INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
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SMR/760-30

"College on Atmospheric Boundary Layer and Air Pollution Modelling"
16 May - 3 June 1994

"Inst-umentation and its Capabilities"

D.P. LALAS
Lambda Technical Corporation
Athens, Greece

Please note: These notes are intended for internal distribution only.

Gaussian Plume Eq.

needed as import $(\sigma_y, \sigma_z, u, h)$

$$\chi(x,y,z,h) = \frac{Q}{2\pi \sigma_y \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+h}{\sigma_z}\right)^2\right]\right\}$$

Effective rise

$$h = h_0 + 1.6\, F_0^{2/3}\, u^{-1}\, x^{2/3}$$

Convective conditions: $h_f = h_0 + 3\left(\frac{F_0}{u}\right)^{3/5} H^{-2/5}$

Near neutral atmospheric conditions: $h_f = h_0 + 1.54\left(\frac{F_0}{u u_*^2}\right)^{2/3} h_0^{1/3}$

also u_* friction velocity

Stable atmospheric conditions: $h_f = h_0 + 2.6\left(\frac{F_0}{us}\right)^{1/3}$

also s stability

plume induced

$$\sigma^2 = \sigma_0^2 + \sigma_t^2.$$

background turbulence induced

$$\sigma_{zt} = \sigma_\phi \times f_z\left(\frac{x}{uT_z}\right)$$

inverted correlations (wyngaard)

required

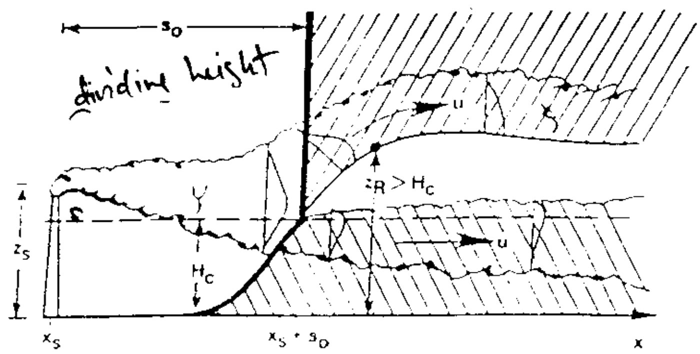
$$\sigma_{yt} = \sigma_\theta \times f_y\left(\frac{x}{uT_y}\right)$$

for CTDM or CTDM+
(complex terrain)

$$\frac{1}{2}u^2(H_c) = \int_{H_c}^{H} N^2(z)(H-z)\,dz$$

$$N^2 = \frac{g}{T_0}\frac{d\theta}{dz}$$

needed



CML model scheme

To compute profiles you need velocity measurement + temperature possibly

$$u(z) = \frac{u_*}{k}\left[\ln\left(\frac{z}{z_0}\right) - \psi_m\left(\frac{z}{L}\right) + \psi_m\left(\frac{z_0}{L}\right)\right]$$

to be computed

$$L = -\frac{u_*^3 \overline{T}}{g k H}\rho c_p \qquad \text{M-O length}$$

$$\left[\quad H = -\rho c_p u_* \theta_* \quad\right]$$

alternatively $\theta_* = kR\Delta\theta \Big/ \left[\ln\frac{z_{T2}}{z_{T1}} - \psi_h\left(\frac{z_{T2}}{L}\right) + \psi_h\left(\frac{z_{T1}}{L}\right)\right]$

$$\Delta\theta = \Delta T + 0.01(z_2 - z_1)$$

$$H = R_n - H_e - H_g$$

R_n = net radiation $= b_0 + b_1 \sin\theta_s + b_2 \sin^3\theta_s$ ... $a_0 + a_1 u + a_2 u^2 + a_3 T^6$

H_e = latent heat flux $= \frac{q(z_0) - q(z)}{r_w}\rho c_p/\gamma$

H_g = heat flux to ground ... αH

$$\frac{d\theta_m}{dt} = \frac{1}{z_i}\left[(\overline{\theta w})_s - (\overline{\theta w})_i\right]$$

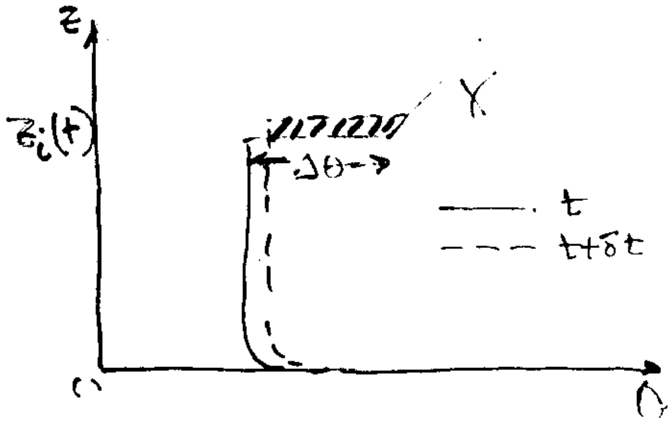
$$\frac{d\Delta\theta}{dt} = \gamma\frac{dz_i}{dt} - \frac{d\theta_m}{dt}$$

$$-(\overline{\theta w})_i = \Delta\theta\frac{dz_i}{dt}$$

$$-(\overline{\theta w})_i = A_e(\overline{\theta w})_s + A_m u_*^3 \overline{T}/(g z_i)$$

Tennekes + Driedonks (1981)

CML scheme to compute mixed layer depth z_i



$$\frac{d\theta_m}{dt} = \frac{1}{z_i}\left[(\overline{\theta w})_s - (\overline{\theta w})_i\right]$$

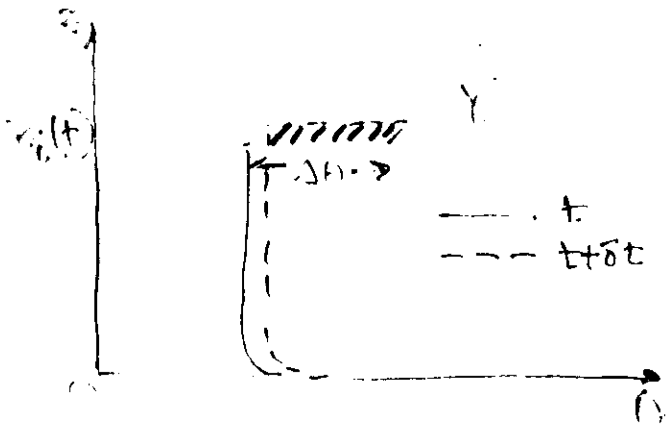
$$\frac{d\Delta\theta}{dt} = \gamma\frac{dz_i}{dt} - \frac{d\theta_m}{dt}$$

$$-(\overline{\theta w})_i = \Delta\theta\,\frac{dz_i}{dt}$$

$$-(\overline{\theta w})_i = A_\theta\,(\overline{\theta w})_s + A_m u_*^3 T/(g z_i)$$

Tennekes + Driedonks (1981)

CTH scheme to compute mixed layer depth z_i



Anemometry

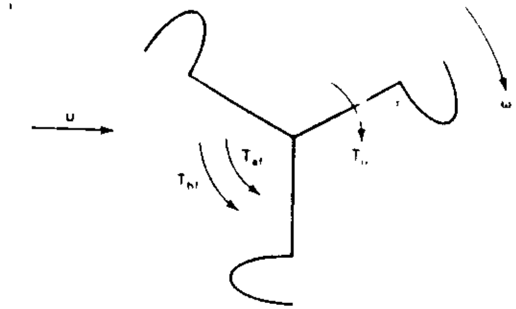


Figure 3.6 Torques or moments existing on a cup type anemometer.

