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SMR/113 - 22

AUTUMN COLLEGE
ON
THE TROPOSPHERE, STRATOSPHERE AND MESOSPHERE

10 September - 19 October 1984

ANNEX TO SMR/113-1 (the MST-radar technique)

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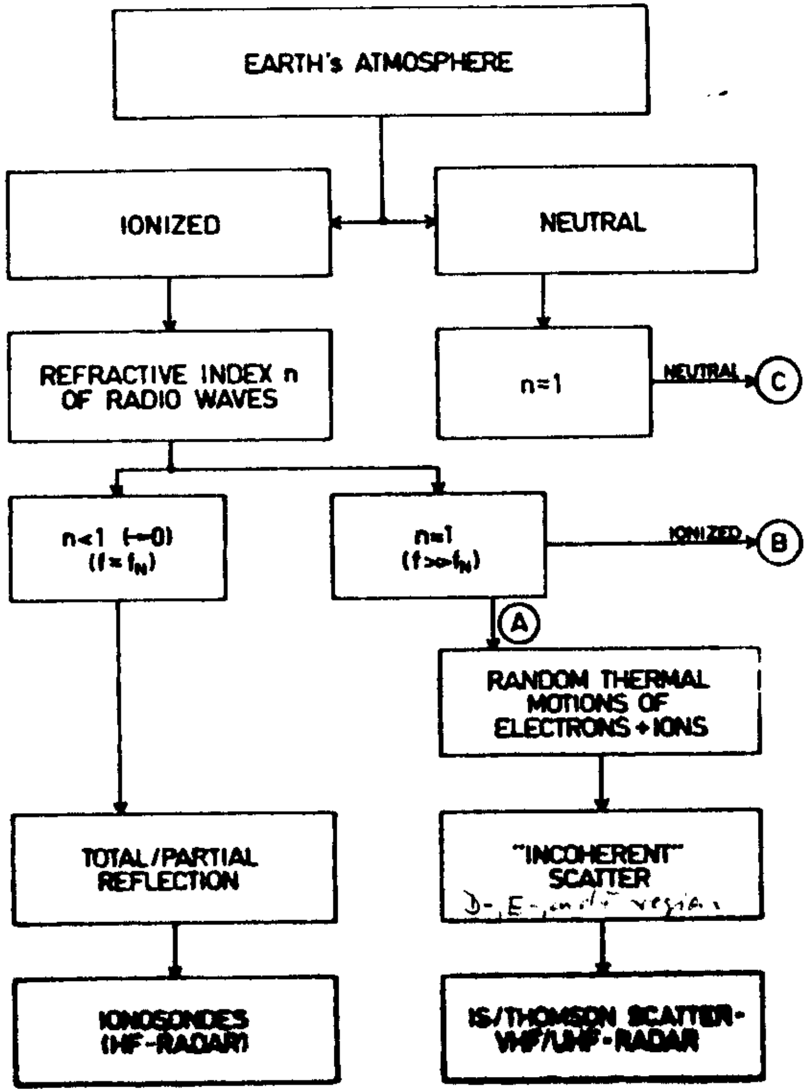

n = radio refractive index
f = radio wave frequency
f_N = plasma frequency

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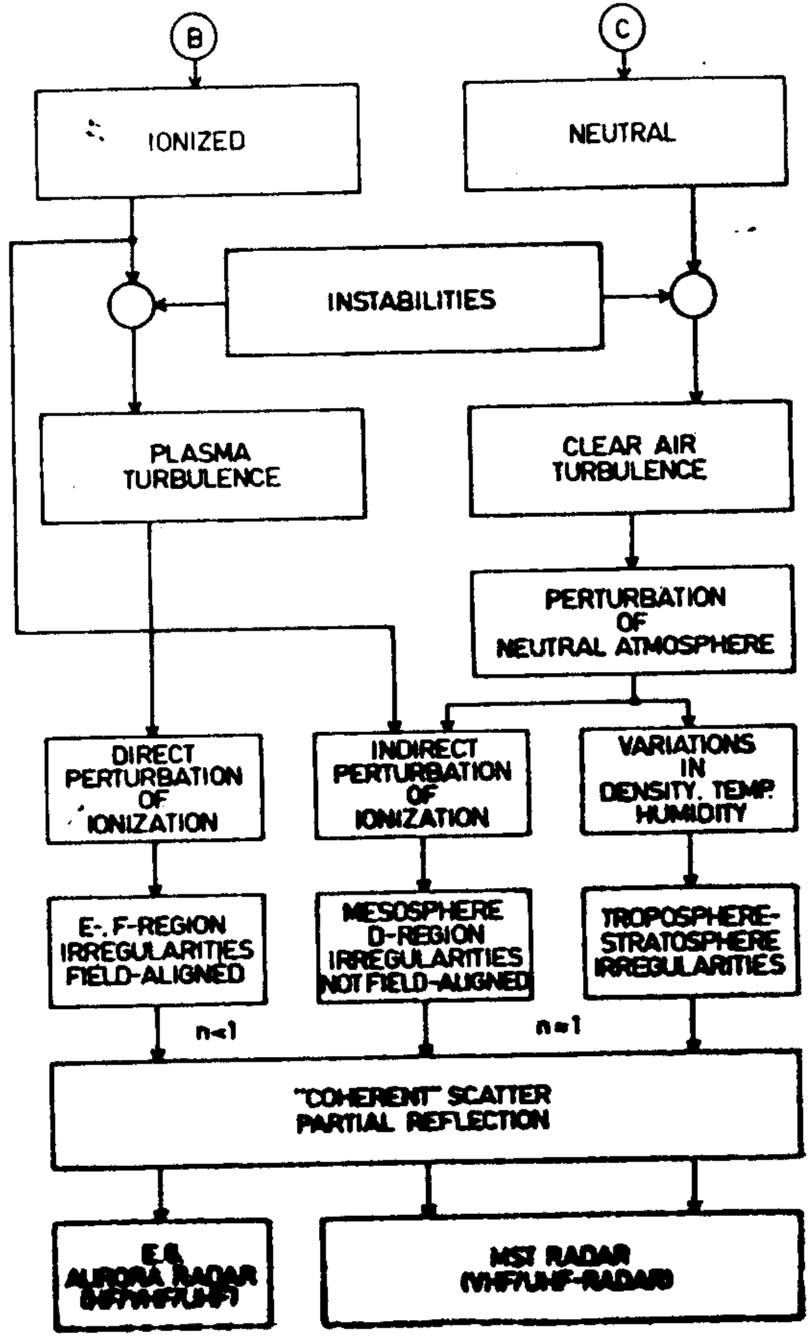

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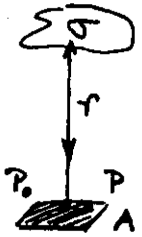
ATMOSPHERE RADIO DETECTING AND RANGING



RADAR EQUATION:

$$P = \frac{P_o\, G}{4\pi r^2} \cdot \frac{\sigma}{4\pi r^2} \cdot A$$

σ = radar cross-section

$$r = \frac{c\ t}{2}\ , \quad A = \frac{G \cdot \lambda^2}{4\pi}$$

A = antenna area

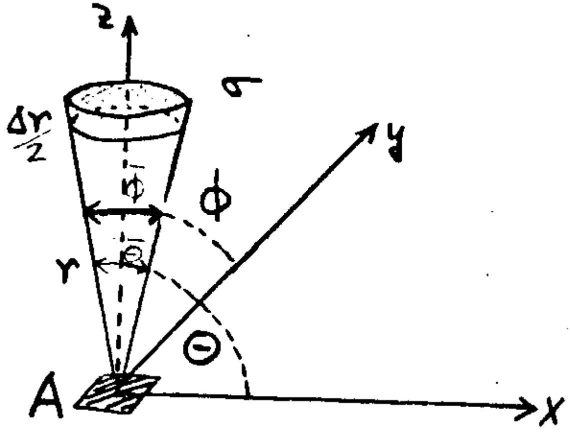
G = antenna gain

P_o = transmitted power

P = received power

r = range to the radar target with cross section σ

t = time the radio wave travelled from the radar to the target and return



volume scatter: $\sigma = \sum_V \sigma_i$

$$V = \pi \left(r \frac{\bar{\Theta}}{2}\right) \left(r \frac{\bar{\Phi}}{2}\right) \frac{\Delta r}{2}$$ (radar volume)

$$P = \frac{P_o\, G^2 \lambda^2\, \bar{\Theta}\, \bar{\Phi}\ \Delta r}{512\, \pi^2\ r^2}$$

with $G = \frac{4\pi A}{\lambda^2} \approx \frac{\pi^2}{\bar{\Theta}\bar{\Phi}}$

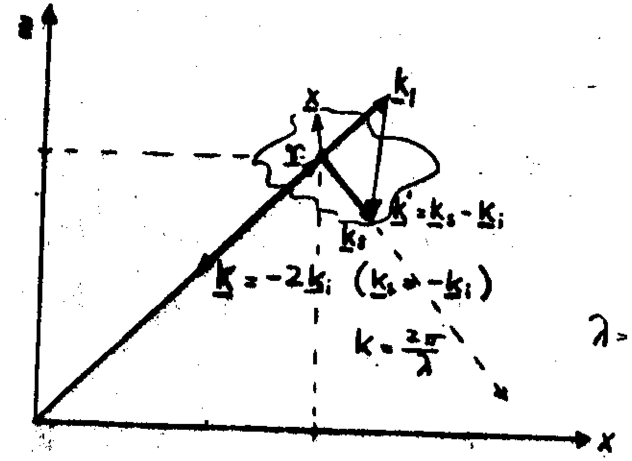
$$P = \frac{\pi\, P_o \cdot \varepsilon \cdot A \cdot \Delta r \cdot \sigma}{128\ r^2}\ , \quad \varepsilon A = \frac{G_o \lambda^2}{4\pi} = A_e$$

$$P = \frac{P_o \cdot G_o \cdot \lambda^2 \cdot \Delta r \cdot \sigma}{512\ r^2}$$

ε = antenna aperture efficiency

A_e = effective antenna area

$\Delta r/2$ is the extent of the radar volume in r-direction ($\hat{=}$ z), it is equal to the radar transmitter pulse length.



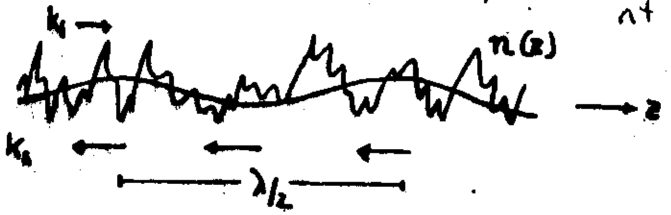
space-time auto-correlation function (ACF) of the radio refractive index:

$$\varrho(\underline{r},\tau) = \overline{n(\underline{x},t)\cdot n(\underline{x}+\underline{r},t+\tau)} - \overline{n(\underline{x},t)}^2$$

auto-correlation function of the backscattered signal:

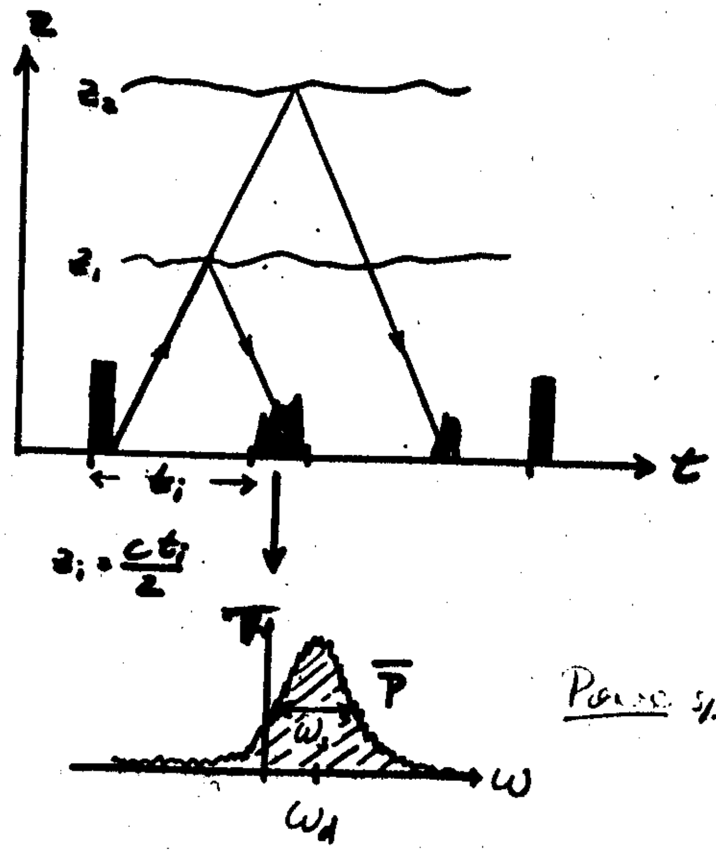
$$\Rightarrow \quad C(\tau) = \int \varrho(\underline{r},\tau)\cdot \exp(-i\,\underline{k}\cdot\underline{r})\, d\underline{r}$$

spatial filter at wavelength $\lambda/2$



The auto-correlation function of the radar signal $C(\tau)$ results from the spatial Fourier transform of the space-time auto-correlation function of the radio refractive index.

Principle of Doppler Radar



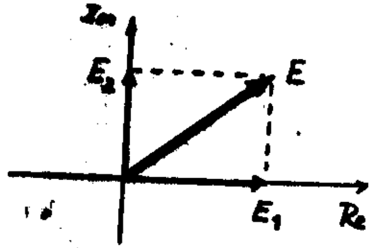
Power spectrum

For each height range z_i the power spectrum $F(\omega)$ has to be evaluated, which yields the moments (parameters):

- average power $\overline{P}$
- Doppler shift ω_d
- spectrum width ω_s

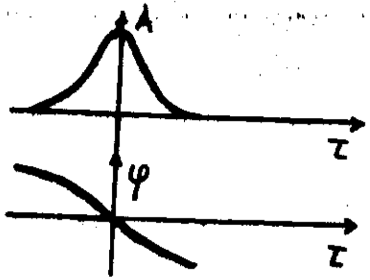
These are related to the space-time variations of the backscatter "radar volume".

Presentation of the real part E_1 and the imaginary part of the signal in the complex plane (Re , Im):



signal:

$$E(t) = E_1(t) + i\,E_2(t)$$



auto-covariance function (ACF):

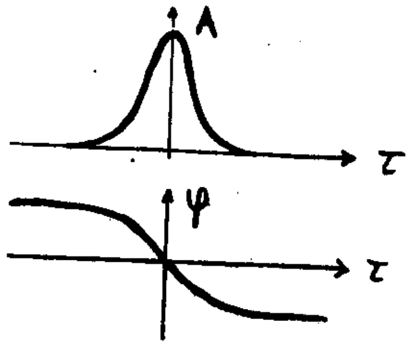
$$C(\tau) = \overline{E(t)\cdot E^*(t+\tau)}$$

$$C(\tau) = A(\tau)\cdot \exp(i\varphi(\tau))$$

The auto-covariance function $C(\tau)$ of the signal can be expressed by it's amplitude A and it's phase φ.

