

# 涡度相关仪器的发展简史、配置 与系统维护

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2015.5.22~23, 北京

# Memory of Bert Tanner (1943 - 2008)



# 目录

- ▶ 45年以前的涡度仪器
- ▶ 1975年到1995年期间的涡度仪器
- ▶ 1996年到2008年期间的涡度仪器
- ▶ 从2009年到现在的涡度仪器
- ▶ 关于涡度仪器配置的一些注意事项
- ▶ 涡度相关通量系统的维护





# 45年以前的涡度仪器

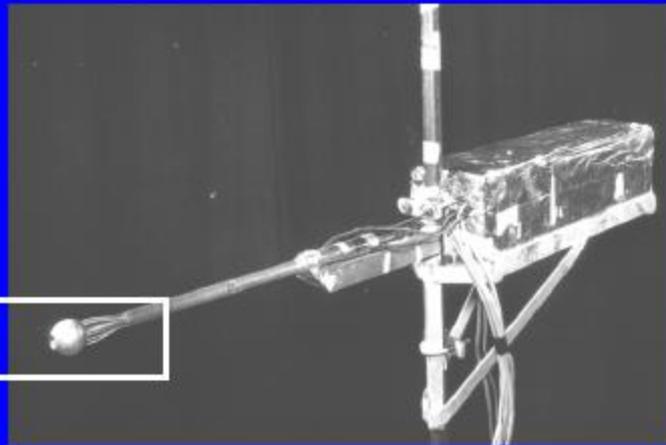
## Instruments GWT & CBT Used

- **Wind:** Anemoclinometer
- **Temperature:** 5  $\mu\text{m}$  tungsten wire on spool
- **Water vapor:** Barium Fluoride humidity sensor
- **Carbon dioxide:** none



# Instruments GWT & CBT Used cont'd

- **Wind:** Anemoclinometer



Courtesy C.B. Tanner Archive



# Anemoclinometer

Hancock, Wisconsin  
1967

22 foot Computer Trailer

Guelph, Canada  
1969



Courtesy Marv Wesely

Courtesy C.B. Tanner Archive



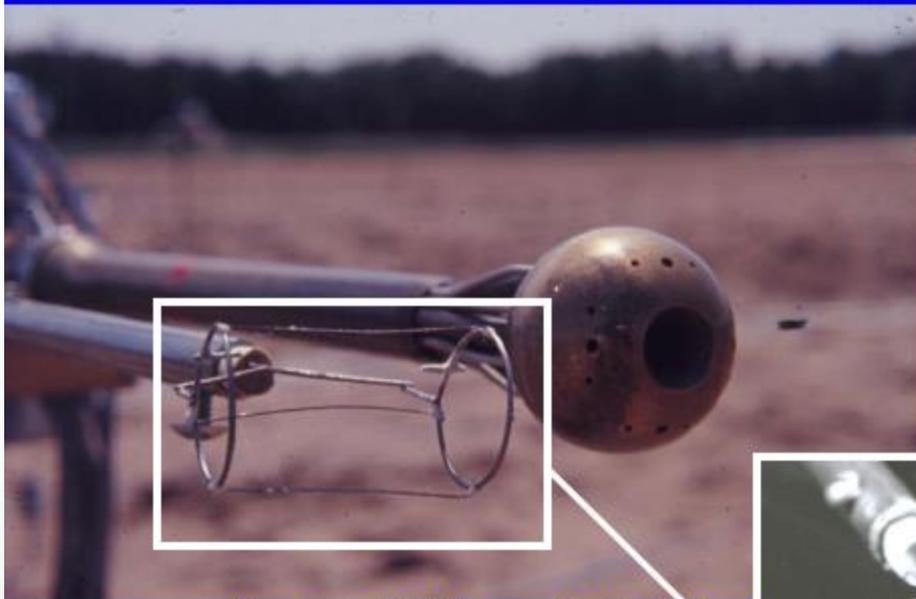


Courtesy C.B. Tanner Archive

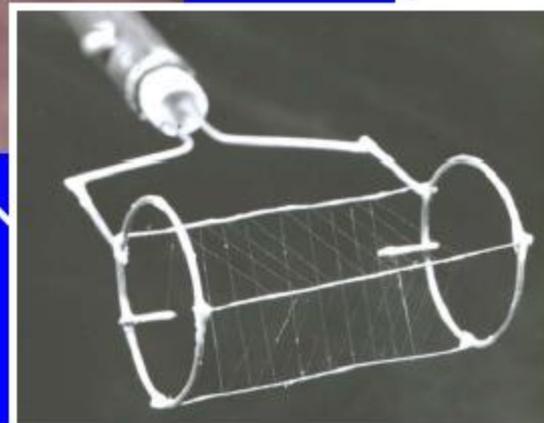
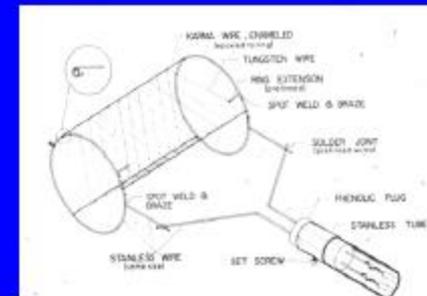


# Instruments GWT & CBT Used cont'd

- Temperature: 5  $\mu\text{m}$  tungsten wire on a spool

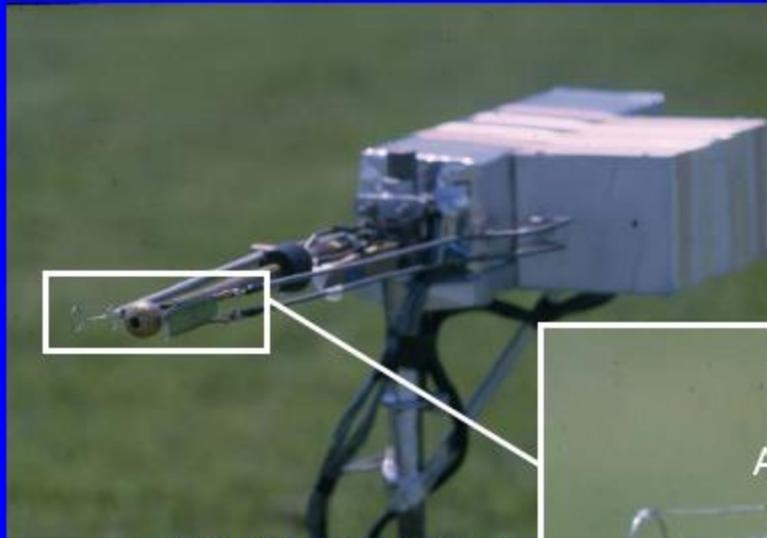


Courtesy C.B. Tanner Archive

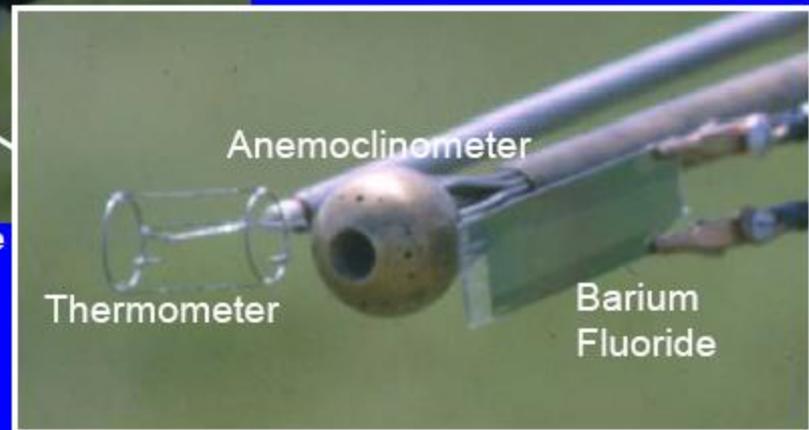


# Instruments GWT & CBT Used cont'd

- **Water Vapor:** Barium Fluoride humidity sensor



Courtesy C.B. Tanner Archive



# Instruments GWT & CBT Used cont'd

- Net Radiation



Courtesy C.B. Tanner Archive

Domed Net Radiometer



Courtesy C.B. Tanner Archive

Suomi Ventilated Net Radiometer



# Interpretation of Measurements cont'd

- Net Radiation



Courtesy C.B. Tanner Archive

Domed Net Radiometer



Courtesy C.B. Tanner Archive

Suomi/Tanner Ventillated  
Net Radiometer

**A Swisteco net radiometer used by Tanner was recalibrated in 1997 using an absolute standard and found accurate within 2%.**



# Instruments GWT & CBT Used cont'd

- Soil Heat Conduction Flux



Courtesy C.B. Tanner Archive



# Instruments GWT & CBT Used cont'd

- Data Collection System:



Courtesy C.B. Tanner Archive

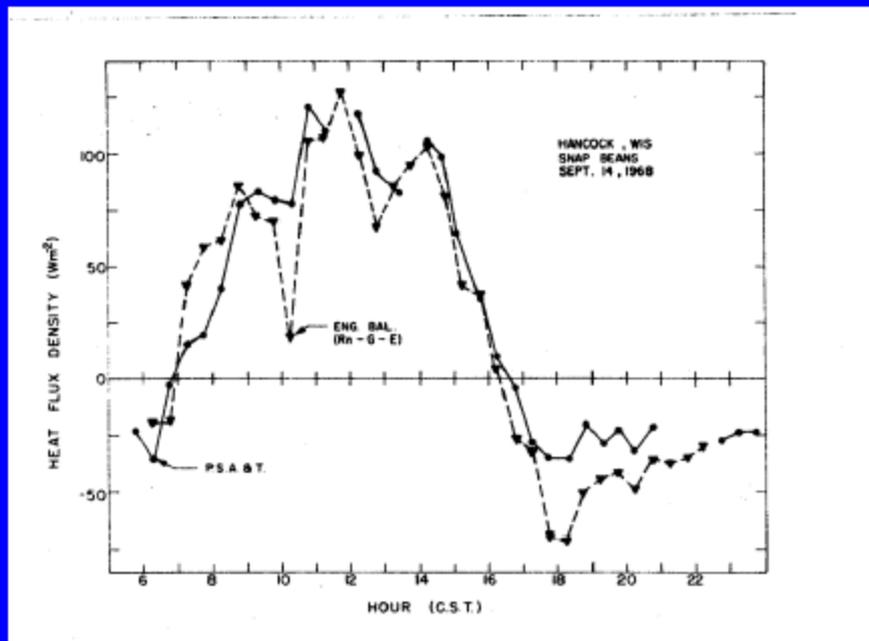


Courtesy of Ken King



# Instruments GWT & CBT Used cont'd

- Sensible Heat Flux Comparison (E.C. vs Bowen Ratio)

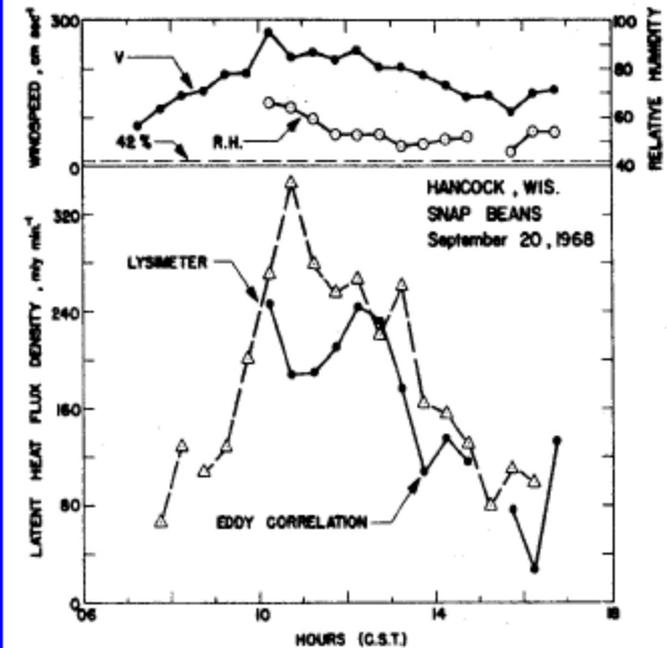
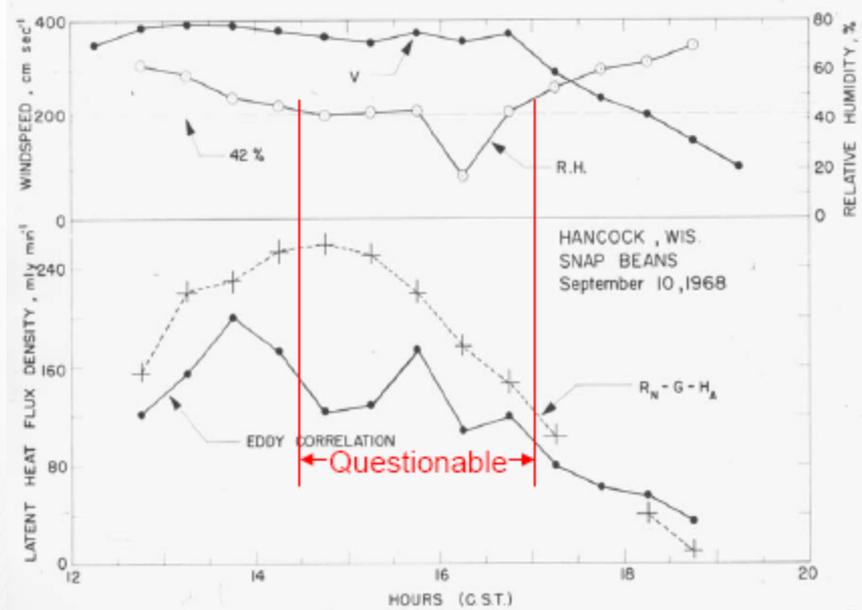


Courtesy Marv Wesely



# Instruments GWT & CBT Used cont'd

- Latent Heat Flux Comparison With  $BaF_2$



## Instruments GWT & CBT Used cont'd

- Results
  - “The field measurements indicate that the barium fluoride film humidity sensor has sufficiently rapid response to allow reliable eddy correlation measurements of vapor flux within a meter or less of the surface” (Goltz et al., 1969)
  - Clearly their eddy covariance system underestimated the latent heat fluxes from snap beans by 0 to 30%



