MICROWAVE RADAR METEOROLOGY Foundations and Applications

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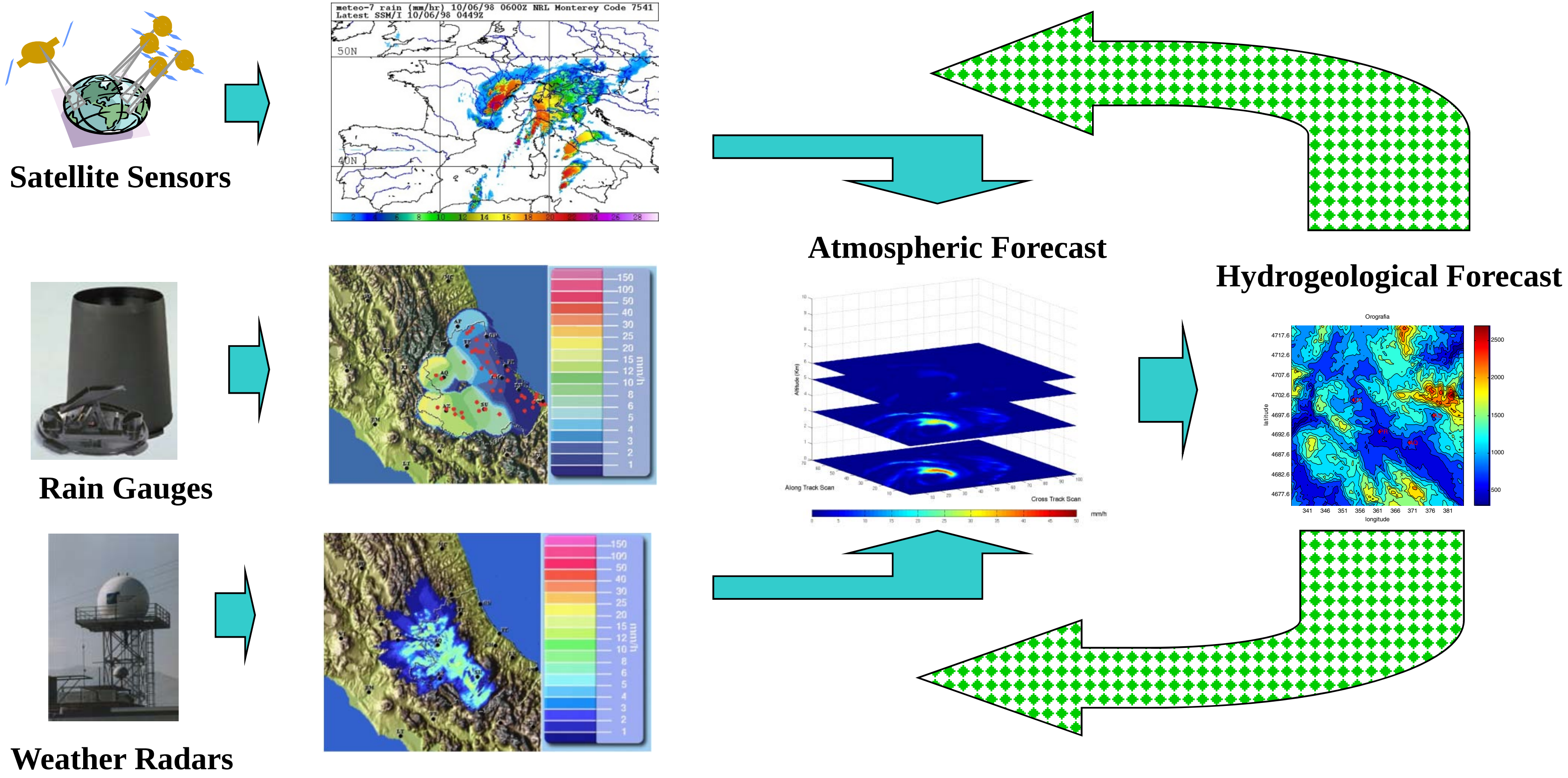
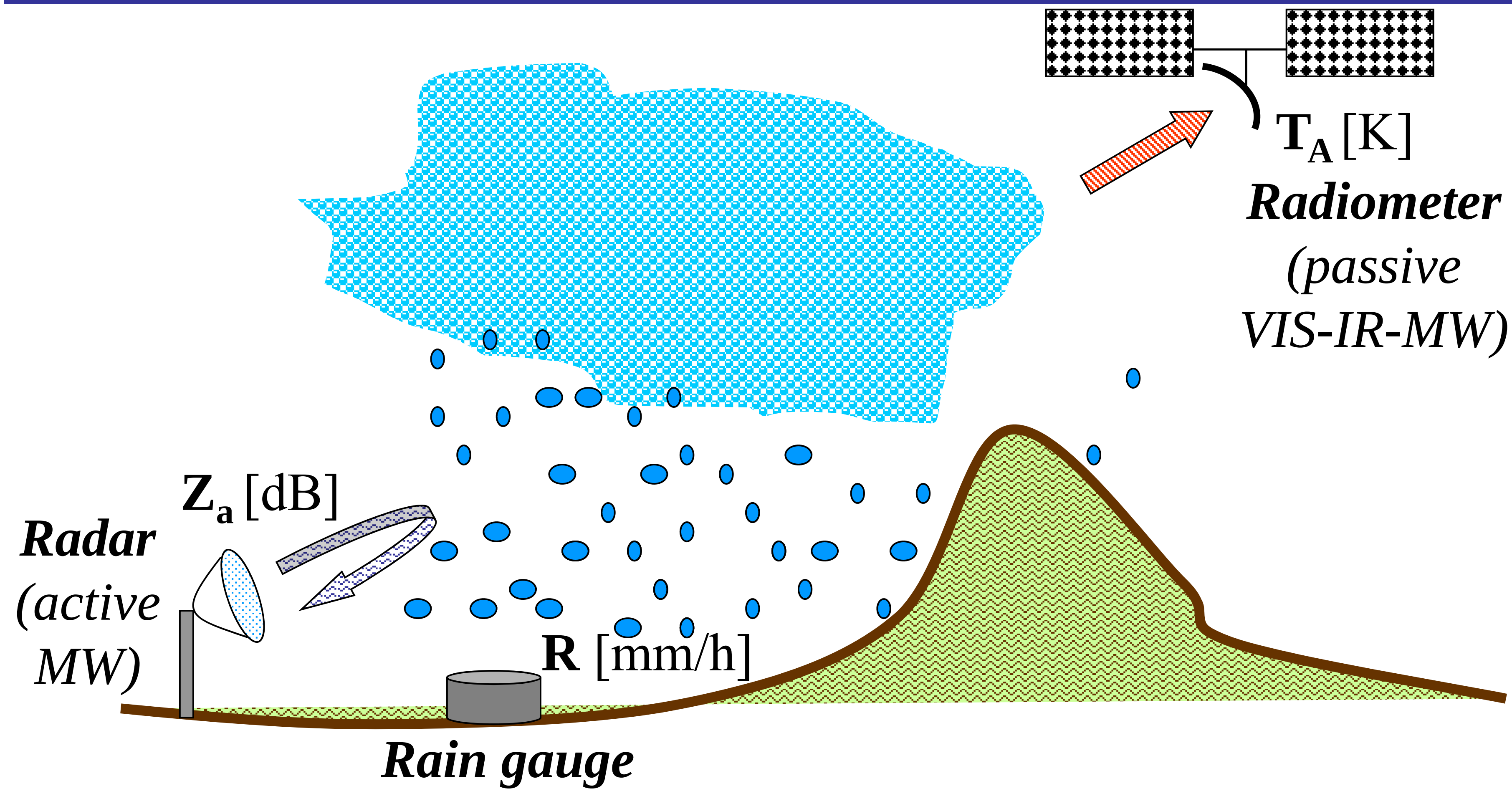
RAINFALL FORECAST
A conceptual diagram



RAINFALL SENSING
Points of view



RADAR METEOROLOGY
Lecture's contents

- Radar sensor
  - Pulsed, Doppler, and polarimetric systems
  - Receiver sensitivity, antenna specifications and radar volume resolution
- Radar equation
  - Atmospheric refraction and attenuation
  - Radar equation for single and distributed scatterers
- Radar signal
  - Signal statistics and decorrelation
  - Noise reduction techniques
- Radar applications
  - Clouds and precipitation
  - Rainfall backscattering and polarimetric measurables
- Radar products
  - Radar measurements and error budget
  - Examples of radar measurements and estimates

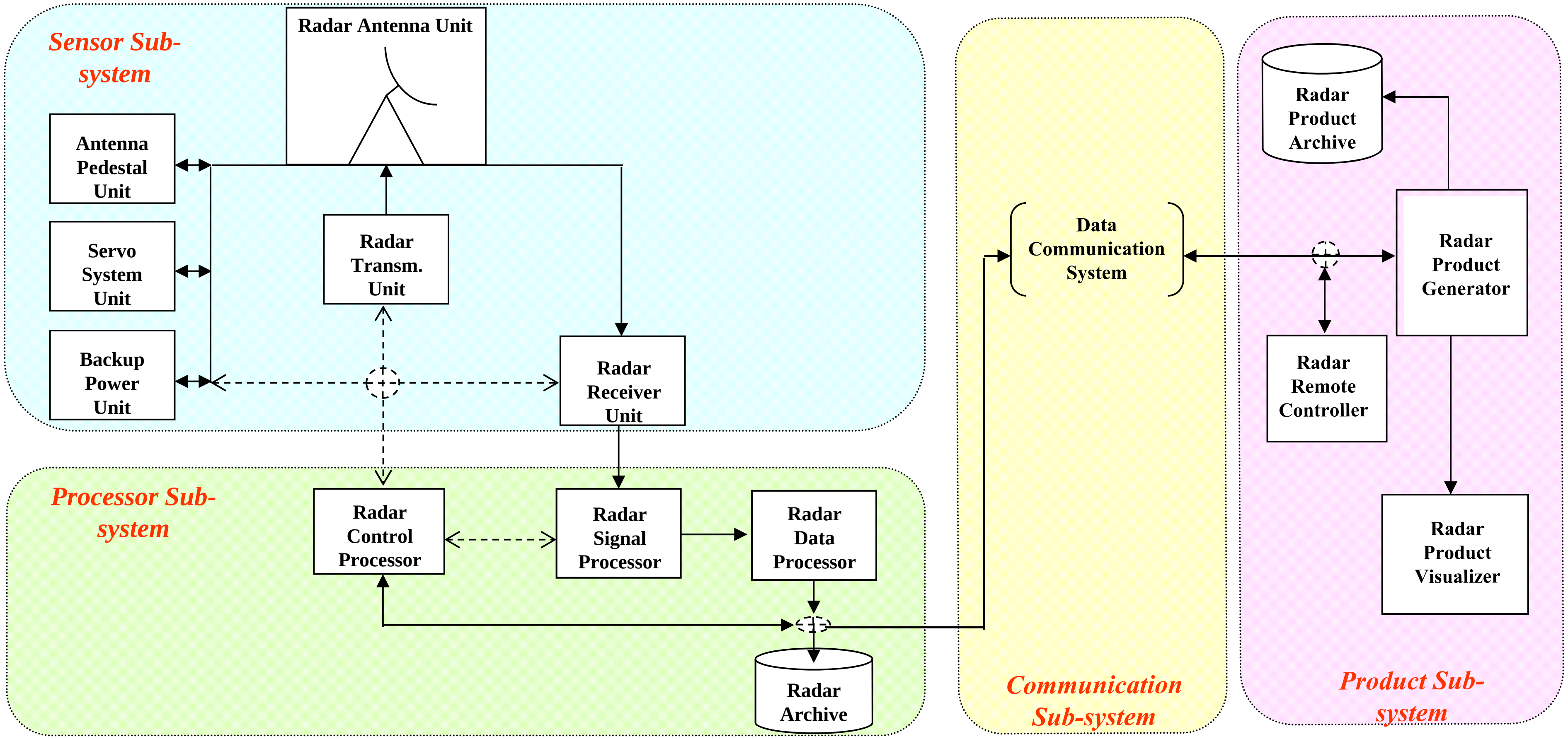
RADAR METEOROLOGY Historical perspective

- Radio era
  - 1886: H. Hertz experiments e.m. wave reflection
  - 1902: G. Marconi carries out radio-propagation experiments
  - 1922: object detection with continuous wave instruments
  - 1932: object detection with pulsed wave instruments
- Radar era
  - 1938: construction of radars for aircraft detection and ranging
  - 1941: first use of radars for cloud observations
  - 1960s: use of radars for quantitative rainfall estimation
  - 1970s: use of Doppler radars at VHF-UHF for turbulence and wind
- Computer era
  - 1980s: impact of computers on data acquisition and processing
  - 1990s: use of digital receivers and pulse forming
  - 1990s: use of radars for weather nowcasting
  - 2000s: spaceborne radars and sensors' synergy

RADAR METEOROLOGY
Context and objectives

- Radar (RAdio Detection and Ranging)
  - Pulsed incoherent and coherent radars (Doppler or MTI)
  - Continuous-wave and frequency modulation (FM-CW)
- Meteorological radars
  - Rain (weather) radars: rainfall monitoring from ground and space
  - Cloud radars: cloud monitoring from ground and space
  - Stratosphere-Troposphere (ST) radars: wind profiling from ground
- Weather (rain) radars
  - Monitoring of three-dimensional (3-D) structure of rainfall and winds
    - Covering large areas (100-400 km) around ground site
    - Measuring of e.m. backscattering due to cloud hydrometeor volumes
  - Advantages with respect to:
    - optical sensors (e.g, higher penetration, any meteo condition)
    - radiometers (e.g., ranging capability,)
    - rain-gauges (e.g., larger effective coverage, rain structure)
  - Disadvantages: high power, complexity, maintenance

RADAR METEOROLOGY
A system approach



RADAR METEOROLOGY
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- **Radar sensor**
  - Pulsed, Doppler, and polarimetric systems
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- **Radar applications**
  - Operational problem overview
  - Clouds and precipitation
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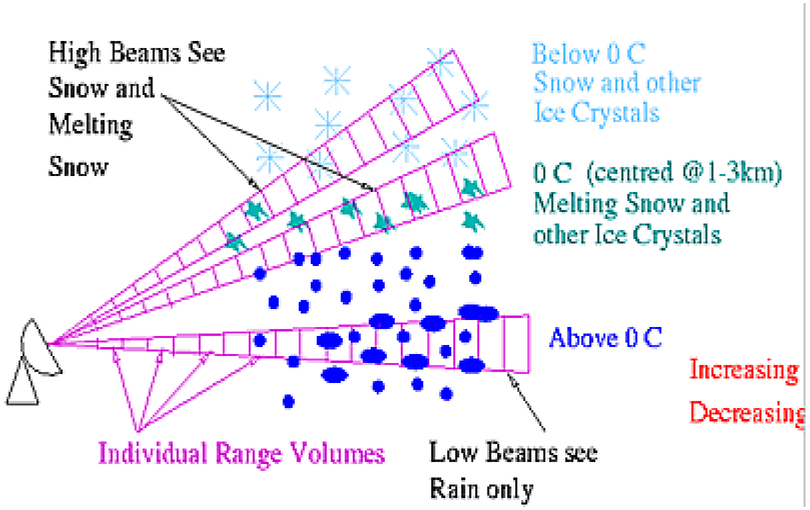
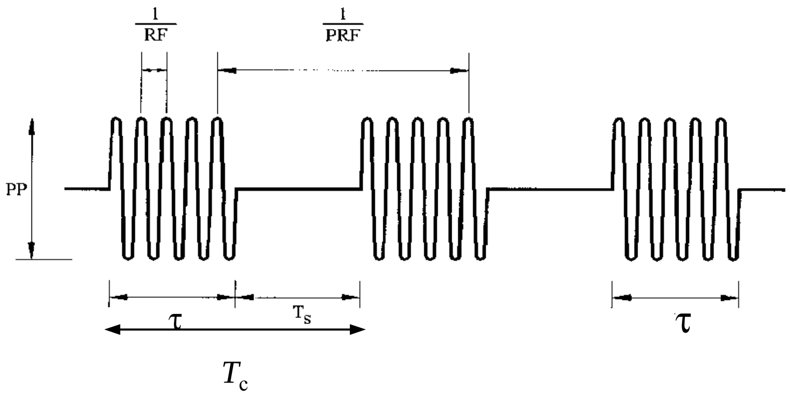
  - Example of radar measurements and estimates

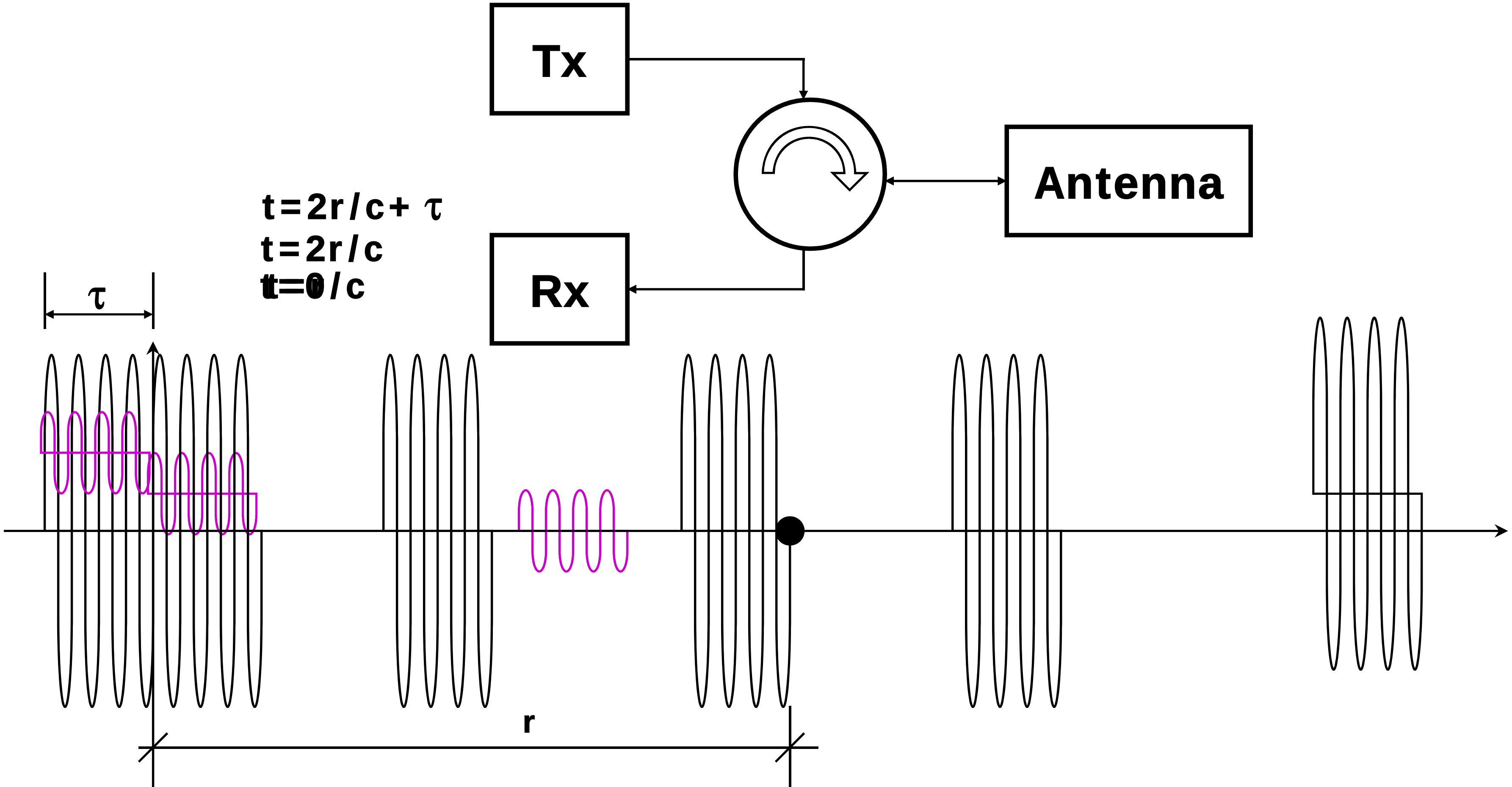
RADAR SENSOR
Pulsed microwave systems

- **Principle**
  - Send a train of short, high-power pulse of e.m. energy at high frequency (GHz)
  - E.m. energy, captured by atmospheric objects, is partially absorbed and re-irradiated (scattered) into many directions among which that of radar (backscattered: radar echo)
  - Angular resolution: derived from the antenna pointing direction and limited by its beam width
  - Range resolution: derived from the two-way time employed by radar pulse echo (antenna-object-antenna) and depending by medium light velocity
- **Legenda**
  - PRF: Pulse Repetition Frequency
  - RF: Radio Frequency (f_0)
  - PP: Peak-to-peak power
  - P_t: Peak power of the transmitter





RADAR SENSOR
Principle of pulsed systems



RADAR SENSOR
Principle of operation

Range resolution

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

Maximum unamb. range

$$r_{\max} = \frac{cT_c}{2}$$

Repetition frequency

$$f_r = \frac{1}{T_c}$$

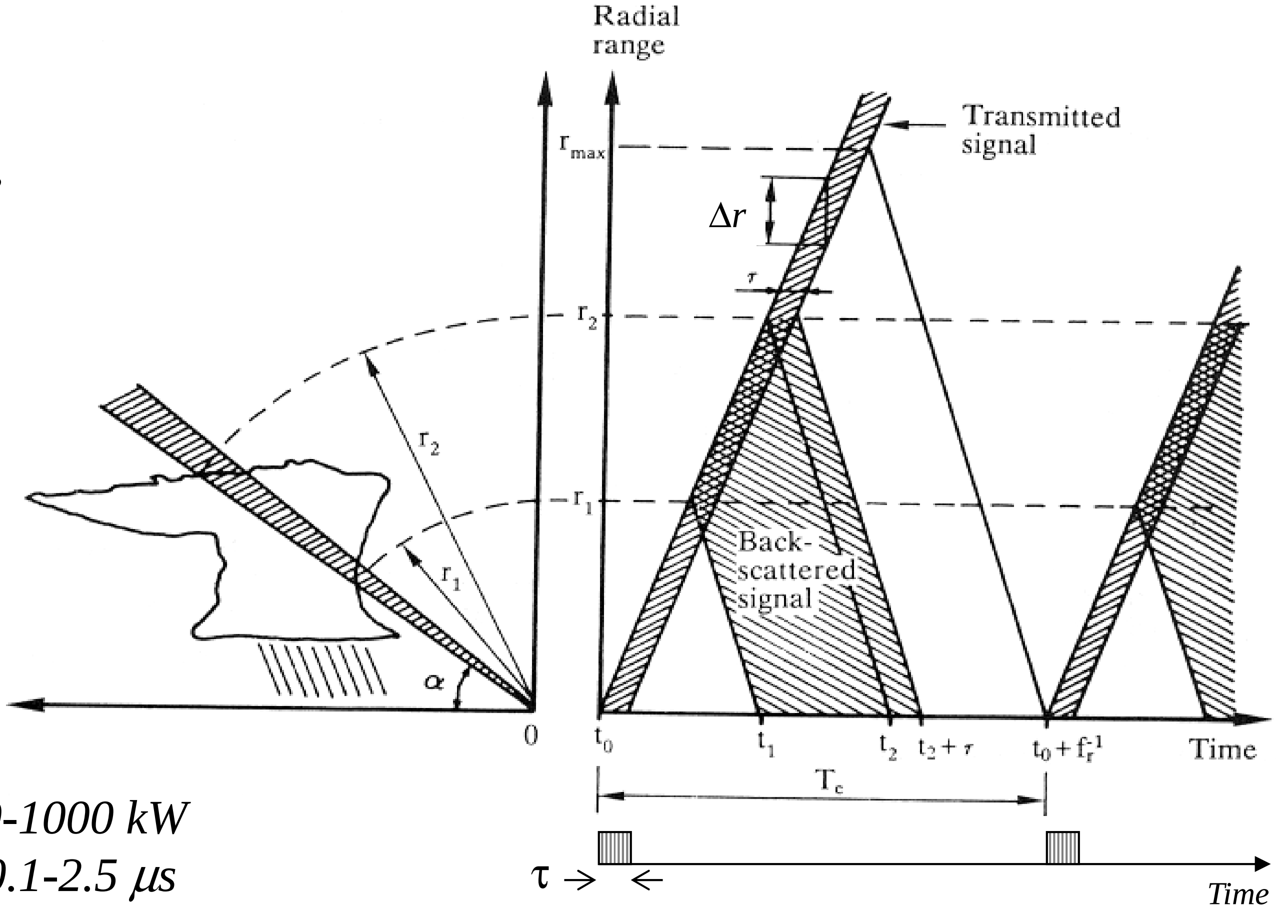
Average TX Power

$$P_{avg} = P_t\left(\frac{\tau}{T_c}\right) = P_t d_c$$

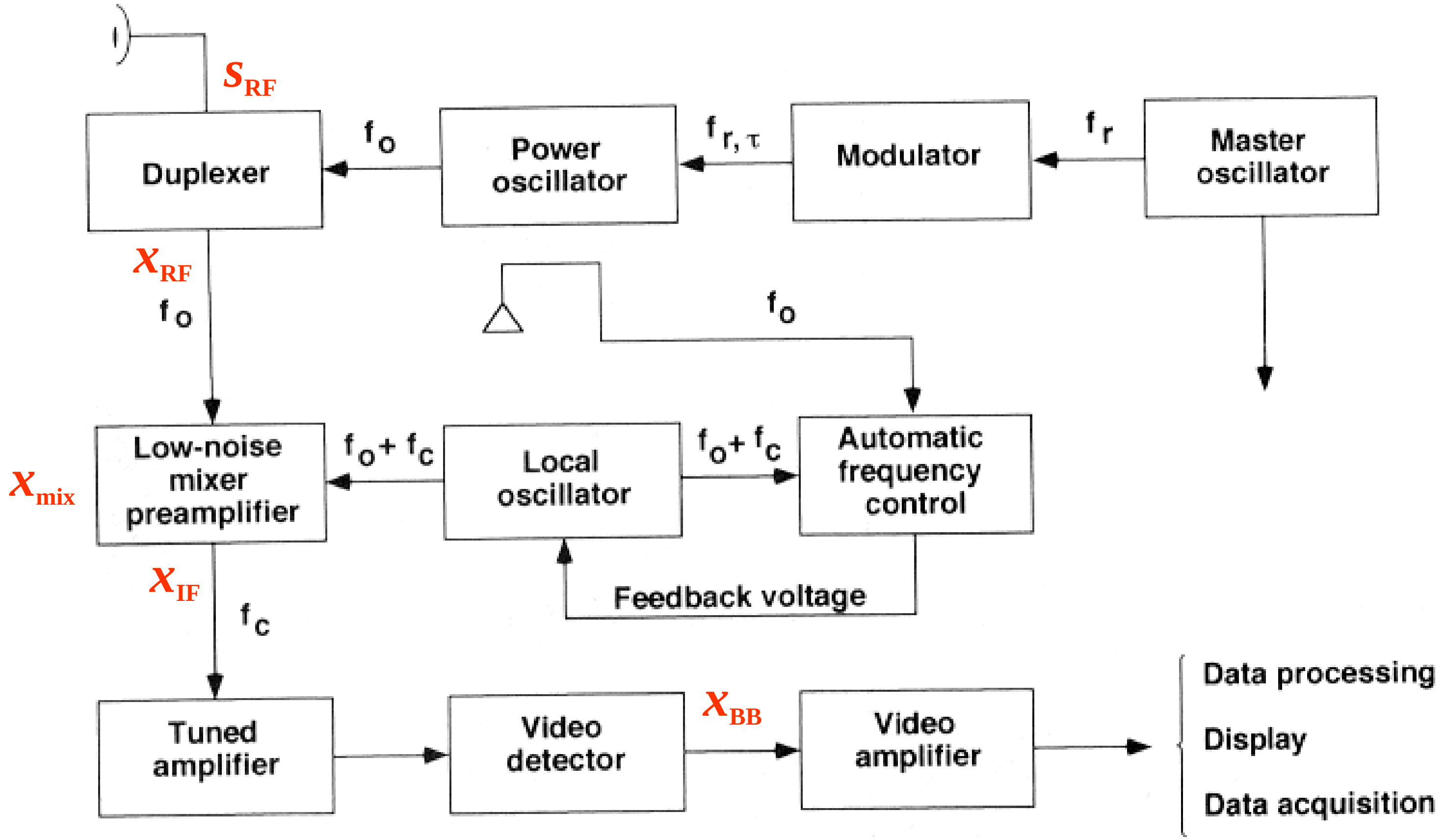
Typical values:

$f_0 \rightarrow$3-90 GHz; $P_t \rightarrow$100-1000 kW

$f_r \rightarrow$250-2500 Hz; $\tau \rightarrow$0.1-2.5 μs



RADAR SENSOR
Pulsed incoherent scheme



$$x_{BB}(t) = |a'(t)|^2$$

RADAR SENSOR
Pulsed incoherent system

Radar components

- Master oscillator (MO): system reference oscillator
- Modulator: device which determines the form e repetition of RF pulse
- Power oscillator: microwave tube (magnetron or klystron amplifier)
- Duplexer: 3-port circulator which separates TX from RX signal
- Local oscillator (LO): device which controls mixer frequency
- Mixer: device which mixes RF signal with LO doing amplification and filtering
- Amplifier: band-pass amplifier and filter for noise reduction of IF signal
- Video detector: detector of IF envelope power at baseband

Signal processing

$$s_{RF}(t) = \left[A\cos(2\pi f_0 t)\right] rect(f_r t)$$

Transmitted Radio Frequency (i.e., GHz)

$$x_{RF}(t) = a(t)\cos\left[2\pi f_0 t + \varphi(t)\right]$$

Received Radio Frequency

$$x_{mix}(t) = a(t)\cos\left[2\pi f_0 t + \varphi(t)\right]\left\{b\cos\left[2\pi\left(f_0 + f_c\right)t\right]\right\}$$

Mixer signals

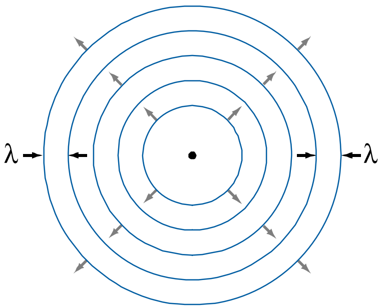
$$x_{IF}(t) = \frac{a(t)b}{2}\cos\left[2\pi f_c t + \varphi(t)\right] = a'(t)\cos\left[2\pi f_c t + \varphi(t)\right]$$

Intermediate Frequency (i.e., MHz)

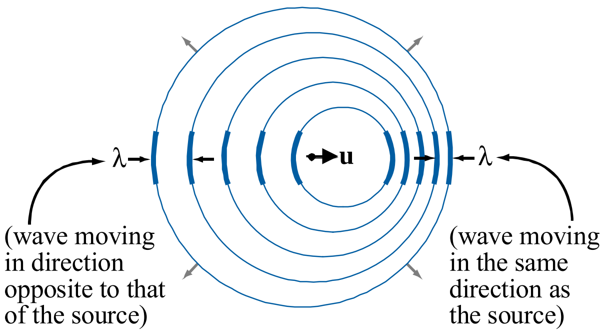
$$x_{BB}(t) = \left|x_{IF}(t)\right|^2 = \left|a'(t)\right|^2$$

Base-band signal (i.e., kHz)

RADAR SENSOR
Doppler frequency shift



(a) Stationary source



(b) Moving source

Doppler frequency shift

$$f_d = -\frac{u_r}{\lambda_0} = -\frac{\mathbf{u}\cdot\hat{\mathbf{r}}}{\lambda_0} = -\frac{u\cos\theta}{\lambda_0}$$

If leaving target:

$\theta<\pi/2 \Rightarrow f_d < 0$

If approaching target:

$\theta>\pi/2 \Rightarrow f_d > 0$

Monostatic Radar

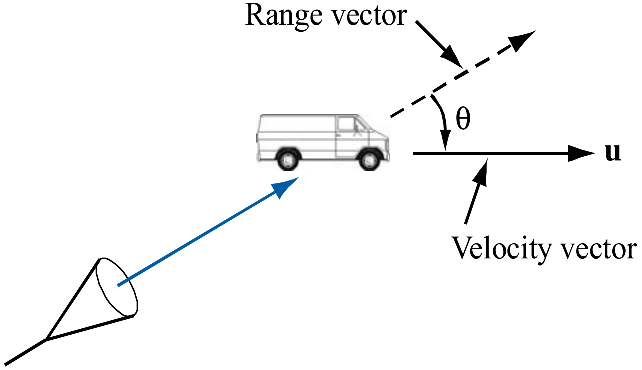
Twice a Doppler frequency shift

- from radar to target

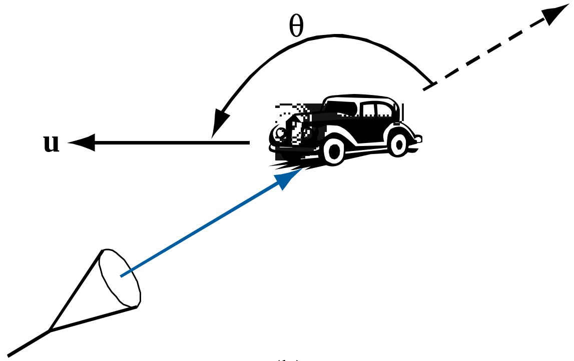
- from target to radar

$$f_{RF} = f_0 + f_d$$

$$f_d = -2\frac{u_r}{\lambda_0} = -2\frac{\mathbf{u}\cdot\hat{\mathbf{r}}}{\lambda_0}$$



(a)

