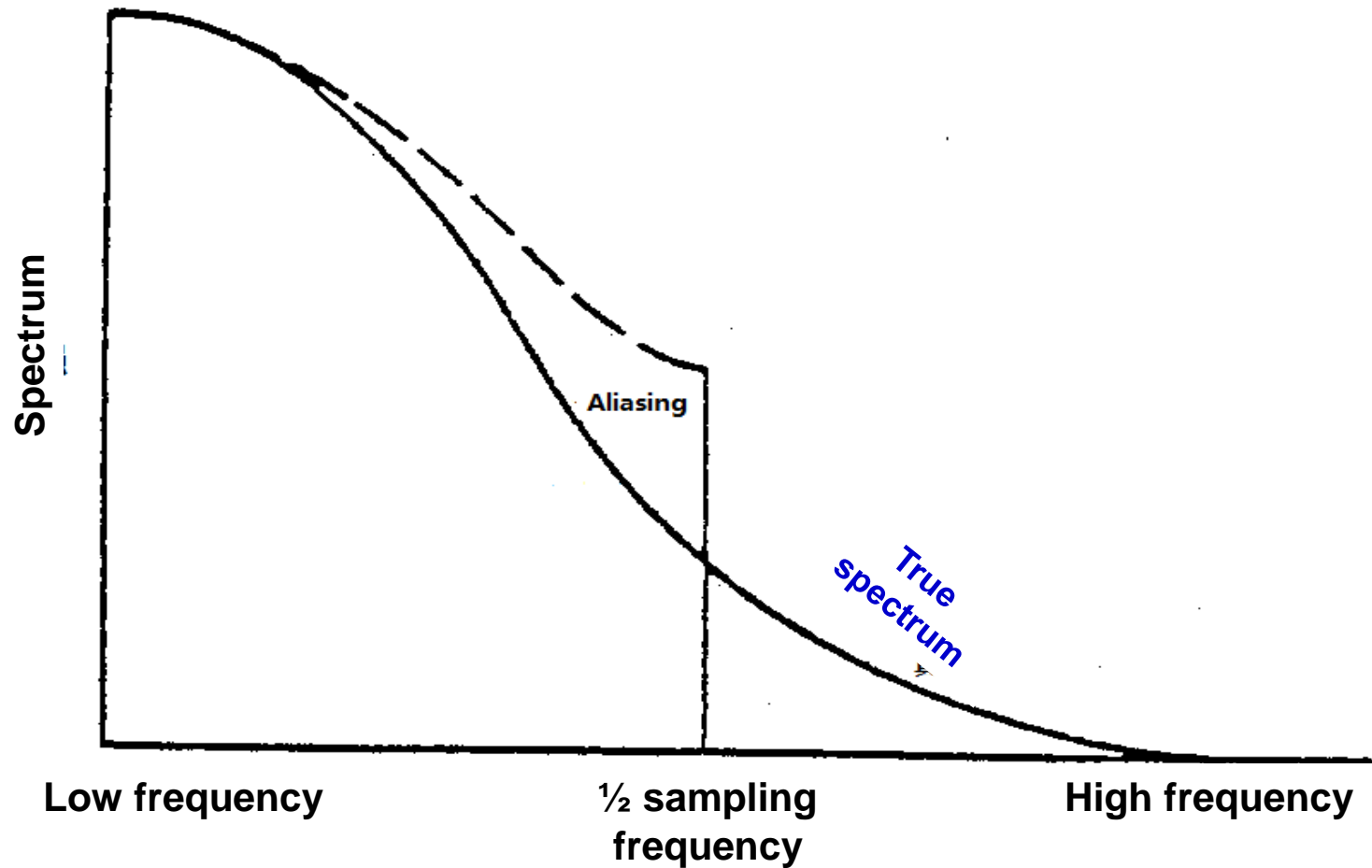
$$f_s = \frac{z_m n_{max}}{\overline{U}}$$

4. 高叠（“杂”）低现象
（Aliasing）

失真
采集的离散时间信号
（video）

Aliasing： 1. 在信号采集过程中，大于 1/2 采样频率的信号在样本中不能在其自己频率出现

2. 然而，这些信号在样本中确出现在小于1/2 采样频率段中.