# 小结

- ▶ 以今天的眼光来看，45年以前的涡度仪器非常简陋、粗糙，使用很不方便
- ▶ 往往只能做短期的实验
- ▶ 奠定了涡度相关的一些理论基础：坐标旋转、WPL修正
- ▶ 快速响应：涡度仪器的必备条件



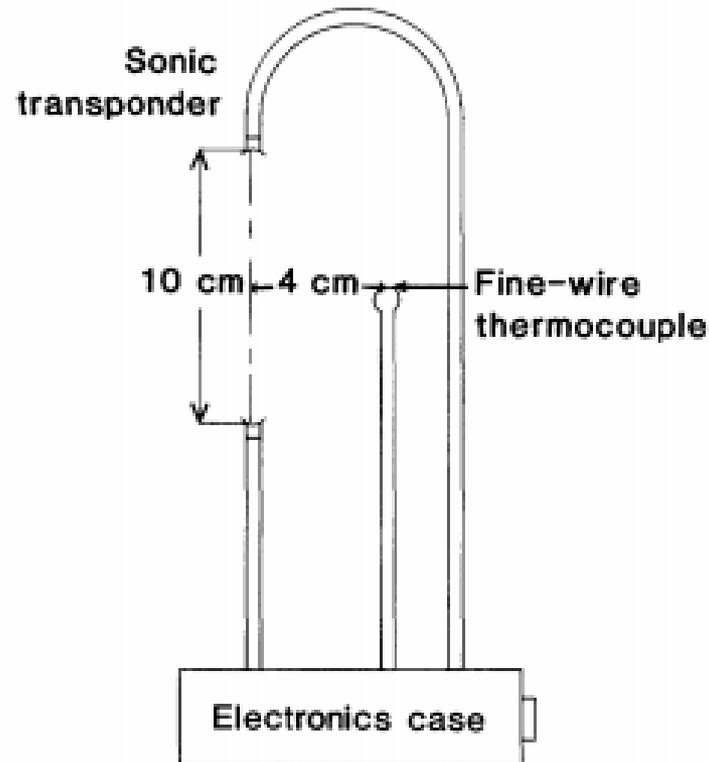


# 1975年到1995年期间的涡度仪 器

# CR5 - 1975

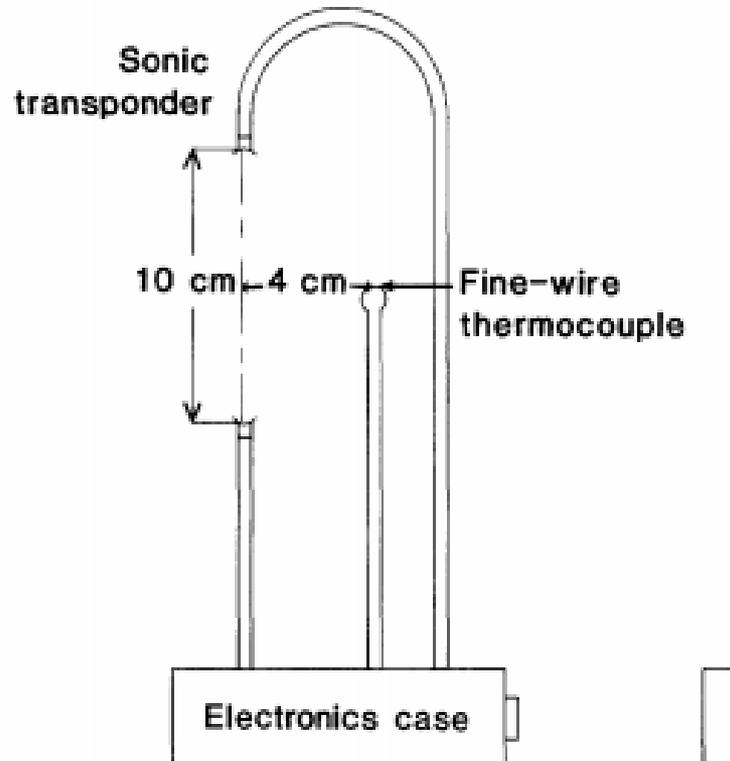


# Goose Neck one dimensional Sonic – 1978 Campbell and Unsworth

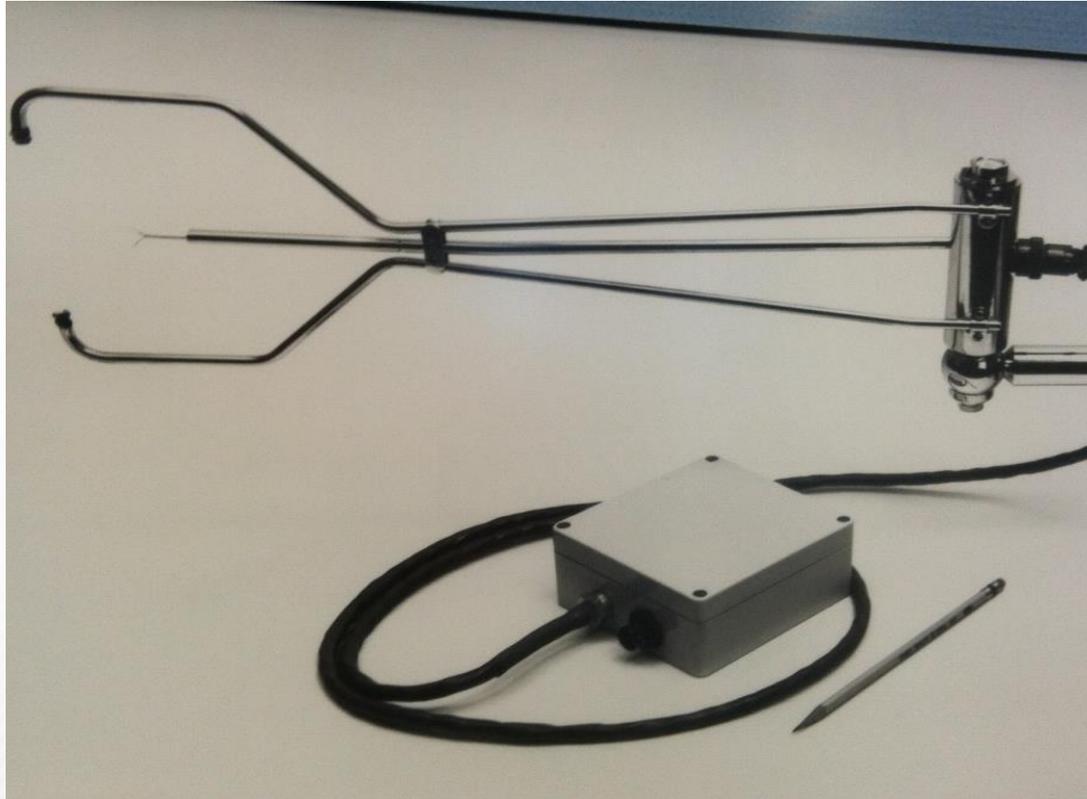


# CA 27 - T - 1979

## Goose Neck



# CA27 - 1979



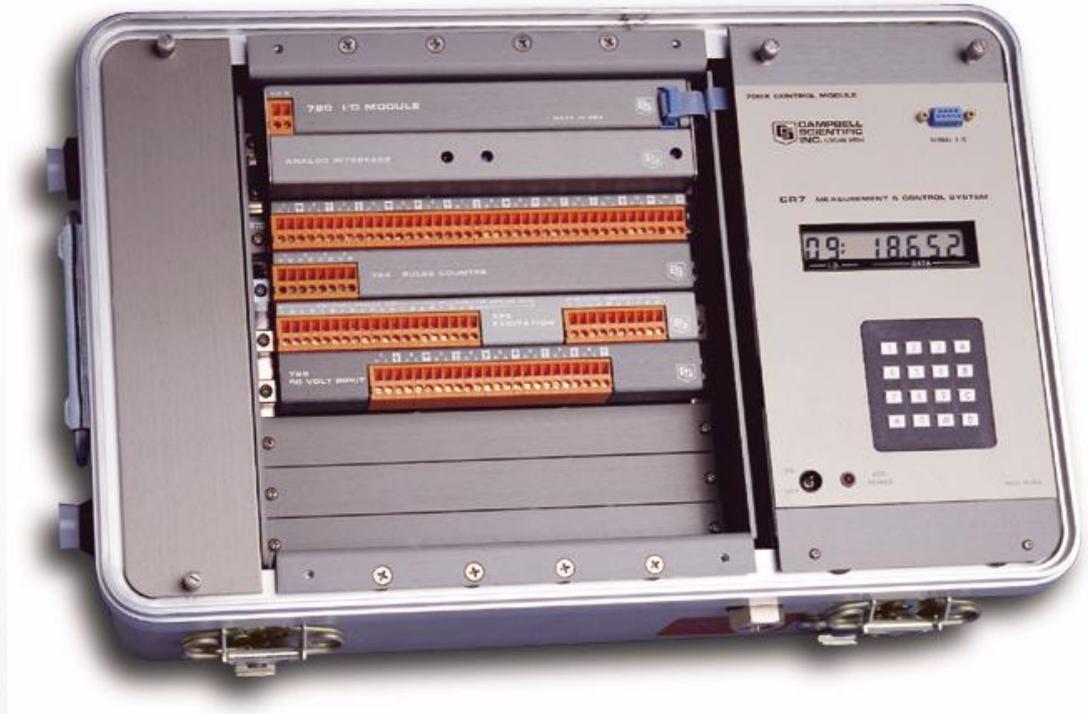
# Model 220 Lyman-Alpha Hygrometer - 1981



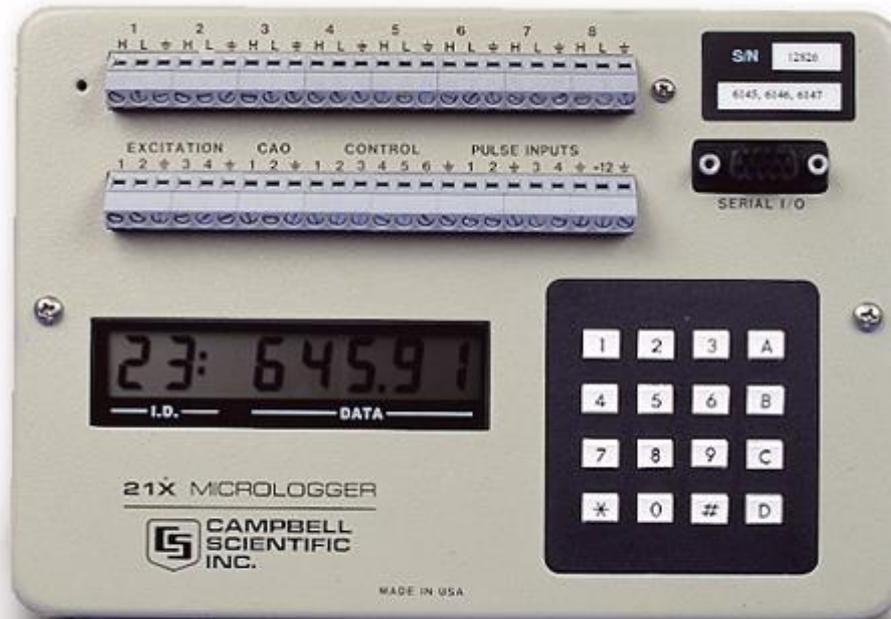
# LI-6200 Series – 1982



# CR7 - 1983

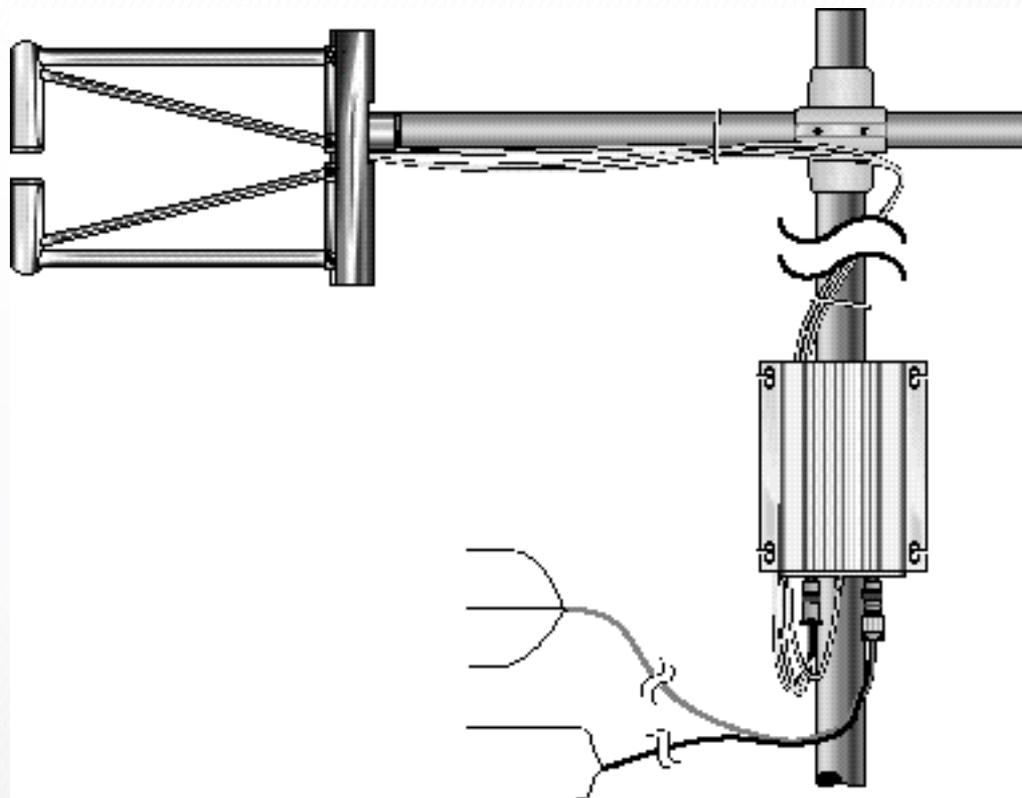


# 21X - 1984



# KH20 – 1985

(U.S. Patent 4,526,034)

