EUFAR - EUropean Facility for Airborne Research

Education & Training

Radars

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RADAR (RAdio Detection And Ranging)

- Active remote sensing instrument (like LIDARs)
- First meteorological applications in 1935
- First pulsed RADAR during WWII
- First Doppler application in the '70
- First polarimetric applications in 1976
- Operative networks established in the '80

- To detect presence, position, speed of objects (targets) by radio (cm to m) or micro (mm to cm) waves
- For meteorological RADARs the target are cloud particles and hydrometeors

Meteorological RADARs

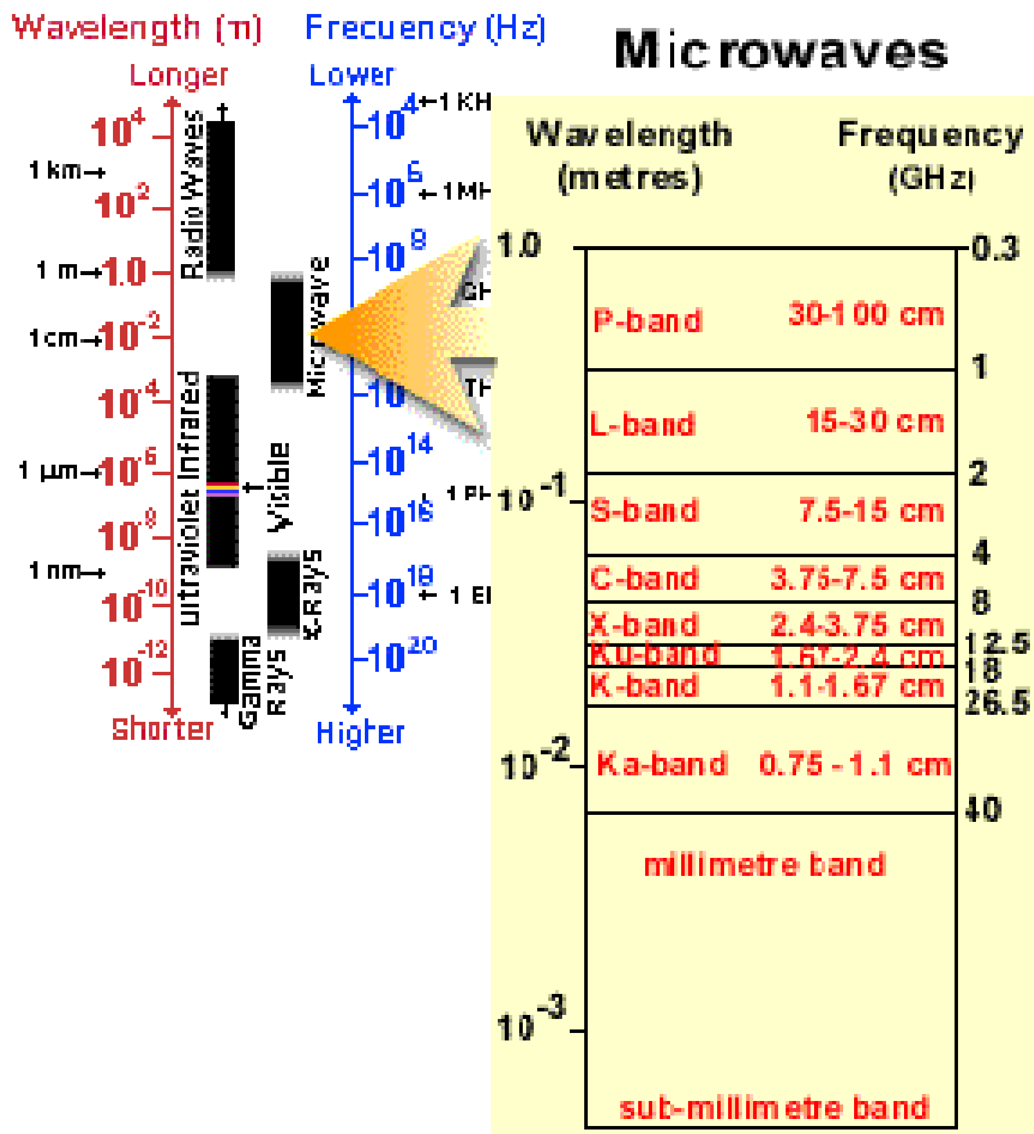
•W Band:
110,000-75,000 MHz; 0.27-0.4 cm