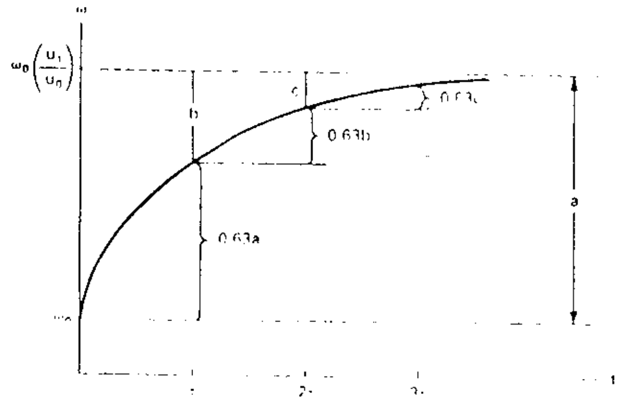


Figure 3.7 Anemometer response to a step function change in wind speed.

ANEMOMETER EQUATIONS

$$\boxed{I\alpha = I\frac{d\omega}{dt} = T_u - T_{bf} - T_{af}}$$

T_u = torque from wind

T_{bf} = torque from bearing friction

T_{af} = torque from aerodyn. friction

I = mom. of inertia

Typically

$$T_{af} \simeq a_0\omega^2 + a_1\omega + a_2 \simeq k_1\omega_0 u$$

$$T_u \sim f(u) \qquad \simeq k_1 \omega u_0$$

$$T_{bf} \simeq k_{bf}\omega$$

Then

$$I\frac{d\omega}{dt} \simeq -(k_{bf} + k_1 u_0)\omega + k_1\omega_0 u$$

Solution (rads/sec)

$$\omega = \frac{\omega_0}{(k_{bf}+k_1u_0)}\left\{k_1u_1 + \left[k_{bf}+k_1(u_0-u_1)\right]e^{-t/\tau}\right\}$$

where $\tau = \dfrac{1}{k_{bf}+k_1u_0}$

OR

$$\boxed{\omega \simeq \omega_0\frac{u_1}{u_0} + (u_0-u_1)\frac{\omega_0}{u_0}e^{-t/\tau}} \qquad \boxed{\tau \simeq \frac{1}{k_1u_0}}$$

Typically during transition

$$u_i \simeq k_1\omega$$

and for cup anemometers tip speed ≃ wind speed

$$\Rightarrow \quad k_1 \simeq O(R)$$

propeller anemometers tip speed ≃ 5-6 u

k_1 ≃ smaller by almost 10

Note at equilibrium

$$u_0 = k_i\omega_0$$

so

$$u_i = k_1\omega = u_1 + (u_0-u_1)e^{-t/\tau}$$

One can rewrite the equation as

$$\dot{\omega} = -au\omega + bu^2 - c\omega^2 - d\omega$$

note then

$$\omega_k - \omega_{k-1} = T\left(-au_{(k)}\omega_k + bu^2_{(k)}\right) \quad \text{note}$$

$$\omega_k = \frac{\omega_{k-1} + bTu_k^2}{1+aTu_k} \rightarrow \hat{y}_k = \frac{a}{b}\bar{\omega}_k = \frac{y_{k-1}+aT\bar{u}_k^2}{1+aT\bar{u}_k}$$

compute $k = \left(\dfrac{\partial y_k}{\partial \bar{u}_k}\right)$

and $\boxed{\hat{u}_k = \bar{u}_k + k(y_k - \bar{y}_k)}$

and for low noise $\boxed{\hat{u}_k \simeq \dfrac{y_k}{2}\left\{1 + \left[1 + 4\dfrac{(y_k - y_{k-1})}{aTy_k^2}\right]^{1/2}\right\}}$

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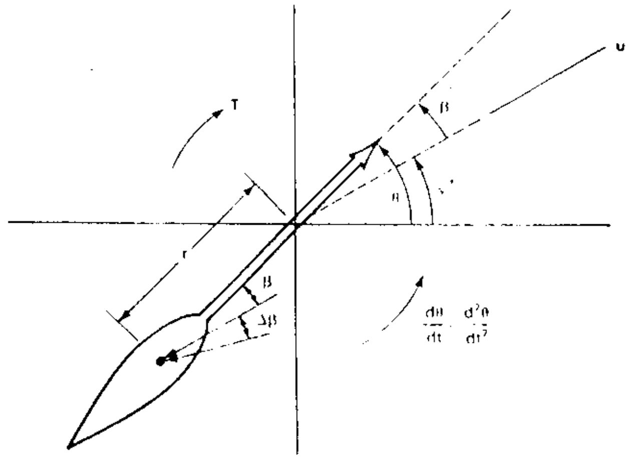
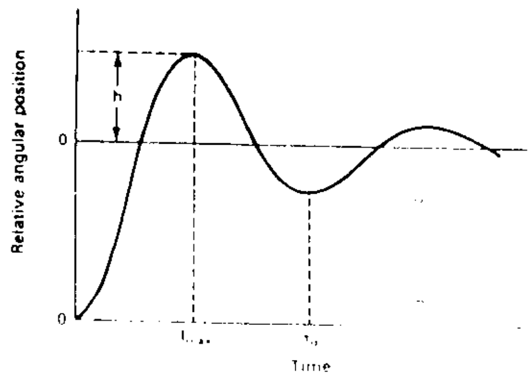
Table 20. Anemometer Characteristics

Manufacturer and Instrument	Model	Distance Constant, m
Teledyne Geotech:		
Standard 3-cup	Series 50	1.5
Staggered 6	Series 50	1.0
Stainless Steel 3-cup	Series 50	2.4
Bendix Friez Instrument Division:		
Aerovane (3-blade prop.)	Model 120	4.6
Aerovane (6-blade prop.)		5.8
Climet Instruments Inc.:		
3-cup	WS-011	1.5
4-blade prop. (bivane)	018-10,-30	0.9
Electric Speed Indicator Co.:		
3-cup	Type F-420C	7.9
R. M. Young Co.:		
Gill anemometer, 3-cup		0.73
Meteorology Research, Inc.:		
Velocity Vane	1057	1.7 to 1.8
Mechanical Weather Station	1071-1075	5.5
Vector Vane (bivane)	1053 III	1.0
C. W. Thornthwaite Associates:		
3-cup		1.07
Climatronics, Corp.:		
3-cup	F460	1.5
3-cup	WM-I	0.76
3-cup	WM-III	2.5
Belfort Instrument Co.:		
Aerovane (3-blade prop.)	Model 120	4.6
3-cup	1250B	7.6
3-cup	Type M	6.4

WIND VANE ANALYSIS



Wind vane angles.



