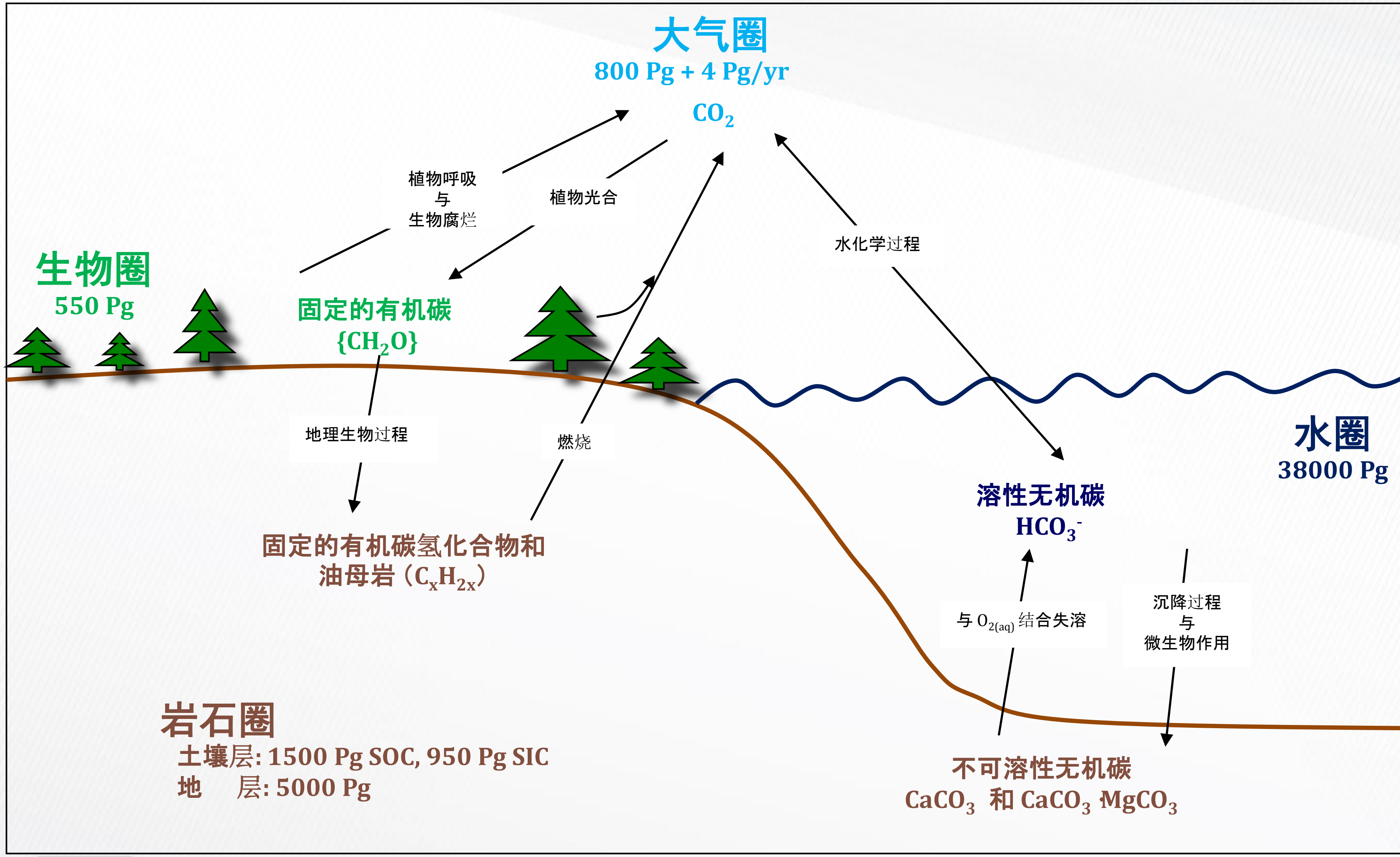
通量数据的处理与在线计算方法

Ryan Campbell, Xaojie Zhen, Ed Swiatek, M. Savage, Shanggang Li, Xinhua Zhou

碳循环简图



大气圈
800 Pg + 4 Pg/yr
CO2
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
{CH2O}
地理生物过程
燃烧
水圈
38000 Pg
溶性无机碳
HCO3-
固定的有机碳氢化合物和
油母岩（CxH2x）
与 O2(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
CaCO3 和 CaCO3 MgCO3

兴趣通量

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

雷诺(Reynolds)变量分解与平均规则

分解规则

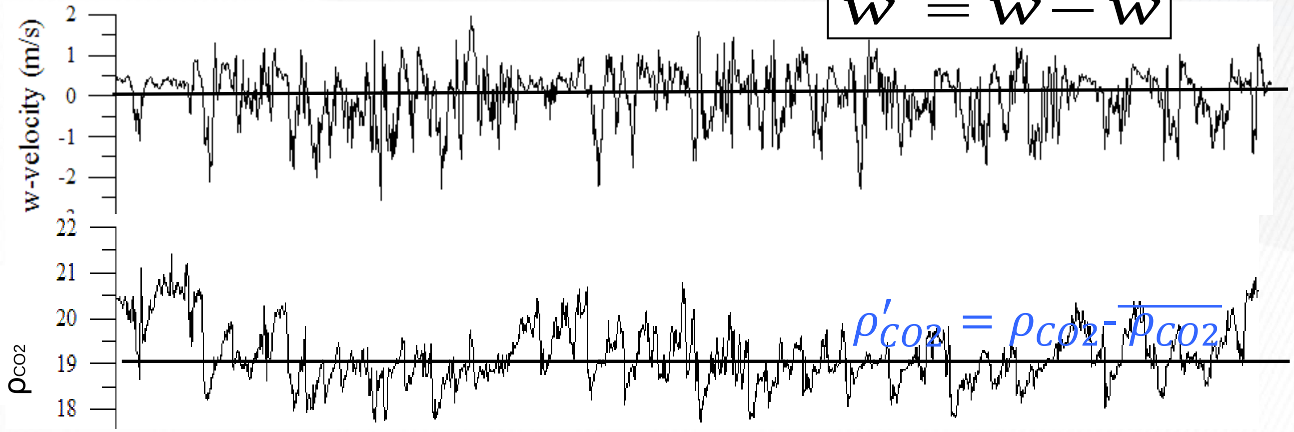
$w = \overline{w} + w'$

平均规则

$\overline{w'}=0$

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

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



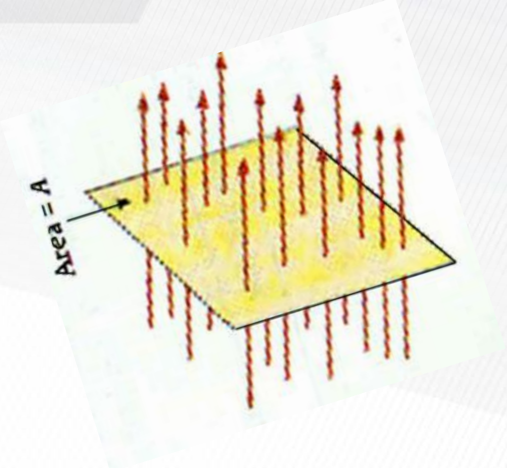
$\overline{w}$

$\rho'_{co2} = \rho_{co2} - \overline{\rho_{co2}}$

$\overline{\rho_{CO2}}$

$$F_C = \frac{1}{n}\sum_{i=1}^{n}(w - \overline{w})(\rho_{co2} - \overline{\rho_{co2}}) = \overline{w'\rho'}_{co2}$$

Flux



CO_2

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

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

H_2O

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

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

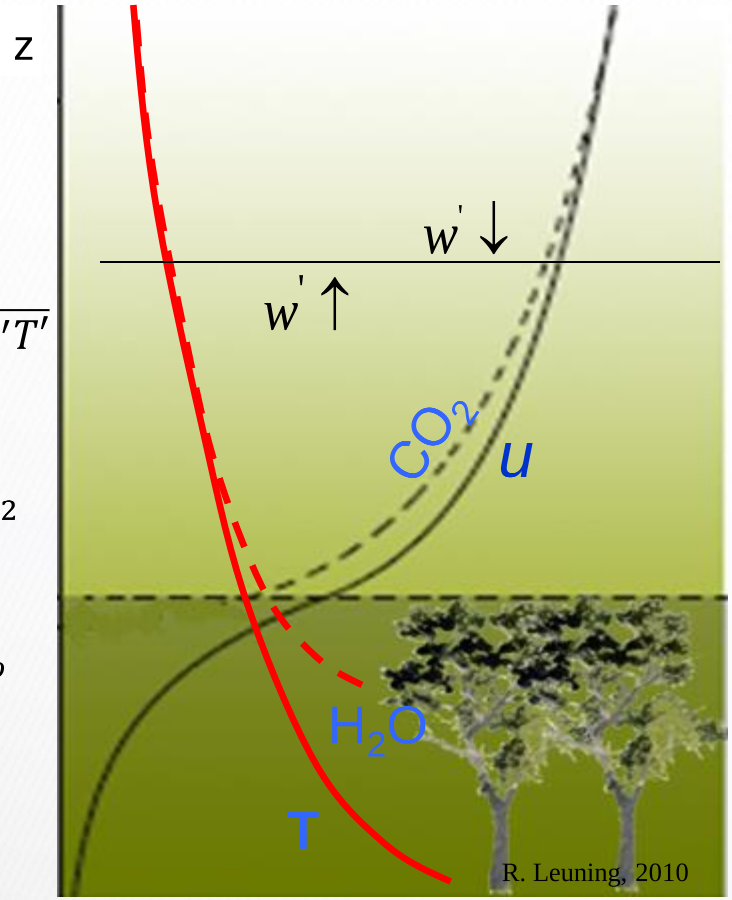
Examples

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

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

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

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

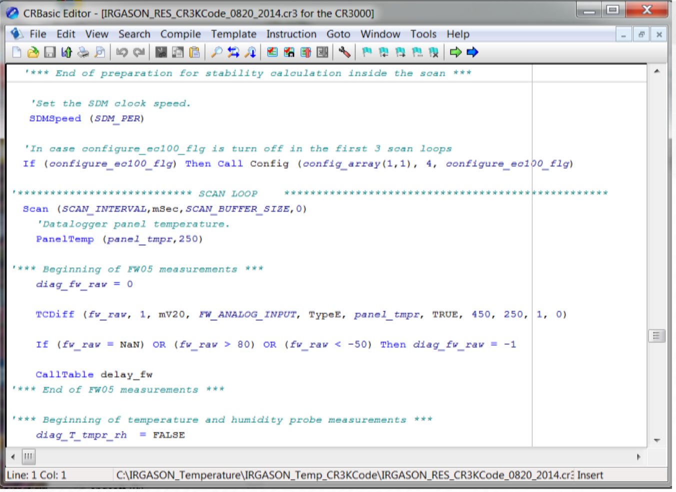


垂直风 m/s	U' m/s	T' °C	ρ'_{CO2} mg/m³	ρ'_{h2O} g/m³
上 w'= 0.1	-1	1	-1	1
下 w'= - 0.1	1	-1	1	-1
通量	↓ -0.2 $\frac{\text{kg m/s}}{\text{m}^2\ \text{s}}$	↑ 200 $\frac{\text{w}}{\text{m}^2}$	↓ -0.2 $\frac{\text{mg}}{\text{m}^2\ \text{s}}$	↑ 0.2 $\frac{\text{g}}{\text{m}^2\ \text{s}}$
	动量	热	CO_2	H_2O

$$\rho_a \approx 1 \frac{\text{kg}}{\text{m}^3}, \qquad C_p \approx 1000 \frac{\text{J}}{{}^{\text{o}}\text{C kg}}$$

e.g Δt= 0.5 s

坎贝尔开路通量测定系统（OPEC200）



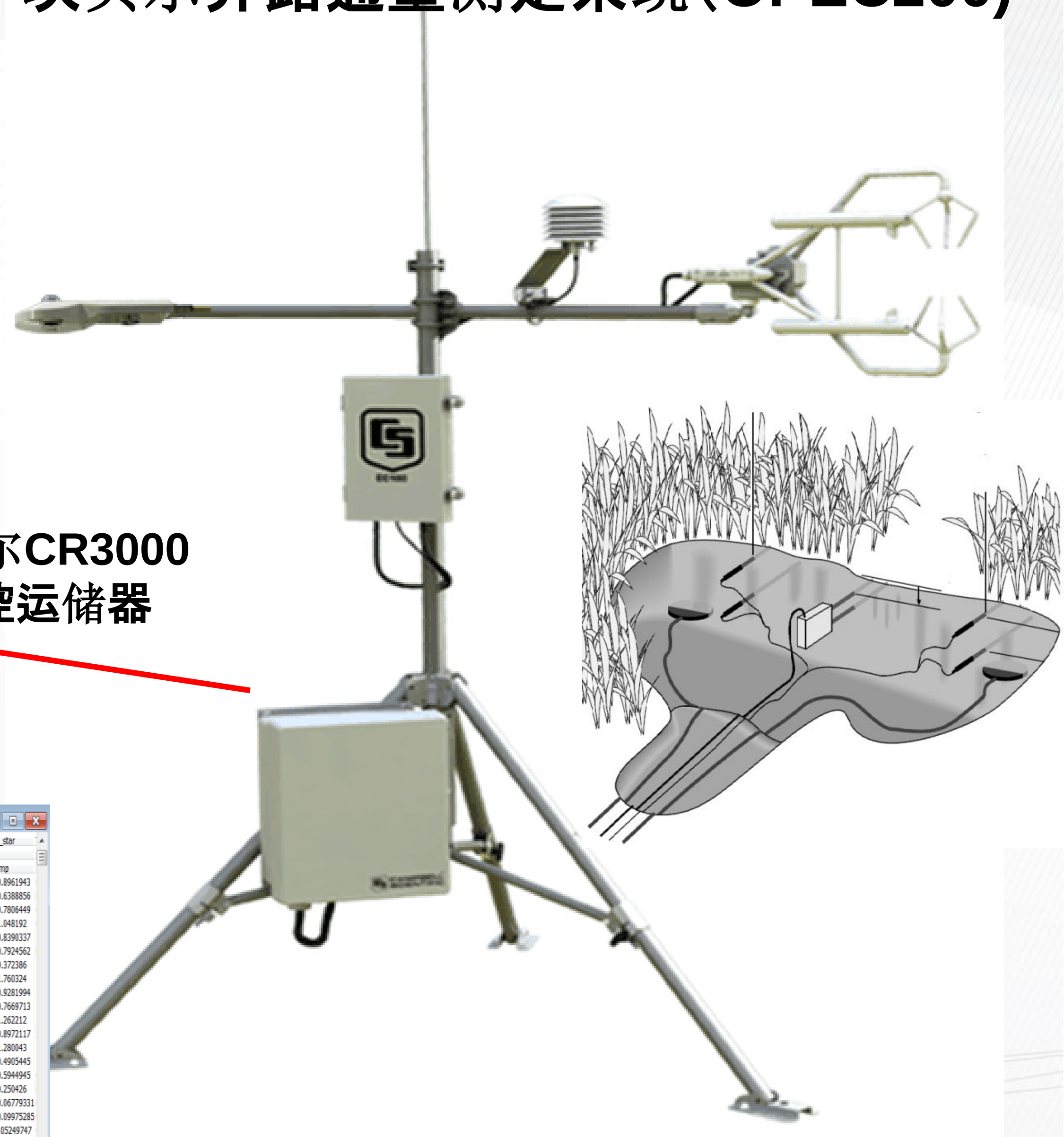
CRBasic Editor - [IRGASON_RES_CR3KCode_0820_2014.cr3 for the CR3000]

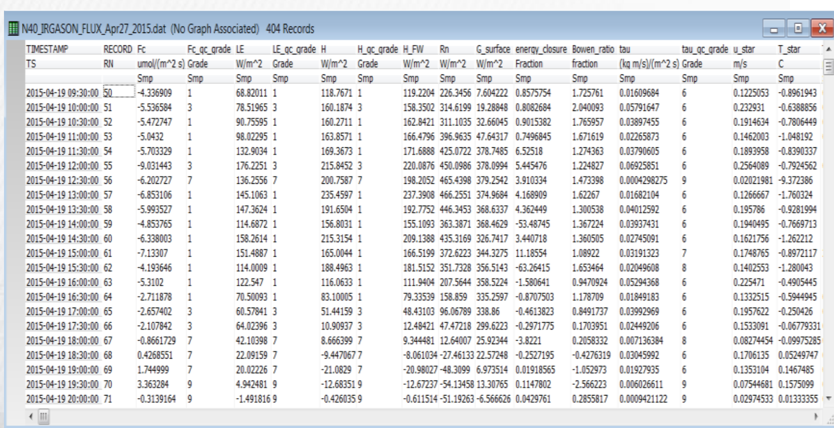
File Edit View Search Compile Template Instruction Goto Window Tools Help

```
'*** End of preparation for stability calculation inside the scan ***

 'Set the SDM clock speed.
 SDMSpeed (SDM_PER)

'In case configure_ec100_flg is turn off in the first 3 scan loops
If (configure_ec100_flg) Then Call Config (config_array(1,1), 4, configure_ec100_flg)

'*************************** SCAN LOOP    ************************************************
 Scan (SCAN_INTERVAL,mSec,SCAN_BUFFER_SIZE,0)
   'Datalogger panel temperature.
   PanelTemp (panel_tmpr,250)

'*** Beginning of FW05 measurements ***
   diag_fw_raw = 0

   TCDiff (fw_raw, 1, mV20, FW_ANALOG_INPUT, TypeE, panel_tmpr, TRUE, 450, 250, 1, 0)

   If (fw_raw = NaN) OR (fw_raw > 80) OR (fw_raw < -50) Then diag_fw_raw = -1

   CallTable delay_fw
'*** End of FW05 measurements ***

'*** Beginning of temperature and humidity probe measurements ***
   diag_T_tmpr_rh  = FALSE
```