The power spectrum $F(\omega)$ and the autocovariance function $C(\tau)$ are Fourier transforms of each other:

$$F(\omega) \Leftrightarrow C(\tau) = A(\tau)\ \exp(i\varphi(\tau))$$



$$C(0) = \overline{E(0)\cdot E^*(0)} = P = A(0) \qquad \Leftarrow$$

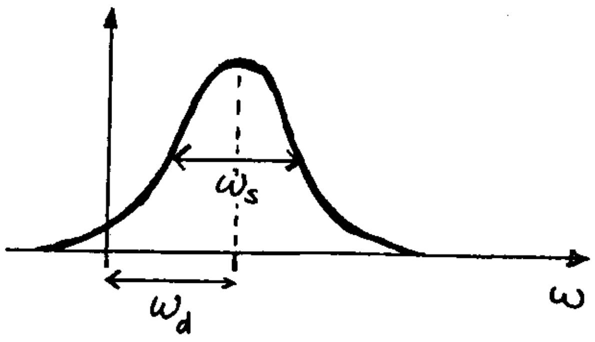
$$C'(0) = i\,m_1 \rightarrow \overline{\omega_d} = \varphi'(0) \qquad \Leftarrow$$

$$C''(0) = -m_2 \rightarrow \omega_s^2 = \frac{A''(0)}{A(0)} \qquad \Leftarrow$$

The 3 essential parameters P, ω_d and ω_s can be deduced from the auto-covariance function, as shown above, as well as from the power spectrum $F(\omega)$:

Deduction of the power P, the Doppler shift ω_d and the spectral width from the first 3 moments of the power spectrum:

$$F(\omega) = \frac{1}{2\pi}\int C(\tau)\exp(-i\omega\tau)\,d\tau$$

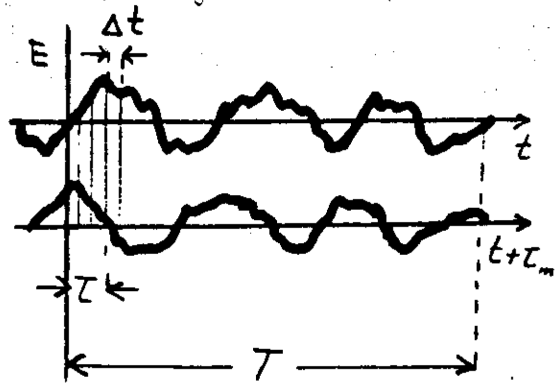


$$P = m_o = \int F(\omega)\,d\omega \quad \Leftarrow$$

$$\omega_d = \frac{m_1}{m_o}, \quad m_1 = \int \omega F(\omega)\,d\omega \quad \Leftarrow$$

$$\omega_s = \sqrt{\frac{m_2}{m_o} - \left(\frac{m_1}{m_o}\right)^2}, \quad m_2 = \int \omega^2 F(\omega)\,d\omega \quad \Leftarrow$$

Numerical [illegible] of [illegible] from the autocovariance function, sampled digitally at intervals Δt:



auto-covariance function (ACF):

$$C(\tau) = \overline{E(t)\cdot E^*(t+\tau)}$$

$$C(\tau) = A(\tau)\cdot\exp(i\varphi(\tau))$$

$$C(\tau_m) = \frac{1}{N}\sum_{k=1}^{N} E_k\cdot E^*_{k+m}$$

$$m = \frac{\tau_m}{\Delta t}$$

$$N = \frac{T}{\Delta t}$$

$$C(\tau_m) = \overline{C_{Re}}(\tau_m) + i\,\overline{C_{Im}}(\tau_m)$$

$$\overline{C_{Re}}(\tau_m) = \overline{E_1(t)\cdot E_1(t+\tau_m) + E_2(t)\cdot E_2(t+\tau_m)}$$

$$\overline{C_{Im}}(\tau_m) = \overline{E_2(t)\cdot E_1(t+\tau_m) - E_1(t)\cdot E_2(t+\tau_m)}$$

$$A(\tau_m) = \overline{(C_{Re}(\tau_m))^2 + (C_{Im}(\tau_m))^2}^{\,1/2}$$

$$\Rightarrow \quad P = A(\tau_o) = \overline{(C_{Re}(\tau_o))^2 + \cancel{(C_{Im}(\tau_o))^2}}^{\,1/2}$$

$$\Rightarrow \quad \omega_d = \varphi(\tau_1)/\tau_1 = \arctan(\overline{C_{Im}}(\tau_1)/\overline{C_{Re}}(\tau_1))/\tau_1$$

$$\Rightarrow \quad \omega_s = A''(\tau_o)/A(\tau_o) = 2(1 - A(\tau_1)/A(\tau_o))/\tau_1^2$$

What is the meaning of the parameters P, ω_d and ω_s ?

measured:

signal ACF

$C(\tau) \sim \int \rho(\underline{r},\tau)\ \exp(-i\,\underline{k}\,\underline{r})\ d\underline{r}$

required:

$\rho(\underline{r},\tau)$

spatial and temporal autocorrelation function of the fluctuations in the scatter volume, which are described by P, ω_d, ω_s :

For pure scattering:

(1) P ~ intensity of turbulence fluctuations ⇐

(2) $\omega_d = \underline{k} \cdot \underline{v}$ = Doppler shift

$\underline{v}$ = mean (bulk) velocity of scattering volume ⇐

$v = -\frac{c}{2}\frac{\omega_d}{\omega_o}$ (ω_o = signal frequency)

(3) $\omega_s = \frac{2 \cdot \sqrt{\overline{\Delta v^2}} \cdot \omega_o}{c}$

$\overline{\Delta v^2}$ = mean squared velocity fluctuations of turbulence in scattering volume ⇐

REFRACTIVE INDEX OF CLEAR AIR UP TO 100 KM ALTITUDE FOR VHF

$$n = 1 + n_1' + n_2' + n_3'$$

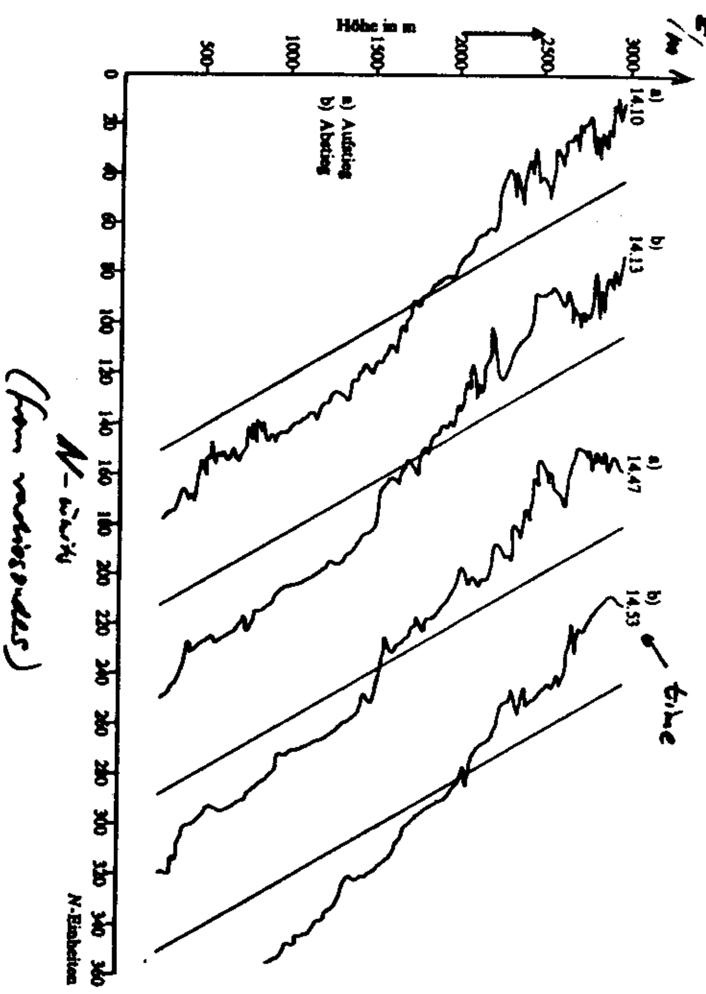
$$n_1' = \frac{3.7 \cdot 10^{-1} e}{T^2} \quad \text{WET TERM}$$

$$n_2' = \frac{77.6 \cdot 10^{-6} p}{T} \quad \text{DRY TERM}$$

$$n_3' = \frac{-40.3 \cdot N_e}{f^2} \quad \text{IONOSPHERIC TERM}$$

e = PARTIAL PRESSURE OF WATER VAPOR IN mb
p = PRESSURE IN mb
T = TEMPERATURE IN K
N_e = NUMBER OF FREE ELECTRONS PER m^3
f = FREQUENCY IN s^{-1}

REFRACTIVITY $N = (n-1) \cdot 10^6$



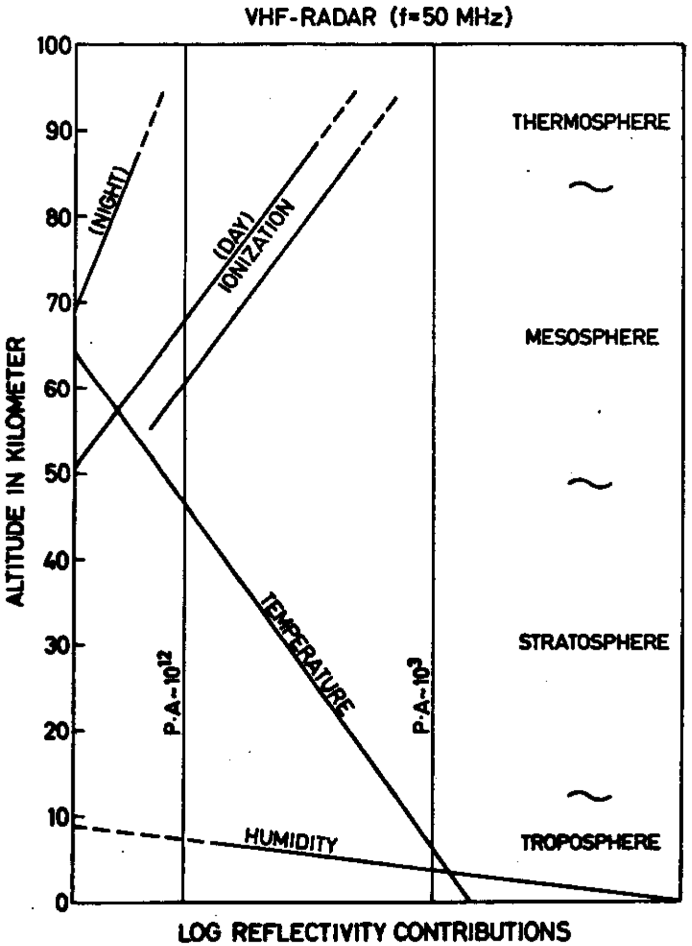
Contributions of the wet term n_1', the dry term n_2' and the ionosphere term n_3' to the refractive index variations

$$n = 1 + n_1' + n_2' + n_3'$$

$$n = 1 + (n_1 + \Delta n_1) + (n_2 + \Delta n_2) + (n_3 + \Delta n_3)$$

	z/km	e/mb	T/K	p/mb	N_e/m^3	$\Delta n_1 + \Delta n_2$	Δn_3
TROPOSPHERE	1	10	280	900	0	$4\cdot10^{-5}\Delta e/e - 4\cdot10^{-4}\Delta T/T + 3\cdot10^{-10}\Delta p/p$	0
STRATOSPHERE	16	0	240	100	0	$-4\cdot10^{-5}\Delta T/T + 4\cdot10^{-10}\Delta p/p$	0
MESOSPHERE	75	0	200	0.02	10^9	$-7\cdot10^{-9}\Delta T/T + 9\cdot10^{-10}\Delta p/p$	$-4\cdot10^{-6}\Delta N_e/N_e$ f=50MHz $-2\cdot10^{-7}\Delta N_e/N_e$ f=224MHz $-1\cdot10^{-8}\Delta N_e/N_e$ f=933MHz

$$n_1' = \frac{3.7\cdot10^{-1}\,e}{T^2} \qquad n_2' = \frac{77.6\cdot10^{-6}\,p}{T} \qquad n_3' = \frac{-40.3 N_e}{f^2}$$



Reflectivity is the total backscatter cross section per unit volume. The reflectivity is determined by the variance of the refractive index.

The echo power at VHF (with quasi-vertical beam) and at UHF (at oblique incidence) is due scattering and partial reflection:

$P = P_s + P_r$

$P_r > P_s$ vertical incidence VHF

$P_r < P_s$ vertical incidence UHF

P_s = scattered power

P_r = partially reflected power

scattering

$$P_s = \frac{P_t\, A\, \Delta z}{4\pi z^2} \cdot \eta$$

P_t = TX power

A = antenna area

Δz = height resolution (≙ radar pulse length)

z = height

$\eta = \frac{\sigma}{V}$ is the radar reflectivity $\quad \eta = \frac{1}{V} \sum_i \sigma_i$

(total backscatter cross section per unit volume)

backscatter cross section

$$\sigma = \frac{4\pi^3}{\lambda^4} \cdot \overline{\left|\frac{\Delta n}{n}\right|^2} \cdot F^*(\underline{k})$$

$F^*(\underline{k})$ = 3-dimensional wave number spectrum of refractive index variations

Thomson scatter (ionized atmosphere):

$F^*(\underline{k})$ ≙ fluctuation density by random thermal motions of charged particles (free electrons).

Turbulence scatter (neutral atmosphere):

$F^*(\underline{k})$ ≙ fluctuation density by random motions of turbulent irregularities in humidity, temperature and density.