数学理解 aliasing

$$w(t) = \sin 2\pi \left(\frac{p + 0.25}{2 \times 0.005} \right) t \qquad \text{If} \qquad p = 1, \text{ Then } \frac{1 + 0.25}{2 \times 0.005} = 125$$

200 Hz 采样频率 (时间隔 = 0.005 sec)

$$w(t_i) = \sin 2\pi \left(\frac{p + 0.25}{2 \times 0.005} \right) (t_i \times 0.005) = \cos p\pi t_i \sin 0.25\pi t_i$$
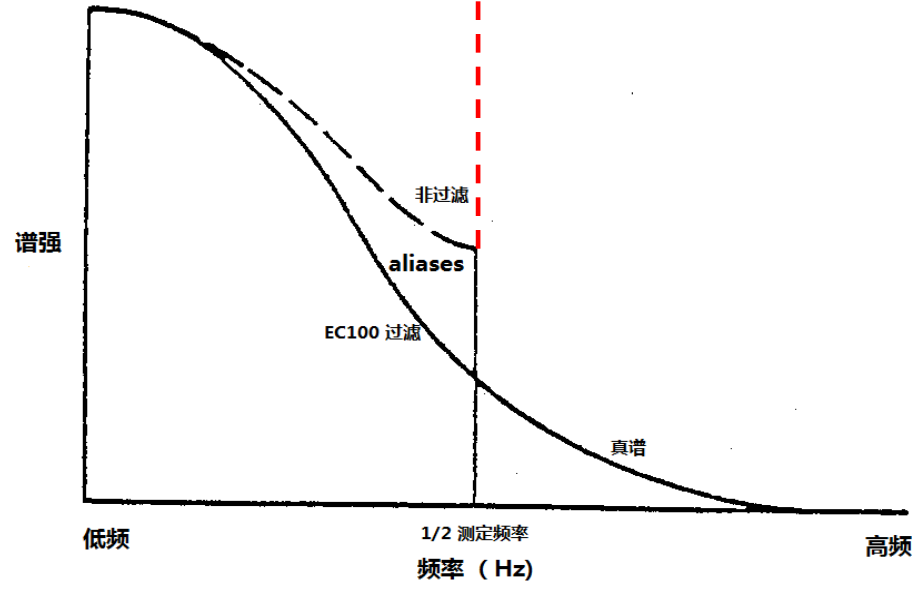
整数

p 为奇数 (p=1, 125 Hz 信号)

$$w(t_i) = (-1)^{t_i} \sin 0.25\pi t_i$$
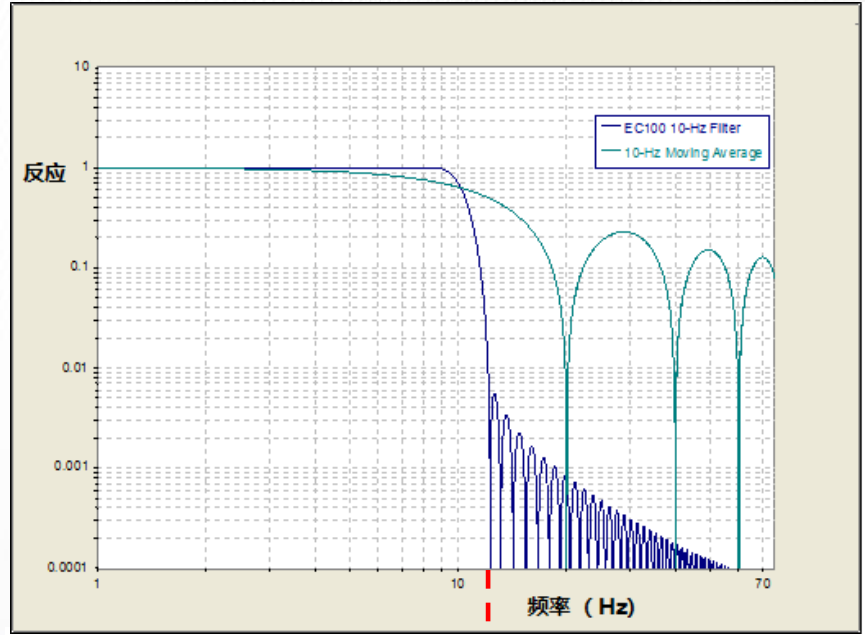$$= \cos \pi t_i \sin 0.25\pi t_i$$
$$= -\sin(2\pi) \times 75 \times (0.005 t_i)$$

200Hz

p 为偶数 (p=2, 225 Hz 信号)

$$w(t_i) = \sin 0.25\pi t_i$$
$$= \sin(2\pi) \times 25 \times (0.005 t_i)$$

200Hz

6. 减少高叠（"杂"）低效应 (Aliases)