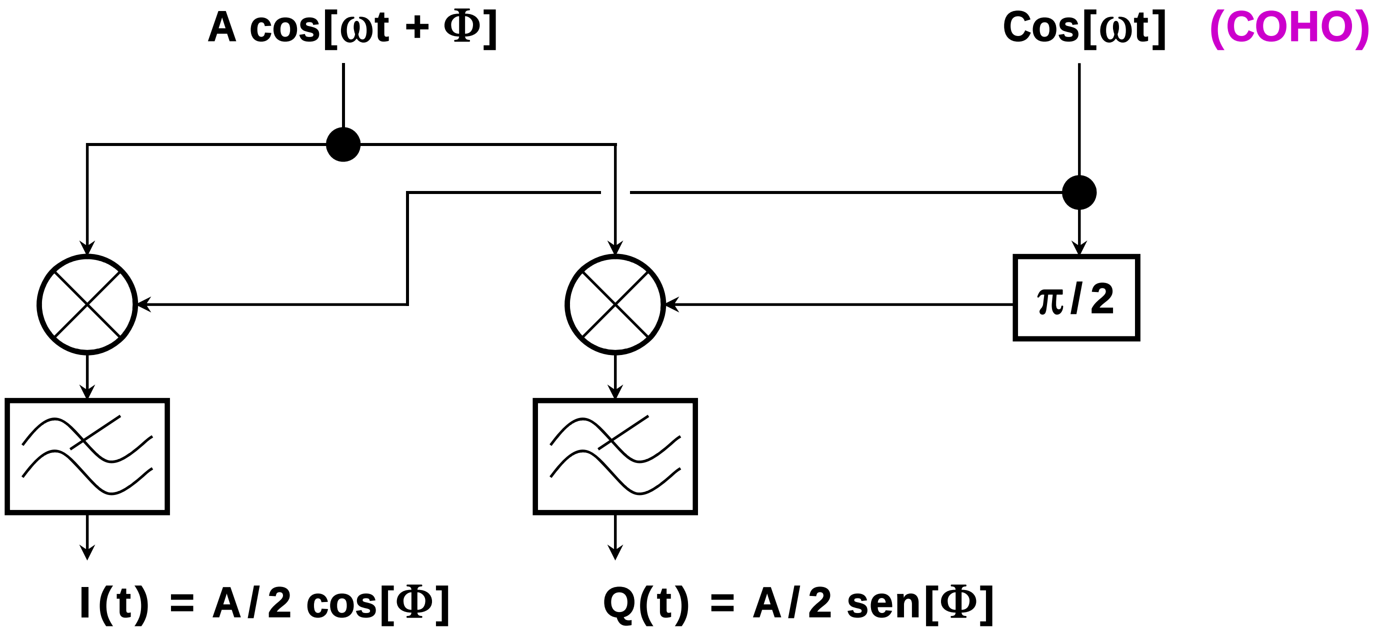


(b)

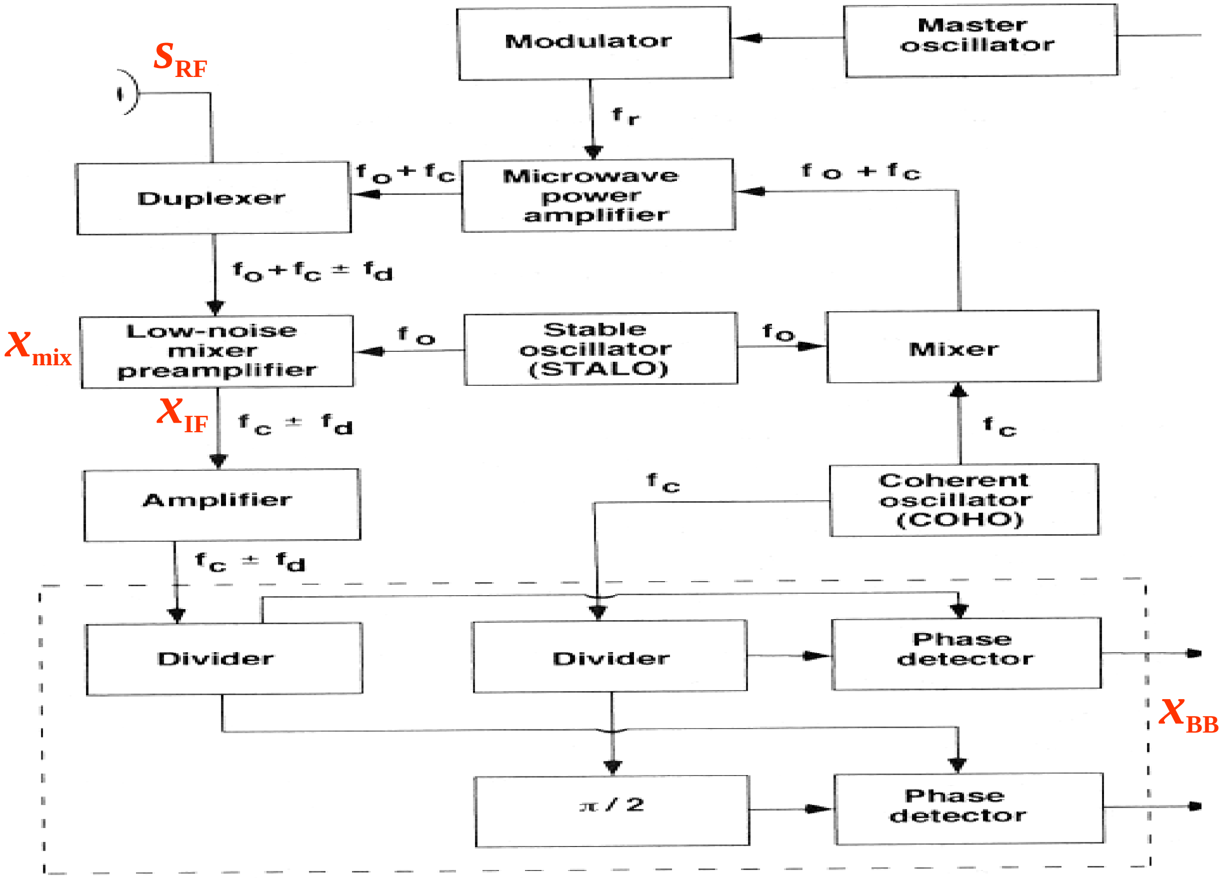
RADAR SENSOR
Pulsed coherent scheme

Per poter determinare la velocità Doppler del bersaglio puntiforme devo usare un

RICEVITORE COERENTE



RADAR SENSOR
Pulsed coherent scheme



Doppler frequency

$$\varphi(t) = -2\left[\frac{2\pi}{\lambda} r(t)\right] \Rightarrow$$

$$\frac{d\varphi(t)}{dt} \equiv \frac{4\pi}{\lambda} u_r(t) \equiv 2\pi f_d(t)$$

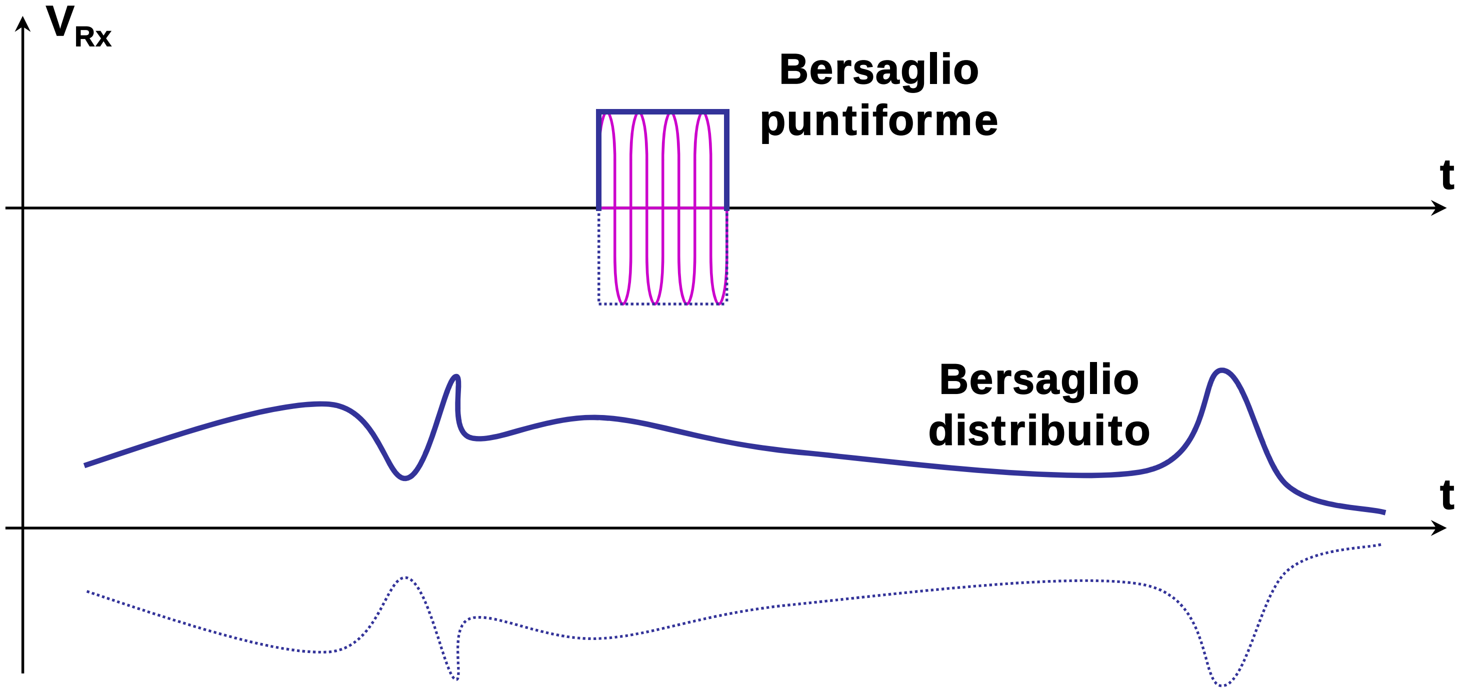
$$\Rightarrow \; f_d(t) = -\frac{2}{\lambda} u_r(t)$$

$$x_{BB}(t) = \begin{cases} I(t) = a'(t)\cos[\varphi(t)] \\ Q(t) = a'(t)\sin[\varphi(t)] \end{cases}$$

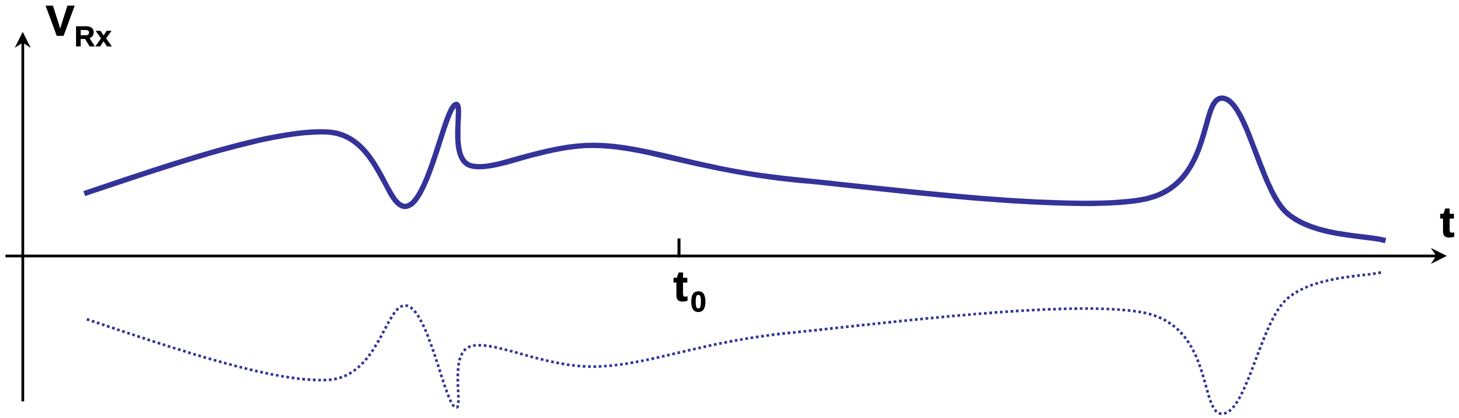
with $V(t) = I(t) + jQ(t)$

RADAR SENSOR
Pulsed coherent scheme

- **L'atmosfera è un bersaglio distribuito, ossia è costituita da un elevato numero di bersagli elementari (idrometeore)**
- **L'eco radar è la somma di tanti contributi elementari del tipo visto in precedenza (impulso rettangolare a RF)**



RADAR SENSOR
Pulsed coherent system



L'eco ricevuto all'istante t0 è la somma dei contributi di tutti i bersagli elementari che si trovano ad una distanza dal radar compresa tra $c \cdot (t_0-\tau)/2$ e $c \cdot t_0/2$

Il segnale ricevuto viene prima campionato (nel GPM-500C con una frequenza di 2.4 MHz, ossia ogni 417 ns) e quindi i campioni vengono processati.

Ogni campione è rappresentativo di un volume elementare (tronco di cono) con altezza pari a $(c \cdot \tau)/2$

RADAR SENSOR
Pulsed coherent system

- Detection of received signal phase

$$\varphi(t) = -2\left[\frac{2\pi}{\lambda} r(t)\right] \Rightarrow \frac{d\varphi(t)}{dt} \equiv -\frac{4\pi}{\lambda}\frac{dr(t)}{dt} = -\frac{4\pi}{\lambda}u_r(t) \equiv 2\pi f_d(t) \Rightarrow \boxed{f_d(t) = -\frac{2}{\lambda}u_r(t)}$$

- Signal processing

$$s_{RF}(t) = [A\cos(2\pi(f_0 + f_c)t)]rect(f_r t) = [A\cos(2\pi f_0' t)]rect(f_r t)$$

$$x_{RF}(t) = a(t)\cos[2\pi f_0 t + \varphi(t)] = a(t)\cos\left[2\pi f_0 t - \frac{2\pi}{\lambda}2r(t)\right]$$

$$x_{mix}(t) = a(t)\cos[2\pi(f_0 + f_c)t + \varphi(t)]\ \{b\cos[2\pi f_0 t]\}$$

$$x_{IF}(t) = a'(t)\cos[2\pi f_c t + \varphi(t)] = a'(t)\cos[\varphi(t)]\cos(2\pi f_c t) - a'(t)\sin[\varphi(t)]\sin(2\pi f_c t)$$

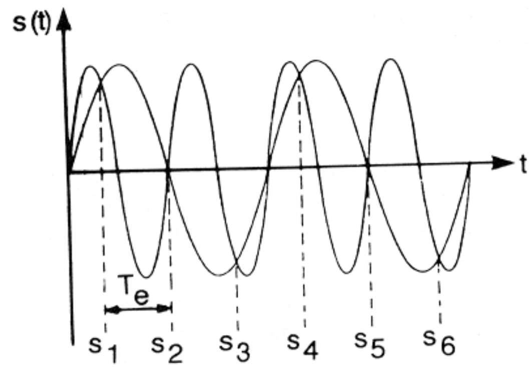
$$x_{IF}(t) \equiv I(t)\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t) = \mathrm{Re}\left\{[I(t) + jQ(t)]e^{j2\pi f_c t}\right\} = \mathrm{Re}\left\{[a'(t)e^{j\varphi(t)}]e^{j2\pi f_c t}\right\}$$

$$x_{BB}(t) = \begin{cases} I(t) = a'(t)\cos[\varphi(t)] \\ Q(t) = a'(t)\sin[\varphi(t)] \end{cases} \quad \text{with} \quad V(t) = I(t) + jQ(t)$$

RADAR SENSOR
Doppler velocity ambiguity

- **Signal sampling (Shannon) theorem**
  - A signal with a finite energy (a maximum spectral frequency f_M) is reconstructed from its temporal samples if the sampling frequency f_s:

$$f_M \geq \frac{f_s}{2} \;\Rightarrow\; T_M \leq \frac{T_s}{2}$$

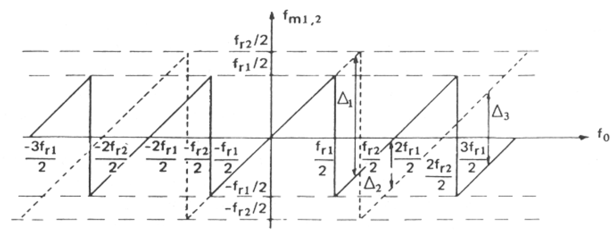


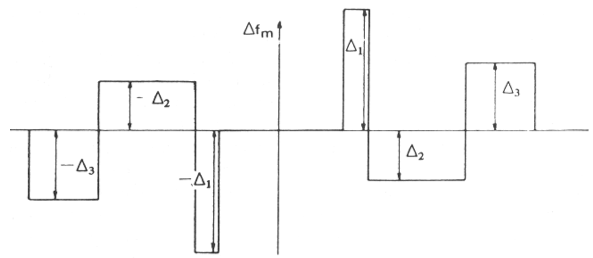
- **Unambiguous Doppler frequency**
  - If maximum frequency is f_r:

$$f_d \geq f_{d\,\max} = \frac{f_r}{2} \;\Rightarrow\; u_{r\,\max} = \pm f_r \frac{\lambda}{4}$$

  - Velocity-range limit

$$u_{r\,\max} r_{\max} = [(f_r \lambda)/4)][cT_c)/2] = (c\lambda)/8$$





- **Ambiguity reduction techniques**
  - Doppler phase measured between 2 pulses
  - Dual-PRF: double of unanmbiguos fd
  - Phase and polarization pulse coding

RADAR SENSOR
Issues on coherent systems

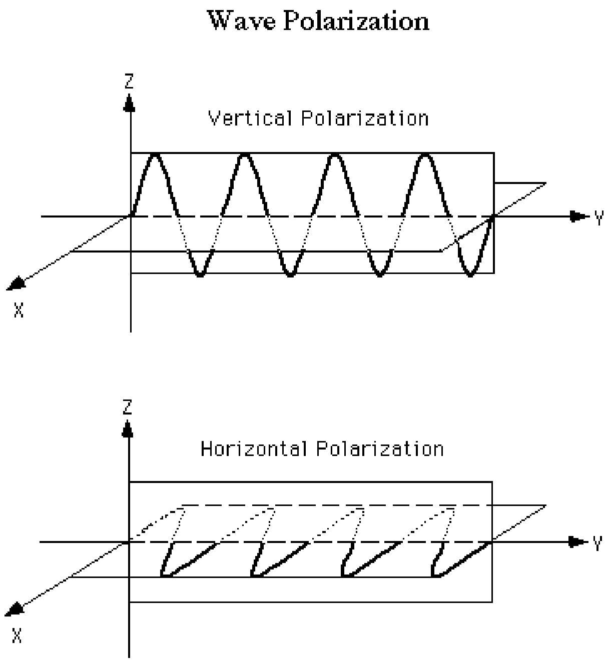
Microwave transmitter

- MAGNETRON: self-oscillating microwave tube with cylindrical structure (cross-field device), able to handle high power (up to 2000 kW peak). A high (up to 50 kV) DC voltage is applied to coaxial cathode (+) and anode (-) together with a static magnetic high field (up to 1 A/m). The emitted electron beam is spatially modulated (bunches) and output is coupled into one of ring resonant cavities. The latter determines the radio-frequency (RF) signal. Oscillation condition is governed by Hartree's curve. Overall efficiency is about 50%.
  - When input voltage is pulsed (as in radars), no inter-pulse coeherence is guaranteed (even though phase information may be retained by injecting a CW signal).
- KLYSTRON: microwave-tube amplifier with a linear (linear-field) structure, able to handle medium power (up to 1000 kW). An electron beam is formed by an electron gun (thermoionic emission by cathode-anode at > 1000 K), passes trhough 2 or more resonant cavities in succession and is collected on a collector. Electric field of first cavity gaps induce electron bunches whose are "focused" on (load) resonant cavities which produce output RF signal.
  - Within pulsed radars, klystron is used as an amplifier excited by a local microwave oscillator. These scheme guarantees a high phase purity (low phase noise) and an inter-pulse coherence.

Base-band detection

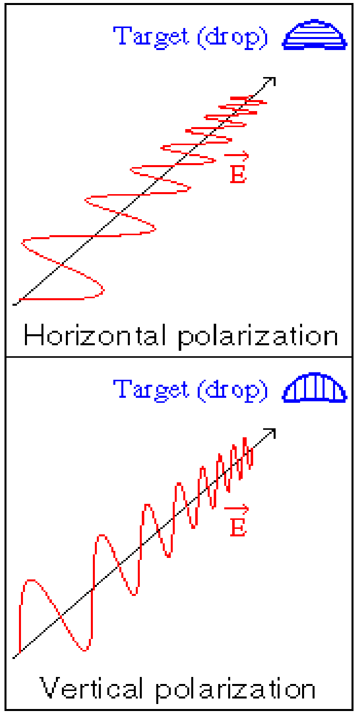
- Amplitude: logarithmic detector in order to deal with large amplitude (i.e., $a'(t)$) dynamics.
- Phase: linear detector to extract in-phase I(t) and quadrature $Q(t)$ components

RADAR SENSOR
E.m. wave polarization



- **Polarization states**

  Curve described in 3-D space by the free end of the mono-chromatic wave vector
  - Horizontal H (w.r.t. ground)
  - Vertical V
  - Circular (LHC, RHC)



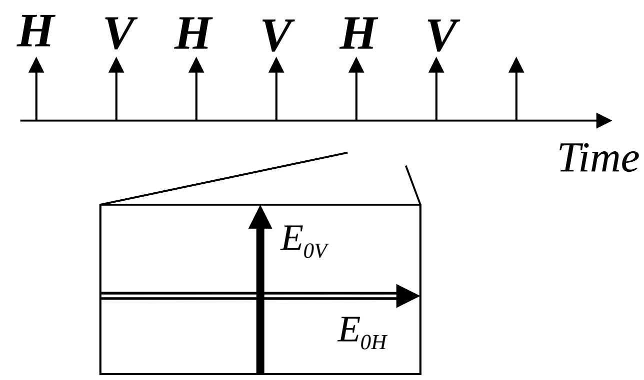
- **Linear polarizations**

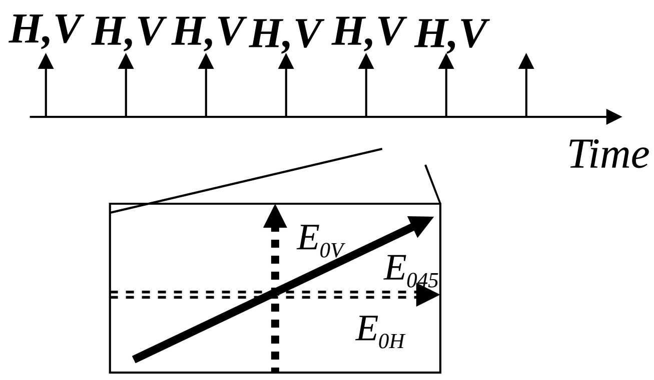
$$\underline{E}(r,t) = \underline{E}_{0p}(t)\cos[2\pi f_0 t + \varphi(t)]$$

$$\underline{E}_{0v}(t) = E_{0v}(t)\underline{\hat{z}}$$
$$\underline{E}_{0h}(t) = E_{0h}(t)\underline{\hat{x}}$$

RADAR SENSOR
Issues on polarimetric radars

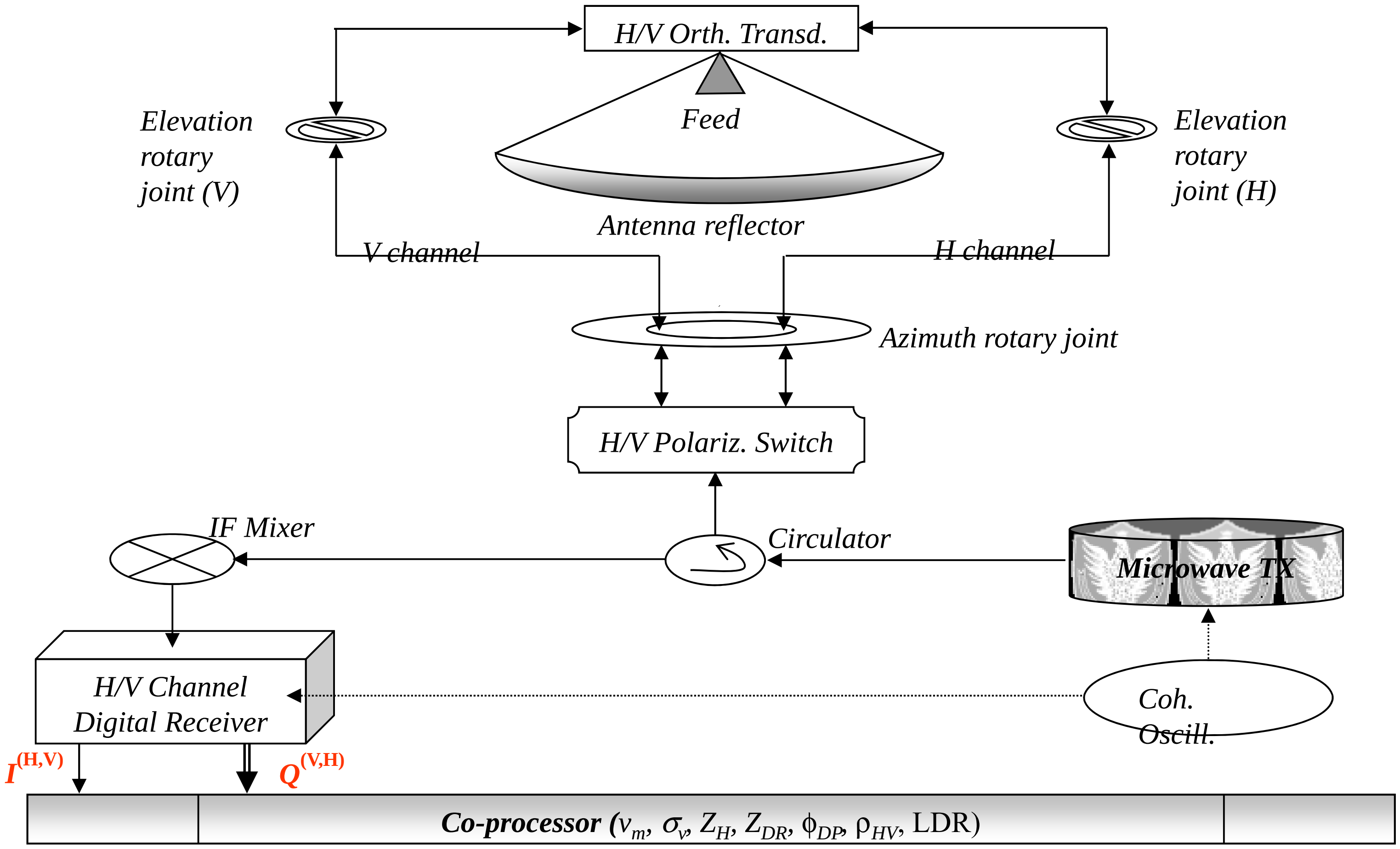
- ## Configuration
  - Alternate transmission
    - Single-transmitter and single-receiver
    - Alternate transmission between H and V fields
    - ↑ Single receiver
    - ↑ Anomalous propagation removal
    - ↓ Polarization switching
    - ↓ H and V non-contemporary data
  - Simultaneous transmission
    - Single transmistter and dual receiver
    - Simultaneous transmission of H and V fields
    - ↑ No polarization switching (costly and loss)
    - ↑ No delay in H and V acquisition data
    - ↑ Fast scanning (half time w.r.t. alternate trans.)
    - ↓ Cross-polarization effects in received data
    - ↓ Dual receiver and limitation in polarimetric features



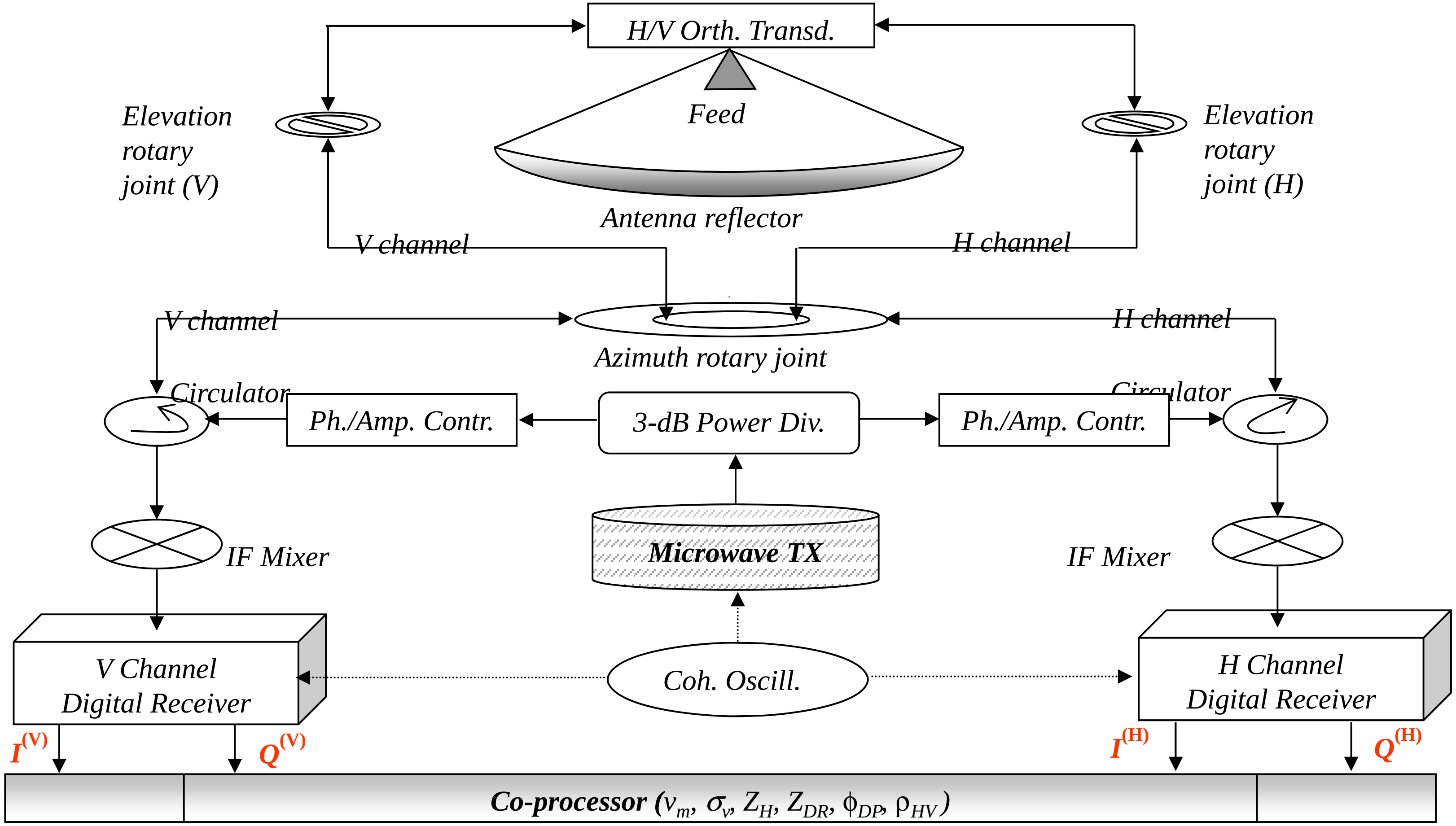


- ## Receiver
  - Digital receiver at IF stage
    - Sampling of IF signal (A/D digitizers)
    - Digital processing of binary I/Q sequences

RADAR SENSOR
Alternate polarim. system



RADAR SENSOR
Simultaneous polarim. system



RADAR SENSOR
Receiver sensitivity

- **Noise sources**
  - cosmic, artificial (human) and atmospheric emission (H_20, 0_2 at MW)
  - internal, due to electron thermal mobility (white Gaussian noise at MW).
- **Internal noise of receiver**
  - Receiver input power with a resistance load at T_0 and bandwith B_n: $N_i=kT_0B_n$
  - Noise figure F_n or equivalent noise temperature T_e: $T_e=T_0(F_n-1)$

$N_i=kT_0B_n$ → **Radar receiver** (G, T_0, B_n) → $N_0=F_n(GN_i)=k(T_0+T_e)B_n$

S_i → **Radar receiver** (G, T_0, B_n) → $S_0=GS_i$

- **Minimum detectable signal**
  - Minimum signal detectable over the noise receiver (e.g., -110 dBm = 10^{-11} mW)

$$F_n=\frac{S_i/N_i}{S_0/N_0} \Rightarrow S_{iMin}=F_nN_i\left.\frac{S_0}{N_0}\right|_{Min}=F_n(kT_0B_n)\left.\frac{S_0}{N_0}\right|_{Min}$$

  - Matched filters to increase S/N: for square pulses. $B_n\approx 1/\tau$ and triangular shape

RADAR SENSOR
Aperture antenna basics

- ## Radar antennas
  - Parabolic reflector antenna
  - Prime-focus feeder (horn)
  - Optional radome protection
  - Optional polarization capability
- ## Antenna radiation
  - Radiation pattern function

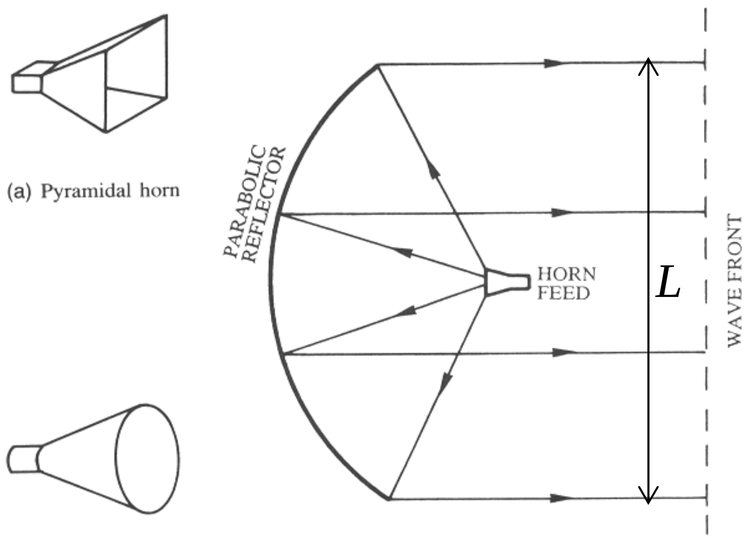
$$f(\theta,\varphi) = FFT\left[E_a(x,y)\right]$$

  - Irradiated eletric far-field (*for* $r \geq L^2/\lambda$)

$$E(r,\theta,\varphi) = E_0 f(\theta,\varphi)\frac{e^{-jkr}}{r}$$

  - Power flux density [W/m^2]

$$P(r,\theta,\varphi) = \frac{1}{2\eta_0}\left|E(r,\theta,\varphi)\right|^2 = \frac{E_0}{2\eta_0 r^2}\left|f(\theta,\varphi)\right|^2$$



(a) Pyramidal horn

(b) Conical horn

(c) Classical parabolic antenna

RADAR SENSOR
Antenna parameters

- **Directivity and Gain**

$$D(\theta,\varphi)=\frac{P(r,\theta,\varphi)}{W_T/4\pi r^2}=\frac{|f(\theta,\varphi)|^2}{W_T/4\pi},\quad G(\theta,\varphi)=\eta_r D(\theta,\varphi)$$