Thomson scatter (ionosphere):

$$\eta = N_e \sigma_e \quad \Rightarrow \quad P \propto N_e$$

$$\sigma_e = 4\pi r_e^2 \left(\frac{\alpha^2}{1+\alpha^2} + \frac{1}{(1+\alpha^2)\cdot(1+T_e/T_i + \alpha^2)} \right)$$

$$\alpha = \frac{4\pi\lambda_D}{\lambda} \qquad \lambda_D = 69 \cdot (T_e/N_e)^{1/2}$$

N_e = number density of free electrons

T_e = electron temperature

λ_D = Debeye length

$4\pi r_e^2$ = scattering cross section of a single electron

Collision dominated Thomson scatter (D-and lower E-region)

$$\Rightarrow \omega_s \propto \frac{T_i}{\nu_{in}} \cdot \sqrt{\frac{m_i + m_n}{m_i m_n}} \cdot (1+\Lambda^-)$$

$$\Lambda^- = \frac{N_i^-}{N_e} = \frac{\text{number density of negative ions}}{\text{number density of free electrons}}$$

ν_{in} = collision frequency of ions and neutrals

$T_{i,n}$ = temperature of ions (neutrals)

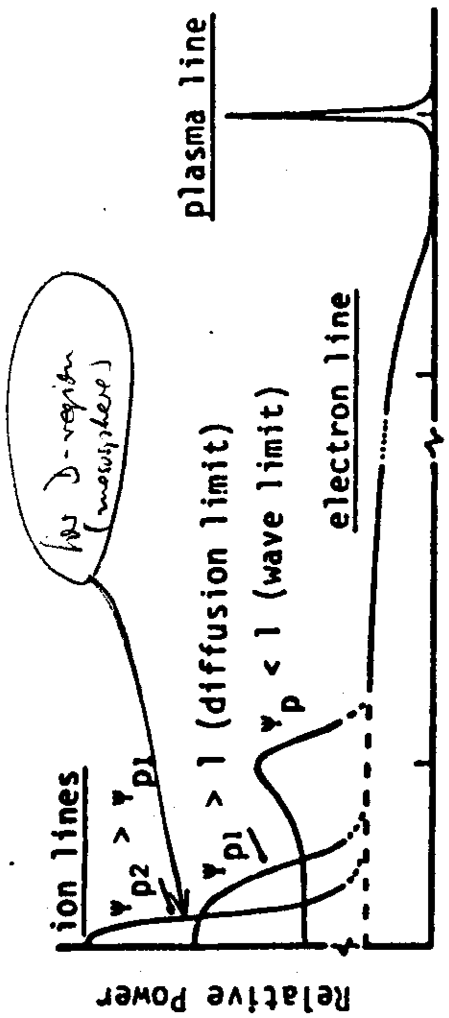
$m_{i,n}$ = mass of ions (neutrals)

$$\Psi_i = \frac{\lambda \nu_{in} \sqrt{m_i}}{4\pi \sqrt{2\kappa T_i}} = \frac{\text{radar wavelength}}{\text{mean free path}}$$

$$\Rightarrow \omega_D = -\frac{4\pi U_i}{\lambda}$$

U_i = bulk velocity of ions (neutrals)

λ = radar wavelength



Spectra of Thomson scatter (ionosphere) (after Mathews and Tanenbaum, Planet. Sp. Sc. 1981, p 335

Turbulence scatter (MST):

For locally homogeneous and isotropic turbulence:

$F_n(k) \propto C_n^2 \cdot k^{-5/3}$ (1-dim spectral density)

C_n^2 = turbulence refractive index structure constant

$$\eta = 0.39\, C_n^2 \cdot \lambda^{-1/3}$$

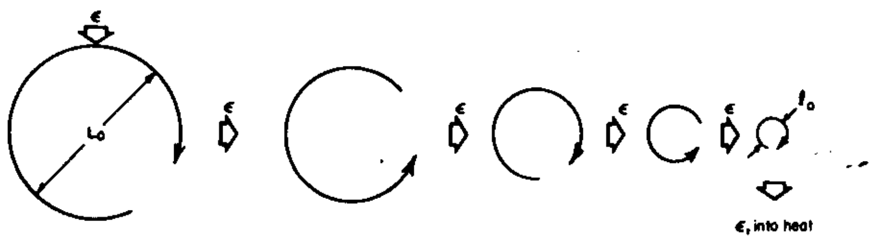
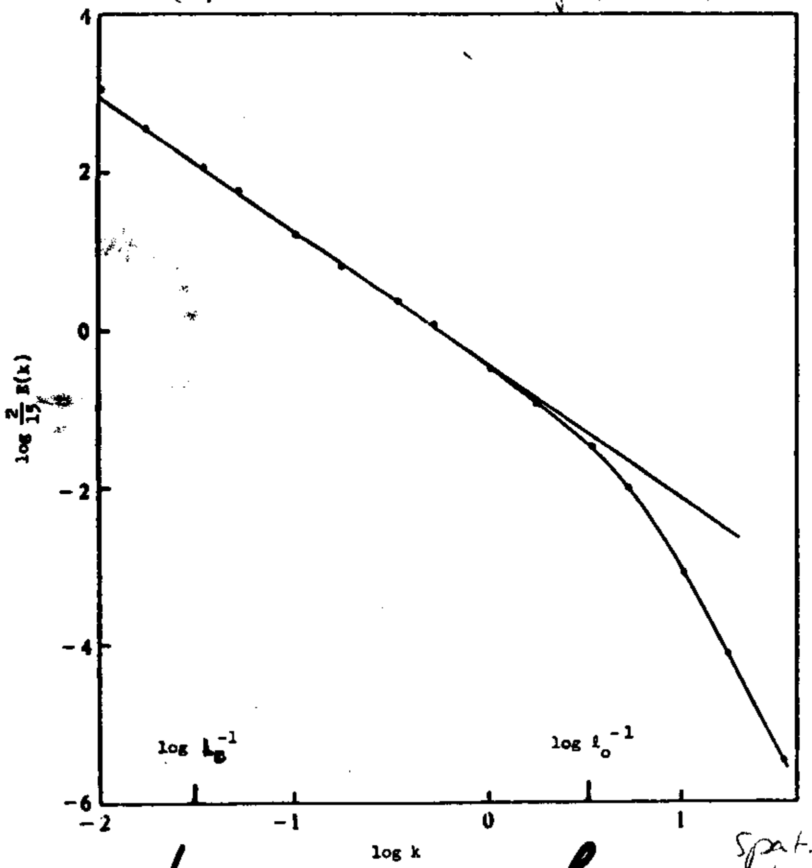


Figure 4.3 *Sketch of the hierarchy of eddies for energy cascade.*

(after Derr, Remote Sensing of the Troposphere, Chapt. 13) 1972



L_o $\quad$ l_o $\quad$ Spatial wavenumber $\frac{2\pi}{l}$

Large turbulence whirls decay into small whirls and energy ε is fed to the smaller scales; this takes place in the inertial subrange of the Kolmogoroff spectrum.

Atmospheric turbulence (Kolmogoroff Spectrum)

macroscale $\quad L_o = 0.35 \sqrt{\varepsilon_t} \cdot \omega_B^{-3/2}$ $\qquad \omega_B^2 = \frac{g}{\theta} \cdot \frac{\partial\theta}{\partial z}$ (Brunt - Väisälä frequency)

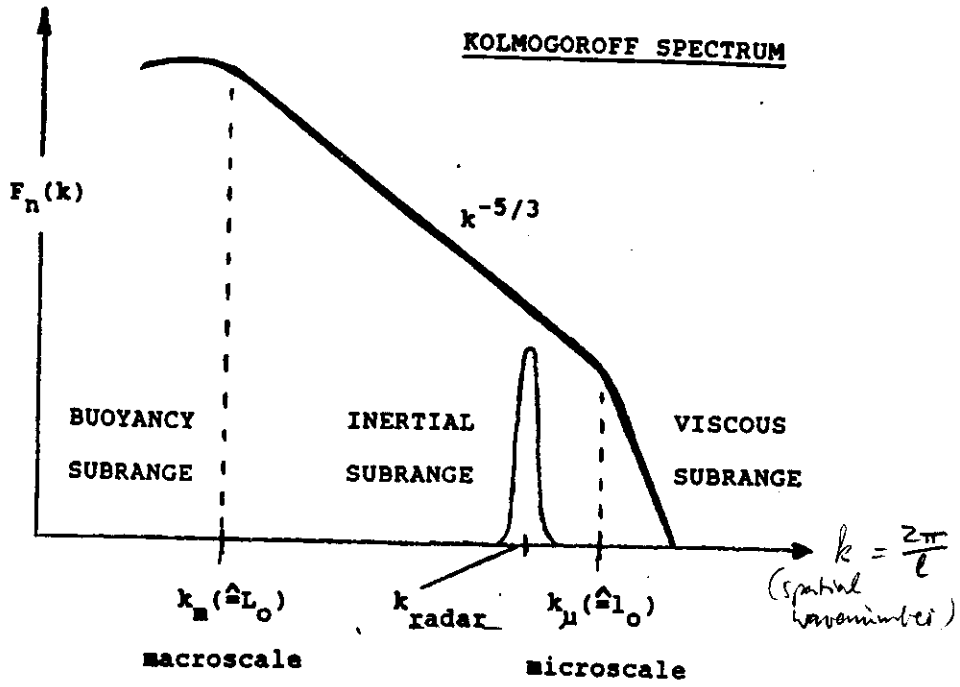
microscale $\quad l_o = \left(\frac{\nu^3}{\varepsilon_t}\right)^{1/4}$ $\qquad \nu = \frac{c_1 \cdot T^{1/2}}{\rho(1+c_2/T)}$ (kinematic viscosity)

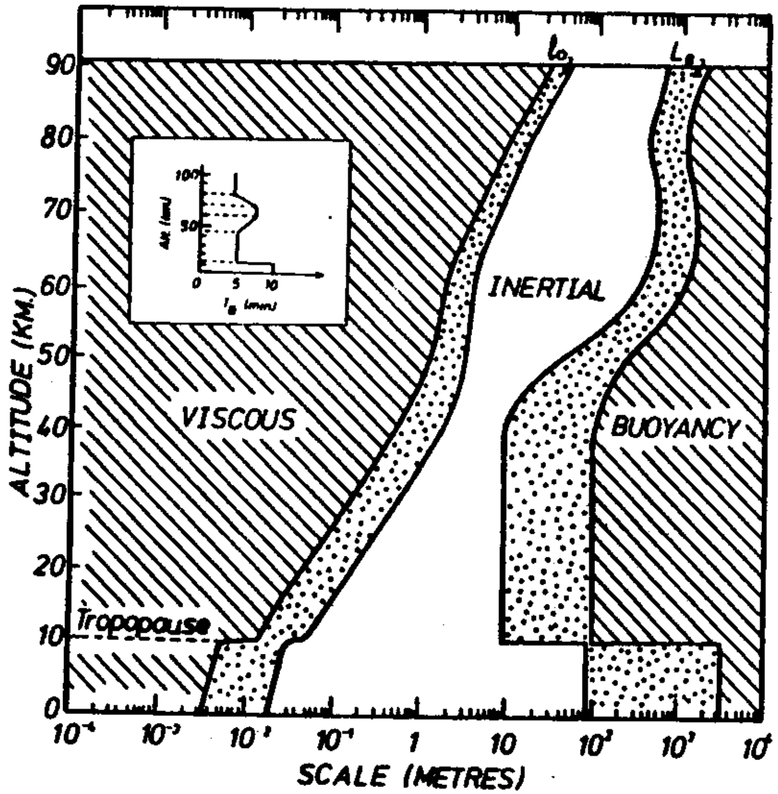
C_1, C_2 = constants

$$C_n^2 = 5.26 \cdot \overline{\Delta n^2} \cdot L_o^{-2/3}$$

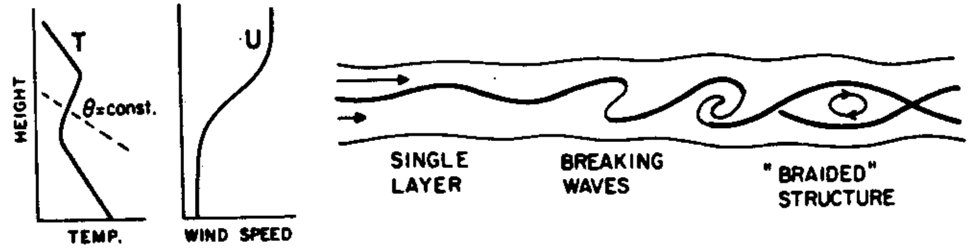
$$\eta = 0.39 \cdot C_n^2 \cdot \lambda^{-1/3}$$ = radar reflectivity (scattering)

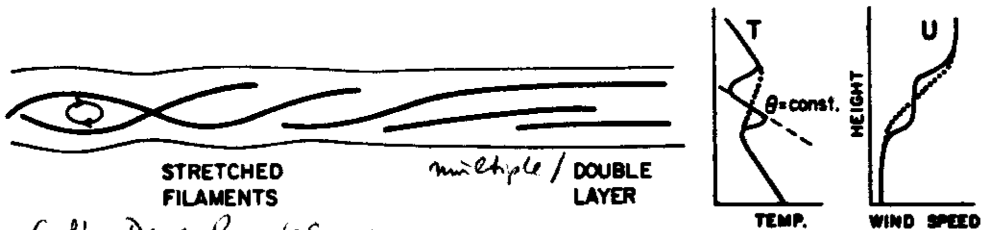
ε_t = turbulent energy dissipation rate





(after Hocking, JATP 1983, 89/103)





(after Derr, Remote Sensing of the troposphere, 1972)

$$Ri = \frac{N^2}{\left(\frac{\partial \bar{u}}{\partial z}\right)^2}$$ (Richardson Number)

Development of clear air turbulence layer in a stable stratified atmosphere and wind shear: a single stratification (e.g. surface of constant temperature) develops into a breaking wave with a braided or "cat's eye" structure which then transits into stretched filaments and multiple layers, also called "fossile turbulence".

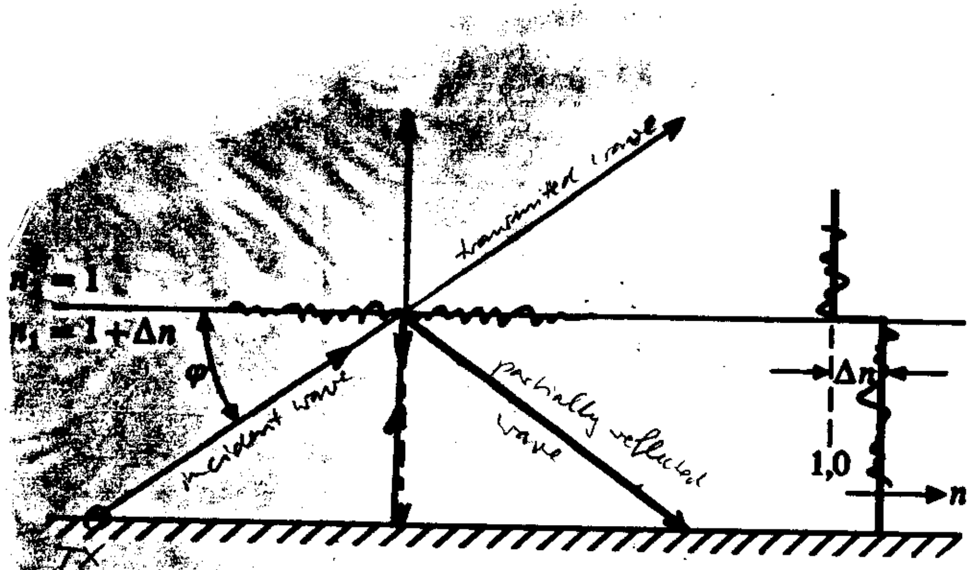
partial reflection

$$P_r = \frac{P_t \cdot \lambda^2}{\lambda^2 z^2} |r|^2$$

r = reflection coefficient

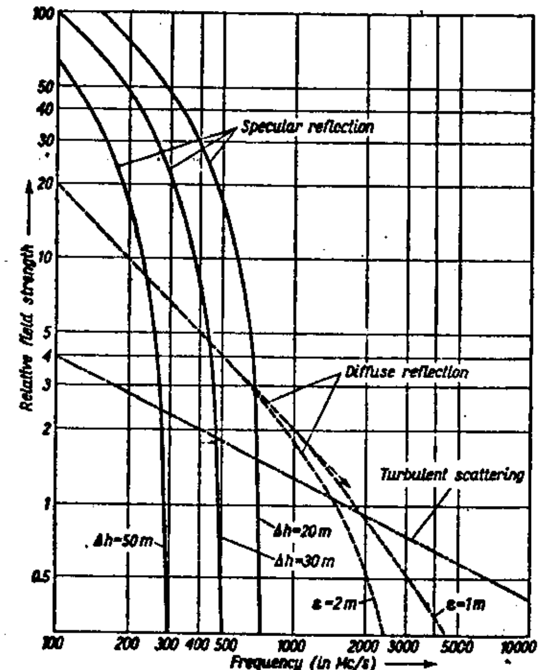
$$r = \int \frac{1}{2n} \frac{\partial n(z)}{\partial z} \exp(-jkz)\,dz$$

Fourier transform of the vertical gradient of refractive index



[redacted]

Partial reflection at a small gradient Δn of refractive index. For a monostatic radar $\varphi = 90°$, thus the partially reflected wave propagates back to the point of transmission (TX).