Line: 1 Col: 1 C:\IRGASON_Temperature\IRGASON_Temp_CR3KCode\IRGASON_RES_CR3KCode_0820_2014.cr3 Insert

坎贝尔CR3000
测控运储器





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

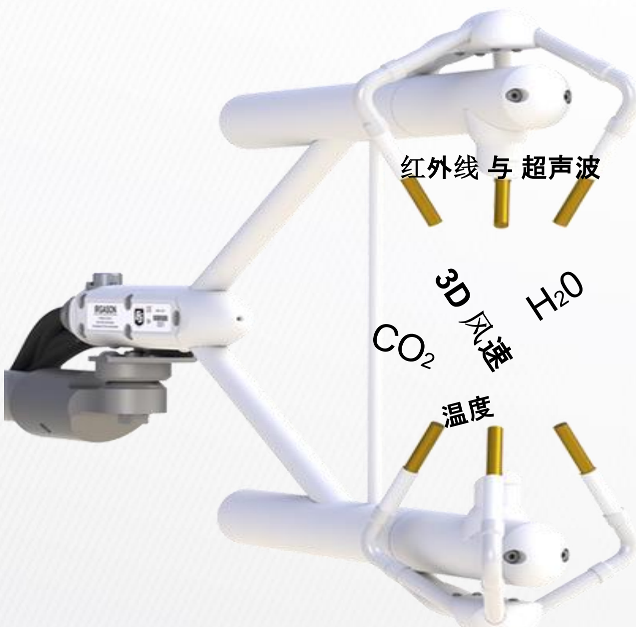
N40_IRGASON_FLUX_Apr27_2015.dat (No Graph Associated) 404 Records

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

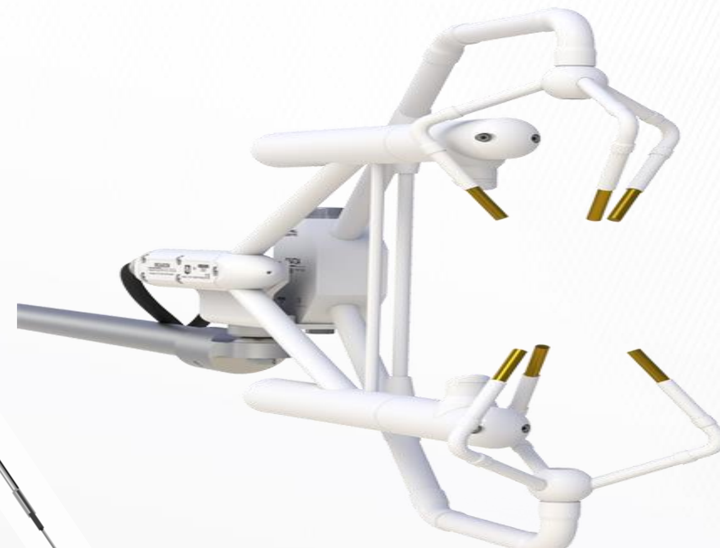
涡动传感器的配置

IRGASON
红外超声碳水热通量“一体式”观测仪

EC150+CSAT3A
红外超声碳水热通量“组装”观测仪

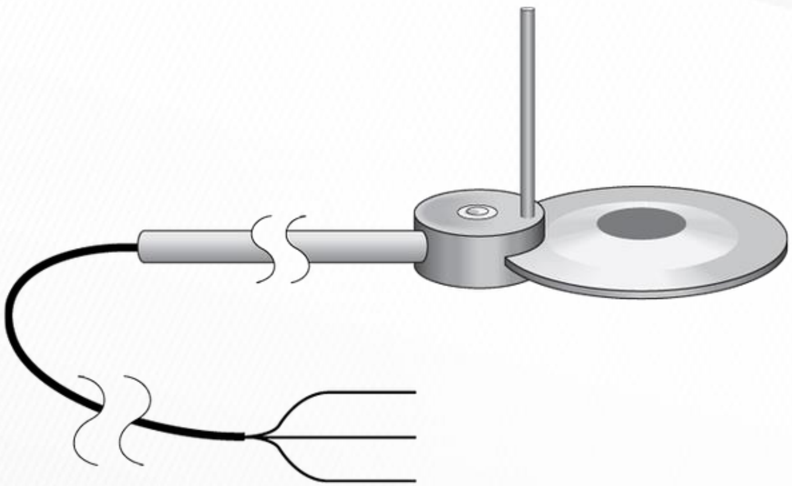


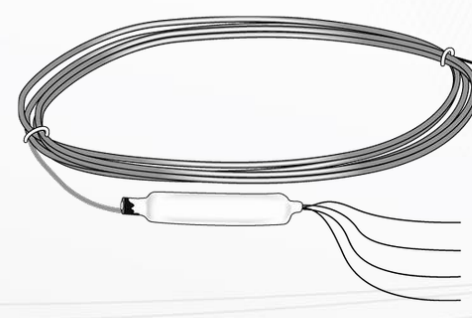
细丝热电偶



净辐射传感器的配置

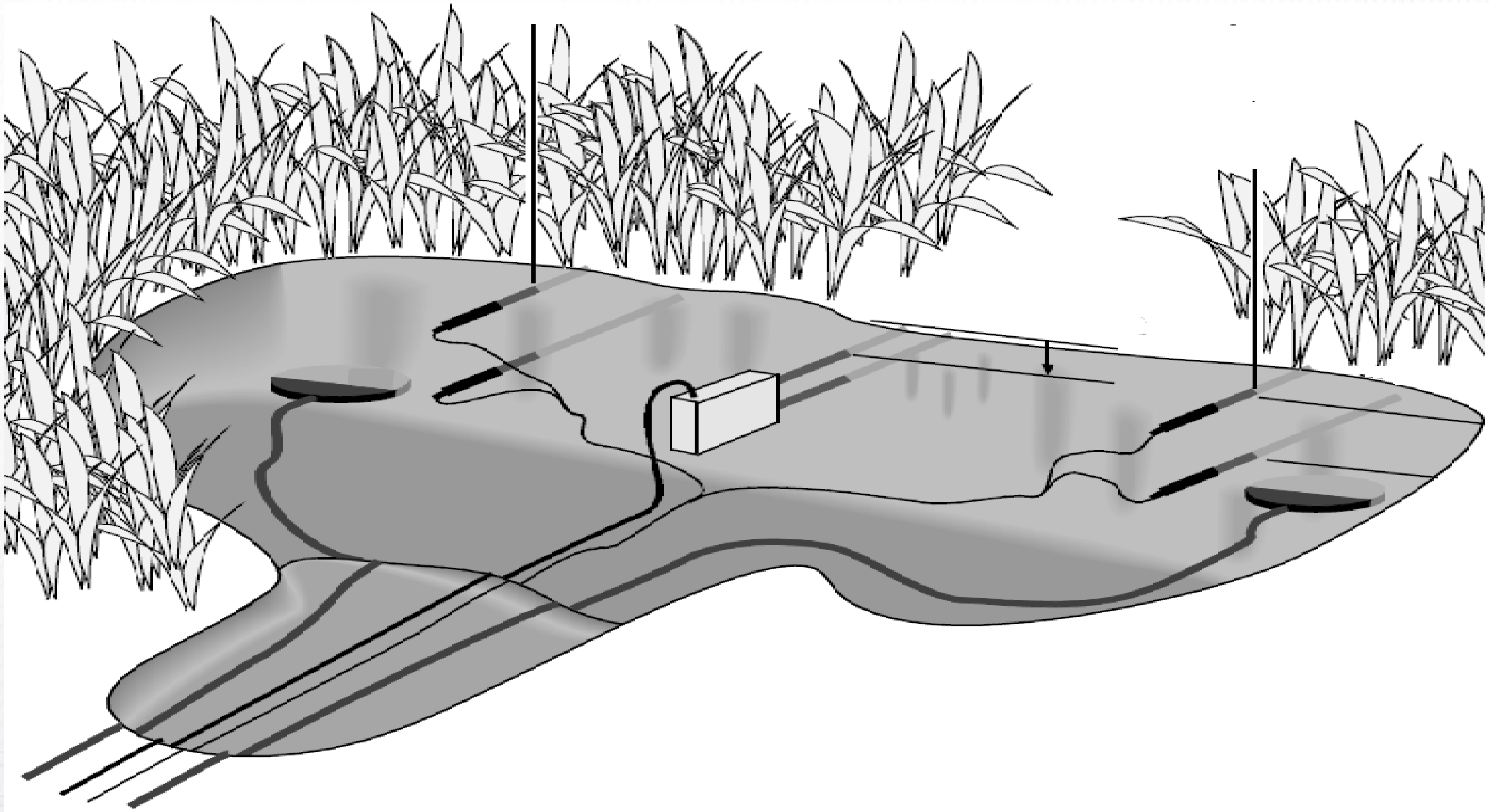
二分量净辐射和单分量辐射传感器配置





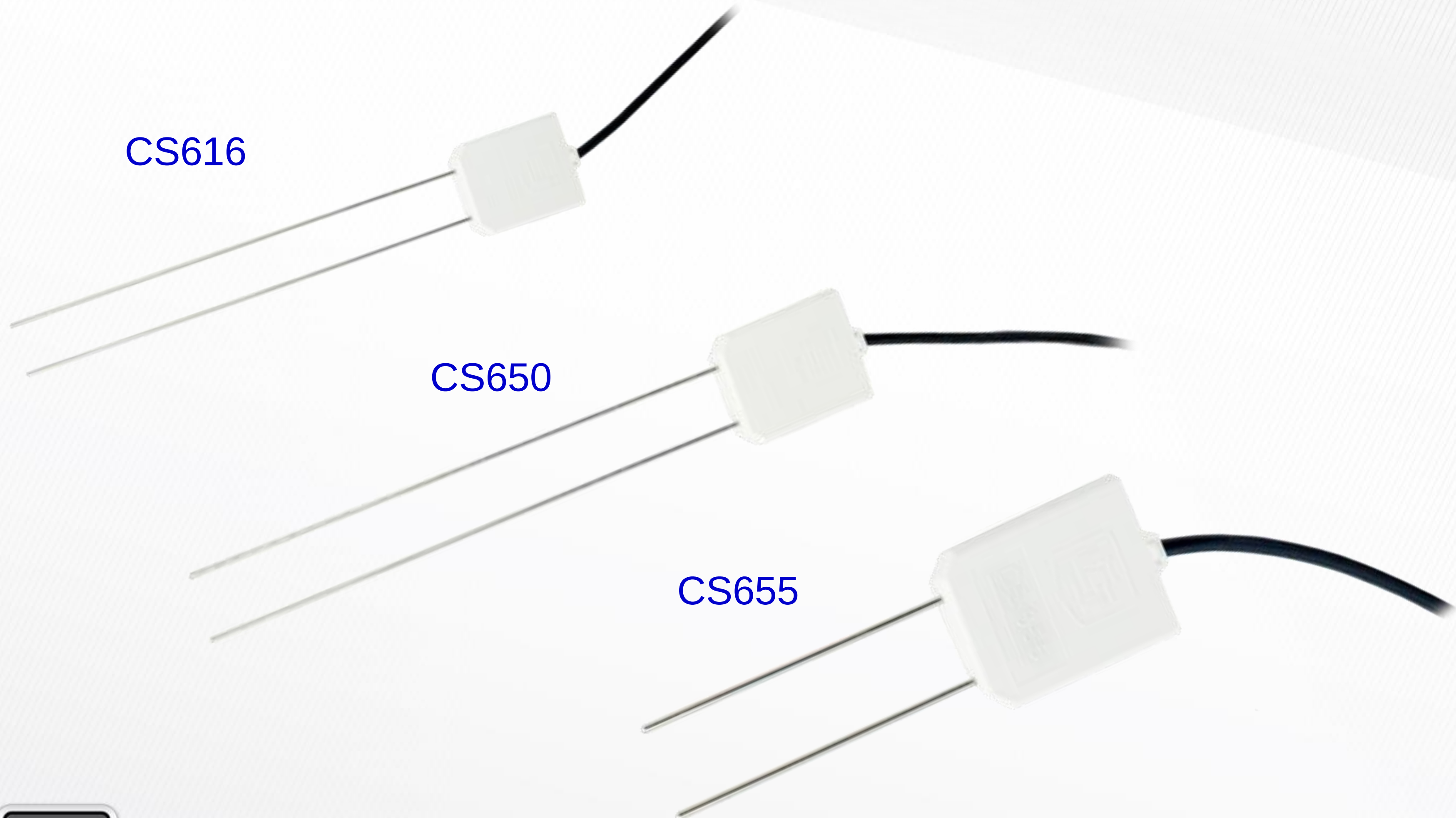
土壤热通量的测定

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

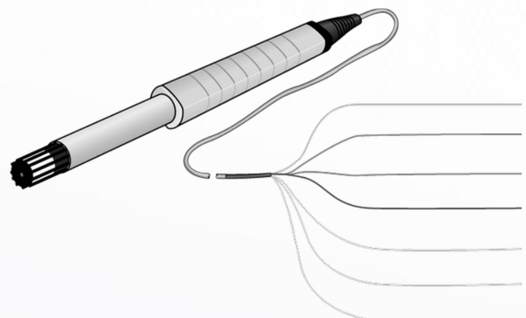


土层内热通量传感器的配置

空气温湿度量传感器的配置

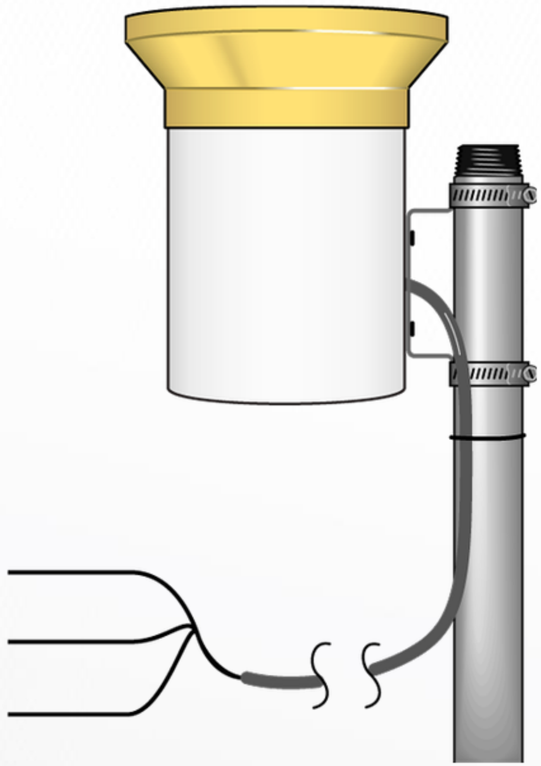
HMP155A

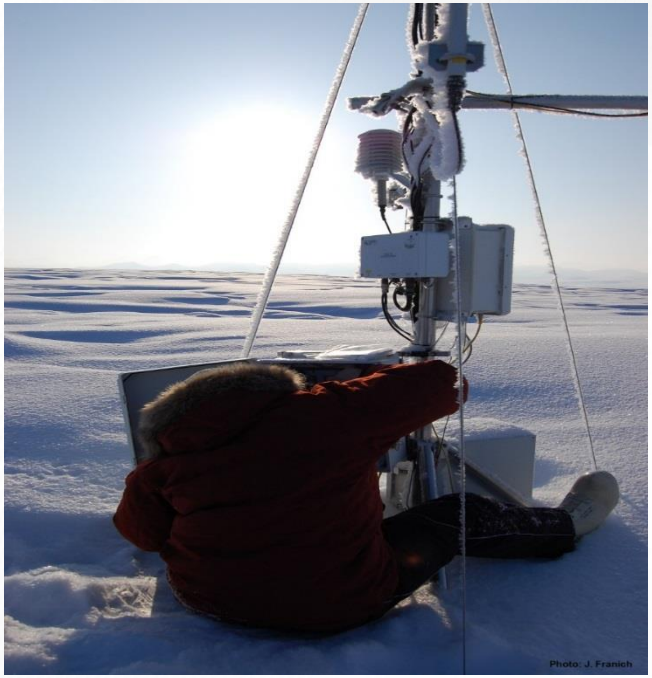
HMP45C



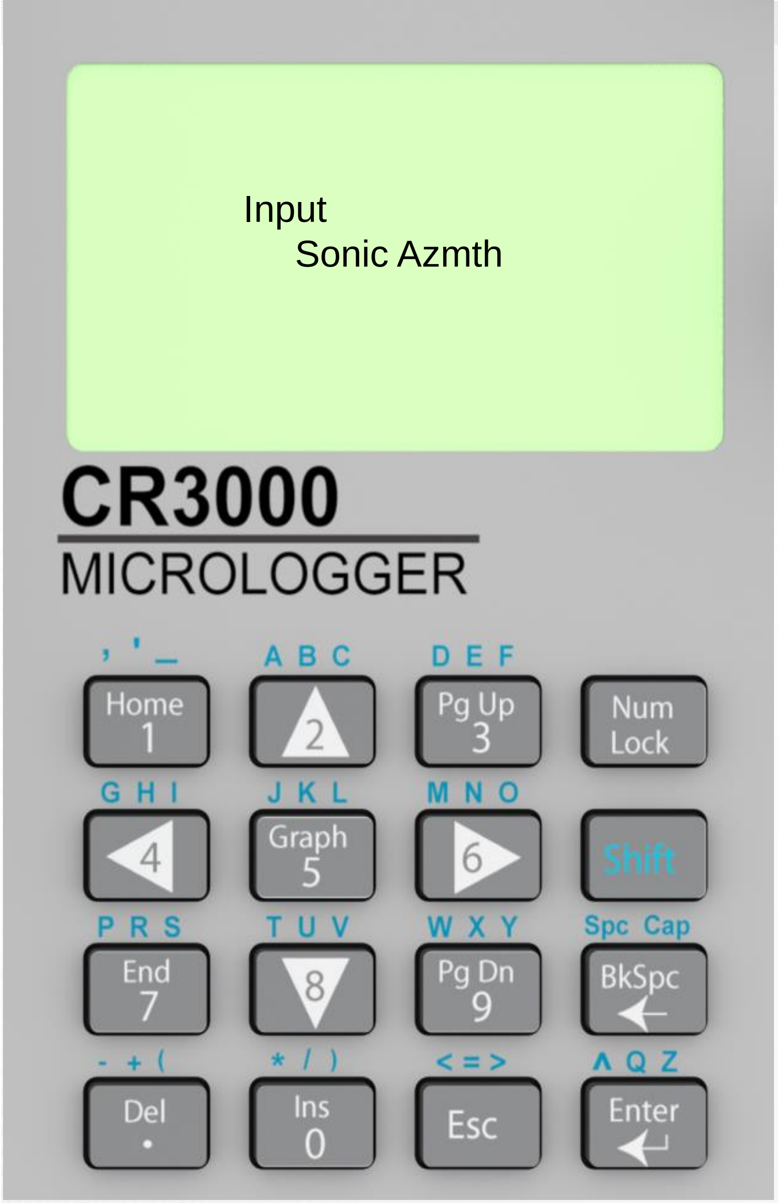
HC2S3

降雨传感器的配置





野外操作


Input
Sonic Azmth
CR3000
MICROLOGGER
Home 1
2
Pg Up 3
Num Lock
Graph 5
6
Shift
End 7
8
Pg Dn 9
BkSpc
Del
Ins 0
Esc
Enter