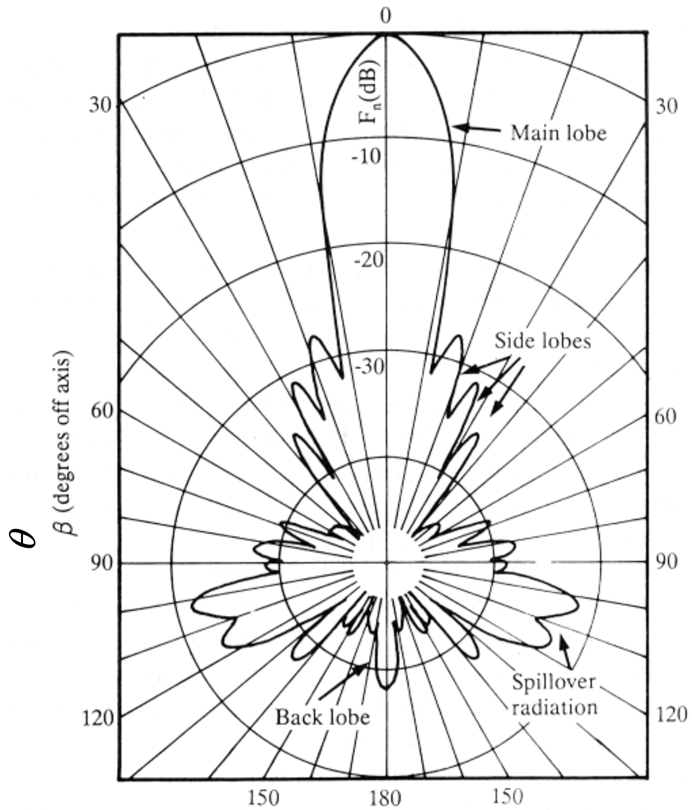
- **Effective area**

$$A_e(\theta,\varphi)=\frac{W_R}{P_i(r,\theta,\varphi)}=\frac{\lambda^2}{4\pi}D(\theta,\varphi)=D_M|f_n(\theta,\varphi)|^2$$

- **Beamwidth (reflector antennas)**

$$|f_n(\Theta_{3dB}/2,\varphi)|^2=0.5\ \Rightarrow\ \Theta_{3dB}\cong 70\frac{\lambda}{L},\quad D_M\cong\frac{4\pi}{(\Theta_{3dB})^2}$$

- **Polarization capability**
  - Ortho-Mode Transducer (H/V) at horn feeder
  - Low sidelobes (<30 dB) similar for H/V patterns
  - Isolation between H/V patterns (no cross-pol.)
    - Azimuthally symmetric radiation pattern at H/V
  - Effects of supporting struts and radome paneling

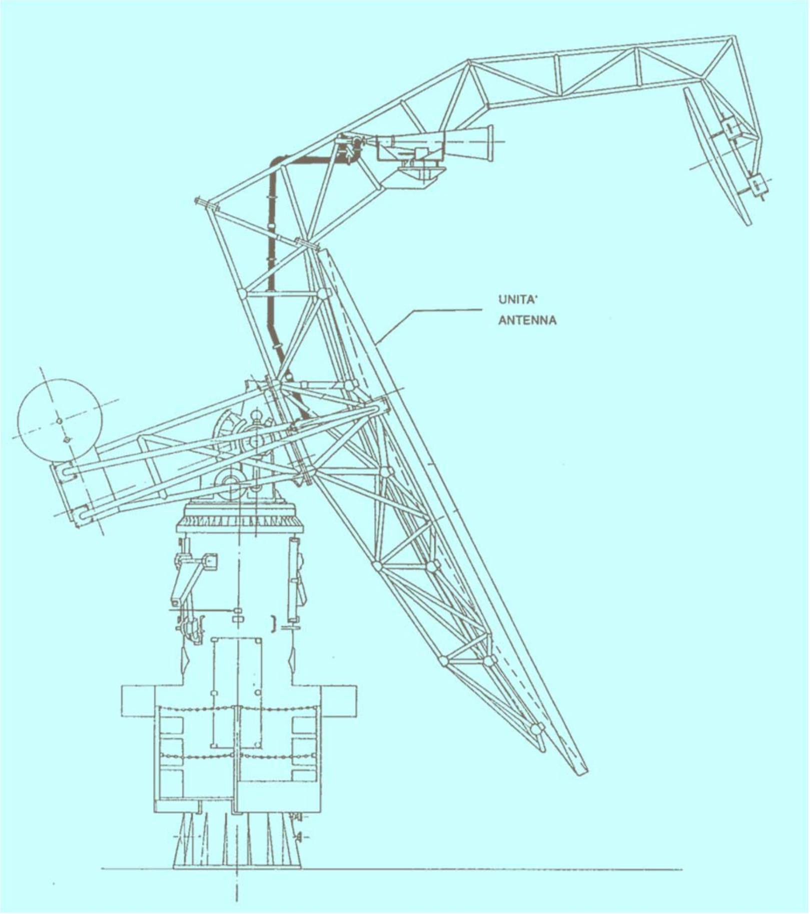


RADAR SENSOR
Antenna parameters

Example:
Radar GPM-500C

Cassegrain dual-offset

- **fascio di 0.9° (a -3 dB)**
- **velocità max 30 deg/s**
- **lobi secondari molto bassi**
- **ottima simmetria tra H e V**

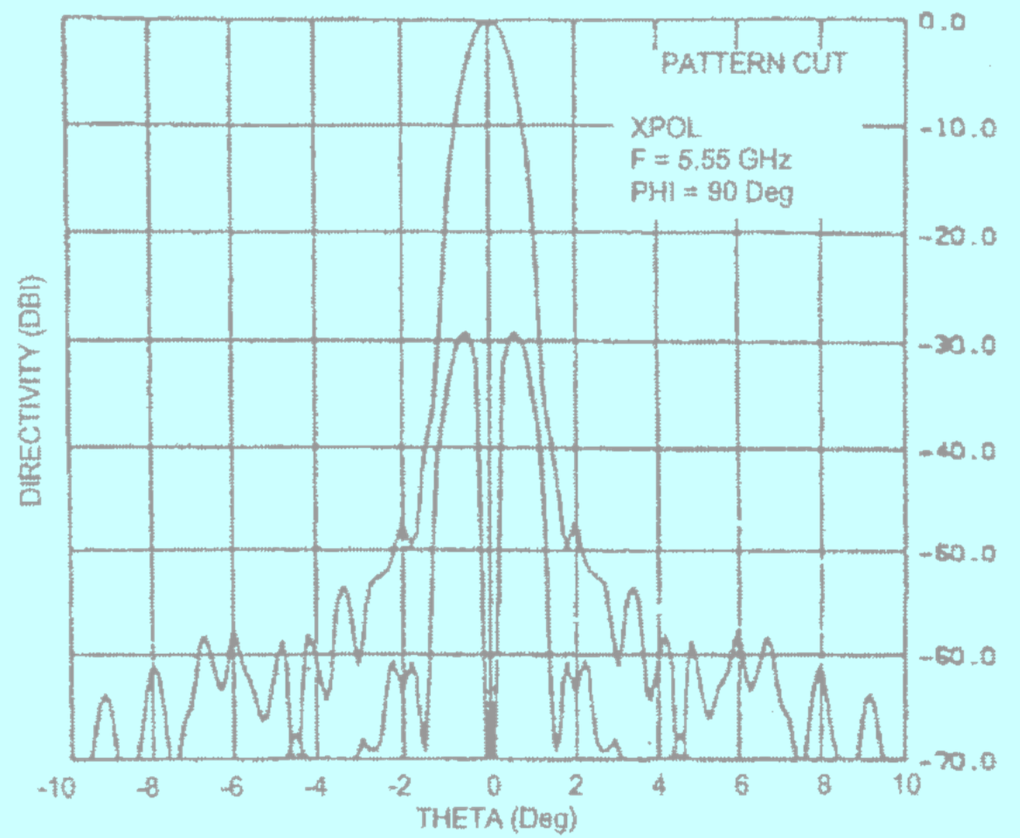


RADAR SENSOR
Antenna diagram

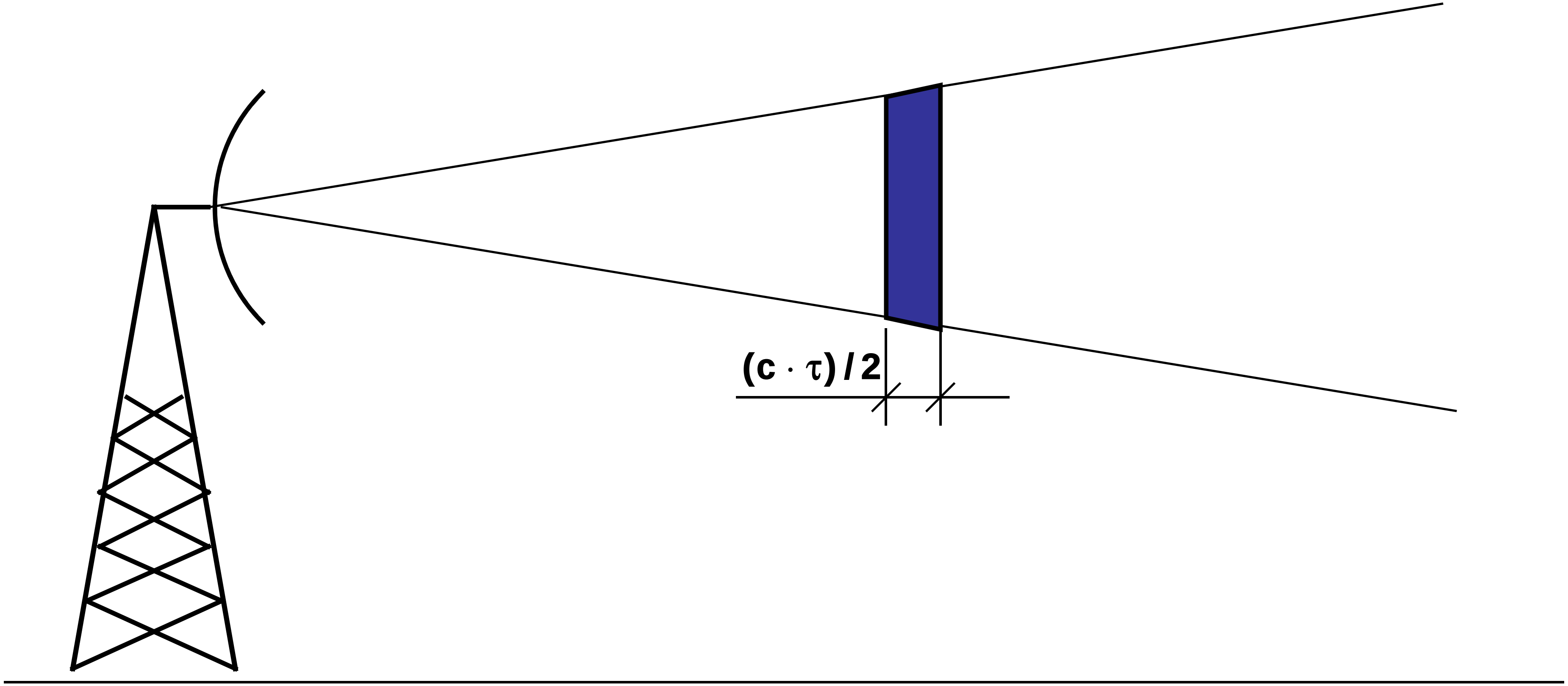
Example:
Radar GPM-500C

Cassegrain dual-offset

- **fascio di 0.9° (a -3 dB)**
- **velocità max 30 deg/s**
- **lobi secondari molto bassi**
- **ottima simmetria tra H e V**

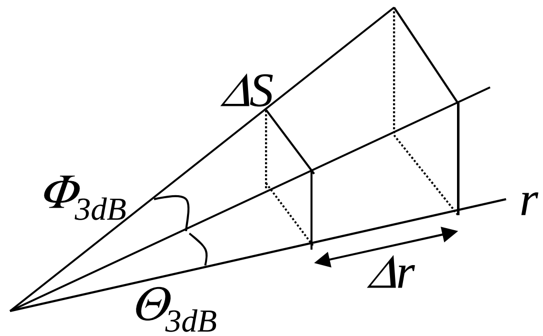


RADAR SENSOR
Volume resolution



RADAR SENSOR
Volume resolution

- **Spatial resolution**
  - Capability of discriminating 2 objects in space (range, zenith and azimuth in spherical coordinates)



- **Radial resolution**
  - Resolution in range: $\Delta r = \dfrac{c\tau}{2}$
    - Matched receivers have a lower radial resolution
    - Use of pulse compression to increase spatial res.
- **Transverse resolution**
  - Resolution in zenith-azimuth: $\Delta\Omega = \dfrac{\Delta S}{r^2} \Rightarrow \Delta S = r^2 \Delta\Omega \cong r^2 \Omega_{3\text{dB}}$
    - Affected by side lobes contribution.
- **Pulse volume resolution**

$$V_{bin} = \Delta r \Delta S = (c\tau/2) r^2 \Omega_{3\text{dB}} \cong \frac{\pi}{4}(c\tau/2) r^2 \Theta_{3dB} \Phi_{3dB}$$

  - Volume varies with range (for 1° and 1 μs, at 100 km Δr=150 m and $\Delta S = 1745^2 \text{ m}^2$)
    - Energy volume distribution can be not uniform in range (e.g., matched filters) and in transverse direction (e.g., directivity angular variation)

RADAR METEOROLOGY Lecture's contents

- Radar sensor
  - Pulsed, Doppler, and polarimetric systems
  - Receiver sensitivity
  - Antenna specifications
  - Radar volume resolution
- Radar equation
  - Atmospheric refraction and attenuation
  - Radar equation for single and distributed scatterers
- Radar signal
  - Signal statistics and decorrelation
  - Noise reduction techniques
- Radar applications
  - Operational problem overview
  - Clouds and precipitation
  - Rainfall backscattering and polarimetric measurables
  - Example of radar measurements and estimates

RADAR EQUATION
Atmospheric refraction

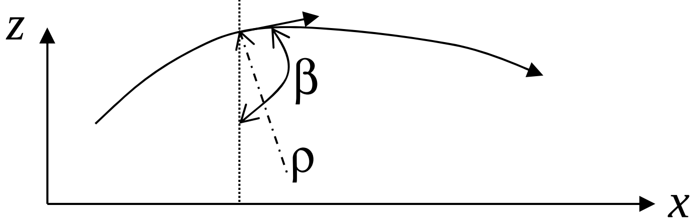
➢ Atmospheric refractivity

- Refractive index:

$$n = \frac{c}{v} = \sqrt{\varepsilon_r} = n' - jn''$$

- Refractivity:

$$N = (n' - 1)10^6 = f(p/T, e/T^2)$$



➢ Optical rays

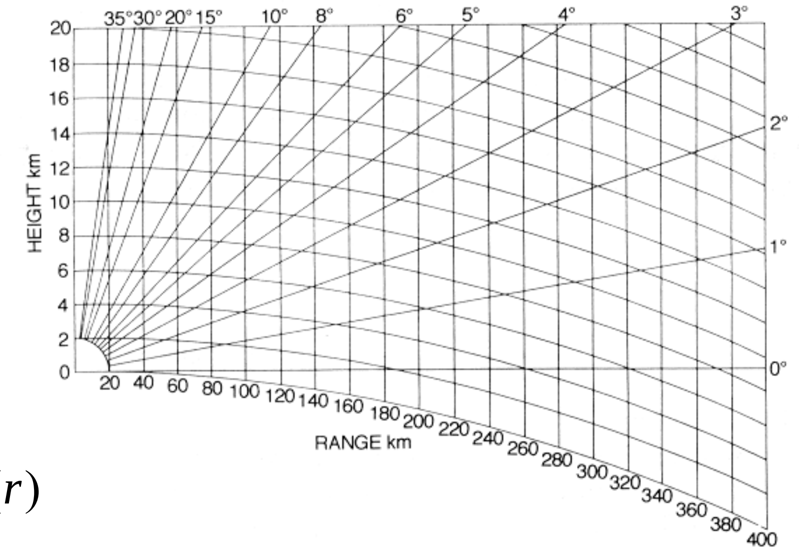
- Geometrical optics equation:

$$\frac{1}{\rho} = \frac{10^6}{n}\frac{dN}{dz}\cos\beta, \quad N(z) = N_0 e^{-z/H}$$

with ρ ray curvature.

- If standard atmosphere, dN/dz=-40 [N/km]
  - Earth effect. radius R_e=4/3R_T=4/3(6370)=8500
  - Rays are rectilinear and Earth flatter

Atmosphere with N_0=313 and H=7 km



➢ Specific attenuation

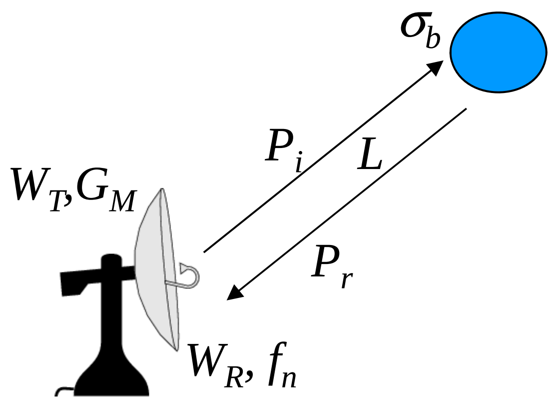
- For two-way path, the attenuation factor L:

$$dW = -2\alpha W dr \;\Rightarrow\; W(r) = W_0 e^{-2\int_0^r \alpha dr} = W_0 L^2(r)$$

RADAR EQUATION
Single scatterer form

- Power flux density upon scatterer

$$P_i(r,\theta,\varphi) = \frac{W_T}{4\pi r^2} G_M \left| f_n(\theta,\varphi) \right|^2 L(r)$$



- Backscattering radar cross section

$$\sigma_b(-\theta,-\varphi,\theta,\varphi) = 4\pi r^2 \frac{P_r(r,\theta,\varphi)}{P_i(r,\theta,\varphi)}$$

- Received power

$$P_r(r,\theta,\varphi) = \frac{\sigma_b}{4\pi r^2} P_i = \frac{\sigma_b}{4\pi r^2} L \frac{W_T}{4\pi r^2} G_M \left| f_n(\theta,\varphi) \right|^2 L \;\Rightarrow\; W_R = A_e P_r = \frac{\lambda^2}{4\pi} G P_r$$

- Radar equation for a single scatterer

$$W_R = \left(\frac{W_T G_M^2 \left| f_n(\theta,\varphi) \right|^4 \lambda^2}{(4\pi)^3} \right) \sigma_b \frac{L^2}{r^4} = \left(\frac{W_T \eta_r^2 A_e^2}{4\pi r \lambda^2} \right) \sigma_b \frac{L^2}{r^4} \;\Rightarrow\; \boxed{W_R = C_1 L^2 \frac{\sigma_b}{r^4}}$$

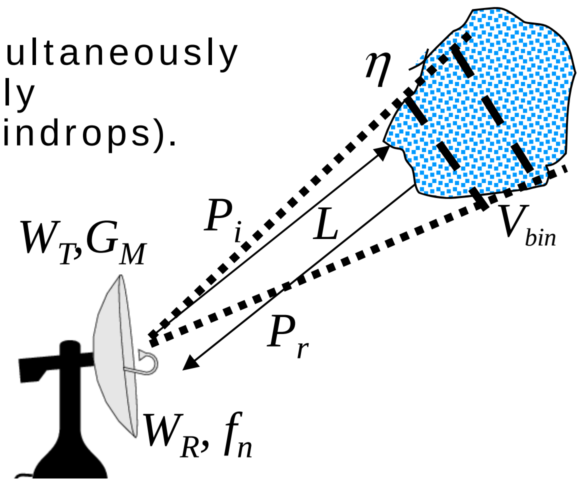
  - For a point target, $f_n=1$ and $W_R \propto 1/r^4$. Constant C_1 depends on radar specs.

RADAR EQUATION
Effect of distributed scatterer

Distributed scatterers

- Set of a large number N_{part} of equal-size scatterers, simultaneously present in the same resolution volume V_{bin} with randomly distrubuted phase and totally filling the volume (e.g. raindrops).
- Volumetric reflectivity [m^{-1}]

$$\eta = \left(\frac{\sum_{i=1}^{N_{part}} \sigma_{bi}}{dV} \right) \Rightarrow \sum_{i=1}^{N_{part}} \sigma_{bi} = dV \left(\frac{\sum_{i=1}^{N_{part}} \sigma_{bi}}{dV} \right) = dV\eta$$



Particle and total received power

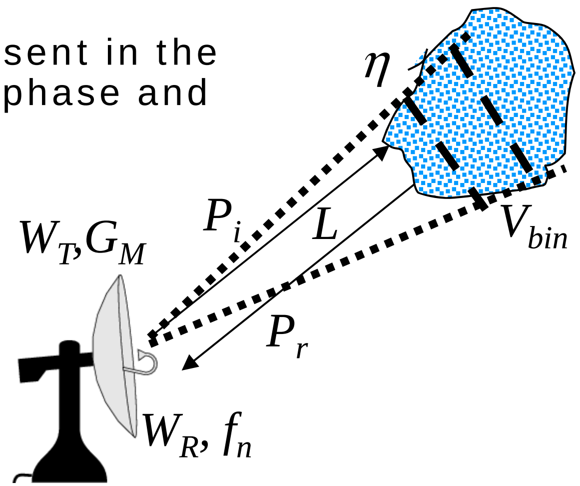
$$dW_{Ri} = \left(\frac{W_T G_M^2 \lambda^2}{(4\pi)^3} \right) \frac{|f_n(\theta,\varphi)|^4}{\mathrm{r}_i^4} \sigma_{bi} = C \frac{|f_n(\theta,\varphi)|^4}{\mathrm{r}_i^4} L^2 \sigma_{bi}$$

$$dW_R = \sum_{i=1}^{N_{part}} dW_{Ri} = \sum_{i=1}^{N_{part}} C \frac{|f_n(\theta,\varphi)|^4}{\mathrm{r}_i^4} L^2 \sigma_{bi} \cong C \frac{|f_n(\theta,\varphi)|^4}{\mathrm{r}^4} L^2 \sum_{i=1}^{N_{part}} \sigma_{bi} \frac{dV}{dV} \cong C \frac{|f_n(\theta,\varphi)|^4}{\mathrm{r}^4} L^2 \eta dV$$

$$W_{Rtot} = \int_{V_{bin}} dW_R = \int_V C \frac{|f_n(\theta,\varphi)|^4}{\mathrm{r}^4} L^2 \eta dV \equiv \langle W_R \rangle$$

RADAR EQUATION
Distributed scatterer form

- **Distributed scatterers**
  - Set of a large number of scatterers, simultaneously present in the same resolution volume V_{bin} with randomly distrubuted phase and totally filling the volume (e.g. raindrops).



- **Total (average) received power**

$$< W_R >= \left(\frac{W_T G_M^2 \lambda^2}{(4\pi)^3} \right) L^2 \int_{V_{bin}} \frac{|f_n(\theta,\varphi)|^4}{\mathrm{r}^4} \eta dV = \left(\frac{W_T G_M^2 \lambda^2}{(4\pi)^3} \right) L^2 \eta \Delta r \int_{V_{bin}} \frac{|f_n(\theta,\varphi)|^4}{\mathrm{r}^2} d\Omega$$

where $dV = dr(r^2 d\Omega)$, $\mathrm{V_{bin}}$: *radar resolution volume*

- **Radar equation for volume scattering**

$$\int_V \frac{|f_n(\theta,\varphi)|^4}{\mathrm{r}^2} d\Omega \cong \frac{1}{r^2} \frac{\pi \Theta_{3dB} \Phi_{3dB}}{8 \ln 2} \quad \text{(Probert - Jones correction)}$$

$$< W_R >= \left(\frac{W_T G_M^2 \lambda^2}{(4\pi)^3} \right) L^2 \eta \Delta r \frac{1}{r^2} \frac{\pi \Theta_{3dB} \Phi_{3dB}}{8 \ln 2} \quad \Rightarrow \quad \boxed{< W_R >= C_2 L^2 \frac{\eta}{r^2}}$$

RADAR SIGNAL
Signal fluctuations

Power fluctuations of radar echo

- Complex envelope due to i-th scatterer:

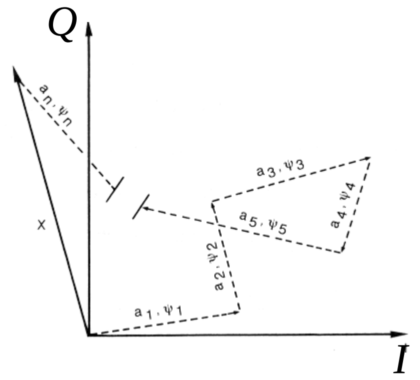
$$V_i(t) = A_i e^{j\varphi_i(t)}, \quad \varphi_i(t) = -4\pi r_i(t)/\lambda + \psi_i$$

- Total complex envelope due to distributed scatterers:

$$V(t) = I(t) + jQ(t) = \sum_i V_i(t) = \sum_i A_i e^{j\varphi_i(t)} = A(t) e^{j\varphi(t)}$$

- In-phase and quadrature components

$$\begin{cases} I(t) = \mathrm{Re}[V(t)] = A(t)\cos\varphi(t) \\ Q(t) = \mathrm{Im}[V(t)] = A(t)\sin\varphi(t) \end{cases} \quad \text{with} \quad A = \sqrt{I^2 + Q^2}, \varphi = artg\frac{Q}{I}$$



Radar echo power

$$W_R(t) = kV(t)V(t)^* = A^2(t) = k\sum_i A_i^2 + k\sum_{i\neq j} A_i A_j e^{j(-4\pi/\lambda)(r_i - r_j)} = \begin{cases} W_{Rdc} + W_{Rac} \\ < W_R > + \widetilde{W}_R \end{cases}$$

- From one pulse to next, power fluctuation W_{ac} are related to scatterer random displacement (velocity or Doppler frequency).
- It results $<W_{ac}>=0$ and W_{ac} decreases doing averages on independent samples (such that displacement > λ). For estimating ΔΦ, samples must be correlated to avoid ambiguity.

RADAR SIGNAL
Statistics of power fluctuations

- Distribution of I, Q
  - For the central limit, V(t) is Gaussian so that I and Q
  - A and Φ are independent random variables with Φ uniformly distributed in 0-2π.

$$p(I,Q) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(I^2+Q^2)/2\sigma^2}, \quad p(I,Q)dIdQ = p(A,\varphi)dAd\varphi, \quad dIdQ = AdAd\varphi$$

- Marginal distribution of A, φ

$$p(A,\varphi) = \frac{A}{\sqrt{2\pi\sigma^2}} e^{-A/2\sigma^2} \Rightarrow \begin{cases} p(A) = \frac{A}{\sqrt{2\pi\sigma^2}} e^{-A/2\sigma^2} & \text{Rayleigh pdf} \\ p(\varphi) = 1/2\pi & \text{Uniform pdf} \end{cases}$$

- Square-law detector statistics of received power

$$W_R = A^2, \; dW_R = 2AdA, \; \mathrm{p(W_R)dW_R = p(A)dA} \Rightarrow \mathrm{p(W_R)} = \frac{1}{2\sigma^2} e^{-W_R/2\sigma^2} \quad \text{Exponential pdf}$$

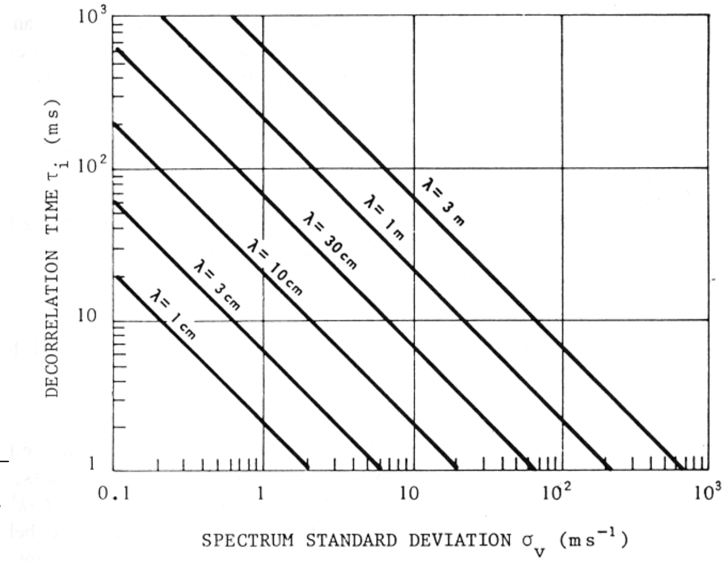
RADAR SIGNAL
Decorrelation time

- **Dopppler spectrum**
  - Duration t_d needed to ensure sample independence depends on volume and wavelength
  - Doppler spectrum is of Gaussian type for uniform regions:

$$p(f_d) = p_0 e^{-f_d^2/2\sigma_f^2}; \qquad f_d = (2/\lambda)u_r$$

  - Time autocorrelation function:

$$R(t_d) = R_0 e^{-t_d^2/2\sigma_t^2}, \sigma_t = \frac{1}{2\pi\sigma_f} = \frac{1}{2\pi(2/\lambda)\sigma_u}$$



Snow: σ_u*=0.5 m/s*
Rain: σ_u*=1 m/s*

- **Decorrelation time t_{inc}**

$$R(t_{inc})/R_0 = 0.02 \quad \Rightarrow \boxed{t_{inc} = 2\lambda/\sigma_v}$$

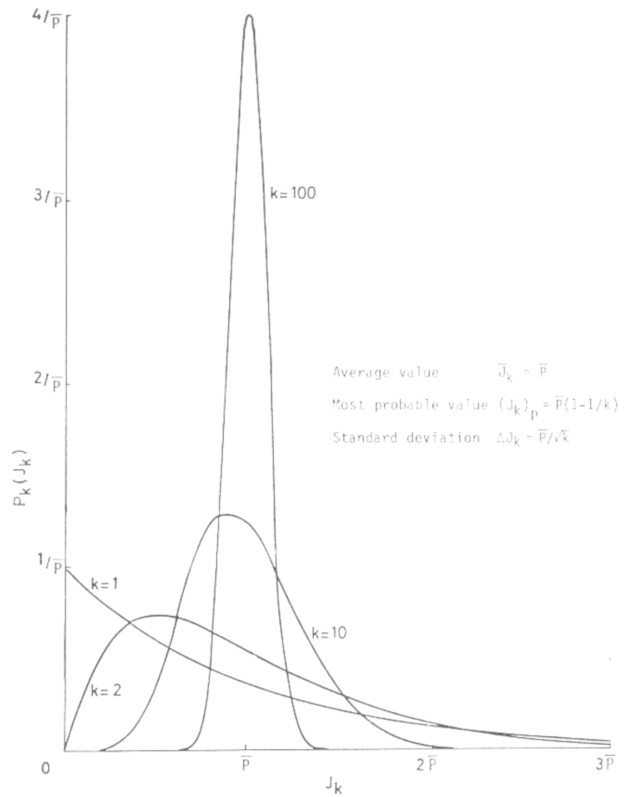
RADAR SIGNAL
Time-space data integration

Signal variance reduction

- For meteorological appliatio, W_{dc} is of interest so that W_{ac} must be reduced
- How many independent samples of received power must be averaged to accurately estimate W_{dc}=<W> using a square-law detector?

$$J_k = \frac{1}{k}\sum_{n=1}^{k} W_{Rn} \quad \text{with} \quad p(J_k)dJ_k = p(A_n^2)d(A_n^2)$$

- The final pdf is almost Gaussian for k>10
- For k=30, <W> error estimate is about 1 dB



Spatial integration

- For fast scannig, spatial averaging is performed together with time integration
- Reduction of measurement spatial resolution (e.g., range similar to transverse)

RADAR METEOROLOGY
Lecture's contents

- **Radar sensor**
  - Pulsed, Doppler, and polarimetric systems
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  - Radar equation for single and distributed scatterers
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  - Signal statistics and decorrelation
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- **Radar applications**
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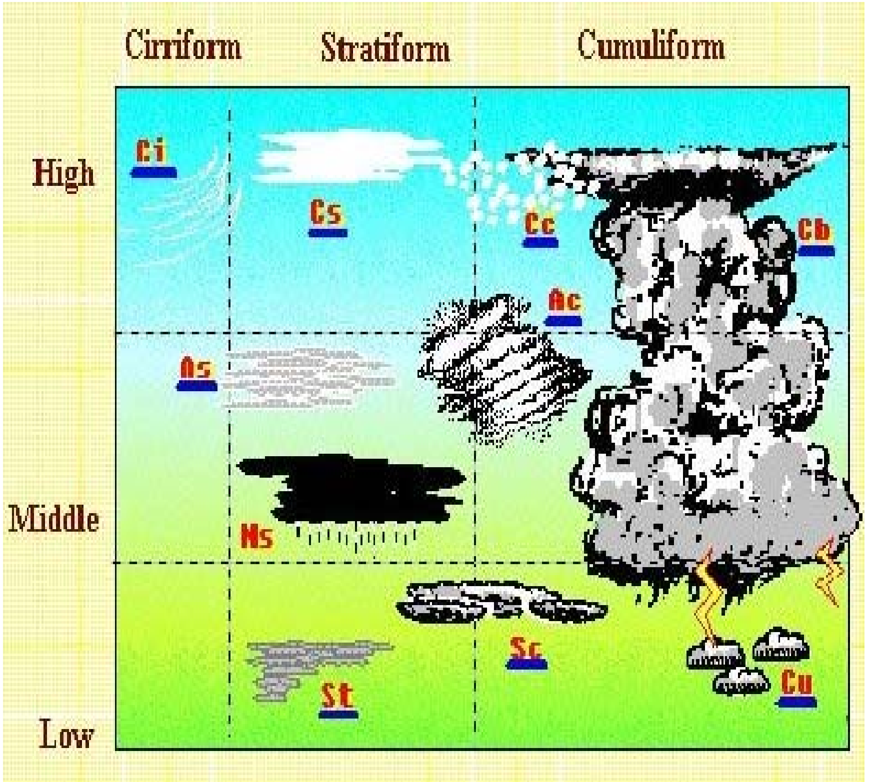
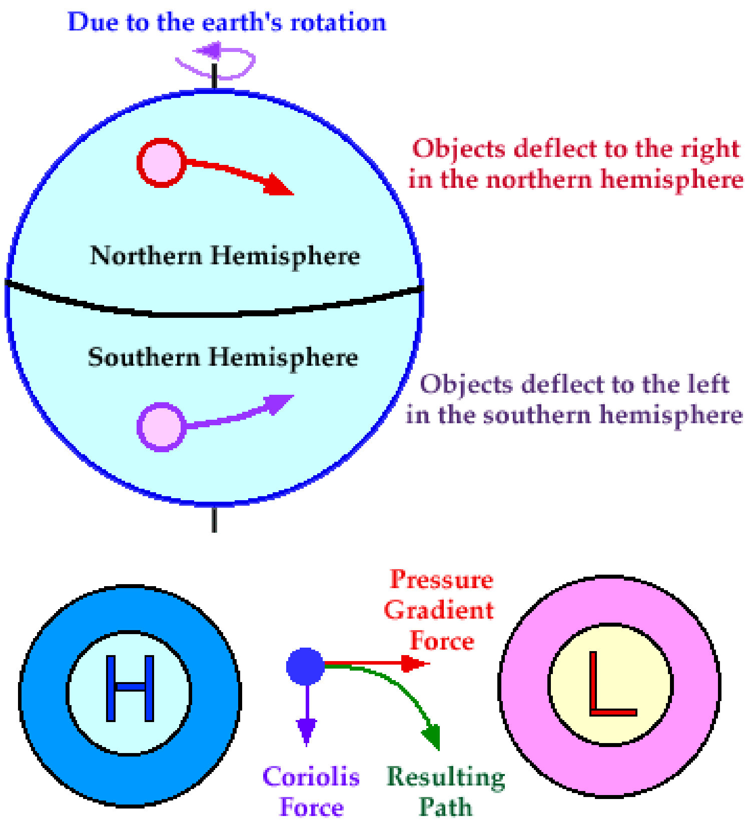
  - Clouds and precipitation
  - Rainfall backscattering and polarimetric measurables
  - Example of radar measurements and estimates

