通量数据质量控制的理论与方法

CAMPBELL SCIENTIFIC
WHEN MEASUREMENTS MATTER

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通量变量

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

净辐射通量　潜热通量　感热通量　地表热通量

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

二氧化碳通量

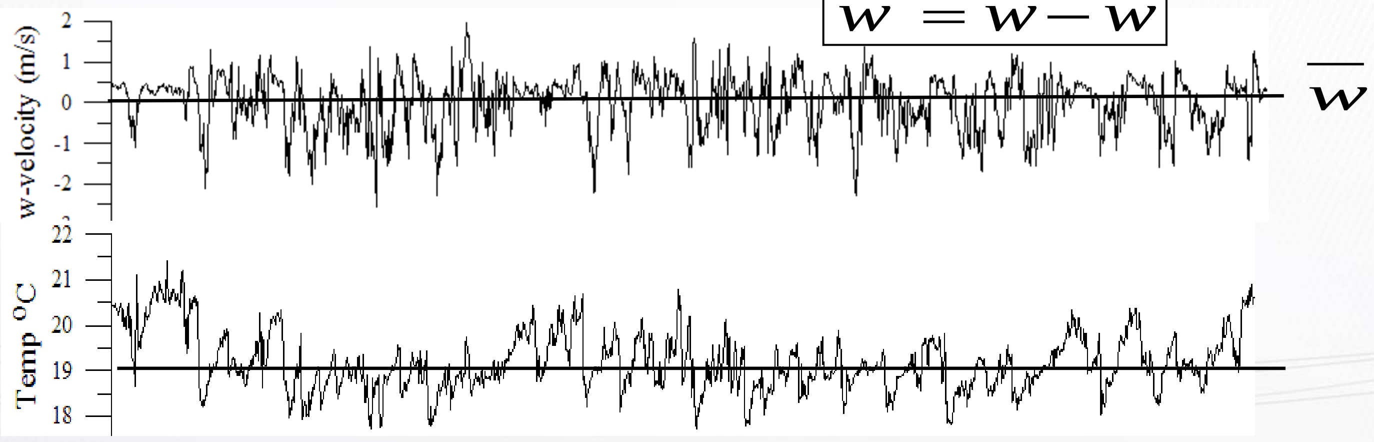
τ $[(kg\ m\ s^{-1})\ m^{-2}\ s^{-1}]$

动量通量

质量控制

1. 概率统计方法
2. 趋势法
3. 大气物理依据
4. 测定实地诊断
5. 仪器物理依据

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



数据插补

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坐标旋转修正

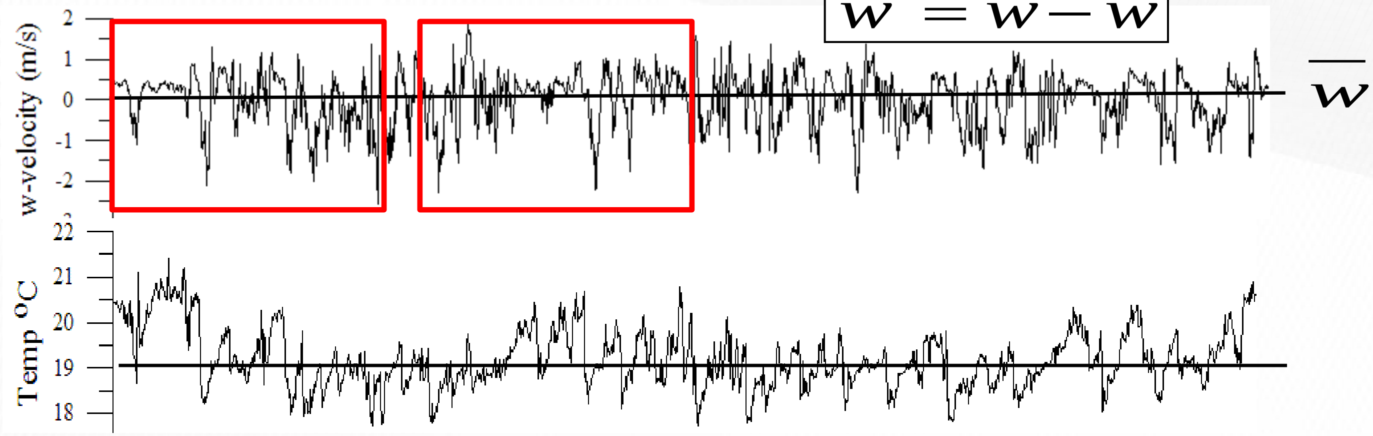
……………………………………

质量评估

1. **通量源区 (footprint，源迹或足源）**
2. 通量理论评估（稳定性要求和相似性理论）
3. 通量测定数据的质量分级

质量控制:概率统计方法去野点

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



Rebmann et al. (2012)

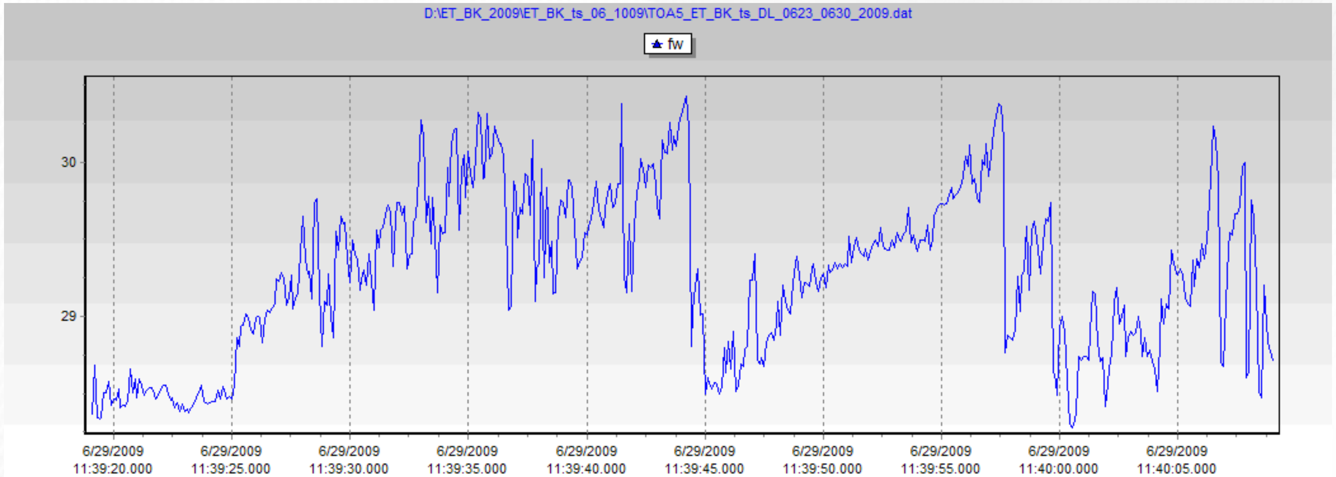
第1步 $$\left|w_{j1i} - \overline{w}_{j1}\right| > 3.5\sigma_j + 0.3\times(1-1)$$ w_{j1i} 是野点

$$\sigma_{jk} = \sqrt{\sum_{i=j}^{j+n_w}\frac{\left(w_{jki} - \overline{w}_{jk}\right)^2}{n_w}}$$