Input geographic information

latitude
hemisphere_NS

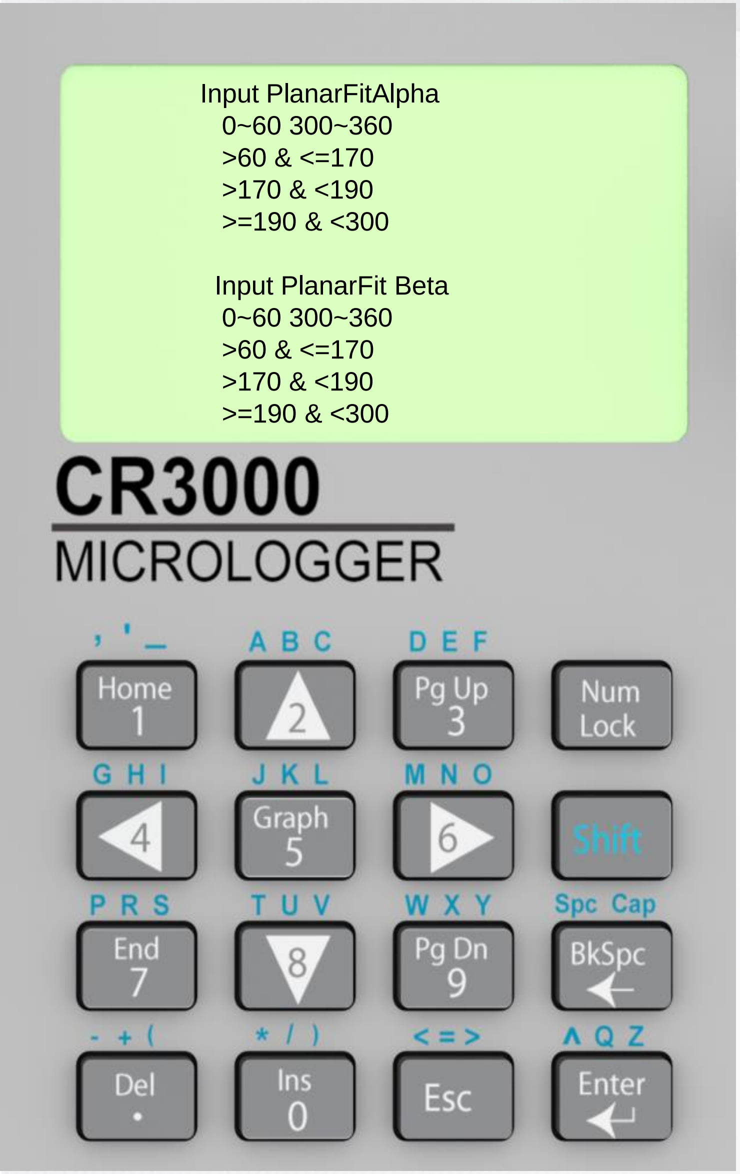
longitude
hemisphere_EW

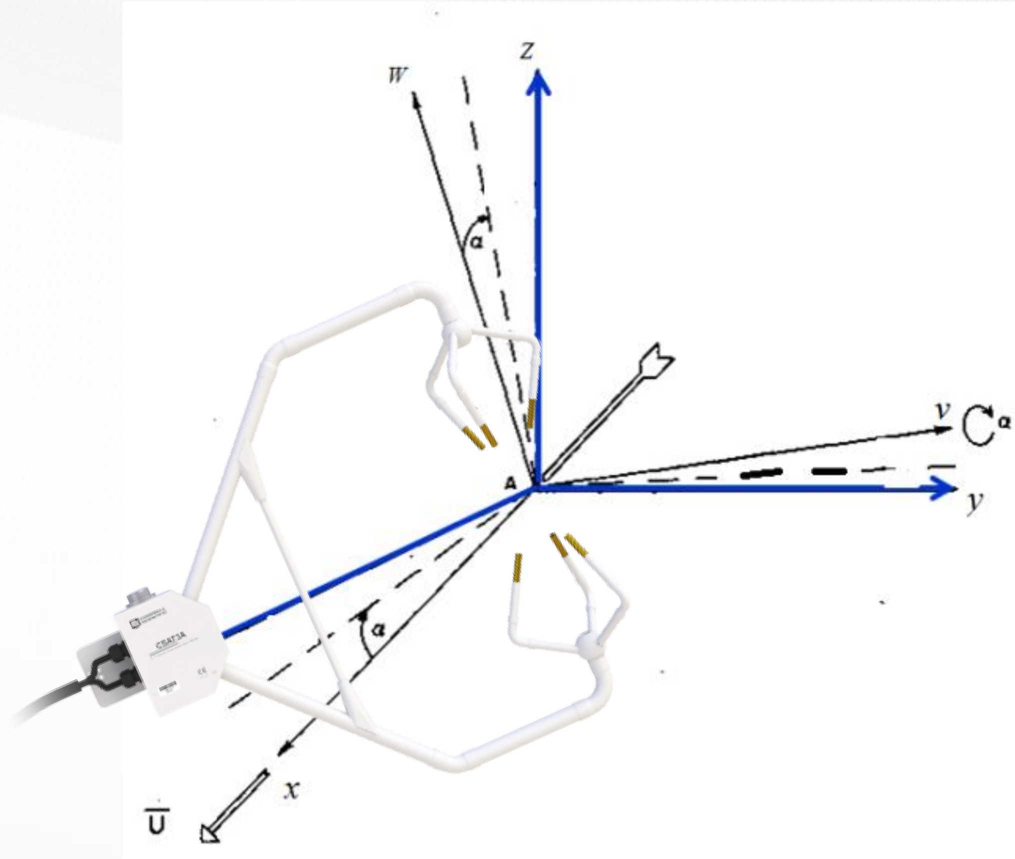
Input

- height_measurement
- displacement_user
- height_canopy
- roughness_user

Input
surface_type

crop = 1
grass = 2
forest = 3
shrub = 4
bare land = 5
water = 6


Input PlanarFitAlpha
0~60 300~360
>60 & <=170
>170 & <190
>=190 & <300
Input PlanarFit Beta
0~60 300~360
>60 & <=170
>170 & <190
>=190 & <300
CR3000
MICROLOGGER
Home 1
2
Pg Up 3
Num Lock
4
Graph 5
6
Shift
End 7
8
Pg Dn 9
BkSpc
Del
Ins 0
Esc
Enter


W
Z
α
v
y
A
x
U

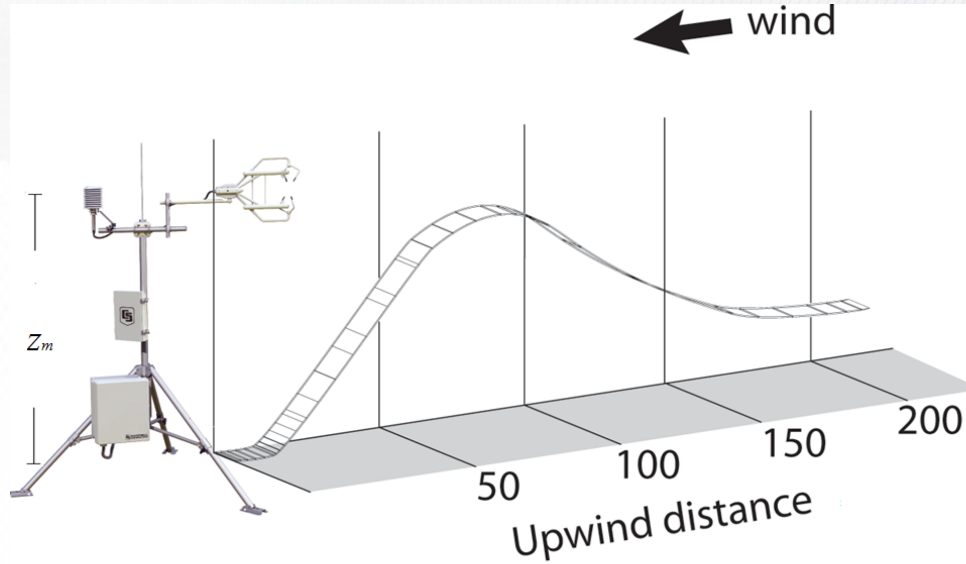
Footprint Dis Intrst

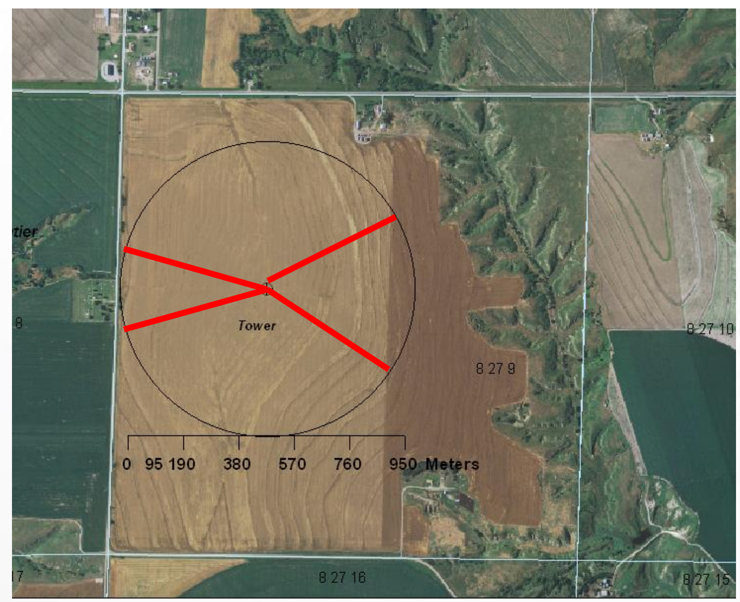
<60° or >300°

≥60° and ≤ 170°

>170° and <190°

≥ 190° and <300°





Input

IRGA Separation

Coord x

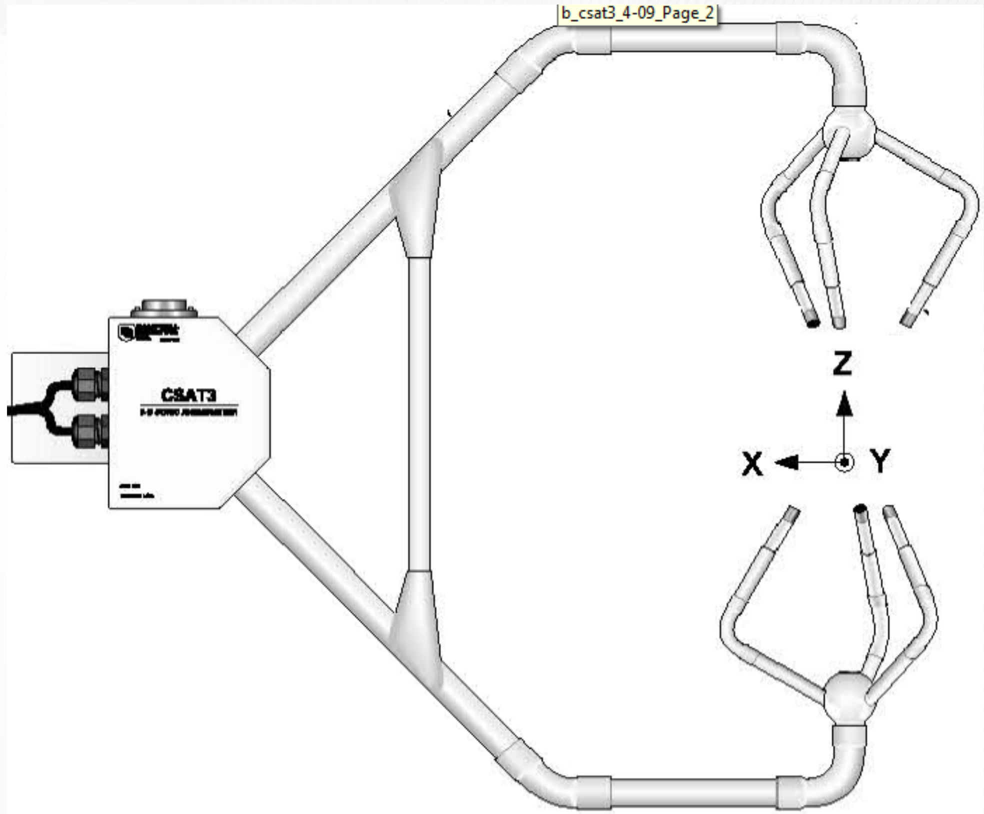
Coord y

FW Separation

Coord x

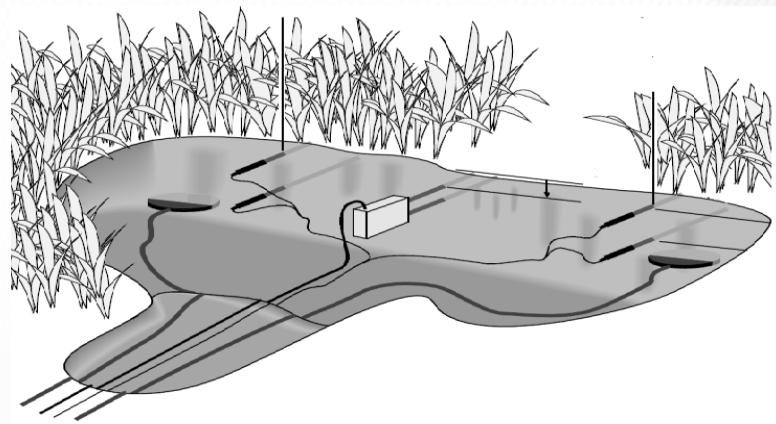
Coord y

FW Dim



Input

- soil_bulk_density
- specific heat of dry mineral soil
- thick_abv_SHFP



程序算法

1. 野点去除（Despike）
2. 延时法找最大协方差（Lag maximization）
3. 坐标旋转 (Coordinate rotation)
   a. 两次旋转（double rotation）
   b. 平面拟合旋转（planar fit）
4. 频率修正（Frequency correction）
   a. 测定路径平均（line averaging）
   b. 时段平均（block averaging）
   c. 传感器分离（sensor separation）
   d. 时间长数（time constant for fine wire thermocouple）
5. 超声感热修真（Sonic sensible heat flux correction）
6. 空气密度修正（WPL correction）
7. 土表热通量（Soil heat flux at surface)
8. 通量源区特征（footprint characteristics）
9. 数据质量分级（data qualification grading)

野点去除（Despike）

	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

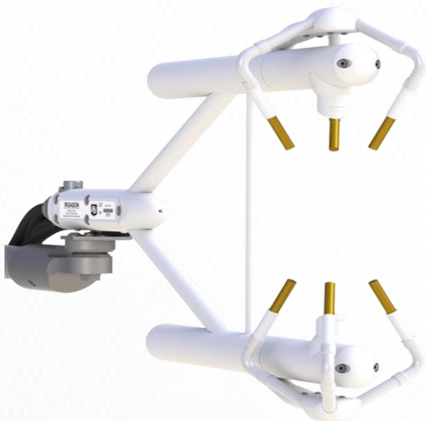
```
DataTable (comp_cov_CO2, TRUE, 1)
    DataInterval (0, OUTPUT_INTERVAL, Min, 1)

  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
```

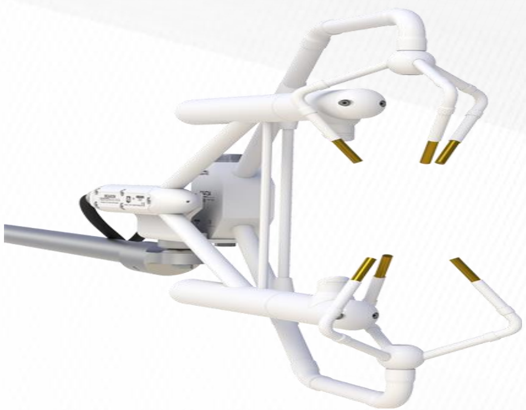
H2O与风速之间协方差计算中的野点去除

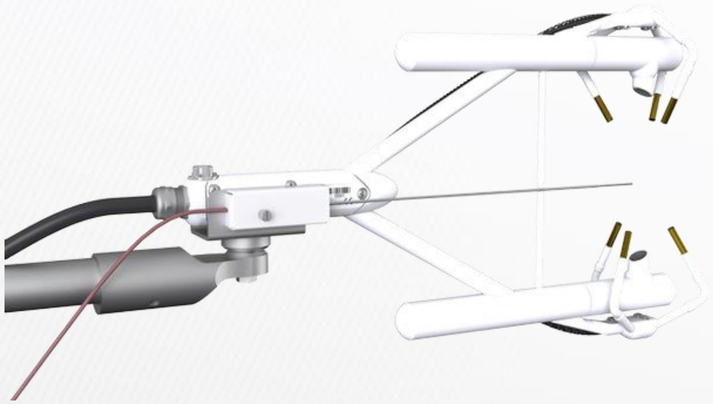
数组元素排列: H2O, Ux, Uy, Uz

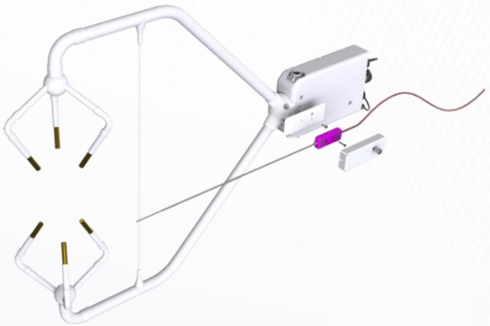
```
DataTable (comp_cov_H2O, TRUE, 1)
   DataInterval (0, OUTPUT_INTERVAL, Min, 1)

    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
```