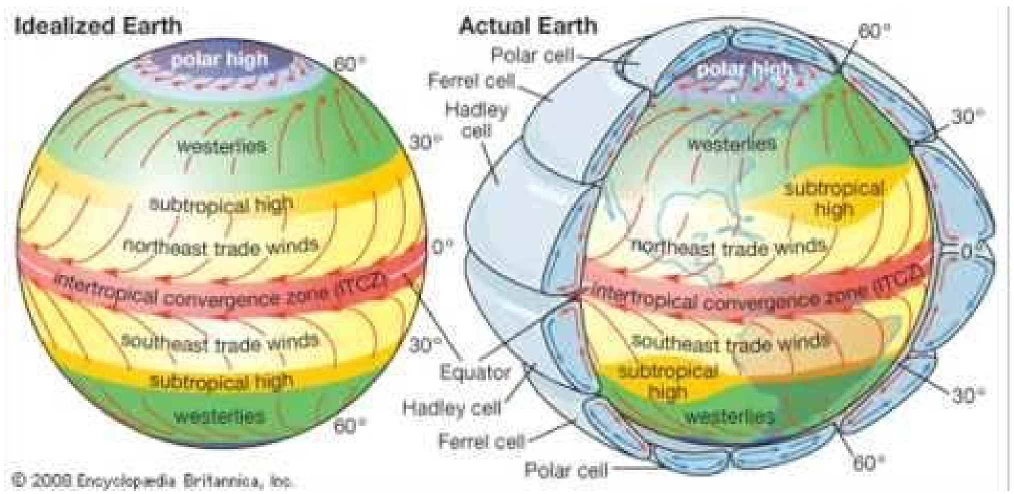
RADAR APPLICATIONS
Clouds and precipitation

Genus	*Sym.*	*Region*	*Species*	*RR (mm/h)*
Cumulus	Cu	Vert. develop. (0-6 Km)	***Mediocris*** ***Congestus*** ***Incus***	0 < 30 < 60
Cumulonimbus	Cb	Vert. develop. (0-12 km)		10÷100
Stratus	St	low (0-2 km)		< 2
Stratocumulus	Sc	low (0-2 km)		< 5
Nimbostratus	Ns	middle (2-6 km)		< 15
Altostratus	As	middle (2-6 Km)		< 2
Altocumulus	Ac	middle (2-6 km)		0
Cirrostratus	Cs	high (6-12 km)		0
Cirrocumulus	Cc	high (6-12 km)		0

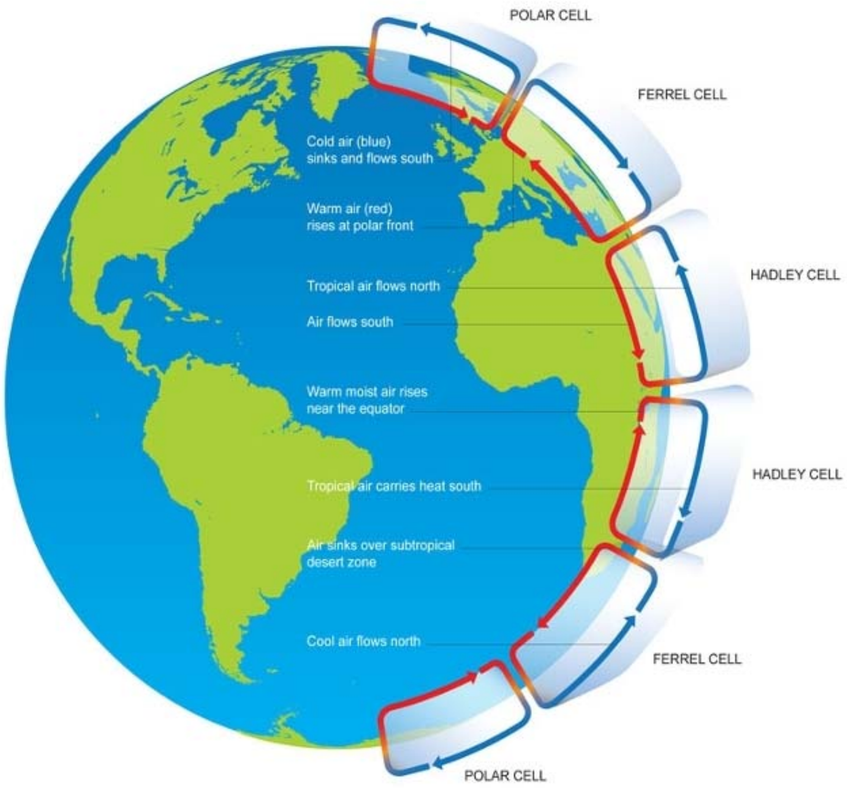


DYNAMIC METEOROLOGY
Air mass flows and winds

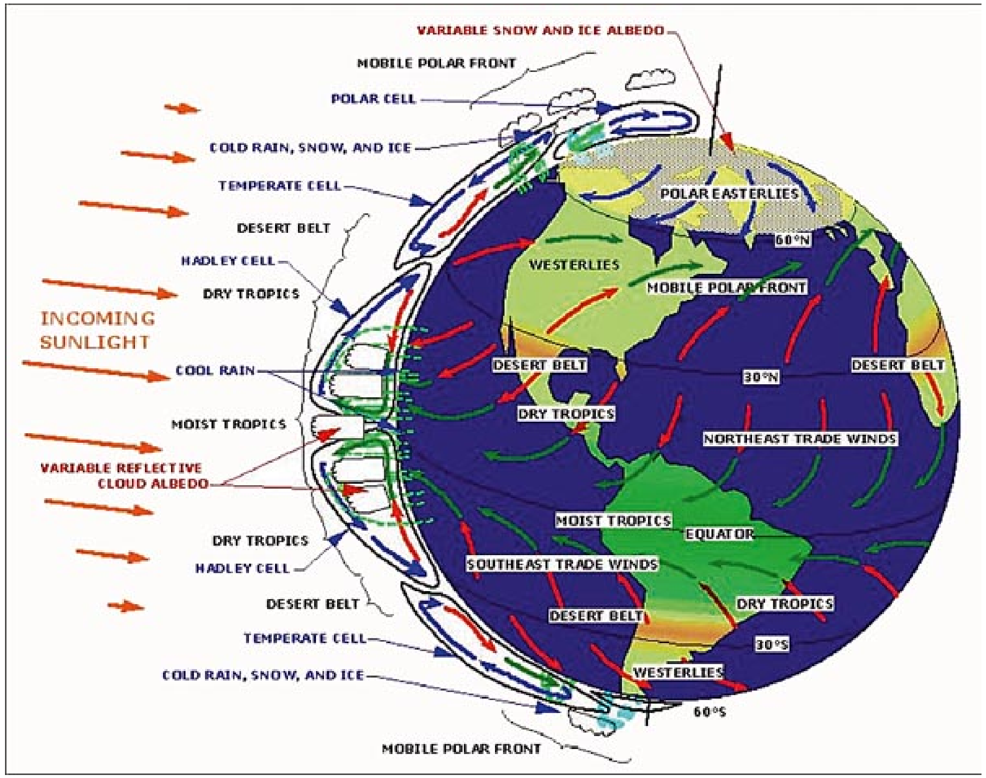




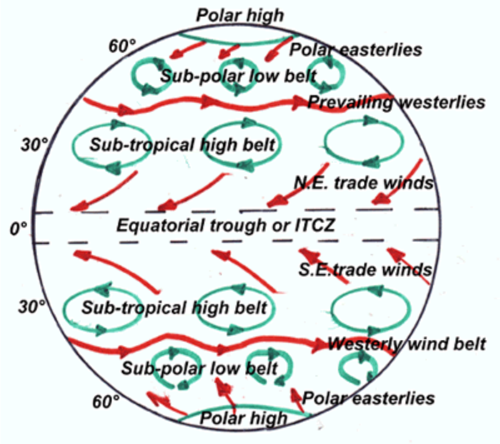
DYNAMIC METEOROLOGY
Circulating cells

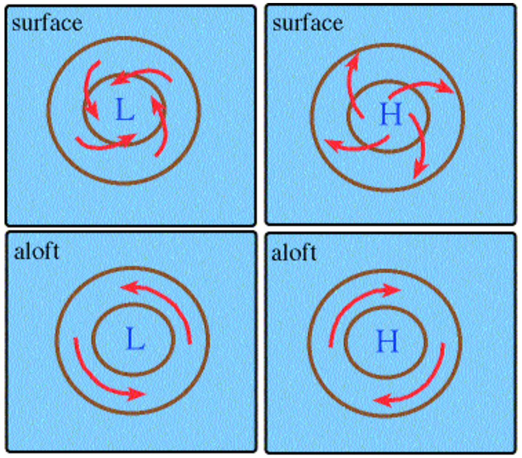


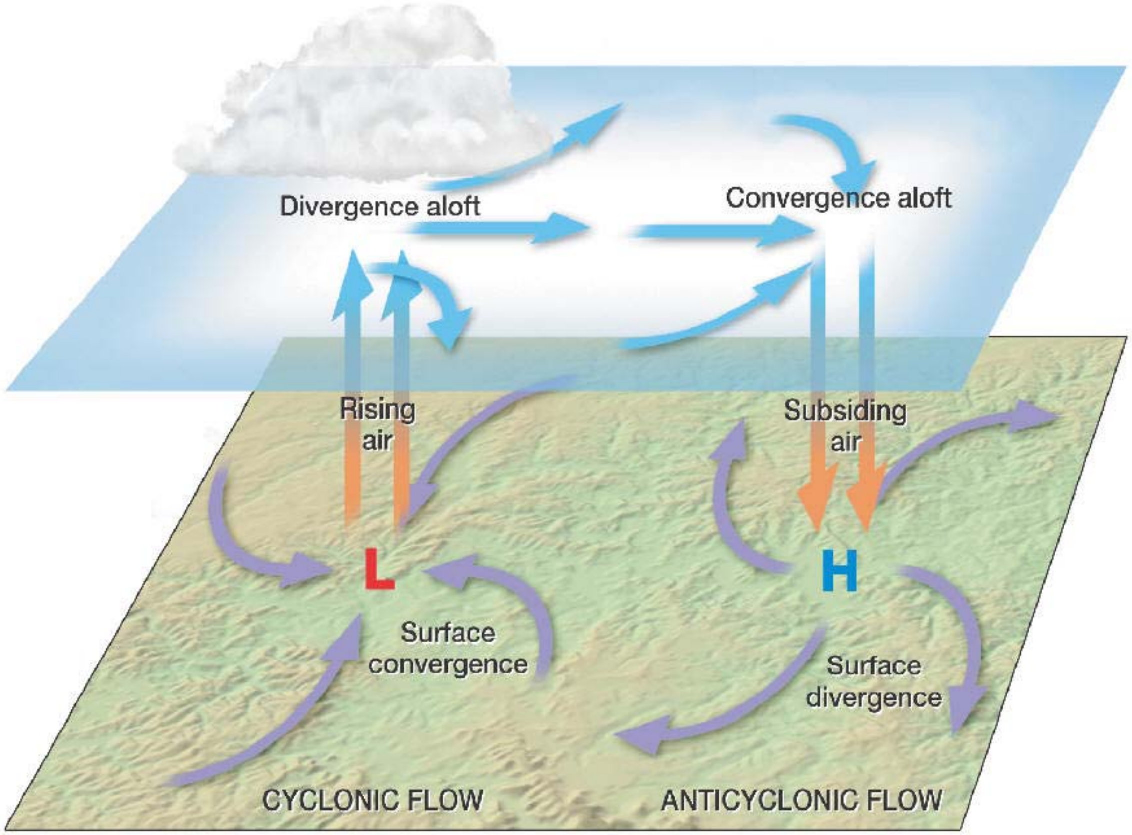
CIRCULATING CELLS
The Hadley cells have the most regular pattern of air movement, and produce extreme wet weather at the equator and extreme aridity on the deserts. The polar cells are the least well-defined.



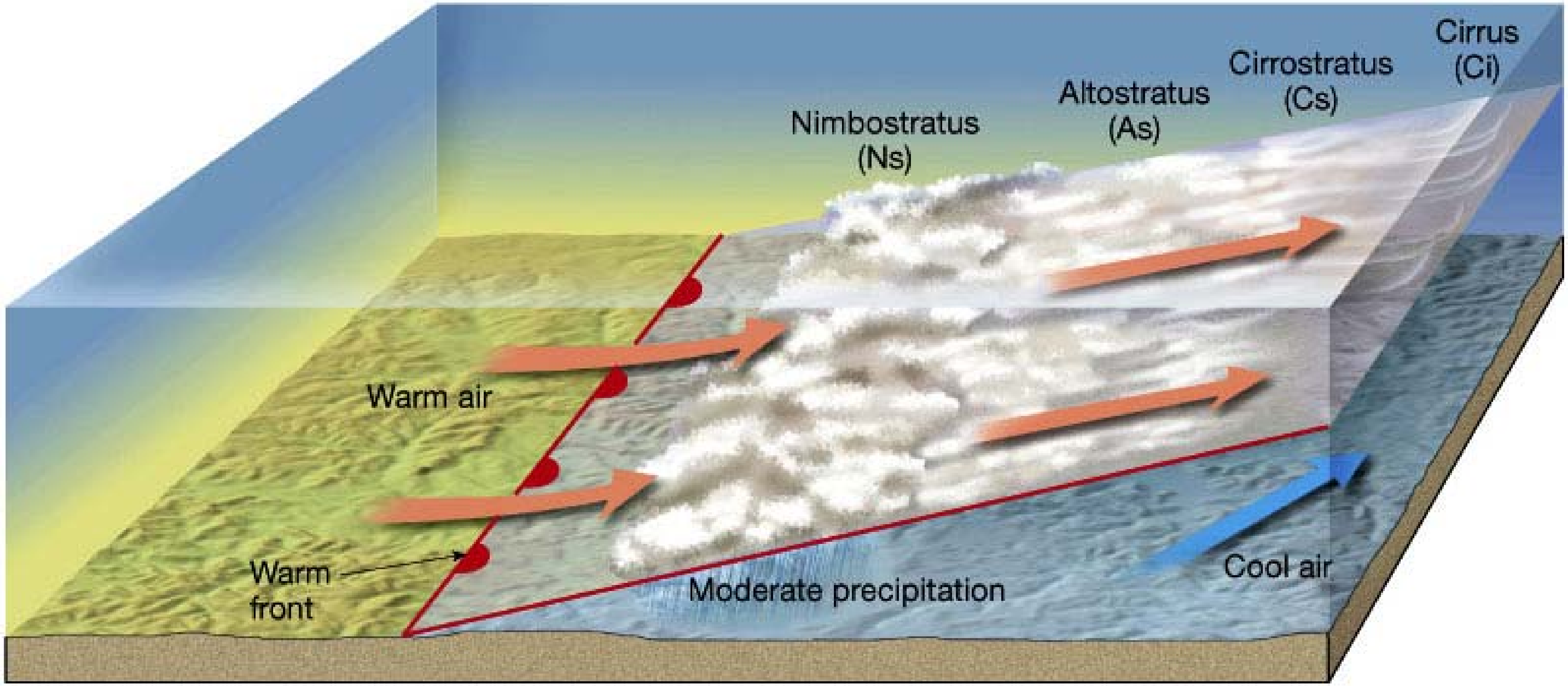
DYNAMIC METEOROLOGY Cyclones and anticyclones



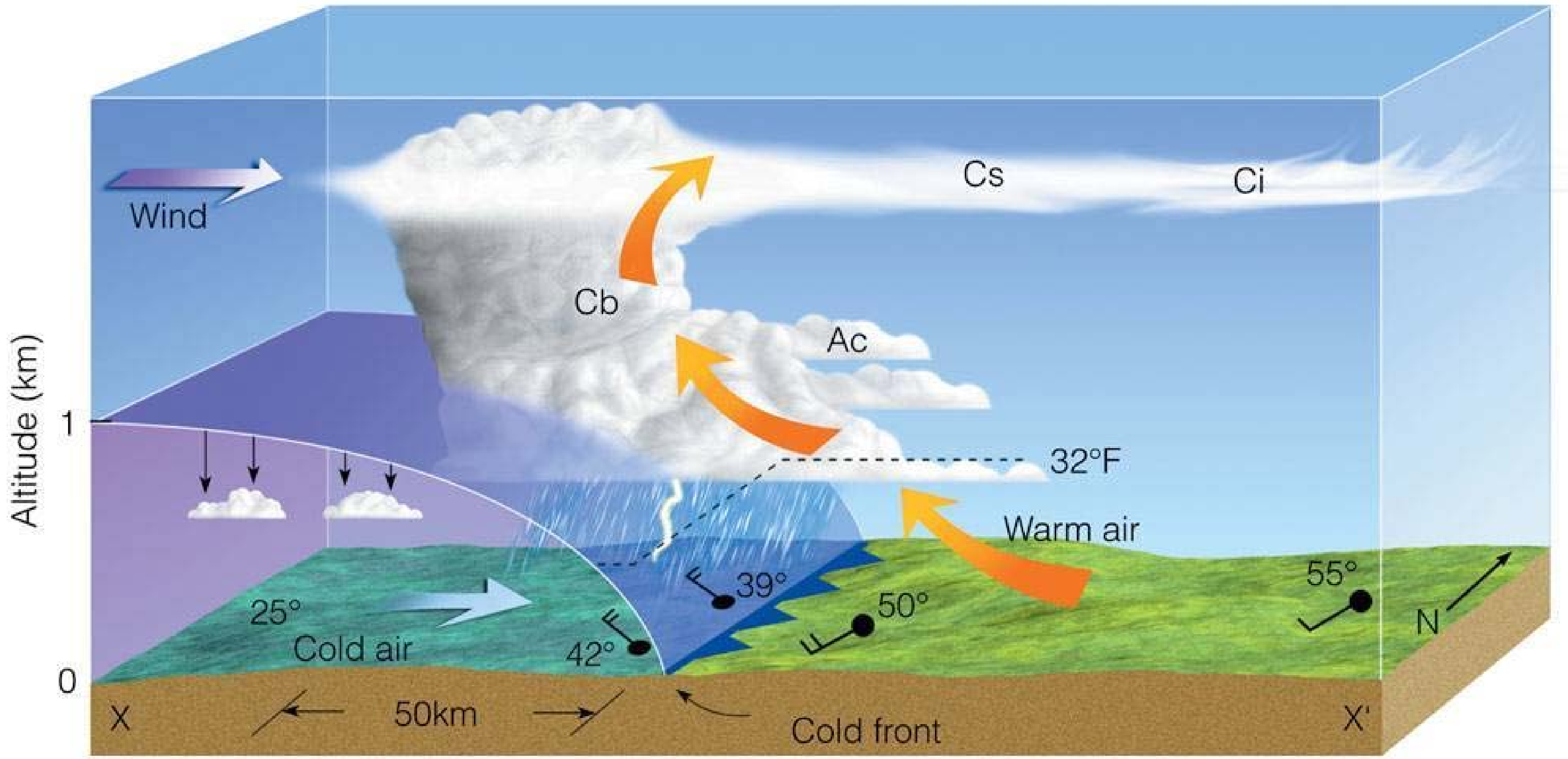




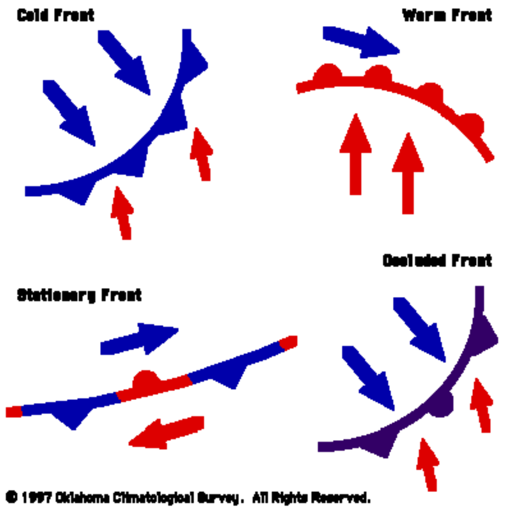
CLOUD GENERA
Warm fronts

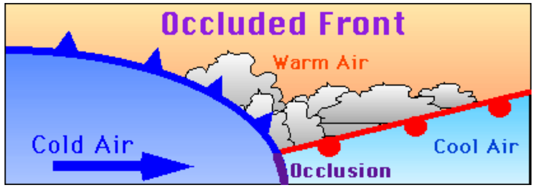


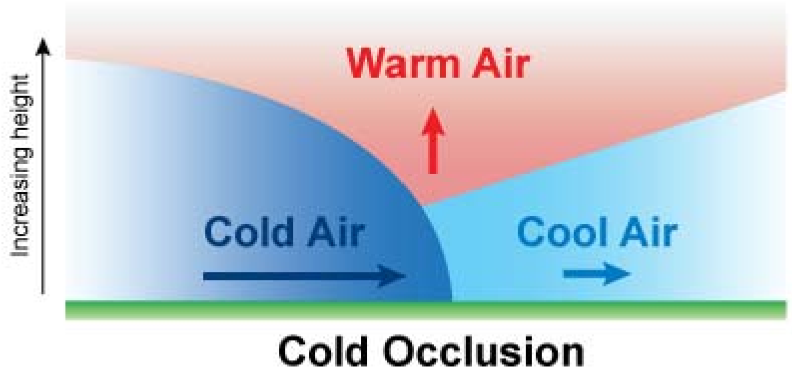
CLOUD GENERA
Cold fronts

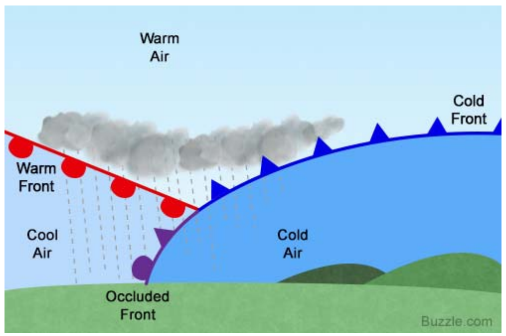


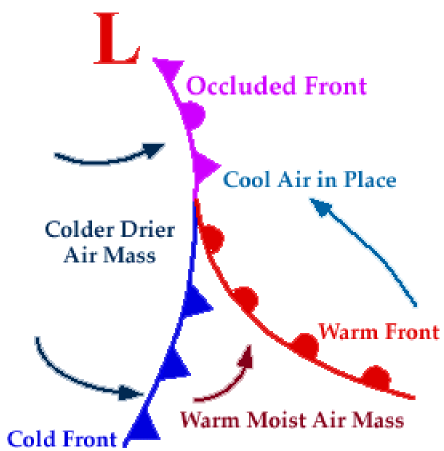
CLOUD FRONTS
Cold, warm and occluded

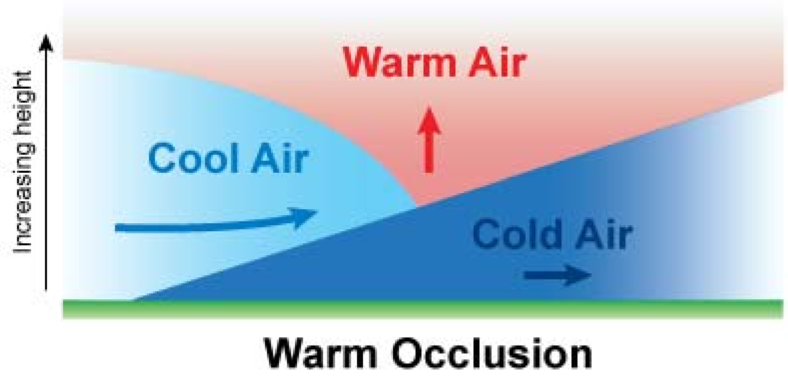








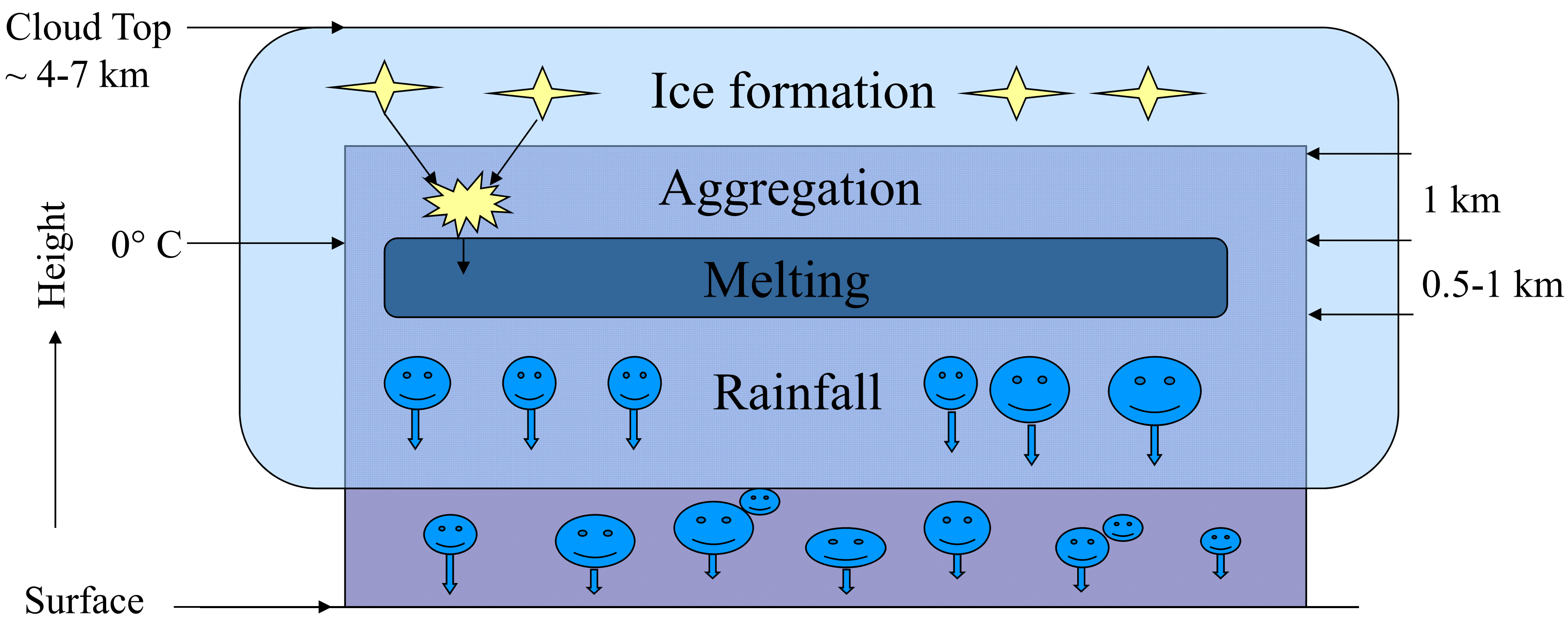




PRECIPITATING CLOUDS
Time and space scales

		CHARACTERISTIC TIME			
		1 day- 1 month	1 hour – 1 day	1 hour – 1 minute	
HORIZONTAL SCALE	**200 - 2000 km**	- *Fronts* - *Hurricanes* (tens of days)			**Meso-α scale**
	20 - 200 km		- *Squall lines* - *Cloud clusters* - *Mountain and lake disturbances* (2 hours to 1 day)		**Meso-β scale**
	2 - 20 km			- *Thunderstorms* (tens of minutes to hours)	**Meso-γ scale**
	0.2 - 2 km			- *Tornadoes* - *Deep convection* (few minutes to 1 hour)	**Micro-α scale**
	0.02 - 0.2 km			- *Thermals* (few minutes)	**Micro-β scale**
	0.001 - 0.02 km			- *Plumes* - *Turbulence* (less than a few minutes)	**Micro-γ scale**

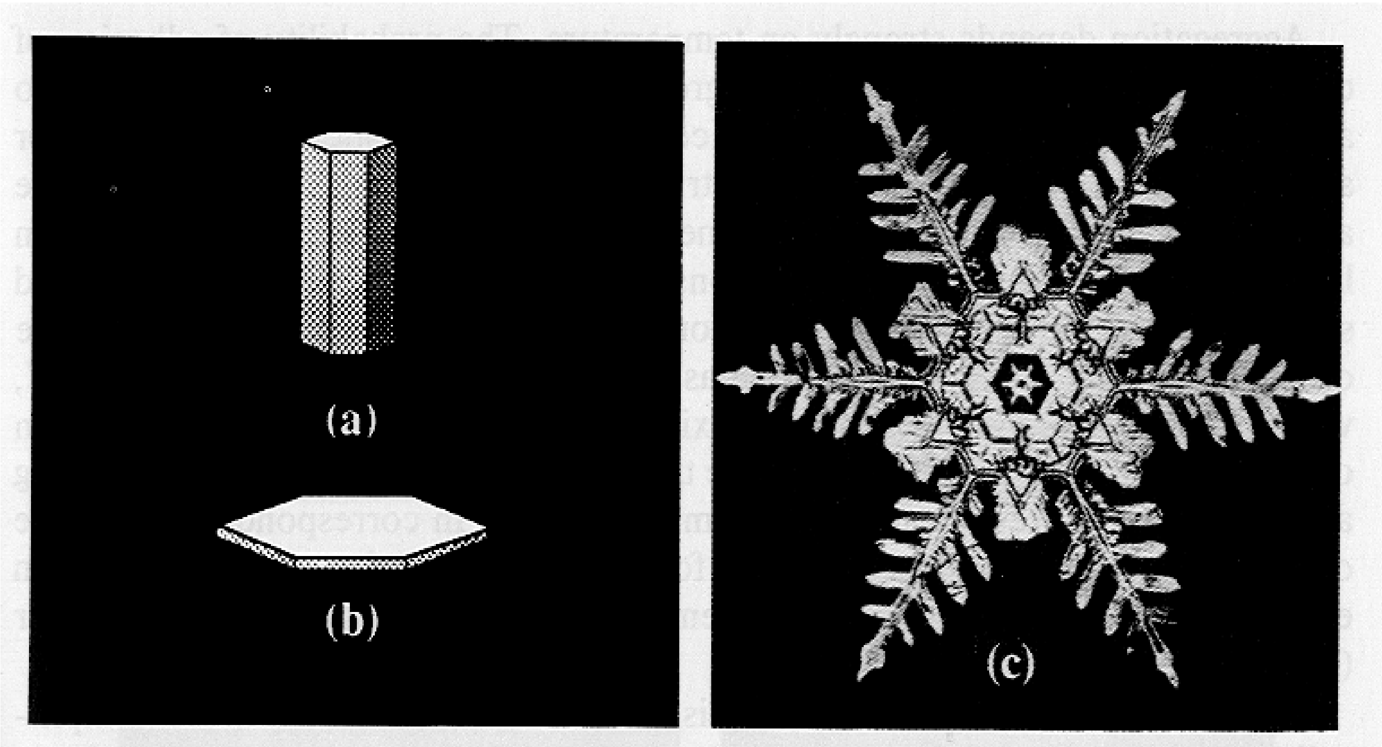
PRECIPITATING CLOUDS
Stratiform process



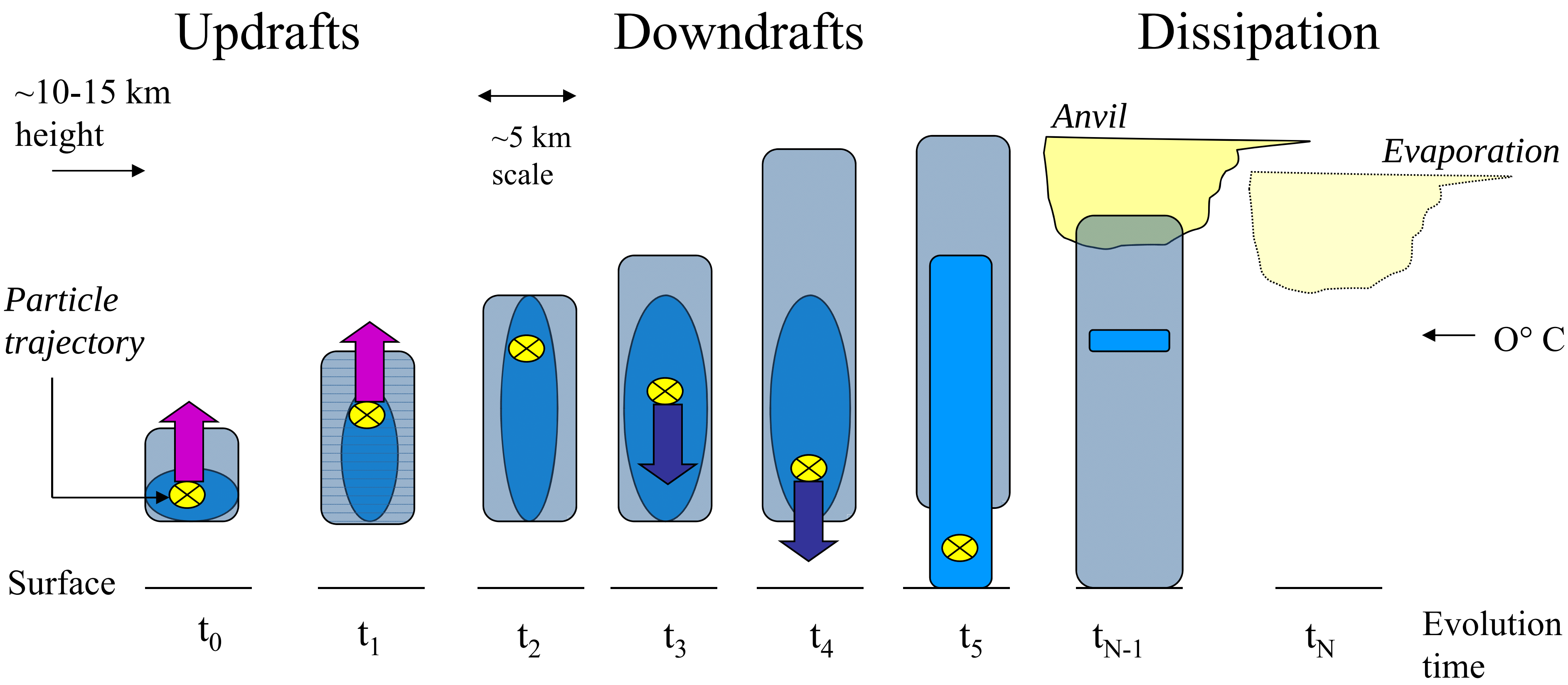
PRECIPITATING CLOUDS
Ice crystals

As for droplets (condensation/evaporation), ice crystals can initially grow by *vapor deposition* and evaporate by *sublimation*. The probability of presence of ice particles in a cloud increases with decreasing temperature below zero.
At -10ºC the probability to find ice is around 50%, while at -20 ºC it raises to 95%.