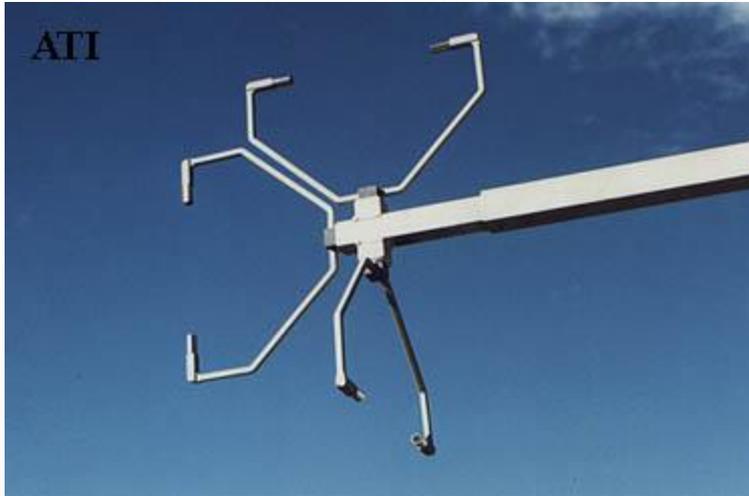


- ▶ 直到今天，Campbell Scientific 仍然在销售KH20。

# Eddy Correlation - 1987



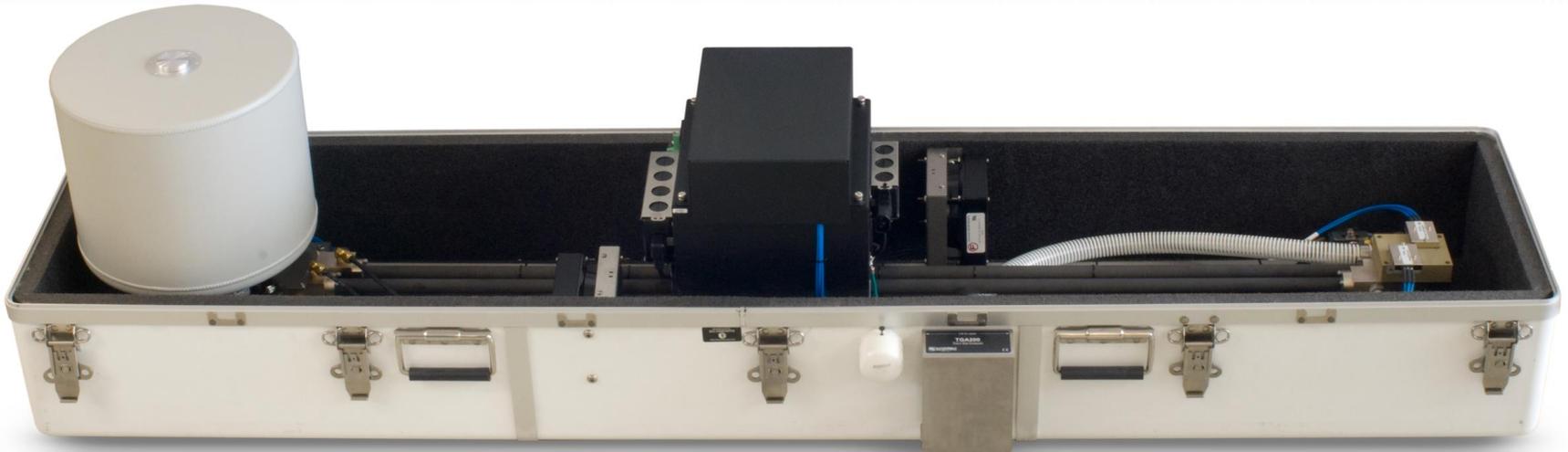
# 3D sonic Anemometers - 1988



# NOAA-ATDD - ~1990



# TGA100 - 1993



# CR9000 - 1995



# 小结

- ▶ 野外数据采集设备有了充足的发展
- ▶ KH20的发明，是H2O涡度测量的重要进步
- ▶ TGA100分析仪可以多种痕量气体及同位素：CO<sub>2</sub>, H<sub>2</sub>O, CH<sub>4</sub>, N<sub>2</sub>O, NH<sub>3</sub>
- ▶ CO<sub>2</sub> 涡度测量以闭路为主
- ▶ 诞生了一些超声风速仪，其设计理念有待改进





# 1996年到2008年期间的涡度仪 器

# CSAT3 - 1996



# CR23X - 1998



# LI-7500 - 1999



# CR5000 - 1999



# LI-7000 - 1999



# CPEC100 - 2002



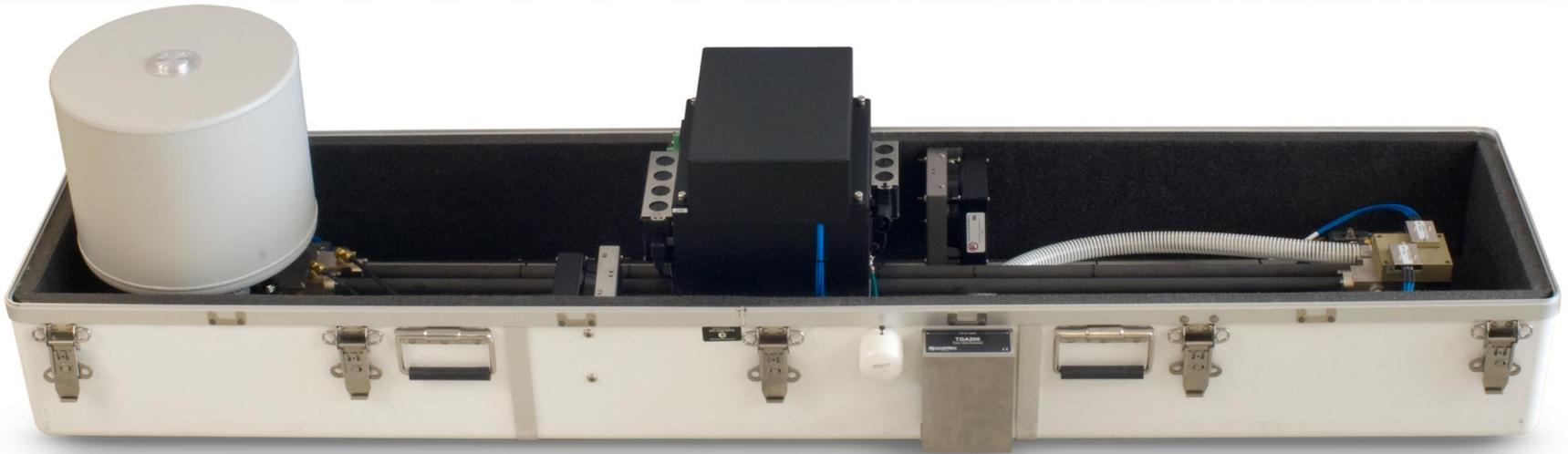
# CR1000 - 2005



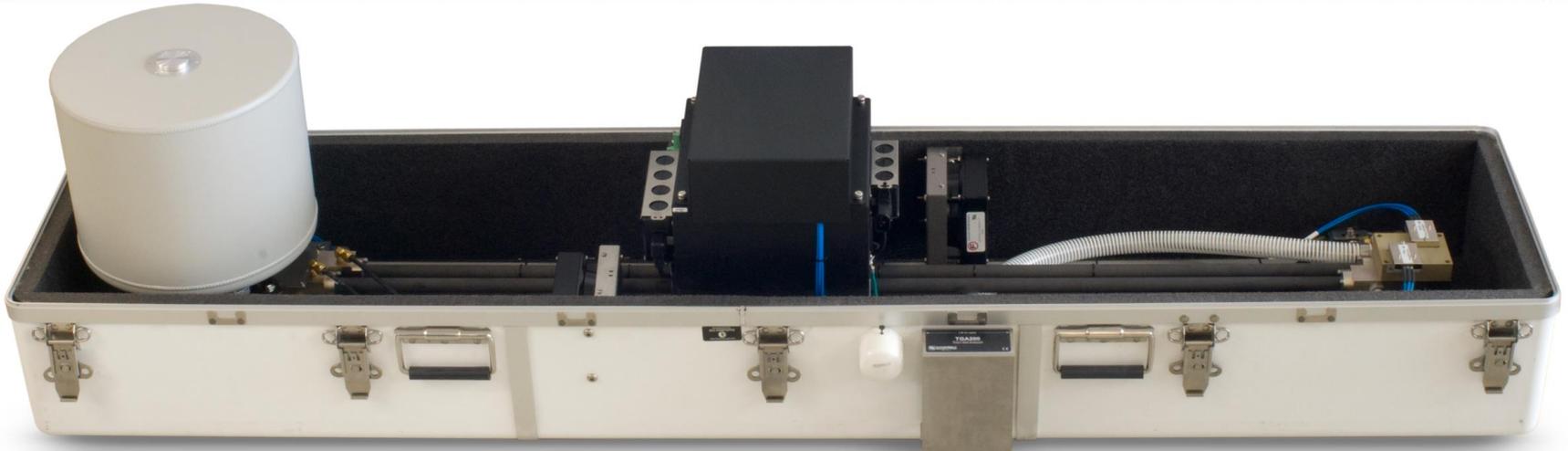
# CR3000 - 2005



# TGA100A - 2005



# TGA200 - 2008





从2009年到现在的涡度仪器

# LI-7700 - 2005



# LI-7500A - 2009



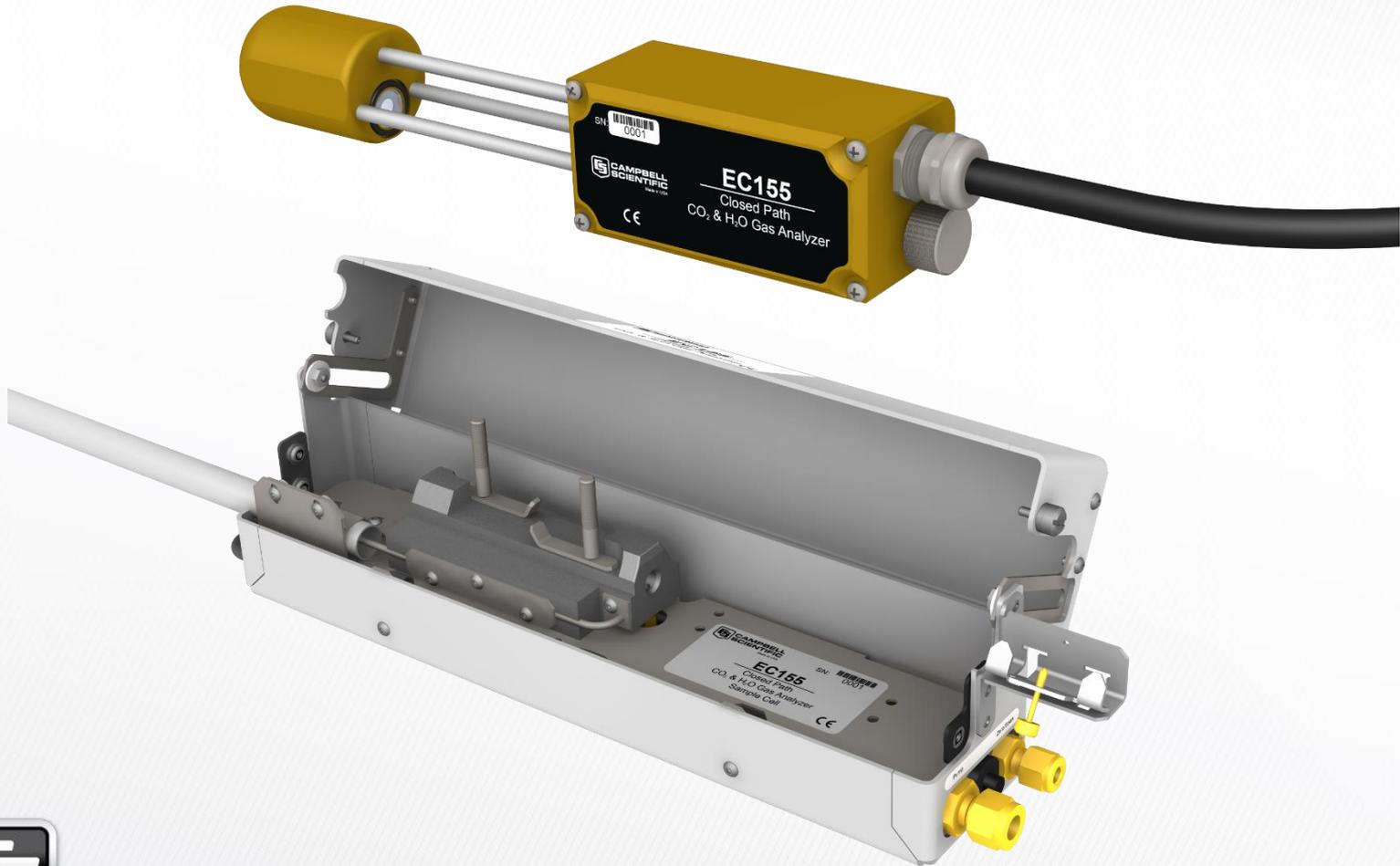
# LI-7200 - 2009



# EC150 - 2010



# EC155 - 2011



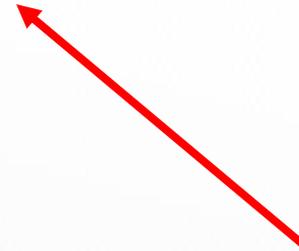
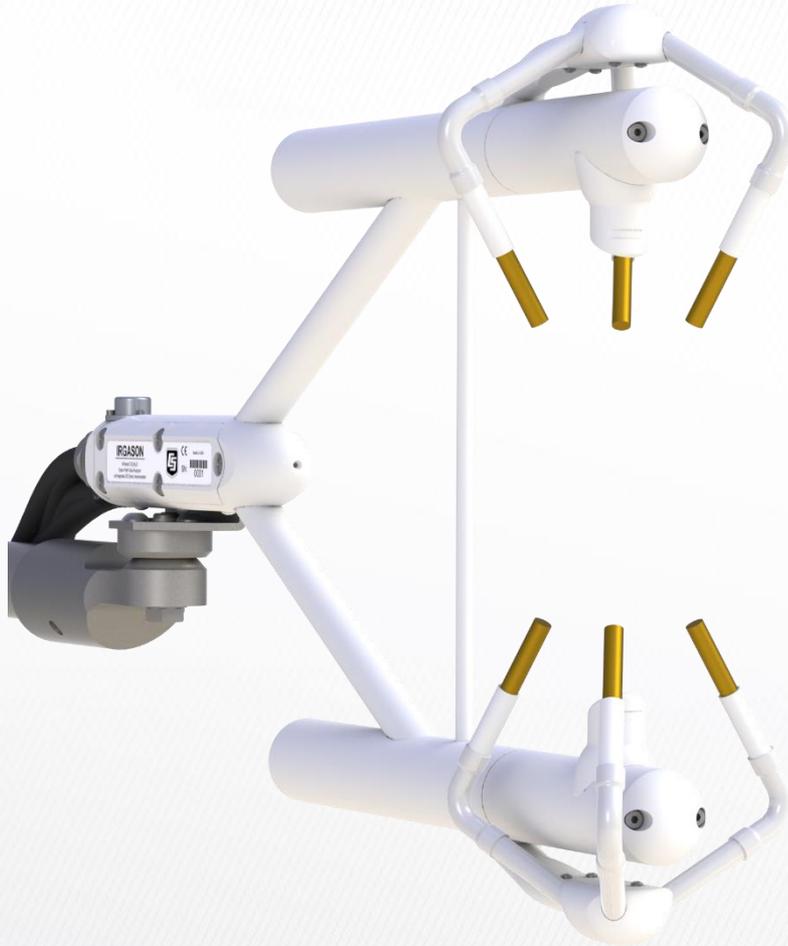
# EC155 - 2011