延时法找最大协方差（Lag maximization）

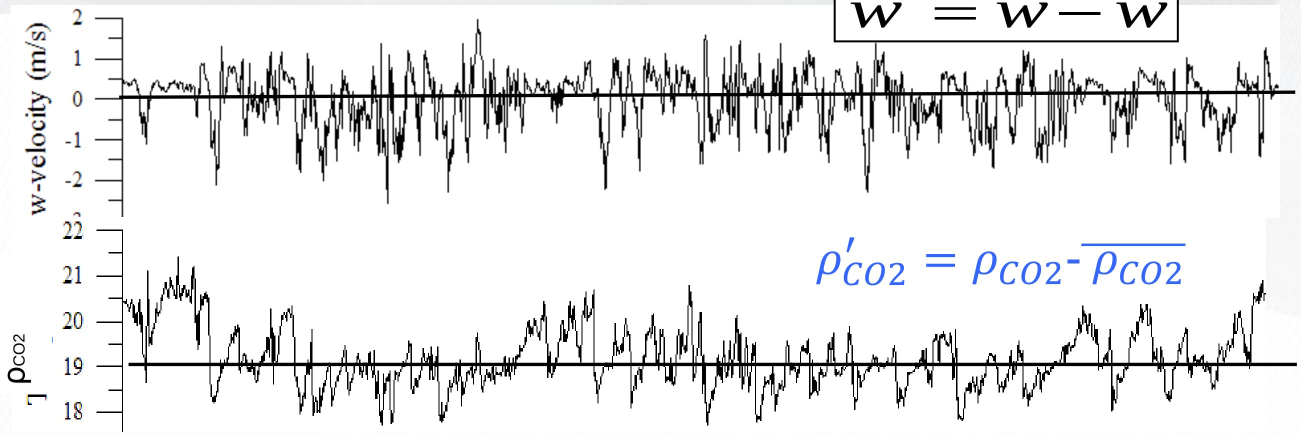








$$w' = w - \overline{w}$$



$$\overline{w}$$

$$\rho'_{CO2} = \rho_{CO2} - \overline{\rho_{CO2}}$$

$$\overline{\rho_{CO2}}$$

$$F_{C\_-2} = \frac{1}{n}\sum_{i=1}^{n}\left(w_i - \overline{w}\right)\left(\rho_{co2\_(i-2)} - \overline{\rho}_{co2\_-2}\right)$$

$$F_{C\_-1} = \frac{1}{n}\sum_{i=1}^{n}\left(w_i - \overline{w}\right)\left(\rho_{co2\_(i-1)} - \overline{\rho}_{co2\_-1}\right)$$

$$F_{C\_0} = \frac{1}{n}\sum_{i=1}^{n}\left(w_i - \overline{w}\right)\left(\rho_{co2\_(i+0)} - \overline{\rho}_{co2\_0}\right)$$

$$F_{C\_+1} = \frac{1}{n}\sum_{i=1}^{n}\left(w_i - \overline{w}\right)\left(\rho_{co2\_(i+1)} - \overline{\rho}_{co2\_+1}\right)$$

$$F_{C\_+2} = \frac{1}{n}\sum_{i=1}^{n}\left(w_i - \overline{w}\right)\left(\rho_{co2\_(i+2)} - \overline{\rho}_{co2\_+2}\right)$$

```
Dim cov_out_CO2(5*(2*MAX_LAG + 1))       'CO2 statistics.
Alias cov_out_CO2(1)  = CO2_mean_b2
Alias cov_out_CO2(2)  = CO2_stdev_lag_b2         ‘b2 indicates backward 2 scan
Alias cov_out_CO2(3)  = CO2_Ux_cov_lag_b2
Alias cov_out_CO2(4)  = CO2_Uy_cov_lag_b2
Alias cov_out_CO2(5)  = CO2_Uz_cov_lag_b2
Alias cov_out_CO2(6)  = CO2_mean_b1
Alias cov_out_CO2(7)  = CO2_stdev_lag_b1         ‘b1 indicates backward 1 scan
Alias cov_out_CO2(8)  = CO2_Ux_cov_lag_b1
Alias cov_out_CO2(9)  = CO2_Uy_cov_lag_b1
Alias cov_out_CO2(10)  = CO2_Uz_cov_lag_b1
Alias cov_out_CO2(11)  = CO2_mean_b1
Alias cov_out_CO2(12) = CO2_stdev_lag_0          '0 indicates zero scan either backward or forward
Alias cov_out_CO2(13) = CO2_Ux_cov_lag_0
Alias cov_out_CO2(14) = CO2_Uy_cov_lag_0
Alias cov_out_CO2(15) = CO2_Uz_cov_lag_0
Alias cov_out_CO2(16)  = CO2_mean_b1
Alias cov_out_CO2(17) = CO2_stdev_lag_f1         'f1 indicats forward 1 scan
Alias cov_out_CO2(18) = CO2_Ux_cov_lag_f1
Alias cov_out_CO2(19) = CO2_Uy_cov_lag_f1
Alias cov_out_CO2(20) = CO2_Uz_cov_lag_f1
Alias cov_out_CO2(21)  = CO2_mean_b1
Alias cov_out_CO2(22) = CO2_stdev_lag_f2         'f2 indicats forward 2 scans
Alias cov_out_CO2(23) = CO2_Ux_cov_lag_f2
Alias cov_out_CO2(24) = CO2_Uy_cov_lag_f2
Alias cov_out_CO2(25) = CO2_Uz_cov_lag_f2
```

问题

1. 风向

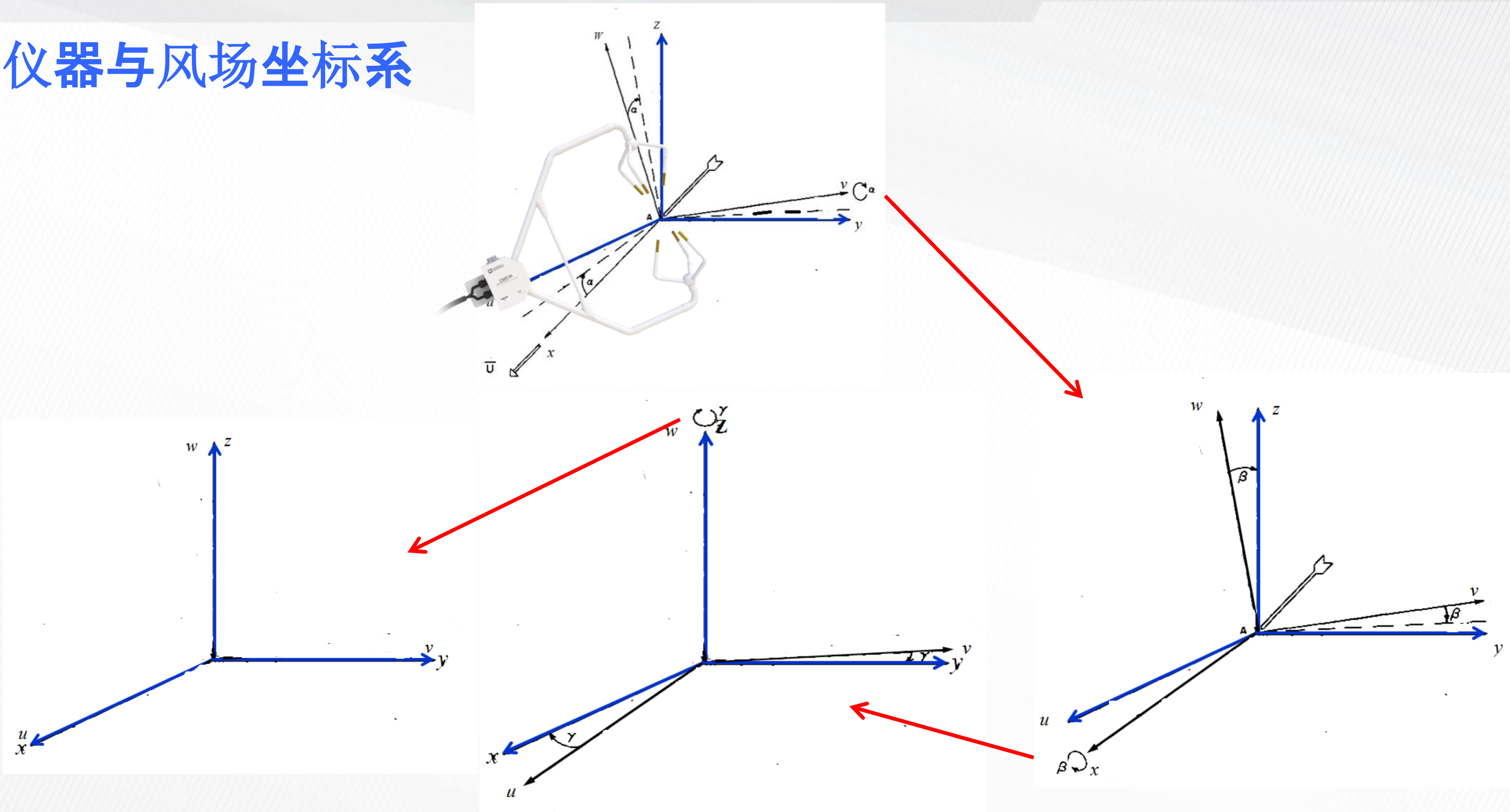
2. 安装

异空安装

$$\begin{bmatrix} \text{time delay distance} \\ \text{separation distance} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_{Separation} \\ y_{Separation} \end{bmatrix}$$

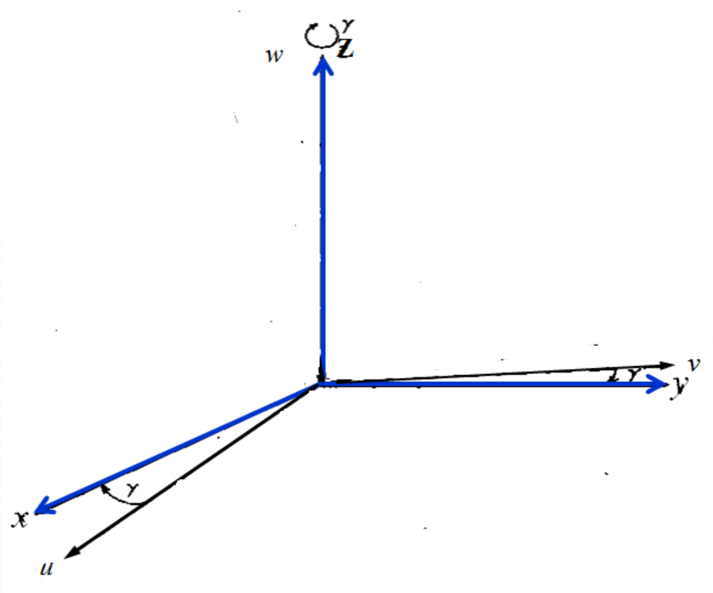
坐标旋转

仪器与风场坐标系

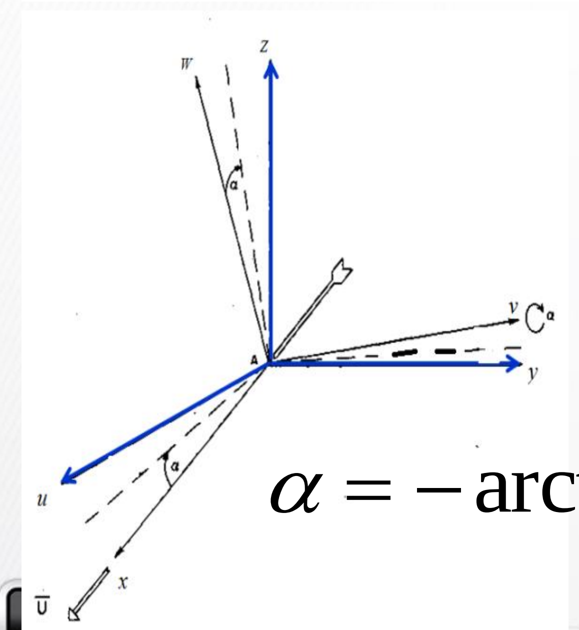


$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ 0 & 1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

角度的计算



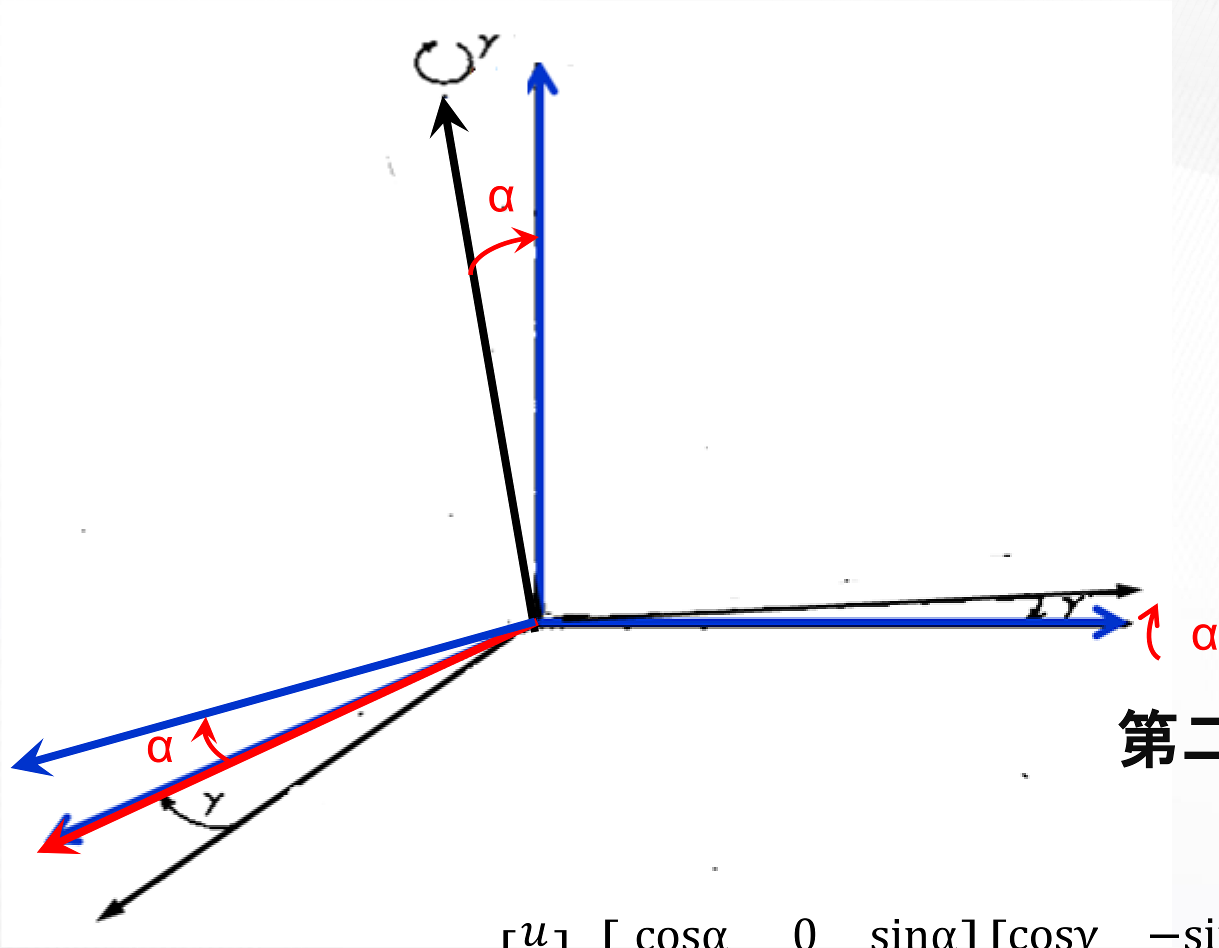
$$\gamma = \arctan\left(\frac{\bar{v}_m}{\bar{u}_m}\right)$$



$$\alpha = -\arctan\frac{\bar{w}_1}{\bar{u}_1} = -\arctan\frac{\bar{w}_m}{\bar{u}_m\cos\gamma + \bar{v}_m\sin\gamma}$$