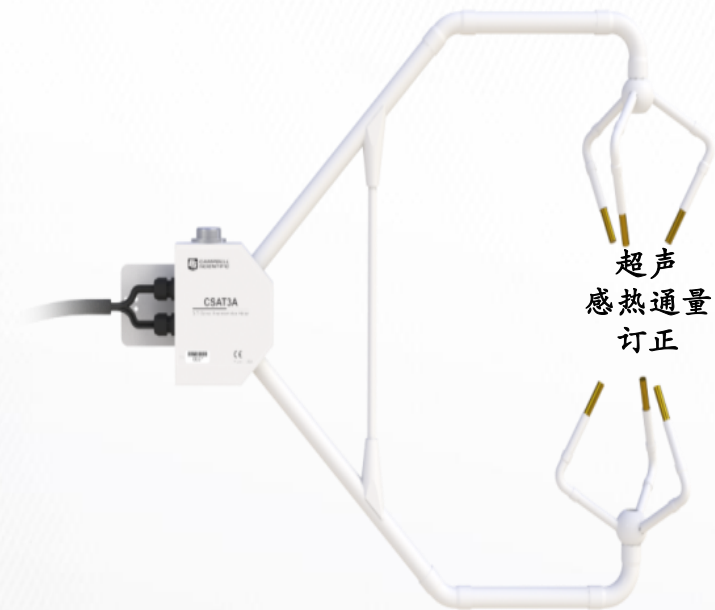# 5. 超声感热通量订正
（SND correction）

$$c^2 = \gamma \frac{P}{\rho}$$

$$\frac{P}{\rho} = R_d T_v = R_d \frac{T}{\left[1 - (1 - \varepsilon)\dfrac{e}{P} \right]}$$

$$T_s = \frac{c^2}{\gamma_d R_d}$$

超声
感热通量
订正

Schotanus et al. (1983)

$$T_S = T(1 + 0.514q)$$

$$T_s^{'} = T^{'} \frac{\overline{T_s}}{\overline{T}} + 0.514 q^{'} \overline{T}$$

6. 氧订正
（Oxygen correction）

水汽通量
氧订正

Tanner et al. (1993)
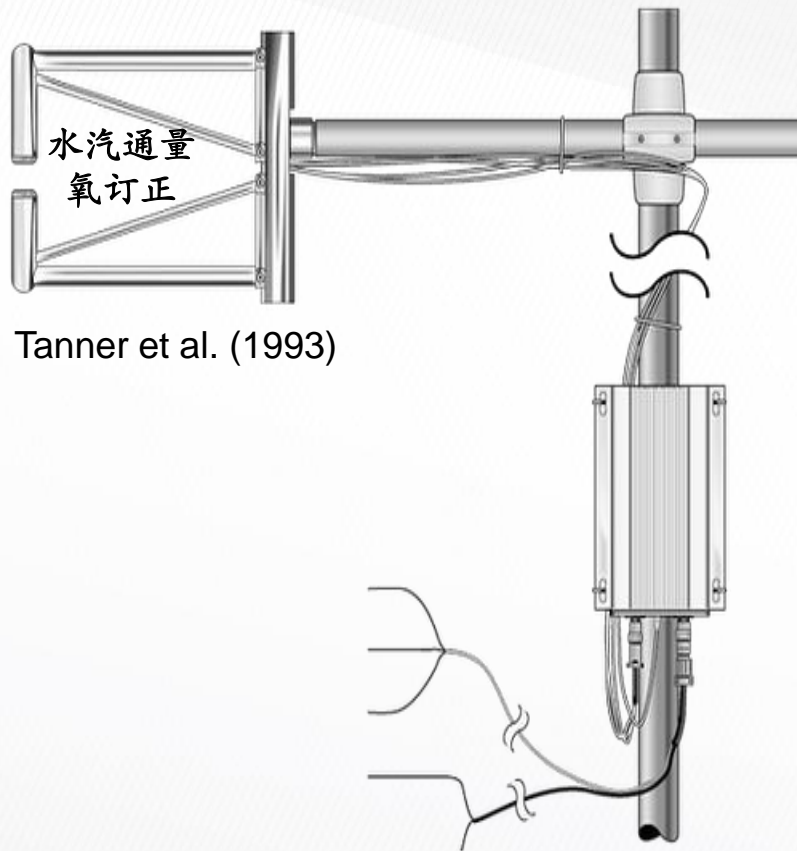
7. 订正测定过程中空气密度的变化影响（WPL correction）