# CPEC200 - 2011



# IRGASON - 2012

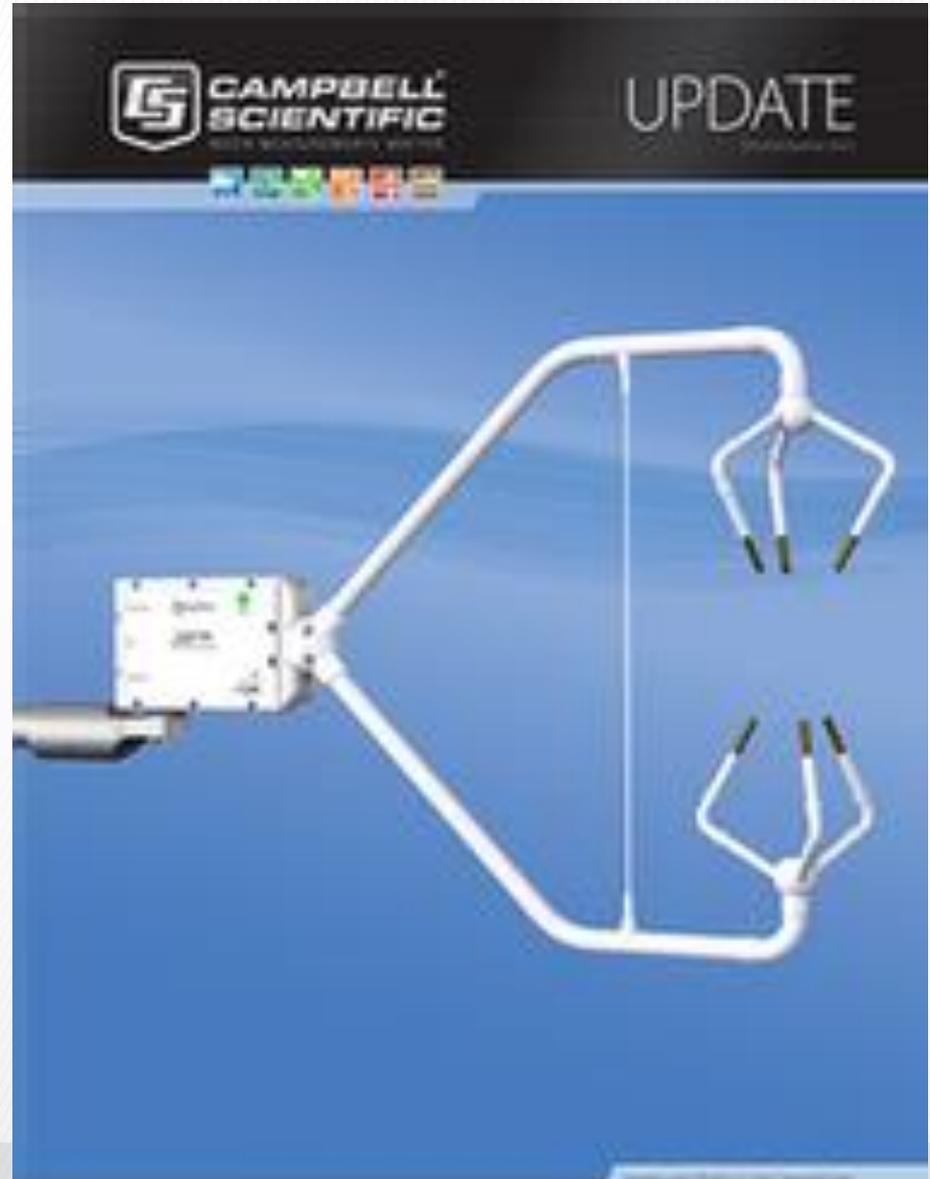


第一种实现了同时空测定三维风速与CO<sub>2</sub>/H<sub>2</sub>O的仪器。



# CSAT3B - 2014

- ▶ 同时支持SDM和CPI（高速）通讯协议





在中国西部的一个CSAT3B传感器网络站点（左）；沿高塔分布的多个CSAT3B测量三维风速和声温的垂直剖面（右）。



# CR6 Multi-purpose Datalogger - 2014

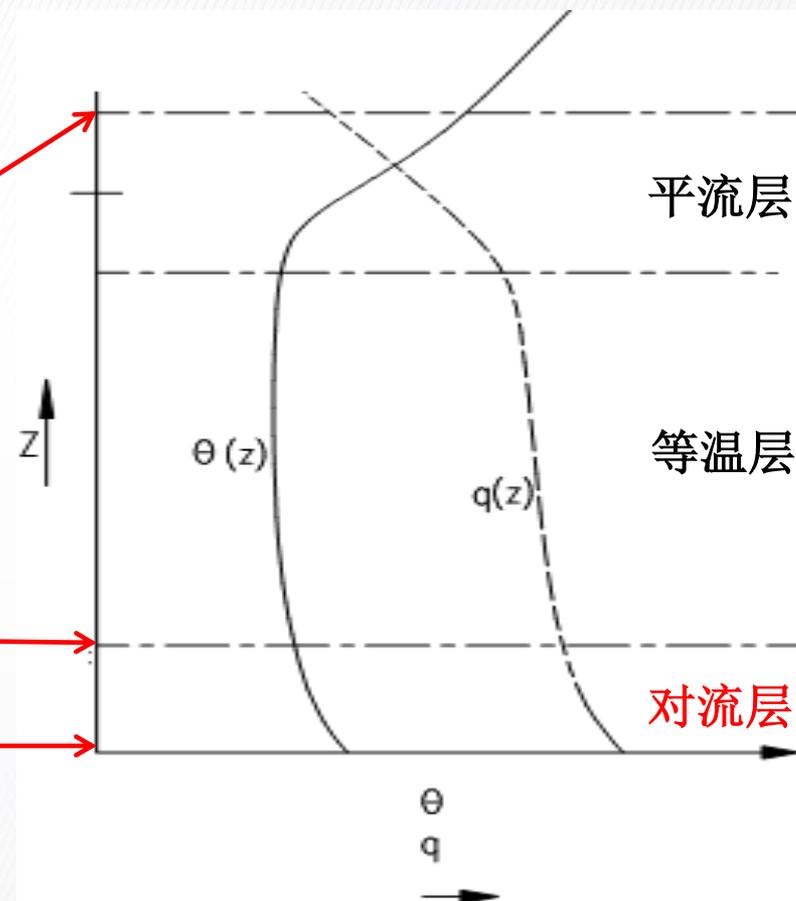
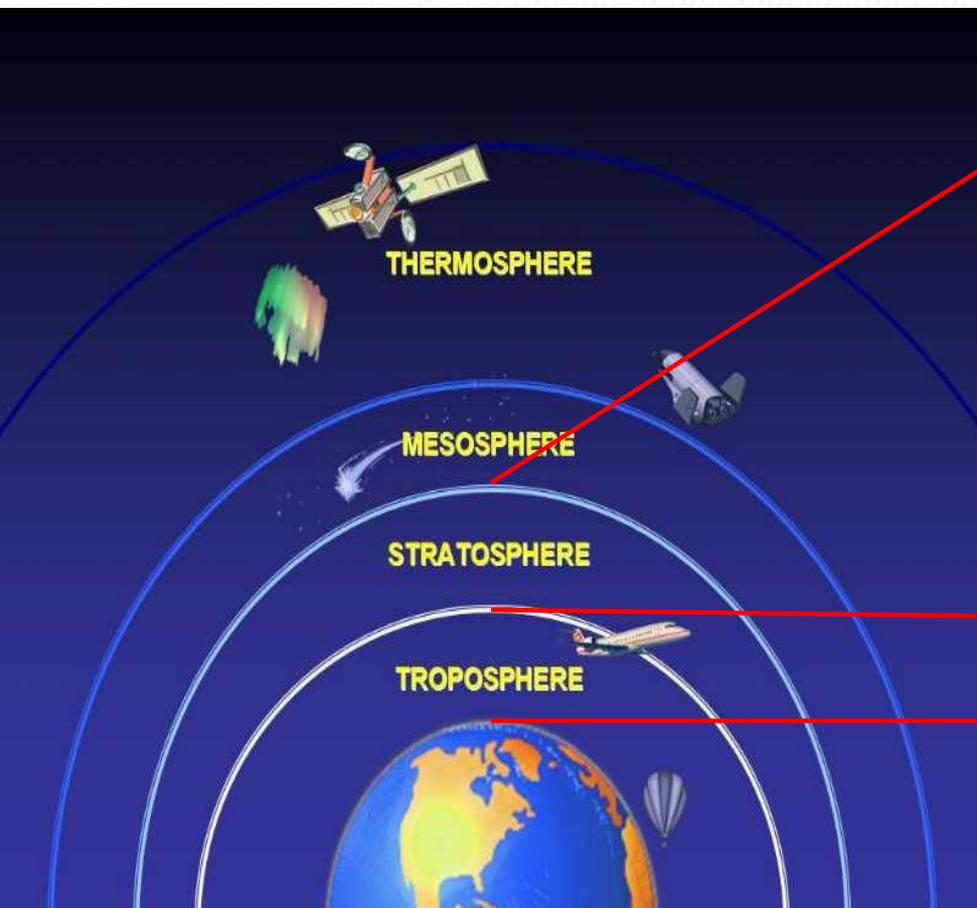
- ▶ Much higher speed of computation than CR3000/CR1000



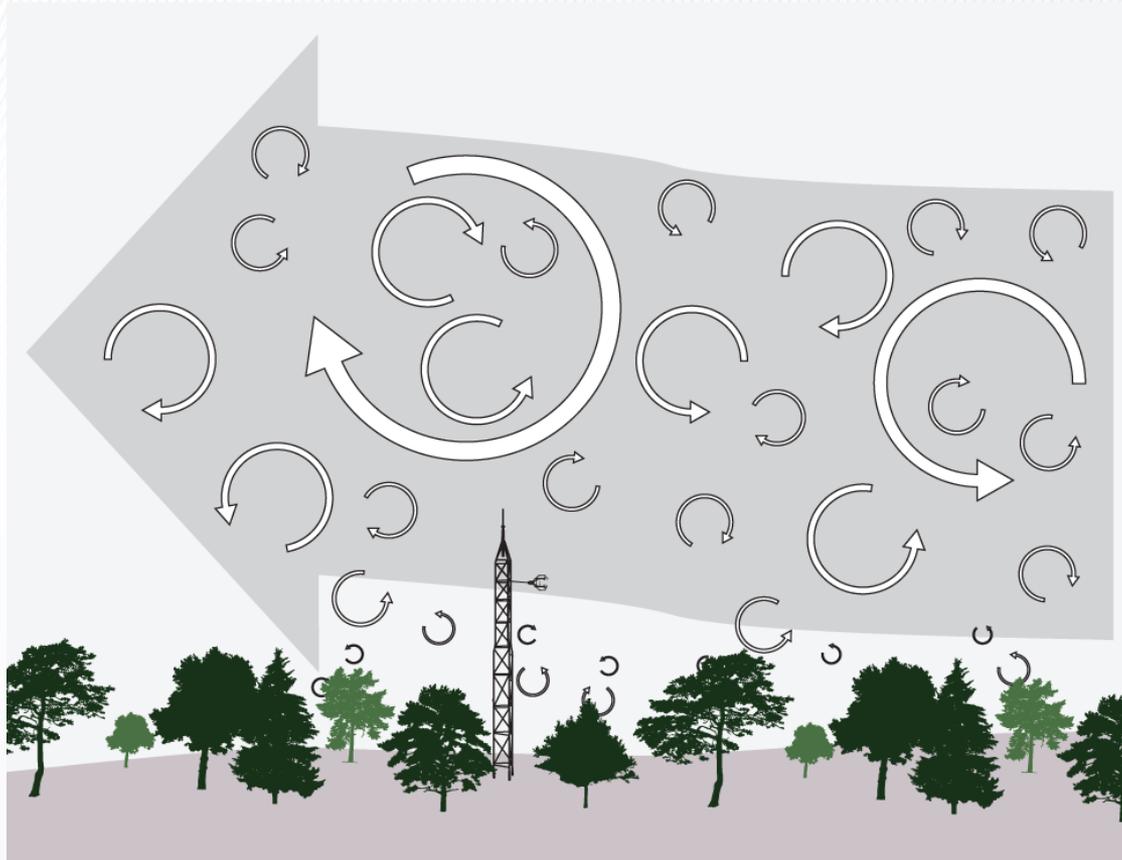


# 关于涡度仪器配置的一些注意 事项

# 大气圈的多层结构



在对流层底部约1000到2000米高度范围内，是风、云、雨、雪等气象现象发生的主要区域，称为**边界层**。



边界层的空气：以水平流动为主的水气热的湍流体

内部特征：1. 无序

2. 三维无规则运动.