Main ice crystal shapes are: (a) columnar or prismatic, (b) disc, (c) dendrite



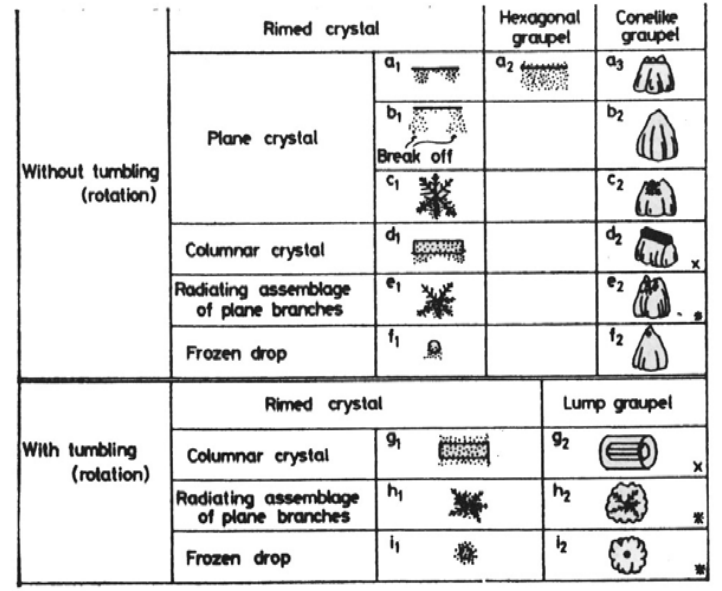
PRECIPITATING CLOUDS
Convective process



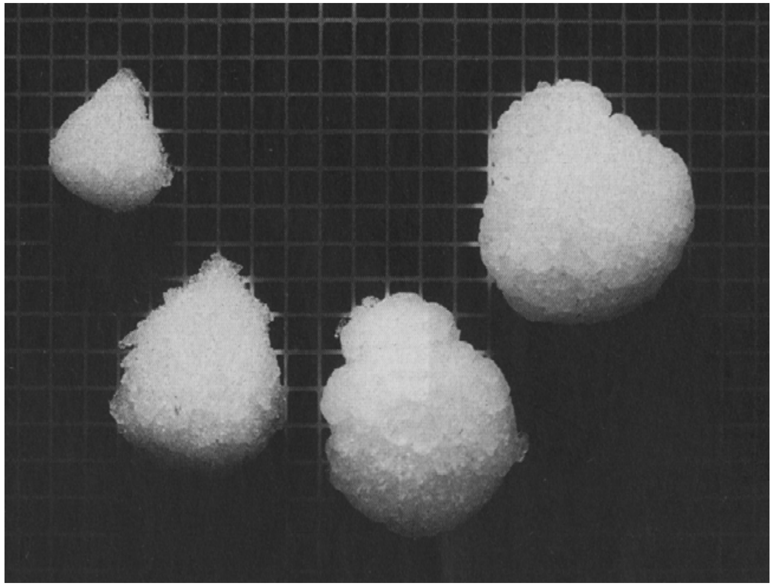
PRECIPITATING CLOUDS
Graupel particles

GRAUPEL FORMATION BY RIMING

- **Ice crystals fall through supercooled cloud droplets**
- **Supercooled droplets, that hit ice crystals, freeze to it**
- **Eventually the frozen droplet can hide the original shape**
- **Due to strong updrafts, hailstones can form**



Natural graupels (boxes are 2 mm on a side)



RADAR APPLICATIONS
Drop size distributions

- Modified Gamma distribution

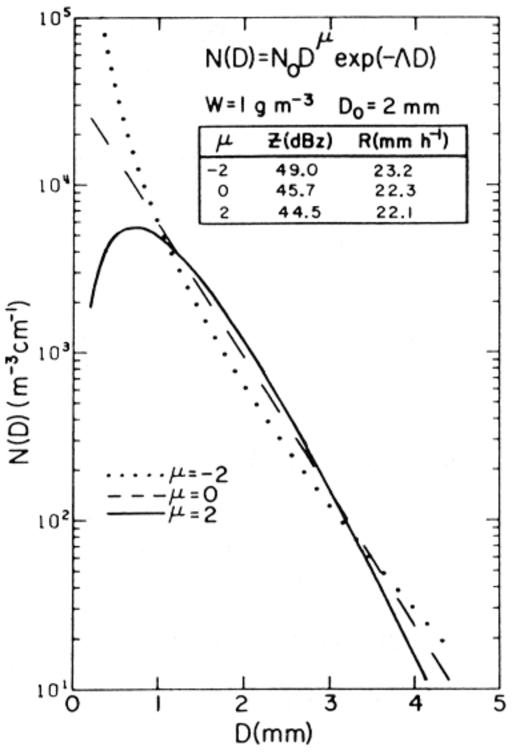
$$\boxed{N(D) = N_0 D^{\mu} e^{-\Lambda D}} \quad \text{with} \quad D: \text{drop diameter; } \mathrm{N}_0, \mu, \Lambda: \text{parameters}$$

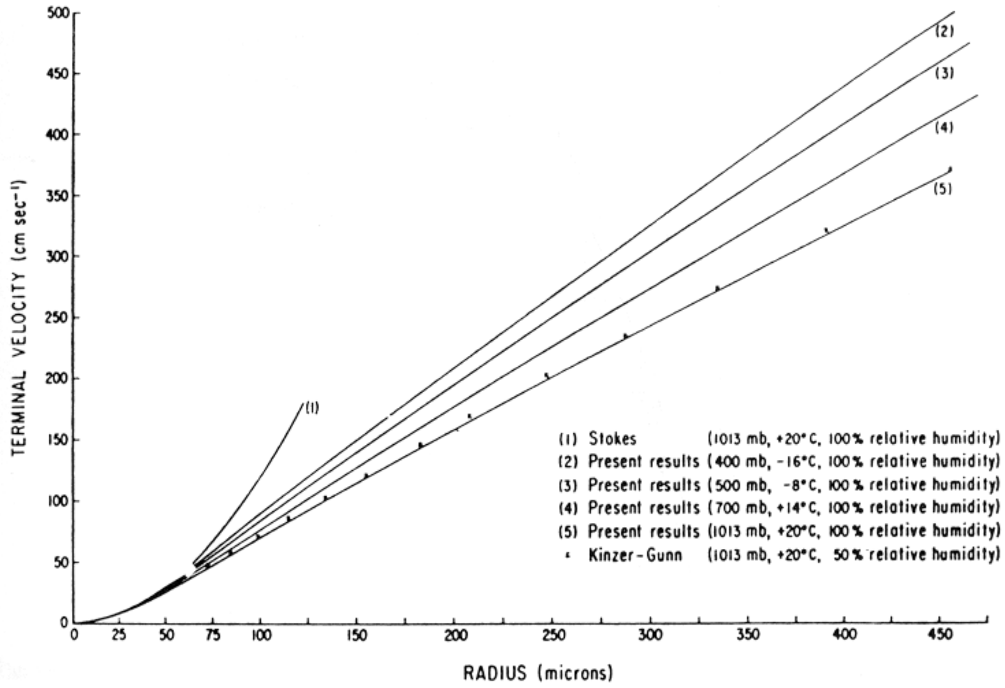
- Moments of order n: $m_n = \int_0^\infty D^n N(D) dD = \frac{N_0 \Gamma(n+\mu+1)}{\Lambda^{n+\mu+1}}$

  - Drop concentration [#/m³]: $N_T = m_0$
  - Equivalent water content [g/m³]: $M = (\pi/6)\rho m_3$
  - Median volumetric diameter [m]: $D_0 = M/2$
  - Precipitation intensity [mm/h]: $R_\rho = (\pi/6)\rho \int_0^\infty D^3 N(D)[u_t(D) - w] dD \quad [\mathrm{kg/m^2}s]$

$$u_t(D) = aD^b \quad \Rightarrow \quad R = R_\rho / \rho = (\pi/6) a m_{3+b} \quad [\mathrm{m/s = mm/h}]$$

RADAR APPLICATIONS
Examples of size distributions



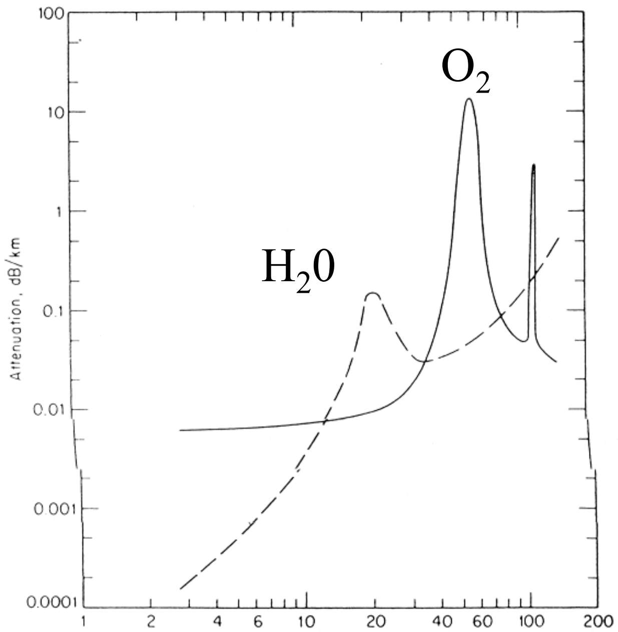


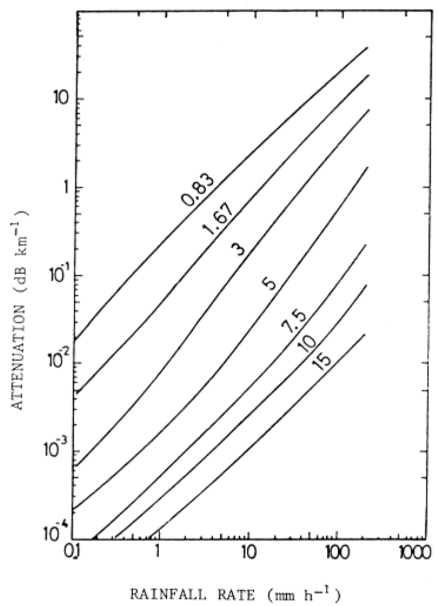
RADAR APPLICATIONS
Atmospheric attenuation

$$\alpha = k_a = 0.4343 \int_0^\infty \sigma_a(D) N(D) dD \quad [\text{dB/km}] \Rightarrow$$

α_g: atmospheric gases
α_c: cloud and ice
α_p: rain and graupel (precipitating)
$\alpha_t = \alpha_g + \alpha_c + \alpha_p$

$$a_p = \kappa_p K$$





RADAR APPLICATIONS
Radar reflectivity

- Volumetric reflectivity of particles with different size

$$\eta = \frac{\sum_{i=1}^{N_{part}} \sigma_{bi}}{dV} \rightarrow \frac{\sum_{i=1}^{N_D} \sigma_b(D_i) N_p(D_i)}{dV} = \sum_{i=1}^{N_D} \sigma_b(D_i) N(D_i) \cong \int_0^\infty \sigma_b(D) N(D) dD \quad \left[\frac{1}{\mathrm{m}}\right]$$

- Rayleigh reflectivity and reflectivity factor

$$Se\ \mathrm{D} << \lambda: \quad \eta = \int_0^\infty \left[\frac{\pi^5 |K|^2}{\lambda^4} D^6\right] N(D) dD \quad \Rightarrow \quad \mathrm{Z} \equiv \int_0^\infty D^6 N(D) dD$$

- Mie reflectivity and equivalent reflectivity factor

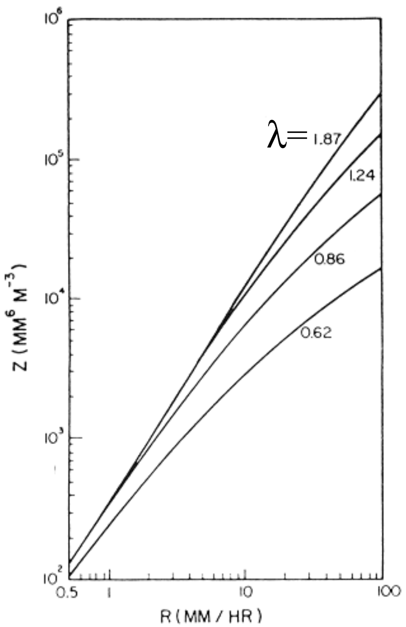
$$Se\ \mathrm{D} > \lambda: \quad \eta = \frac{\pi^5 |K|^2}{\lambda^4} Z_\mathrm{e} \quad \Rightarrow \quad Z_\mathrm{e} \equiv \frac{\lambda^4}{\pi^5 |K|^2} \int_0^\infty \sigma_b(D) N(D) dD$$

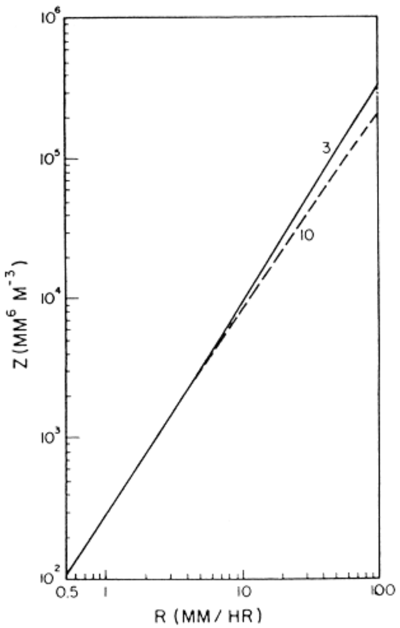
- Dielectric factor K

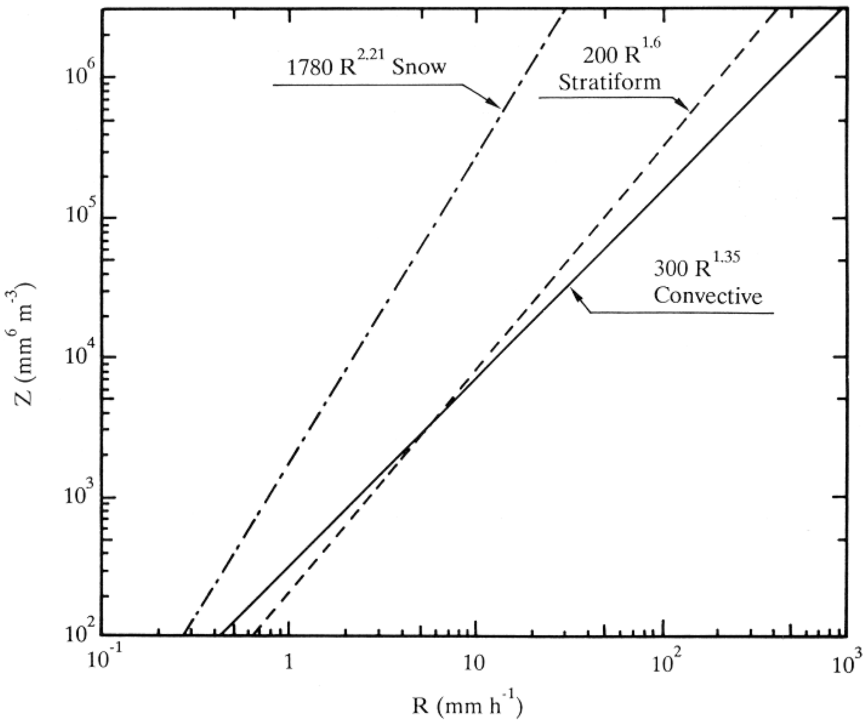
Water	$\lvert K \rvert^2 = 0.930$
Ice	$\lvert K \rvert^2 = 0.176$
Melt	$\lvert K \rvert^2 = 0.208$

RADAR APPLICATIONS
Examples of radar reflectivity

Power-law relation: $Z=aR^b$







RADAR APPLICATIONS Hydrologic relationships

Parameter	Stratiform [Marshall and Palmer, 1948]	Thunderstorm [Sekhon and Srivastava, 1971]	Snow [Sekhon and Srivastava, 1970]
Z-R	$Z = 200\ R^{1.6}$	$Z = 300\ R^{1.35}$	$Z = 1780\ R^{2.21}$
M-R	$M = 0.072\ R^{0.88}$	$M = 0.052\ R^{0.94}$	$M = 0.250\ R^{0.86}$
D_0-R	$D_0 = 0.09\ R^{0.21}$	$D_0 = 0.13\ R^{0.14}$	$D_0 = 0.14\ R^{0.45}$
Γ-R	$\Gamma = 41\ R^{-0.21}$	$\Gamma = 38\ R^{-0.14}$	$\Gamma = 22.9\ R^{-0.45}$
N_0-R	$N_0 = 0.08$	$N_0 = 0.07\ R^{0.37}$	$N_0 = 0.025\ R^{-0.94}$
Γ-M	$\Gamma = 22\ M^{-0.24}$	$\Gamma = 25\ M^{-0.15}$	$\Gamma = 11\ M^{-0.52}$

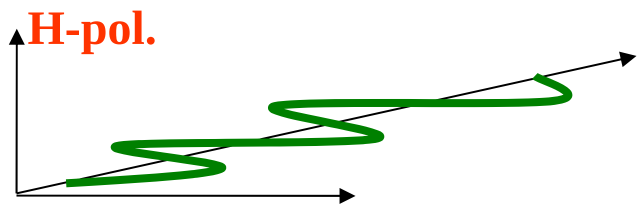
Note:
Z is in mm^6 m^{-3}, R is in mm h^{-1}, M is in g m^{-3} m^{-3}, D_0 is in cm, Γ is in cm^{-1}, N_0 is in cm^{-4}.

RADAR APPLICATIONS
Polarized measurements

➢ Backscattering matrix

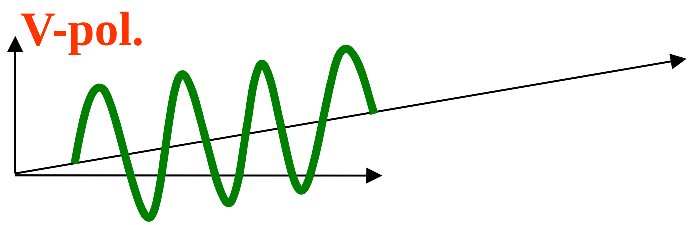
- The scattering field is related to the incident one by:

$$\begin{bmatrix} E_h^{\ s} \\ E_v^{\ s} \end{bmatrix} = \frac{e^{-j\beta r}}{r} \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \begin{bmatrix} E_h^{\ i} \\ E_v^{\ i} \end{bmatrix}$$



- The S matrix is the complex backscattering matrix, whose terms are:

$$S_{pp} = \left| S_{pp} \right| e^{j\varphi_{pp}}$$



➢ Interpretation and Symmetry

- Diagonal terms S_{HH} and S_{VV} represent linear co-polarized components
  - S_{HH} : H transmission, H reception
- Off-diagonal terms are cross-polarized components
  - S_{VH} : H transmission, V reception
- For a spherical particles, the cross-polarized terms are zero.
- The cross-pol. terms are equal for reciprocity (unless medium is anysotropic).

RADAR APPLICATIONS Polarimetric definitions

- **Polarimetric form of radar equation**
  - Radar equation can be generalized to polarimetric form
  - Complex envelope V will be polarization dependent, i.e. V_{pp}
- **Co-polar radar reflectivity ($mm^6 m^{-3}$)**

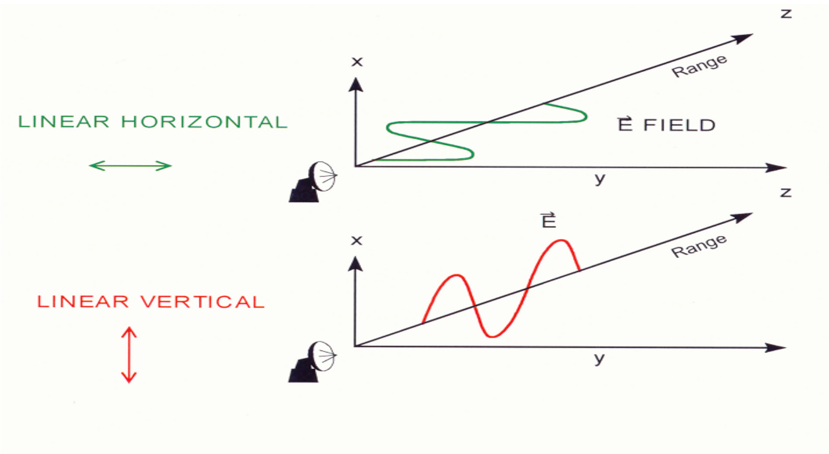
$$Z_{HH} = (\lambda^4 / \pi^5 |K|^2) < |S_{HH}|^2 >, \qquad Z_{VV} = (\lambda^4 / \pi^5 |K|^2) < |S_{VV}|^2 >$$

- **Differential reflectivity**

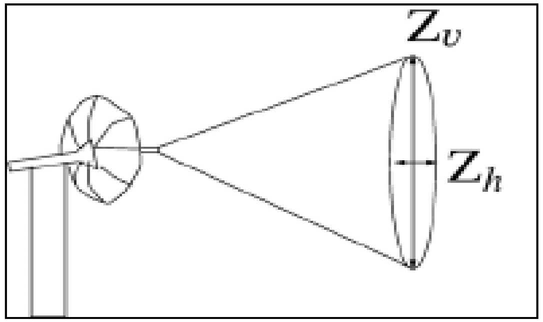
$$Z_{DR} = 10 Log \frac{< |S_{HH}|^2 >}{< |S_{VV}|^2 >}$$

- **Linear Depolarization Ratio (LDR)**

$$LDR = 10 Log \frac{< |S_{HV}|^2 >}{< |S_{HH}|^2 >}$$

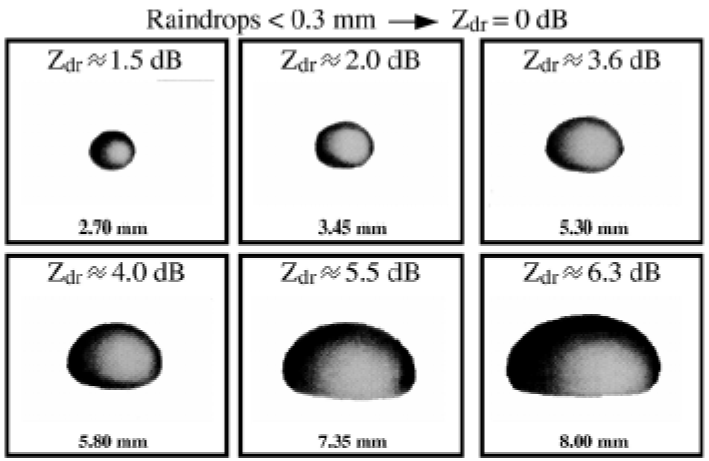


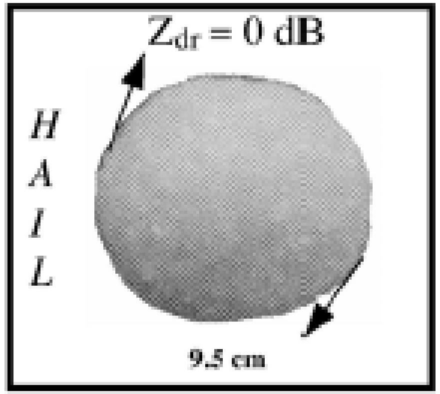
RADAR APPLICATIONS
Polarimetric examples

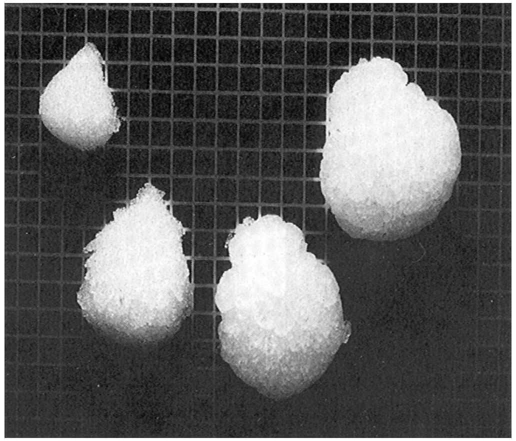


$$Z_{DR} = 10 Log \frac{<|S_{HH}|^2>}{<|S_{VV}|^2>}$$

Oblate → $Z_{DR} > 0$
Sphere → $Z_{DR} = 0$
Prolate → $Z_{DR} < 0$







RADAR APPLICATIONS
Polarimetric definitions

- Correlation coefficient

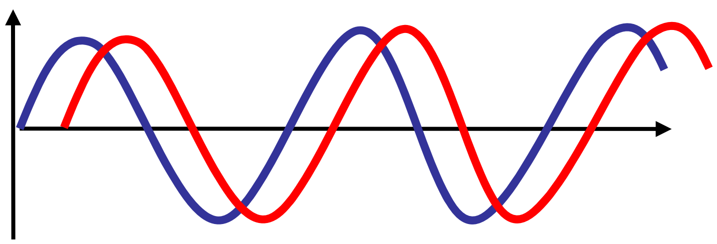
$$\rho_{HV} = \frac{< S_{VV} S_{HH}^* >}{\sqrt{<|S_{HH}|^2><|S_{VV}|^2>}} = |\rho_{hv}| e^{j\delta_{hv}}$$

- Differential propagation-phase shift (°/km)

$$K_{DP} = \frac{180}{\pi} \lambda \,\mathrm{Re}\left[\int_0^D [f_{HH}(D) - f_{VV}(D)] N(D) dD \right]$$

$$\phi_{DP} = 2\int_0^r K_{DP}(r')dr' + \delta_{hv}$$

$$\delta_{hv} = \arg\left(< S_{VV} S_{HH}^* >\right)$$



- Oblate particles tend to slow down **H-pol.** waves with respect to **V-pol.** ones
- This effect is larger for liquid than ice particles
- δ is due to particle-induced phase shift

RADAR APPLICATIONS Polarimetric definitions

- Specific attenuation (1/km)

$$\alpha_{HH} = 2 \cdot 10^{-3} \frac{180}{\pi} \lambda \, \mathrm{Im}\left[< 4\pi S_{HH}^{f}(D_e, \phi) > \right]$$

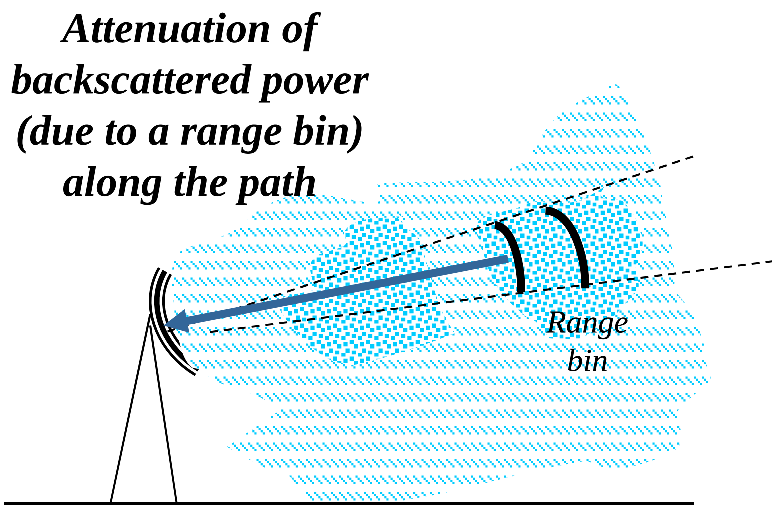
- One-way path attenuation

$$A_{HH}(r) = \int_0^r \alpha_{HH}(r') dr'$$

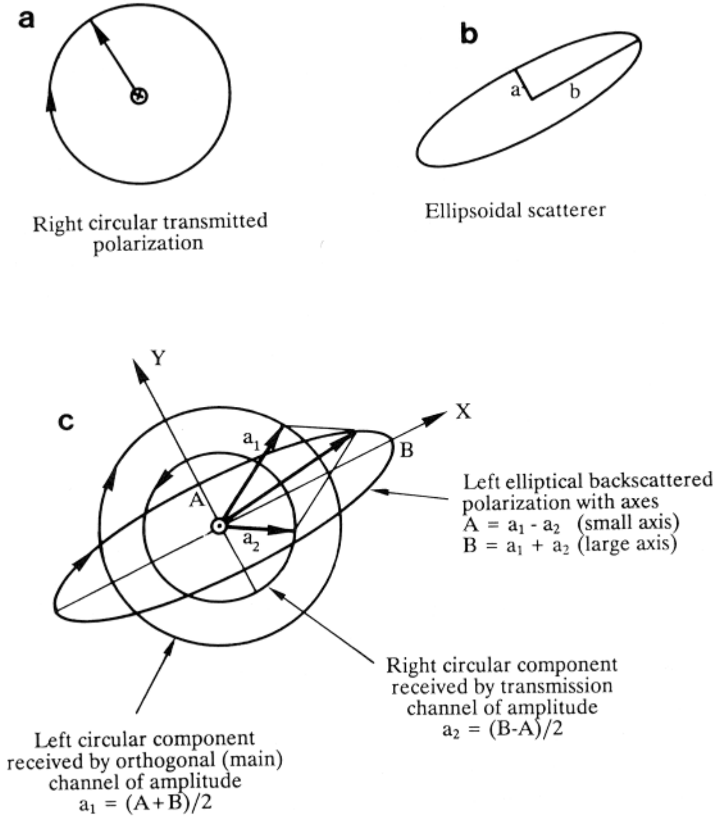
• Application

$$< W_{Rh} >= C_2 L_{HH}^2(r) \frac{Z_{HH}(r)}{r^2} =$$

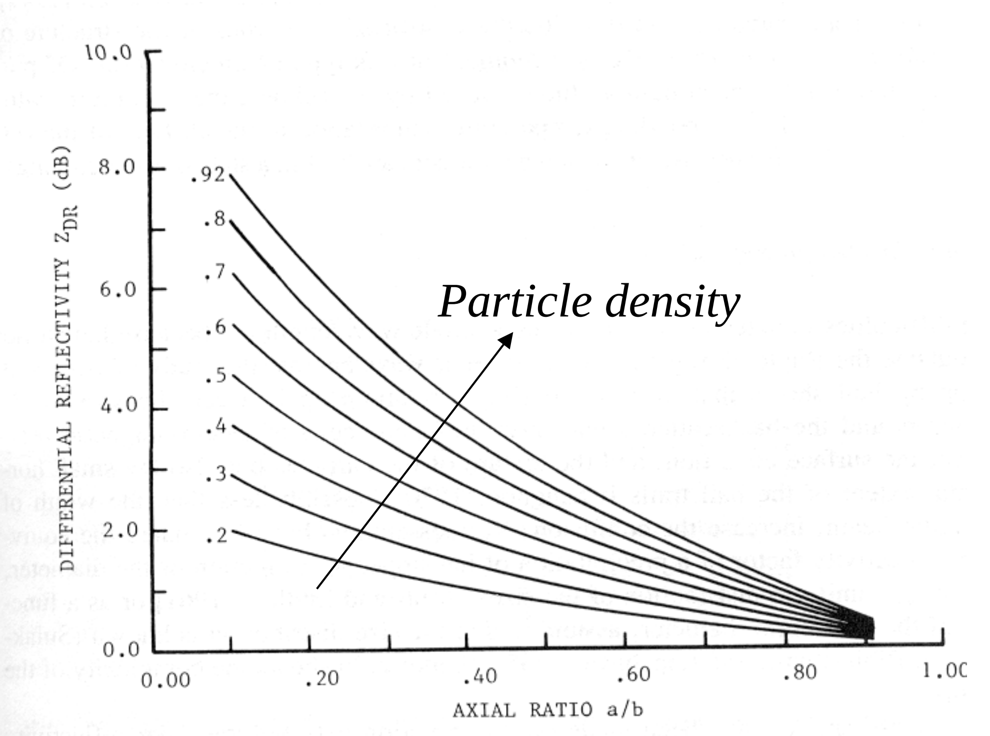
$$= C_2 \left(e^{-2 A_{HH}(r)} \right) \frac{Z_{HH}(r)}{r^2}$$



RADAR APPLICATIONS
Polarimetric theory



Differential reflecivity vs. ellipsoid axial ratio



RADAR APPLICATIONS
Polarimetric features

Table 1. Values of polarimetric variables for precipitation types (from Doviak and Zrnić 1993).

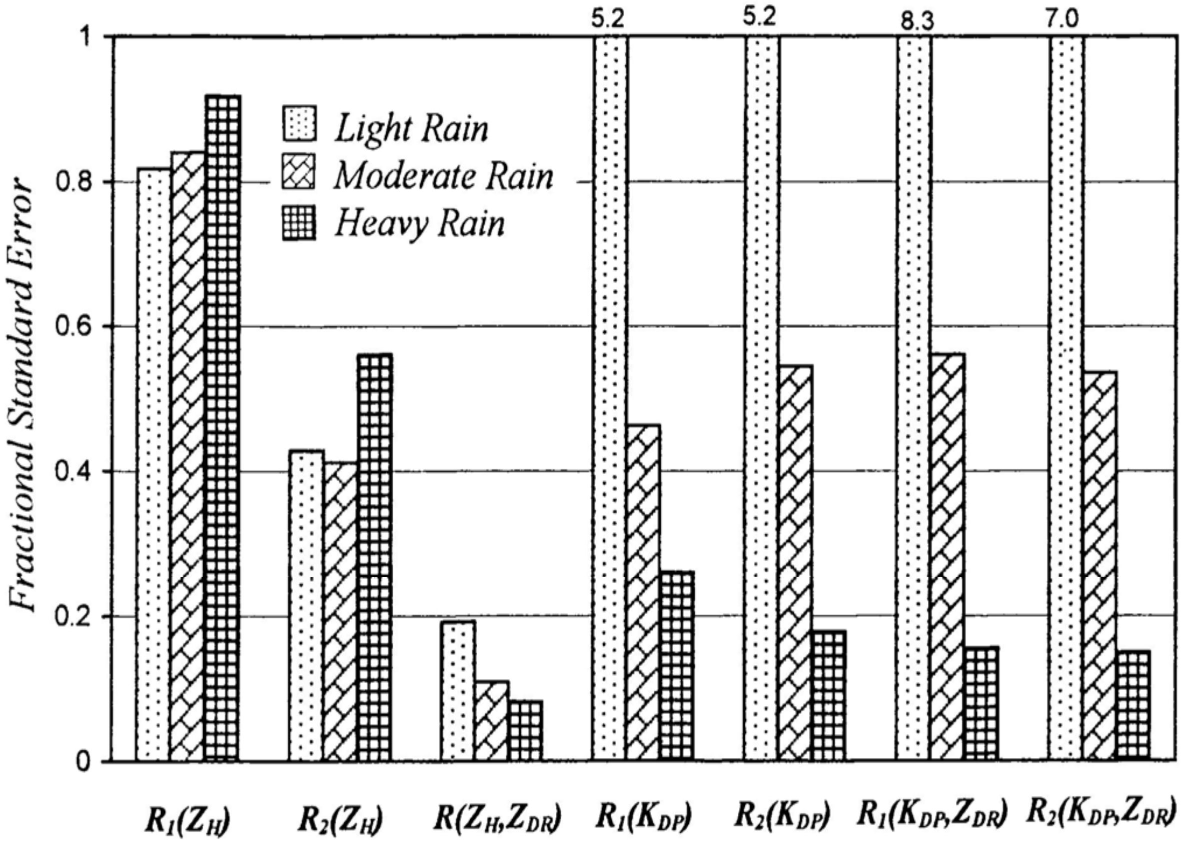
	Z_h (dBZ)	Z_{DR} (dB)	ρ_{hv}	K_{DP} (° km^{-1})	LDR (dB)
Drizzle	< 25	0	>0.99	0	<-34
Rain	25 to 60	.5 to 4	>0.97	0 to 10	-27 to -34
Dry snow	< 35	0 to .5	>0.99	0 to 0.5	<-34
Dense snow	< 25	0 to 5	>0.95	0 to 1	-25 to -34
Wet snow	< 45	0 to 3	0.8 to 0.95	0 to 2	-13 to -18
Dry graupel	40 to 50	-0.5 to 1	>0.99	-0.5 to 0.5	< -30
Wet graupel	40 to 55	-0.5 to 3	>0.99	-0.5 to 2	-20 to -25
Wet hail (< 2 cm)	50 to 60	-0.5 to 0.5	>0.95	-0.5 to 0.5	<-20
Wet hail (> 2 cm)	55 to 70	<-0.5	>0.96	-1 to 1	-10 to -15
Rain/hail	50 to 70	-1 to 1	>0.90	0 to 10	-10 to -20

RADAR APPLICATIONS
Polarimetric advantages

TABLE 1. Attributes of polarimetric variables (for 5- and 10-cm wavelengths).

