ACTRIS CCRES

Introduction to Doppler Cloud Radar

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CCRES/CLU Training school, Munich, 2-5 Sept. 2025

Outline

Introduction

1. Radar principles & cloud radars
2. Radar equation (Power)
3. Doppler velocity (Phase)
4. From DSD to Moments
5. Doppler Spectra
6. Polarimetry

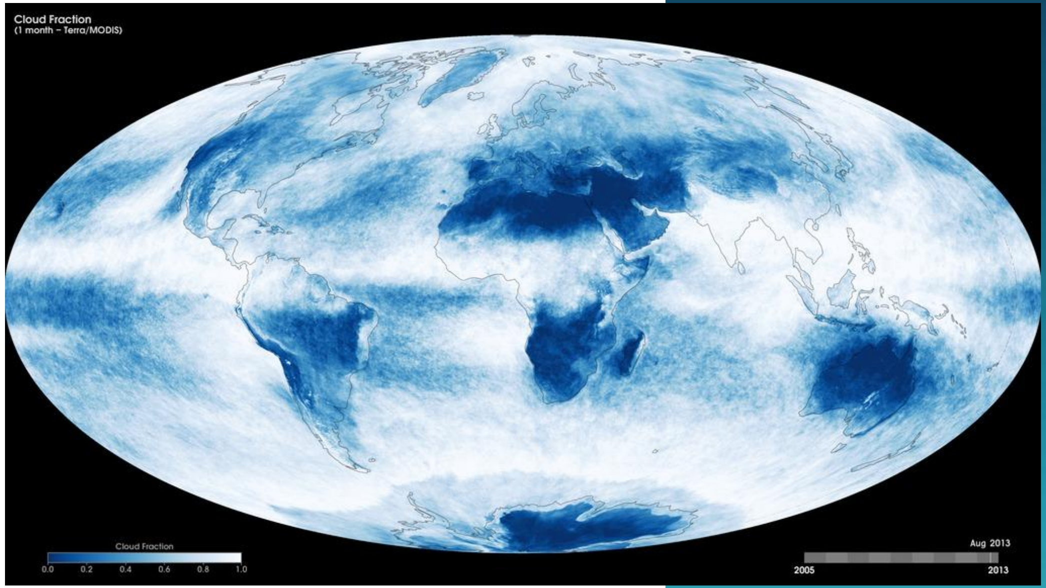
References

Introduction: why observe Clouds ?

Clouds: a key Climate regulator

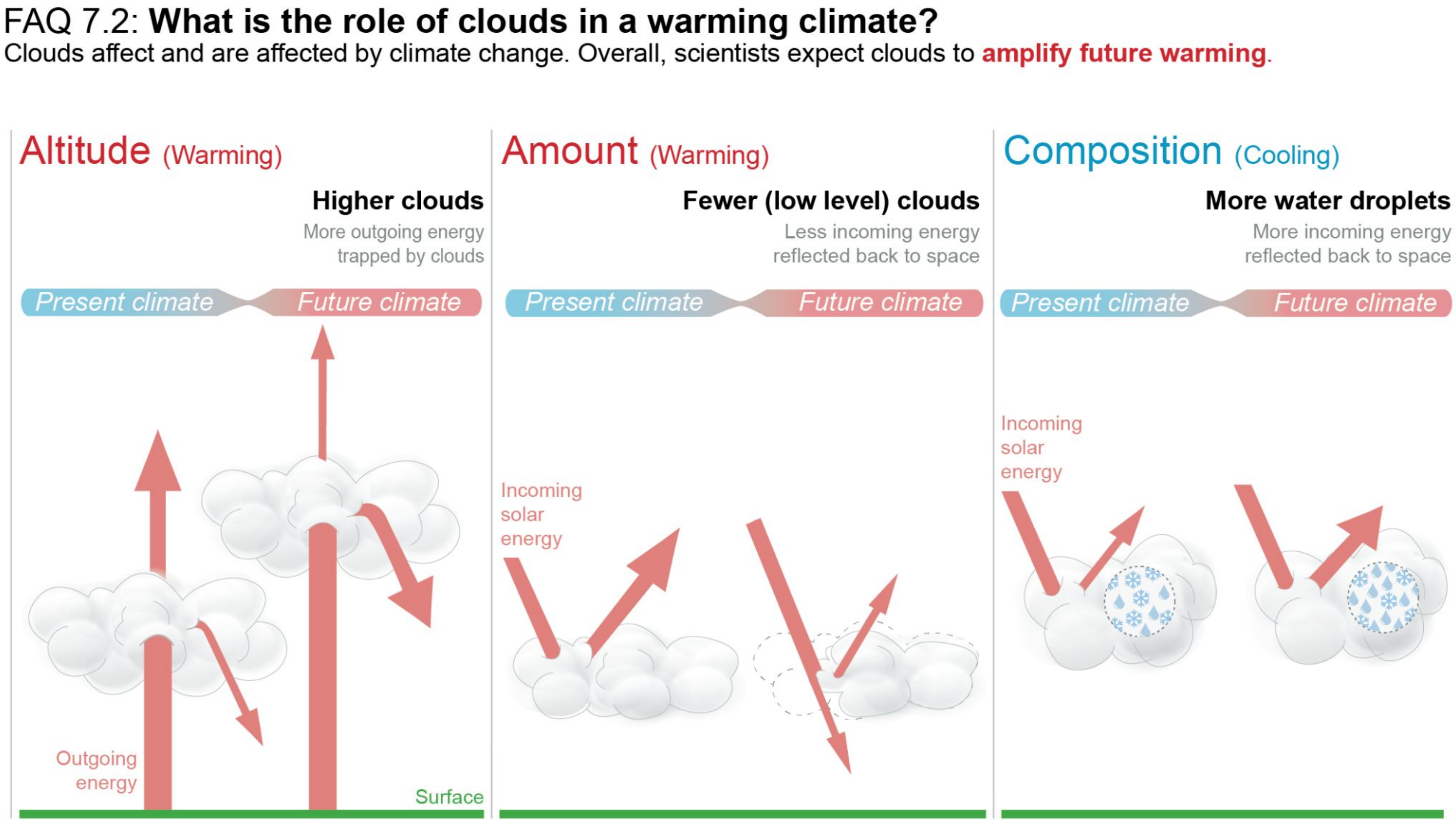
- **Clouds cover** about **⅔ of Earth's surface** and play a **complex role** in the **climate system**