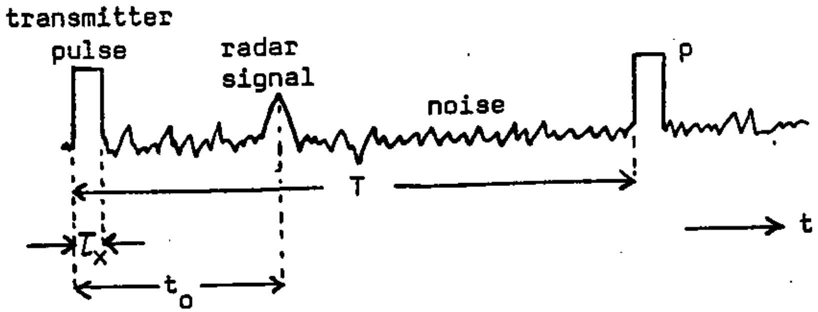


Comparison of the frequency dependences of turbulent scattering, diffuse reflection and specular reflection. The values of the three components include an unspecified constant factor.

(after Beckmann and Spizzichino, 1967)

<u>definition of technical terms used in</u>

<u>radar experiments</u>



T = interpulse period (IPP), also T_{IPP}

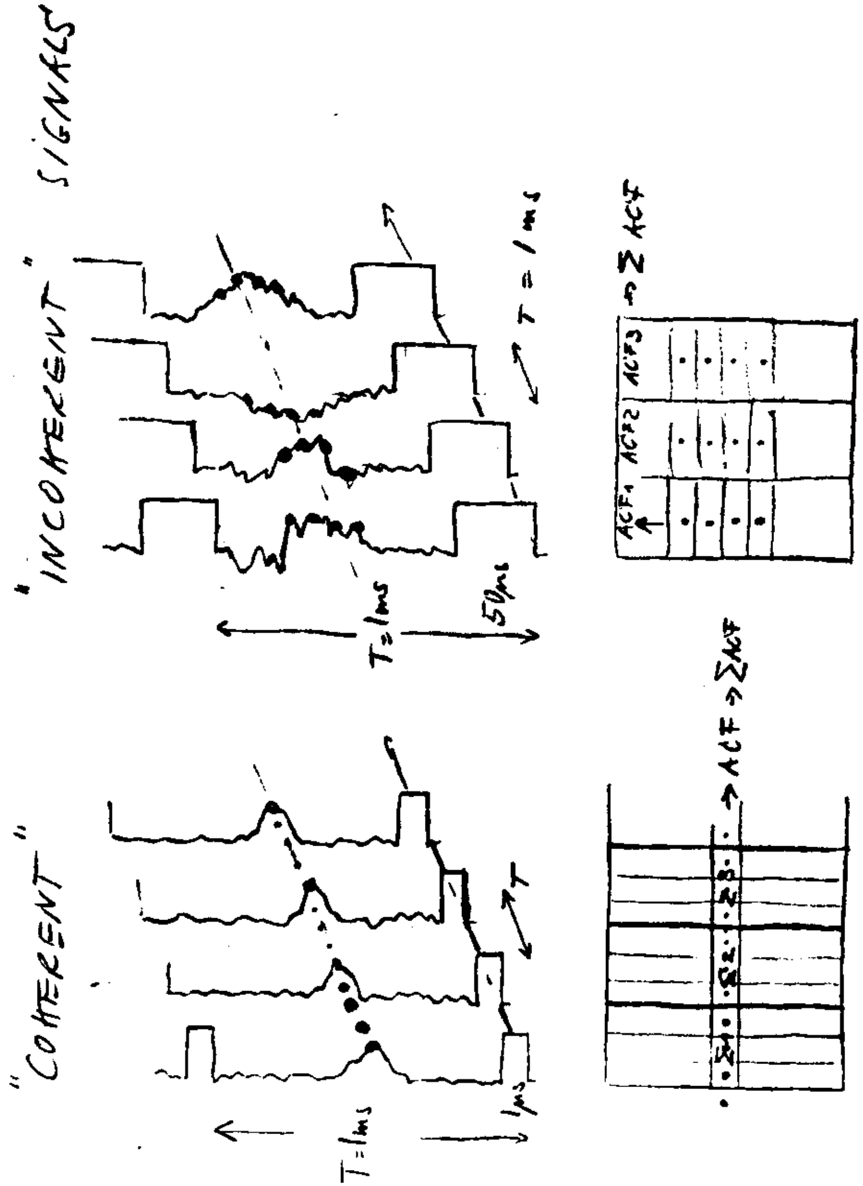
$f_T = \frac{1}{T}$ = pulse repetition frequency (PRF)

τ_x = pulse length (duration), p = pulse peak power

$\frac{\tau_x}{T}$ = duty cycle, $\frac{\tau_x}{T} \cdot p$ = average power

one-way distance to the radar target:

$$r = \frac{c \cdot t_o}{2}$$



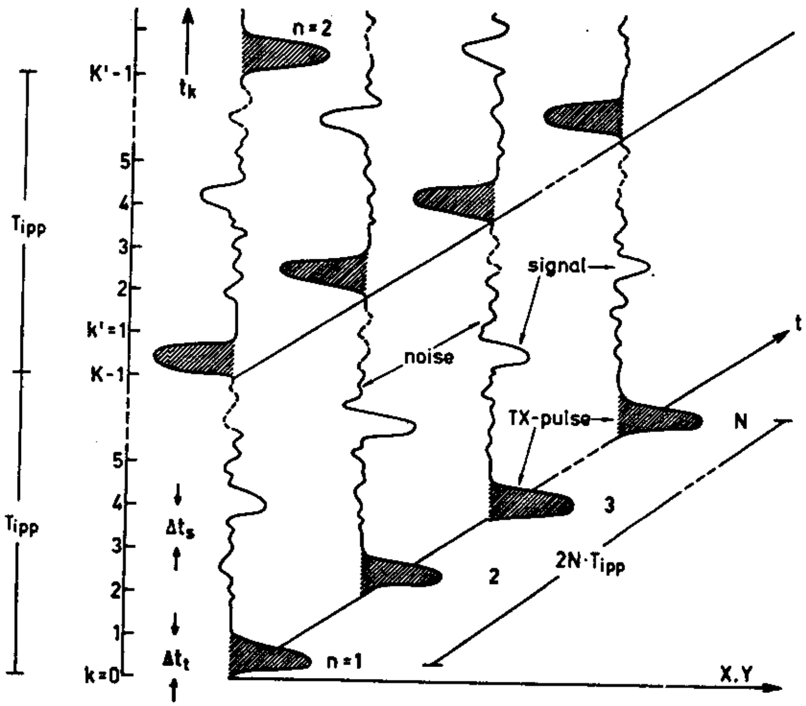
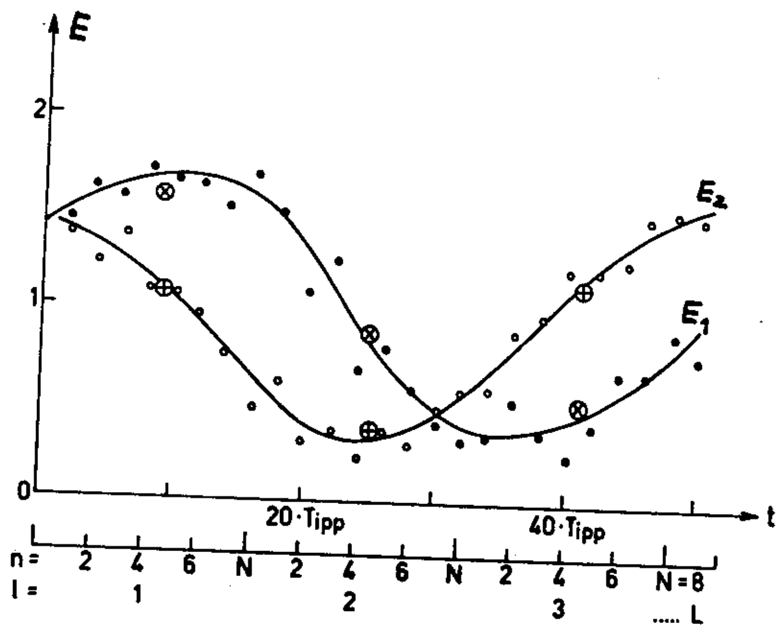
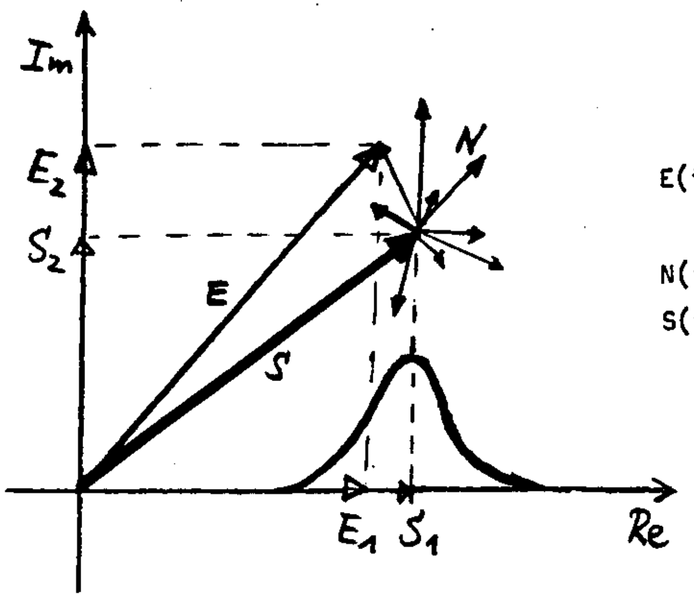


Fig 4 of main paper (MST Radar Techn)



ref. Fig 5 of main paper (MST Radar Technique)

signal in noise:



$$E(t) = E_1(t) + i\,E_2(t)$$
$$= S(t) + N(t)$$
$$N(t) = N_1(t) + i\,N_2(t)$$
$$S(t) = S_1(t) + i\,S_2(t)$$

incoherent addition or integration

(postdetection filtering):

$$p^+ = \overline{E_1^2 + E_2^2}$$

$$= \overline{S_1^2 + \cancel{2S_1N_1} + N_1^2 + S_2^2 + \cancel{2S_2N_2} + N_2^2}$$

$$\underline{p^+ = \overline{S^2} + \overline{N^2}} \qquad (\overline{N^2} \neq 0)$$

coherent addition or integration

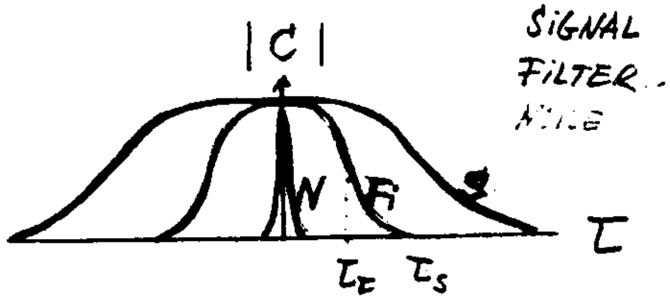
(predetection filtering):

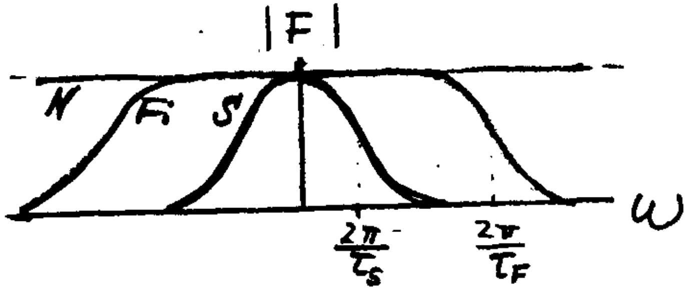
$$P = \overline{E_1}^2 + \overline{E_2}^2 \qquad S \approx \text{const}$$

$$= \overline{S_1}^2 + \cancel{\overline{2S_1N_1}^2} \cancel{+\overline{N_1}^2} + \overline{S_2}^2 + \cancel{\overline{2S_2N_2}^2} \cancel{+\overline{N_2}^2}$$

$$\underline{P = \overline{S}^2}$$

coherent integration to improve the "signal-to-noise" ratio:





coherent signal S ($\approx$ const)

(vector addition)

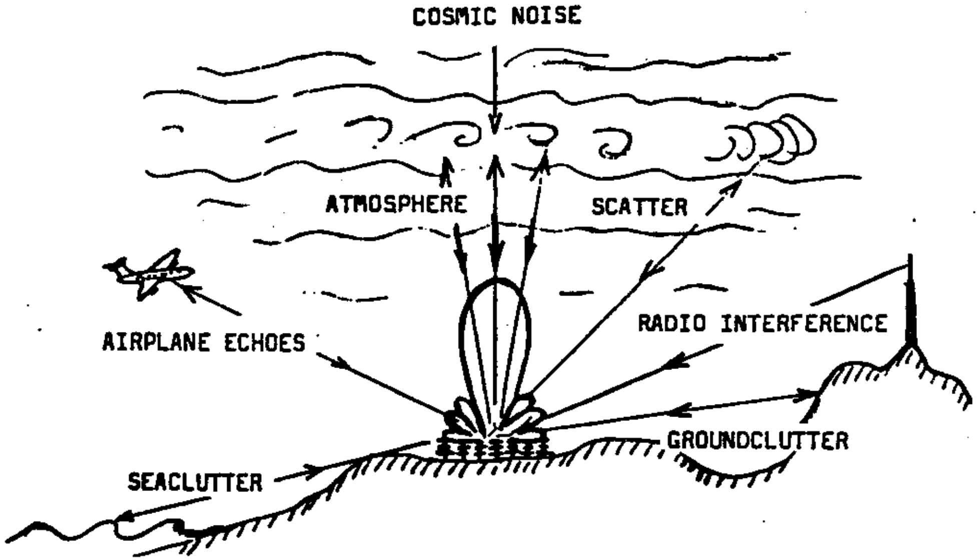
$$P_S = \overline{S}^2 = \Big(\sum^n S\Big)^2 = (n\cdot S)^2$$
$$\overline{S} = \sqrt{P_S} = n\cdot S$$