第2步 $$\left|w_{j2i} - \overline{w}_{j2}\right| > 3.5\sigma_{j2} + 0.3\times(2-1)$$ w_{j2i} 是野点

第3步 $$\left|w_{j3i} - \overline{w}_{j3}\right| > 3.5\sigma_{j2} + 0.3\times(3-1)$$ w_{j3i} 是野点

质量控制:趋势法去野点



Schmid et al. (2000)

1. 用指数过滤函数计算点对点自相关，计算自相关系数

2. 用自相关系数，从以前时间序列数中计算出实验数（w_{ti})

3. 用自相关系数和当前数（w_i) 计算出标准差（σ_i）

$$\left| w_i - \overline{w}_{ti} \right| > D\sigma_i$$

w_i 为野点

$$D = 3.3 \sim 4.9$$

质量控制：大气物理依据

1. 水平风速 < 30 m/s

2. 近地面层垂直风速 <5 m/s

3.（超声温度 – 当前月平均温度）< 20 ^{o}C

4. 能量闭合 $$\frac{LE + H}{R_n - G} > 0.8$$

质量控制：大气物理依据

$LE > H$　水面和湿地，晴天

$LE < H$　沙地与荒漠，晴天

质量控制：仪器物理依据

超声报警

幅度低 (sonic_amp_l_flg)
幅度高 (sonic_amp_h_flg)
非可靠信号 (sonic_sig_lck_flg)
温度差 (sonic_del_T_flg)
信号获得 (sonic_aq_sig_flg)
标定信息 (sonic_cal_err_flg)

红外气体分析仪报警

非可靠信号	irga_bad_data_flg	bad data warning
总错误	irga_gen_fault_flg	General fault warning
启动	irga_startup_flg	Starting up warning
电机速度	irga_motor_spd_flg	Motor speed out of bounds warning flag
电冷	irga_tec_tmpr_flg	Thermoelectric cooler temp out of bounds warning
光源能量	irga_src_pwr_flg	Source power out of bounds warning
光源温度	irga_src_tmpr_flg	Source temperature out of bounds warning
光源电流	irga_src_curr_flg	Source current out of bounds warning
未供电	irga_off_flg	Analyzer is powered down
脉冲协调	irga_sync_flg	Non-synchronized with home pulse warning
CO2 测定光强	irga_CO2_I_flg	CO2 I out of bounds warning
CO2 参考光强	irga_CO2_Io_flg	CO2 Io out of bounds warning
H2O 测定光强	irga_H2O_I_flg	H2O I out of bounds warning
H2O 参考光强	irga_H2O_Io_flg	H2O Io out of bounds warning
CO2参考光滑动方差	irga_CO2_Io_var_flg	CO2 Io moving variation out of bounds warning
H2O参考光滑动方差	irga_H2O_Io_var_flg	H2O Io moving variation out of bounds warning
CO2 信号强度	irga_CO2_sig_strgth_flg	CO2 signal strength warning
H2O信号强度	irga_H2O_sig_strgth_flg	H2O signal strength warning
标定信息	irga_cal_err_flg	Calibration data signature error
加热器	irga_htr_ctrl_off_flg	Heater control disabled by EC100

辅助传感器报警

测定环境气温 irga_amb_tmpr_flg Invalid ambient temperature warning
测定环境气压 irga_amb_press_f Invalid ambient pressure warning

平均值计算中的野点去除

```
DataTable (comp_mean, TRUE, 1)
   DataInterval (0, OUTPUT_INTERVAL, Min, 1)

  Average (1, amb_tmpr,  IEEE4, irga_amb_tmpr_f)

  Average (1, RH,      IEEE4, (irga_disable_f OR sonic_disable_f OR (H2O <0) OR irga_amb_press_f) )

  Average (1, e_sat,   IEEE4, (irga_disable_f OR sonic_disable_f OR (H2O <0) OR irga_amb_press_f) )

  Average (1, e,        IEEE4, (irga_disable_f OR sonic_disable_f OR (H2O <0) OR irga_amb_press_f) )

  Average (1, amb_press, IEEE4, irga_amb_press_f)

  Average (1, rho_d,   IEEE4, (irga_disable_f OR sonic_disable_f OR (H2O <0)) )

  Average (1, rho_a,   IEEE4, (irga_disable_f OR sonic_disable_f OR (H2O <0)) )

  Average (1, Tc,       IEEE4, (irga_disable_f OR sonic_disable_f OR (H2O <0) OR irga_amb_press_f) )

EndTable
```

风速与超声温度变量之间协方差计算中的野点去除

数组元素排列: Ts, Ux, Uy, Uz

```
DataTable (comp_cov_3d, TRUE, 1)
  DataInterval (0, OUTPUT_INTERVAL, Min, 1)

 'Compute Ux mean and covariance of Ux with Ux, Uy, and Uz from CSAT data.
  Average     (1,  Ux, IEEE4, sonic_disable_f )
  Covariance (3,  Ux, IEEE4, sonic_disable_f, 3 )      UxUx, UxUy, and UxUz

 'Compute Uy mean and covariance of Uy with, Uy, Uz from CSAT data.
  Average     (1, Uy, IEEE4, sonic_disable_f)
  Covariance (2, Uy, IEEE4, sonic_disable_f, 2)        UyUy and UyUz

  'Compute Uz mean and covariance of Uz with Uz from CSAT data.
  Average     (1, Uz, IEEE4, sonic_disable_f)
  Covariance (1, Uz, IEEE4, sonic_disable_f, 1)        UzUz

 'Compute Ts mean and covariance of Ts with Ts, Ux, Uy, and Uz from CSAT data.
  Average     (1,Ts, IEEE4, sonic_disable_f)
  Covariance (4,Ts, IEEE4, sonic_disable_f, 4)         TsTs, TsUx, TsUy, TsUz

  WindVector (1,Uy, Ux, IEEE4, sonic_disable_f, 0, 1, 2)

EndTable
```