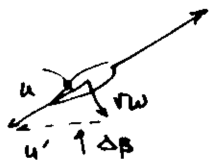
Overshoot h and damped period τ_d of direction vane tested in a

WIND VANE EQUATION

$$\boxed{I\frac{d^2\theta}{dt^2} = -T = -Fr \simeq cA\rho\frac{u^2}{2}(\beta+\Delta\beta)}$$

A = area

c = constant



$\rightarrow \Delta\beta = \frac{rw}{u}$ $\quad \frac{d\theta}{dt} = w$ & $\beta = \theta - \gamma$

$$\frac{d^2\theta}{dt^2} + \frac{cA\rho u r^2}{2I}\frac{d\theta}{dt} + \frac{cA\rho u^2 r}{2I}\theta = \frac{cA\rho u^2 r}{2I}\gamma$$

or

$$\frac{d^2\theta}{dt^2} + 2\xi\omega_n\frac{d\theta}{dt} + \omega_n^2\theta = f(t)$$

with $\quad \omega_n = u\sqrt{c\rho A r/2I}$

$\quad \xi = \sqrt{c\rho A r^3/8I}$

---

and I.C.s $\quad \theta(0^+) = 0 \quad , \omega(0^+) = 0$

and initially $\gamma = 0$ but $\gamma(0^+) = \gamma_1$

General solution $\quad \Theta = A_1e^{s_1t} + A_2e^{-s_1t} \quad s_{1,2} = -\omega_n\xi \pm \omega_n\sqrt{\xi^2-1}$

Instead write this as:

$$\boxed{\theta = \gamma_1 + Be^{-\omega_n\xi t}\sin(\omega_d t + \sigma)}$$

where $\quad \omega_d = \omega_n\sqrt{1-\xi^2}$

WIND VANE EQs - 2

with damped sinusoid solution & I.C.s

$$B = -\gamma_1/\sin\sigma$$

$$\sigma = \tan^{-1}\left(\frac{\omega_d}{\omega_n\xi}\right) = \tan^{-1}\left(\frac{\sqrt{1-\xi^2}}{\xi}\right)$$

Then if $\xi = 0$, $\omega_d = \omega_n$ = "natural frequency"

ξ = "damping ratio"

typically we want $\xi \approx 0.5 - 0.6$ $\quad$ * $\quad \xi < 1.0$ oscillations - underdamped

$\xi > 1.0$ monotonic change - overdamped

$\xi = 1.0$ critically damped

If you use a step input, then you observe the values for overshoot, h, damped period, τ_d and time for overshoot, $t_{max} = \frac{\tau_d}{2}$, then

$$\theta(t = t_{max}) = \gamma_1 + h = \gamma_1\left[1 - e^{-\omega\xi t_{max}}\frac{\sin(\sigma+\pi)}{\sin\sigma}\right]$$

$$\Rightarrow \quad \xi = \frac{-\ln h}{\sqrt{\pi^2 + (\ln h)^2}} \quad \& \quad \tau_n = \tau_d\sqrt{1-\xi^2}$$

so $\quad \lambda_g = u\tau_n$ = "gust wavelength"

note $\quad \tau_d = 2t_{max} = \frac{2\pi}{\omega_d} = \frac{\tau_n}{\sqrt{1-\xi^2}}$

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Table 21. Values of the Damping Ratio and Gust Wavelength for Various Wind Vanes

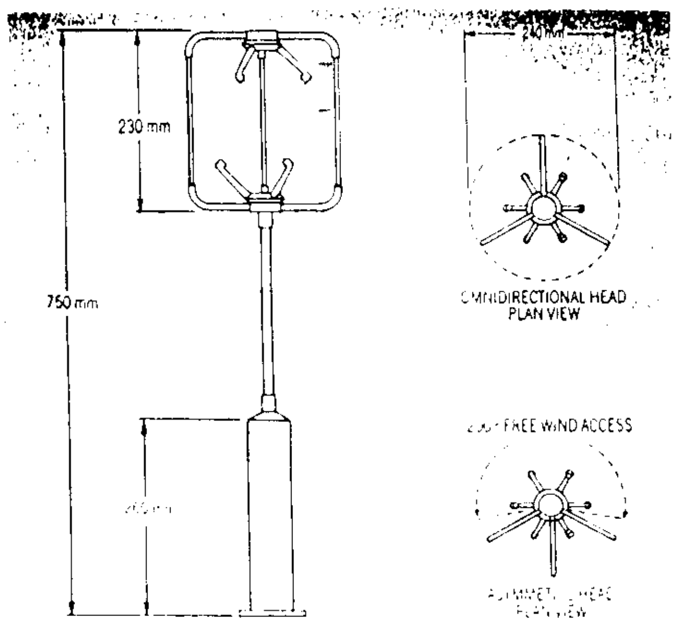
Manufacturer	Model	Damping Ratio (ζ)	Gust Wavelength (λ_n), m
Bendix Friex Instrument Division:			
Aerovane	120	0.28	10.4[a]
Wind Vane	–	0.5	1.8[a]
Climet Instrument Inc.:			
Wind Vane	WD-012-10	0.4	1.0[a]
Bivane	018-10-50	0.6	1.0[a]
Electric Speed Indicator Co.:			
Splayed Vane	F420C	0.14	17.7
R. M. Young Company:			
Gill Anemometer-Bivane		0.60	4.4
Belfort Instrument Co.:			
Splayed Vane	Type M	0.20	9.5
Aerovane	Type L & N	0.30	10.4
Meteorology Research, Inc.:			
Wind Vane	1022	0.4	1.13[a]
Vector Vane (bivane)	1053	0.6	1.0[a]
Mechanical Weather Station	1071-1075	0.50-0.60	6.8
Weather Measure Corp.:	W101-P-AC	0.20-0.28	18.0
	W101-P-HF	0.22-0.29	16.5
Climatronics Corp.	F460	0.4	1.12
	WM-I	0.4-0.6	0.76
	WM-III	0.4-0.6	2.45
Teledyne Geotech.	53.1	0.6	1.7[a]
	53.2	0.4	1.1[a]
	107-61	0.2	0.5[a]

[a]Reported as distance constants.