Variable \ Attribute	Independent of absolute radar	Immune to propagation effects calibration	Immune to noise bias	Used for quantitative estimation	Independent of concen-tration
Z_h	no	no	no	yes	no
Z_{DR}	yes	no	no	yes	yes
K_{DP}	yes	yes	yes	yes	no
ρ_{hv}	yes	yes	no	no	yes
δ	yes	no	yes	no	yes
LDR	yes	no	no	no	yes

RADAR APPLICATIONS
Rainfall polarimetric estimators



From single-pol.

$$R = R(Z_h, Z_{dr})$$

To dual-pol. retrieval

$$R = R(Z_h, Z_{dr})$$

$$R = R(K_{dp}, Z_{dr})$$

$$R = R(K_{dp})$$

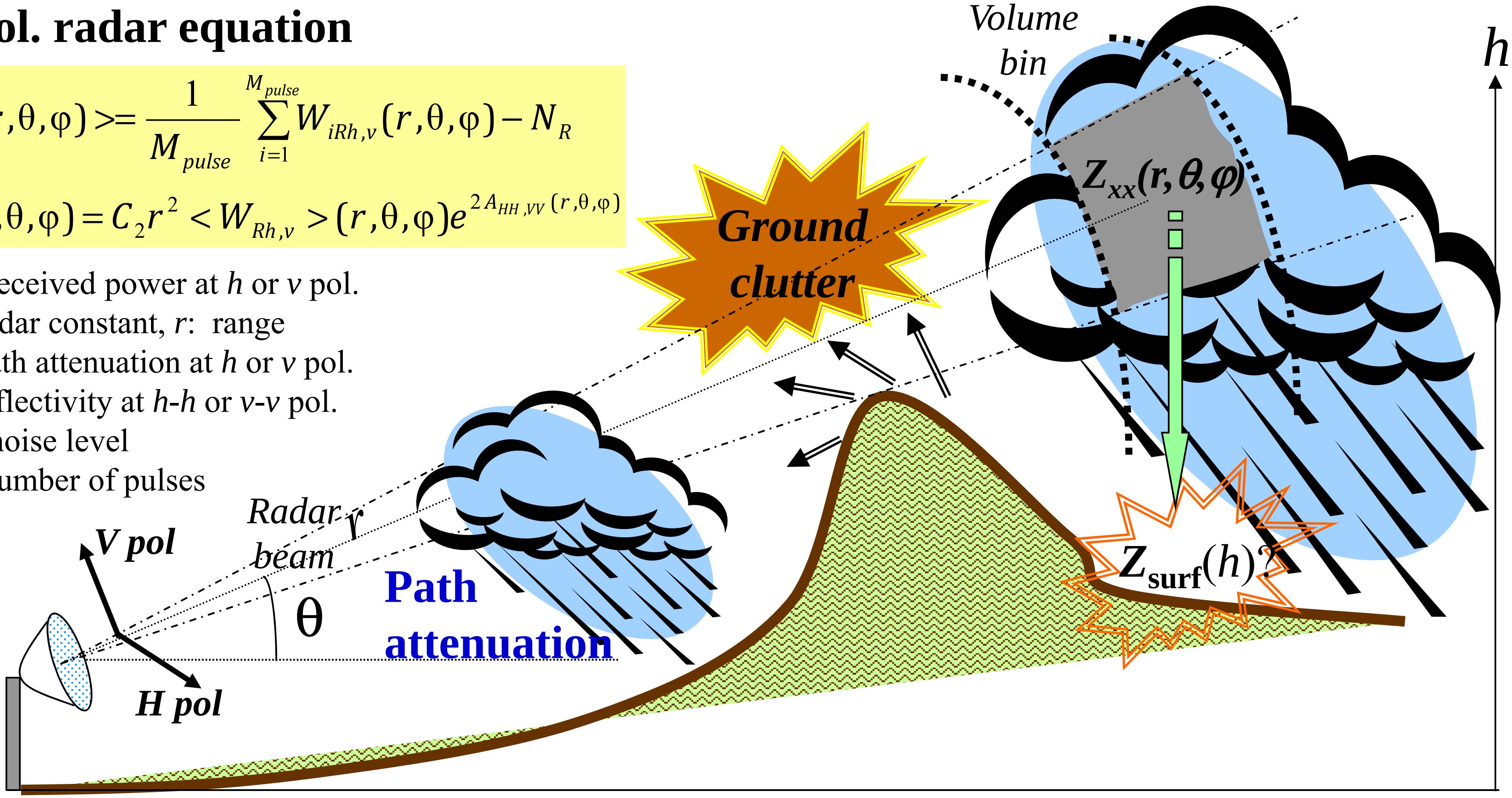
RADAR APPLICATION Measurement issues

Dual-pol. radar equation

$$< W_{Rh,v}(r,\theta,\varphi) >= \frac{1}{M_{pulse}} \sum_{i=1}^{M_{pulse}} W_{iRh,v}(r,\theta,\varphi) - N_R$$

$$Z_{HH,VV}(r,\theta,\varphi) = C_2 r^2 < W_{Rh,v} > (r,\theta,\varphi) e^{2A_{HH,VV}(r,\theta,\varphi)}$$

where P_R: received power at *h* or *v* pol.
C: radar constant, *r*: range
A: path attenuation at *h* or *v* pol.
Z: reflectivity at *h*-*h* or *v*-*v* pol.
N_R: noise level
M: number of pulses



RADAR APPLICATIONS
Operational issues

Calibration objective

- Determine with precision and accuracy the instrumental constant C in radar equation equation
    - Transmistter power, loss of radiofrequency chain (e.g., guides, mixers, couplers)
    - Noise level in the receiver chain, receiver gain and linear dynamics (no distortions)

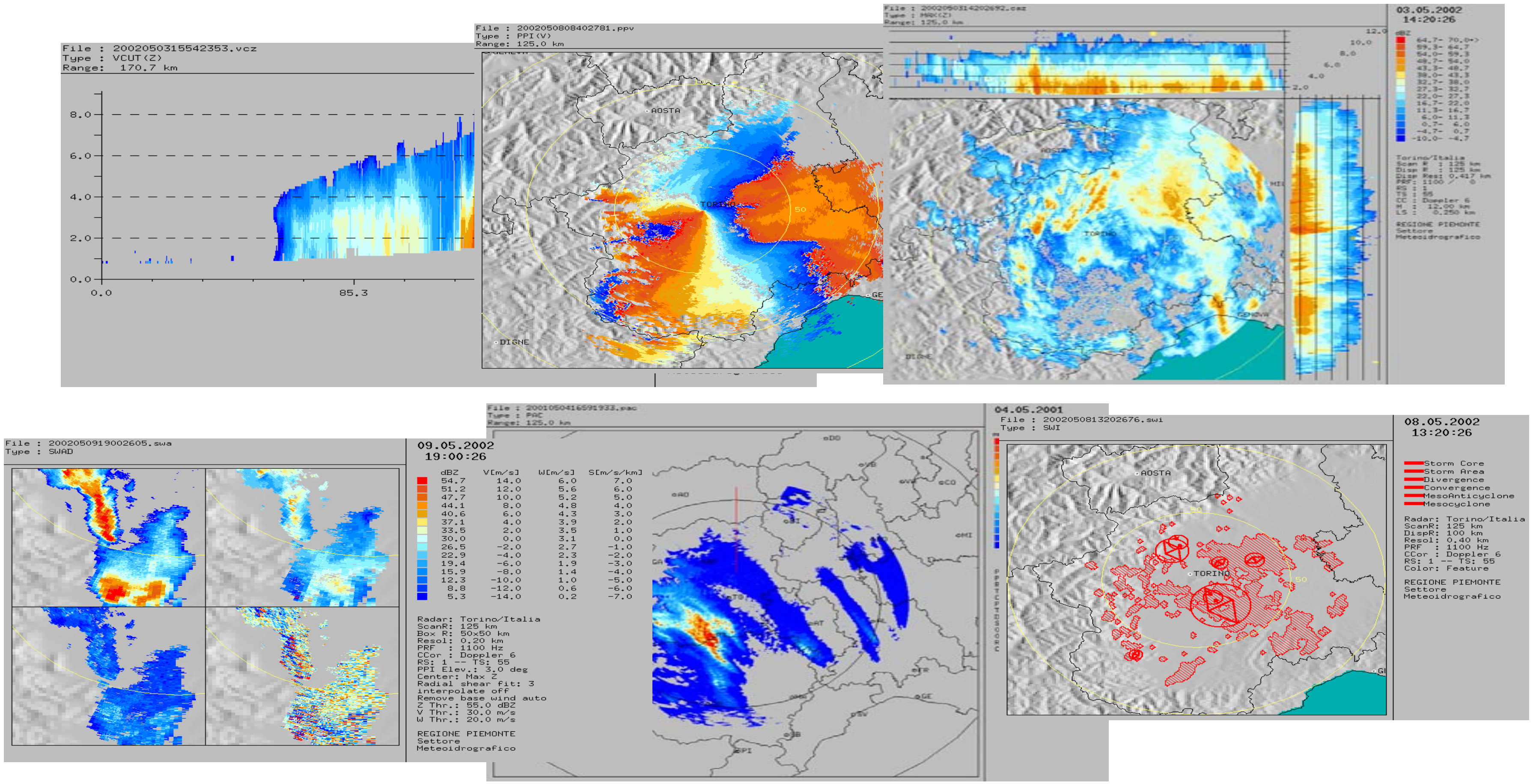
Calibration techniques

- Internal calibration: measurement of each radar component and module
    - Suitable instrumentation (e.g., synthetic pulse generator, network analyzer)
    - Periodic controls (antenna, TX) vs. frequent controls (oscillators, noise)
- External calibration: measurement of reference radar targets
    - Large metallic spheres such that σ_b is equal to the geometric section
    - Rain-gauge time-series data
    - Difficult measurement set up and ambiguities
- Overall calibration obtainable: ≥1 dB

Ground-clutter contamination

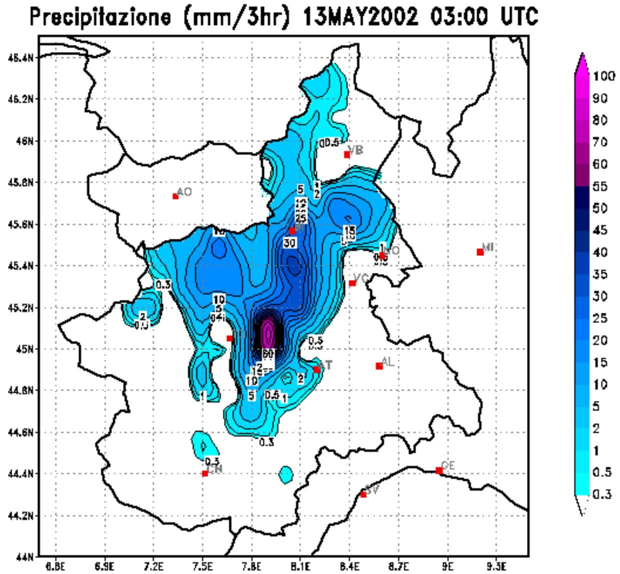
- Spurious echoes backscattered by ground and obstacles
- Spectral, statistical and static removal techniques
- Coupling with beam occulation, anomalous propagation, reflectivity gradients

RADAR PRODUCTS
An overview

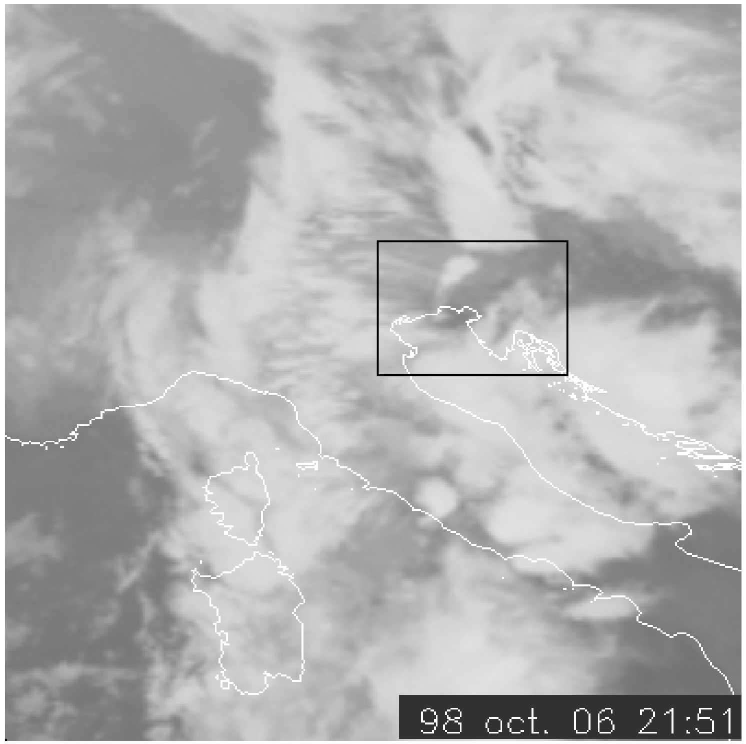


RADAR PRODUCTS
Comparison among instruments

Rain gauges

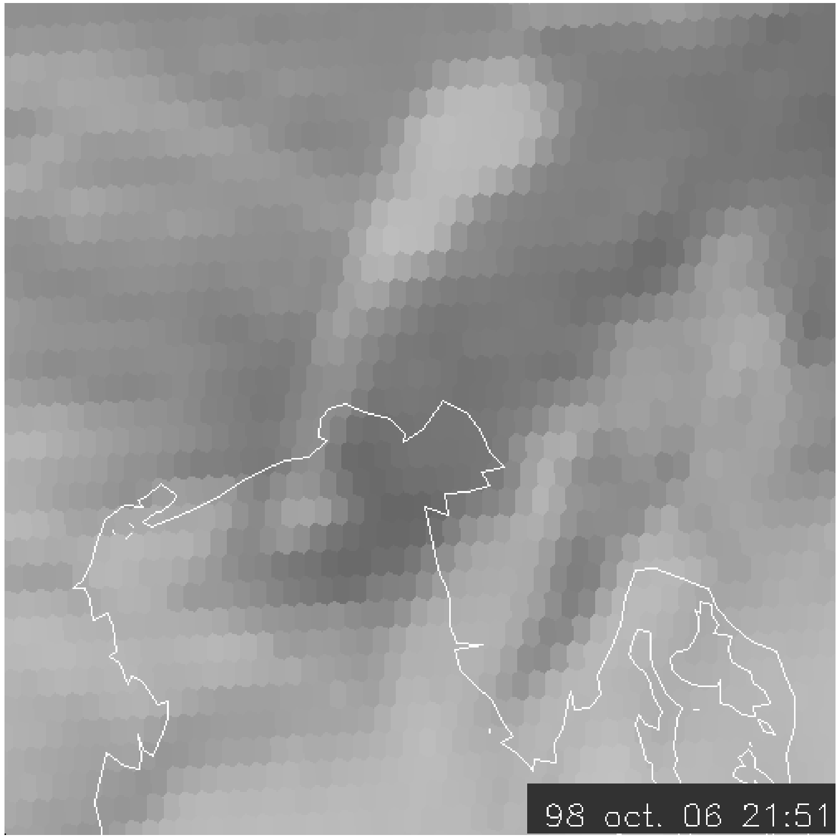


Meteosat IR

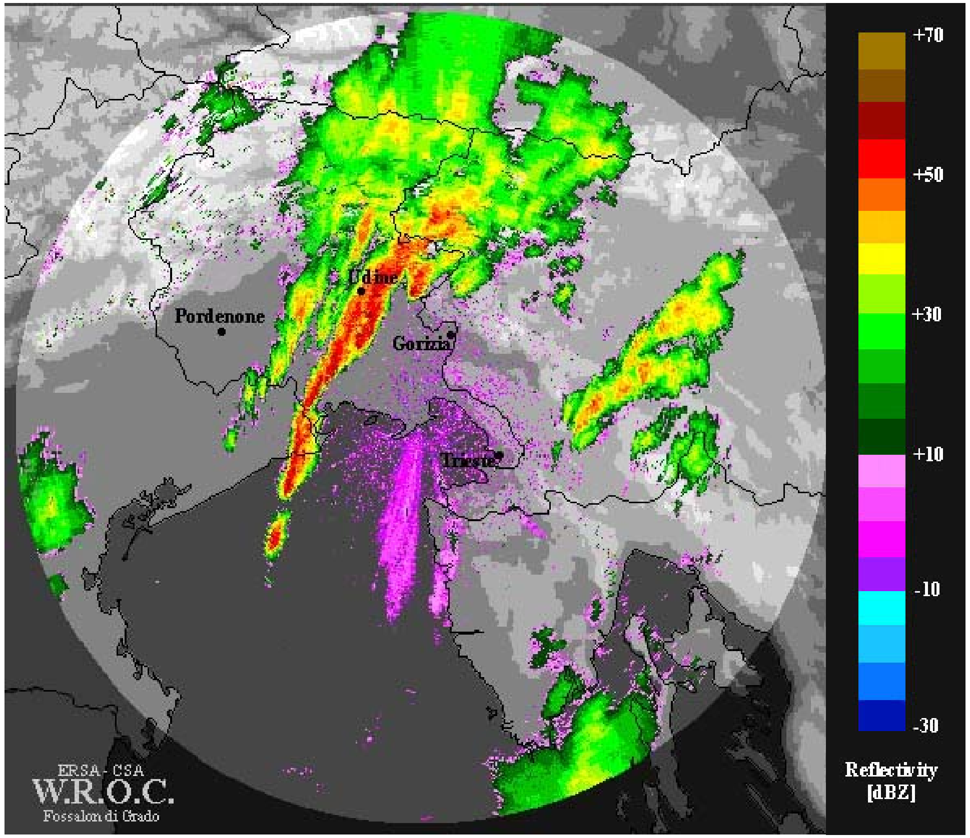


RADAR PRODUCTS
Comparison among instruments

Meteosat IR

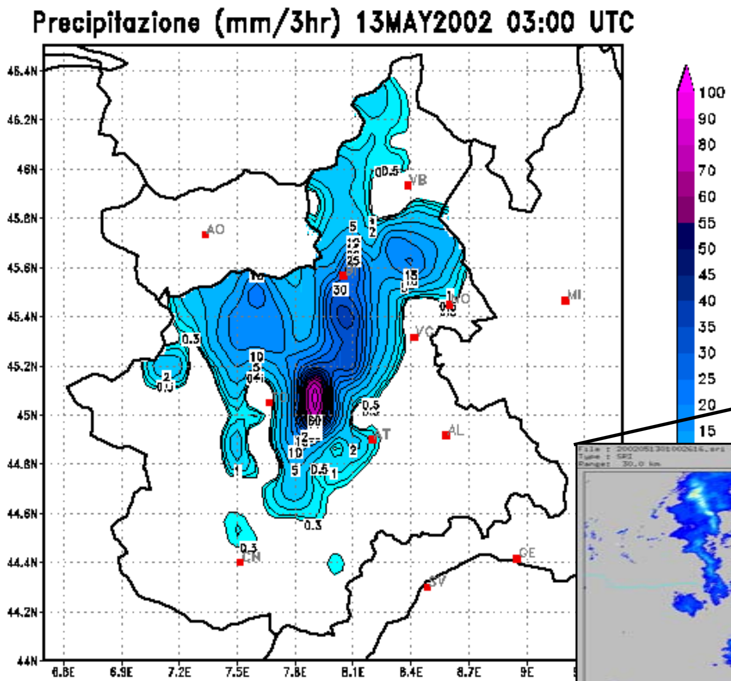


C-band Radar (ARPA-FVG)

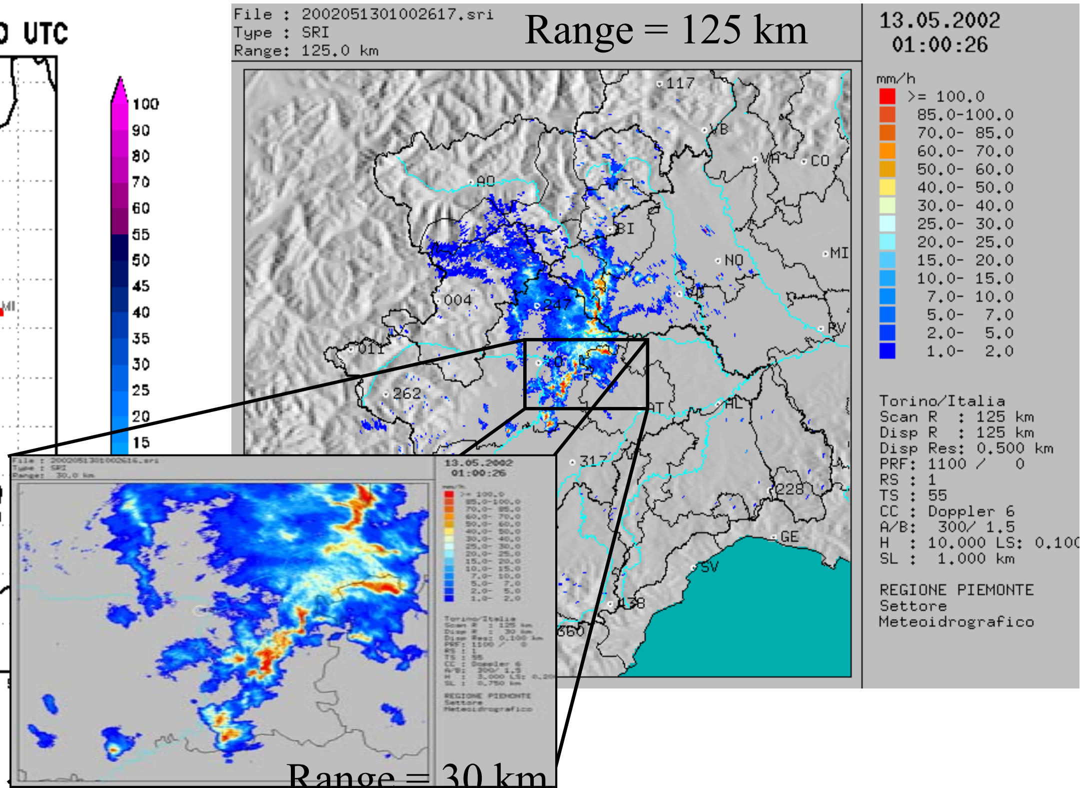


RADAR PRODUCTS
Comparison among instruments

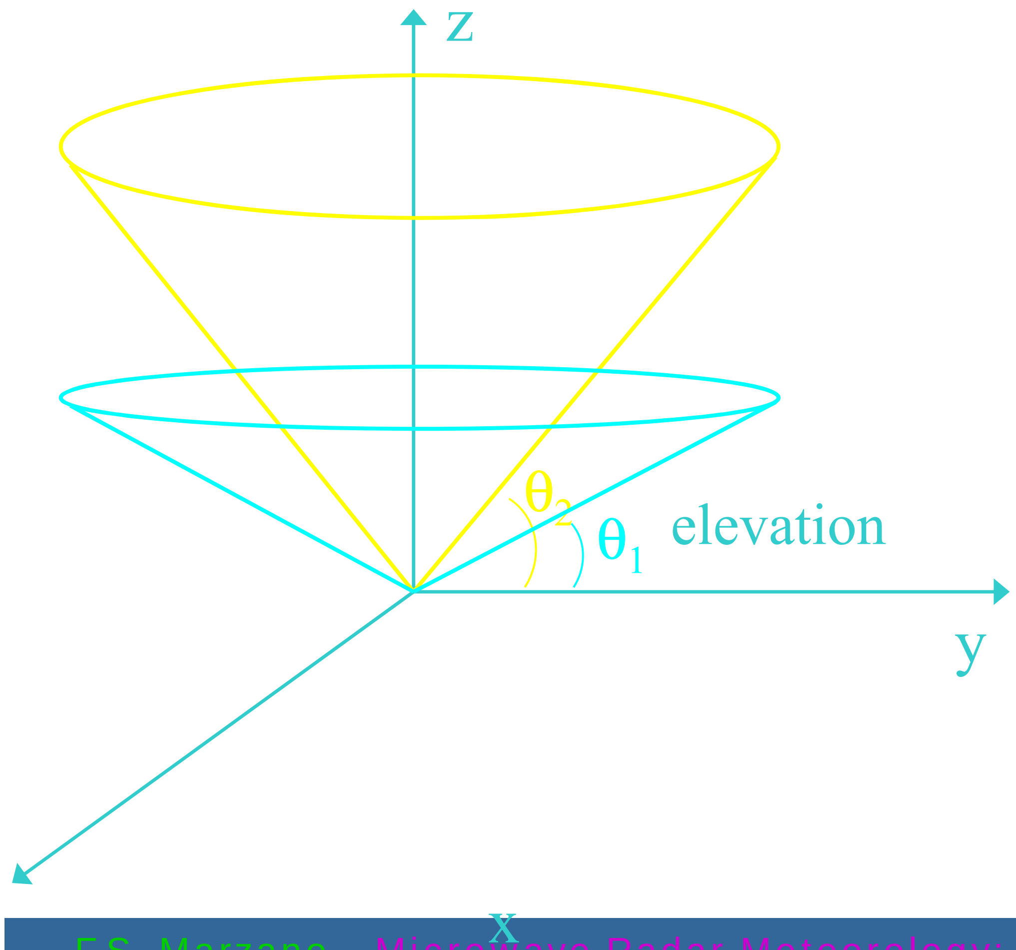
Rain field spatially interpolated from rain gauges



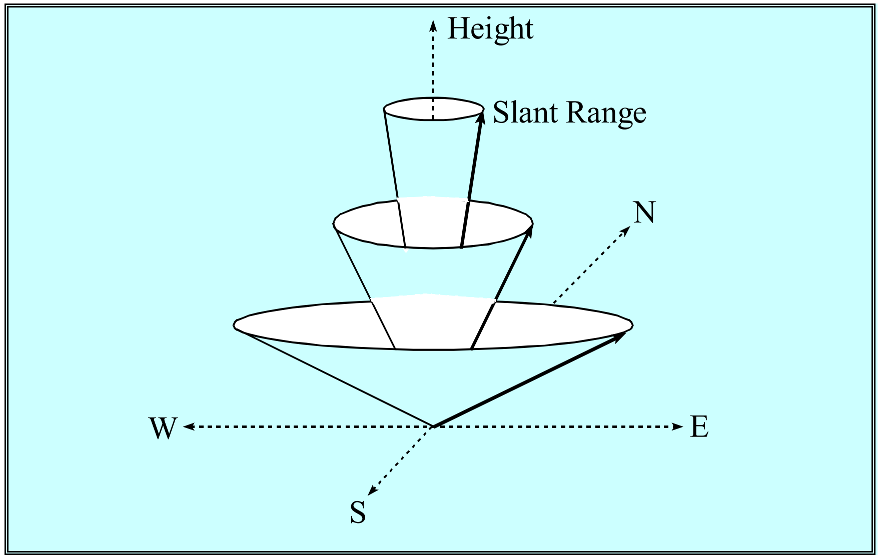
Rain field derived from ARPAP C-band radar



RADAR PRODUCTS
Polar volume scanning

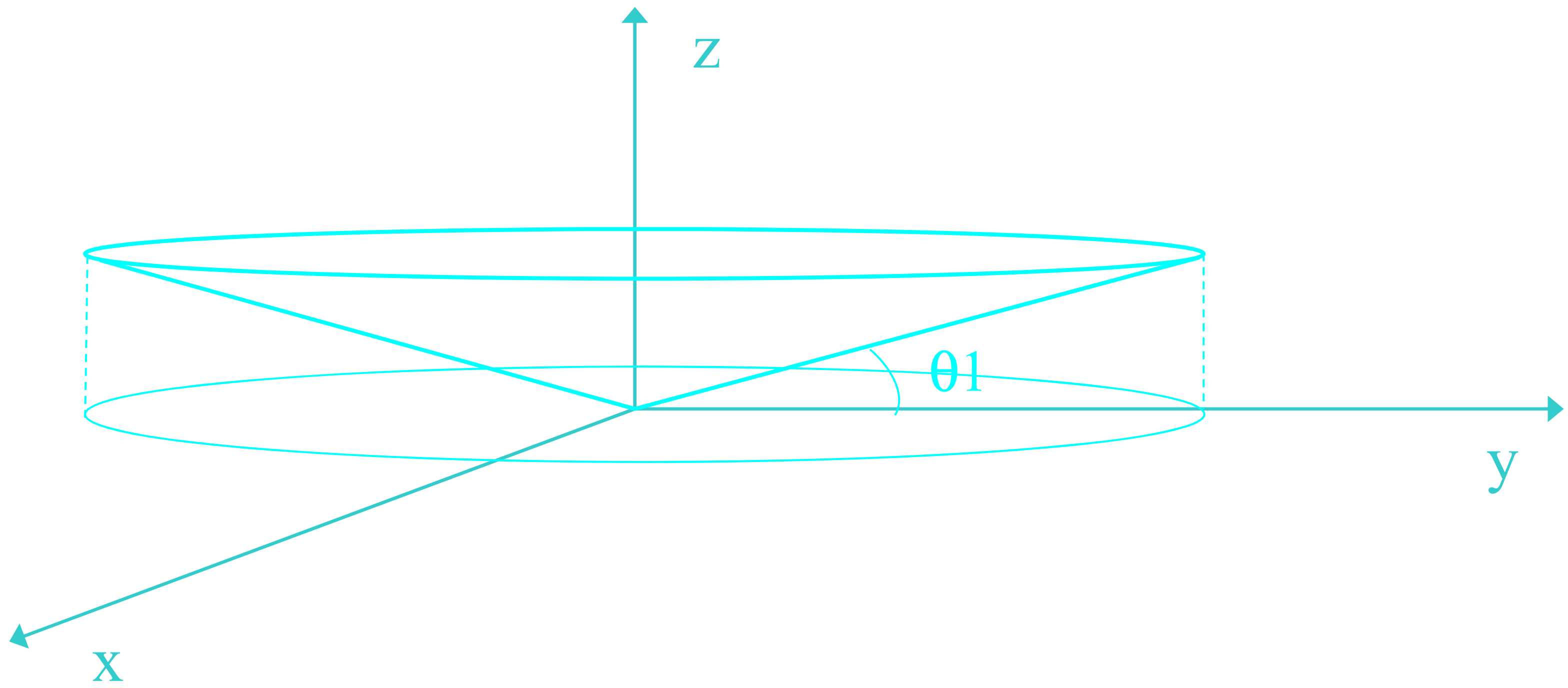


SCANNING STRATEGY
Elevation angle θ: 0-20 with variable step
Azimuth angle φ: 0-360° with 1° step



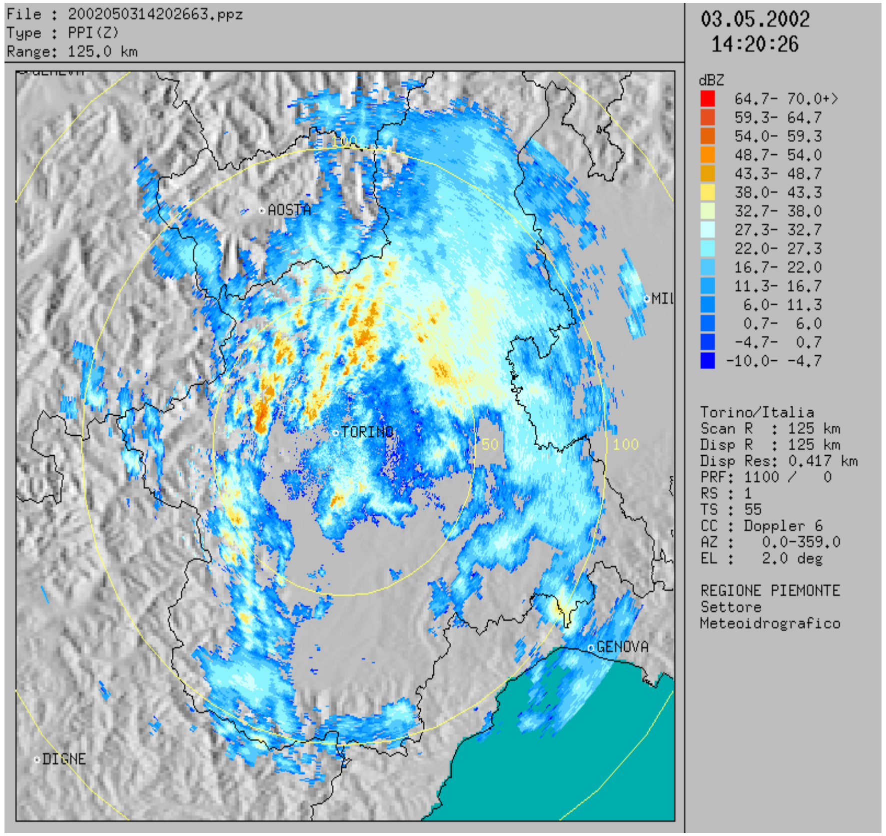
RADAR PRODUCTS
Plan Position Indicator (PPI)

Projection on the ground plane of radar 3-D polar data acquired upon a conical surface (constant elevation, azimuth betwen 0° and 360°)