•V,Q Band:
60,000-40,000 MHz; 0.5-0.8 cm

•Ka Band:
40,000-26,000 MHz; 0.8-1.1 cm

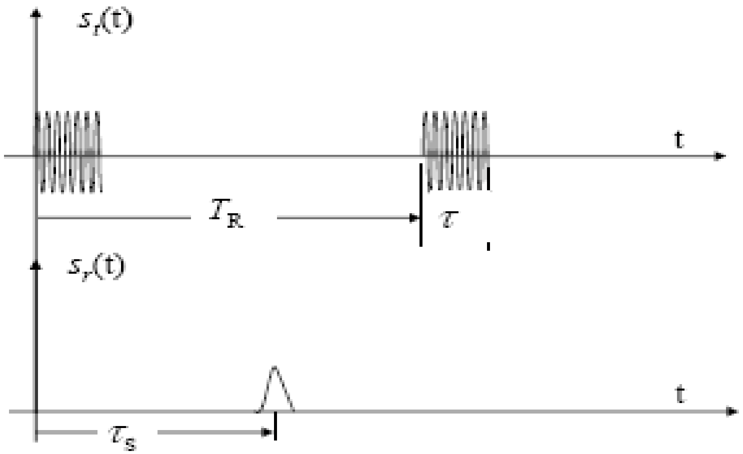
•K Band:
•26,500-18,500 MHz; 1.1-1.7 cm

•Ku Band:
•12,500-18,000 MHz; 1.7-2.4 cm



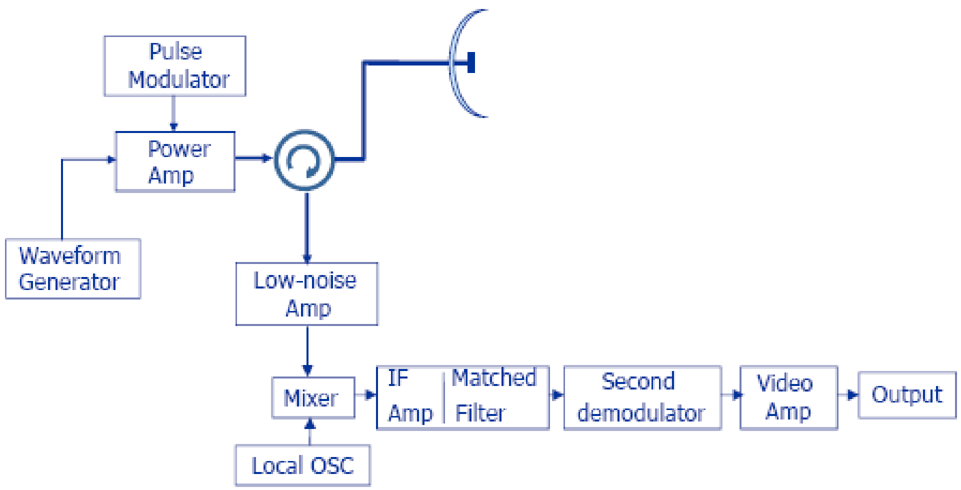
RADAR scheme

A pulsed beam is transmitted into the atmosphere



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

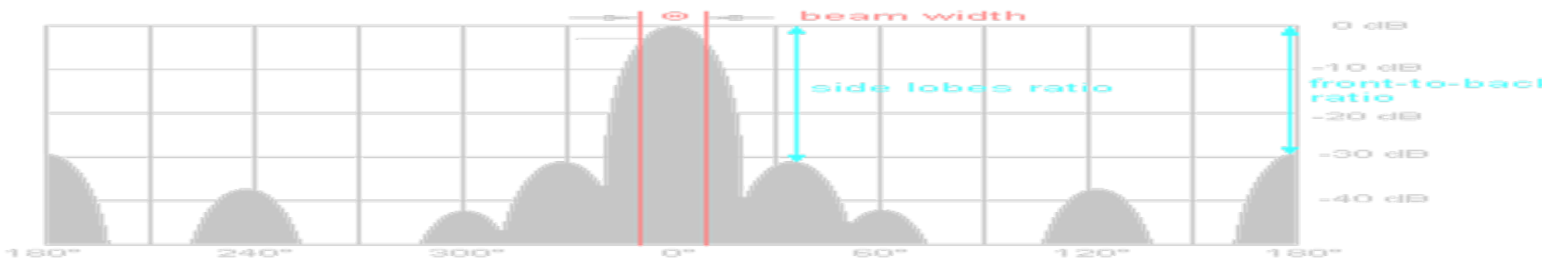
$$R_{max} = \frac{c \cdot T_R}{2}$$



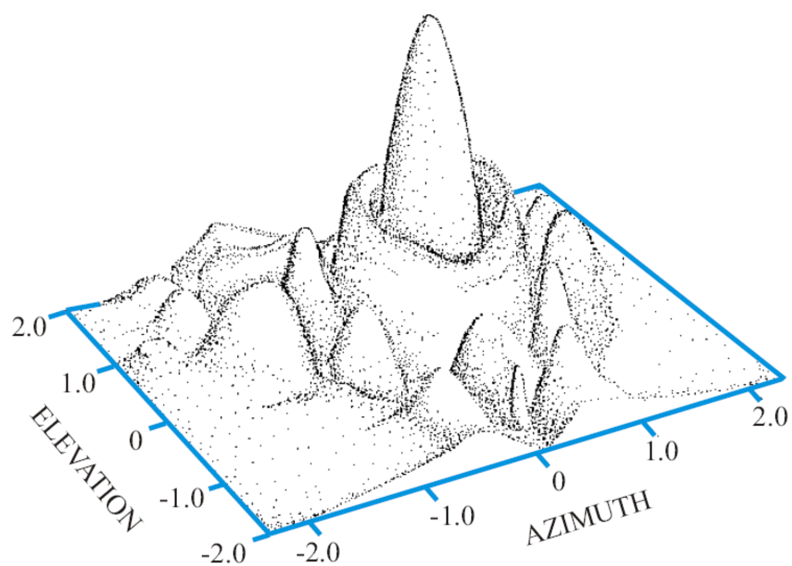
Scattering from a far object

Electric field at distance r

$$\overline{E}_i = \frac{A_i(\theta,\phi)\cdot e^{i\phi_t}}{r}\cdot e^{i(k_c\cdot r+\omega_c\cdot t)}\,\overline{e_i}$$



3-D Antenna Beam Pattern



Let's suppose interaction with a single scatterer, and neglet depolarization effects, then at the radar receiving antenna:

$$E = \frac{S(180°) \cdot A(\theta_m, \varphi_m)}{k_c \cdot r_m^2} \cdot e^{i(2k_c r_m - (\omega_c - \omega_{d,m})t + \phi_{s,m} + \phi_t)}$$

Let's assume the transmitter phase and scatteres phase shift are constant.