- They **both cool and warm the planet**, but the **net effect** depends on their **type, altitude, and structure**
  - **Low clouds** (e.g. stratus) are typically thick, extensive and reflective → they tend to **cool** the planet by reflecting incoming solar radiation ("parasol" effect)
  - **High clouds** (e.g. cirrus) are cold and thin, letting solar radiation in but trapping outgoing longwave radiation → they tend to **warm** the planet
  - **On average**, **clouds** have a **net cooling effect on Earth** (mainly due to low clouds)



https://earthobservatory.nasa.gov/

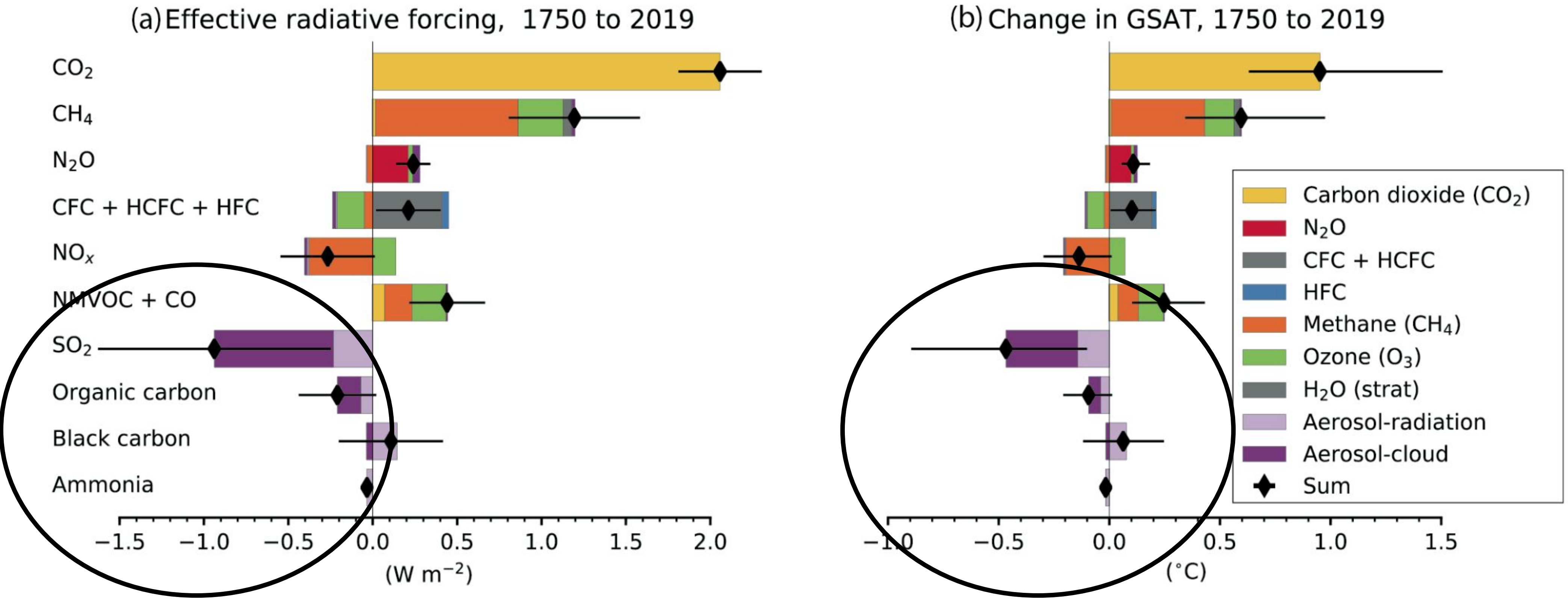
Introduction: why observe Clouds ?



IPCC, 2021 – FAQ 7.2 Fig. 1, AR6 WG1, Chap. 7: Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. DOI: https://doi.org/10.1017/9781009157896.009

Introduction: why observe Clouds ?

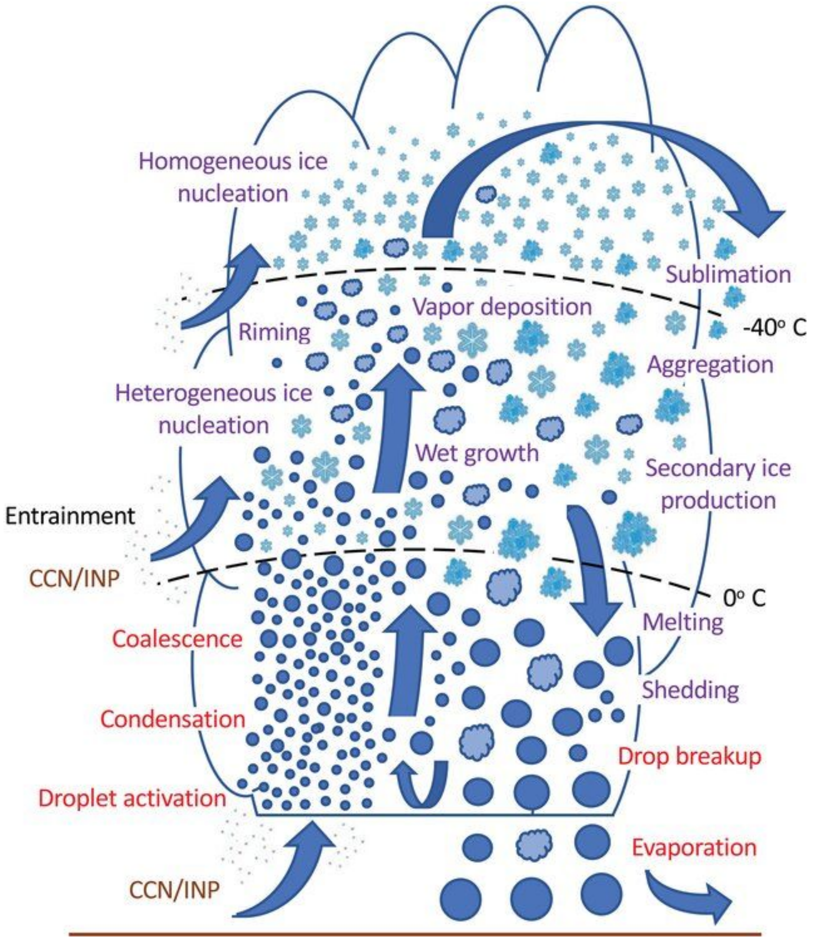
Cooling wins → but **large** associated **uncertainties**