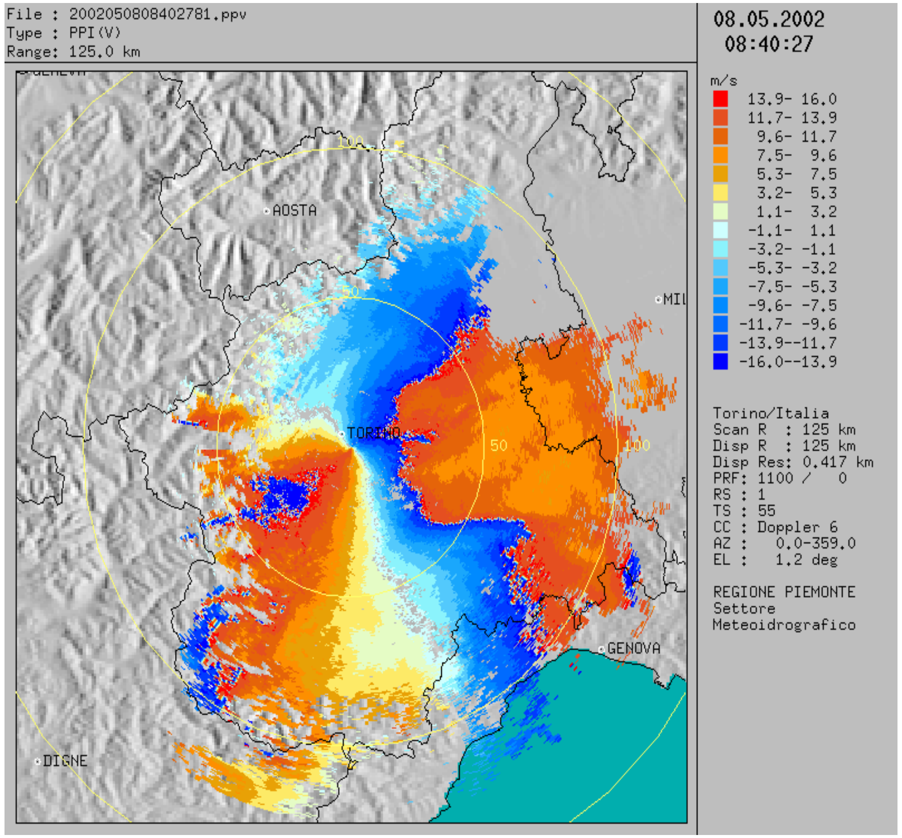


RADAR PRODUCTS
Example of PPI

H-pol. Reflectivity at 2° elevation



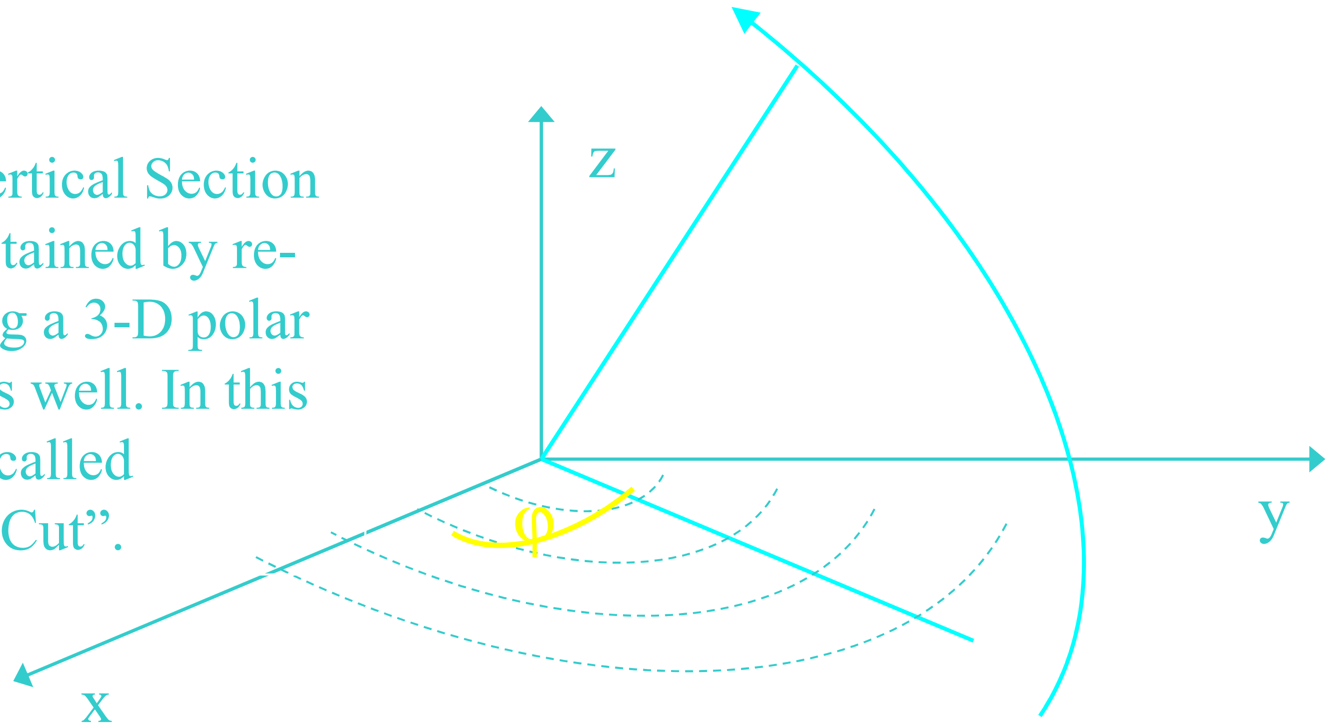
Radial velocity at 2° elevation



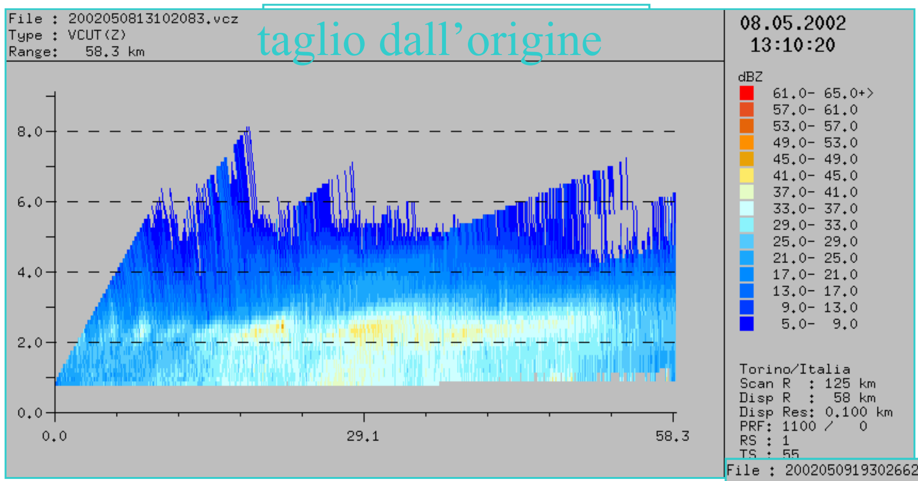
RADAR PRODUCTS
Range Height Indicator (RHI)

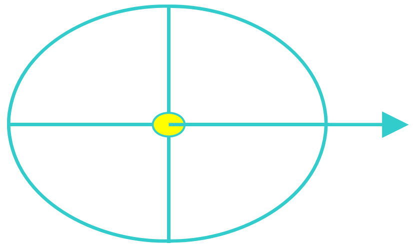
RHI: Vertical scan for constant azimuth angle φ

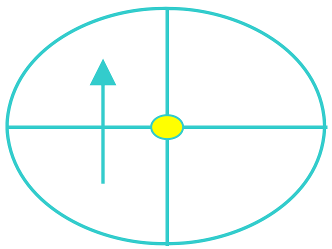
N.B. A vertical Section can be obtained by re-processing a 3-D polar volume as well. In this case it is called "Vertical Cut".

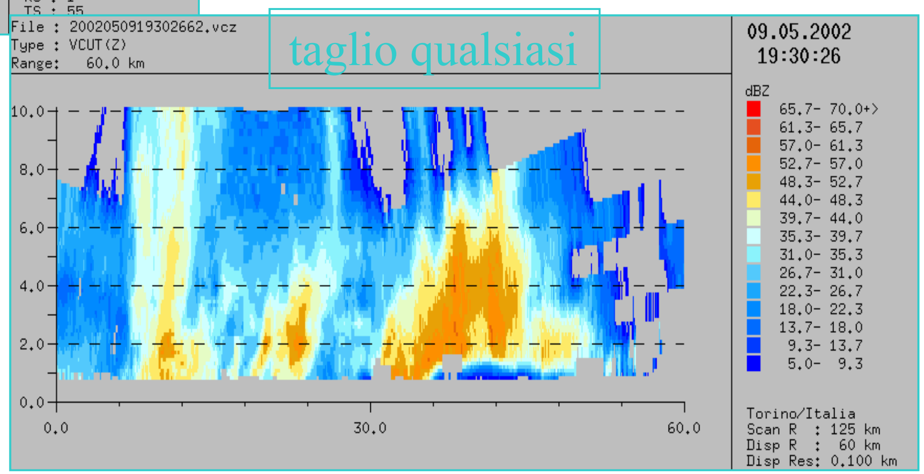


RADAR PRODUCTS
Example of RHI and VCut



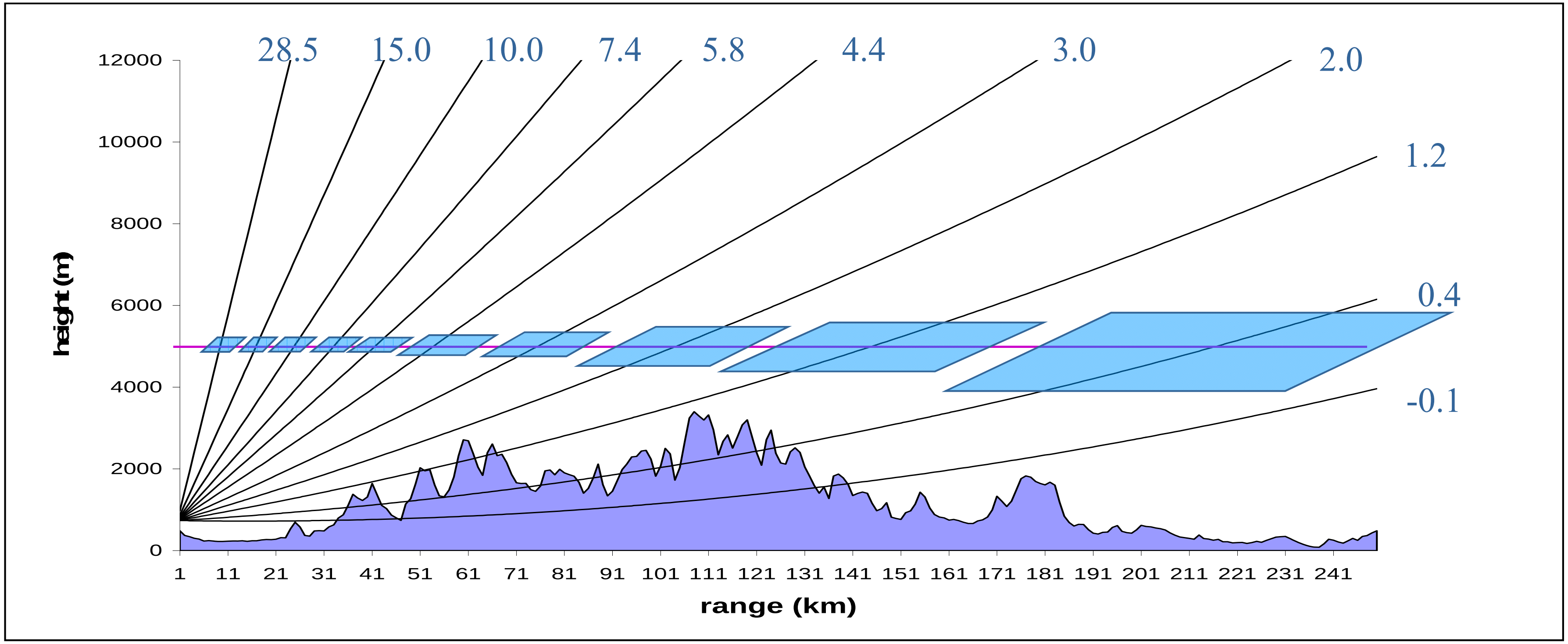




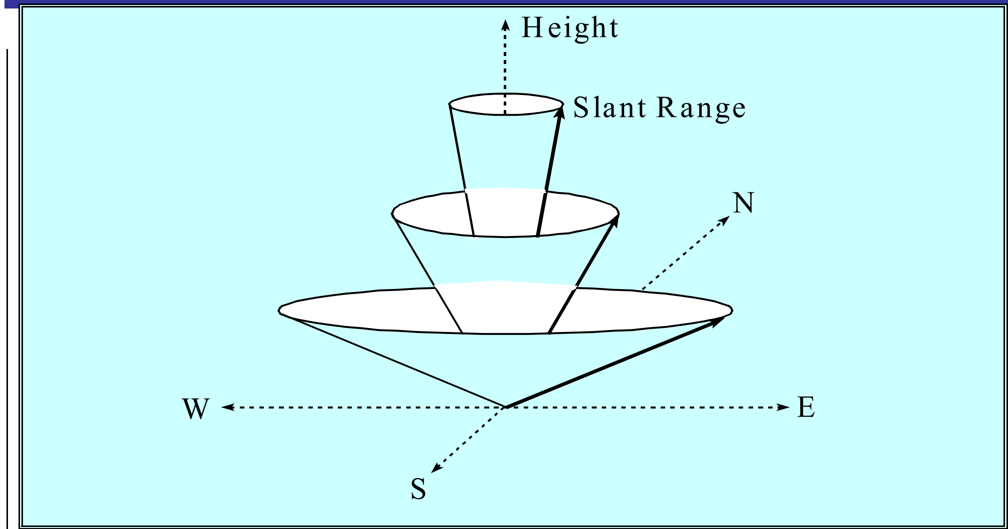


RADAR PRODUCTS
Constant Altitude PPI

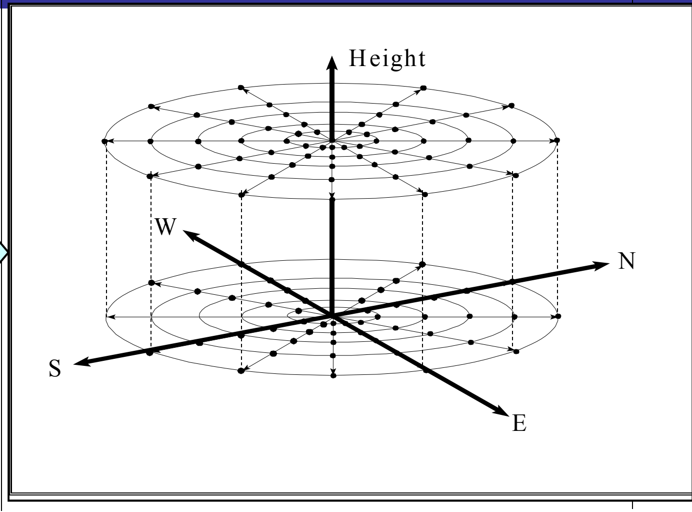
CAPPI: Horizontal cut of polar volume at a constant altitude

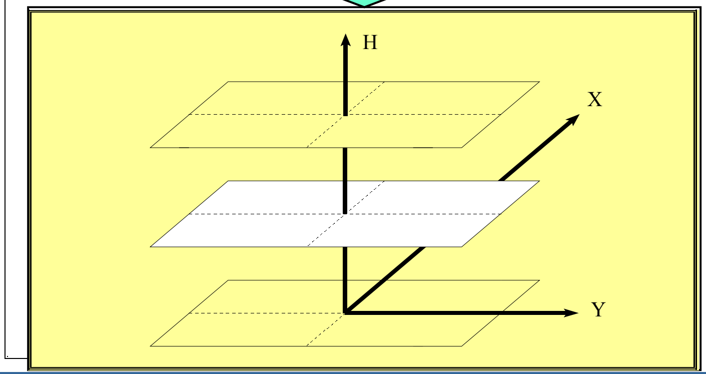


RADAR PRODUCTS
CAPPI processing



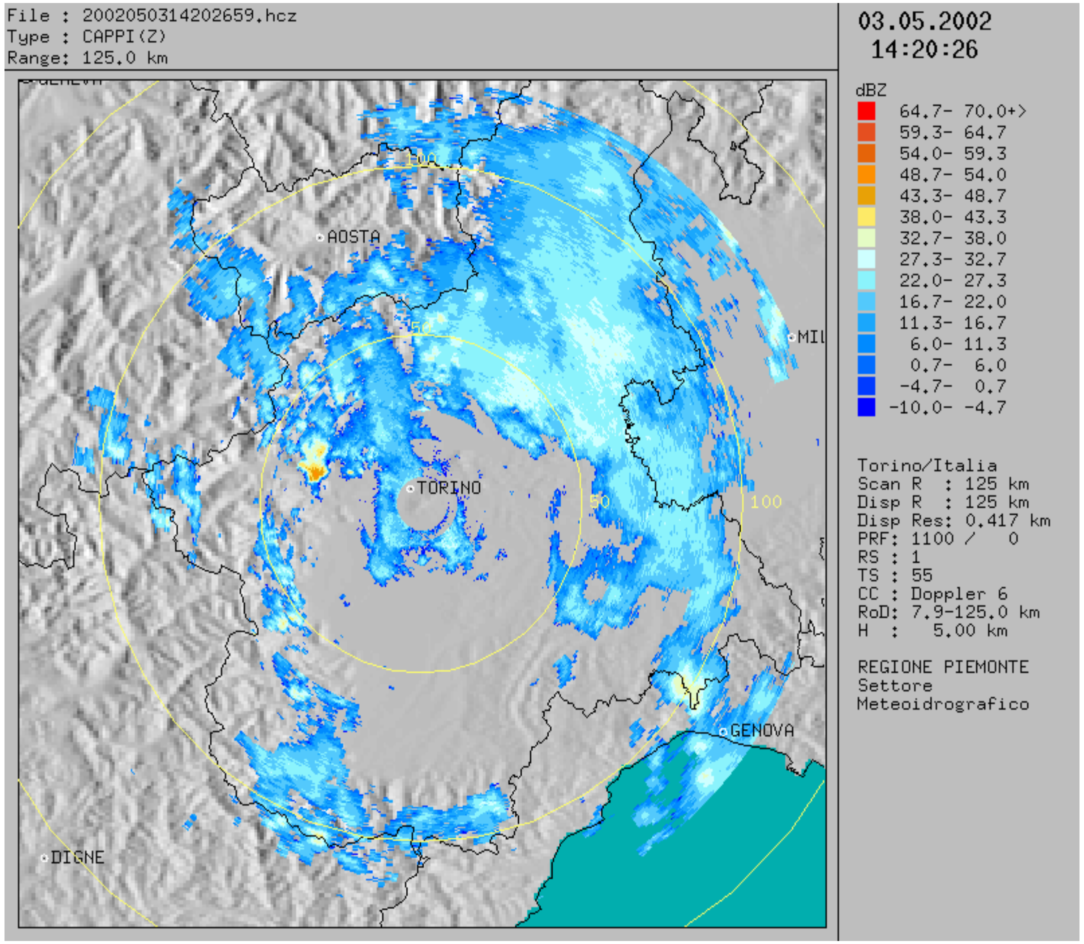
Volume polare





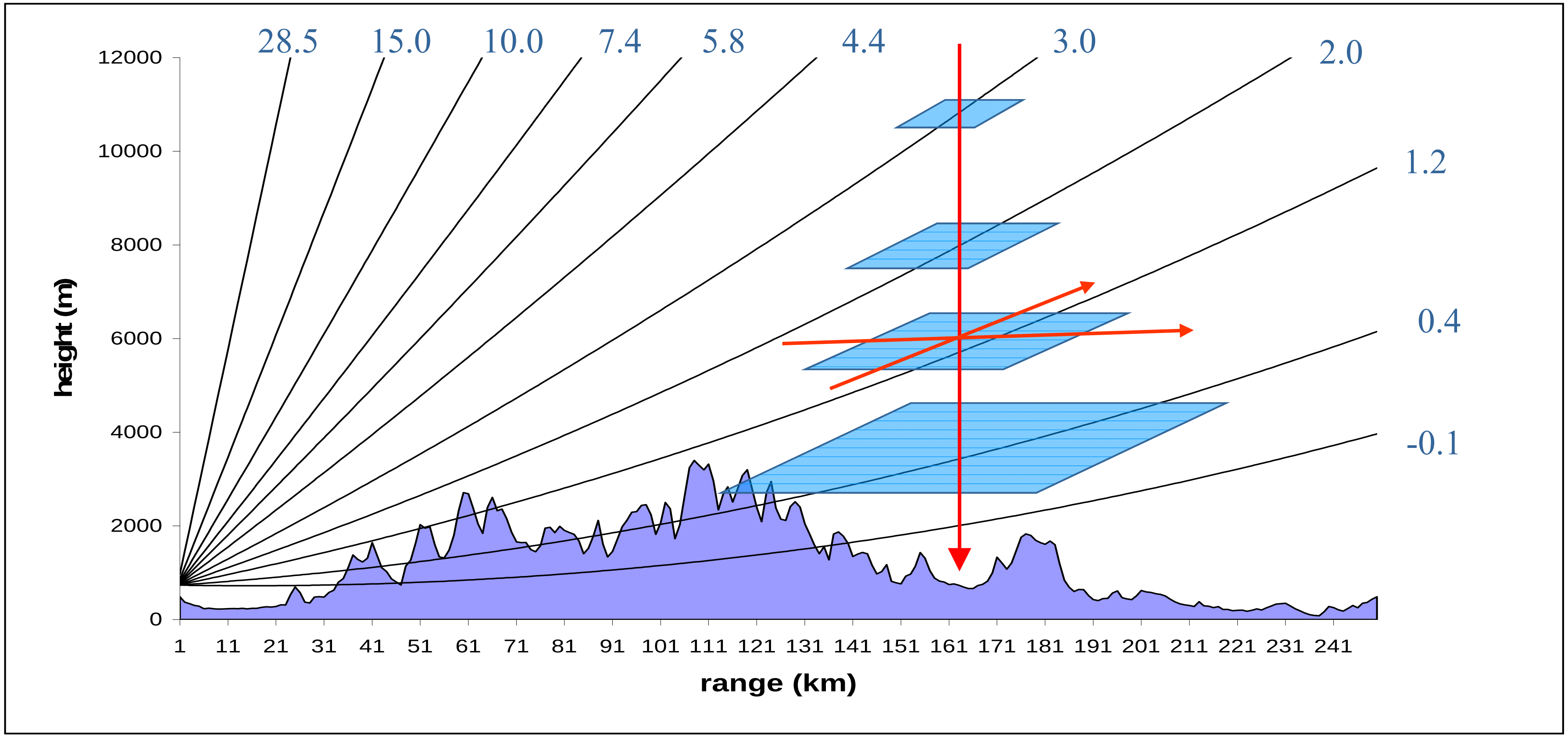
Volume cartesiano

RADAR PRODUCTS
Example of CAPPI

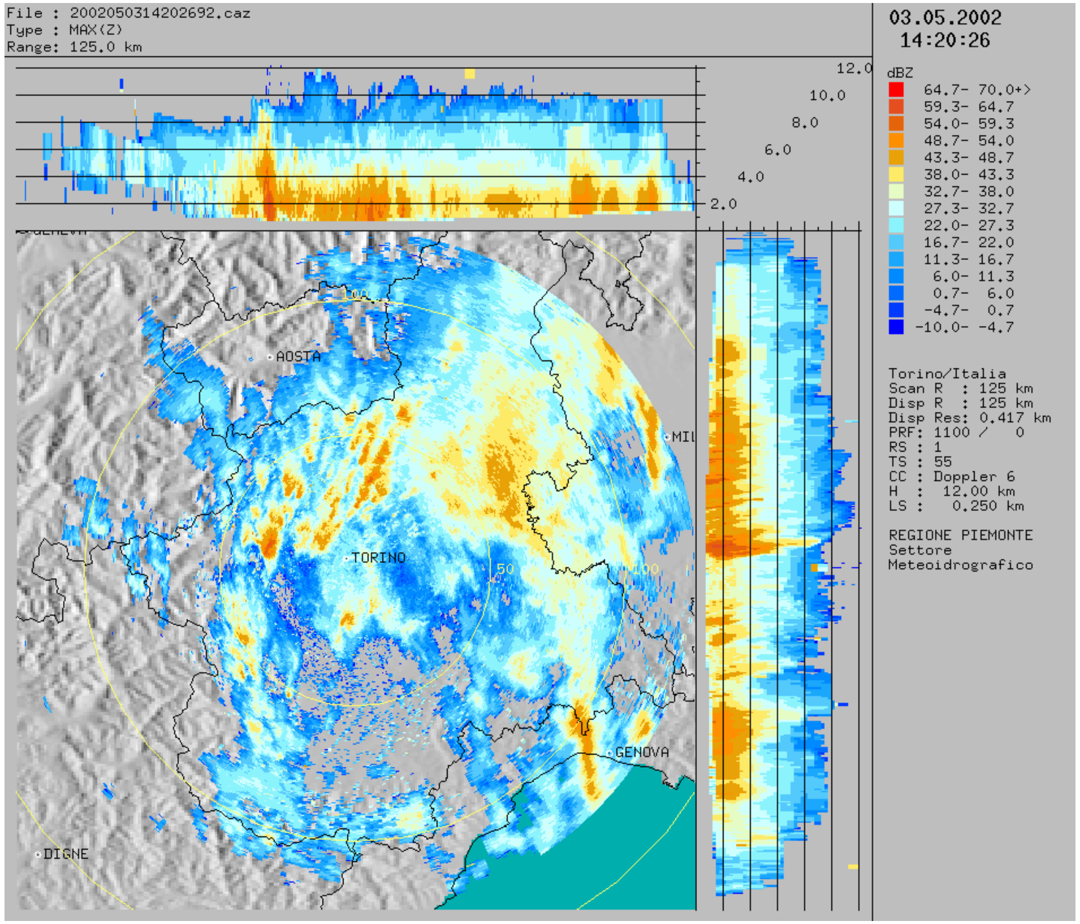


RADAR PRODUCTS
Hor.-Vertical Maximu Intensity

HVMI: Horizontal-vertical projection (3 axes) of maximum reflectivity

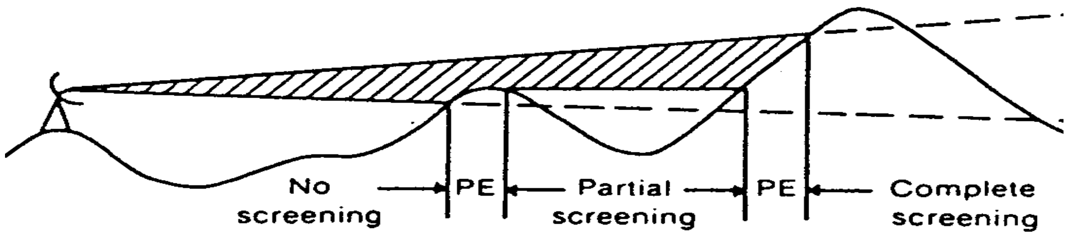


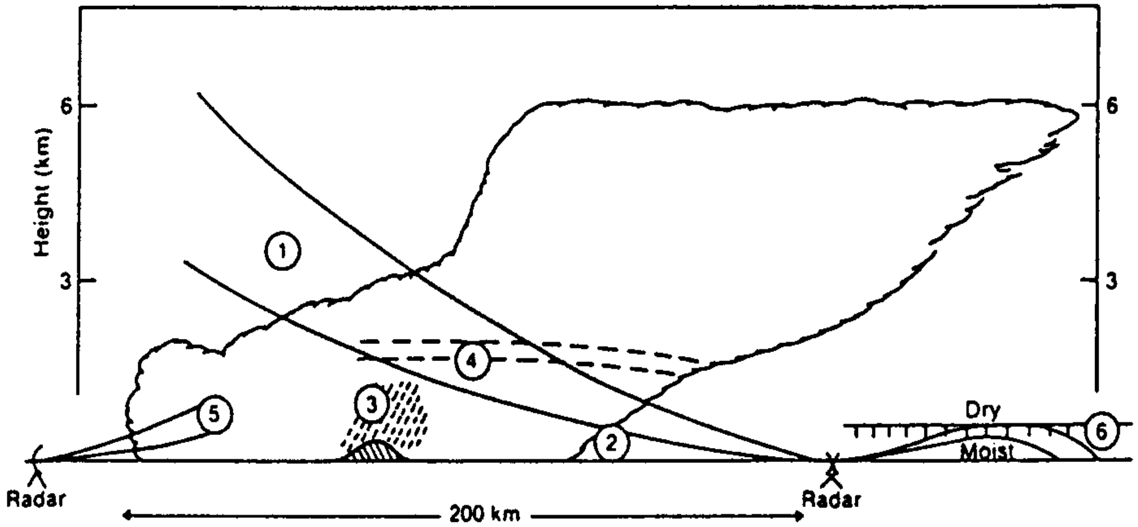
RADAR PRODUCTS
Example of VMI



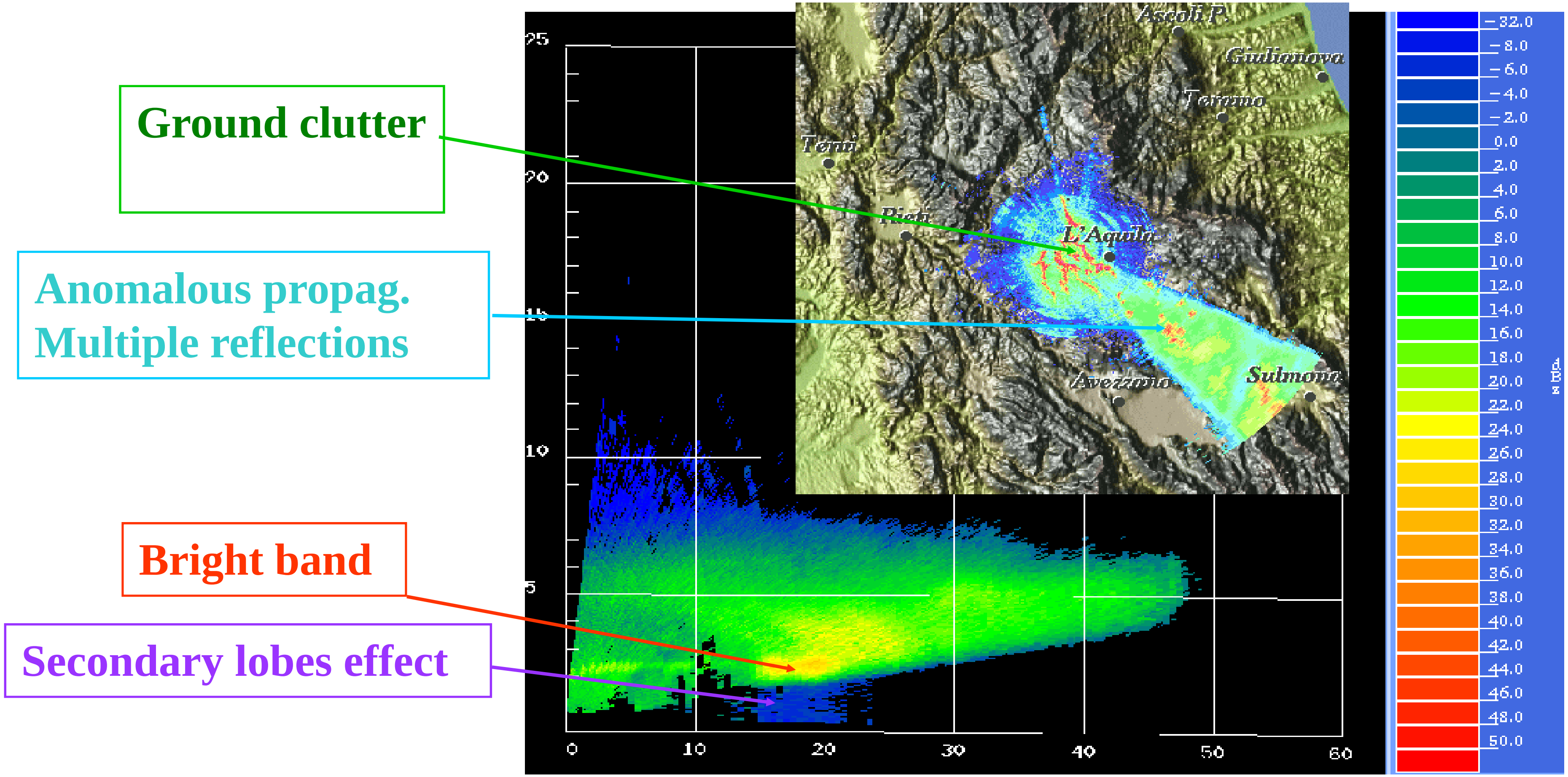
RADAR PRODUCTS
Errors in rainfall retrieval

1. Inhomogenheity of rain cloud within the radar beam
2. Evaporation of rainfall below the radar beam
3. Understimation due to orographic effects on rainfall process
4. Bright-band effects due to melting layer
5. Path attenuation due clear-air gases (water vapor and oxygen) and rain
6. Anamolous propagation due to air refractivity – second-trip echoes
7. Beam screening due to presence of obastacles (hills, mountains)
8. Calibration erros within the radar system

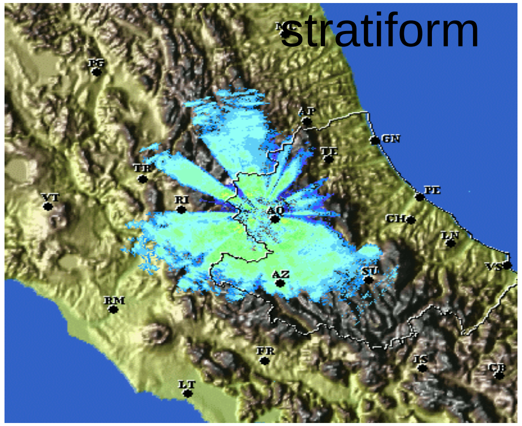


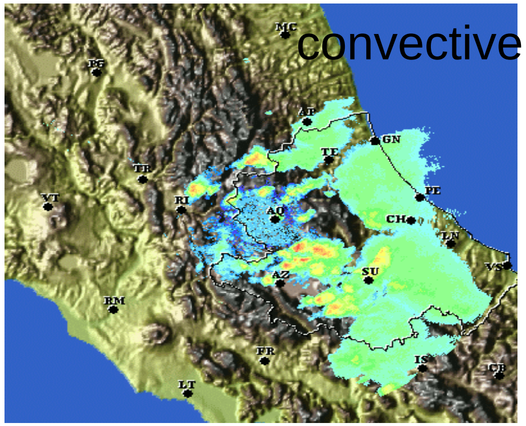


RADAR PRODUCTS
Examples of radar artifacts (1)

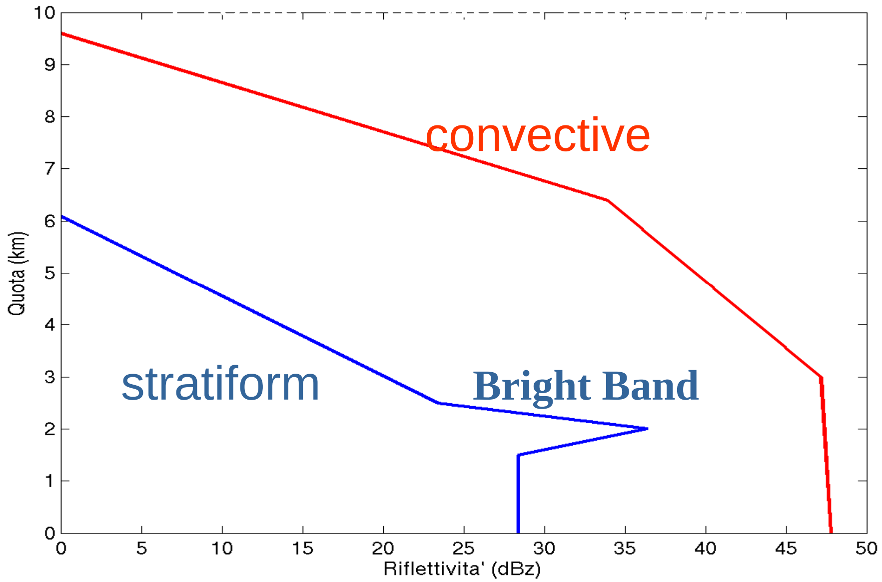


RADAR PRODUCTS
Examples of radar artifacts (2)



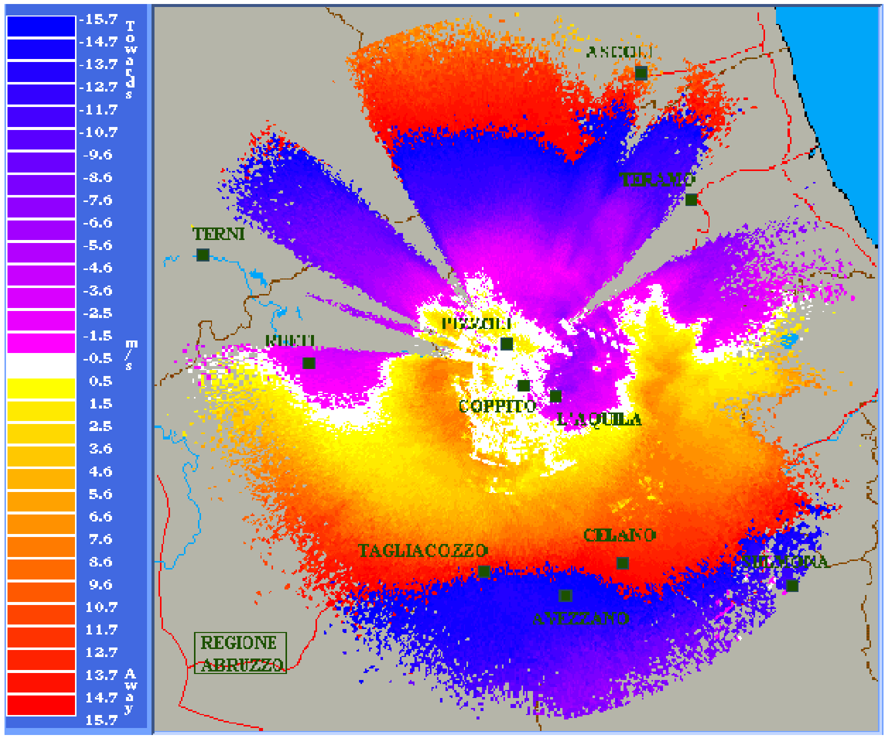


Estimate of surface rainfall from stratiform or convective Z-R relation ?