CO2与风速之间协方差计算中的野点去除

数组元素排列: CO2, Ux, Uy, Uz

```
DataTable (comp_cov_CO2, TRUE, 1)
    DataInterval (0, OUTPUT_INTERVAL, Min, 1)

  Average      (1, CO2, IEEE4, irga_bad_data_flg)
  Covariance (4, CO2, IEEE4, (sonic_disable_f OR irga_bad_data_flg), 4)   CO2CO2, CO2Ux, CO2Uy, CO2Uz

EndTable
```

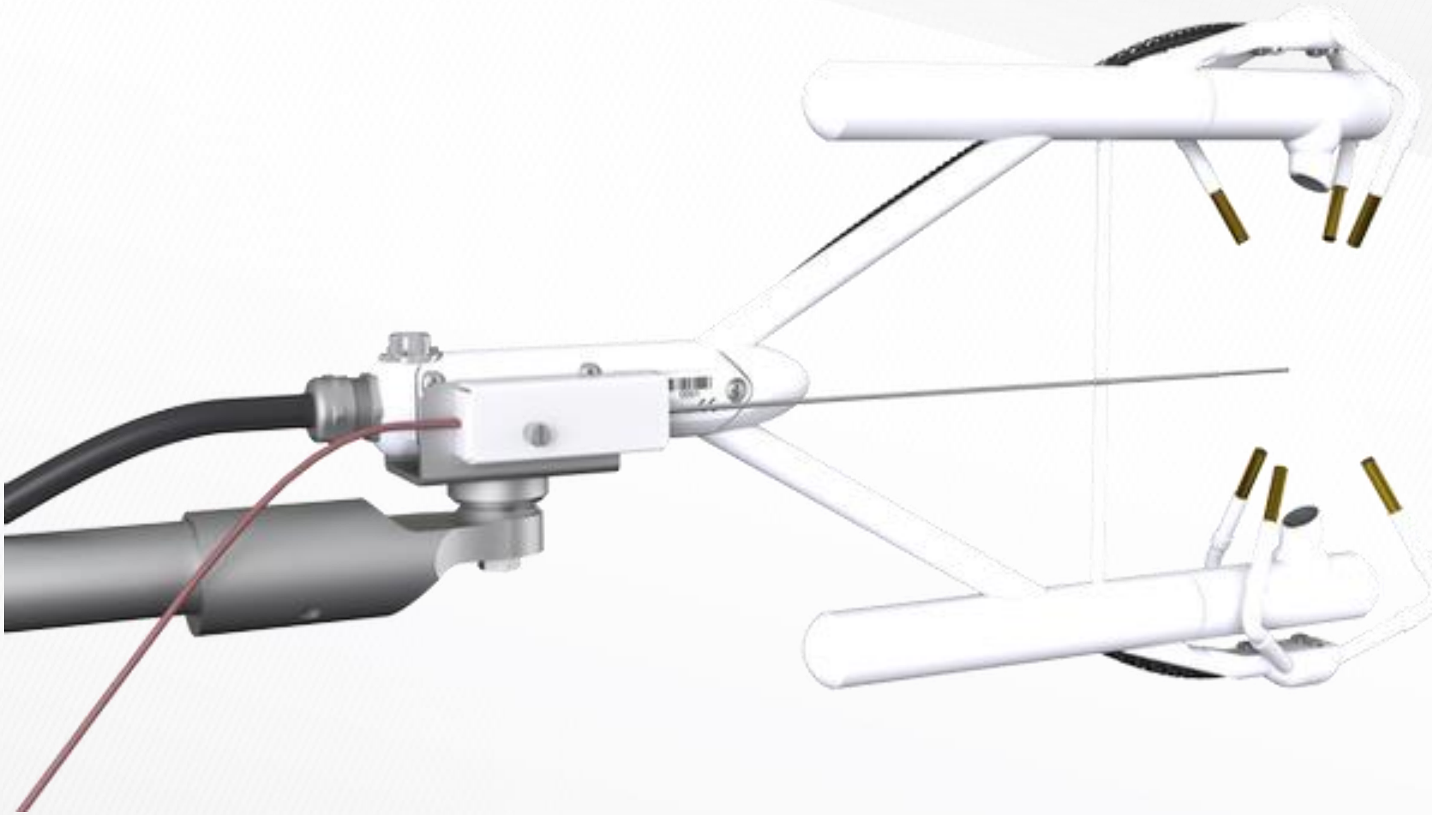
H2O与风速之间协方差计算中的野点去除

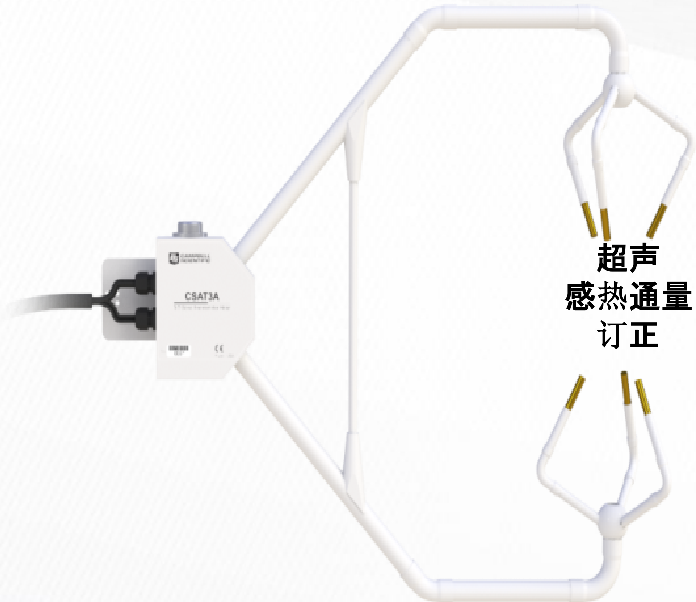
数组元素排列: H2O, Ux, Uy, Uz

```
DataTable (comp_cov_H2O, TRUE, 1)
   DataInterval (0, OUTPUT_INTERVAL, Min, 1)

    Average    (1, H2O, IEEE4, (irga_bad_data_flg OR (H2O<0)) )
   Covariance (4, H2O, IEEE4, (sonic_disable_f OR irga_bad_data_flg OR (H2O<0)) ) ,4)   H2OH2O, H2OUx, H2OUy, H2OUz

EndTable
```