空气密度变化对通量测定影响
– 在没有CO_2交换下垫面，可测得明显的CO_2负通量

Kondo & Tsukamoto (2008) J Agric Meteorol (Japan) 64, 1-8
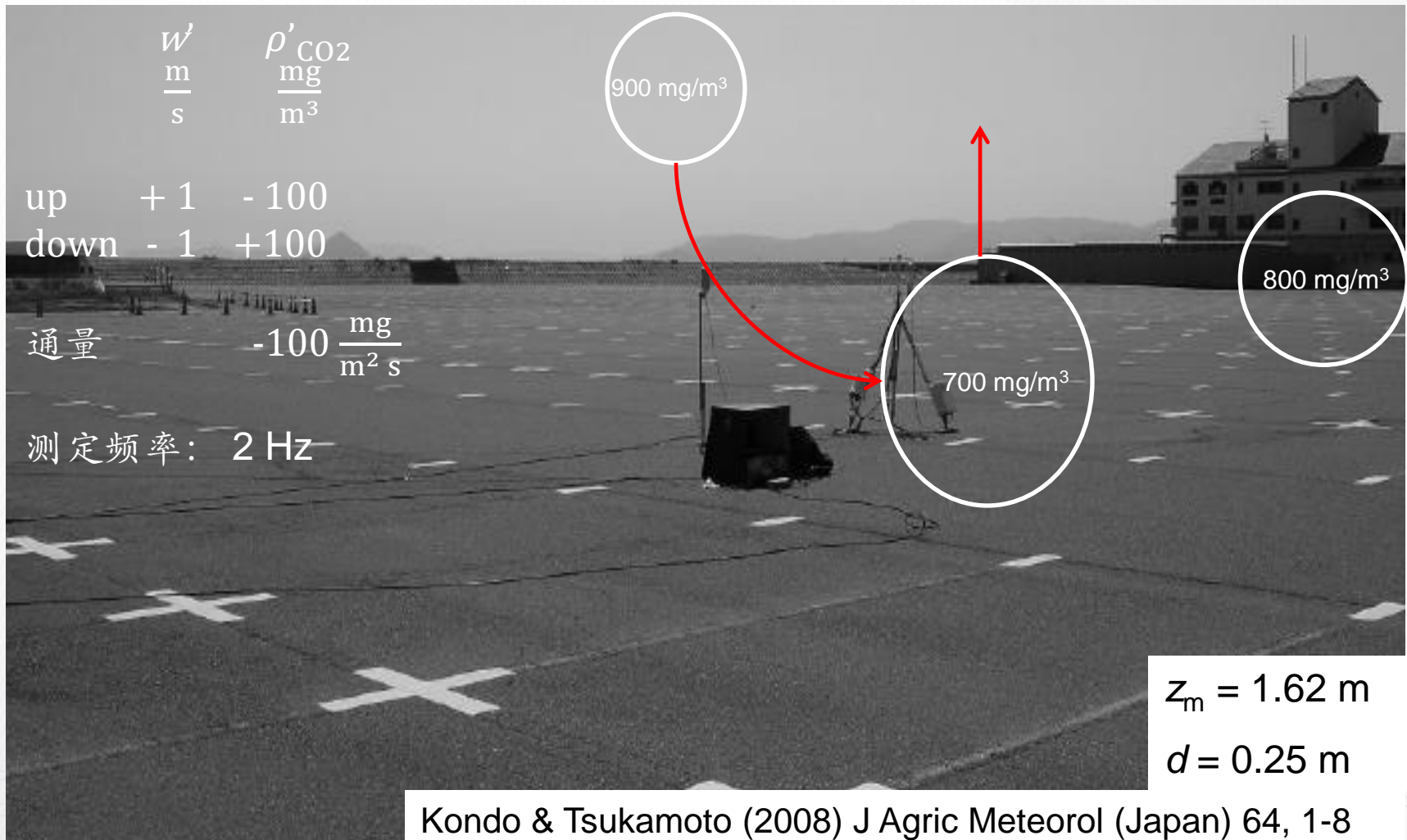
WPL correction
订正空气密度变化所引起的测定误差