ULTRASONIC ANEMOMETER RANGE

Abbreviated Specifications

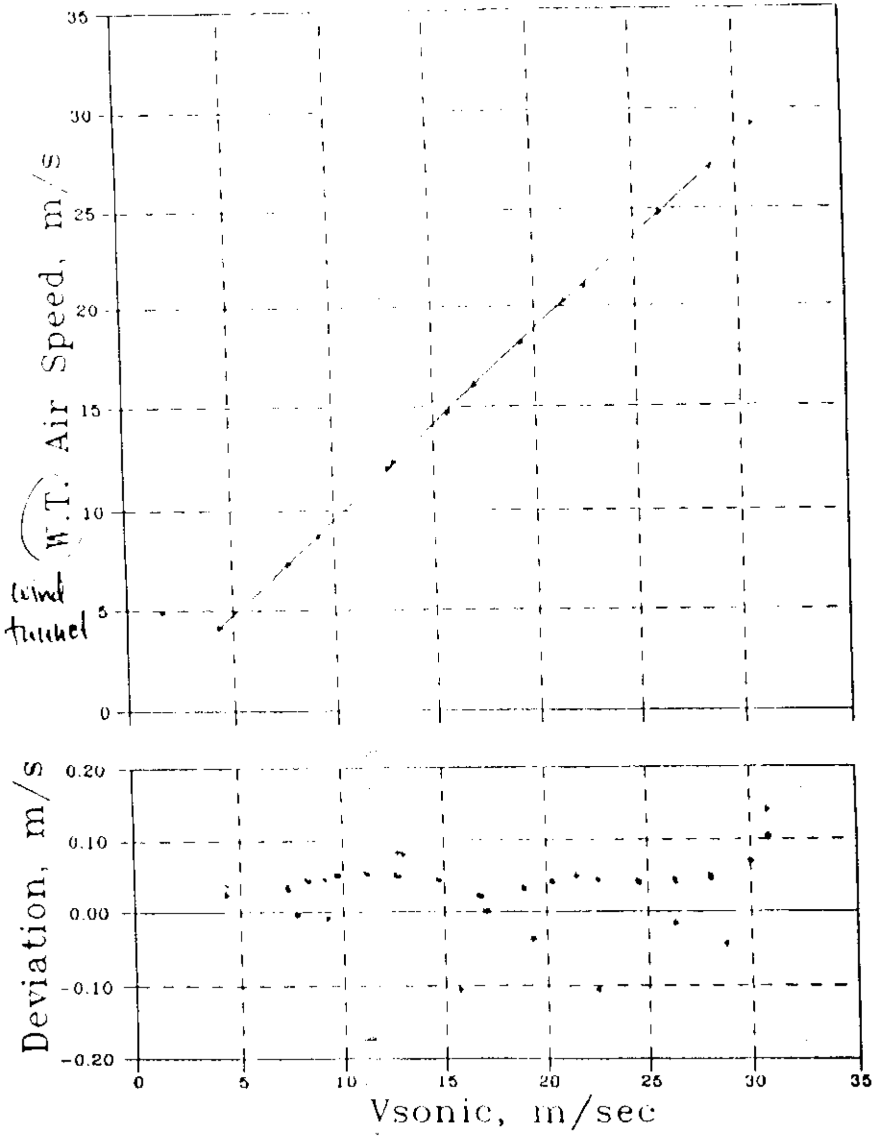
	STANDARD	MET/LOGGING	RESEARCH
Principal Application	Operational meteorology	Survey/AWS	Micrometeorology
Ultrasonic Sampling Rate per vector set	20/second	50/second	168/second
Data Output Rate	1/second 0.5Hz	4/second 2Hz	21/second 10HZ or 56/second 28HZ
Windspeed Range	0 – 60 m/s	0 – 60 m/s	0 – 60 m/s
Power Requirement (or 110/240V AC via PSU)	9 – 30V DC 110mA max	9 – 30V DC 130mA max	9 – 30V DC 150mA max
Calibration	Generic	Generic	Custom
Windspeed Accuracy (10 Sec Average)	<30m/s ±3% >30m/s ±5%	<30m/s ±3% >30m/s ±5%	<30m/s ±1% >30m/s ±2%
Instantaneous Accuracy			<30m/s ±3%
Windspeed offset	±0.02m/s	[illegible]	±0.02m/s
Direction Accuracy (10 Sec Average)	<30m/s ±2° >30m/s ±4°	[illegible]	<30m/s ±1° >30m/s ±2°
Speed of Sound Accuracy	–	[illegible]	<30m/s ±0.5%
Cal/maintenance requirement	None	[illegible]	None
Analogue Output	0 – 5V 10bit	[illegible]	2.5V ±2.5V 11bit total
Analogue Output Data	Direction, Speed, [illegible] vertical speed	[illegible]	U V W Speed of Sound or 2.5V Ref
Analogue O/P Speed Range	60m/s	[illegible]	±30m/s or ±60m/s



Calibration

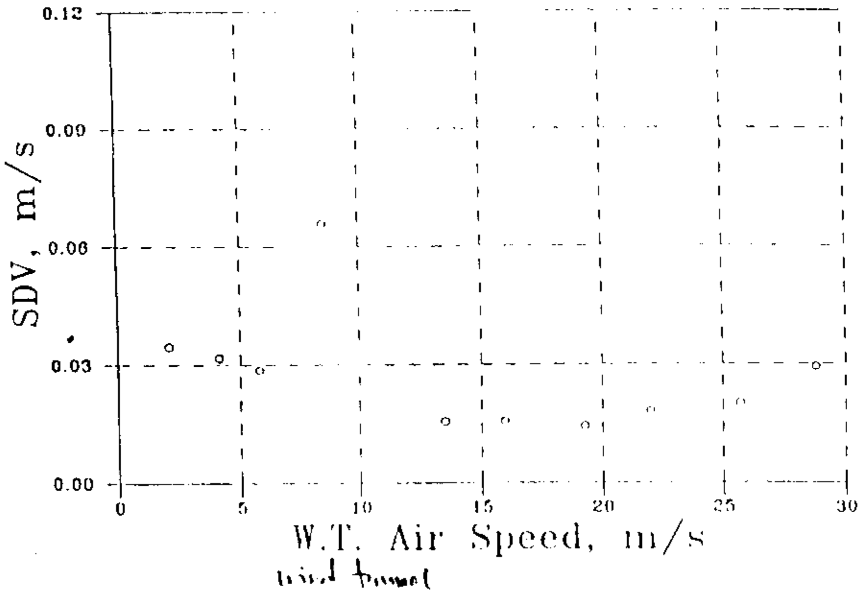
SONIC GILL, 0 deg, Date 4-3-1993

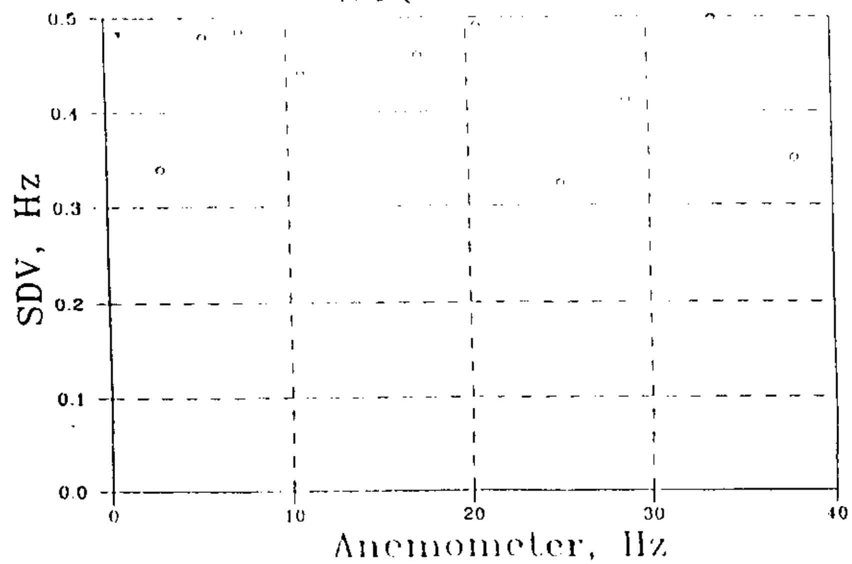
$V_{WT}(m/sec) = 0.940 * V_{son}(m/sec) + 0.061$