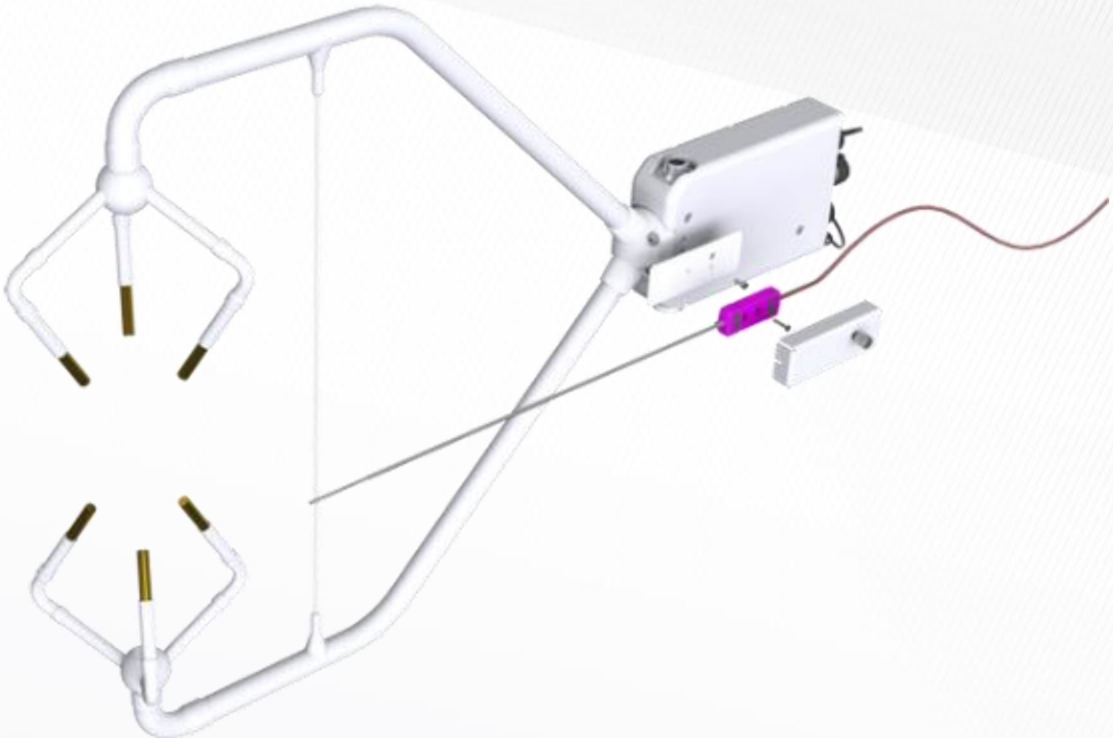
Schotanus et al. (1983)
Dijk (2002)

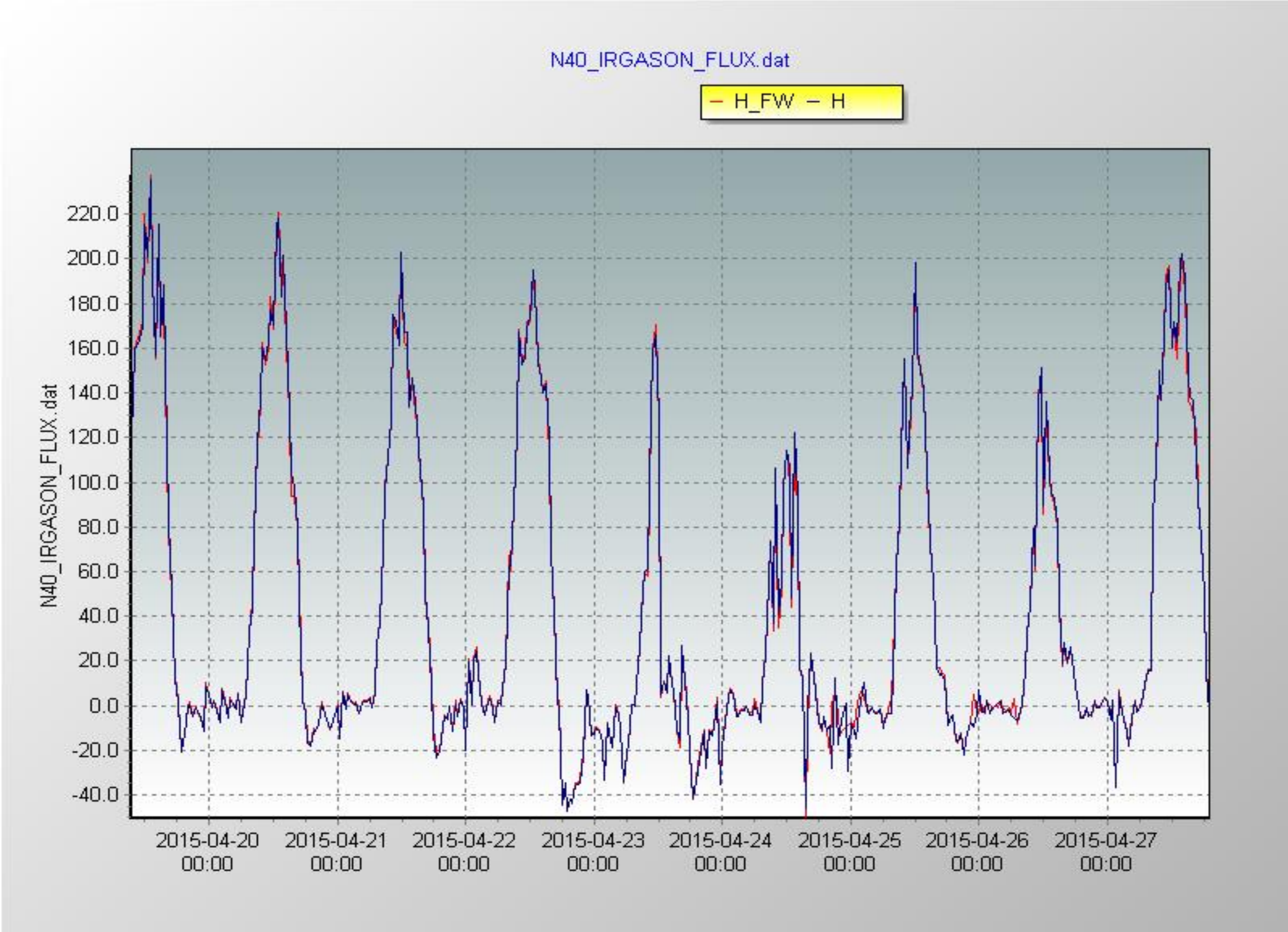
$$T = T_s\left(1 - 0.51q\right)$$

$$T' = T_s'(1 - 0.51\bar{q}) - 0.51q'\bar{T}_s$$

$$\overline{w'T'} = \overline{w'T_s'}(1 - 0.51\bar{q}) - 0.51\overline{w'q'}\bar{T}_s$$