4. 各气体组分充分混合



# 涡度理论三个假设

水平面空间上的一致性

$$\frac{\partial}{\partial x_1} = 0 \text{ and } \frac{\partial}{\partial x_2} = 0$$

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

时域上的稳定性

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

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

干空气物质守恒

$$\overline{u_3} = 0$$

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

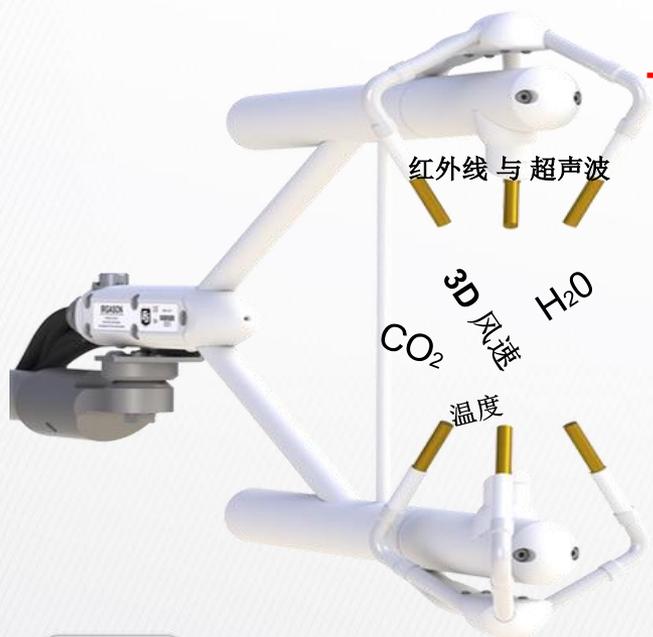
$$\rho_0 \overline{(u_1 - \bar{u}_1)(u_3 - \bar{u}_3)}$$

$$\frac{\text{kg}}{\text{m}^3} \quad \frac{\text{m}}{\text{s}} \quad \frac{\text{m}}{\text{s}}$$

$$\frac{\text{kg m/s}}{\text{m}^2 \text{s}}$$



# 涡度系统测量什么



**IRGASON**

(红外超声碳水热通量集成观测仪)

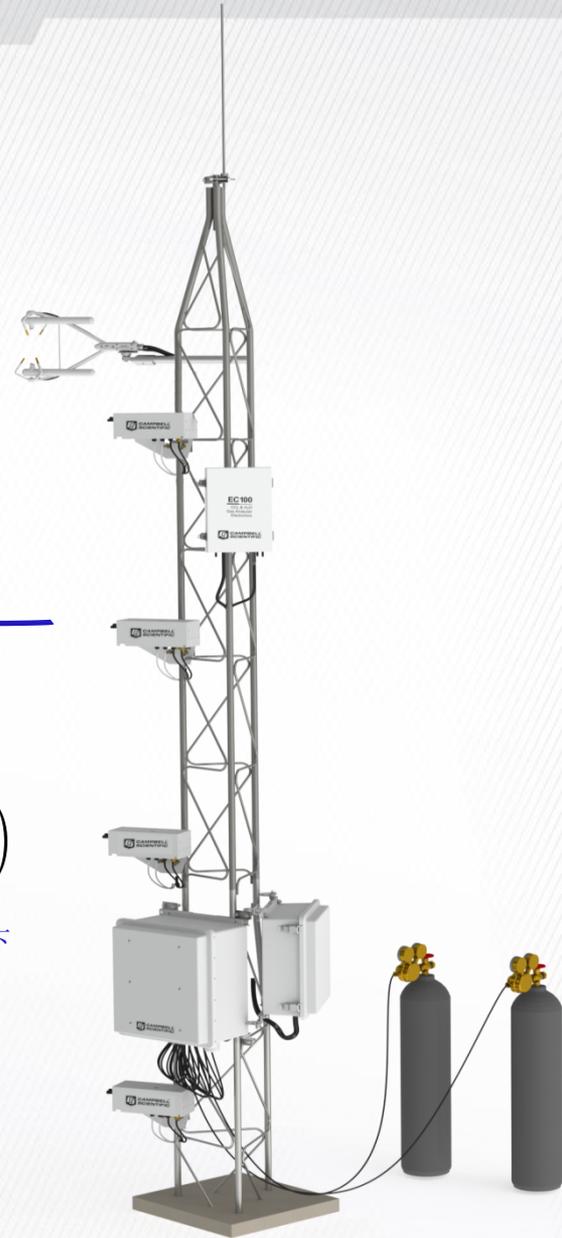
$$NEE_{CO_2} \approx \overline{C_d} \left( \overline{w'X'_{CO_2}}|_h + \int_0^h \frac{\partial X_{CO_2}}{\partial t} dz \right)$$

干空气  
密度

CO<sub>2</sub>  
湍流通量

通量测定高度下  
CO<sub>2</sub> 存储增减

Gu et al./Ag For Meteorol (2012)



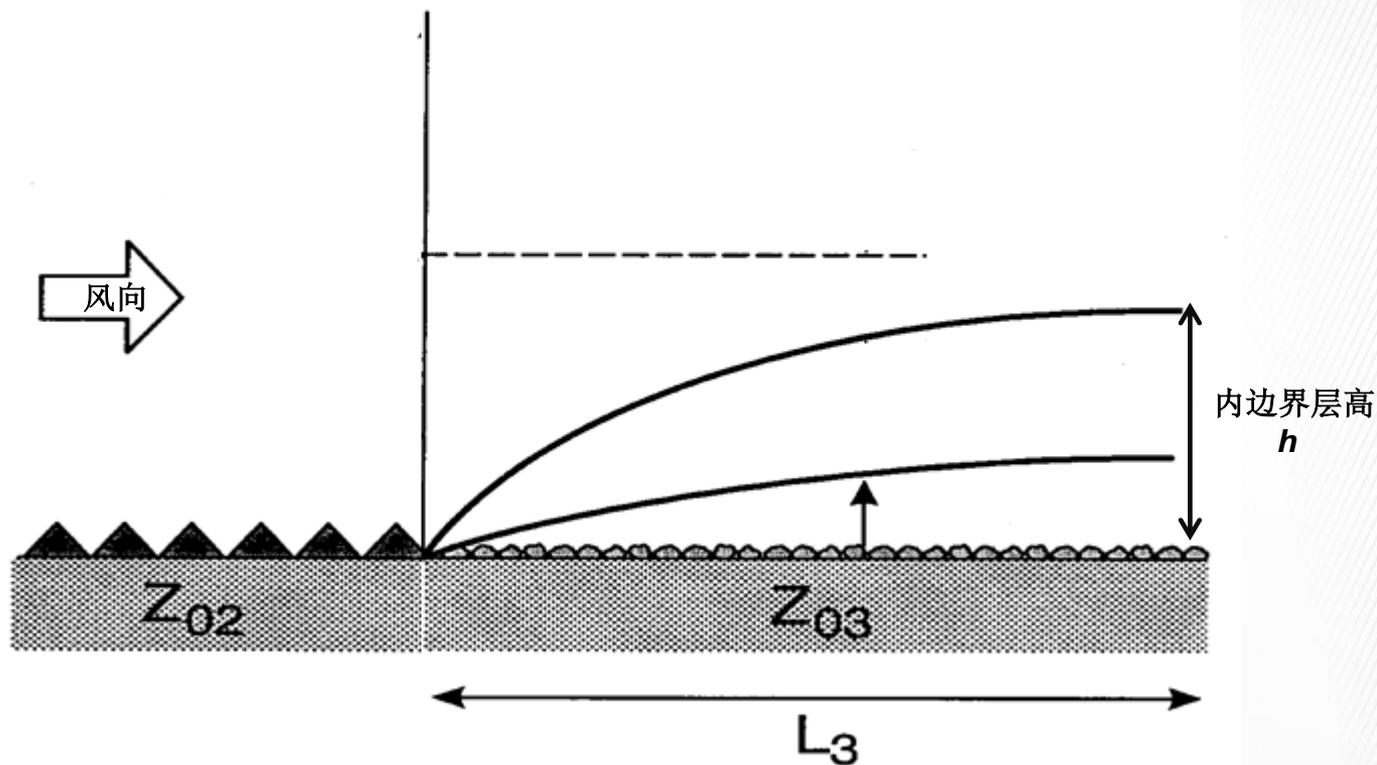
**AP200**

(红外大气碳水热纵断面观测系统)



# 涡度的气象尺度

距地表变化起始点的下距离 (**Fetch, Stull (1988) page 596**)



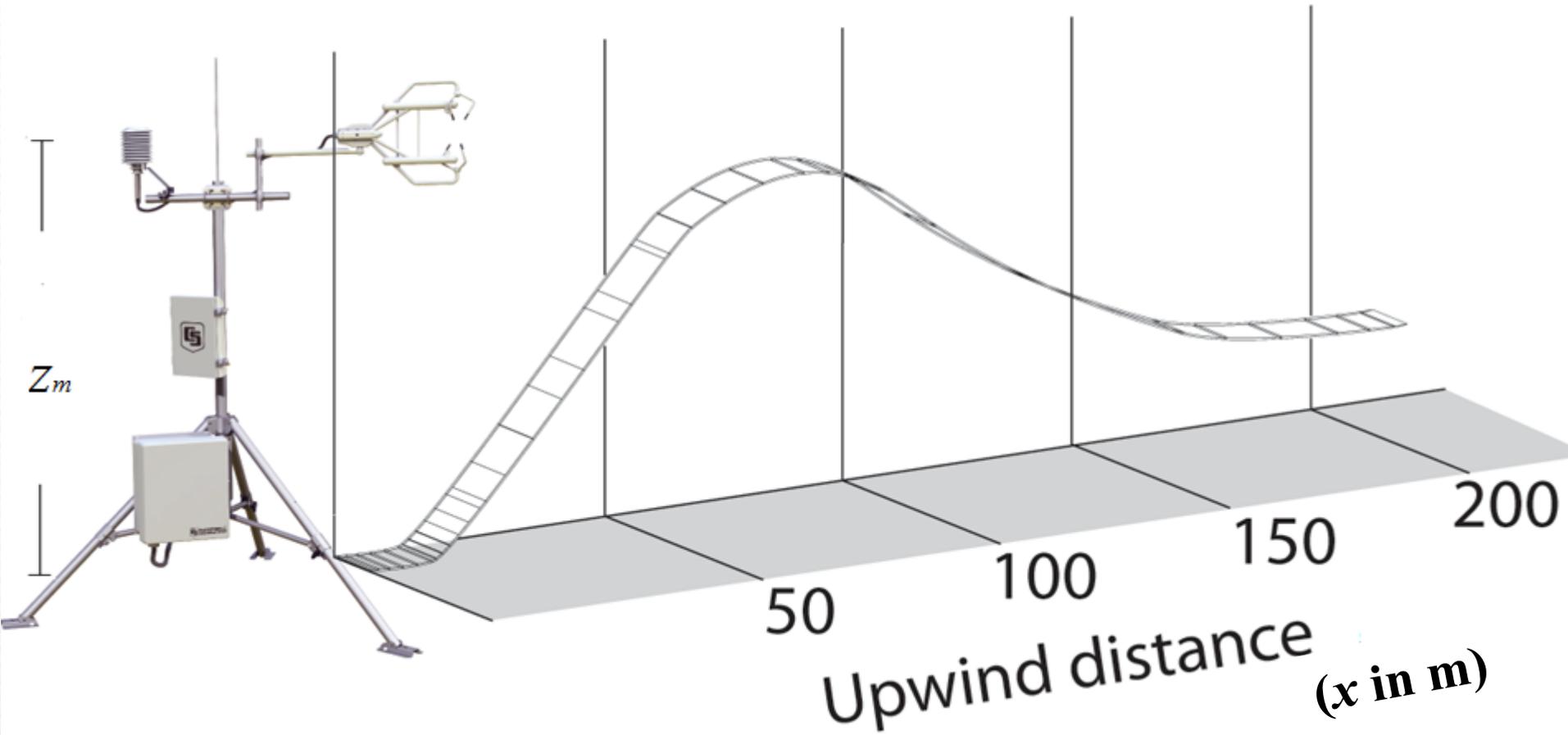
$$L_3 = \left( \frac{10h}{z_{03}^{1/5}} \right)^{5/4}$$

Rosenberg et al. (1983).  
Page 140.



← wind

Footprint: 传感器接收到的信号概率分布



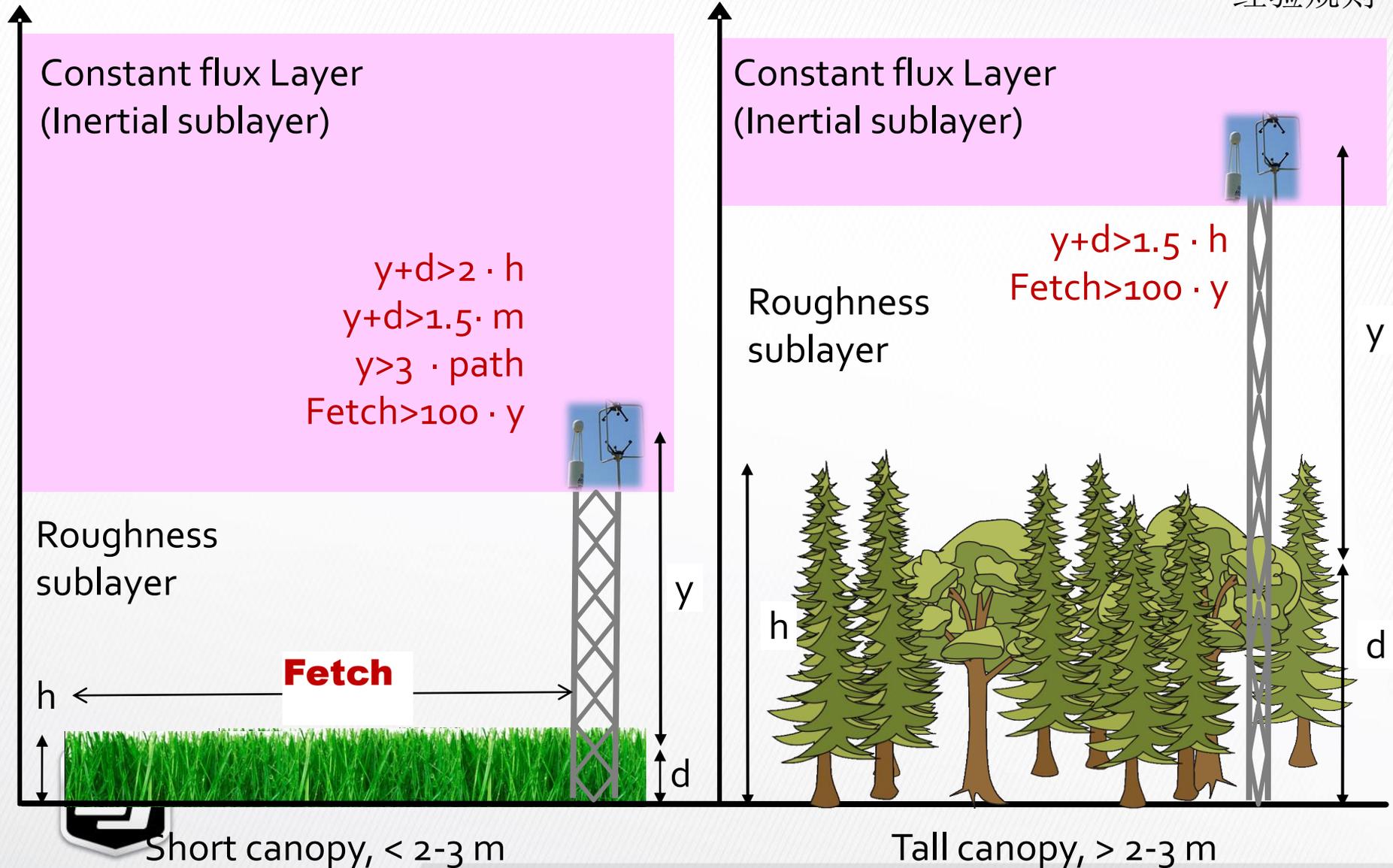
$$f(x) = \frac{Uz_m}{ku_* x^2} \exp\left[-\frac{Uz_m}{ku_* x}\right]$$