Calibration

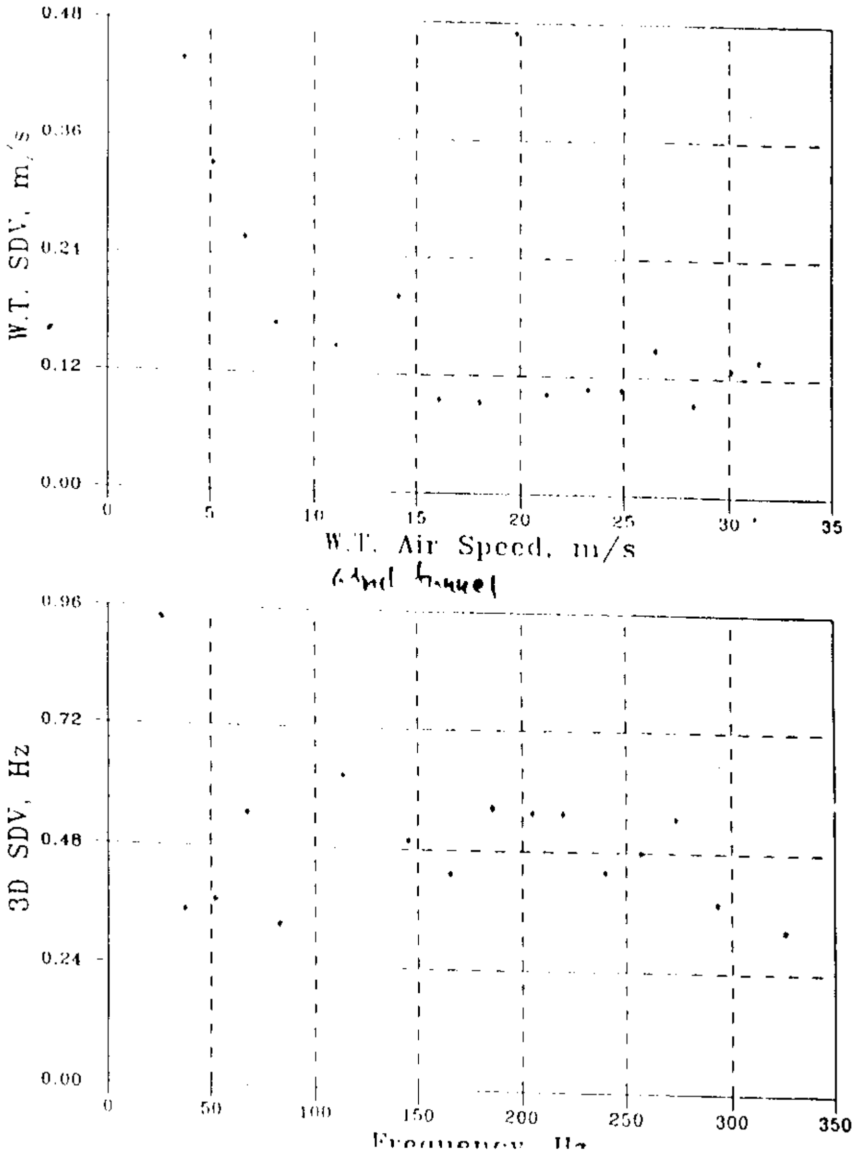
CUP NRG OTC 212, Date 26-2-1993





Calibration

3P FRIEDRICH, Date 19-2-1993



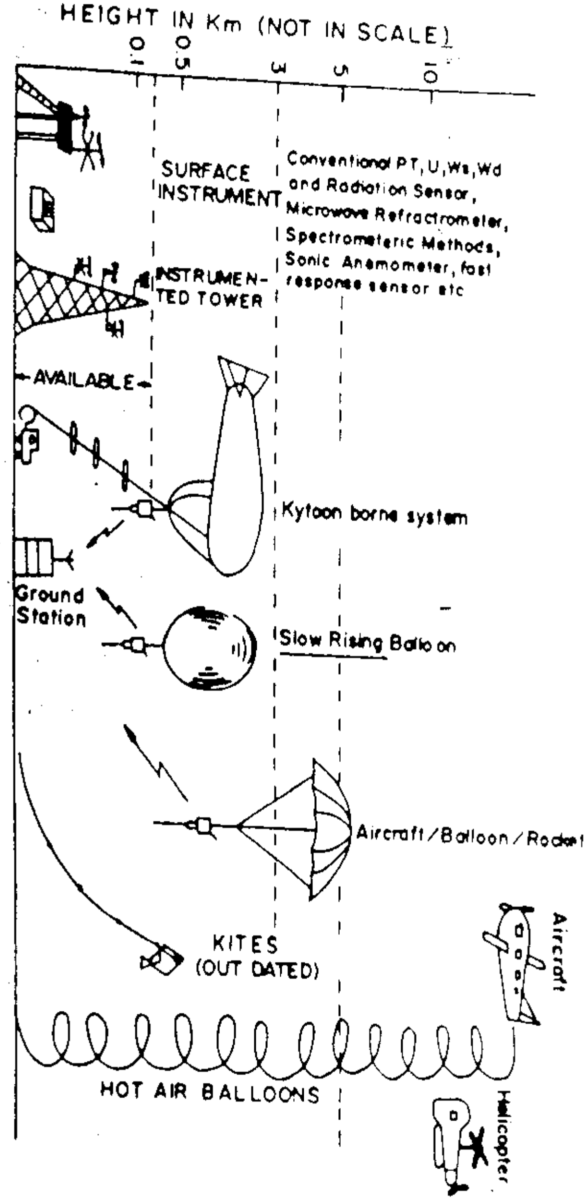
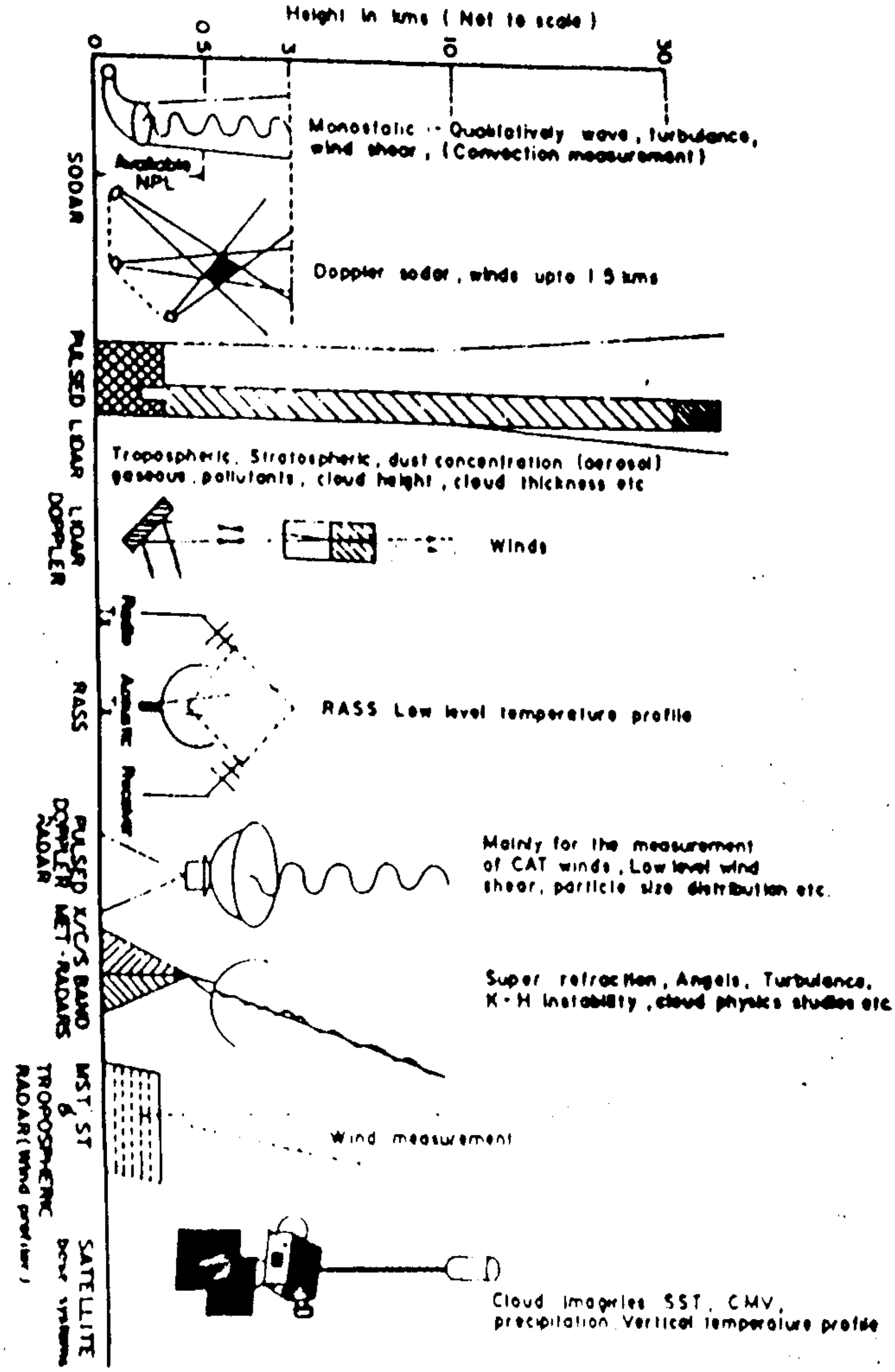