$$\overline{w'T'}$$

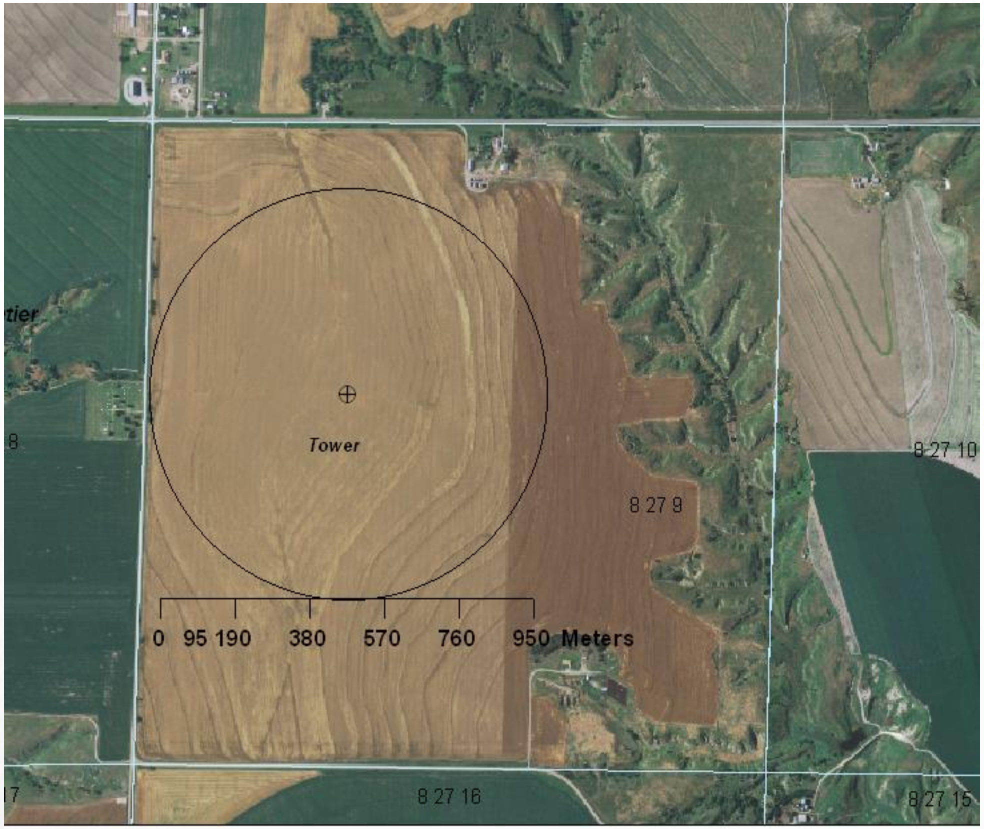


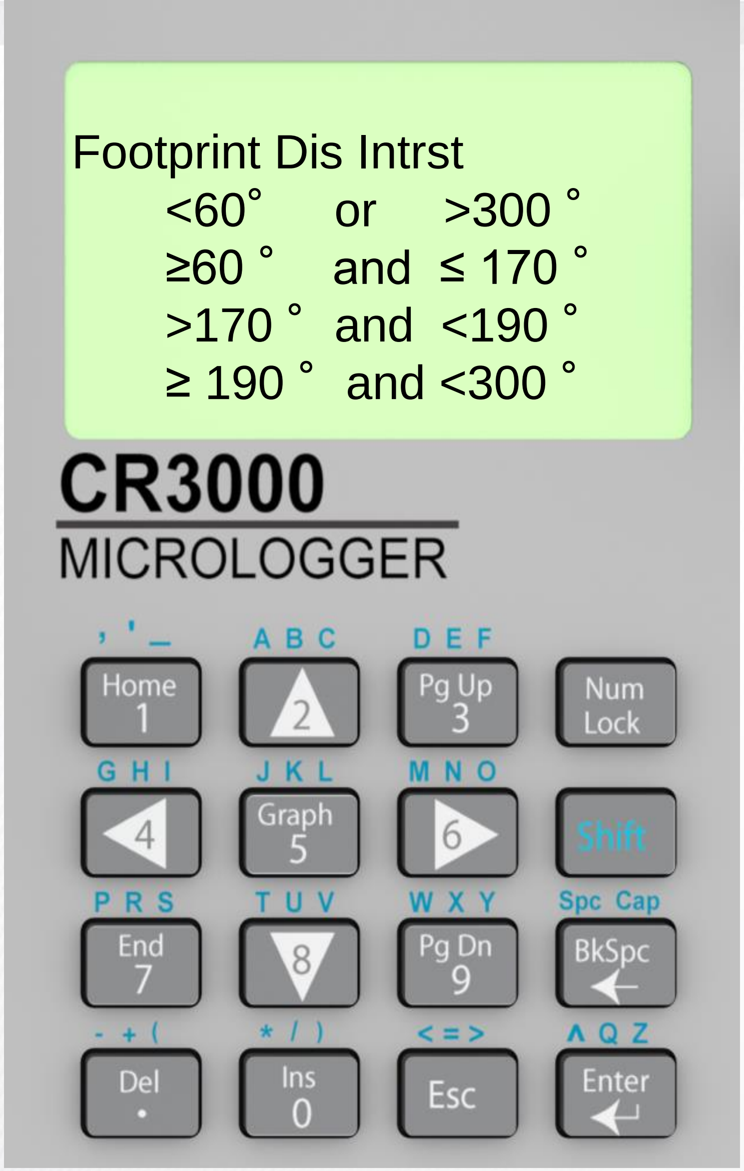


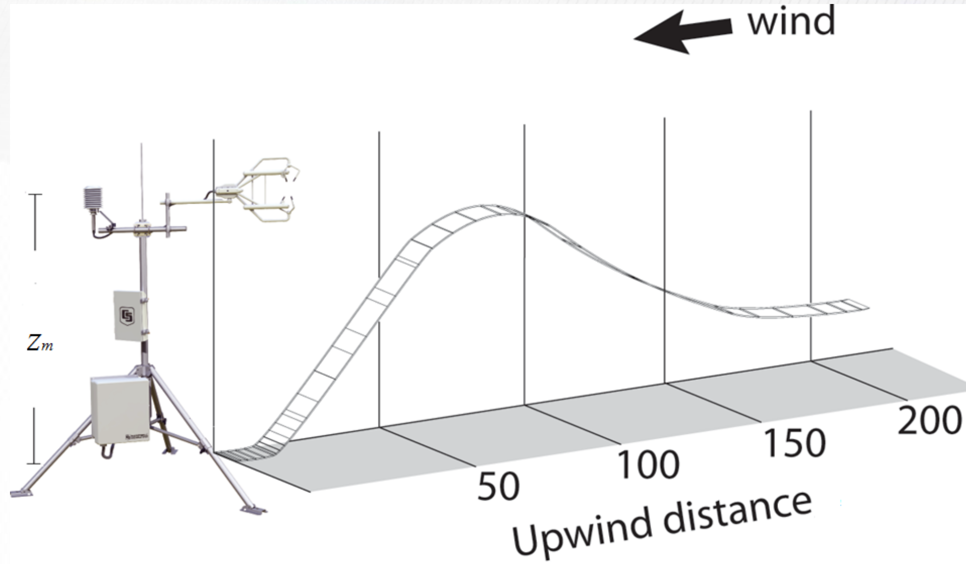
N40_IRGASON_FLUX.dat
H_FW
H
N40_IRGASON_FLUX.dat
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
2015-04-20 00:00
2015-04-21 00:00
2015-04-22 00:00
2015-04-23 00:00