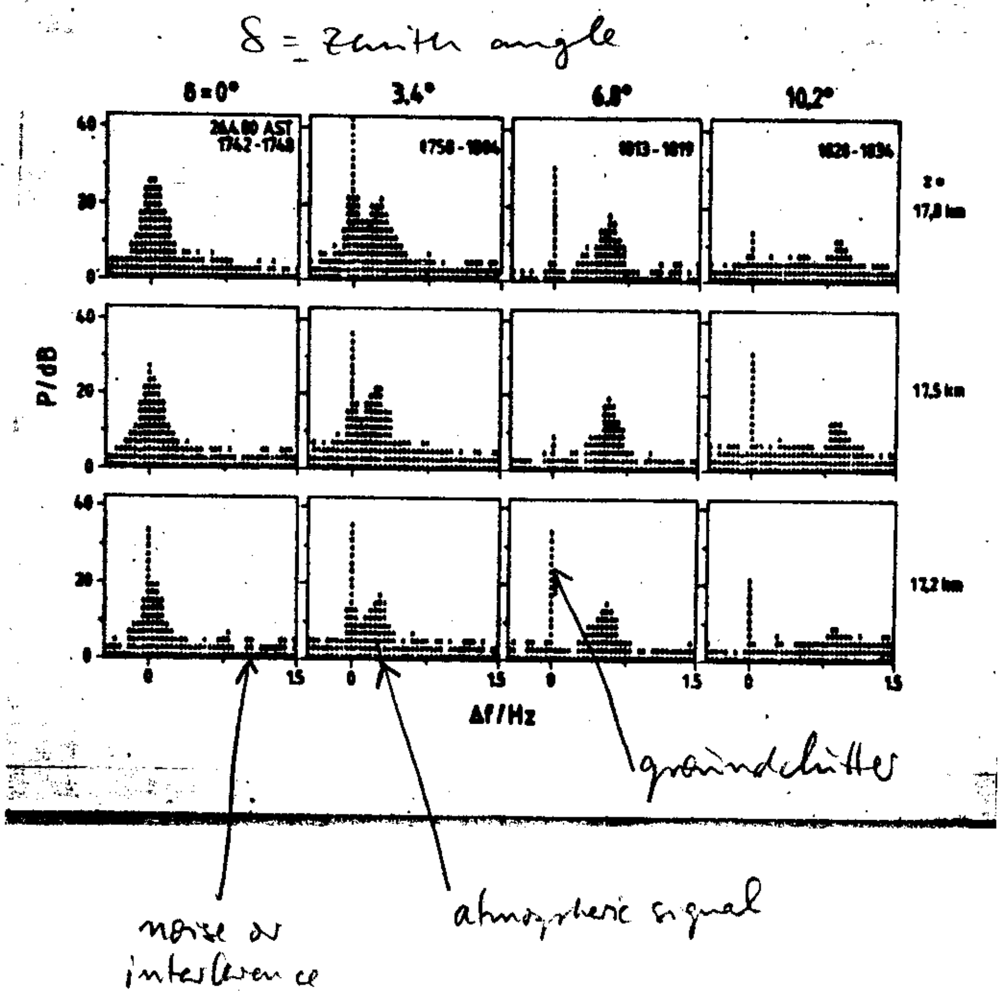
incoherent "signal" N (e.g., noise)

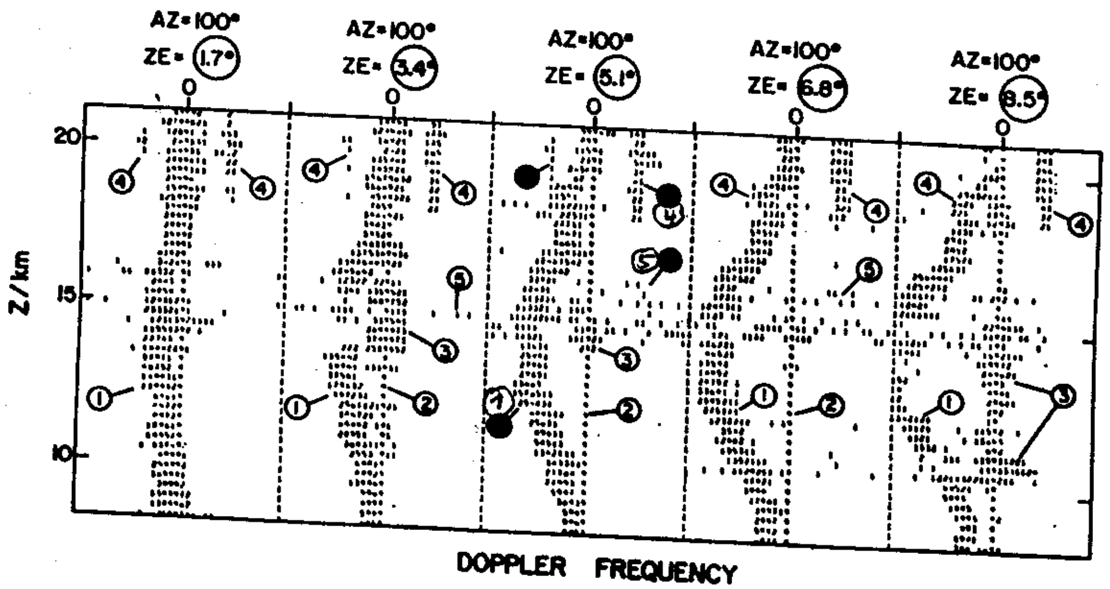
$$P_N = \sum^n N^2 = n\cdot N^2$$
$$\overline{N} = \sqrt{P_N} = \sqrt{n}\,N$$

improvement of signal-to-noise ratio S/N:

$$\overline{S}/\overline{N} = \sqrt{n}$$


COSMIC NOISE
ATMOSPHERE
SCATTER
AIRPLANE ECHOES
RADIO INTERFERENCE
GROUNDCLUTTER
SEACLUTTER

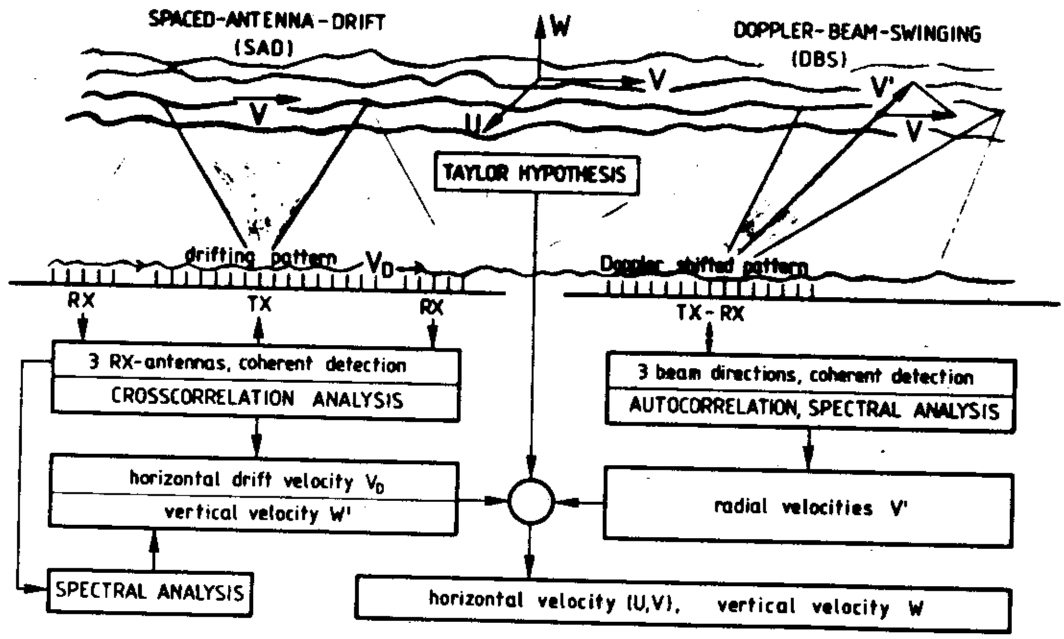

δ = zenith angle
δ = 0°
3,4°
6,8°
10,2°
26.4.80 AST 1742-1748
1758-1804
1813-1819
1828-1834
z =
17,8 km
17,5 km
17,2 km
P / dB
40
20
0
0
1.5
Δf / Hz
groundclutter
noise or interference
atmospheric signal

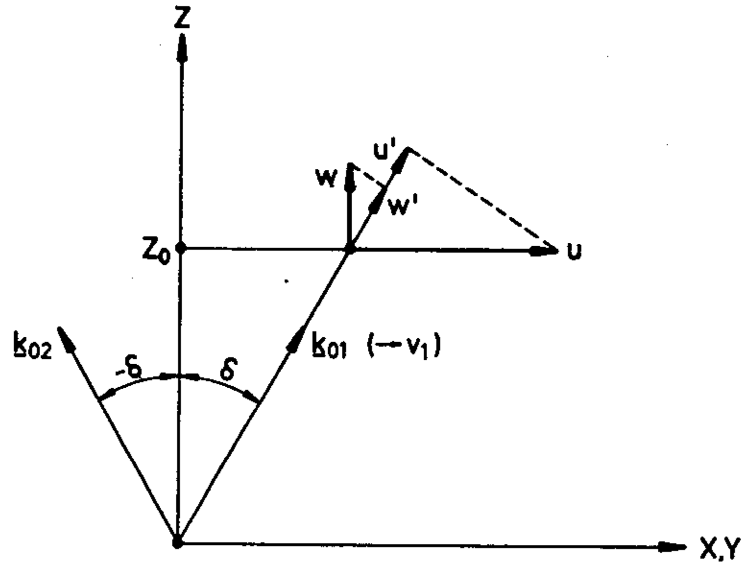


Spectra-height-intensity plots of VHF radar signals:

1 = atmospheric echo, 2 = nonfading ground clutter, 3 = atmospheric clutter due to sidelobe into zenith direction, 4 = sea clutter, 5 = noise.

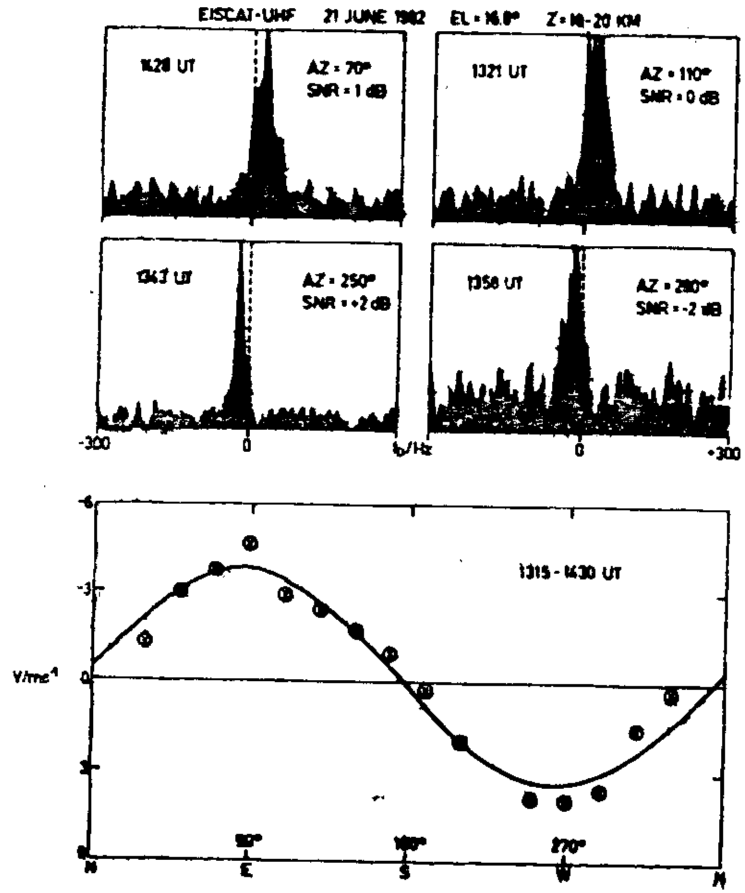
The two basic methods to measure wind velocities:





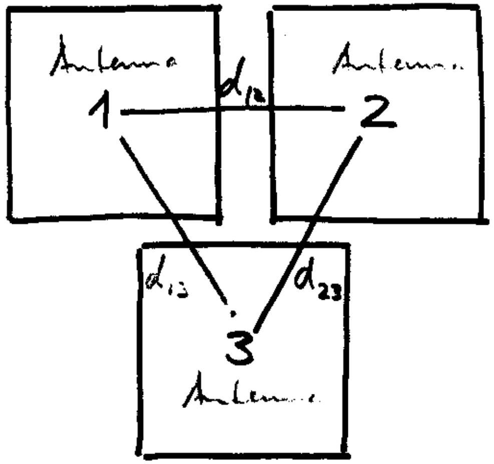
$$u = \frac{v_1 - v_2}{2 \sin \delta} \quad , \quad w = \frac{v_1 + v_2}{2 \cos \delta}$$

Doppler beam swinging technique



VAD = VELOCITY - AZIMUTH - DISPLAY

SPACED ANTENNAS



Radar signals measured with 3 spaced antennas are cross-correlated and from the off-set of the cross-correlation functions τ_{ij}, knowing the distances d_{ij} between the 3 antennas, the pattern drift velocity and, resultingly, the wind velocity is deduced.