From field to power densities

Power density over a cycle $$P_t = \frac{1}{\eta_0}\overline{E_t^2}$$

at a distance r (with attenuation) $$\frac{P_t}{4\pi \cdot r^2} f^2(\theta,\phi)\cdot G \cdot l^{-1}$$

attenuation $$l^{-1} = e^{-\int_0^r k(r)dr}$$

At the receiver detector, after scattering $$P_{r,m}(r_m,\theta_m,\phi_m) = \frac{P_t f^4(\theta_m,\phi_m)G^2\sigma_{b,m}\lambda_c^2}{(4\pi)^2 r^4 l^2}$$

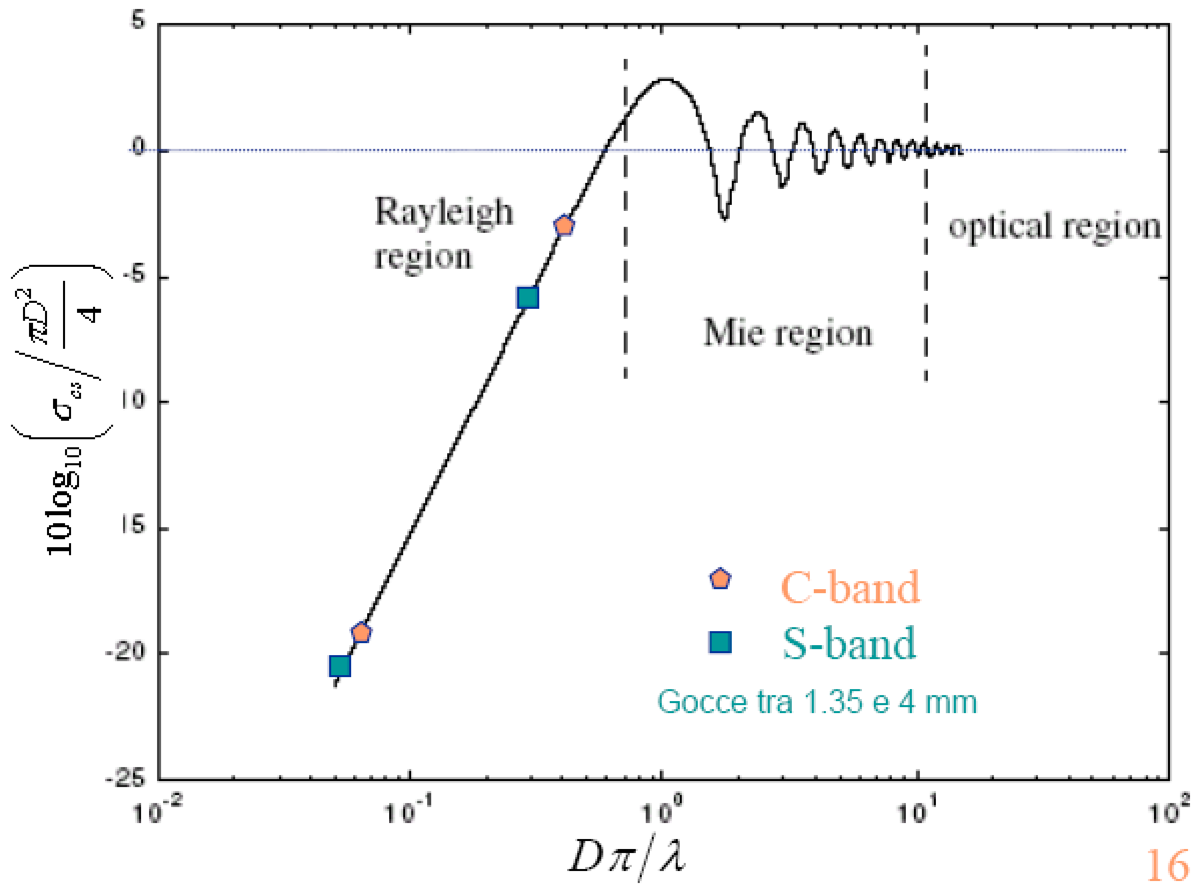
$$\sigma_{b,m} = 4\pi\left(\frac{S_{2,m}(180°)}{k_c}\right)^2$$

$$A_i(\varphi,\vartheta) = \sqrt{\frac{P_t G_t \eta_0}{2\pi l_t}} f_t(\varphi,\vartheta)$$