2015-04-24 00:00
2015-04-25 00:00
2015-04-26 00:00
2015-04-27 00:00

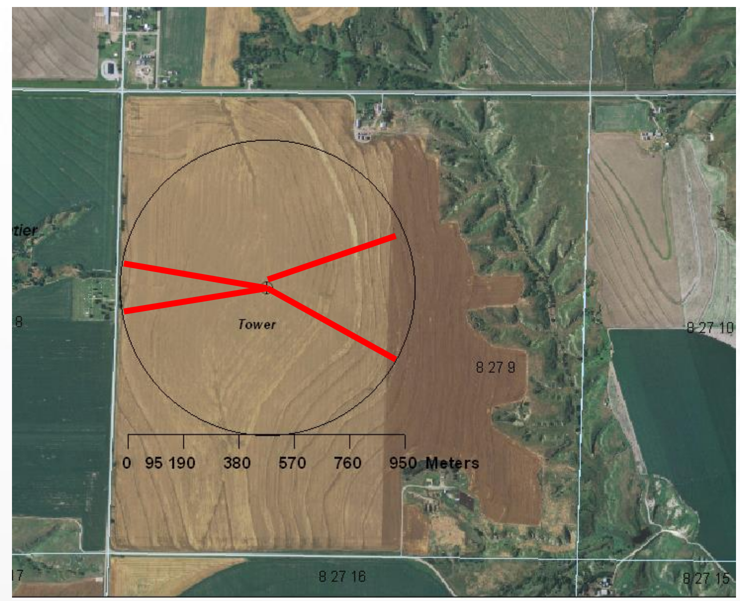
质量评估: 通量源区 (footprint，源迹或足源）

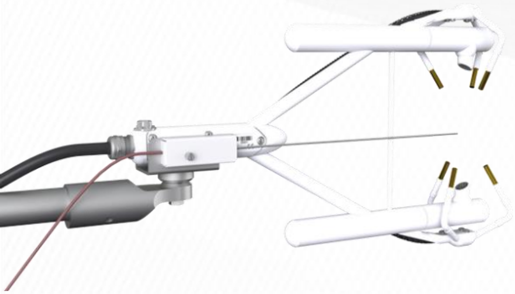
通量足源在测定目标区的累计(积分)量，即所测通量来自于测定目标区的百分数。




Footprint Dis Intrst
<60° or >300 °
≥60 ° and ≤ 170 °
>170 ° and <190 °
≥ 190 ° and <300 °
CR3000
MICROLOGGER