Correlation between two signal time series

$$E_x(t) = E_{x1}(t) + i\, E_{x2}(t)$$

$$E_y(t) = E_{y1}(t) + i\, E_{y2}(t)$$

Cross-covariance function (CCF):

$$C_{xy}(\tau) = \overline{E_x(t)\cdot E_y(t+\tau)}$$

Cross spectrum:

$$F_{xy}(\omega) = \frac{1}{2\pi}\int C_{xy}(\tau)\, \exp(-i\omega\tau)\, d\tau$$

Power spectra:

$$F_{xx}(\omega) = \frac{1}{2\pi}\int C_{xx}(\tau)\, \exp(-i\omega\tau)\, d\tau$$

$$F_{yy}(\omega) = \frac{1}{2\pi}\int C_{yy}(\tau)\, \exp(-i\omega\tau)\, d\tau$$

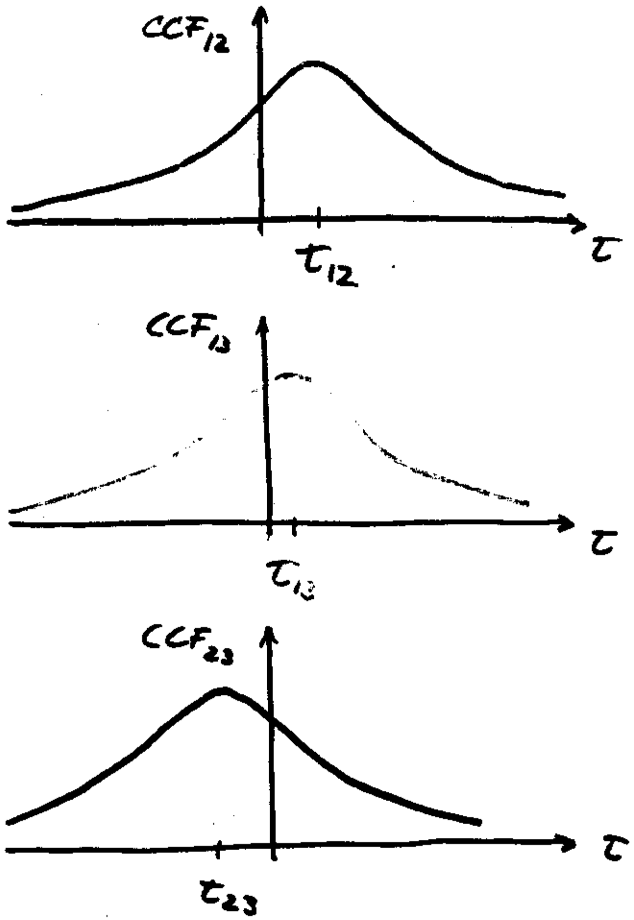
$$F = \tilde{F} + i\, \tilde{\tilde{F}}$$

Coherence:

$$H^2(\omega) = \frac{\tilde{F}_{xy}^2 + \tilde{\tilde{F}}_{xy}^2}{(F_{xx}^2 \cdot F_{yy}^2)^{1/2}}$$

Phase:

$$\tan\psi = -\tilde{\tilde{F}}_{xy}/\tilde{F}_{xy}$$



$$V_a = V_a(d_{ij}/\tau_{ij}) \Rightarrow V$$ (wind speed)

SOUSY-VHF-RADAR

MAX-PLANCK-INSTITUT FÜR AERONOMIE

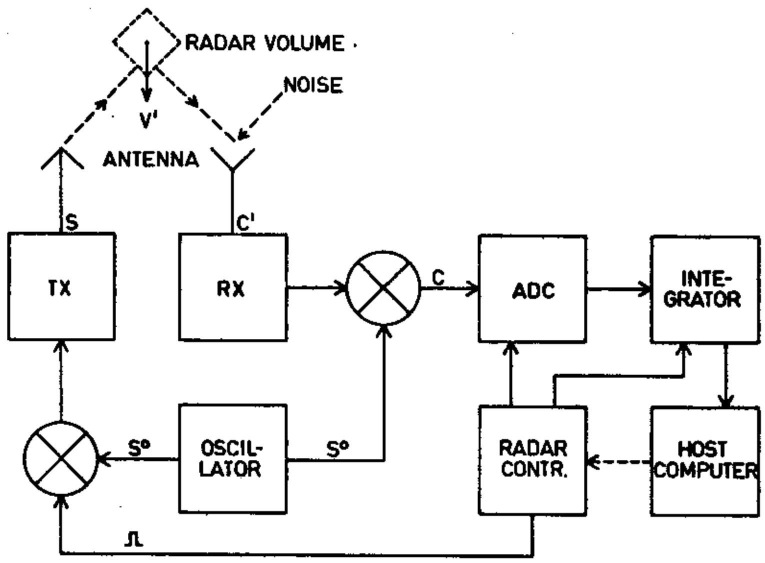
COHERENT PULSED VHF RADAR
53.5 MHz, 600 kW (24 kW av.)

ANTENNAS (QUASI-VERT. BEAM):
196 YAGIS (STEERABLE), 31 dB
3x32 YAGIS (DRIFT), 3x22 dB

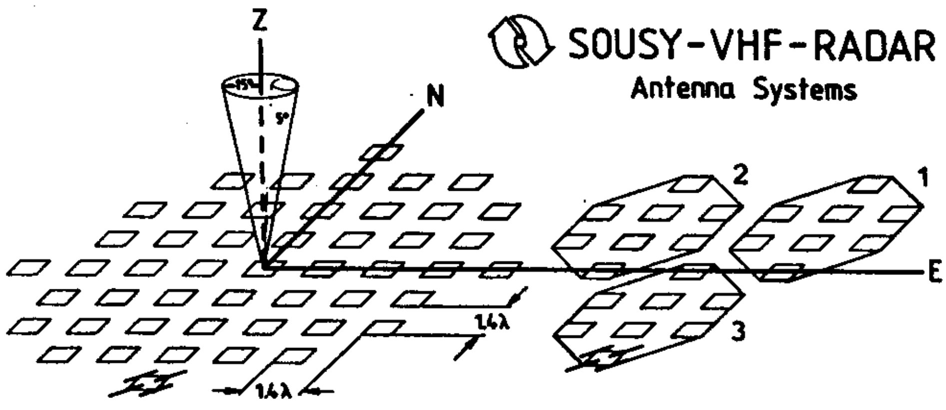
OPT. HEIGHT RESOLUTION ~50 m

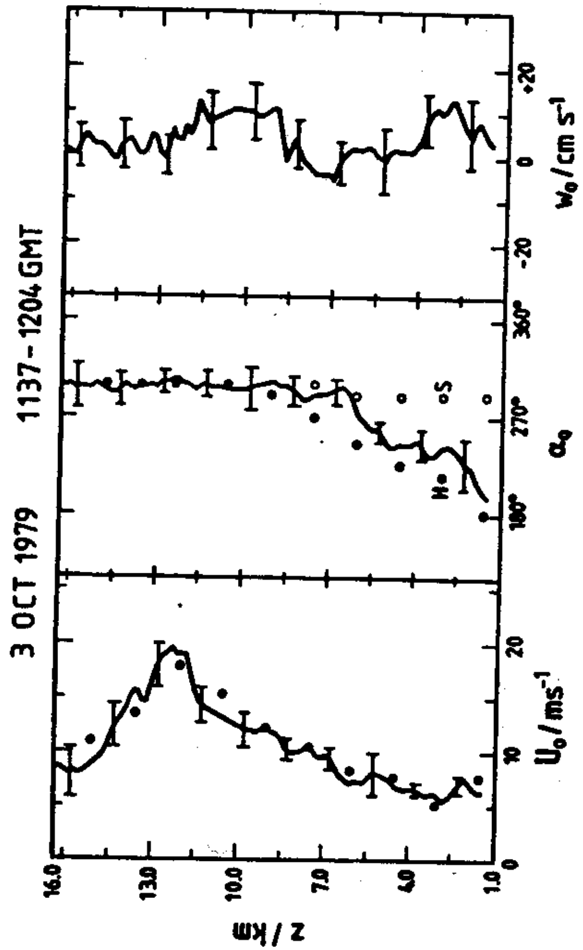
INVESTIGATIONS OF THE STRUCTURE AND DYNAMICS OF TROPOSPHERE, STRATOSPHERE, AND MESOSPHERE

47

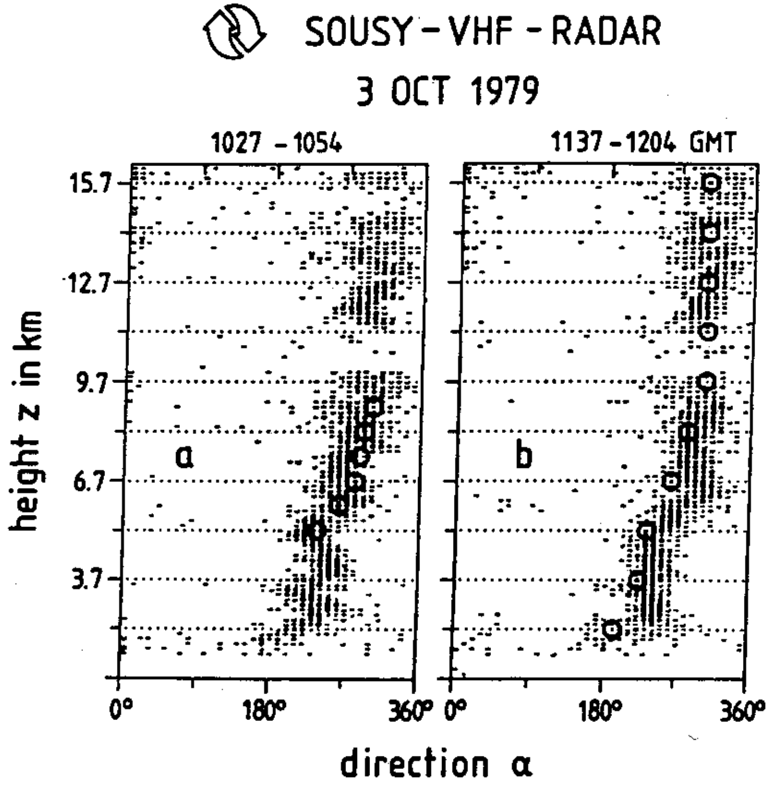

RADAR VOLUME
NOISE
V'
ANTENNA
S
C'
TX
RX
C
ADC
INTE-
GRATOR
OSCIL-
LATOR
S°
S°
RADAR
CONTR.
HOST
COMPUTER

48

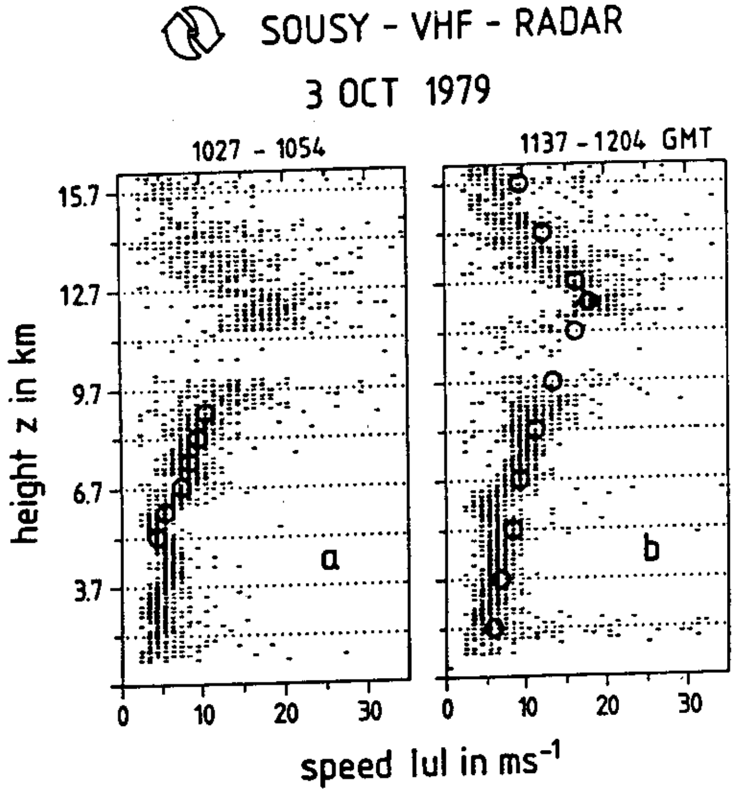

SOUSY-VHF-RADAR
Antenna Systems
Z
N
E
1
2
3
1.4λ
1.4λ



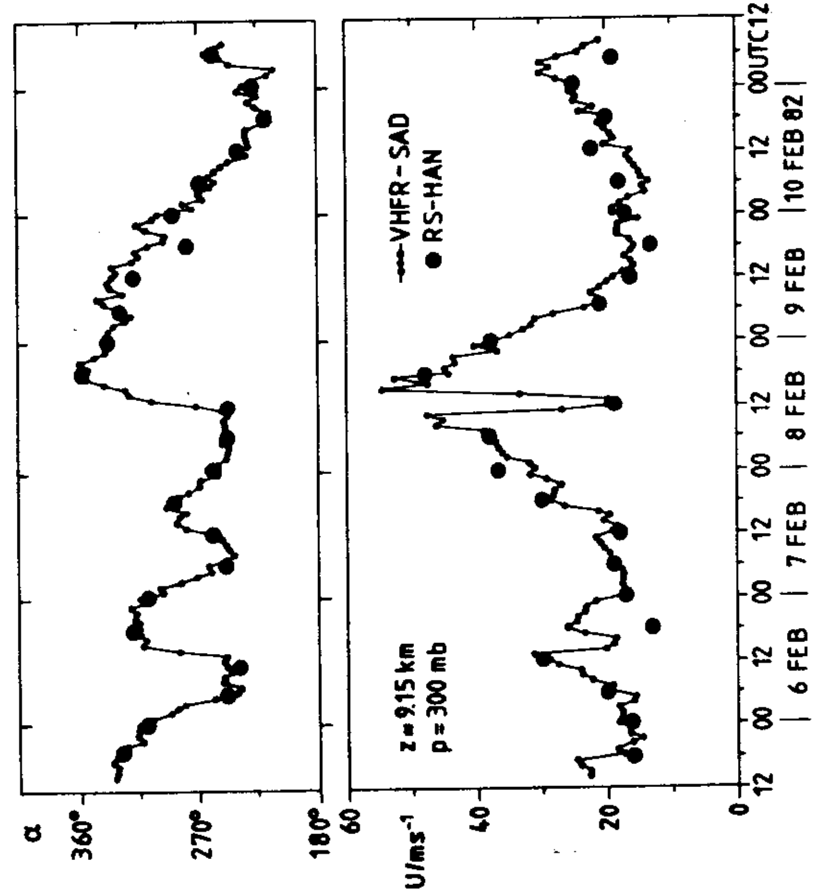
Wind speed U_0 and direction α_0 and vertical velocity measured with the spaced antenna technique. The circles denote radiosonde data (from Röttger, JATP, 1981, p277)



ref. Fig 7 of main paper



ref. Fig 7 of main paper



Time series of speed antenna wind measurements, compared with radiosonde data (circles). From Röttger (Proc. of the 21. Conference on Radar Meteorology, 1983).