Radar equivalent section of a reflection sphere

Rayleigh region
D<10λ
σ - D⁶/λ⁴

Optical region
σ – D²



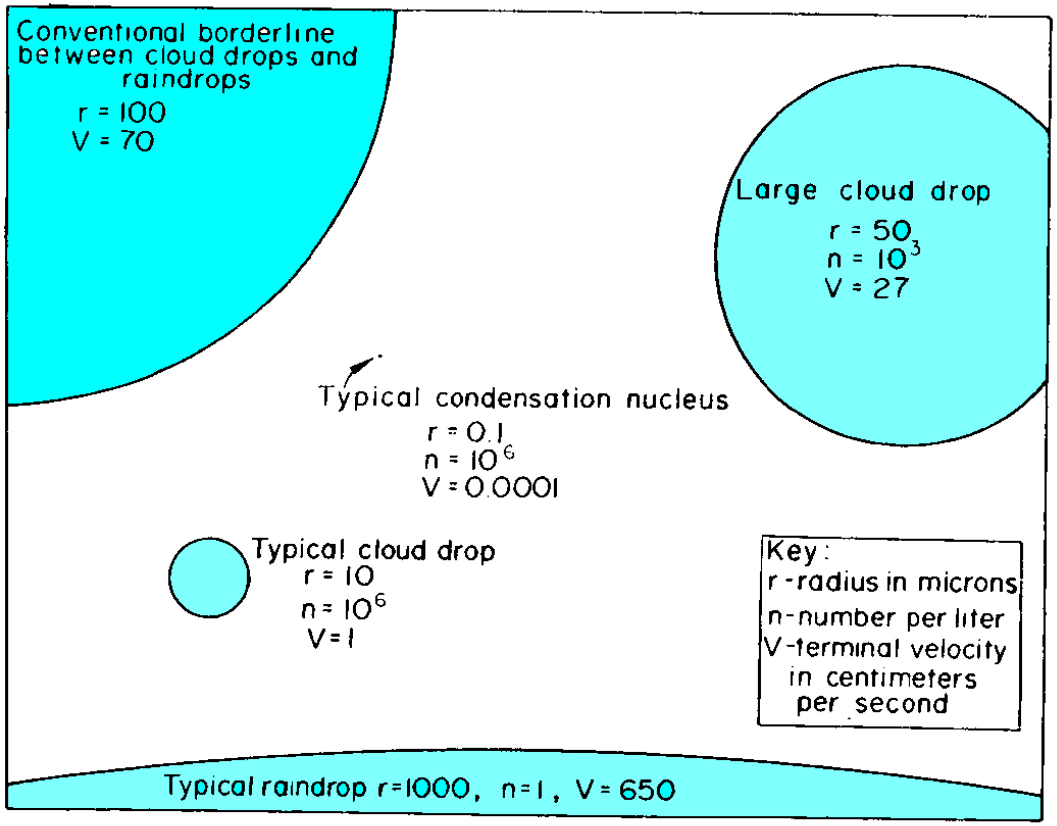


FIG. 6.1. Comparative sizes, concentrations, and terminal fall velocities of some of the particles included in cloud and precipitation processes. (From McDonald, 1958.)

...from many scatteres

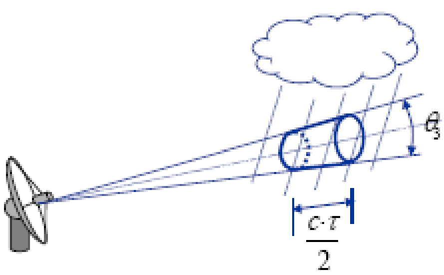
Under the assumption of single, incoherent scatterings

$$\sigma_{b,m} \Rightarrow \eta(r) = \int_D \sigma(D) N(D,r) dD \cdot dV$$

$$P_r(r,\theta,\varphi) = \int_{r_b}^{r_t} \int_0^{\pi} \int_0^{2\pi} \frac{P_t f^4(\theta,\varphi) G^2 \eta(r) dV \lambda_c^{\ 2}}{(4\pi)^3 r^4 l^2}$$

If the radar resolution lenght τ and the resolution volume is small, and the antenna pattern is Gaussian and symmetric

$$P_r(r) = \frac{P_t G^2 \lambda_c^{\ 2} \eta(r) c \tau \pi \theta^2}{(4\pi)^3 r^2 l^2 (r) 16 \ln(2)} = \frac{C \eta(r)}{r^2 l^2}$$