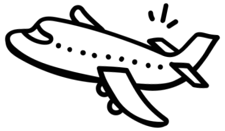
From Figure 6.12 in IPCC, 2021: Chapter 6, DOI: https://doi.org/10.1017/9781009157896.008

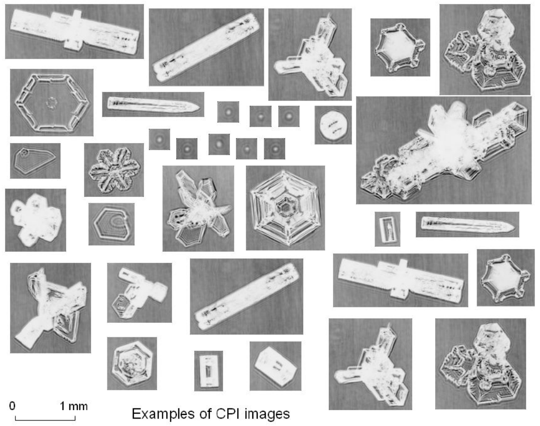
Introduction: the complexity of clouds

Processes responsible for formation and evolution of **clouds** are **complex !**



Morrison et al., 2020
https://doi.org/10.1029/2019MS001689





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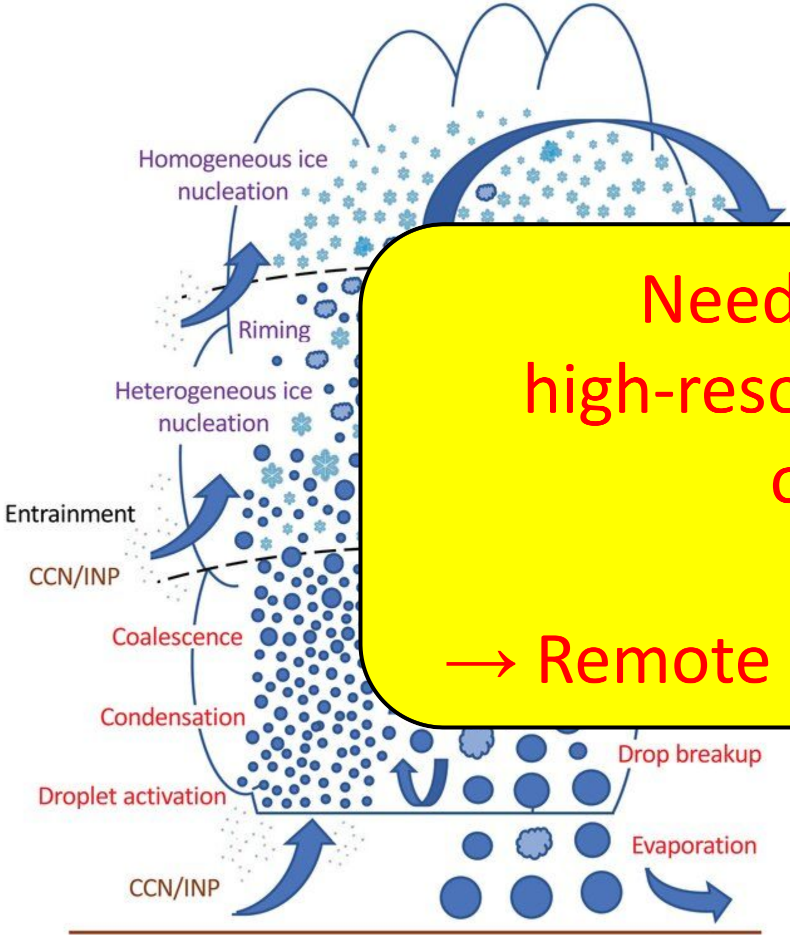