(Gash 1986; Schuepp et al. 1990)



# 涡度仪器的安装高度 (Courtesy to Liukang Xu)

经验规则



# 涡度仪器的频率响应

## ▶ 需要有充足的频率响应

– 采样频率  $\neq$  频率响应

## ▶ 无量纲频率

$$n = fz / \bar{u}$$

## ▶ 要求设备频率响应， $f_{\text{req}}$ （经验规则）

$$n \geq 10$$

$$f_{\text{req}} \geq 10 \bar{u} / z$$

$z$  为安装高度，单位为 米

$u$  为水平风速，单位为 米/秒

$f$  为频率，单位为 Hz



# 涡度频率响应

<u>z (m)</u>	<u>u (m/sec)</u>	<u>f<sub>req</sub> (Hz)</u>
2.5	2.5	10
2.5	10	40
10	10	10
30	10	3.3

$$f_{\text{req}} \geq 10 \bar{u}/z$$



# 在不同风速和截止频率下的总通量的占比

Mean U (m/s)	n	f_cut-off = n u/z (Hz)	Flux Fraction (% of total)
0.76	1	0.36	93.6
2.43	1	1.16	91.0
4.07	1	1.94	89.0
0.76	2	0.72	97.1
2.43	2	2.32	96.2
4.07	2	3.88	95.2
0.76	4	1.45	98.8
2.43	4	4.63	98.4
4.07	4	7.75	98.0
0.76	10	3.62	99.7
2.43	10	11.57	99.7
4.07	10	19.38	99.7

Requiring  $f \geq 10 u/z$  may be a bit pessimistic.



# EC150/IRGASon的波宽 (Bandwidth) 选项

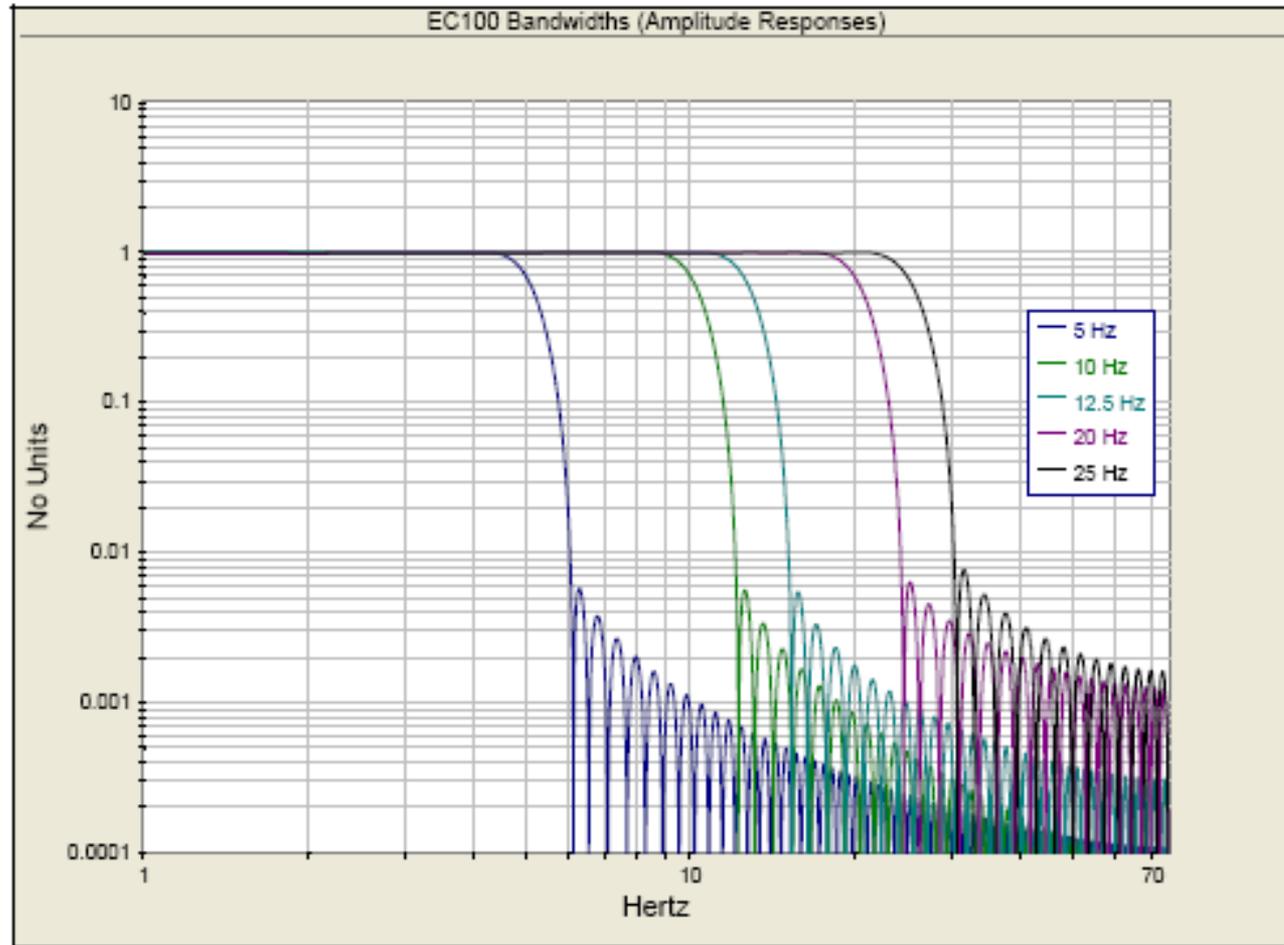


FIGURE A-1. Frequency and amplitude response of EC100 filter at various bandwidths



# EC150/IRGASon的10Hz波宽与50ms移动平均之间的频率响应对比

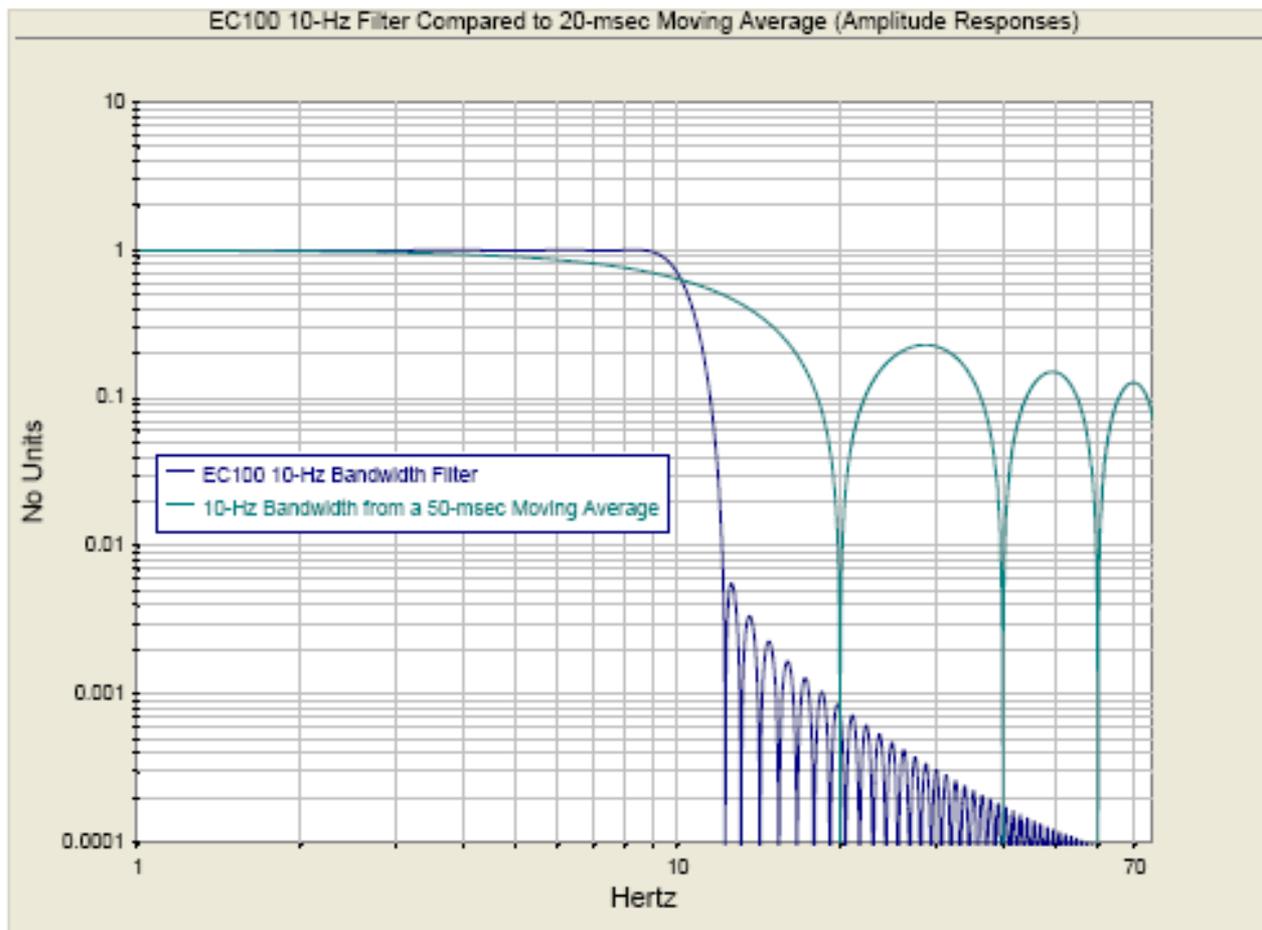


FIGURE A-2. Frequency response comparison of the EC100 10 Hz bandwidth and a 50 ms moving average



# 波宽设置与安装高度之间的折衷

## ▶ 安装高度较低（农田、草地）

- 湍流的频率较高
- 一般设置较高的波宽 (20 Hz, 出厂默认)
- 若采样频率为10 Hz, 会有信号混迭 (aliasing)问题

## ▶ 安装高度较高（森林）

- 湍流的频率降低
- 一般设置波宽为采样频率的一半(5 Hz), 假设采样 $f = 10$  Hz
- 排除信号混迭问题



# 仪器选择：开路还是闭路？

## › 开路系统

- 无管路，频率响应高
- 功耗低
- 受雨雪天气干扰
- 更少的维护

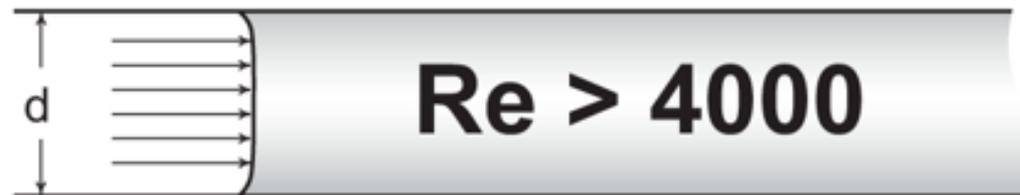
## › 闭路系统

- 可保证数据更准确
- 在雨雪天气条件下获取的有效数据更多
- 可配置在线自动校准
- 需要配置管路和泵，功耗更高
- 管路吸附造成的频率衰减（特别是对H<sub>2</sub>O、NH<sub>3</sub>等极性分子）



# 闭路系统设计：泵速和管径（雷诺数）

## *Velocity Profile in Sample Tubing*



**Re is proportional to  $Q / d$**

**Q is flow rate**



# 闭路系统设计：泵速和管径（雷诺数）

**雷诺数**（**Reynolds number**）一种可用来表征流体流动情况的无量纲数。 $Re=pvd/\mu$ ，其中v、 $\rho$ 、 $\mu$ 分别为流体的流速、密度与黏性系数，d为一特征长度。例如流体流过圆形管道，则d为管道的当量直径。利用雷诺数可区分流体的流动是层流或湍流，也可用来确定物体在流体中流动所受到的阻力。