FIG 1 DIRECT SENSING TECHNIQUES.


Height in kms (Not to scale)
0
0.5
3
10
30
SODAR
Available NPL
Monostatic -- Qualitatively wave, turbulance, wind shear, (Convection measurement)
Doppler sodar, winds upto 1.5 kms
PULSED LIDAR
Tropospheric, Stratospheric, dust concentration (aerosol) gaseous pollutants, cloud height, cloud thickness etc
LIDAR DOPPLER
Winds
RASS
RASS Low level temperature profile
PULSED DOPPLER RADAR
Mainly for the measurement of CAT winds, Low level wind shear, particle size distribution etc.
X/C/S BAND MET-RADARS
Super refraction, Angels, Turbulence, K-H Instability, cloud physics studies etc
MST, ST & TROPOSPHERIC RADAR (Wind profiler)
Wind measurement
SATELLITE
Cloud imageries SST, CMV, precipitation Vertical temperature profile

Remote Sensing Techniques

SODAR (ΔN qualitative)

DOPPLER SODAR (winds)

LIDAR (Aerosol concentration)

DOPPLER LIDAR (Winds)

DOPPLER RADAR (Winds)

VHF/UHF RADAR (Winds)

S/X band RADAR (Super refraction)

RASS-Radio acoustic sounding system (Temperature profile)

Satellite based systems

ACOUSTIC SOUNDING

$$P_r = P_t \, c \, \tau \, \sigma(\gamma) \, A \, \frac{B}{2R^2} \exp\left(-2\bar{a}R\right)$$

c = speed of sound

τ = pulse length

A = area of antenne

B = beam shape factor

$\bar{a}$ = mean attenuation coefficient

$\sigma(\gamma)$ = scattering cross section

R = range

For homogeneous & isotropic turbulence

$$\sigma(\theta) = 0.03\, k^{1/3} \cos^2\theta \left[\frac{C_v^2}{c^2} \cos\frac{\theta}{2} + 0.136 \frac{C_T^2}{T^2} \right] \left(\sin\frac{\theta}{2}\right)^{-11/3}$$

" acoustic power scattered per unit incident flux per unit solid angle at a scattering angle θ (or γ)"

$$C_v^2 = \overline{\left[V(x) - V(x+r)\right]^2} / r^{2/3}$$

$$C_T^2 = \overline{\left[T(x) - T(x+r)\right]^2} / r^{2/3}$$

Atmospheric structure parameters

ACOUSTIC SOUNDING - 2

But also (Kaimal 78)

$$C_x^2 = 13.6\, S_x \left(\frac{f}{u}\right)^{2/3} f$$

S_x = power spectrum of x
u = mean wind speed
f = frequency

But from Obukhov + Kolmogorov

$$C_T^2 \simeq \alpha^2\, \epsilon^{-1/3}$$

while

$$C_V^2 \simeq 2.0\, \epsilon^{2/3}$$

Note that (Wyngaard) also

$$\boxed{C_T^2 \simeq 2.68 \left(\frac{g}{T}\right)^{-2/3} \left(\rho c_p \frac{z}{H}\right)^{-4/3}}$$

where H = sensible heat flux

ACOUSTIC SOUNDING - 3

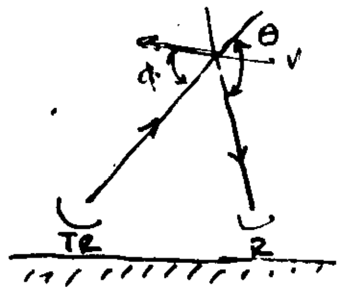
By Doppler effect

$$\Delta f = -\frac{2 f_0 V_i}{c}$$

f_0 = transmitted frequency
V_i = radial velocity
c = speed of sound

or

$$\Delta f = -\frac{2 f_0}{c} V \cos\phi \sin\frac{\theta}{2}$$



then for monostatic SODAR

$$w = \left(\frac{n_0}{n_d} - 1\right)\frac{c}{2}$$

n_d = Doppler-shifted freq.
n_0 = transmitted freq.