Radar Methods for Investigations of the Middle Atmosphere

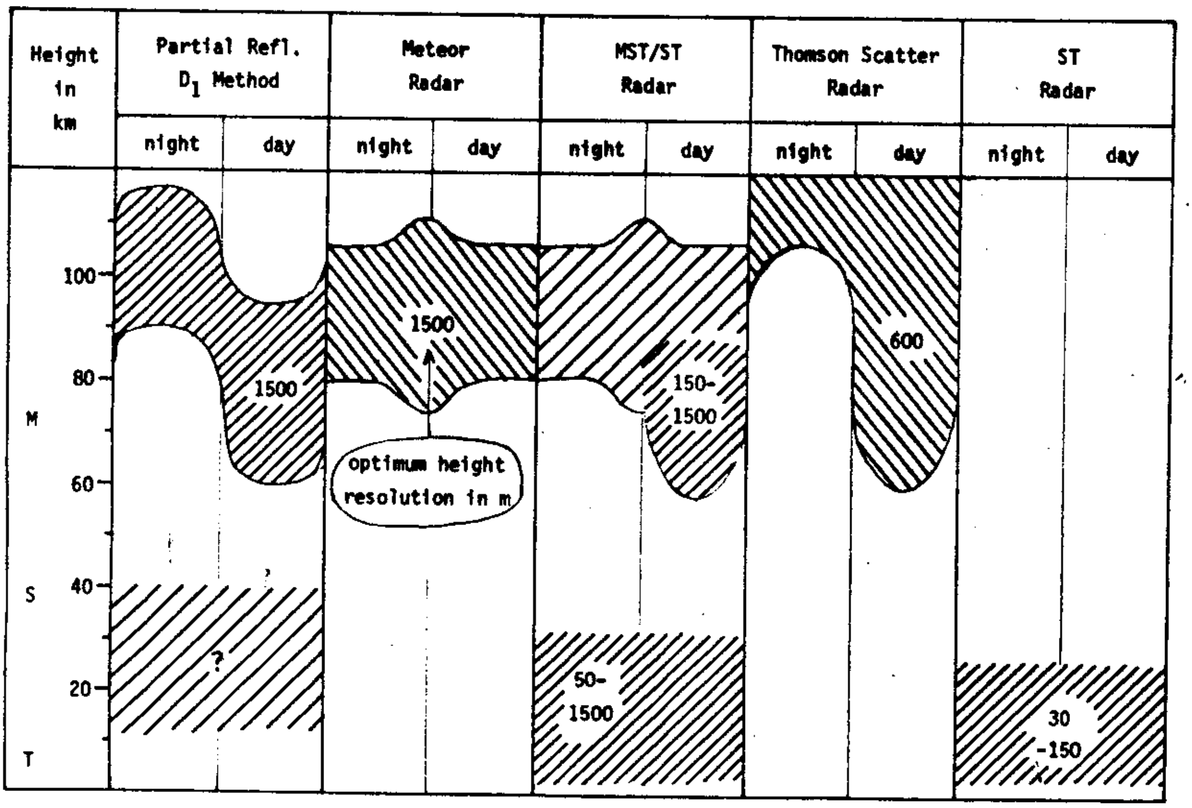
Typical Operational Parameters:

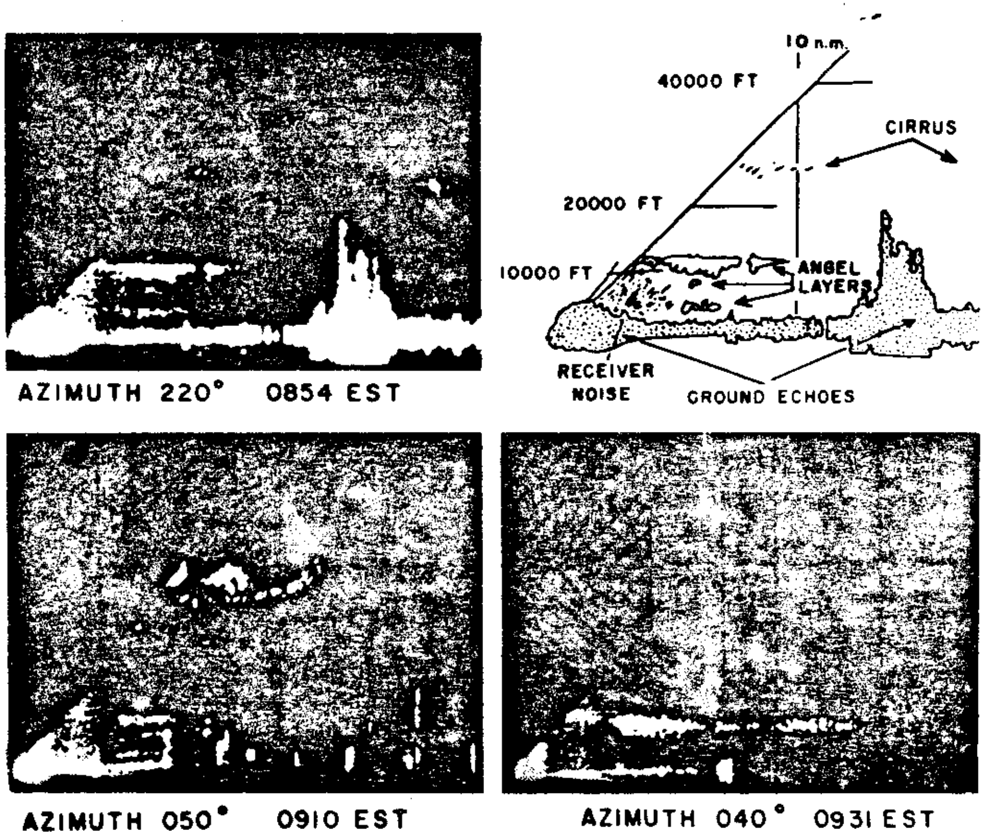
Method	Frequency Range	Wavelengths in m	Average Power in kW	Antenna Dimension in λ	Height Region
Partial Reflection (D_1 method)	MF-HF	150-50	0.1-10	2-10	M
Meteor Radar	HF-VHF	10-6	1-10	2-10	M
MST/ST Radar	VHF	~6	10-100	5-50	MST
Thomson Scatter Radar	UHF	0.7	150	300	M
ST Radar	UHF-SHF	0.7-0.03	50-500	100-1000	ST

MF = 0.3-3.0 MHz
HF = 3.0-30 MHz
VHF = 30-300 MHz

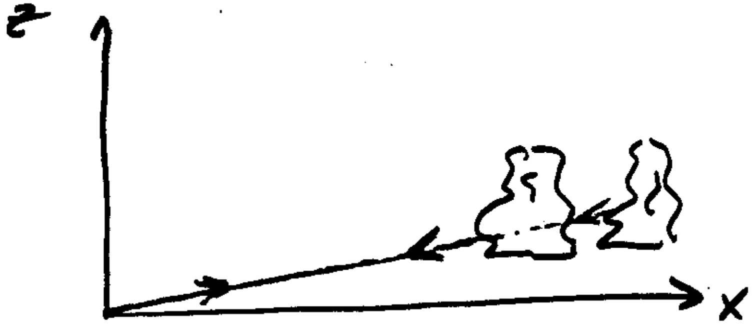
UHF = 300-3000 MHz
SHF = 3-30 GHz

M = Mesosphere
S = Stratosphere
T = Troposphere



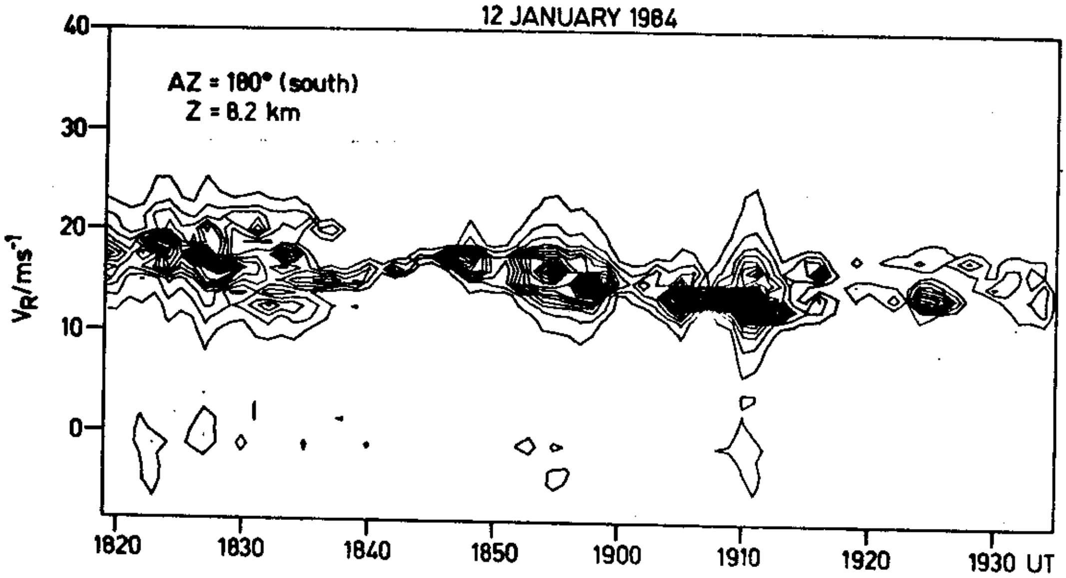


Early range-height-intensity display of echoes from clouds (from Battan, 1973).



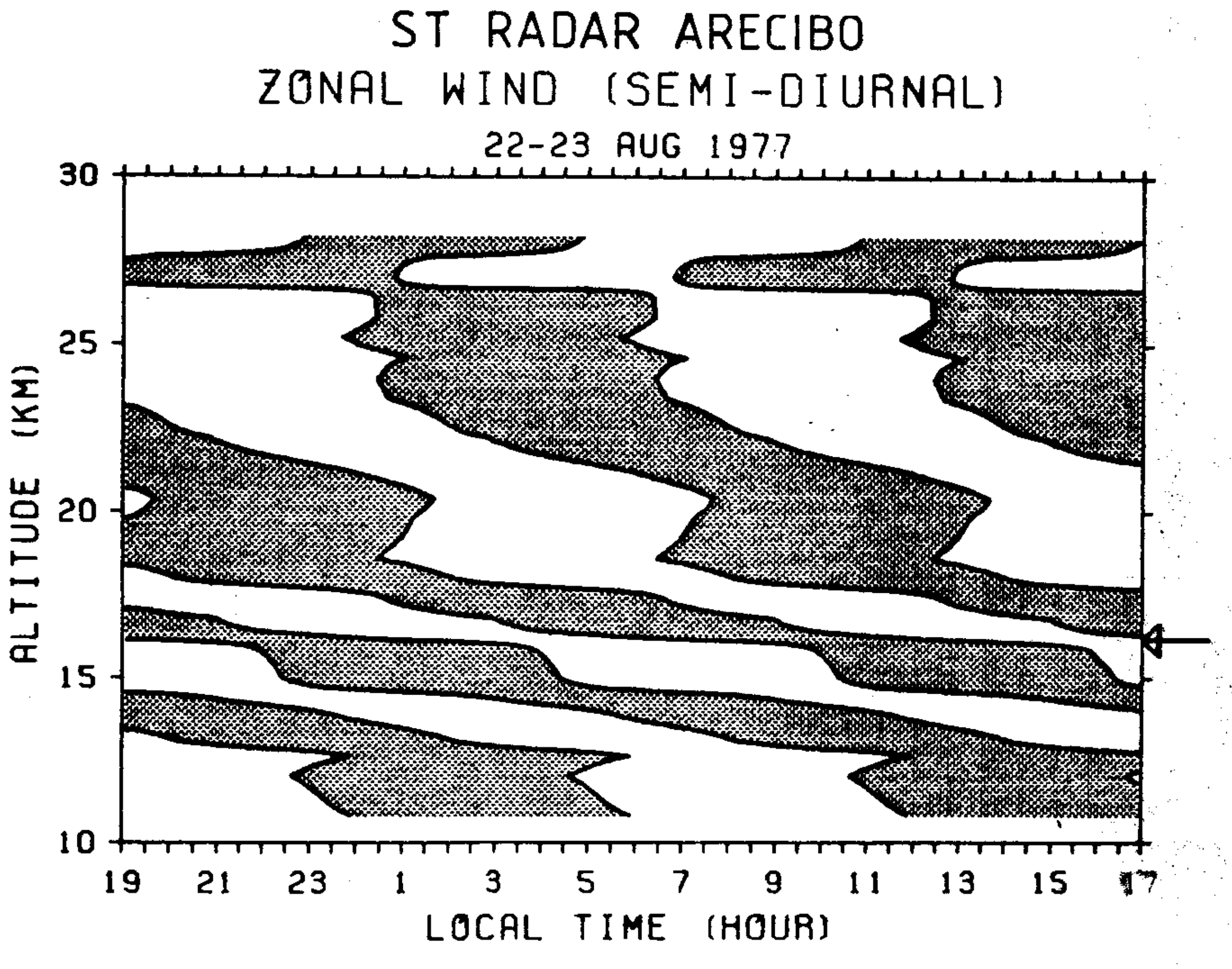
PPI-display of cloud echoes (from Battan, 1973)

57

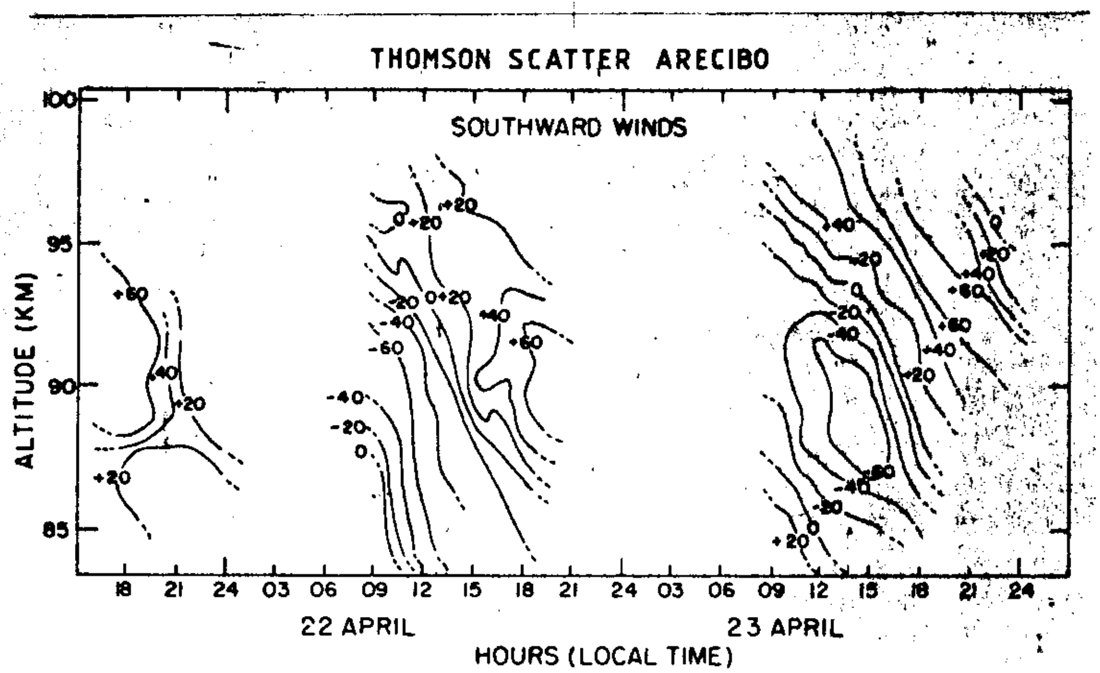


Troposphere clear air turbulence measured with the EISCAT UHF radar.