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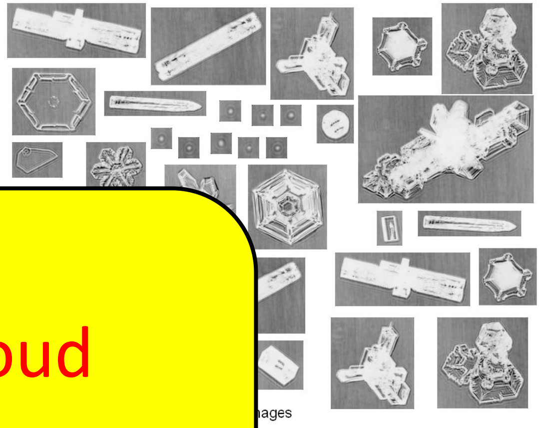
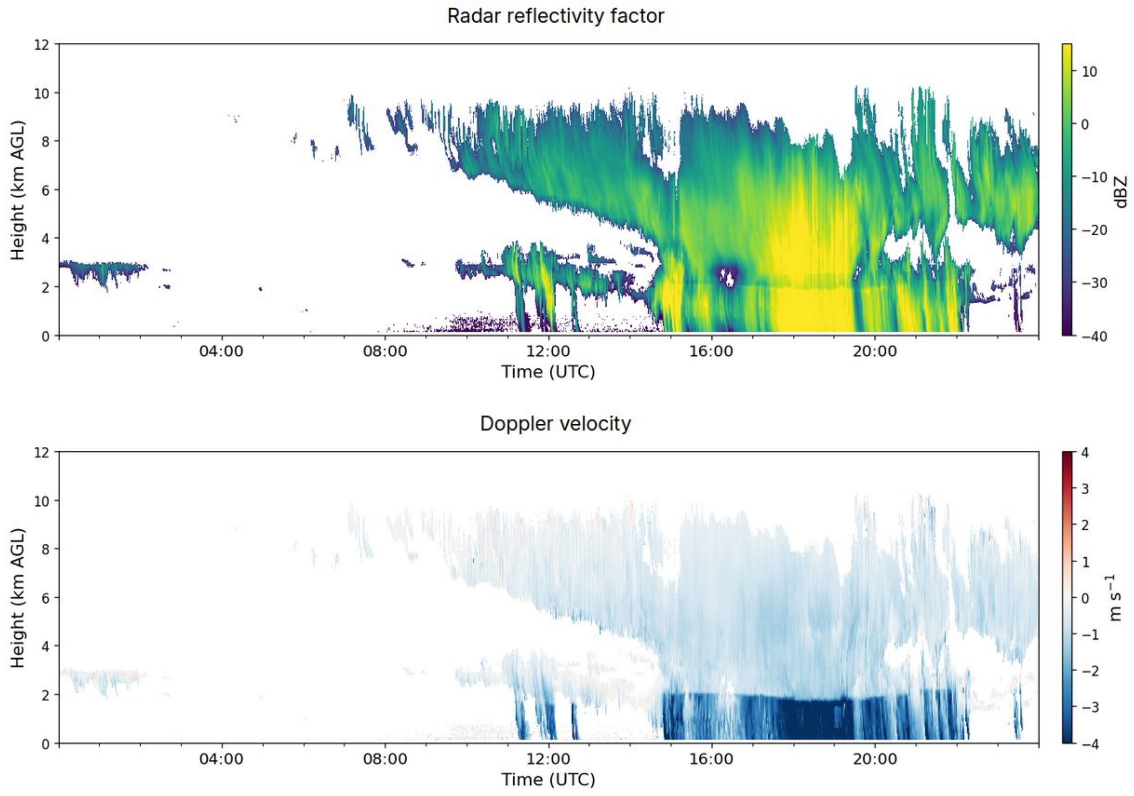


Need for long-term &
high-resolution vertical cloud
observations

→ Remote sensing measurements

Motivation

Granada, Spain
20/01/2025
https://cloudnet.fmi.fi/



Motivation

ACTRIS
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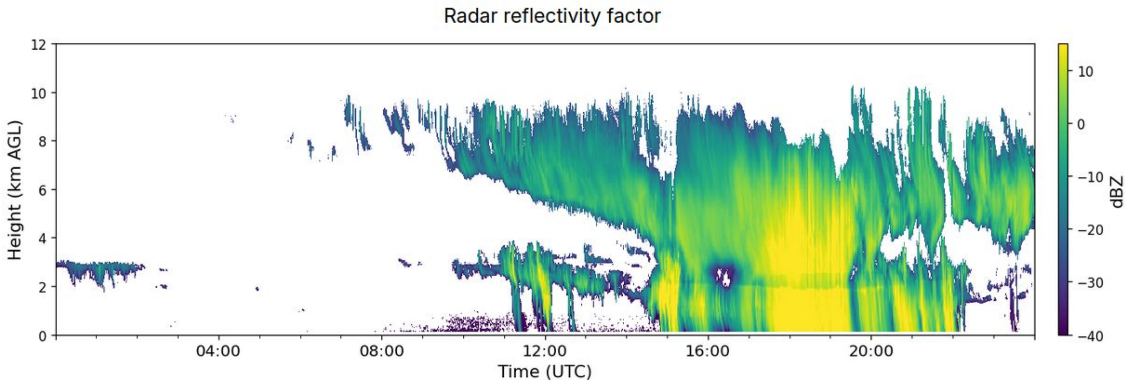
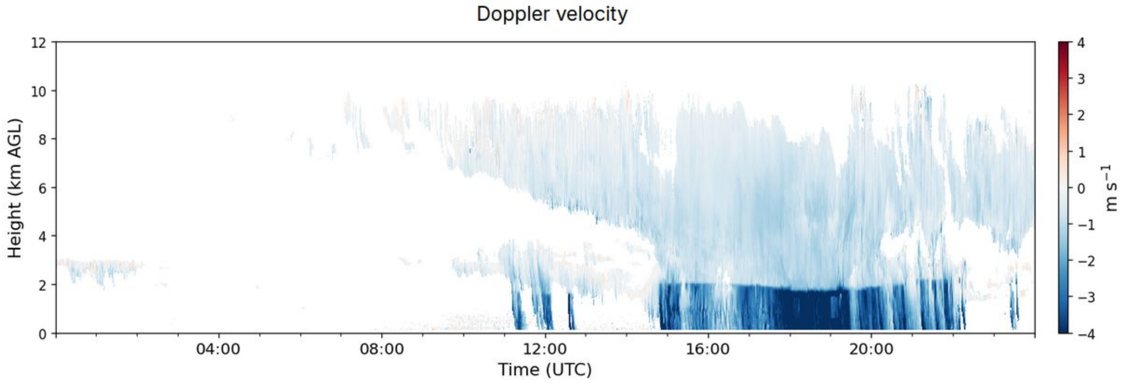
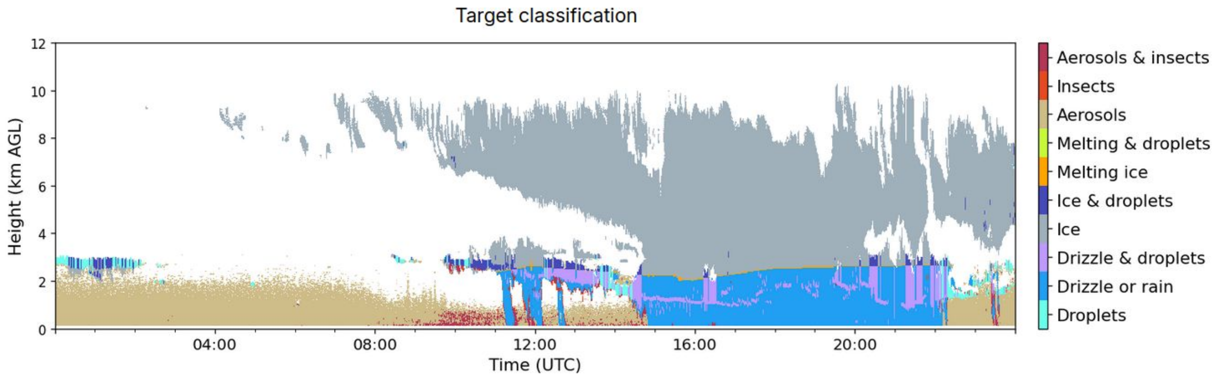