wind
z_m
50
100
150
200
Upwind distance

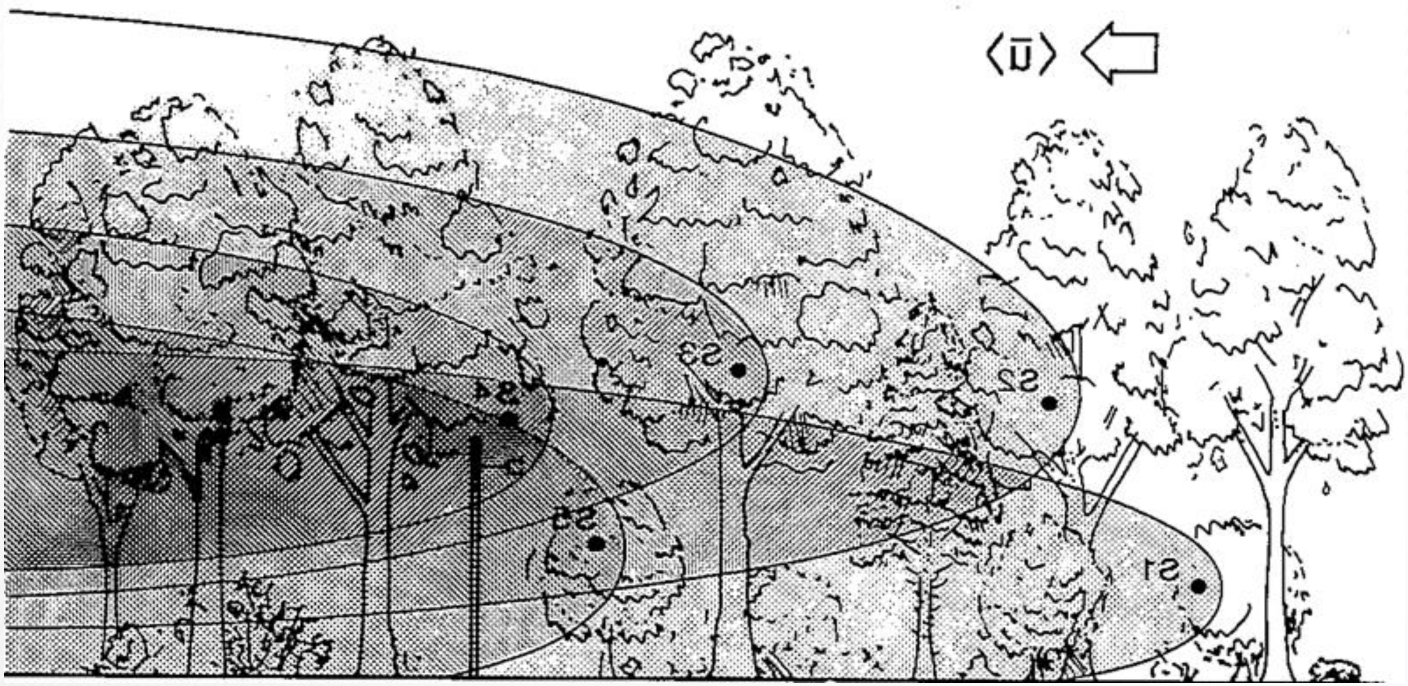

Tower
0 95 190 380 570 760 950 Meters
8 27 9
8 27 10
8 27 16
8 27 15




⟨ū⟩
S3
S2
S1

$$F(0,0,z_m) = \int_{-\infty}^{\infty}\int_{0}^{\infty} F\left(x,y,0\right) f\left(x,y,z_m\right) dxdy$$

$$f(x,y,z) = -K(z)\frac{dc(x,y,z)}{dz}$$



Kljun et al (2004) 通量源区模型

$a.\ -200 \le (z_m - d)/L \le 1$

$b.\ u_* \ge 0.2$

$c.\ z_m - d \ge 1$ m

$$F_*(X_*) = k_1 \left(\frac{X_* + k_4}{k_3} \right)^{k_2} \exp\left[k_2 \left(1 - \frac{X_* + k_4}{k_3} \right) \right]$$

$$X_* = \left(\frac{\sigma_w}{u_*} \right)^{a_1} \frac{x}{z}$$

Buckingham Π method
see Stull （1988)

$$F_* = \left(\frac{\sigma_w}{u_*} \right)^{a_2} \left(1 - \frac{z}{h} \right)^{-1} z f_y(x, z)$$

$$p_F(R) = 100\int_{-R_{k4}}^{R} f_y(x,z)\,dx$$

$$R_{k4} = k_4 z\left(\frac{u_*}{\sigma_w}\right)^{a_1}$$

Kormann and Meixner (2001) 通量足源模型

$$f_y(x,z) = \frac{1}{\Gamma(\mu)} \xi^{\mu} \left(\frac{z^{m+1}}{x^{\mu+1}} \right) \exp\left(-\xi \frac{z^r}{x} \right),$$

$$r = 2 + m - n$$

$$\mu = \frac{m+1}{r}.$$

$$\xi = \frac{U}{kr^2}$$

$$u(z) = Uz^m$$

$$K(z) = kz^n$$

$$p_F(R) = 100\frac{\xi^{\mu} z^{m+1}}{\Gamma(\mu)} \lim_{\Delta x \to 0} \int_{0+\Delta x}^{R} \frac{1}{x^{\mu+1}} \exp\left(-\xi \frac{z^{r}}{x}\right) dx$$

数据质量分级

$$p_F(R) > 95\%?$$

数据质量分级

1. 时序非稳定性
2. 综合湍流特征吻合性
3. 表达超声风速仪坐标系的风向

时序非稳定性的度量

$$RN_{\mathrm{cov}} = 100 \times \left| \frac{\frac{1}{6}\sum_{i=1}^{6}\left(\overline{s'w'}\right)_{ri} - \left(\overline{s'w'}\right)_{r}}{\left(\overline{s'w'}\right)_{r}} \right|$$

综合湍流特征

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

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

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

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

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

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

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

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

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）

综合湍流特征吻合性的度量

a. 动量变量

$$ITC_{\alpha} = 100 \times \frac{\left| ITC_{\alpha\_model} - \left(\frac{\sqrt{\left(\overline{\alpha'^2}\right)_r}}{u_*} \right)_{measured} \right|}{ITC_{\alpha\_model}}$$

$$ITC_{\alpha\_model} = \begin{cases} c_{\alpha 1} \ln \frac{z_+ f}{u_*} + c_{\alpha 2} & -0.200 < z / L < 0.400 \\ c_{\alpha 1} \left(\frac{z}{|L|} \right)^{c_{\alpha 2}} & z / L \le -0.200 \end{cases}$$

a. 温度变量

$$ITC_T = 100 \times \frac{\left| ITC_{T\_model} - \left(\frac{\sqrt{\left(\overline{T'^2}\right)_r}}{\left|T^*\right|} \right)_{measured} \right|}{ITC_{T\_model}}$$

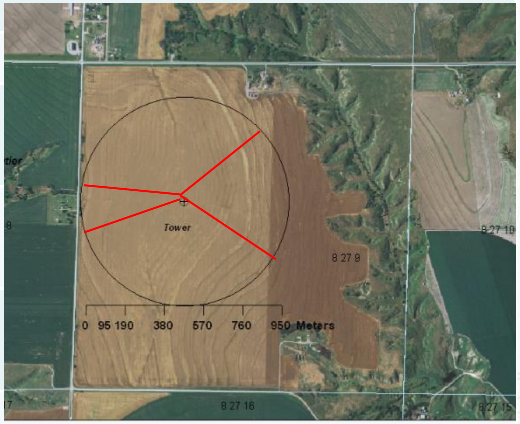
$$T^* = -\frac{\overline{T'w'}}{u_*}$$

$$ITC_{T\_model} = c_{T1} \left(\frac{z}{|L|} \right)^{c_{T2}}$$

数据质量分级

相对时序非稳定变性，相对综合湍流特征的非吻合性和超声系统风向的数据质量分级[由**Foken et al. (2012) 表4.4** 简化而来]

时序非稳定变性 Foken et al. (2012) 模型 2.3		综合湍流特征 非吻合性 Foken et al. (2012) 模型 2.3		风向 （定义在超声坐标系）	
级	范围 (%)	**级**	范围 (%)	级	范围
1 (高)	[0 , 15)	**1 (高)**	[0 , 15)	1 **(高)**	$[0-150^o],[210-360^o]$
2	[15 , 30)	**2**	[15 , 30)	2	$(150-170^o],[190-210)$
3	[30 , 50)	**3**	[30 , 50)	3 **(低)**	$(170-190)^o$
4	[50 , 75)	**4**	[50 , 75)		
5	[75 , 100)	**5**	[75 , 100)		
6	[100 , 250)	**6**	[100 , 250)		
7	[250 , 500)	**7**	[250 , 500)		
8	[500 , 1000)	**8**	[500 , 1000)		
9 (低)	>1,000%*	**9 (低)**	>1,000%		