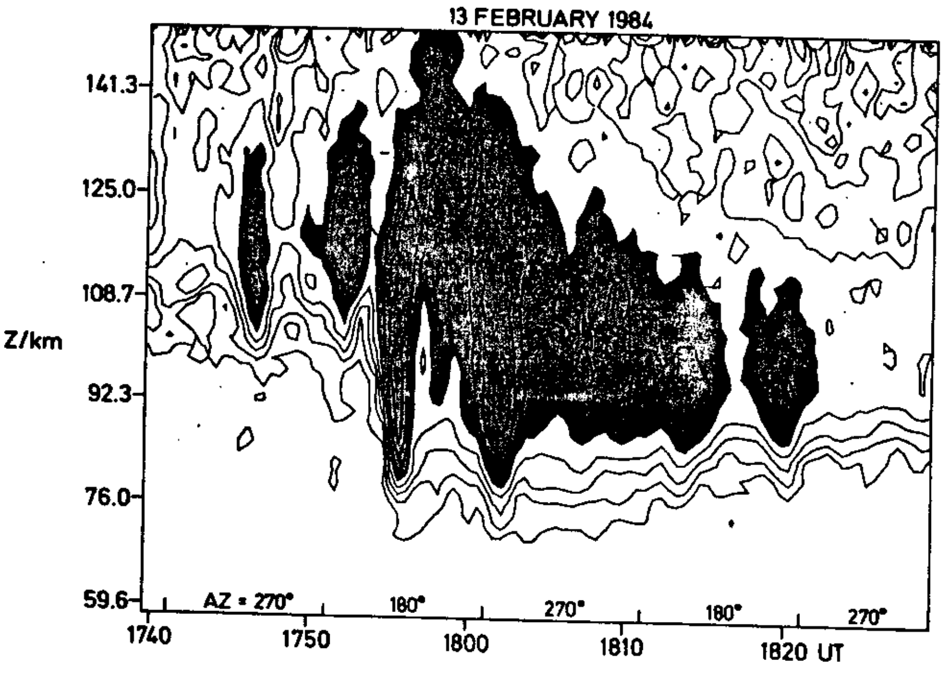
58



59

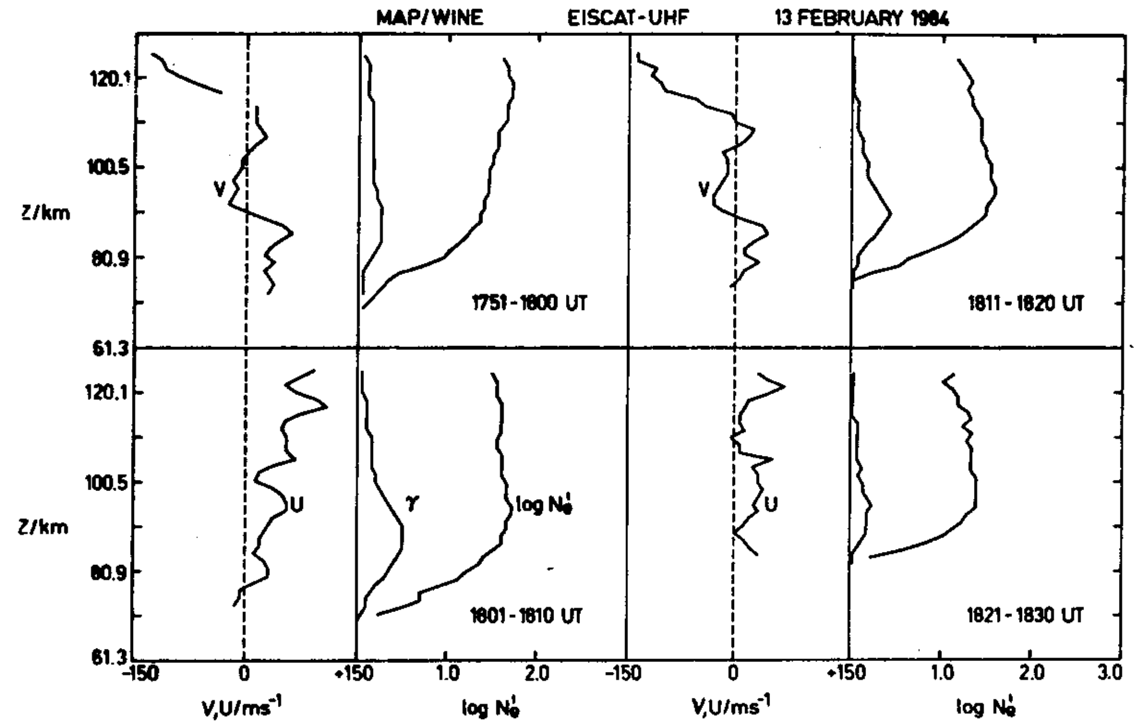


60

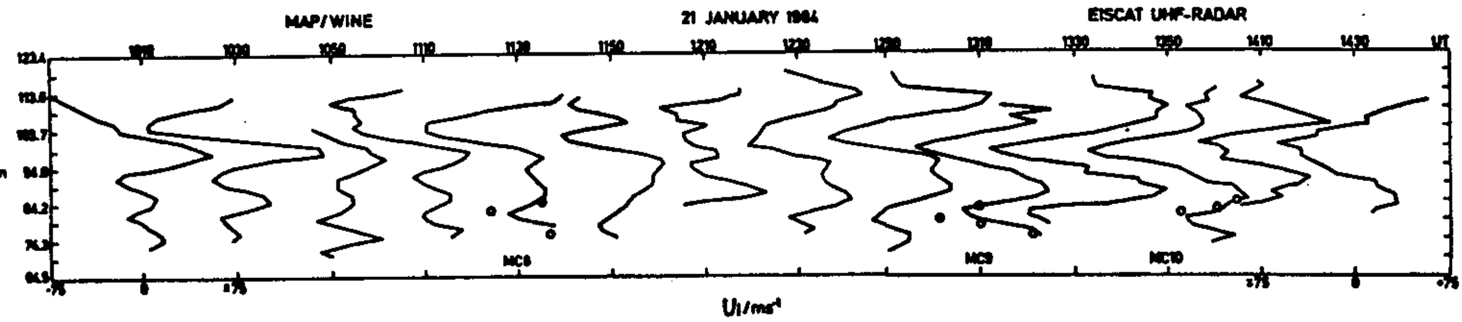


Electron density measurements with the EISCAT UHF-Radar during particle precipitation events.

61

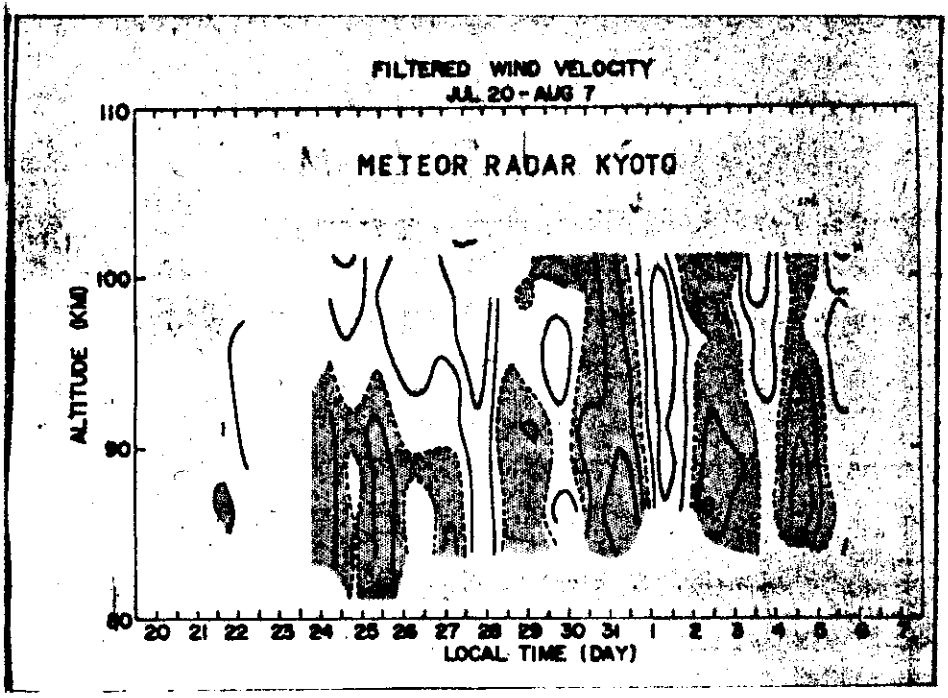


Electron density profiles Ne' and zonal (U) and meridional (V) wind

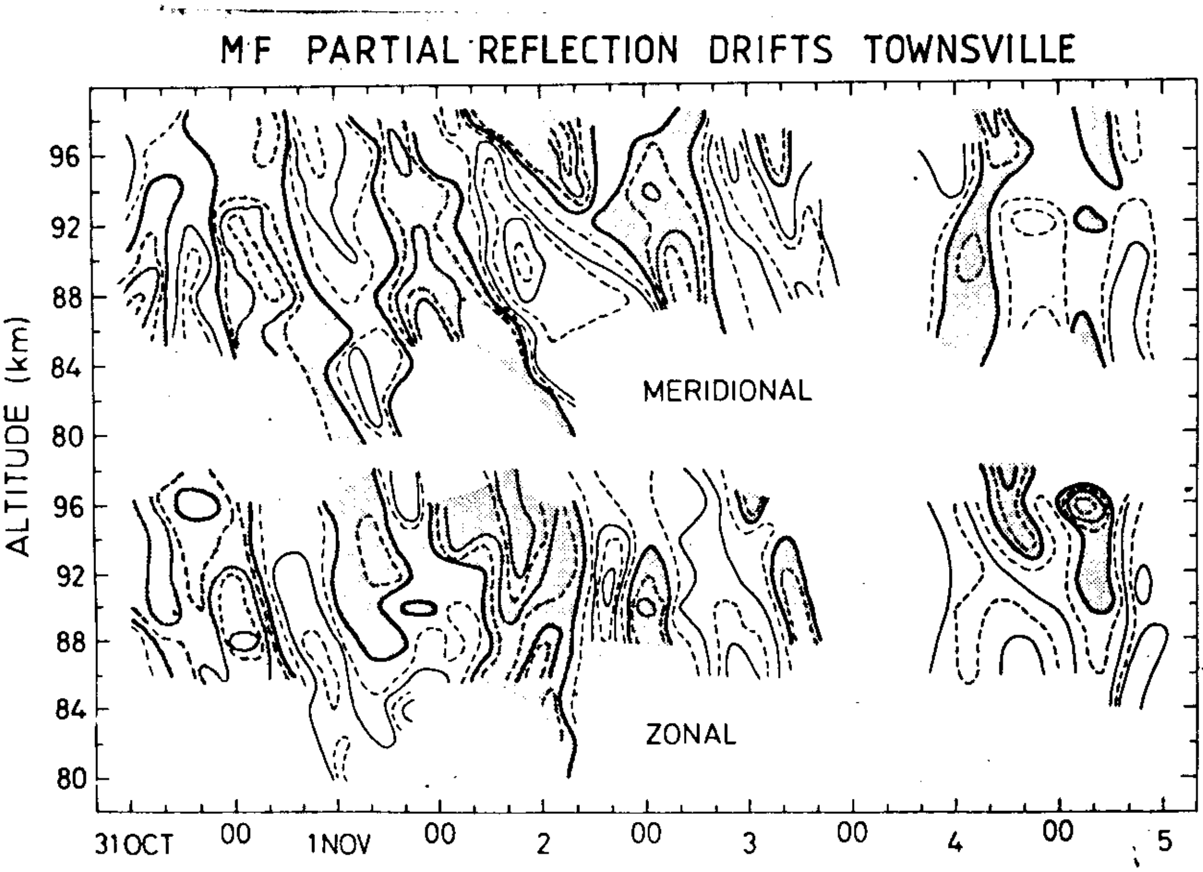


62

[redacted] Time series of zonal winds. The open circles denote chaff wind data (courtesy of U.von Zahn).

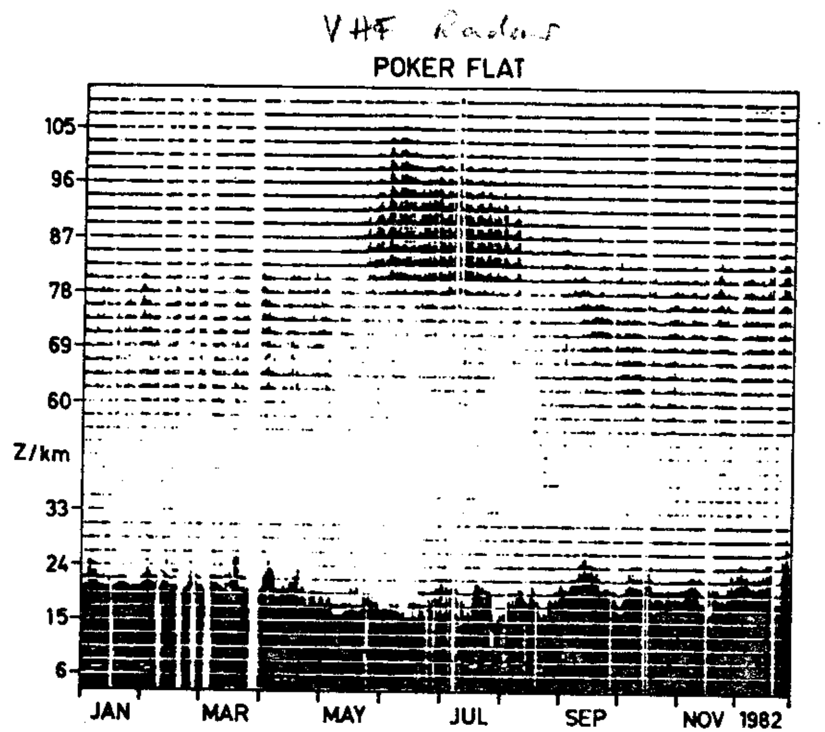


63

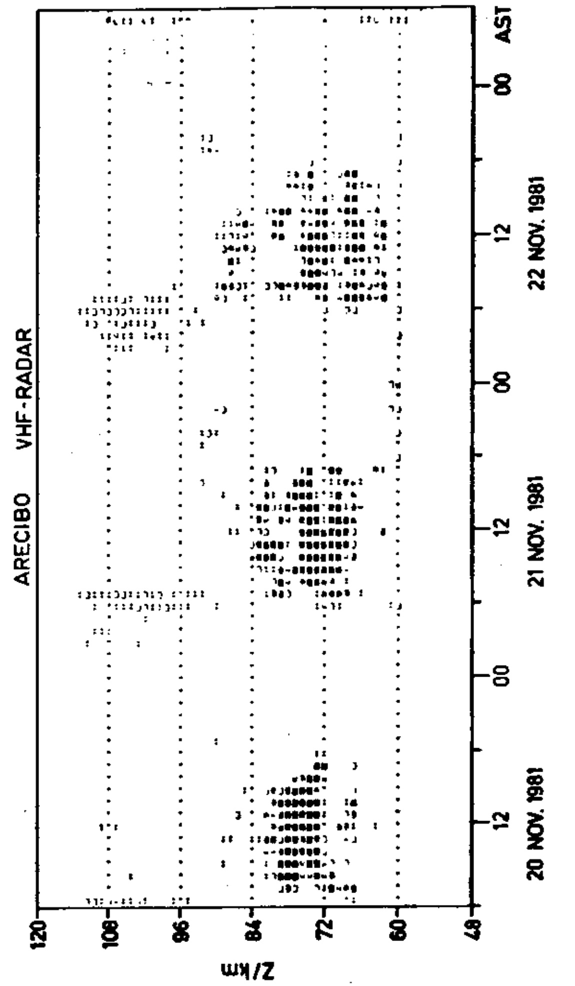


from Vincent (1983)

64



ref. Fig 16 of main paper



ref. Fig. 19 of main paper.

MST RADARS ARE CAPABLE TO OBSERVE:

(1) Reflectivity Structure:

(a) morphology of turbulence,
e.g., intensity, intermittency, thickness
and anisotropy

(b) stability index (coherency $\propto \partial\Theta/\partial z$),
e.g., air mass mixing zones, inversion layers
and tropopause

(2) Velocity Field:

(a) mean horizontal and vertical velocities u,v,w,
e.g., winds and convective processes

(b) fluctuating (oscillating) velocities u',v',w',
e.g., gravity waves and turbulence