Remote sensing synergy →
Level 2 product



CCI

RADAR PRINCIPLES & CLOUD RADARS

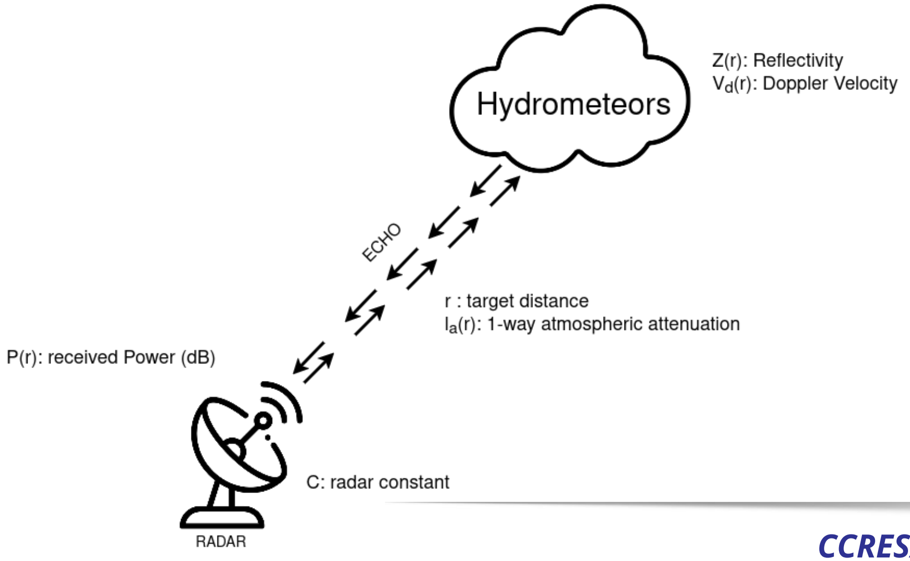
I - Main principles of radar

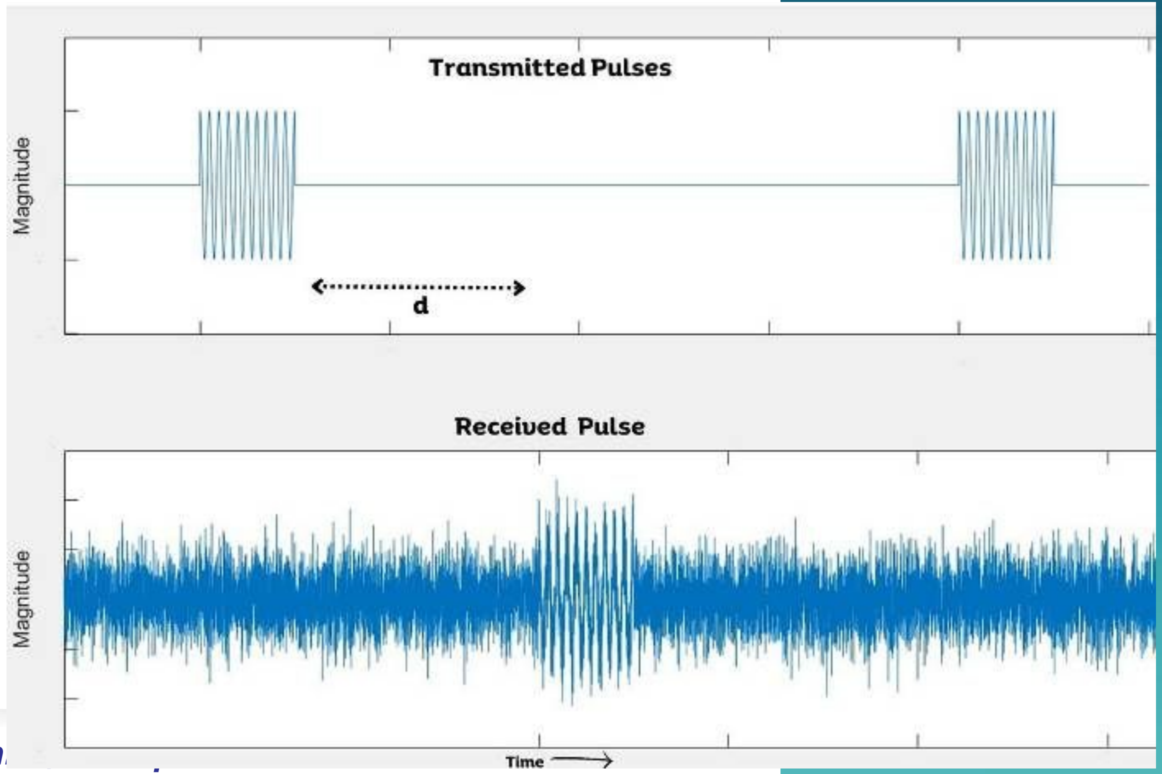
RADAR = Radio **D**etection **A**nd **R**anging

Active remote sensing

A radar system has 2 main functions:

1. **Transmission** of pulsed/continuous radiation in a specific direction
2. **Detection** of the radiation reflected by the target
    a. Intensity and phase of the signal (detection)
    b. Distance and location (ranging)





I - Main principles of radar

What do we measure with a radar ?
How can we use EM waves ?