$$\overline{w} \neq 0$$

1. 水和CO_2出入地面
2. 感热通量引起的空气度变化

$\overline{W}$ − 0.75 ~ 1.5 mm/s
LE - 200 ~ 600 W/m²

CAST 分辨率：0.25 ~ 2.00 mm/s
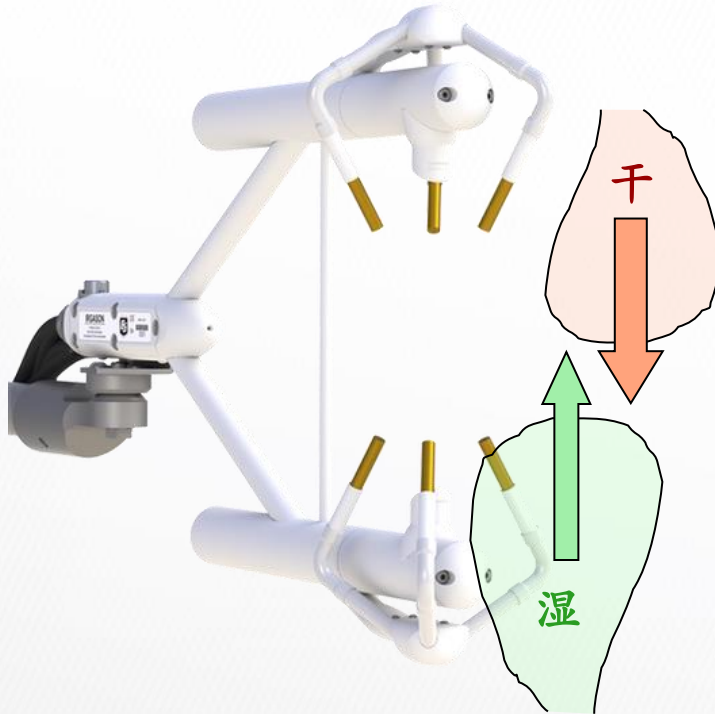
Webb, Pearman & Leuning (1980) 理论
稳态, 水平一致的湍流