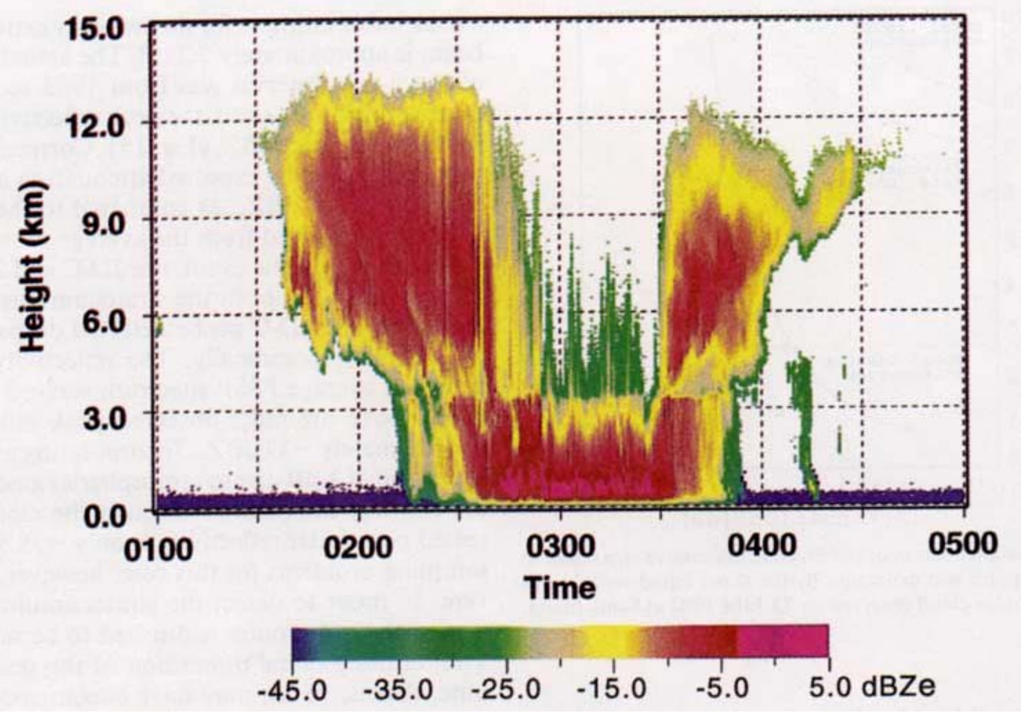


A bit of jargon; RADAR reflectiviy

$$P_r(r) = CZr^{-2}$$

Z [$mm^6\ m^{-3}$] is the Reflectivity Factor, often expressed logaritmically

$Z(dBZ) = 10 \log_{10}(Z)$



Clothiaux et al., 1995

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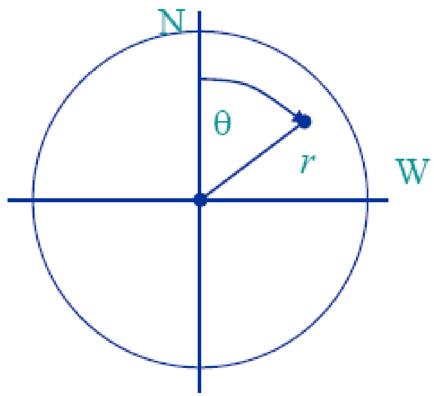
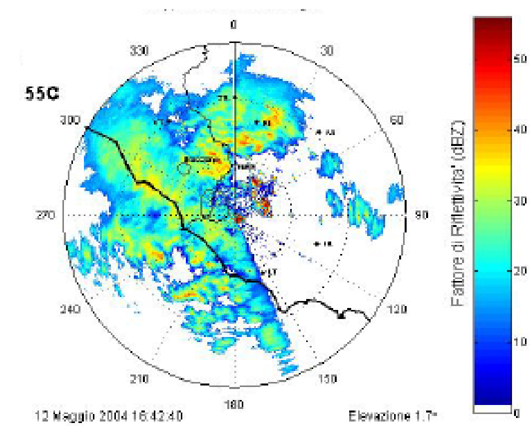
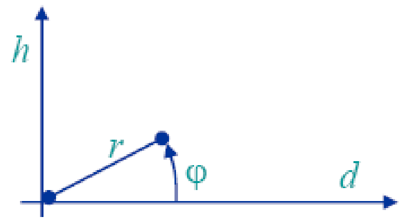
visualization

- Slant paths (Plan PositionIndicator, given elevation, all azimuth),
- Vertical curtains, (RangeHeightIindicator, elevation scan, fixed azimuth

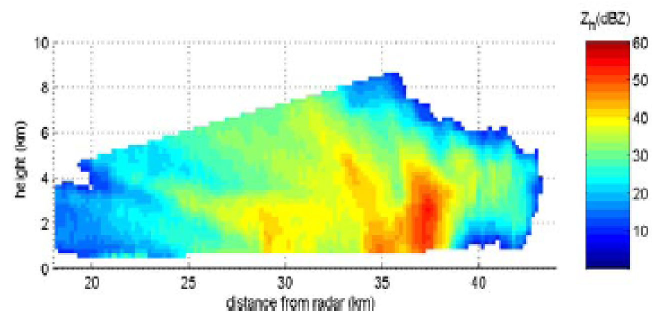


PPI



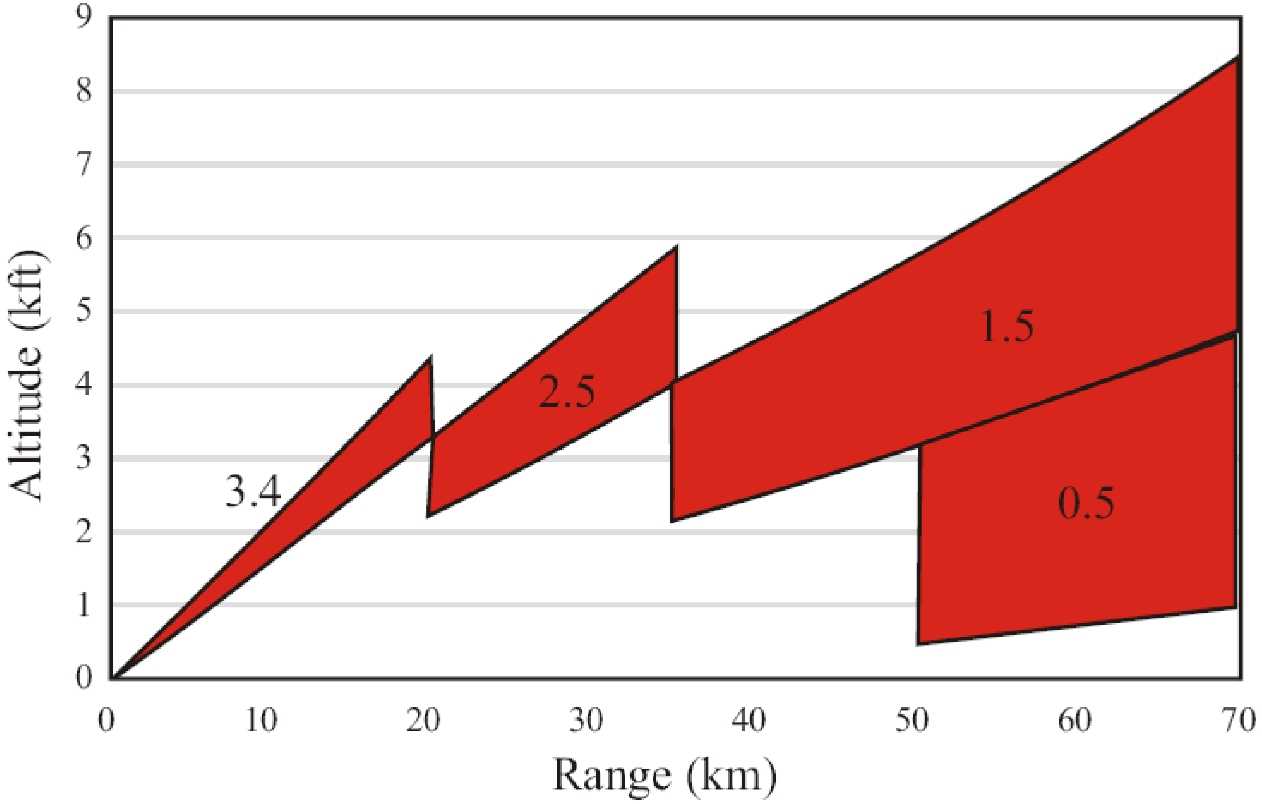


RHI



Data courtesy L. Baldini

Vertical cross sections
(Constant Altitude Plan Position Indicator)



Radar Receiver

From the antenna, the e.m. signal passes to a mixer and preamplifier, that

- Transform the high carrier frequency ω_c to al lower one ω_i
- Produce a signal voltage proportional to the scattered field

From a single scatterer:

$$V(t) = V \cdot e^{i(2k_c r - (\omega_i + \omega_{d,m})t + \phi_{s,m} + \phi_t)}$$

$$\omega_{d,m} = 2\pi v_m / \lambda_c$$

- Incoherent detection
- Coherent (Doppler) detection:
  - allow the determination of the phase of the received signal;
  - From phase variation it is possible to infer the radial velocity