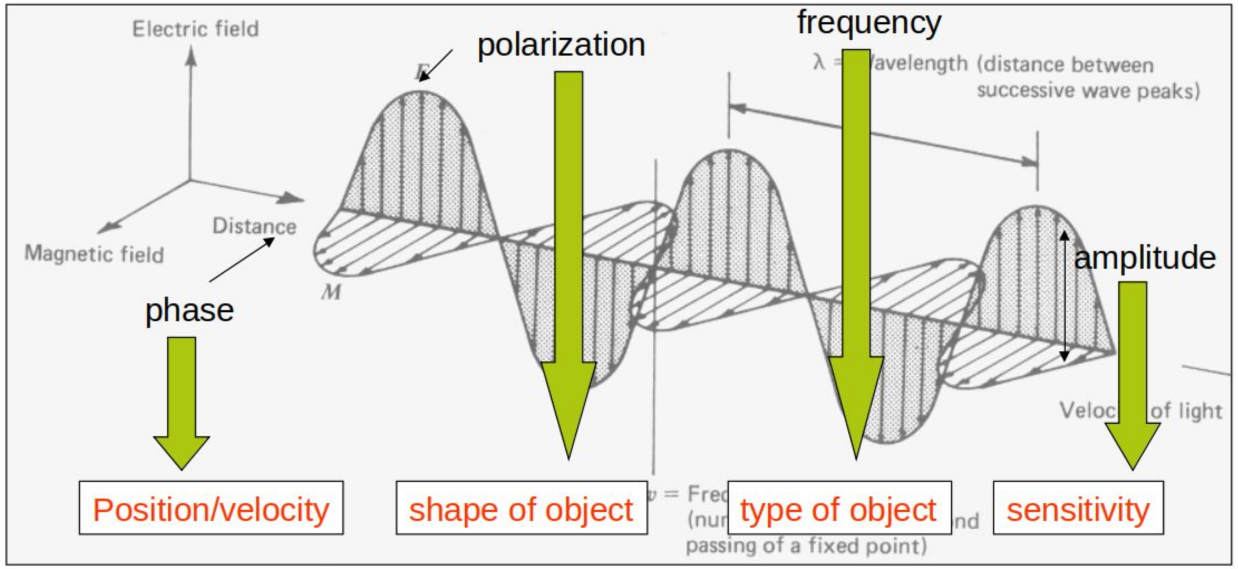
Inverse problem: measures signal reflected by hydrometeors, but we seek to retrieve cloud structure and content

An EM wave can be described mathematically as:

$$s(t) = A \cos(2\pi f \cdot t + \varphi)$$

- **Frequency (f)** → determines sensitivity to particle type/size
- **Amplitude (A(t))** → related to reflectivity, indicates concentration of hydrometeors (Power ∝ A^2)
- **Phase (φ)** → gives position and velocity (via time delay and Doppler shift)
- **Polarization** → reveals shape of particles (e.g. raindrops vs ice crystals)

→ Radar measures how the wave is modified by the cloud, and infers its structure, content, and motion

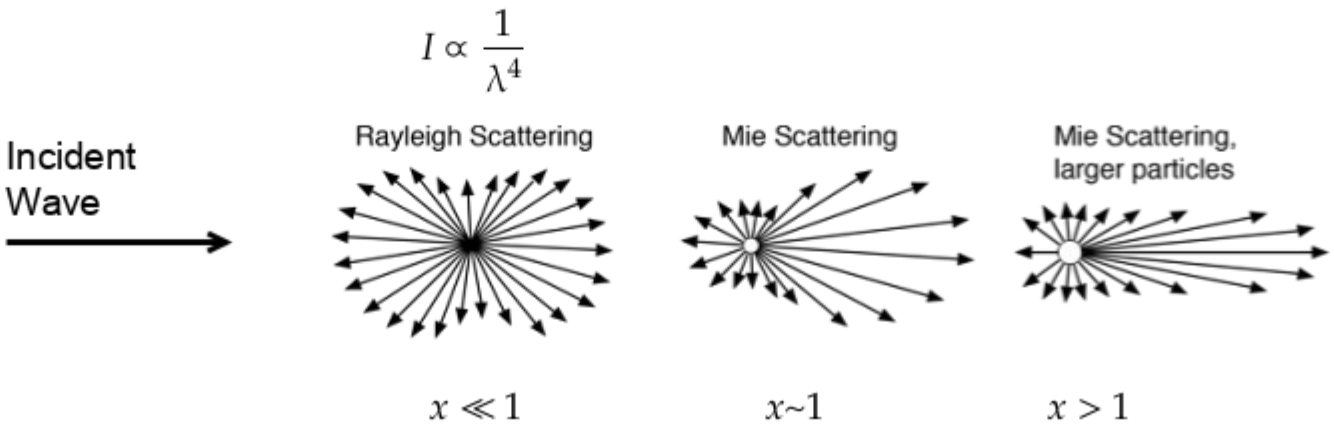


From H. Russchenberg
TU Delft Master lesson on cloud radar 2015

I - Wave Scattering

- Size parameter :

$$x = \frac{\pi D}{\lambda}$$



The standard radar equation assumes that the particle diameter/wavelength ratio is in the Rayleigh scattering range. In this case, the radar cross section for a single particle is:

$$\gamma_v(D) = \frac{\pi^5 K^2}{\lambda^4} D^6$$

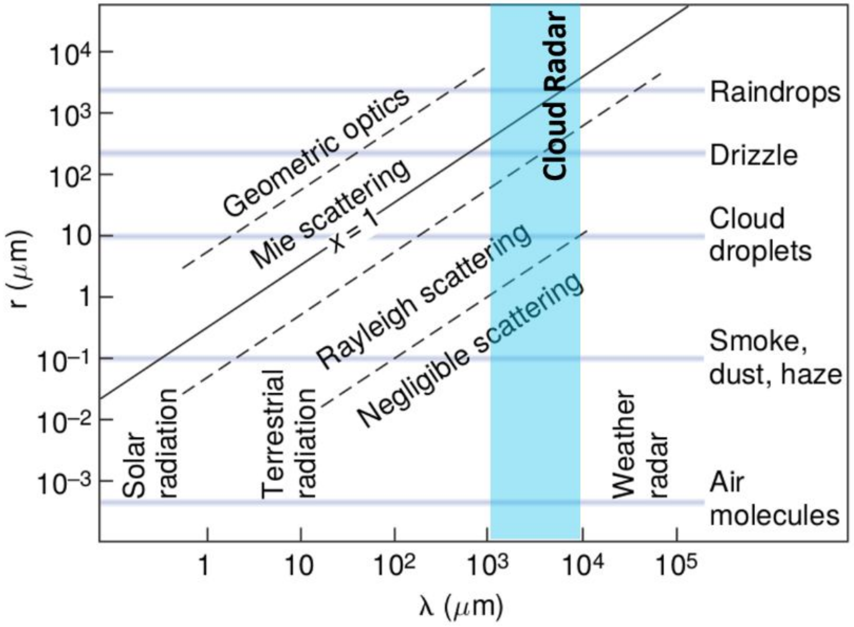
$K^2 = (\varepsilon_r - 1)^2/(\varepsilon_r + 2)^2$ is the dielectric factor, depends on particles complex relative permittivity ε_r