中文名	雷诺数	属性	无量纲数
外文名	Reynolds number	符号	Re
		计算公式	$Re=pvd/\mu$

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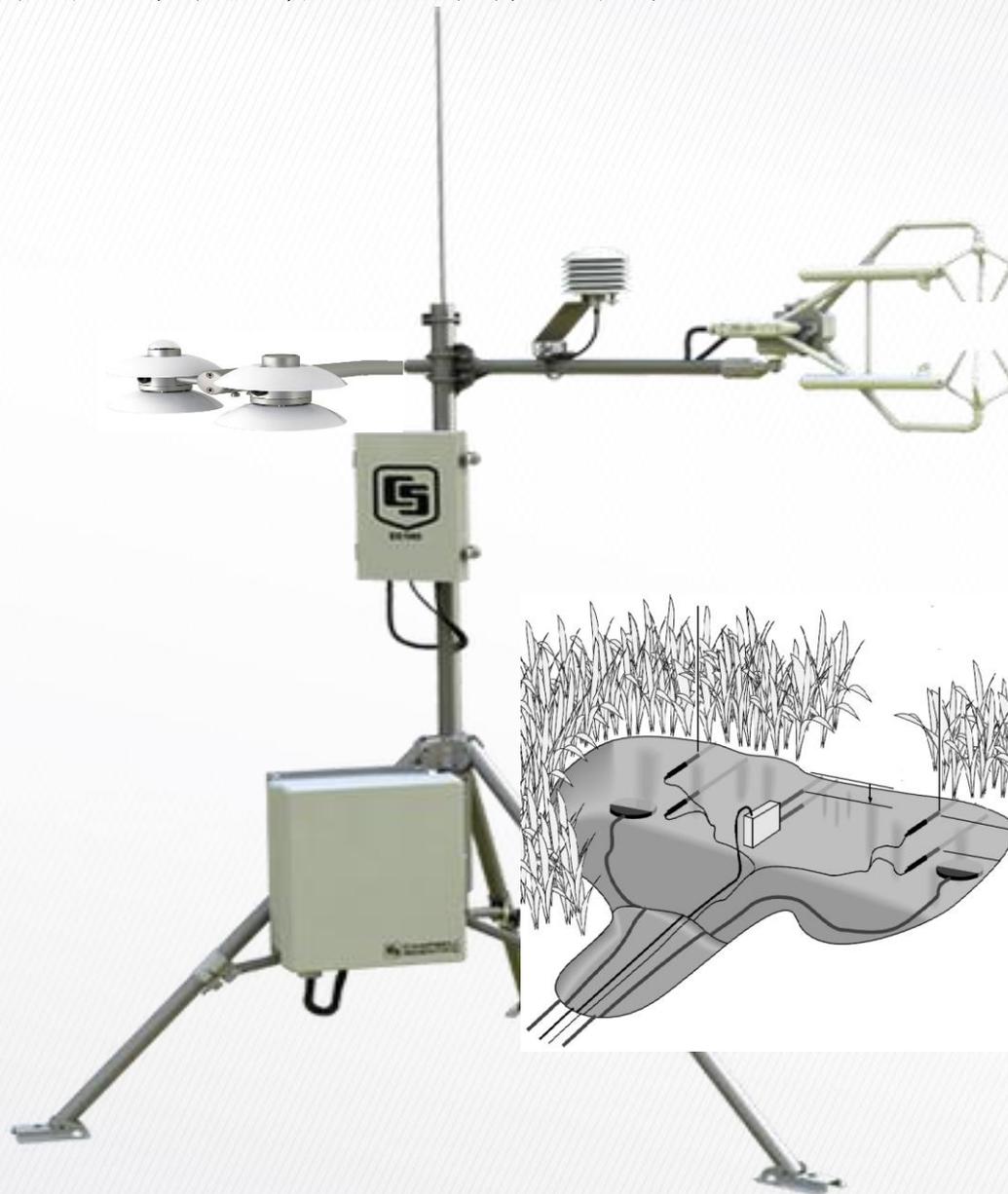
流体力学中，**雷诺数**（**Reynolds number**）是流体**惯性力** $\frac{\rho v^2}{L}$ 与**黏性力** $\frac{\mu v}{L^2}$ 比值的量度，它是一个**无量纲量**。

雷诺数较小时，黏滞力对流场的影响大于惯性力，流场中流速的扰动会因黏滞力而衰减，流体流动稳定，为**层流**；反之，若雷诺数较大时，惯性力对流场的影响大于黏滞力，流体流动较不稳定，流速的微小变化容易发展、增强，形成紊乱、不规则的**紊流**流场。



# 涡度相关通量系统的维护

# 坎贝尔开路通量测定系统 (OPEC200)



# OPEC200 开路通量系统的部件



## OPEC200 日常站点检查

- ▶ 检查EC100电子控制机箱内的湿度指示卡，若变成粉红色，则需要更换干燥剂。
- ▶ 机箱内的Power, Gas, Power 指示灯都必须是绿色。如果不是，确认所有的传感器是否连接正常。



## 分析仪防雨网

- ▶ 由防紫外材料制成，分上下两种
- ▶ 定期检查；若发现损坏则更换

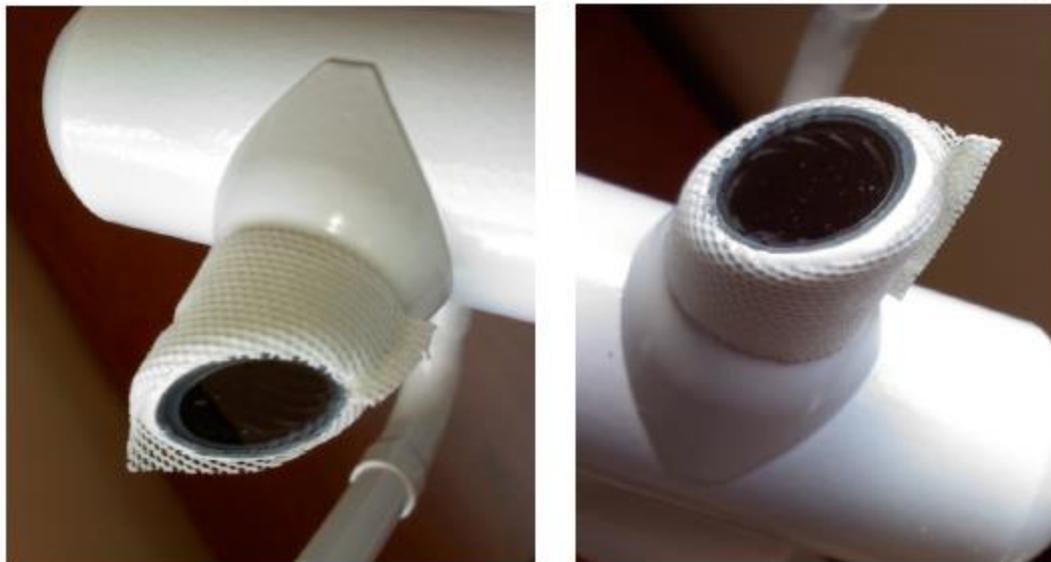


FIGURE 9-1. Proper location of the gas analyzer top wick (left) and bottom wick (right)



## 分析仪窗口清洁

- ▶ 出厂信号强度为1。  
若降至0.7以下，则  
数据不可靠
- ▶ 定期检查；若信号强  
度明显下降（0.05或  
0.1），则使用纯净  
水或酒精清洁



# 分析仪的零点和跨度校准

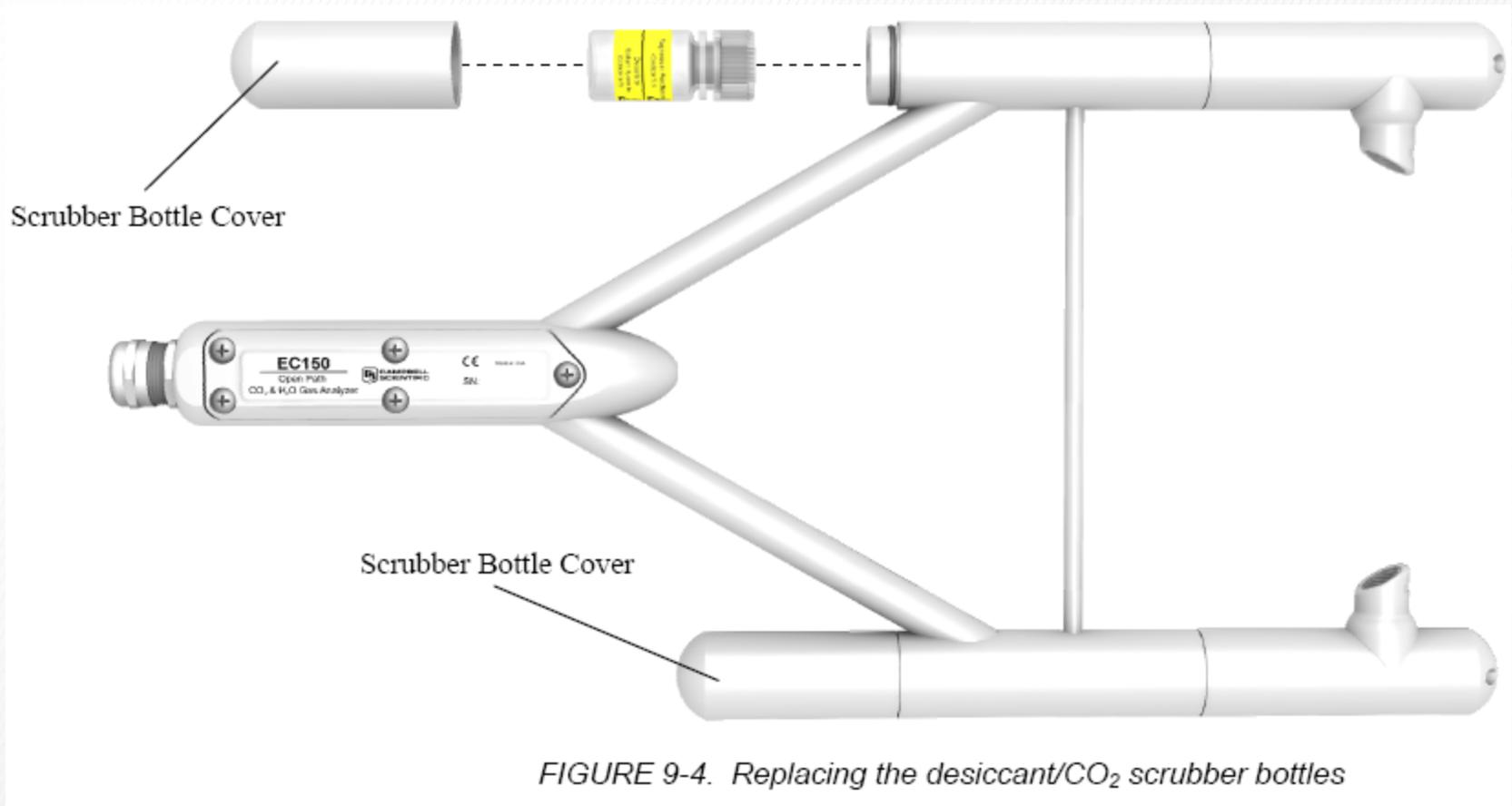
- ▶ 为什么要校准：随着站点条件变化和使用时间延长，分析仪会产生漂移
- ▶ 初次安装，检查分析仪的准确性
- ▶ 按一定时间周期定期地检查或校准，有条件的话，最好每月或每季度校准一次；如果较难操作，最好每半年或每年校准一次。



坎贝尔新开发的31022零气发生气。

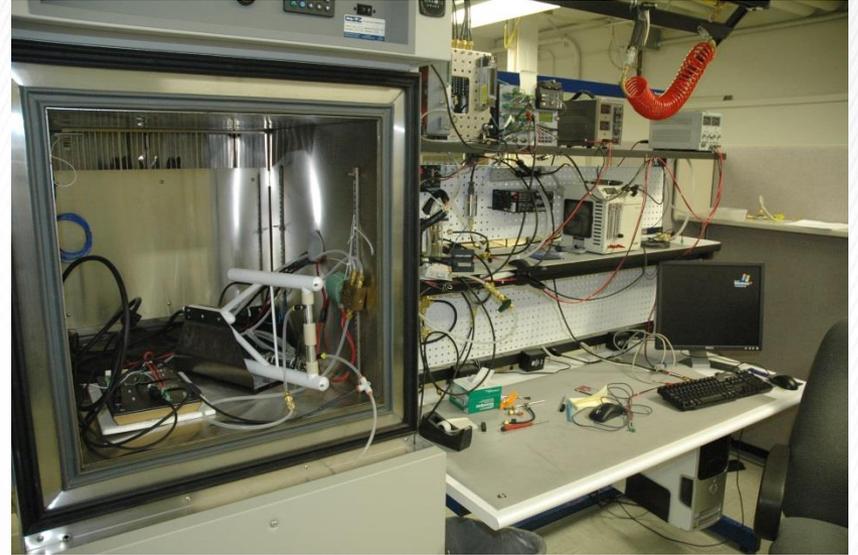


# 分析仪内部CO<sub>2</sub>/H<sub>2</sub>O吸收剂



- 建议每年更换一次。更换后需要放置48小时后再进行零点和跨度校准。

# 工厂校准



^ factory calibration ( CO<sub>2</sub> concentrations, pressures, temperatures and dew points in combinations encountered in practice)

- ▶ 追溯到WMO标准
- ▶ 若分析仪发生较大漂移，建议做工厂校准



# 坎贝尔闭路通量测定系统 (CPEC200)



# 机箱干燥剂

- ▶ CPEC200系统主机箱、EC100电子控制机箱
- ▶ 检查湿度指示卡，有3种颜色级别。  
当中间圆点变成粉红色，更换干燥剂

## CAUTION

Campbell Scientific strongly suggests replacing desiccant instead of reactivating old desiccant. Improper reactivation can cause the desiccant packets to explode.