But also note that

$$\sigma_\phi \simeq \sigma_w / u$$

$$\sigma_\theta \simeq \sigma_v / u$$

and also

$$\sigma_w \simeq 0.6\, w_* \quad \text{convective turbulence}$$
$$\simeq 1.1\, u_* \quad \text{mechanical turbulence}$$

OR Baerentsen 1984 $\sigma_w \simeq 1.24\, w_* (z/h)^{1/3} \exp(-z/h)$ unstable
Nieuwstadt 1984 $\simeq 1.30\, u_* (1 - z/h)^{3/4}$ stable

ACOUSTIC SOUNDING - 4

- Note that

$$w_* = \left[\frac{g H z_i}{\rho C_p \bar{T}} \right]^{1/3}$$

where H = sensible heat flux

z_i = mixing depth (also h)

so with $\sigma_w \approx 0.6 w_*$ if σ_w is known $\rightarrow$ H computed

- Besides direct estimates of σ_q & σ_θ

use of σ_w and/or echo patterns

(Thomas, 1986) Singal (1985)

to predict stability categories

$\Longrightarrow$ standard curves

- Mixing depth o.k. for early morning hours (after sunrise)

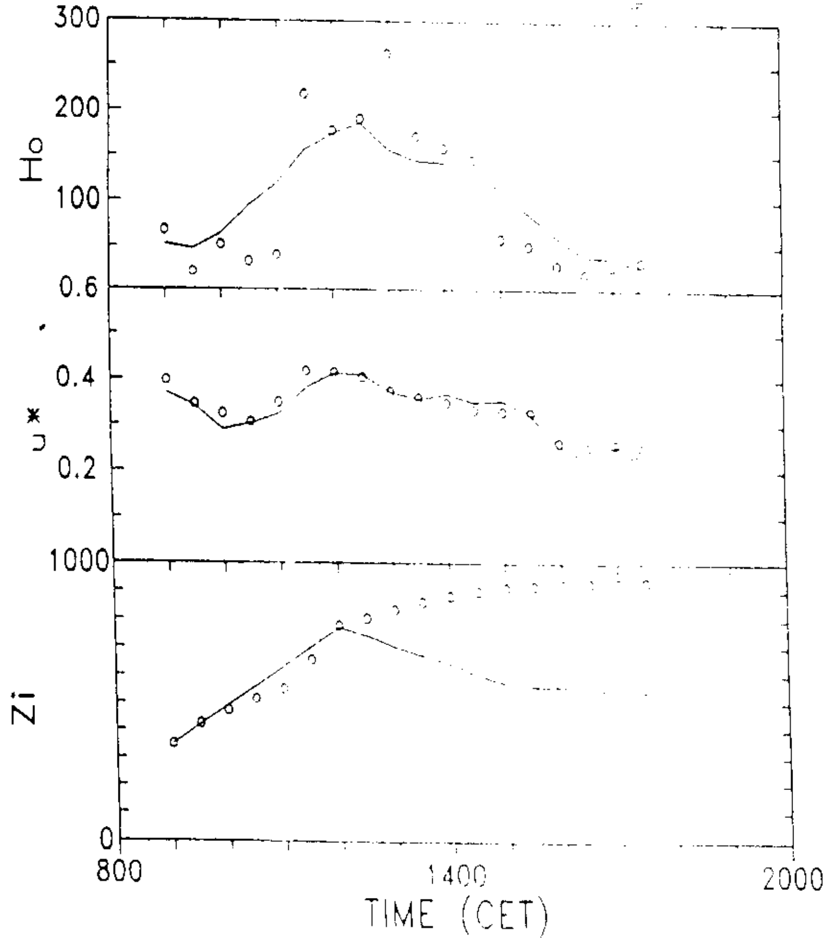


Figure 1. The diurnal variation [illegible] depth, z_i (m), the friction velocity, u_* (ms^{-1}), [illegible] H_0 (Wm^{-2}). Solid line: observations [illegible] estimations based on Equations (2)-(5).

$$\sigma_w = 1.24\, w_* \left(\frac{z}{h}\right) \exp(-z/h) \quad \text{UN}$$

$$\sigma_w = 1.30\, u_* \left(1 - \frac{z}{h}\right)^{0.75} \quad \text{ST}$$

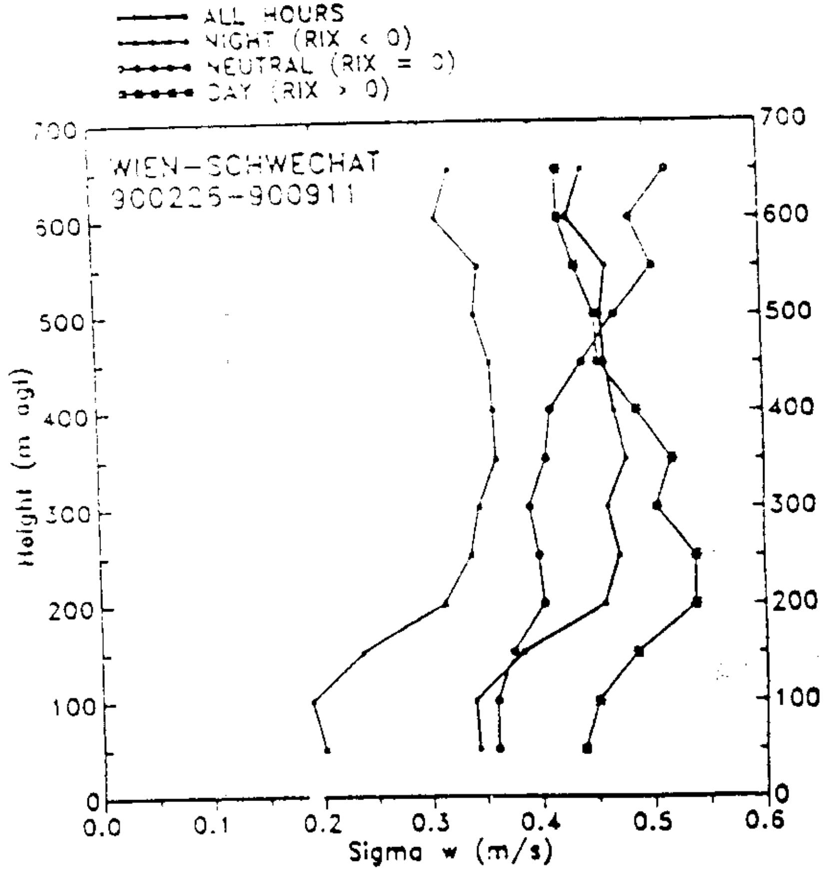


Fig. 2: Mean vertical profiles of σ_w at Schwechat for all hours and for different ranges of the radiation index RIX.