Typically K^2 = 0.86 or = 0.75

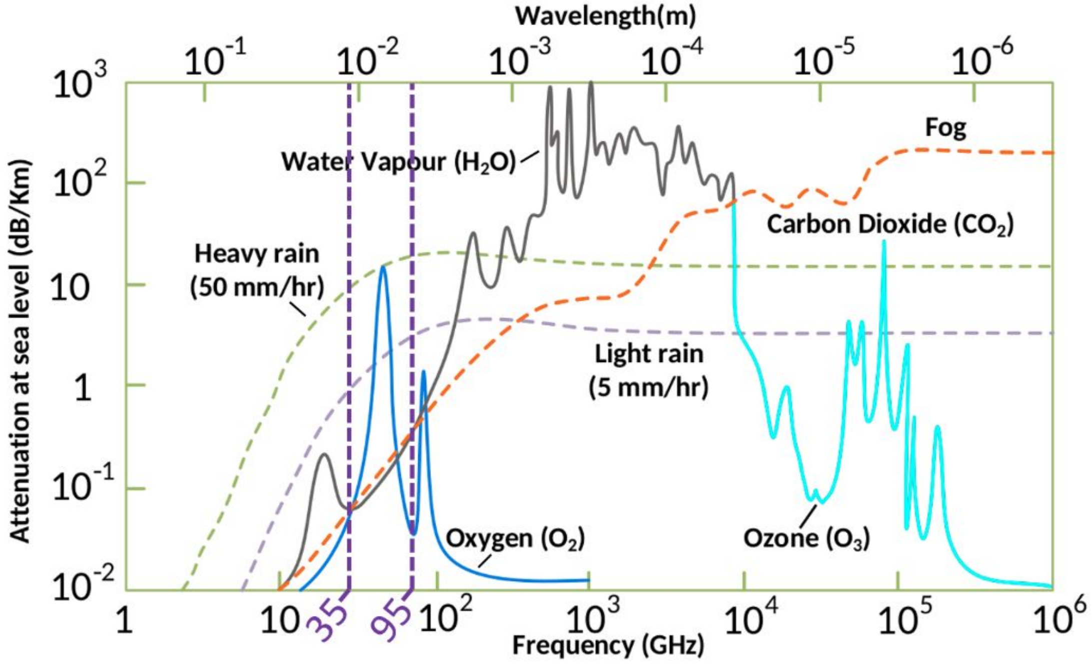
I - Main principles of radar: Cloud radars frequency band

- They usually operate in the
  a. **Ka** band (~**35 GHz**): ~ **3mm**
  b. **W** band (~**95 GHz**): ~ **9mm**
- **Rayleigh scattering** with **cloud particles** (**10-100µm**)
- Lower atmospheric attenuation, “atmospheric windows”

(a) Scattering regime versus wavelength and particle radius



(b) Electromagnetic absorption of different atmospheric components versus frequency



II - Cloud Radar types

- Frequency-modulated continuous wave **(FMCW) vs. Pulsed**
- **Single / Double** polarization
- **Vertical pointing** vs **scanning**

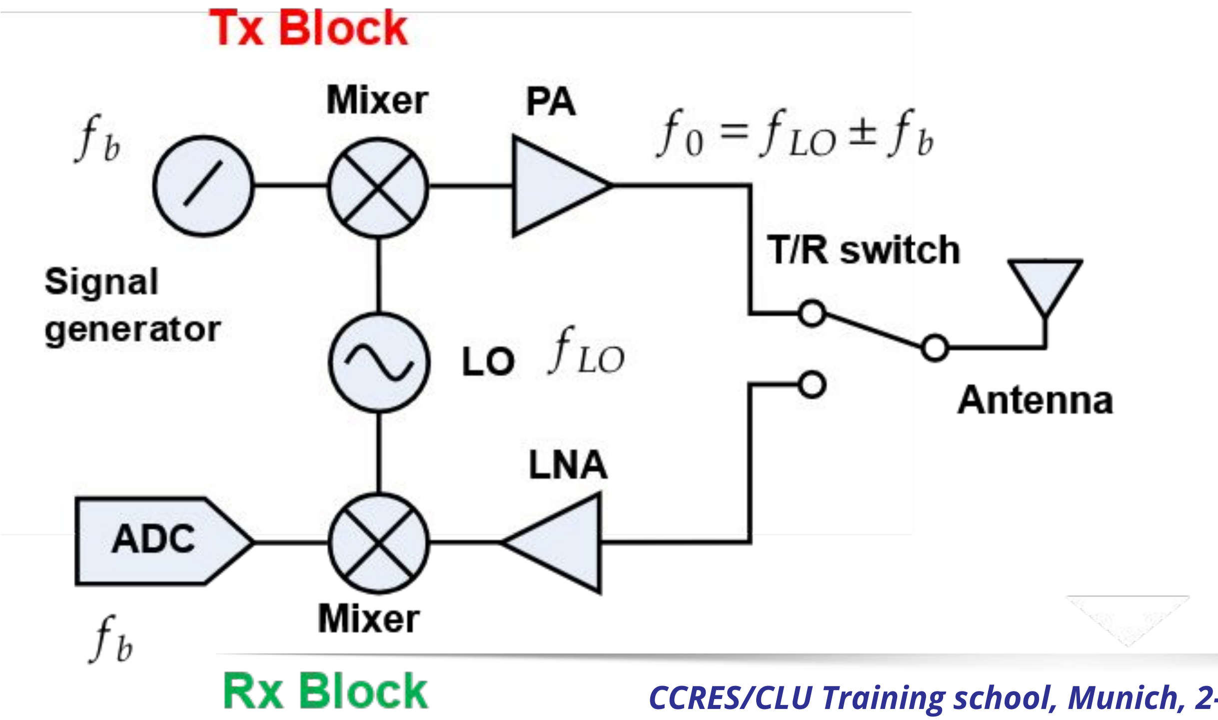
- **Differ in terms of:** operation mode, capabilities, data quality, size/weight, advanced products