# EC155分析仪的进样管过滤器

- ▶ EC155内部有一个差压传感器，量程为  $\pm 7$  kPa，测量样品室相对于环境大气压的差压
- ▶ 2种规格：20  $\mu\text{m}$  和 40  $\mu\text{m}$ . 当过滤器堵塞的程序增加时，差压会加大。当差压达到 -7 kPa时，无效测量数据
- ▶ 坎贝尔新开发了涡旋过滤器，显著增加了分析仪的清洁周期



FIGURE 4-11. Intake filter of EC1



# 分析仪窗口清洁



FIGURE 9-4. The EC155 analyzer and sample cell with shell top open

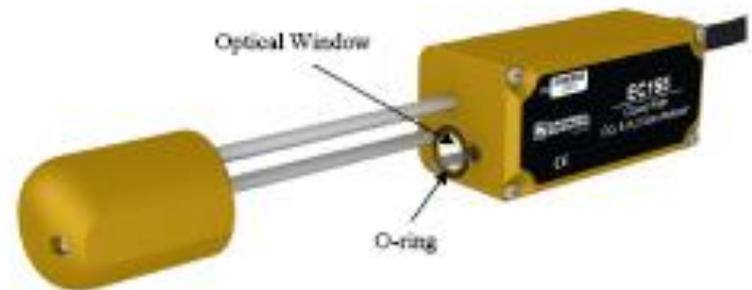


FIGURE 9-6. Analyzer removed from sample cell and shell



# 分析仪内部CO<sub>2</sub>/H<sub>2</sub>O吸收剂



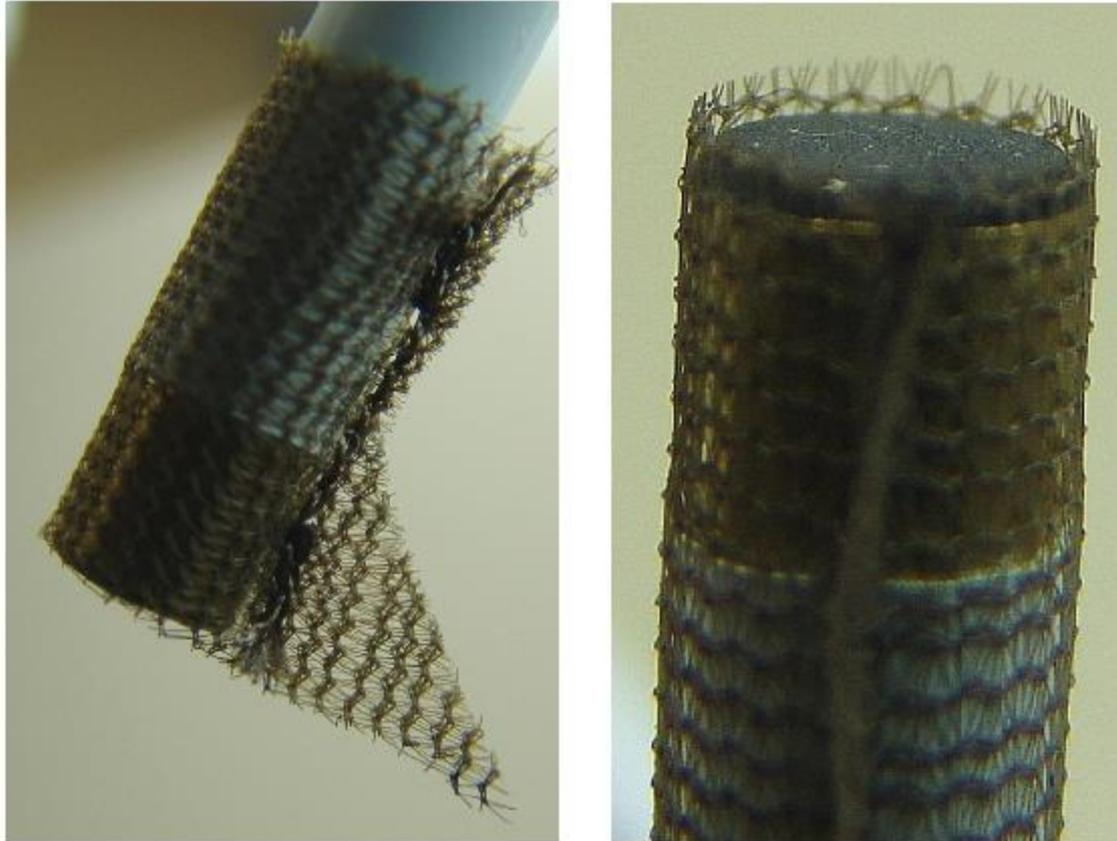
FIGURE 9-7. Replacing the source housing desiccant/scrubber bottle



FIGURE 9-8. Replacing the detector housing desiccant/scrubber bottle



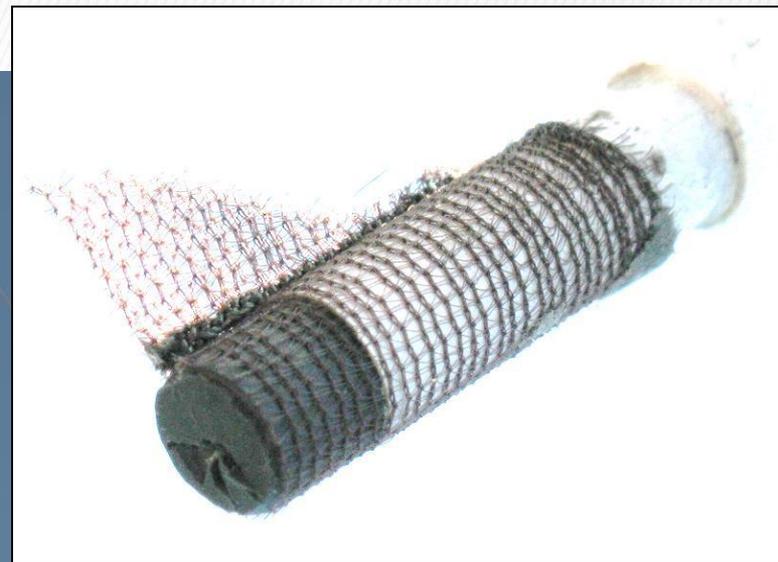
# 超声探头防雨网



*FIGURE 11-1. Proper location of the top (p/n 17388) and bottom (p/n 17389) wicks*



# 其它, Some problems in the field:

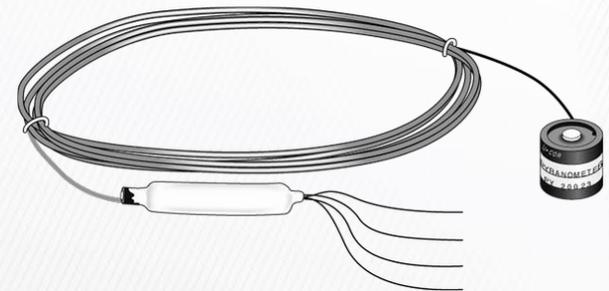
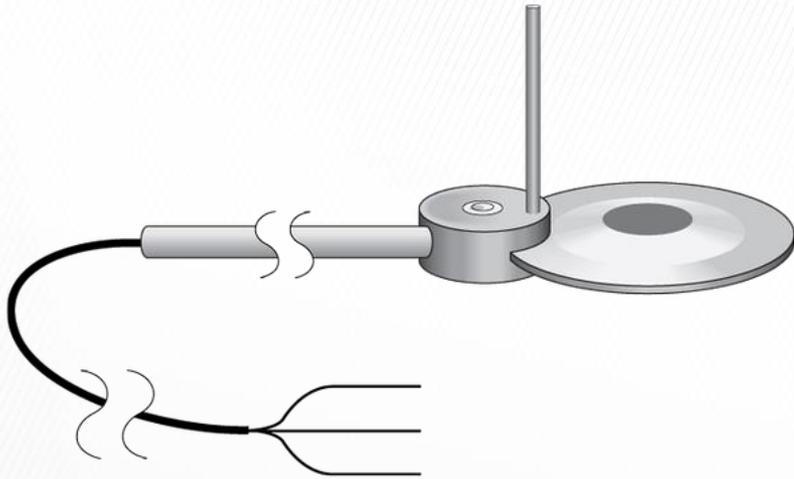


# 其它：常规传感器

## 净辐射传感器的配置

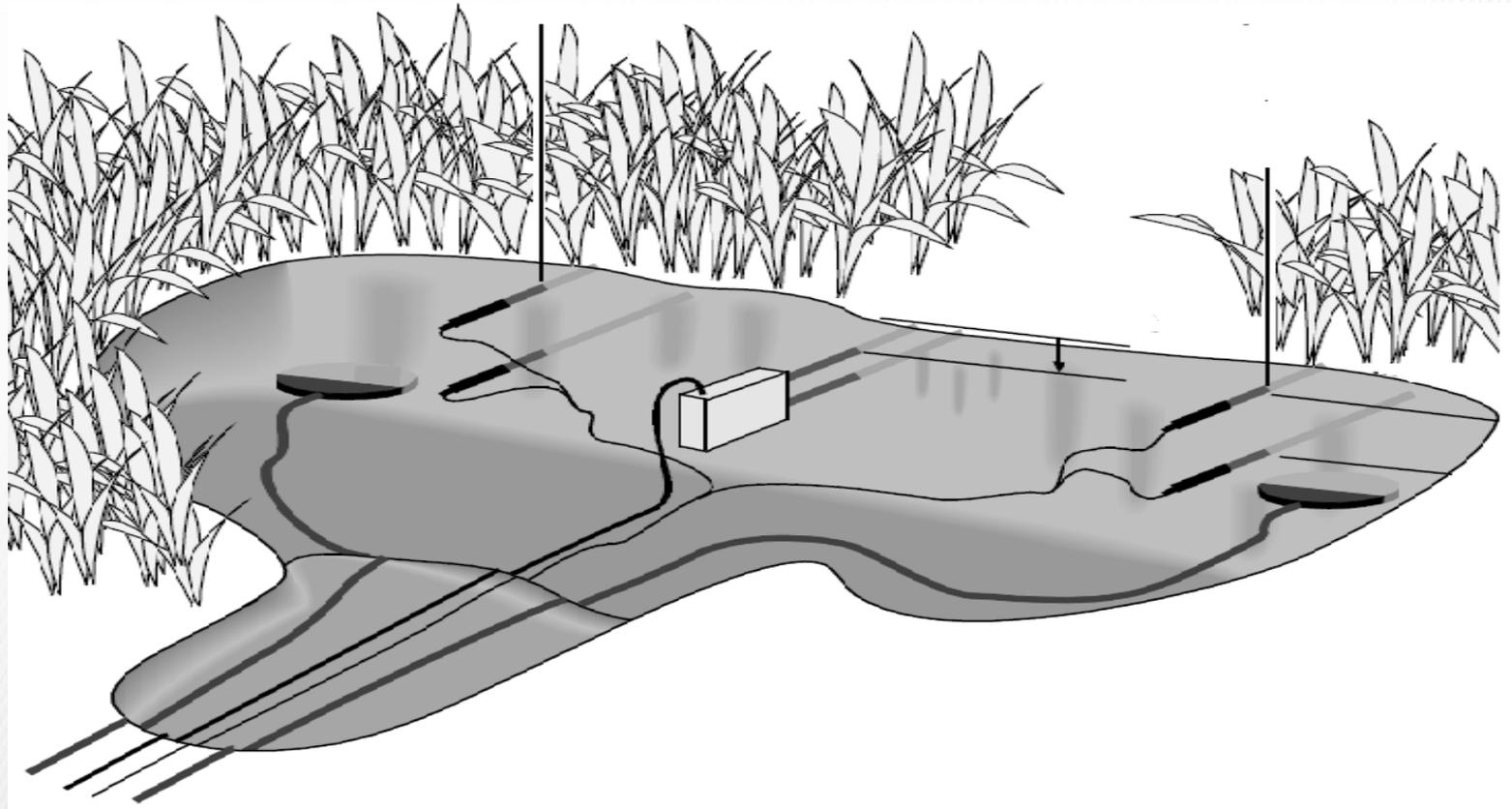


# 二分量净辐射和单分量辐射传感器配置



# 土壤热通量的测定

1. 土表层热通量
2. 土壤某一深度的热通量



# 土壤温度传感器的配置



# 土壤湿度传感器的配置

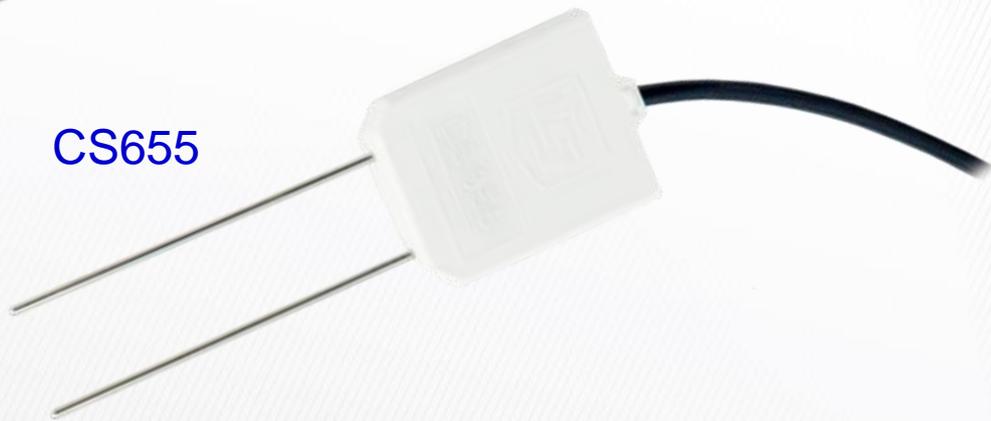
CS616



CS650



CS655



# 土层内热通量传感器的配置

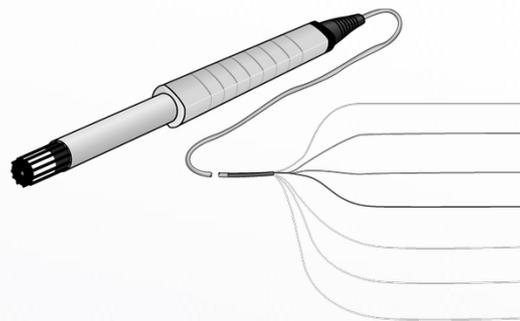


# 空气温湿度传感器的配置

HMP155A



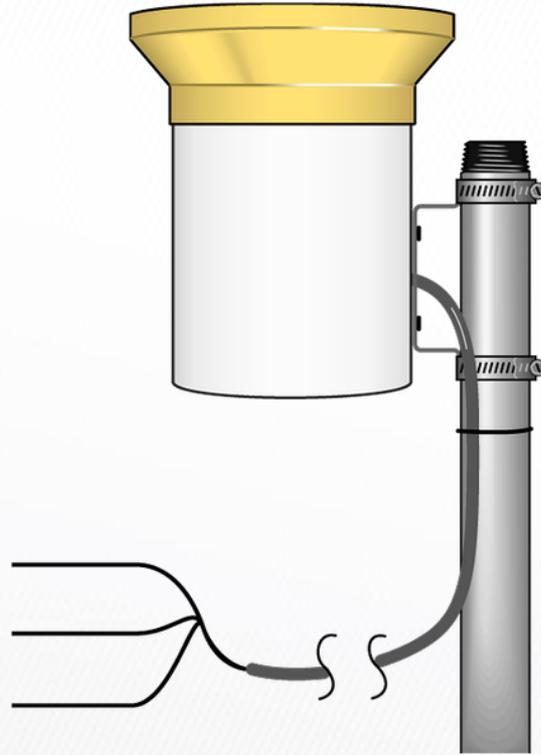
HMP45C



HC2S3



# 降雨传感器的配置





***Thank You!***

[www.campbellsci.com](http://www.campbellsci.com)  
[www.campbellsci.com.cn](http://www.campbellsci.com.cn)

## References

Bert Tanner et al., Campbell Scientific and Eddy-Covariance Flux Systems: A Brief History.

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Xinhua Zhou, [2013] Flux Technology Training Course, 边界层生态系统湍流质能通量仪器测定的数理依据