综合相对时序非稳定变性，相对综合湍流特征的非吻合性和超声系统风向的数据质量总分级 [由Foken et al. (2012) 表4.4 简化而来]

总质量 等级	RN_{cov}	ITC_{sw}	wnd_dir_sonic
	时序非稳定变性	综合湍流特征非吻合性	风向
1 (高)	1	1 - 2	1
2	2	1 - 2	1
3	1 – 2	3 - 4	1
4	3 – 4	1 - 2	1
5	1 – 4	3 - 5	1
6	5	5	2
7	6	6	2
8	7 – 8	7 – 8	2
9 (低)	9	9	3

N40_IRGASON_FLUX_Apr27_2015.dat (No Graph Associated) 404 Records

TIMESTAMP	RECORD	Fc	Fc_qc_grade	LE	LE_qc_grade	H	H_qc_grade	H_FW	Rn	G_surface	energy_closure	Bowen_ratio	tau	tau_qc_grade	u_star	T_star
TS	RN	umol/(m^2 s)	Grade	W/m^2	Grade	W/m^2	Grade	W/m^2	W/m^2	W/m^2	Fraction	fraction	(kg m/s)/(m^2 s)	Grade	m/s	C
		Smp	Smp	Smp	Smp	Smp	Smp	Smp	Smp	Smp	Smp	Smp	Smp	Smp	Smp	Smp
2015-04-19 09:30:00	50	-4.336909	1	68.82011	1	118.7671	1	119.2204	226.3456	7.604222	0.8575754	1.725761	0.01609684	6	0.1225053	-0.8961943
2015-04-19 10:00:00	51	-5.536584	3	78.51965	3	160.1874	3	158.3502	314.6199	19.28848	0.8082684	2.040093	0.05791647	6	0.232931	-0.6388856
2015-04-19 10:30:00	52	-5.472747	1	90.75595	1	160.2711	1	162.8421	311.1035	32.66045	0.9015382	1.765957	0.03897455	6	0.1914634	-0.7806449
2015-04-19 11:00:00	53	-5.0432	1	98.02295	1	163.8571	1	166.4796	396.9635	47.64317	0.7496845	1.671619	0.02265873	6	0.1462003	-1.048192
2015-04-19 11:30:00	54	-5.703329	1	132.9034	1	169.3673	1	171.6888	425.0722	378.7485	6.52518	1.274363	0.03790605	6	0.1893958	-0.8390337
2015-04-19 12:00:00	55	-9.031443	3	176.2251	3	215.8452	3	220.0876	450.0986	378.0994	5.445476	1.224827	0.06925851	6	0.2564089	-0.7924562
2015-04-19 12:30:00	56	-6.202727	7	136.2556	7	200.7587	7	198.2052	465.4398	379.2542	3.910334	1.473398	0.0004298275	9	0.02021981	-9.372386
2015-04-19 13:00:00	57	-6.853106	1	145.1063	1	235.4597	1	237.3908	466.2551	374.9684	4.168909	1.62267	0.01682104	6	0.1266667	-1.760324
2015-04-19 13:30:00	58	-5.993527	1	147.3624	1	191.6504	1	192.7752	446.3453	368.6337	4.362449	1.300538	0.04012592	6	0.195786	-0.9281994
2015-04-19 14:00:00	59	-4.853765	1	114.6872	1	156.8031	1	155.1093	363.3871	368.4629	-53.48745	1.367224	0.03937431	6	0.1940495	-0.7669713
2015-04-19 14:30:00	60	-6.338003	1	158.2614	1	215.3154	1	209.1388	435.3169	326.7417	3.440718	1.360505	0.02745091	6	0.1621756	-1.262212
2015-04-19 15:00:00	61	-7.13307	1	151.4887	1	165.0044	1	166.5199	372.6223	344.3275	11.18554	1.08922	0.03191323	7	0.1748765	-0.8972117
2015-04-19 15:30:00	62	-4.193646	1	114.0009	1	188.4963	1	181.5152	351.7328	356.5143	-63.26415	1.653464	0.02049608	8	0.1402553	-1.280043
2015-04-19 16:00:00	63	-5.3102	1	122.547	1	116.0633	1	111.9404	207.5644	358.5224	-1.580641	0.9470924	0.05294368	6	0.225471	-0.4905445
2015-04-19 16:30:00	64	-2.711878	1	70.50093	1	83.10005	1	79.33539	158.859	335.2597	-0.8707503	1.178709	0.01849183	6	0.1332515	-0.5944945
2015-04-19 17:00:00	65	-2.657402	3	60.57841	3	51.44159	3	48.43103	96.06789	338.86	-0.4613823	0.8491737	0.03992969	6	0.1957622	-0.250426
2015-04-19 17:30:00	66	-2.107842	3	64.02396	3	10.90937	3	12.48421	47.47218	299.6223	-0.2971775	0.1703951	0.02449206	6	0.1533091	-0.06779331
2015-04-19 18:00:00	67	-0.8661729	7	42.10398	7	8.666399	7	9.344481	12.64007	25.92344	-3.8221	0.2058332	0.007136384	8	0.08274454	-0.09975285
2015-04-19 18:30:00	68	0.4268551	7	22.09159	7	-9.447067	7	-8.061034	-27.46133	22.57248	-0.2527195	-0.4276319	0.03045992	6	0.1706135	0.05249747
2015-04-19 19:00:00	69	1.744999	7	20.02226	7	-21.0829	7	-20.98027	-48.3099	6.973514	0.01918565	-1.052973	0.01927935	6	0.1353104	0.1467485
2015-04-19 19:30:00	70	3.363284	9	4.942481	9	-12.68351	9	-12.67237	-54.13458	13.30765	0.1147802	-2.566223	0.006026611	9	0.07544681	0.1575099
2015-04-19 20:00:00	71	-0.3139164	9	-1.491816	9	-0.426035	9	-0.611514	-51.19263	-6.566626	0.0429761	0.2855817	0.0009421122	9	0.02974533	0.01333355


Questions
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谢谢