Doppler Radar

In two I and Q demodulators, to get rid of the frequency ω_i , the signal is multiplied by two reference voltages, a quarter out of phase, originated by a sample of the transmitted signal, then low pass filtered to obtain:

$$I(t) = V\cos(2k_c r - \omega_{d,m} t + \phi_{s,m}) = V(\tau_i, T_s)\cos(\theta(\tau_i, T_s))$$

$$Q(t) = V\sin(2k_c r - \omega_{d,m} t + \phi_{s,m}) = V(\tau_i, T_s)\sin(\theta(\tau_i, T_s))$$

The I and Q voltage amplitudes are a representation of the scattered e.m. field. Their Variability enable to produce power spectra. The istantaneous power at the antenna is proportional to :

$$P(t) = C(I^2(t) + Q^2(t))$$

from one to many scatterers (1)

e.m. field from one scatterer:

$$E(t) = A_m \cdot e^{i[2k_c r_m - (\omega_c + \omega_{d,m})t + \phi_{s,m} + \phi_t)}$$

e.m. field from many:

$$E(t) = \sum_m A_m \cdot e^{i[2k_c r_m - (\omega_c + \omega_{d,m})t + \phi_{s,m} + \phi_t)}$$

Power received:

$$P(t) = \frac{1}{2R_0} E(t) \cdot E^*(t) = \frac{1}{2R_0} \Big(\sum_{m=1,N} A^2{}_m + \sum_{\substack{m \neq n \\ m,n=1,N}} A_m A_n \cdot e^{i[2k_c (r_m - r_n) - (\omega_{d,m} - \omega_{d,n})t + (\phi_{s,m} - \phi_{s,n})]} \Big)$$

$$P = \lim_{T_{M \to \infty}} \frac{1}{M} \sum_{j=1,M} P_j = \frac{1}{2R_0} \sum_m A_m^2$$

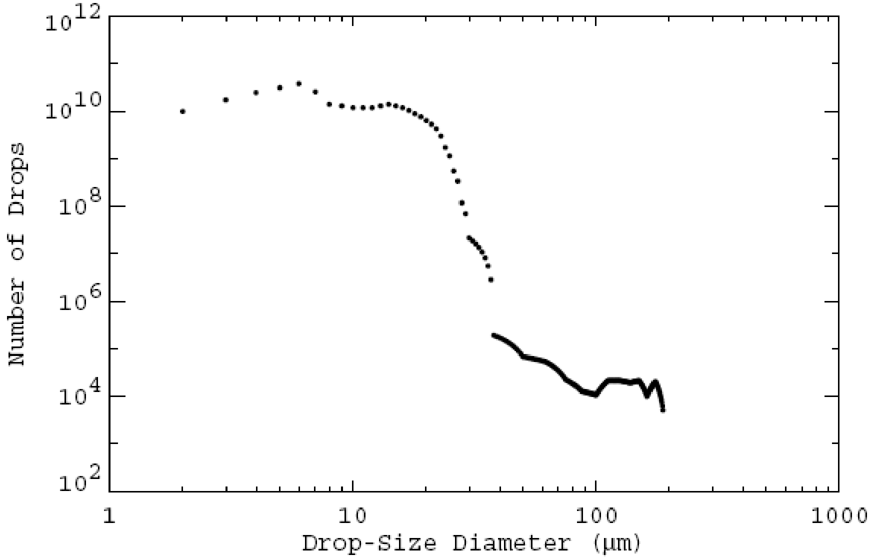
The first term contains the information on the total cross section. The second term disappear over long averaging over many pulses.

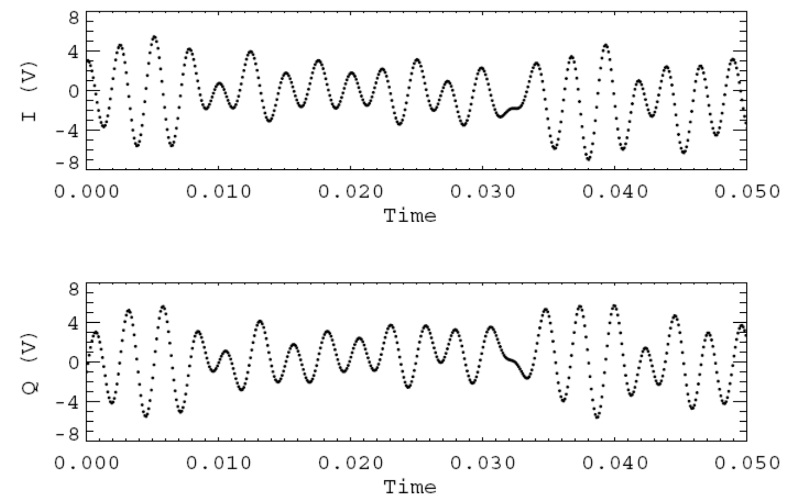
From one to many scatterers (2)

At the demodulators output:

$$I(t) = \sum_{m=1,N} V_m \cos(2k_c r_m - \omega_{d,m} t + \phi_{s,m})$$

$$Q(t) = \sum_{m=1,N} V_m \sin(2k_c r_m - \omega_{d,m} t + \phi_{s,m})$$





Simulation with a fall speed depending on the diameter

Clotiaux et al., 2001

Some statistical properties (1)

The remainder of $2k_c r_m$ MOD2π is uniformly distributed over 0 2π

Cosines and sines are random variables undiformly distributed between -1 and 1

(C. L. Th.) Their sum tends to be gaussian distributed around 0

$$p[I(t)] = \frac{e^{-I^2(t)/2\sigma^2}}{\sqrt{2\pi}\sigma}; p[Q(t)] = \frac{e^{-Q^2(t)/2\sigma^2}}{\sqrt{2\pi}\sigma}$$

Some statistical properties (2)