$$\overline{F_c} = \overline{c_d\,\overline{w'\chi_c'}} = \overline{w'c_c'} + \overline{\chi_c}\left[\overline{w'c_v'} + \overline{c}\,\frac{\overline{w'T'}}{\overline{T}}\right]$$
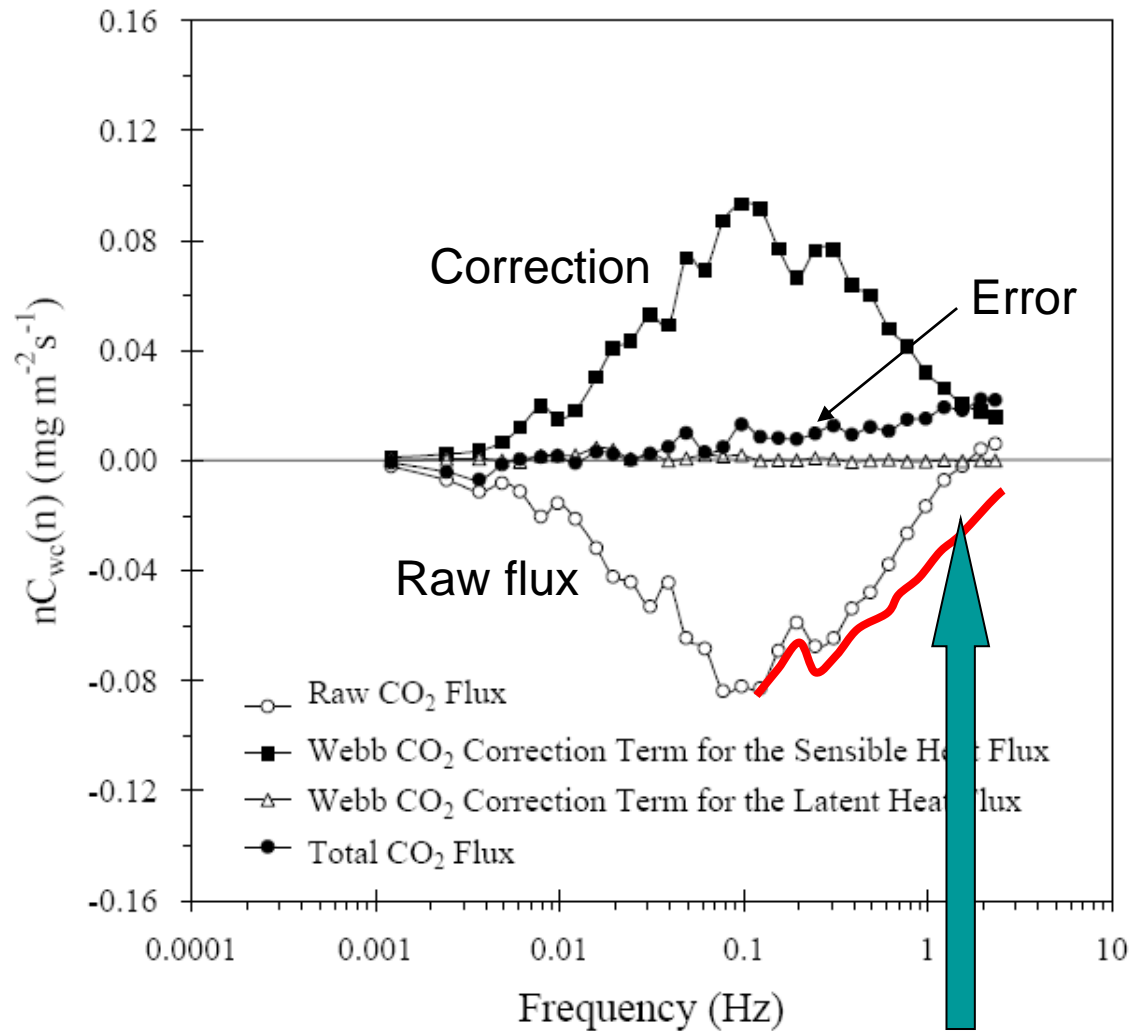
| Raw CO_2 flux | Water vapor flux | Heat flux |