两次旋转

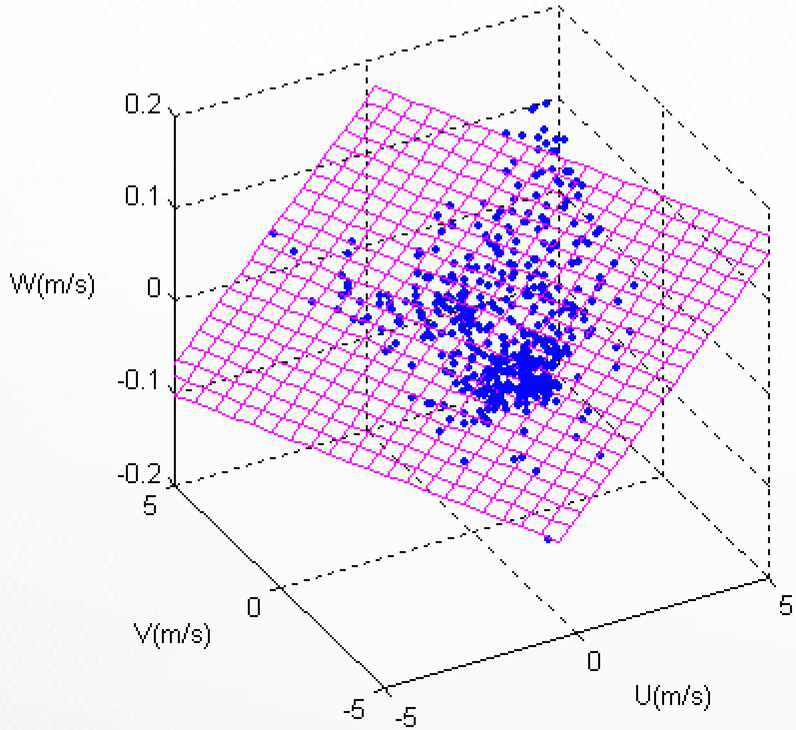
第一次旋转



第二次旋转

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

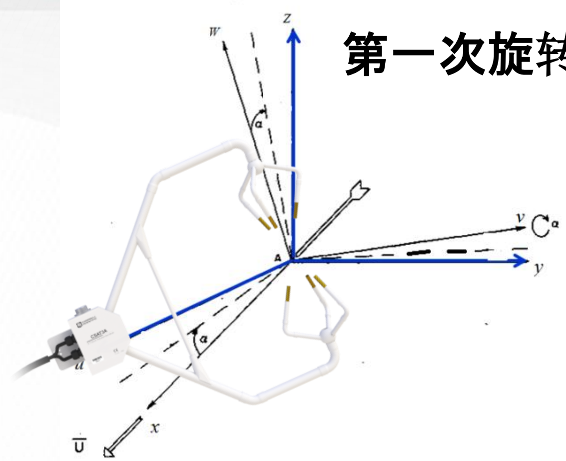
平面拟合坐标旋转角度计算



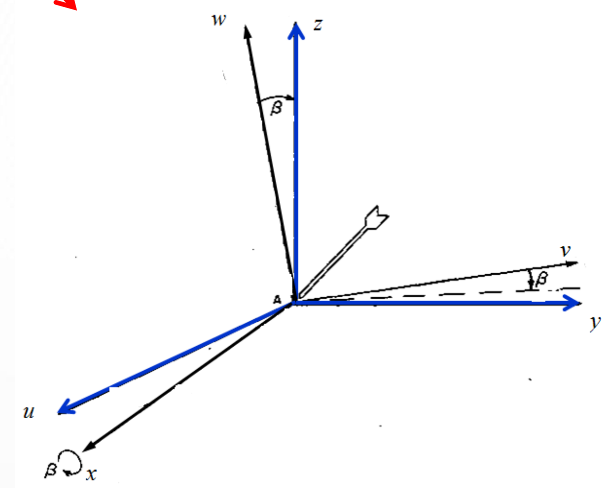
Coordinate System Rotated About This Plane

平面拟合
坐标旋转

第一次旋转



第二次旋转



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

频率修正

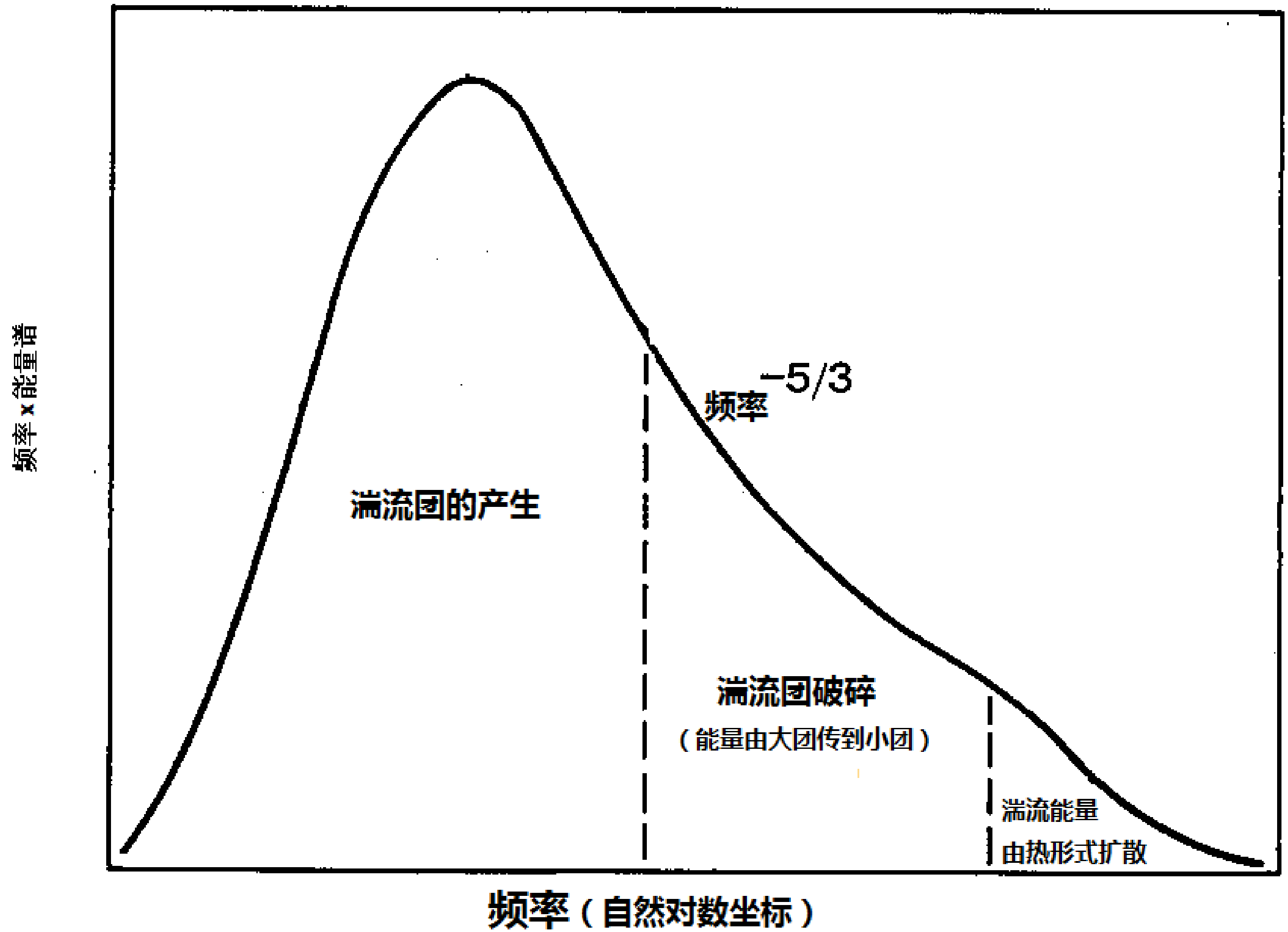
a. 测定路径平均（line averaging）

b. 时段平均（block averaging）

c. 传感器分离（sensor separation）

d. 时间常数（time constant for fine wire thermocouple）

湍流能量谱的一般形式



协方差与协谱

协方差

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

协谱与富利叶变换对

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

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

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

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

协方差与协谱

协方差

$$R_{\alpha w}(\tau) = \overline{\alpha'(t)w'(t+\tau)}$$

协方差与富利叶变换对

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

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

$$R_{\alpha w}(0) = \overline{\alpha'(t)w'(t+0)} = \overline{\alpha' \boldsymbol{w}'}$$

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

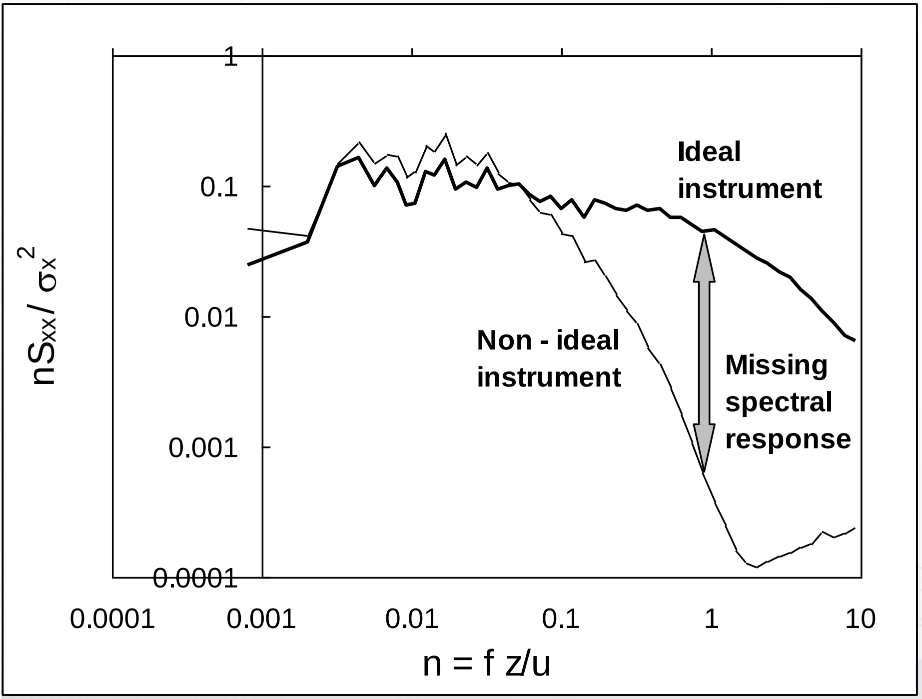
频率修正

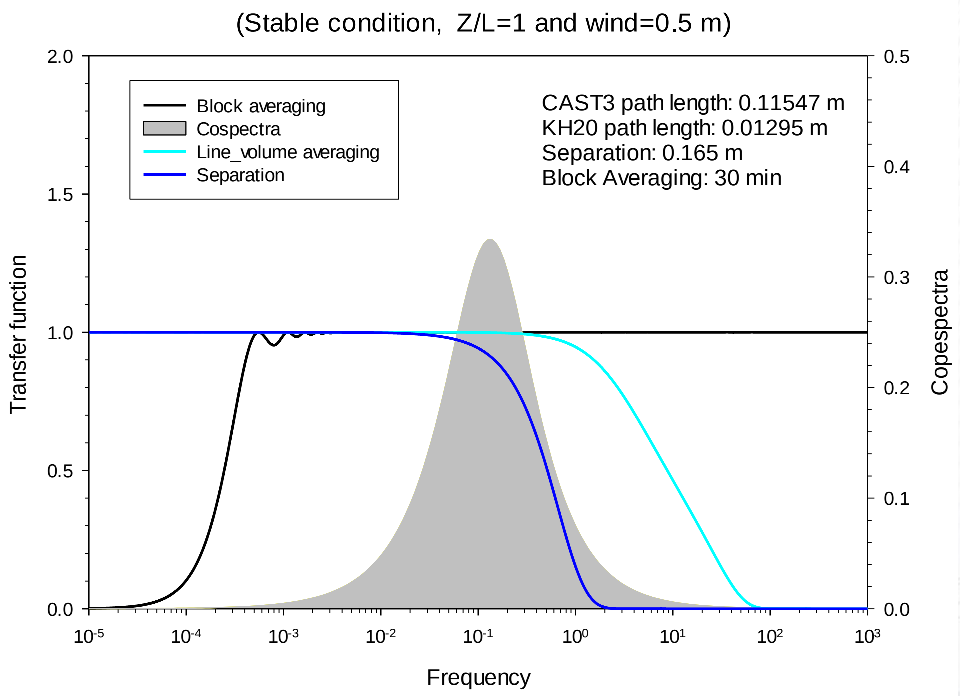
$$\overline{\alpha' w'} = \left(\overline{\alpha' w'}\right)_m \left\{ \frac{\int_0^\infty S_{\alpha w}(f)df}{\int_0^\infty T_{\alpha w}(f) S_{\alpha w}(f)df} \right\}$$

‘真’协谱

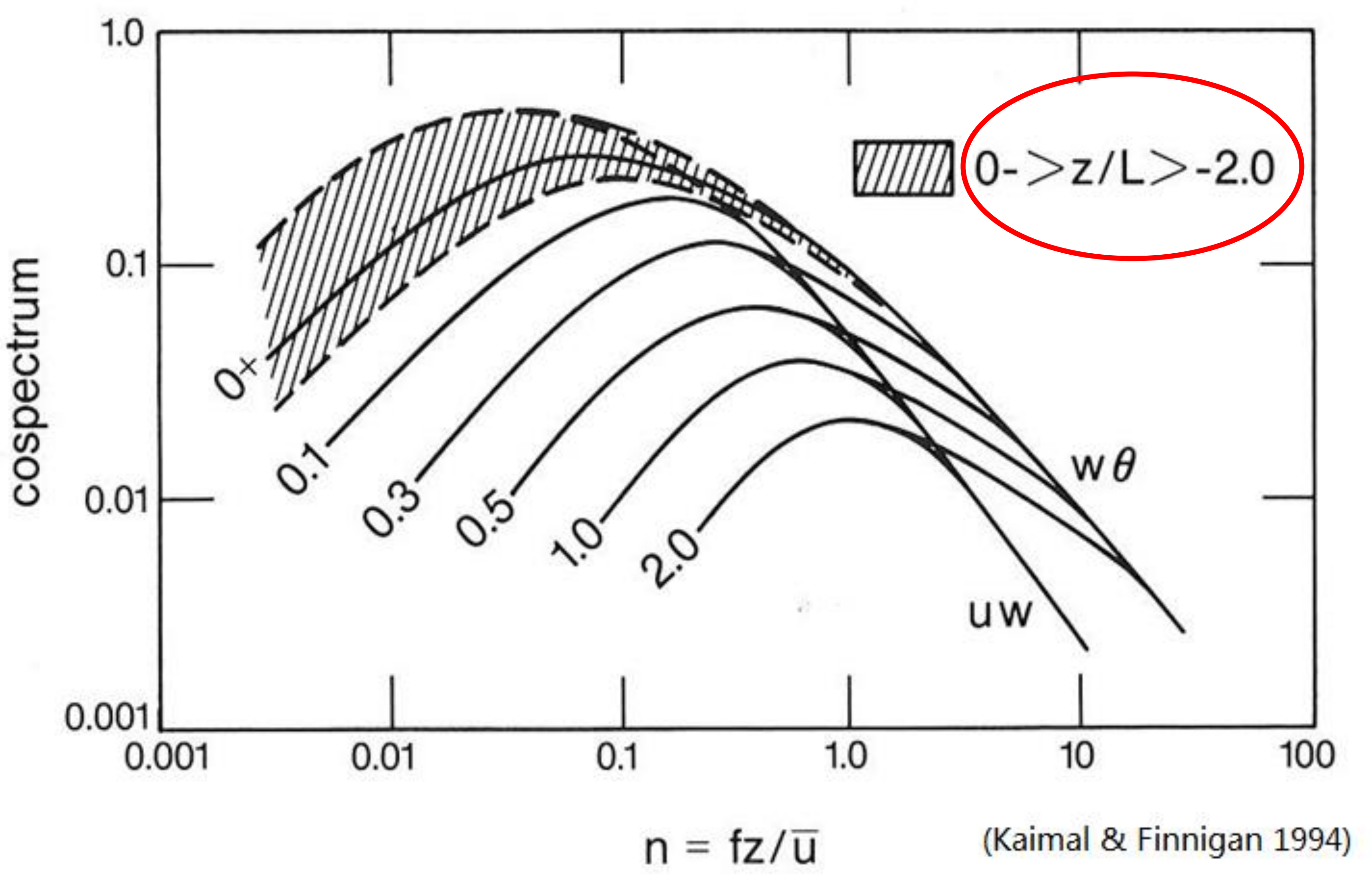
测得的协方差

频率反应函数





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



协湍流谱

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

垂直风速与水平风速

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

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

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

垂直风速与气温

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

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

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

协湍流谱

$$\frac{Z}{L} =< 0$$

垂直风速与水平风速

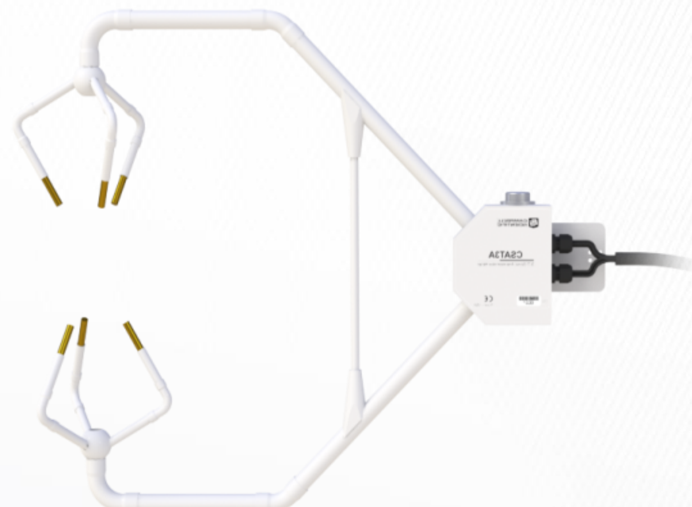
$$fS_{uw}(f) = \begin{cases} \dfrac{20.78\ fz/u}{\left(1+\dfrac{31z}{u}f\right)^{1.575}} & \dfrac{z}{u}f < 0.24 \\[2ex] \dfrac{12.66\ fz/u}{\left(1+\dfrac{9.6z}{u}f\right)^{2.4}} & \dfrac{z}{u}f \geq 0.24 \end{cases}$$