I(t) and I(t-L) show a degree of correlation if L is not too large

I(t) and Q(t) are not correlated

I(t) and Q(t+L) show a degree of correlation if L is not too large

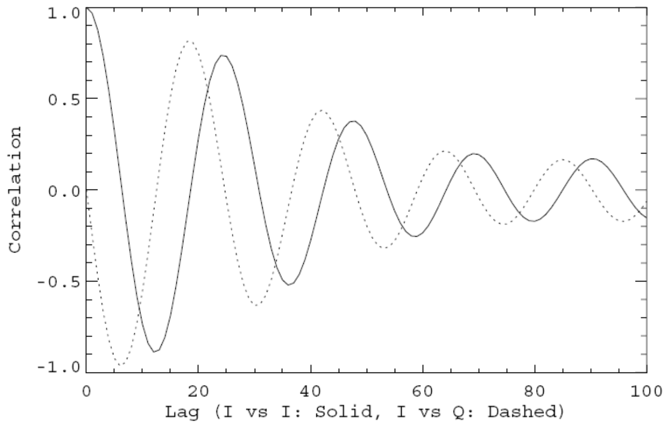


Figure 14. Correlation of I with itself (solid line) and with Q (dashed line) for lag times from 0 to 30 T_s, where $T_s = 0.0001$ is the simulated pulse repetition period for the forward simulation.

Clotiaux et al., 2001

The instrument noise is gaussian distributed, but is uncorrelated

Some statistical properties (3)

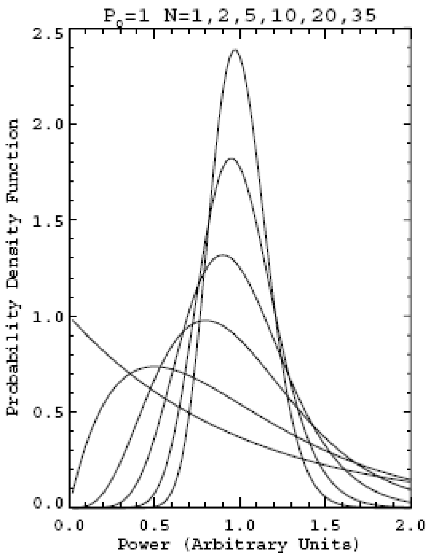
and

$$p[I(t) \cap Q(t)] = p[I(t)] \cdot p[Q(t)] = \frac{e^{-(I^2(t)+Q^2(t)/2\sigma^2}}{2\pi\sigma^2} = p[P(t)]$$

The power probability density is exponential with peak probability 0 and mean value $2\sigma^2$

And for N averages of power samples:

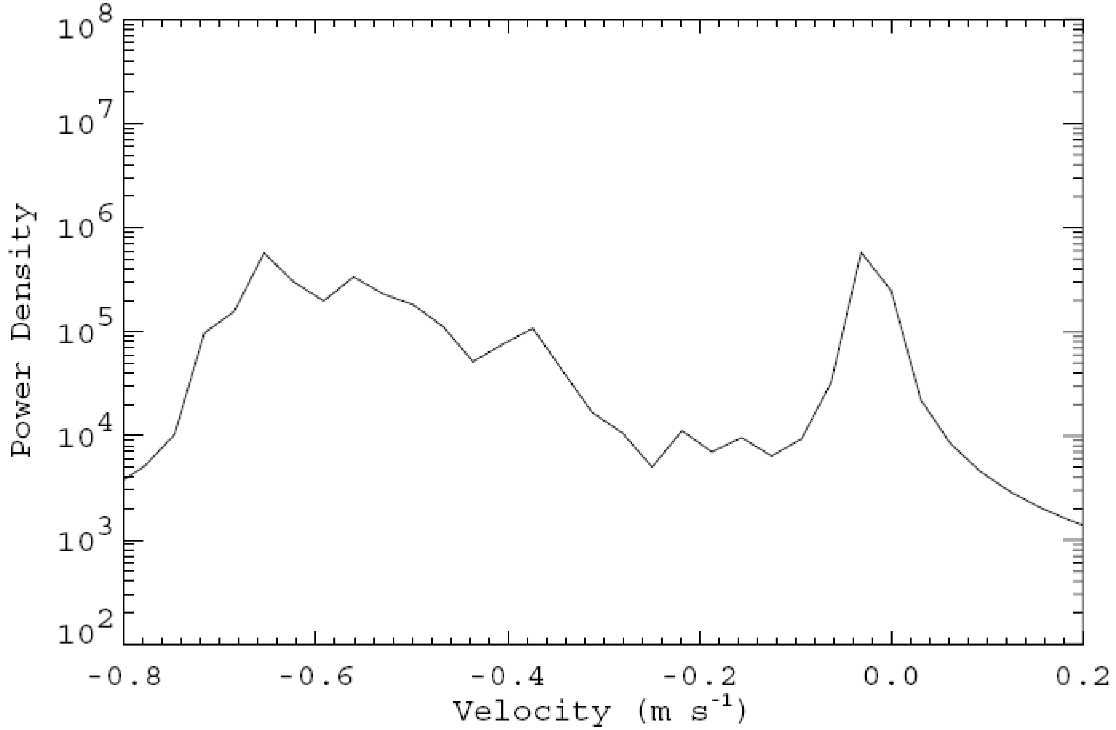
$$p[P_N] = \frac{N^N P_N^{N-1} e^{-NP_N/P_0}}{P_0^N (N-1)}$$



From $P_N(r)$ we retrieve informations about $\eta(r)$, hence the quantity and location of cloud particles.

Doppler moments (1)

Use I(t) and Q (t) as the real and complex array input for a FFT brings the power density spectrum $S(\omega_m)=S(4\pi v_m/\lambda_c)$



τ fixes the max and min retrievable velocity.