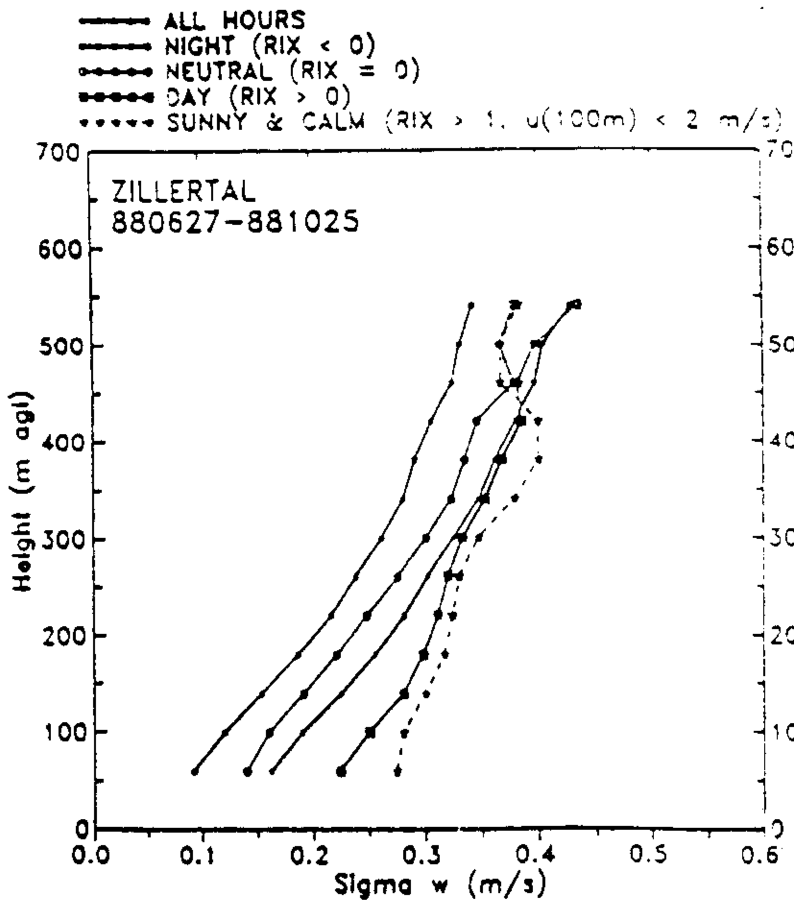


Fig. 3: Mean vertical profiles of σ_w at Zillertal.

Parameter	Acoustic	Radio
Frequency	360 Hz	159.000 MHz
Wave–lenght	0.94 m	1.88 m
Power	200 W	20 W
Array	9 folded horns	8 dipoles with reflector (each)
Beam	$7 \times 7\ m^2$	$25^o \times 25^o$
Location of antenna	half–way between radar antennas	20 m between antennas

Table 4: List of main parameters of the RASS

$$T = \left(\frac{4.7 \cdot 10^{-2} f_D}{1 + 4.714 \cdot 10^{-5}(H - 30)\cos(\operatorname{arctg}(\frac{d}{h}))}\right)^2$$

f_D = Doppler frequency shift

H = rel. humidity

d = $\frac{1}{2}$ distance between 2 antenna

h = height of observation

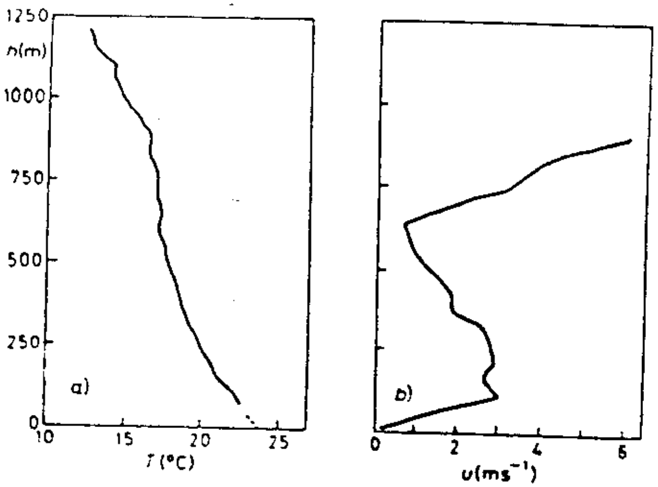


Fig. 8.2 - a) Example of thermal profile measured by RASS. June 2, 1982, 11 h; b) wind speed profile measured by Doppler SODAR in the same period.

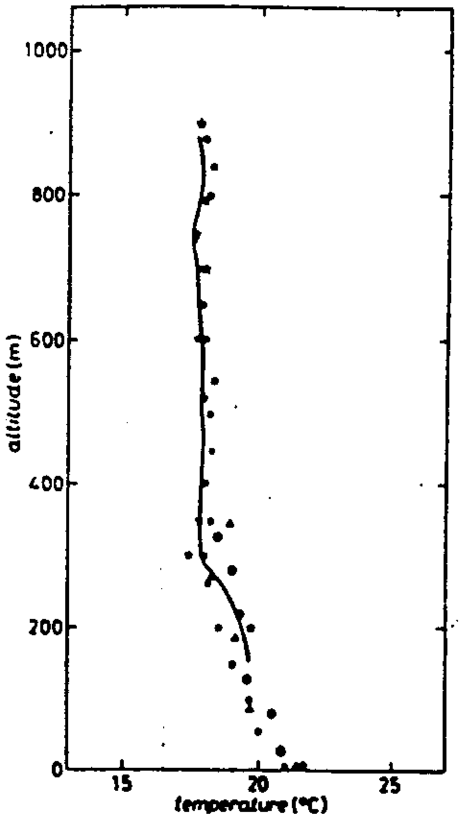


Fig. 8.3

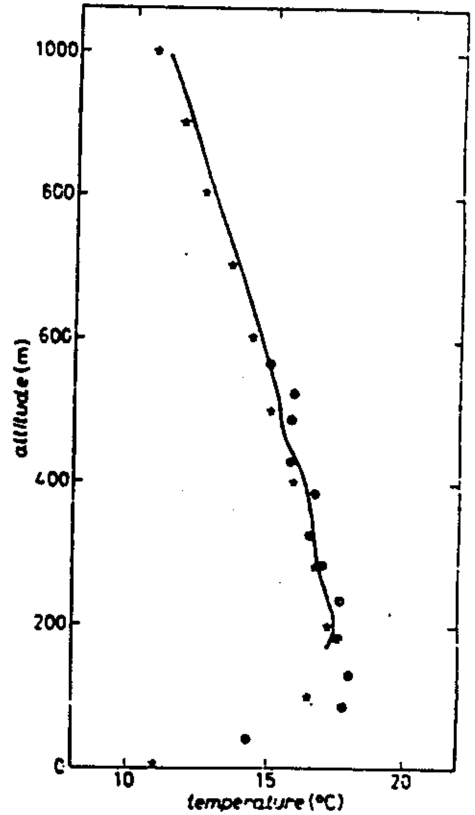


Fig. 8.4

Fig. 8.3 – Comparison of thermal profiles, September 15, 1979, 11 h 25 min: — RASS, ● radiosonde on tethered balloon (Istituto di Cosmo-geofisica), ★ radiosonde on disposable balloon (Joint Research Centre), ■ radiosonde on model aircraft (Central Electric Research Laboratory), ▲ radiosonde on tethered balloon (Université Catholique, Louvain).

Fig. 8.4 – Comparison of thermal profiles, September 17, 1979, 22 h 05 min: — RASS, ● radiosonde on tethered balloon (Istituto di Cosmo-geofisica), ★ radiosonde on disposable balloon (Joint Research Centre).