垂直风速与气温

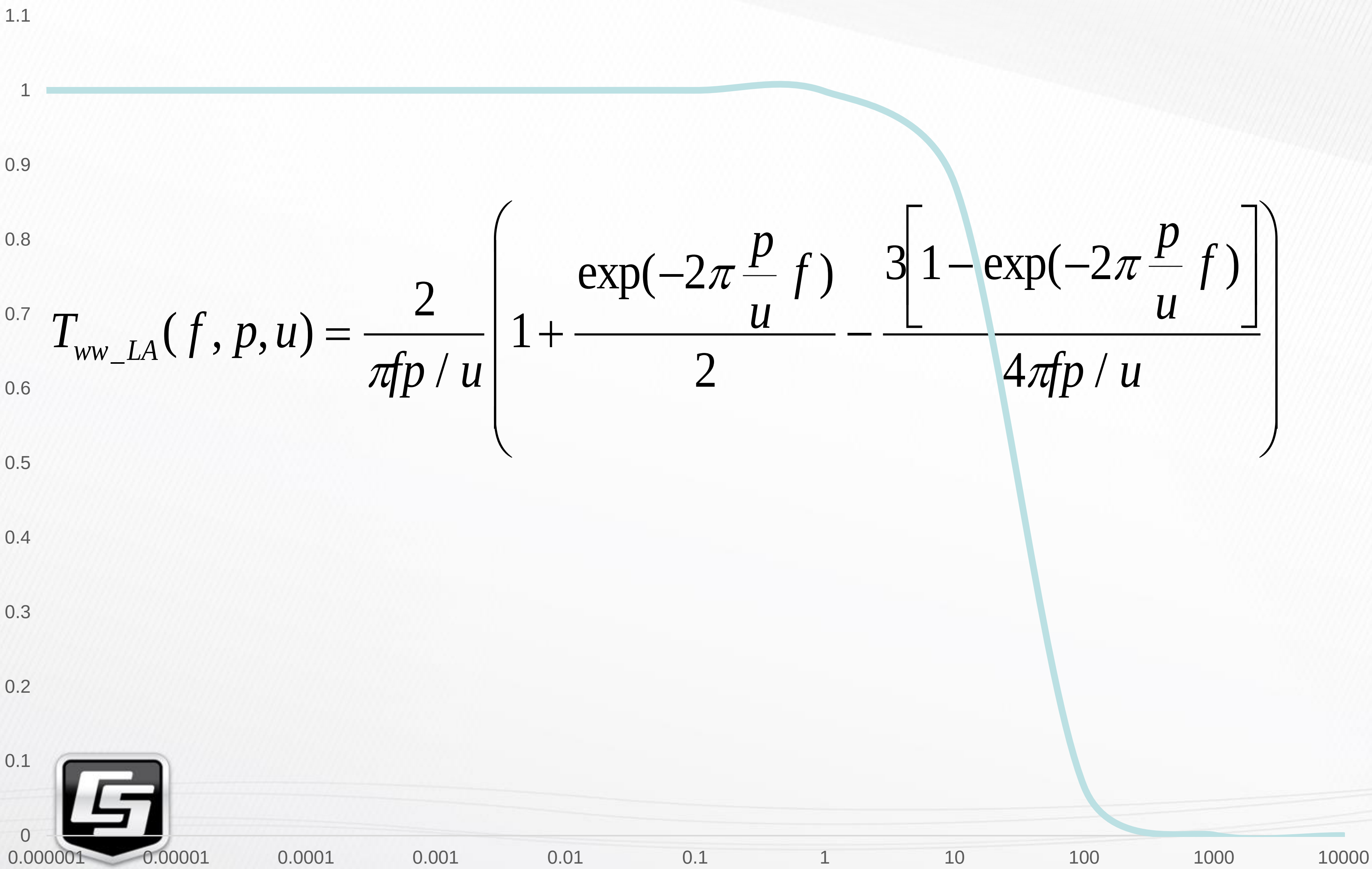
$$fS_{Tw}(f) = \begin{cases} \dfrac{12.92\ fz/u}{\left(1+\dfrac{26.7z}{u}f\right)^{1.375}} & \dfrac{z}{u}f < 0.54 \\[2ex] \dfrac{4.378\ fz/u}{\left(1+\dfrac{3.8z}{u}f\right)^{2.4}} & \dfrac{z}{u}f \geq 0.54 \end{cases}$$

测定路径平均

(path length averaging)

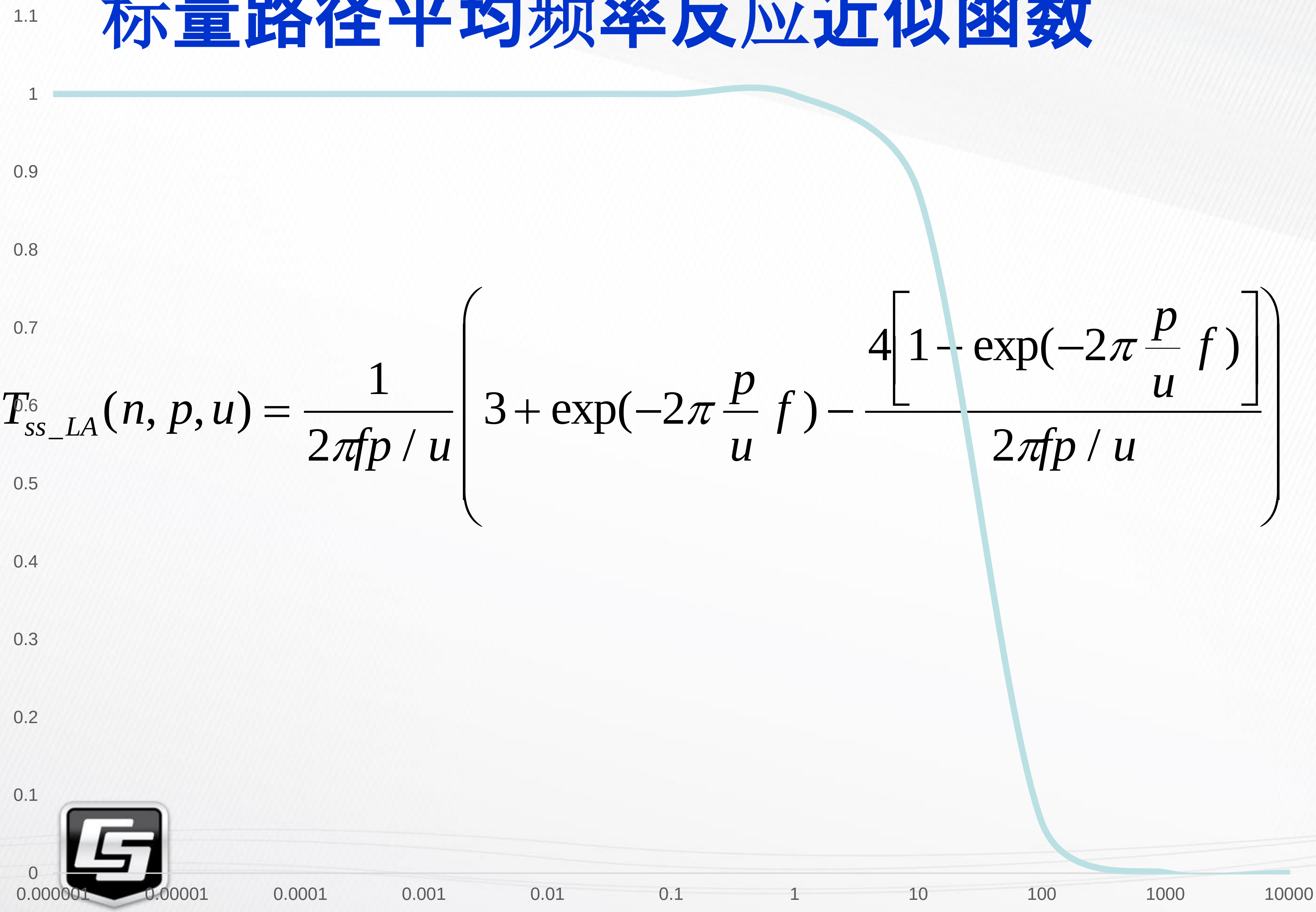


垂直风速路径平均频率反应近似函数



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

标量路径平均频率反应近似函数



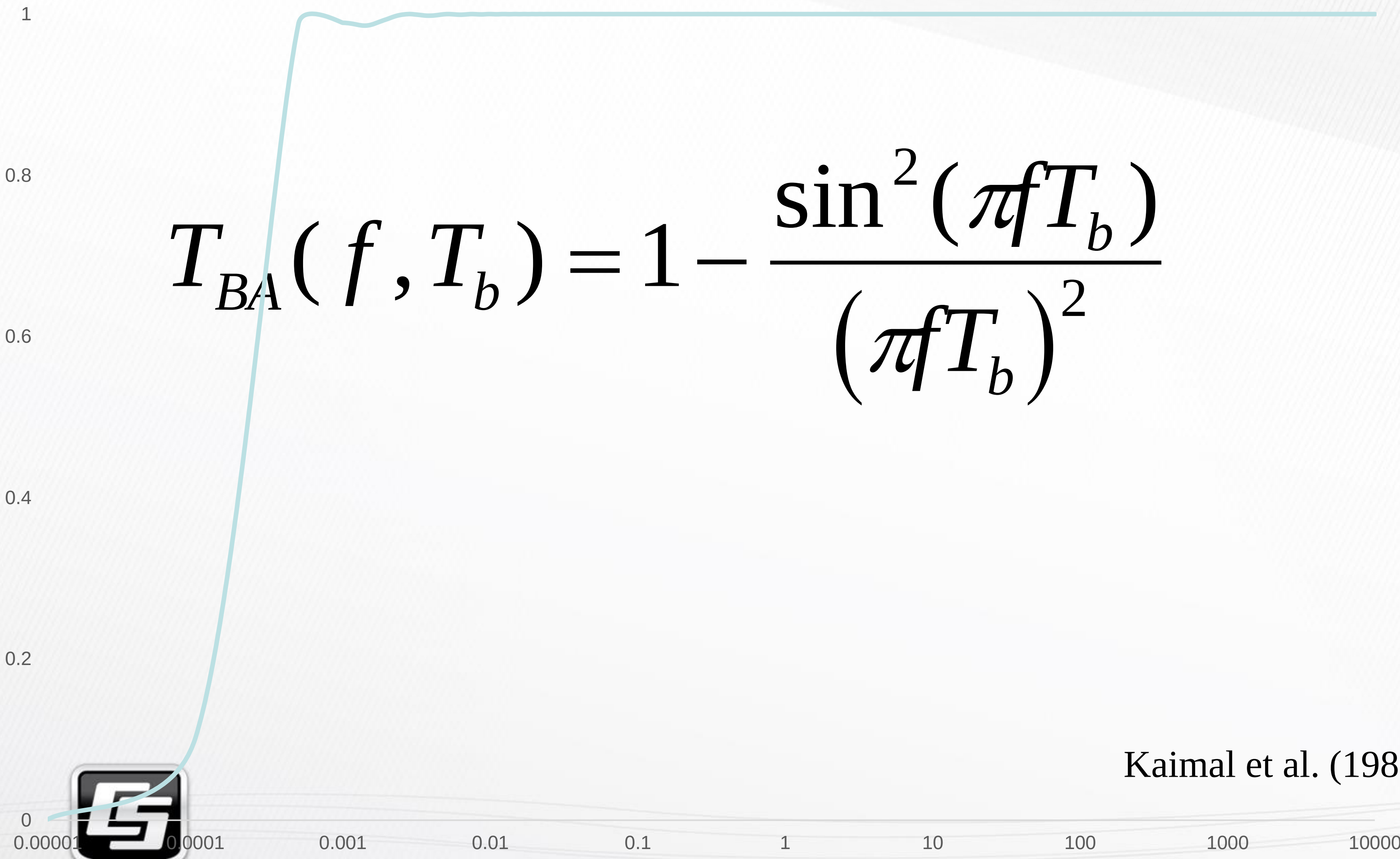
$$T_{ss\_LA}(n,p,u)=\frac{1}{2\pi f p/u}\left(3+\exp\left(-2\pi\frac{p}{u}f\right)-\frac{4\left[1-\exp\left(-2\pi\frac{p}{u}f\right)\right]}{2\pi f p/u}\right)$$

CSAT超声热通量路径平均频率反应函数 Dijk（2002）

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

时段平均频率损失修正

$$T_{BA}(f, T_b) = 1 - \frac{\sin^2(\pi f T_b)}{(\pi f T_b)^2}$$

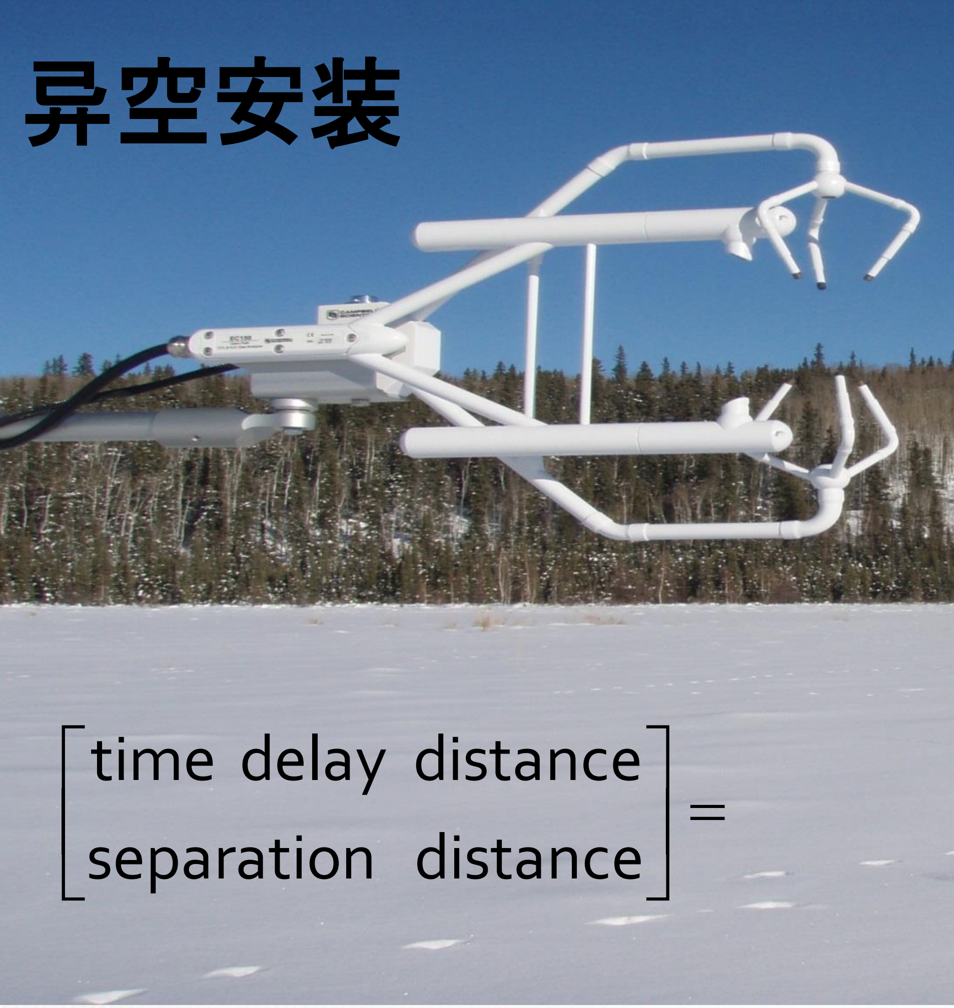


Kaimal et al. (1989)

仪器分离频率损失修正

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

异空安装



$$\begin{bmatrix} \text{time delay distance} \\ \text{separation distance} \end{bmatrix} =$$

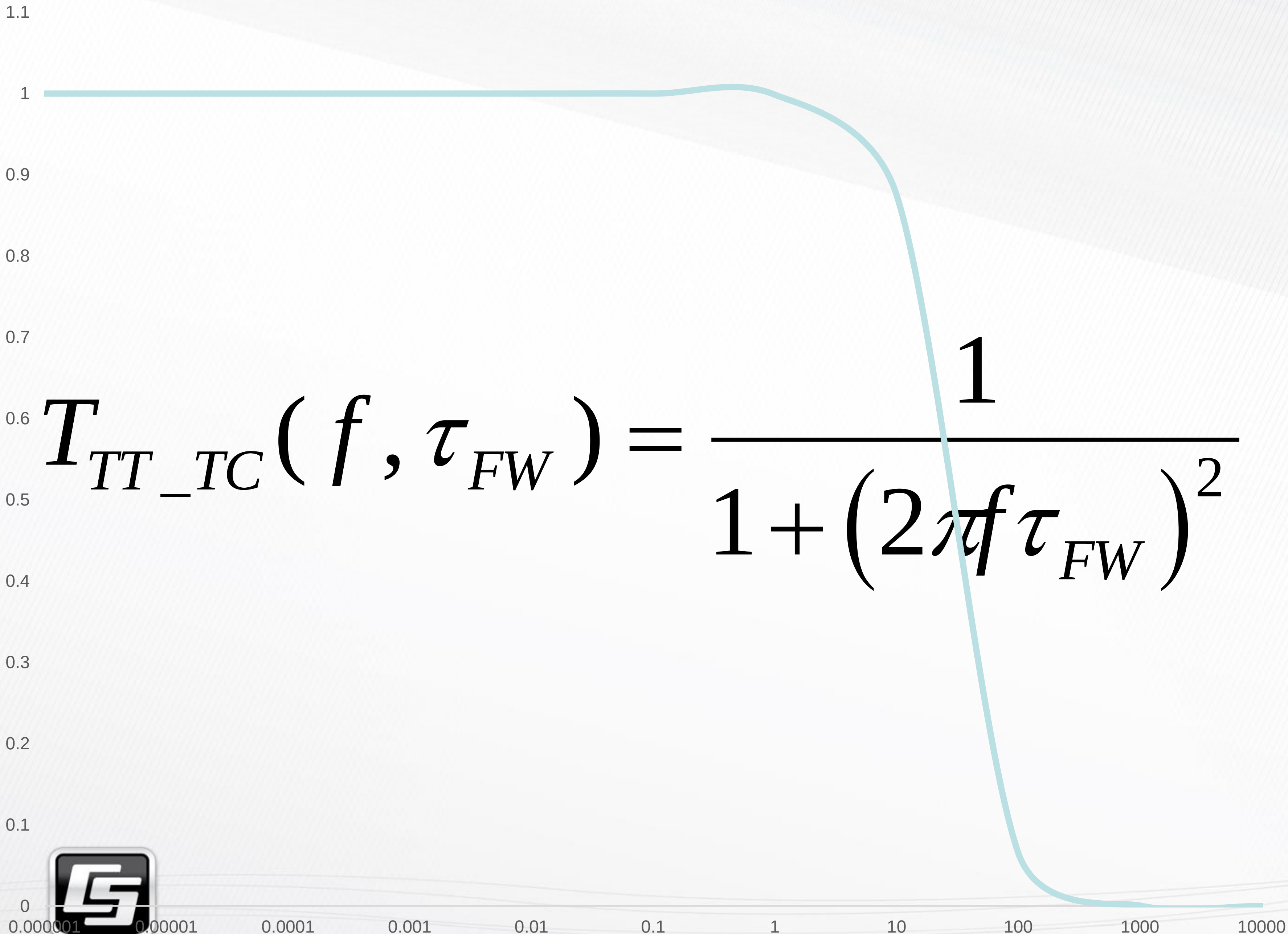
$$\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_{Separation} \\ y_{Separation} \end{bmatrix}$$