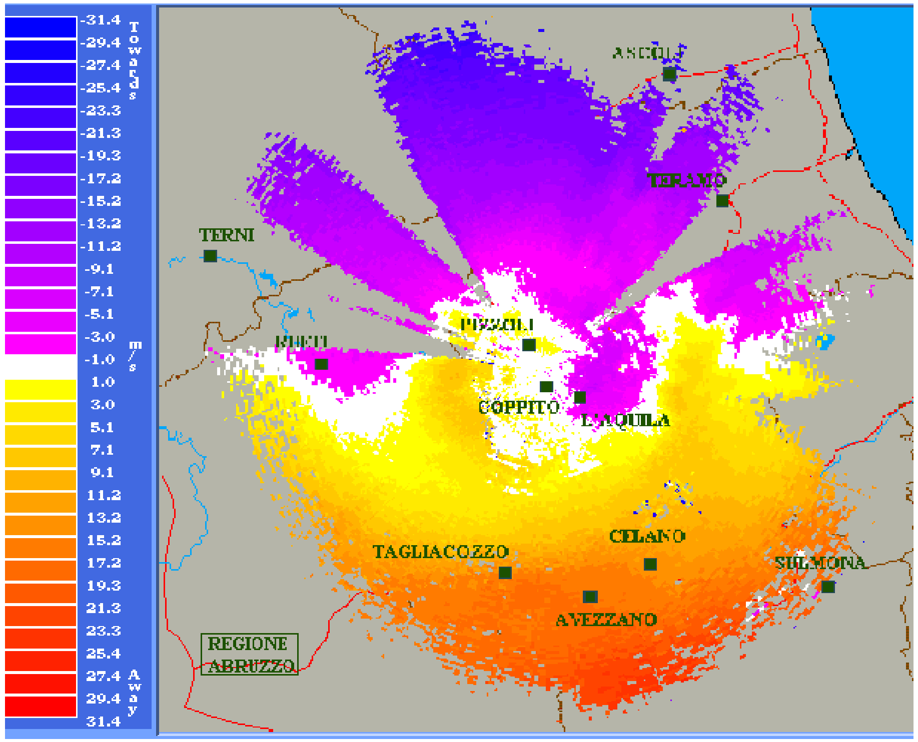


RADAR PRODUCTS
Examples of radar artifacts (3)

Max. unamb. velocoty: $u_{max} = \pm 16$m/s
Mode: single PRF=1180 Hz

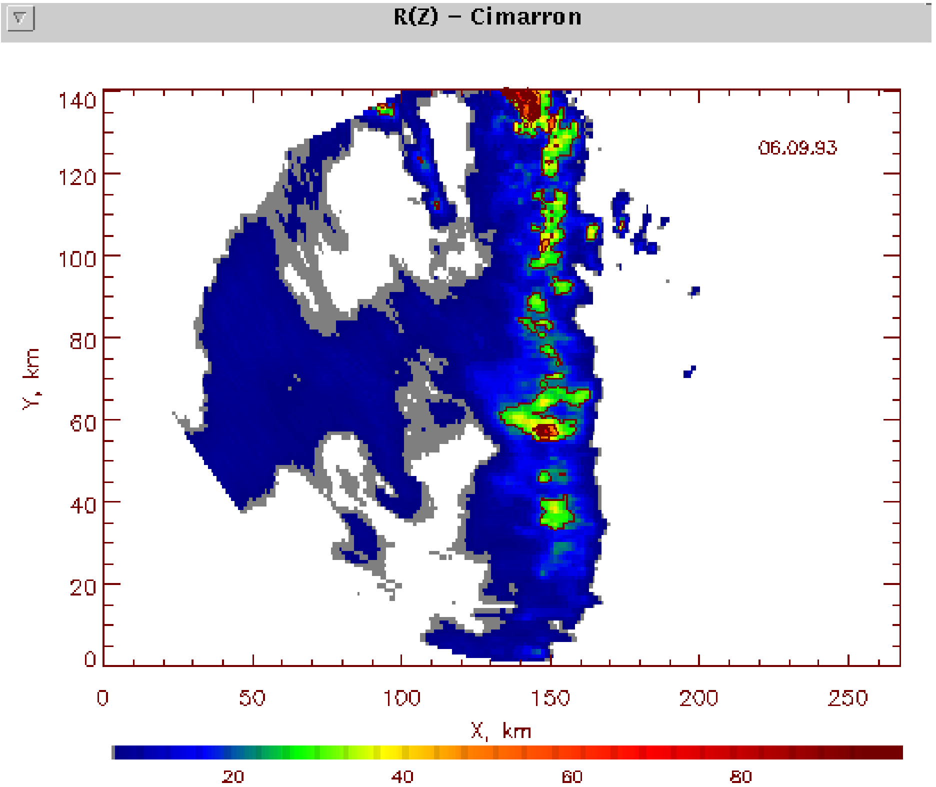


Max. unamb. velocoty: $u_{max} = \pm 32$m/s
Mode: dual PRF=1180 Hz, 787 Hz

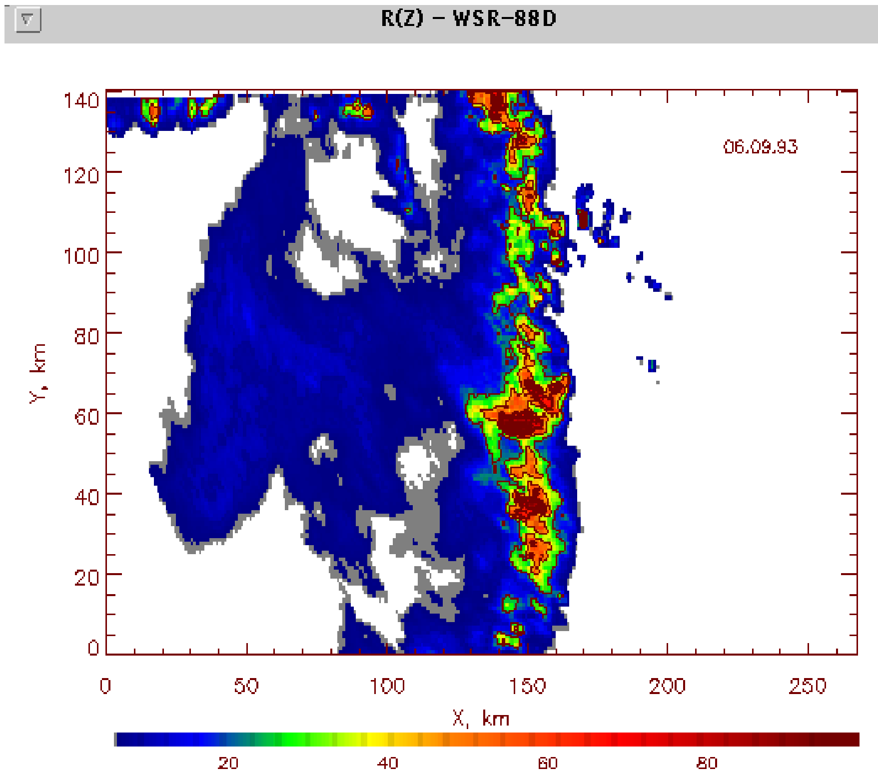


RADAR PRODUCTS
Examples of radar artifacts (4)

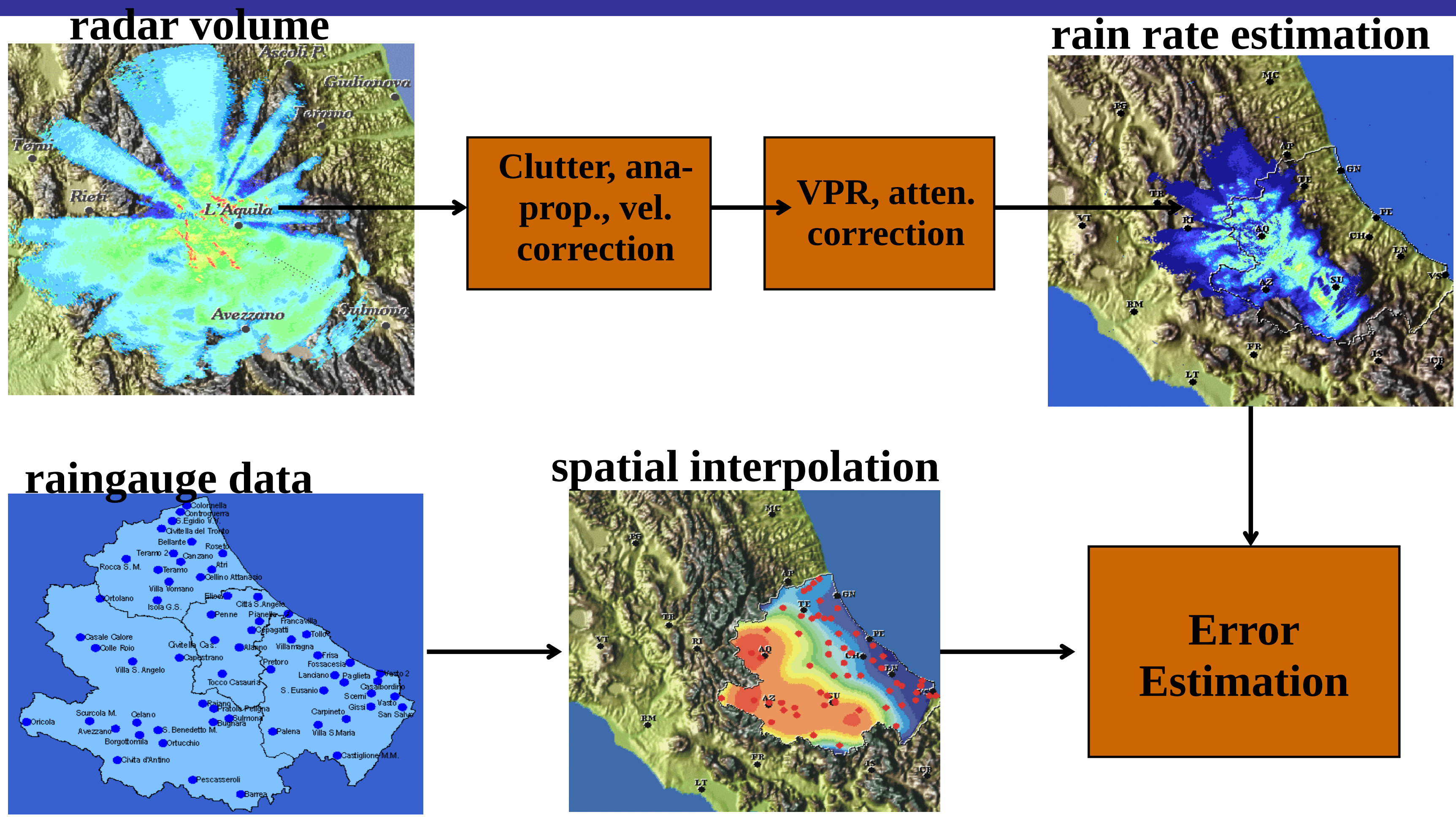
C-band radar: affected by rain path attenuation



S-band radar: immune to rain path attenuation



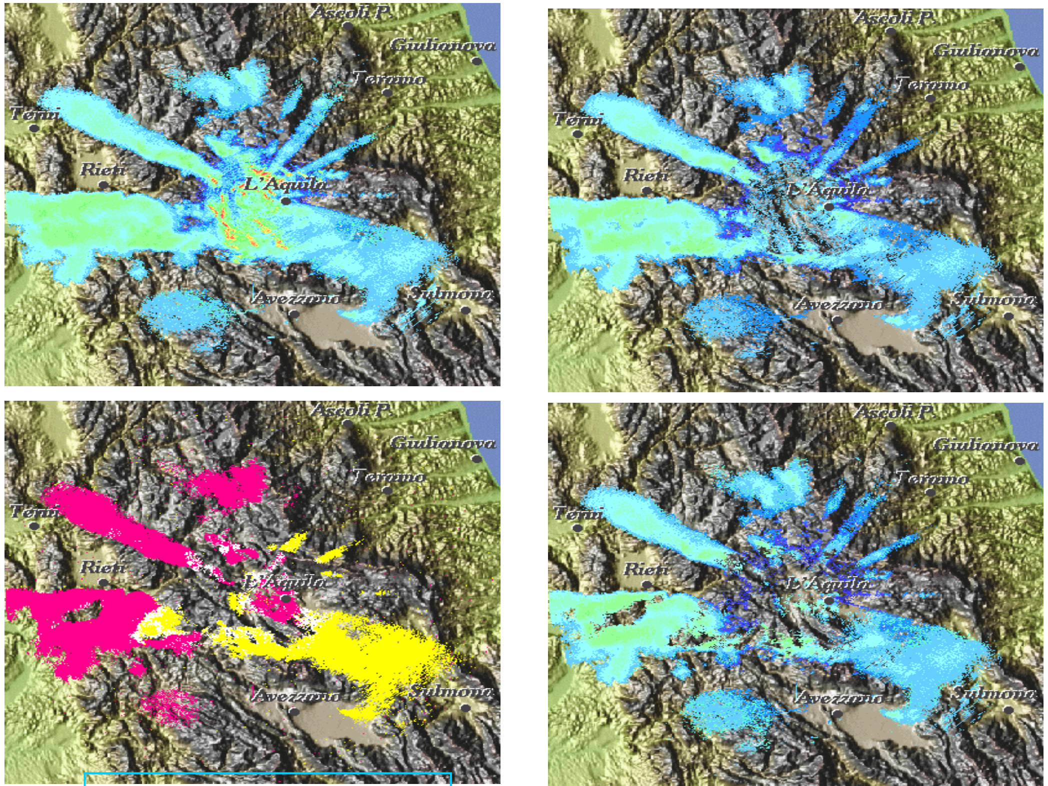
RADAR PRODUCTS
Radar data processing



RADAR PRODUCTS
Example of data processing

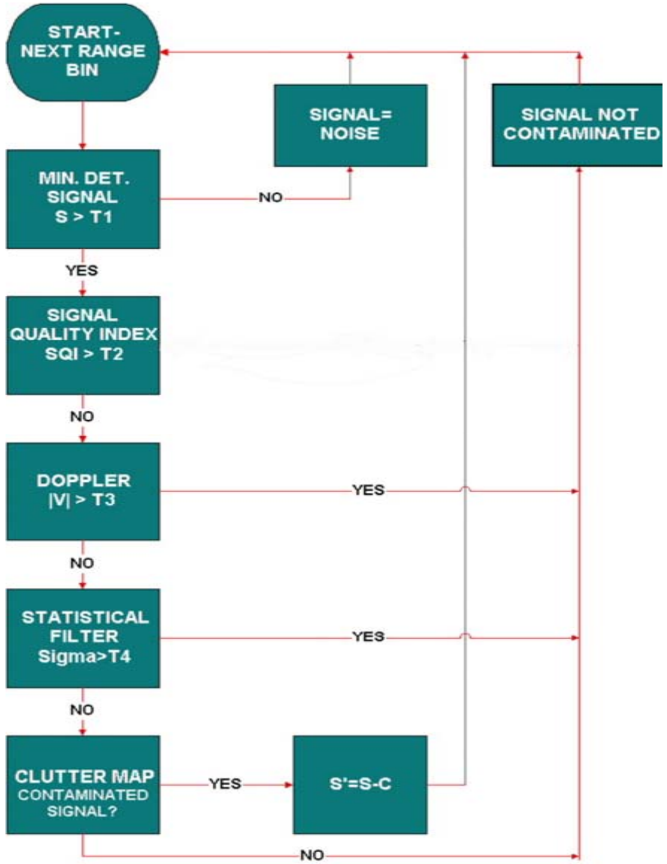
Z uncorrected

Z corrected

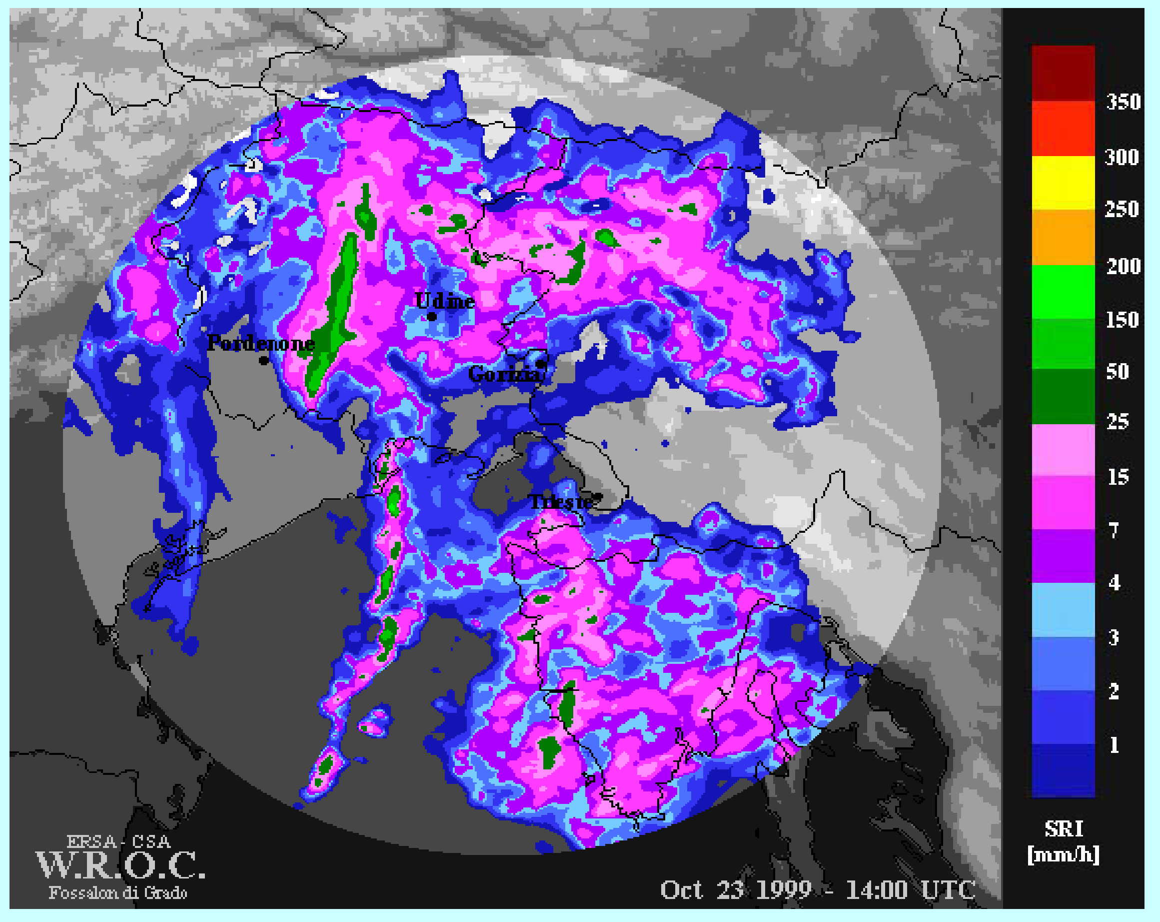


Radial velocity

Spectral filter

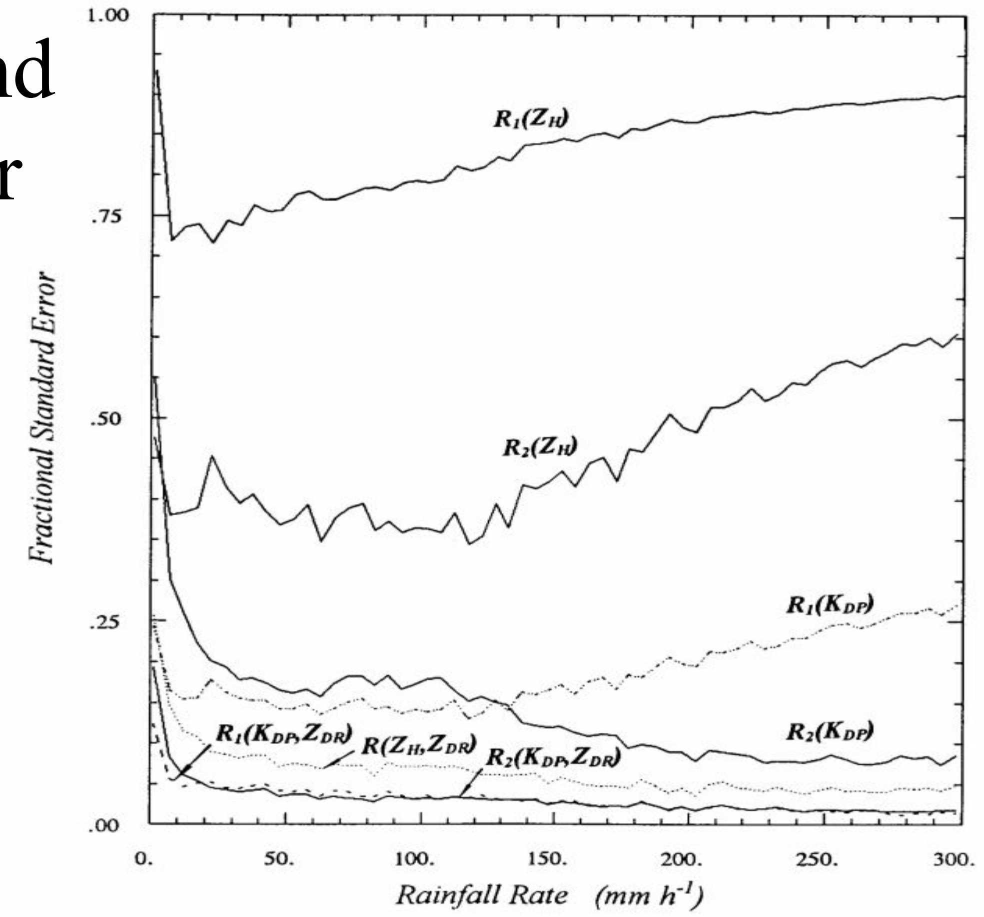


RADAR PRODUCTS
Surface rainfall C-band retrieval



RADAR PRODUCTS
Retrieval expected accuracy

S-band radar



Fractional Standard Error

$$FSE = \frac{\left\langle \left[\hat{R}_{est} - R_{sim}\right]^2 \right\rangle^{1/2}}{\left\langle R_{sim} \right\rangle}$$

Algorithms:

R_1=M-P

R_2=WSR-88D

R_{dp}= G. et al. (rob)

$R_1(K_{dp})$=S-Z

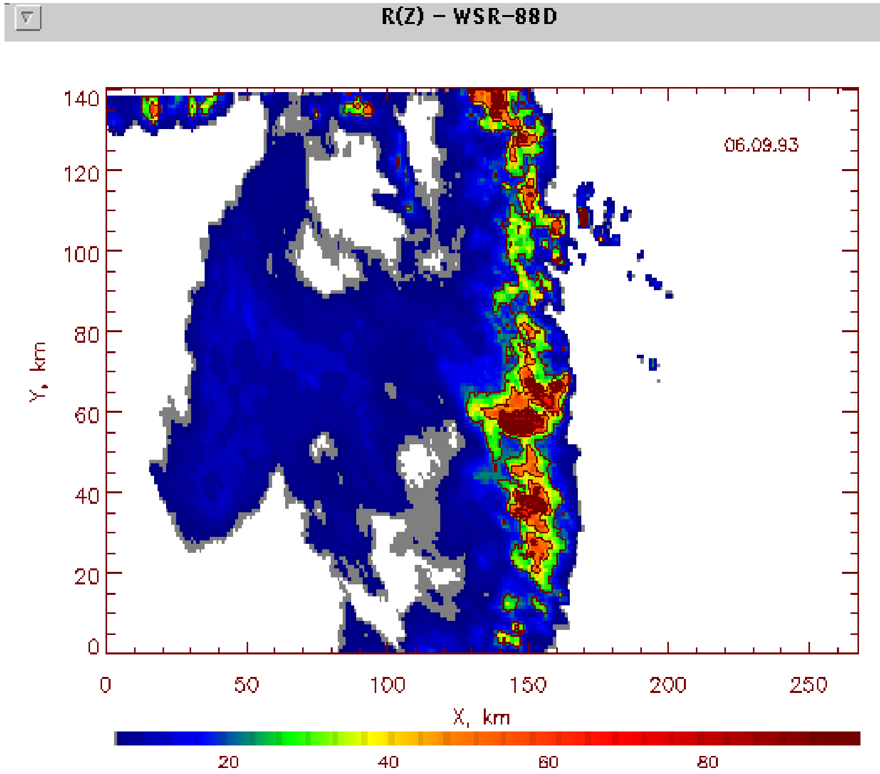
$R_2(K_{dp})$=G-S (lin)

R_{dp1}=G-S (rob)

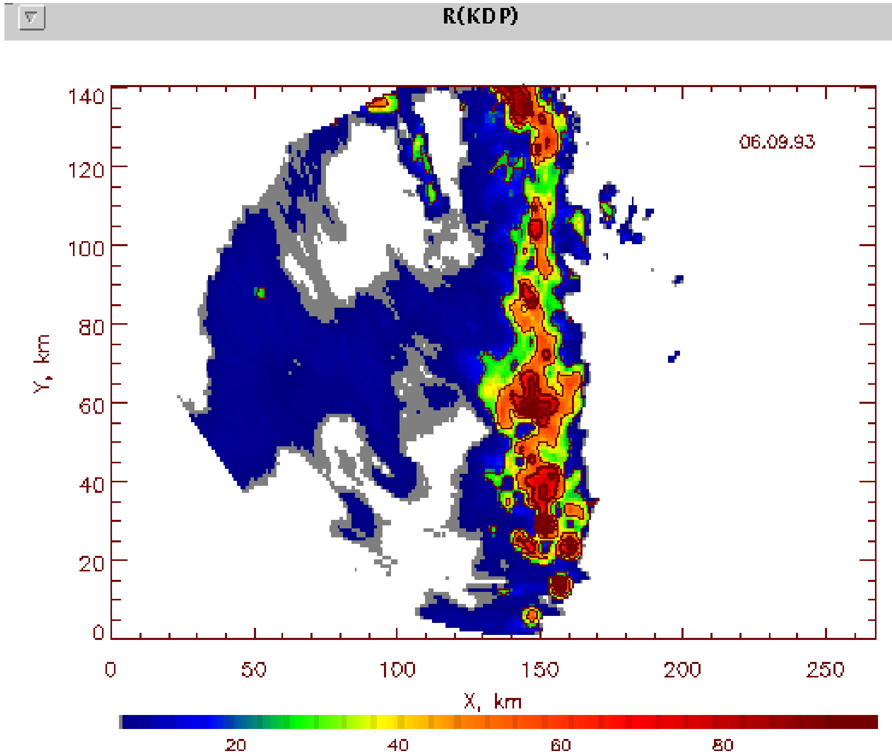
R_{dp2}=R-Z (log)

RADAR PRODUCTS
Path attenuation mitigation

S-band radar: immune to rain path attenuation

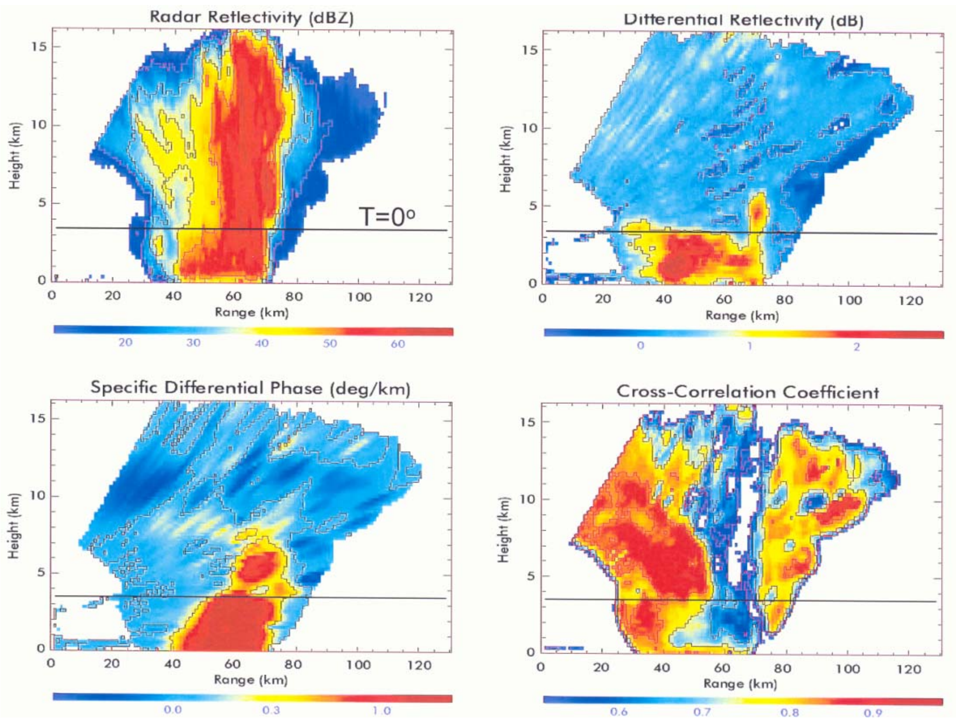


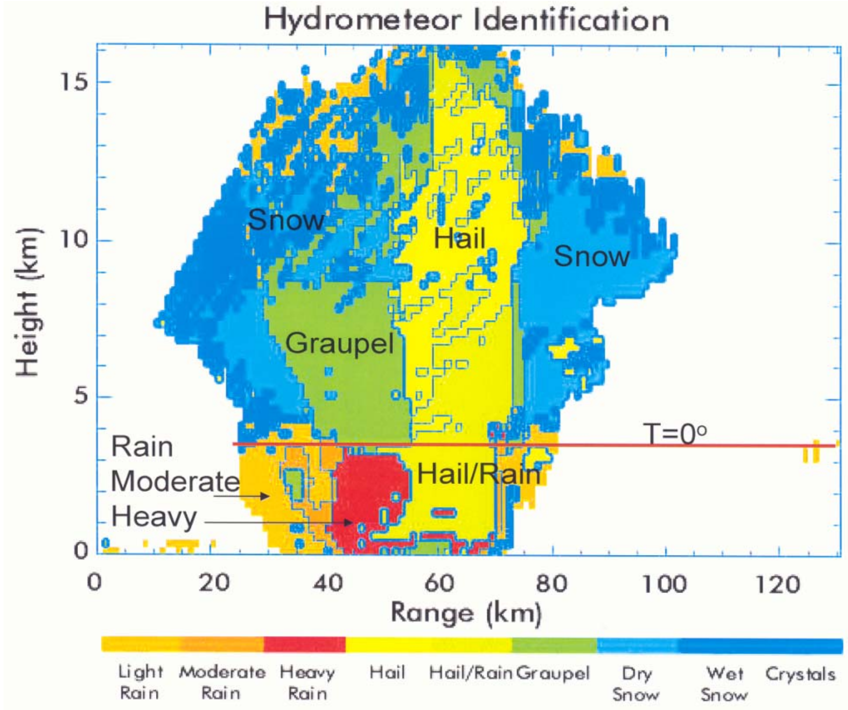
C-band radar: corrected for rain path attenuation using fully polarimetric data (Zh, Zdr, Kdp)



RADAR PRODUCTS
Hydrometeor classification

Hailstorm in Florida observed by S-band polarimetric radar





... and derived hydrometeor classification