T fixes the min velocity increment

Doppler moments (2)

Mean power weighted radiant speed

$$\bar{v} = \sum_{-N_n/2}^{-N_n/2} v(m) \cdot S_{norm}(m)$$

Spectral width

$$\sigma_v^2 = \sum_{-N_n/2}^{N_n/2} \left| \bar{v} - v(m) \right|^2 \cdot S_{norm}(m)$$

These quantities, together with the received power (zero moment) are the radar observables delivered by a Doppler system.

Pulse Pair correlation

Pulse Pair autocovariance technique:

$$V(m) = I(m) + iQ(m) \quad m = 1, \ldots, N$$

$$R = \frac{1}{N-1} \sum_{m=1,N} V^*(m) V(m+1)$$

$$R_{re} = \frac{1}{N-1} \sum_{m=1,N} \left[I(m) I(m+1) + Q(m) Q(m+1) \right]$$

$$R_{im} = \frac{1}{N-1} \sum_{m=1,N} \left[I(m) Q(m+1) - Q(m) I(m+1) \right]$$

$$|R| = \sqrt{R_{re}^2 + R_{im}^2}$$

$$\phi = \arctan\left(\frac{R_{im}}{R_{re}}\right)$$

Mean backscatter-weighted radial velocity:

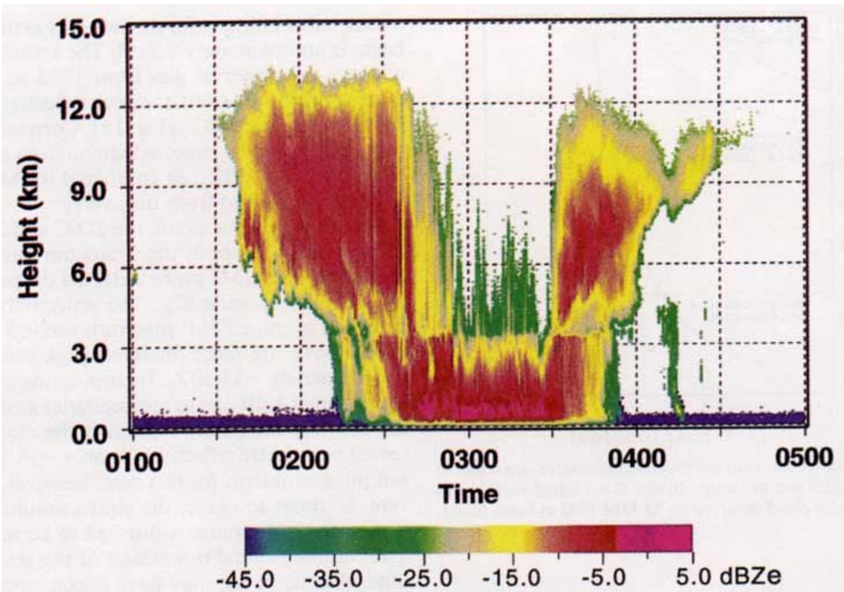
$$v = -\left(\frac{\lambda}{4\pi T}\right)\cdot\phi$$

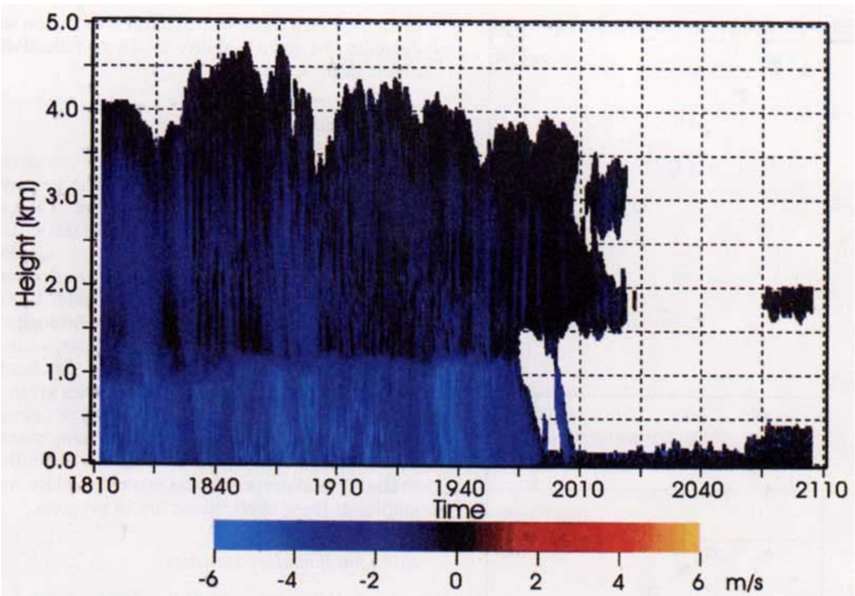
Spectral width:

$$\sigma_v = \left(\frac{\lambda}{2\pi T\sqrt{2}}\right)\cdot\left|\ln\left(\frac{S}{|R|}\right)\right|^{\frac{1}{2}}$$

$$S = \frac{1}{N}\sum_{m=1,N}\left|V(m)\right|^2(-noise)$$

Reflectivities and vertical speeds





Clothiaux et al, 1995

…what we have skippd

- Z- Precipitation Intensity; - Cloud Liquid/Ice water content
- The effect of attenuation, negligible in S band, not so at shorter wavelenghts
- Georeferetiability (variability of refractive index with height)
- Polarimetric measurements
- Sources of errors; minimum detectable signal
- Calibration issues
- Etc, etc…

To learn more

Bringi,V.N. and V.Chandrasekar, 2001: ***Polarimetric Doppler Weather Radar: Principles and Applications. Cambridge University Press, 636 pp.***

Doviak D.S. and Zrnic'D. ***,Doppler radar and weather observations.*** **Second edition, Academic Press,1993.**

Clothiaux et al., ***Ground Based Remote Sensing of Cloud Properties using Millimeter Wave Radar*****, Edited by Raschke,E., Radiation and Water in Climate System, Nato ASI Series, Springer-Verlag,1996.**