时间常数(τ)的理论定义

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

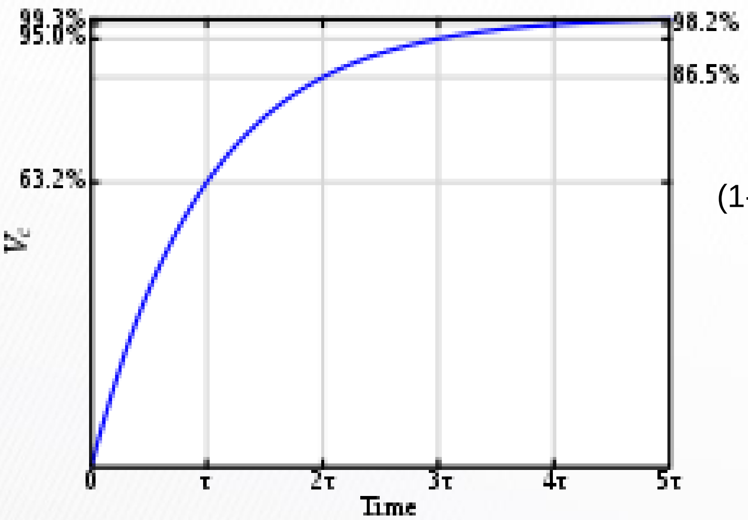
$T(t)$ 时间 t 时的被测温度

$T_m(t)$ 时间 t 时传感器测得的温度



$$T_{TT\_TC}(f,\tau_{FW}) = \frac{1}{1+\left(2\pi f\tau_{FW}\right)^2}$$

传感器反应速度与湍流团频率



时间常数(τ_{FW})

传感器感应到63.2%被测物理量所需的时间。

$(1-\frac{1}{e})=0.632$

$$\tau_{FW} = 0.167 D^2 \frac{\rho_{FW} C_{FW}}{k_a \mathbf{Nu}}$$

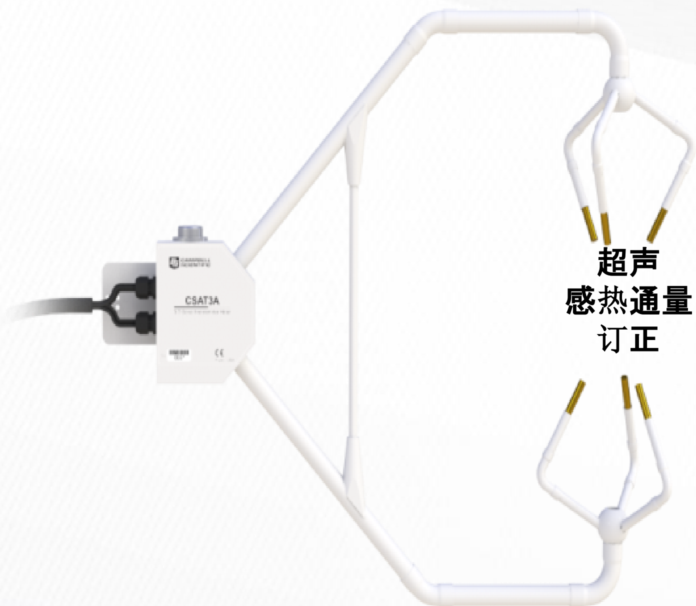
D dimension

ρ_{FW} material density of thermocouple

C_{FW} specific heat of thermocouple materials

k_a thermal conductivity of air

Nu Nusselt number



Schotanus et al. (1983)

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

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

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

WPL 修正

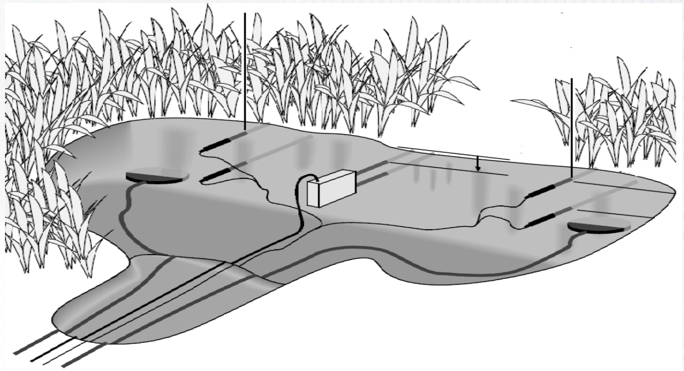
Correct *H*, *E* & F_c co-spectra first for high & low frequency filtering

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

2) $\overline{E} = (1 + \overline{\chi}_v)\left[\overline{w'c_v'} + \frac{\overline{c}_v}{\overline{\overline{T}}} \frac{\overline{H}}{\overline{\overline{\rho}} c_p}\right]$

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

土表热通量计算



RealTime(realtime_array(1))
Offset_intv = ((3600*hour + 60* minute + seconds) MOD (60*OUTPUT_INTERVAL))

Δ_soil_heat = ((Tsoil_current_Avg - Tsoil_prev_Avg)*CDS*soil_bulk_density +
(Tsoil_current_Avg*soil_wtr_current_Avg –
Tsoil_prev_Avg*soil_wtr_prev_Avg)*1000*CW)*
thick_abv_SHFP/(60*OUTPUT_INTERVAL-Offset_intv)

Offset_intv = 0 'Reset time interval offset

G_surface = G + Δ _soil_ht_storage

通量源区特征

footprint characteristics

1. Footprint_dist_interest　兴趣范围内通量累计贡献率
2. Footprint_max　通量贡献率最大位置
3. Footprint_40%　累计通量贡献率40%范围
4. Footprint_55%　累计通量贡献率55%范围
5. Footprint_90%　累计通量贡献率90%范围

Kljun et al (2004) 通量源区模型

$$-200 \le \left(z_m - d\right)/L \le 1$$

$$u_* \ge 0.2$$

$$z_m - d \ge 1\,\mathrm{m}$$

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

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

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

Kormann and Meixner (2001) 通量足源模型

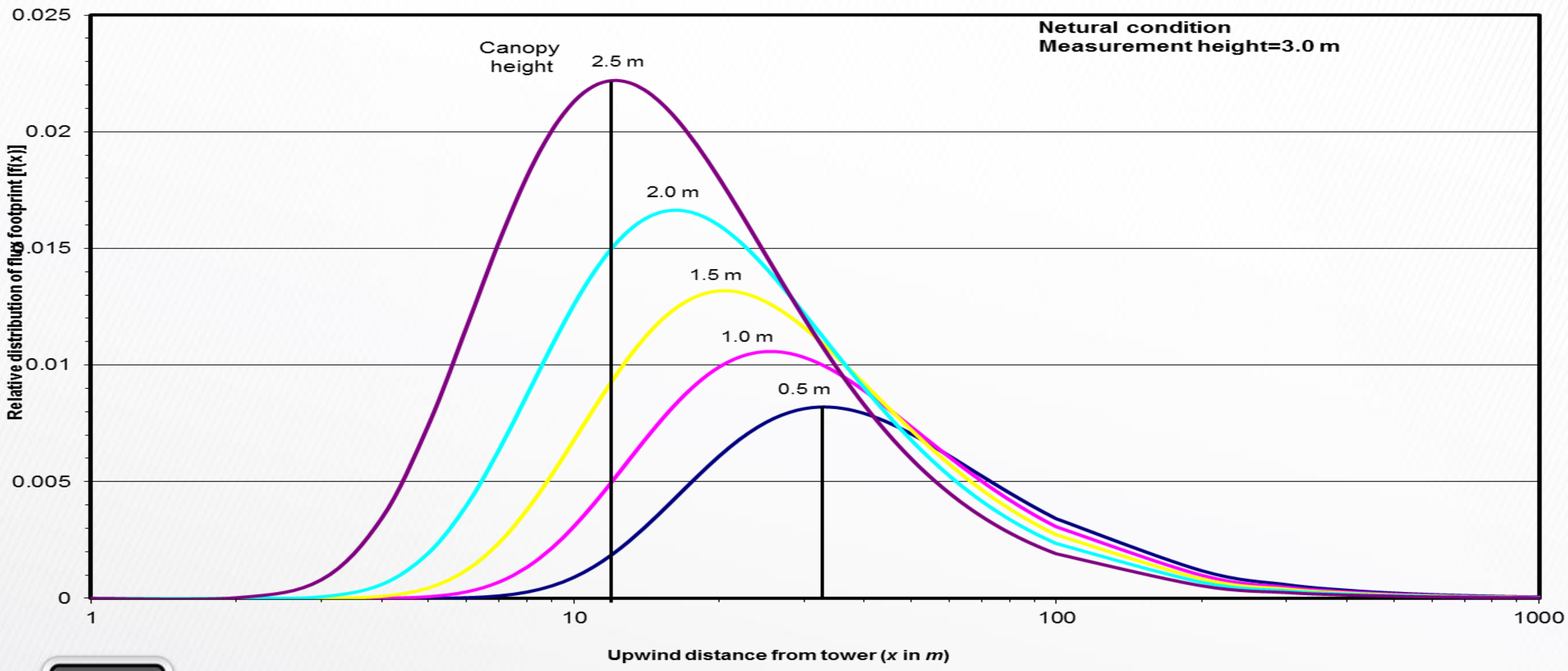
$$f_y(x,z) = \frac{1}{\Gamma(\mu)} \xi^{\mu} \left(\frac{z^{m+1}}{x^{\mu+1}} \right) \exp\left(-\xi \frac{z^r}{x} \right),$$

$$r = 2 + m - n$$

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

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

通量足源特征计算的数字积分方法



数据质量分级

相对大气非稳定性，相对综合湍流特征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]

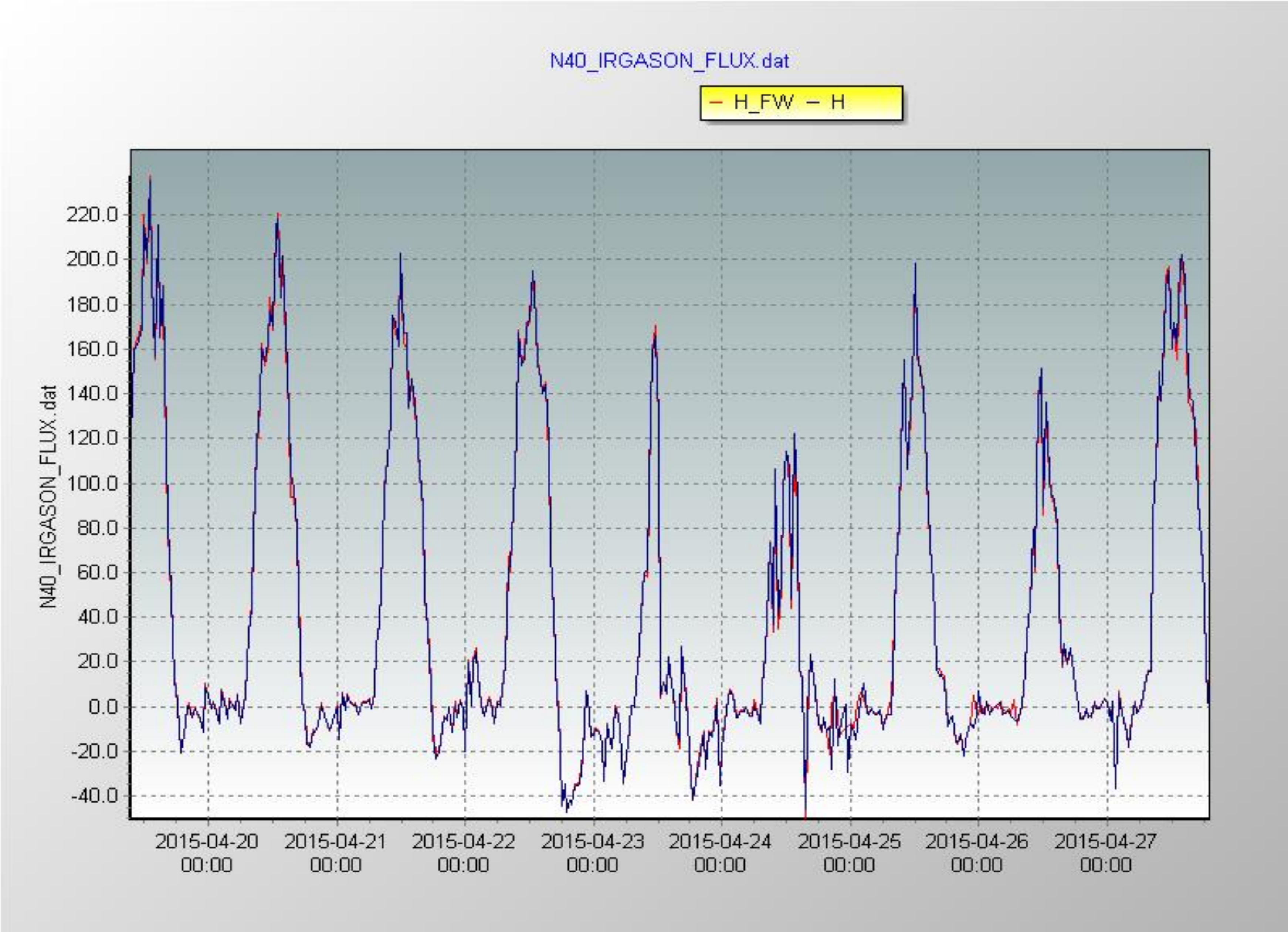
相对大气非稳定性 Foken et al. (2012) 模型 2.3		相对综合湍流特征 Foken et al. (2012) 模型 2.3		风向 （定义在超声坐标系）	
级	范围 (%)	**级**	范围 (%)	级	范围
1 (高)	[0 , 15)	**1 (高)**	[0 , 15)	1 **(高)**	$[0-150^o],[210-360^o]$
2	[15 , 30)	**2**	[15 , 30)	2	$(150-170^o],[190-210)$
3	[30 , 50)	**3**	[30 , 50)	3 **(低)**	$(170-190)^o$
4	[50 , 75)	**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%		

综合相对大气非稳定性，相对综合湍流特征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]

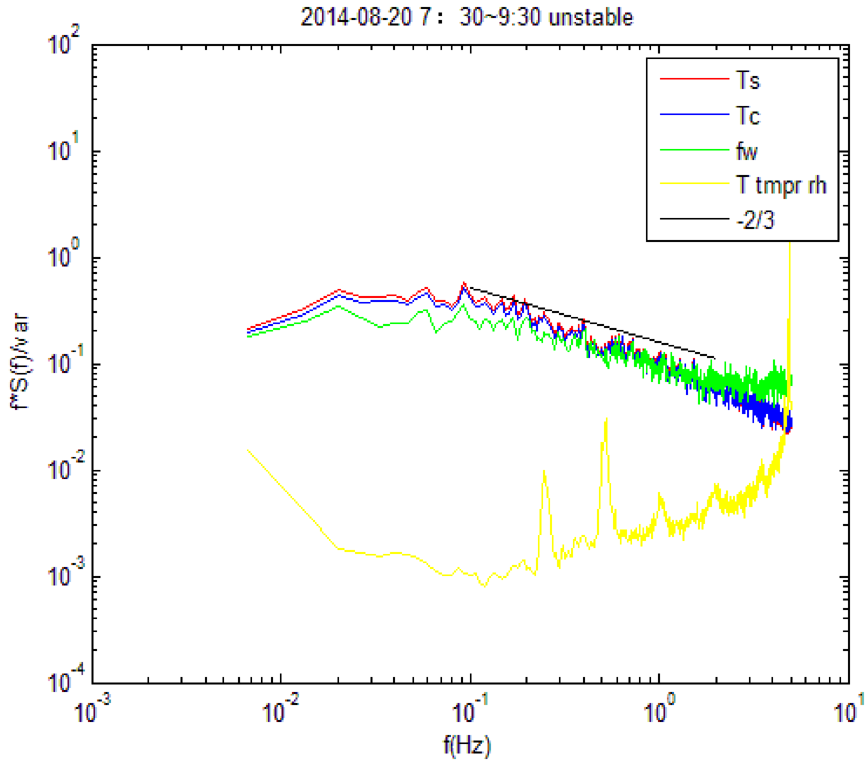
总质量等级	RN_{cov}	ITC_{sw}	wnd_dir_sonic
	相对大气非稳定性	相对综合湍流特征	风向
1 (高)	1	1 - 2	1
2	2	1 - 2	1
3	1 – 2	3 - 4	1
4	3 – 4	1 - 2	1
5	1 – 4	3 - 5	1
6	5	5	2
7	6	6	2
8	7 – 8	7 – 8	2
9 (低)	9	9	3