Leuning (2007) showed original WPL still correct

For non-steady state flows

协湍流谱

Error due to differing frequency responses for cospectra of wT and wc_c

Correction

Error

Raw flux

Raw CO_2 Flux
Webb CO_2 Correction Term for the Sensible Heat Flux
Webb CO_2 Correction Term for the Latent Heat Flux
Total CO_2 Flux

Need to correct for loss of covariance before WPL correction

开路湍流通量测定的计算

1) $\overline{H} = \overline{\rho} c_p \overline{w' T'}$

2) $\overline{E} = (1 + \overline{\chi_v}) \left[\overline{w' c_v'} + \dfrac{\overline{c_v}}{\overline{\overline{T}}} \dfrac{\overline{H}}{\overline{\rho c_p}} \right]$

3) $\overline{F}_c = \overline{w' c_c'} + \overline{c_c} \left[\dfrac{\overline{E}}{\overline{\overline{c}}} + \dfrac{\overline{H}}{\overline{\overline{\rho c_p \overline{T}}}} \right]$

有时WPL 对开路测定订正非常大
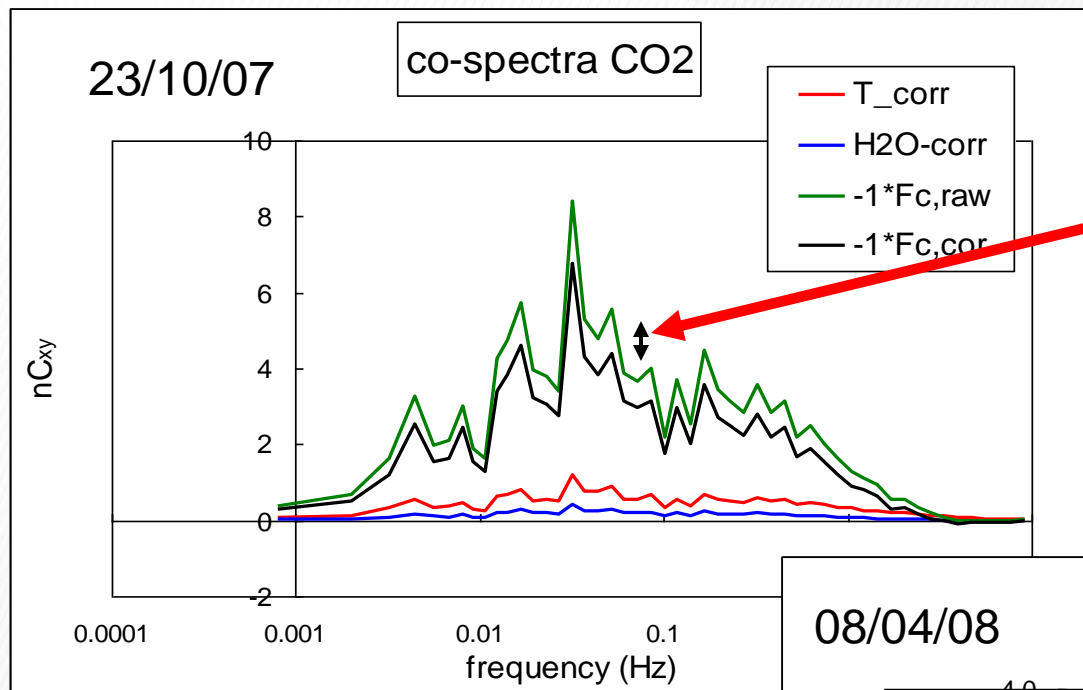
小 wT WPL 订正
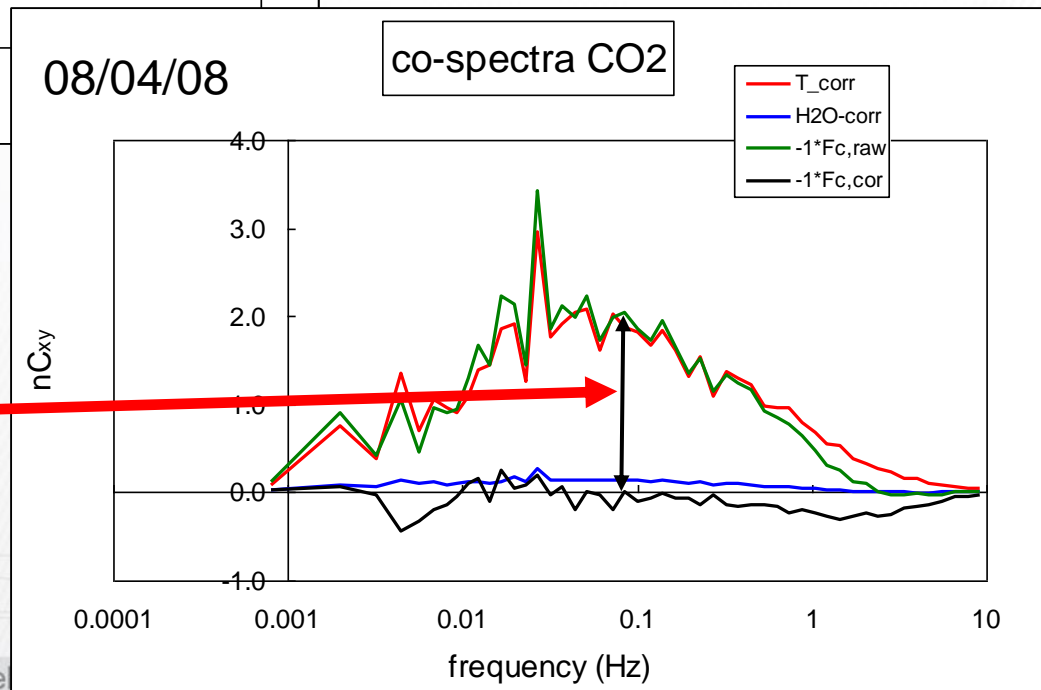
大 wT WPL 订正

最新模型
Gu et al./Ag For Meteorol (2012)

最新仪器系统
IRGASON and AP200

净CO_2通量 (N_{co2})

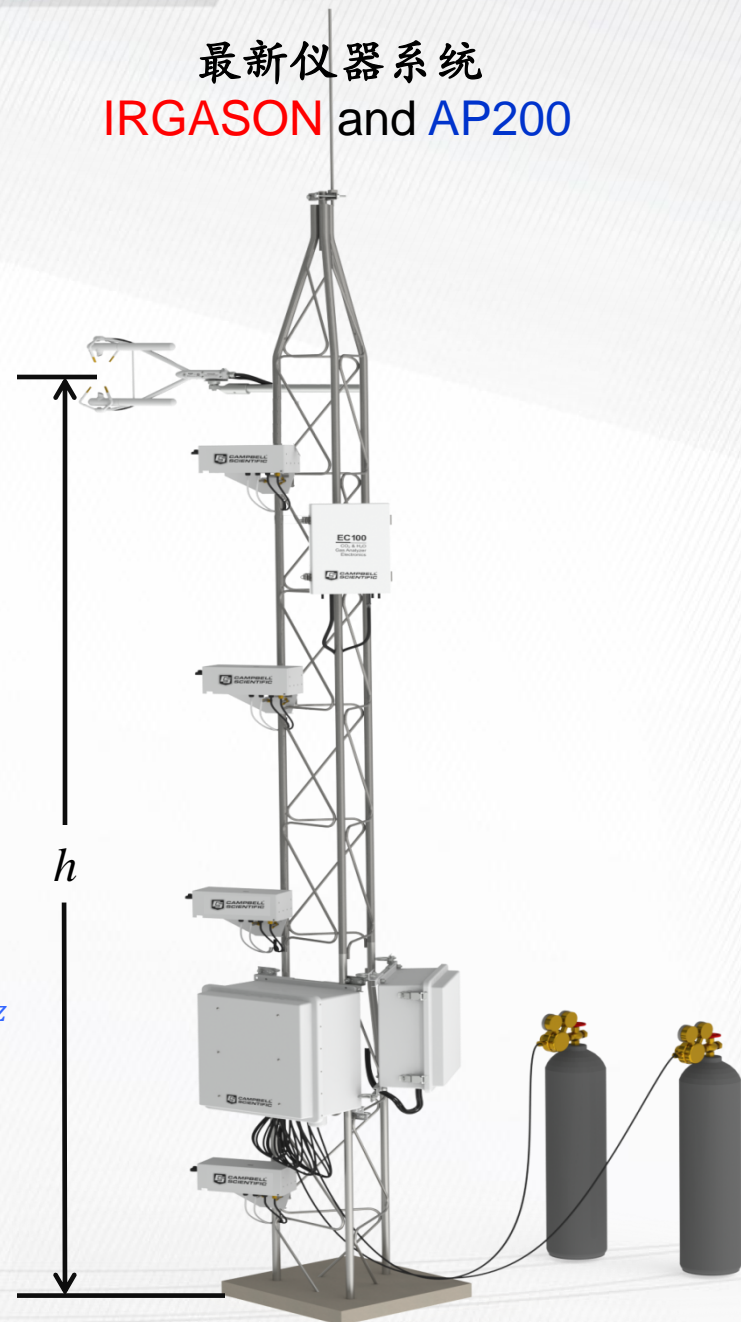$$N_{co2} = \overline{w'c'_{co2}}|_h + \frac{\overline{c_{co2}}}{\overline{C_d}}\left[\overline{w'c'_{h2o}} + \bar{c}\,\overline{\frac{w'T'}{\overline{T}}}\right]_h + \int_0^h \overline{\frac{\partial c_{co2}}{\partial t}}\,dz - \frac{\overline{c_{co2}}}{\overline{C_d}}\,h\int_0^h \overline{\frac{\partial c_d}{\partial t}}\,dz$$
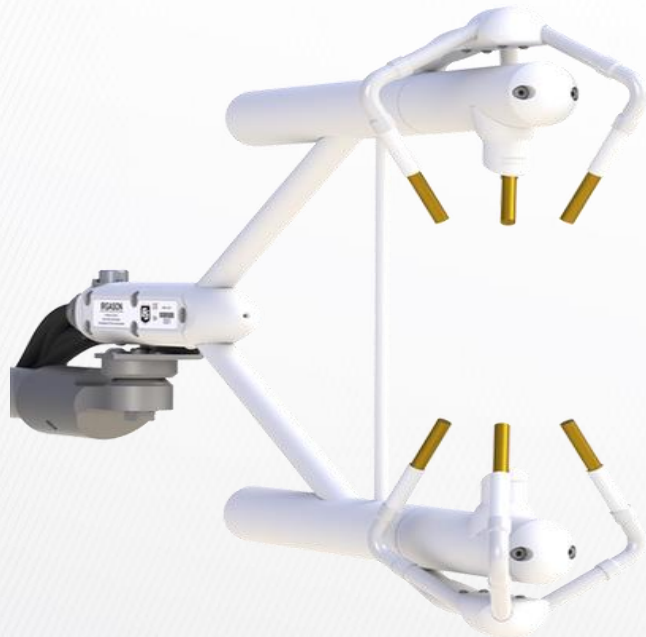
干空气
密度

湿空气
密度

净H_2O通量 (N_{h2o})

$$N_{h2o} = \overline{w'c'_{h2o}}|_h + \frac{\overline{c_{h2o}}}{\overline{C_d}}\left[\overline{w'c'_{h2o}} + \bar{c}\,\overline{\frac{w'T'}{\overline{T}}}\right]_h + \int_0^h \overline{\frac{\partial c_{h2o}}{\partial t}}\,dz - \frac{\overline{c_{h2o}}}{\overline{C_d}}\,h\int_0^h \overline{\frac{\partial c_d}{\partial t}}\,dz$$

h

少假设
少订正
少不确定性
高精度

Fewer assumptions used
Fewer corrections needed
Less uncertainty
Better accuracy

IRGASON
(红外超声碳水热通量集成观测仪）

AP200
（红外大气碳水热纵断面观测系统）

CPEC200
(闭路红外超声碳水热通量观系统）

谢谢

Welcome to Campbell Scientific