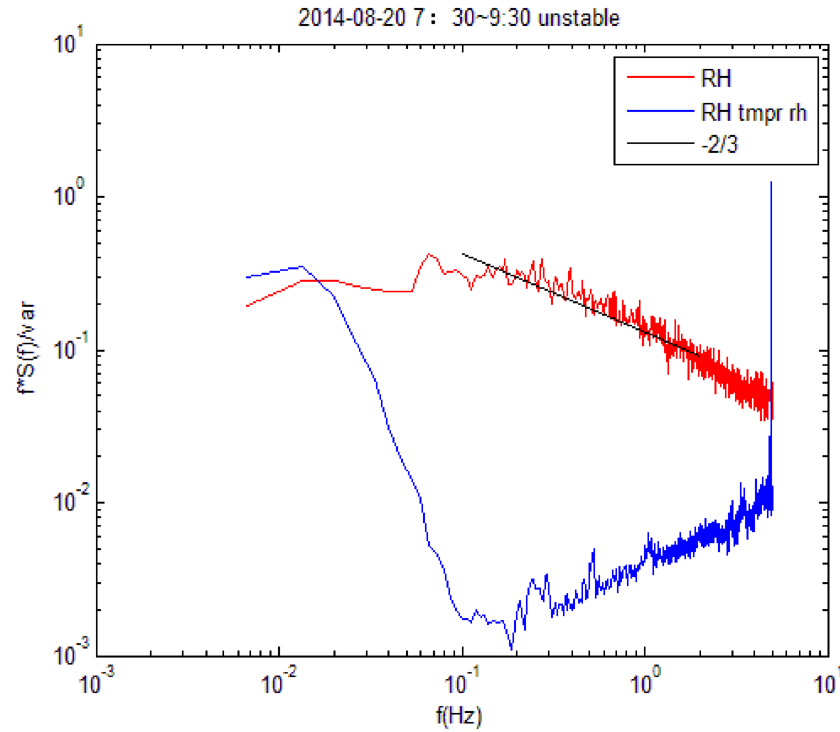
系统优点

1. 野点去除基于仪器物理技术和大气物理
2. CO_2和H_2O与风速是同时测得
3. CO_2和H_2O与风速是同空测得（IRGASON）
4. 真感热通量
5. 高频温湿度

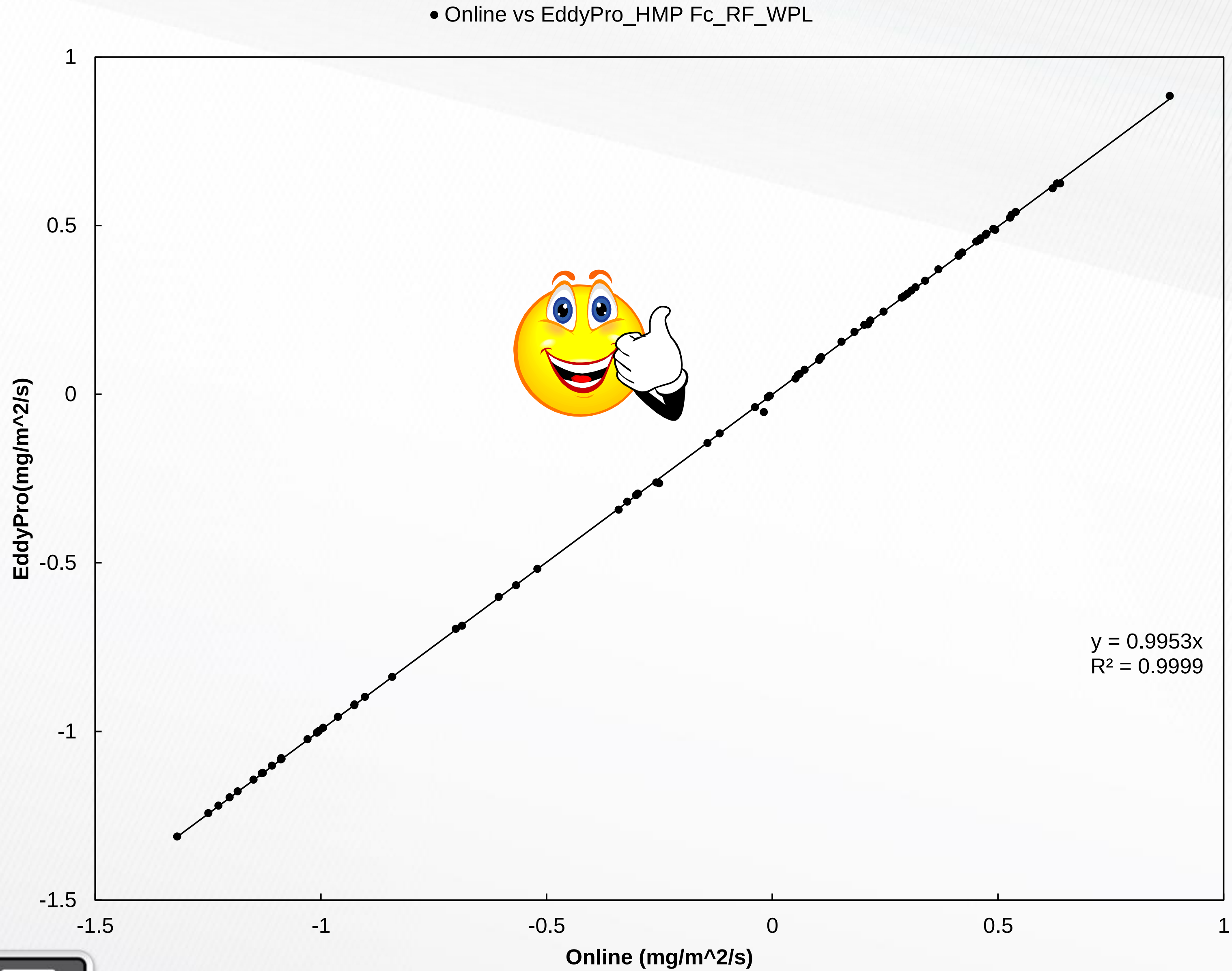


N40_IRGASON_FLUX.dat
H_FW
H
N40_IRGASON_FLUX.dat
220.0
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
2015-04-20 00:00
2015-04-21 00:00
2015-04-22 00:00
2015-04-23 00:00
2015-04-24 00:00
2015-04-25 00:00
2015-04-26 00:00
2015-04-27 00:00

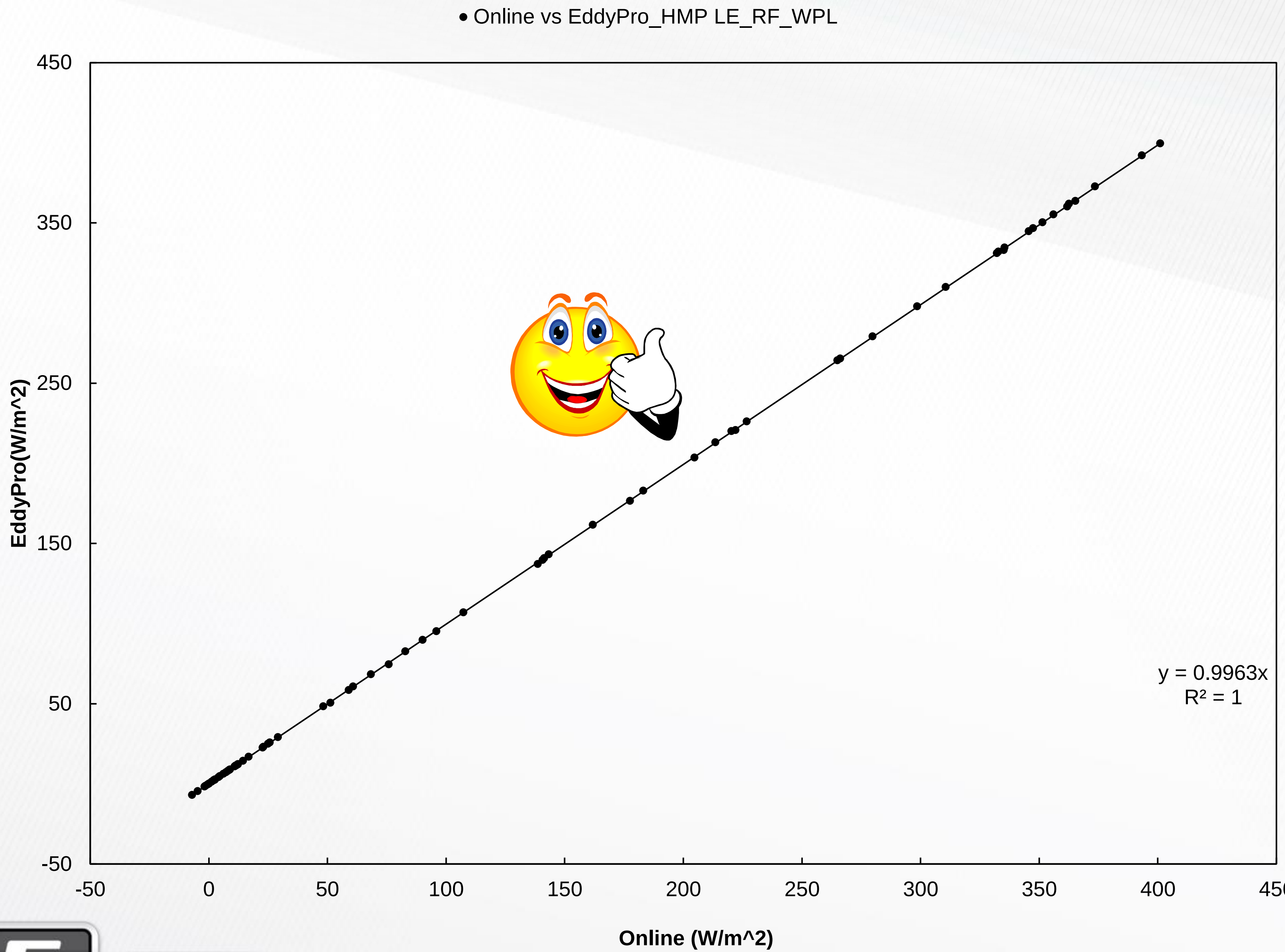

2014-08-20 7： 30~9:30 unstable
Ts
Tc
fw
T tmpr rh
-2/3
f*S(f)/var
f(Hz)


2014-08-20 7： 30~9:30 unstable
RH
RH tmpr rh
-2/3
f*S(f)/var
f(Hz)


EC100

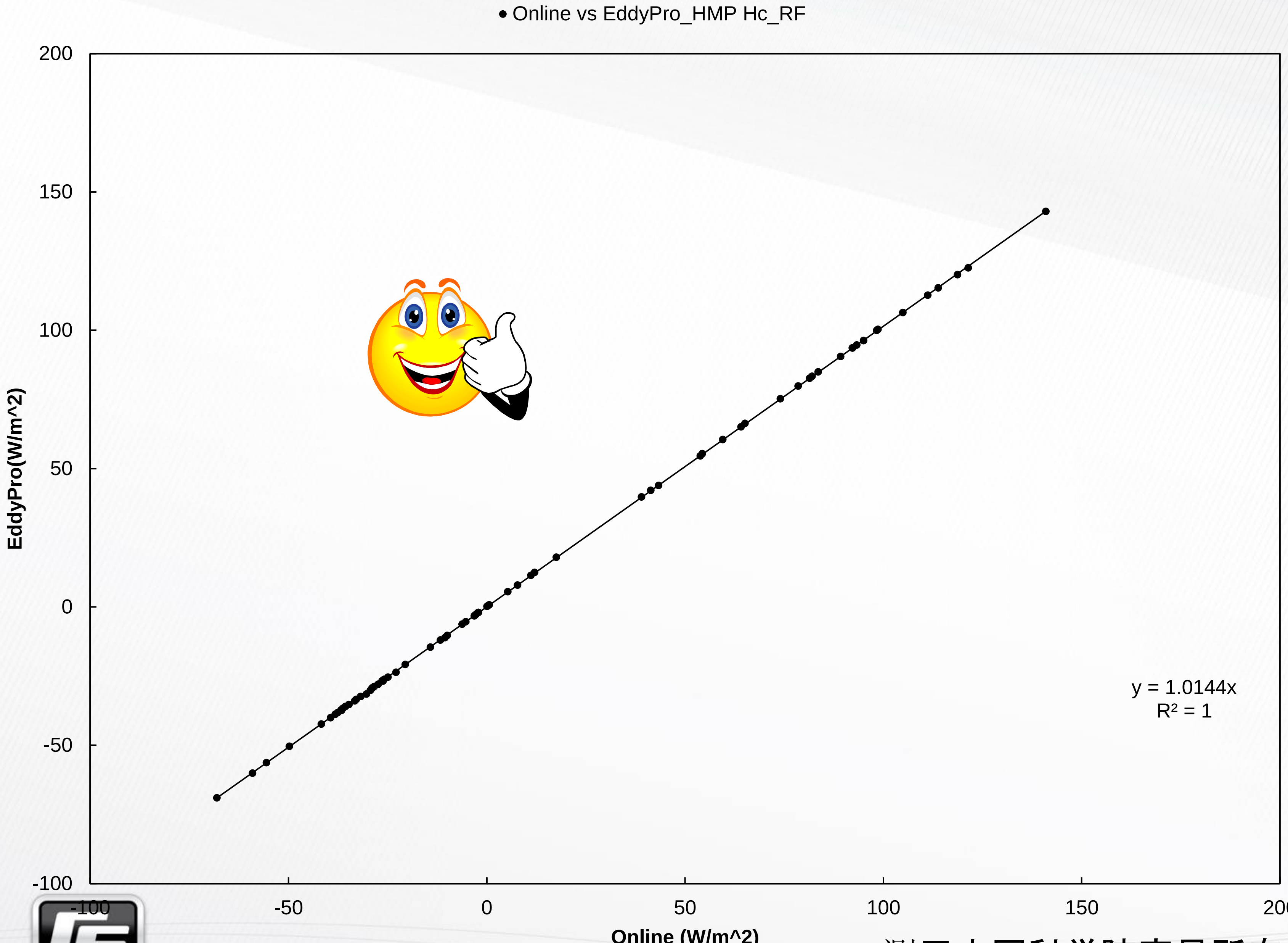


测于中国科学院寒旱所奈曼站
土地类型:玉米



测于中国科学院寒旱所奈曼站

土地类型:玉米



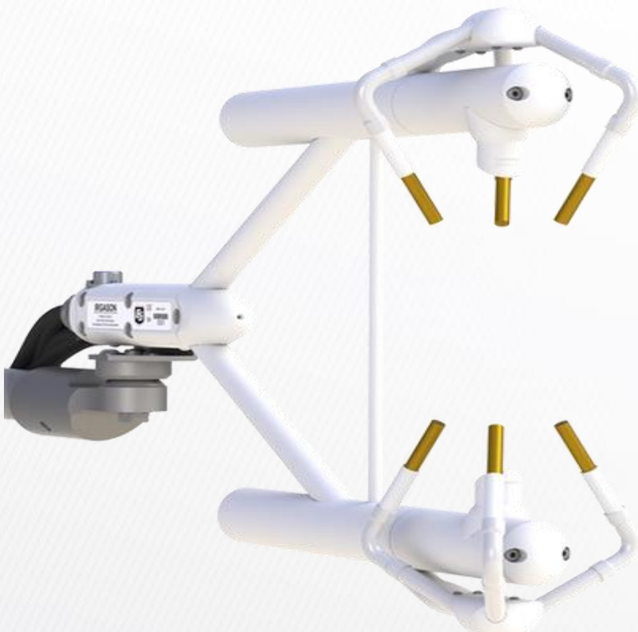
测于中国科学院寒旱所奈曼站
土地类型:玉米

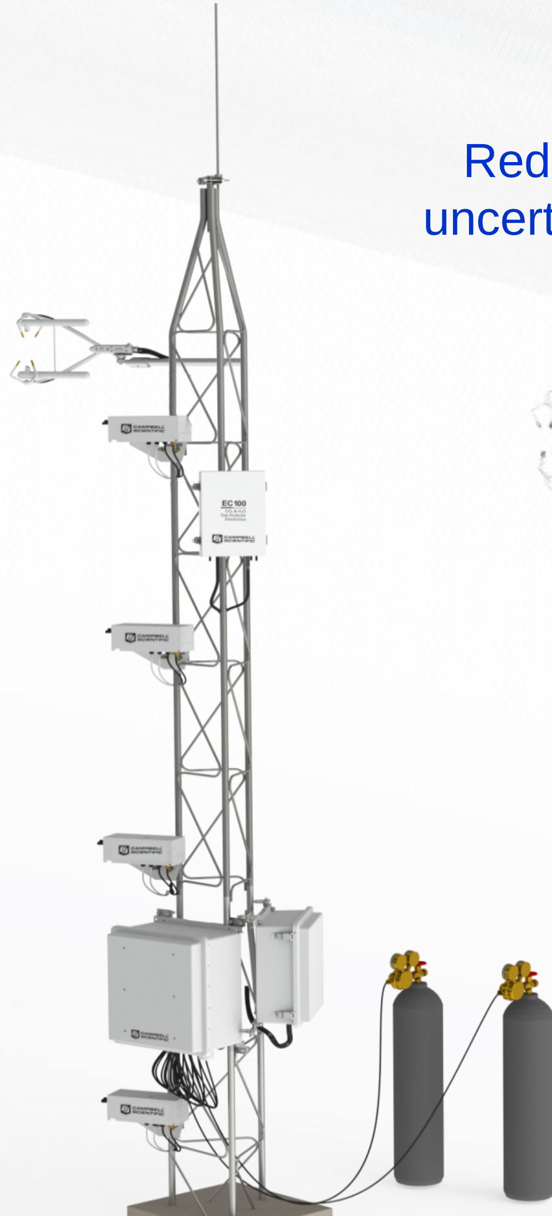
Less hypothesis

Fewer corrections

Reduced uncertainties

Better Accuracy





IRGASON
Integrated Infrared and sonic CO2/H2O gas analyzer

AP200
Atmospheric Profile system

CPEC200
Close-Path Eddy Covariance system


Questions
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谢谢