RPG	BOWEN	METEK
FMCW-94/35	BASTA	MIRA-35
35-94GHz / 94GHz	94 GHz	35 GHz
FMCW	FMCW	Pulsed

II - Radar Hardware

Hardware overview

- Pulsed and FMCW radars have **transmitter** and **receiver** blocks
- There is a very large number of possible architectures and implementations that can work as a radar. However, many of them have some key components in common.
- Frequency generation and conversion stages are usually implemented with **mixers** and **local oscilators (LO)**, and RF chains include **power amplifiers (PA)** and **low noise amplifiers (LNA)** to increase the instrument sensitivity.



f_0 : Radar carrier frequency (you pick on of the two sidebands in the ±)

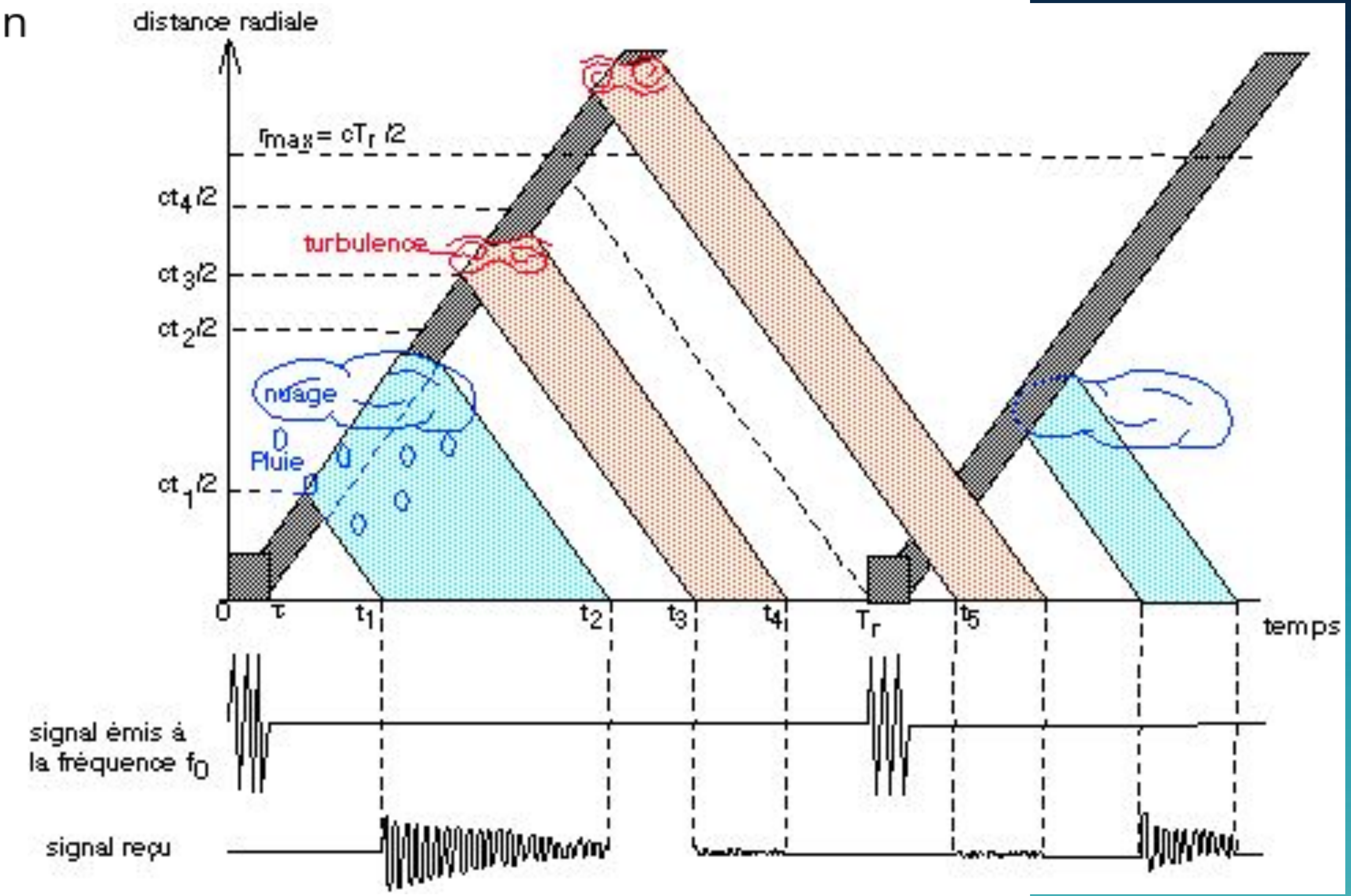
f_b : baseband frequency

f_{LO} : local oscilator frecuency

Pulsed Radar Operation

Operation of a pulsed radar

- The pulsed radar emits pulses with a duration of τ, a frequency f_0 and mean power P_t
- Suppose a signal that bounces back with a time delay t from the pulse generation
- Range to the object:
  - $r = {}^{ct}/_{2}$
- Range resolution:
  - $\delta r = {}^{c\tau}/_{2}$
- Blind range or zone, the pulse hides other signals:
  - $r_{min} = {}^{c\tau}/_{2}$
- Unambiguous range
  - $r_{max} = {}^{cT_r}/_{2}$
  - T_r = Pulse repetition time (PRT)
  - $F_r = 1/T_r$ = Pulse repetition frequency (PRF)



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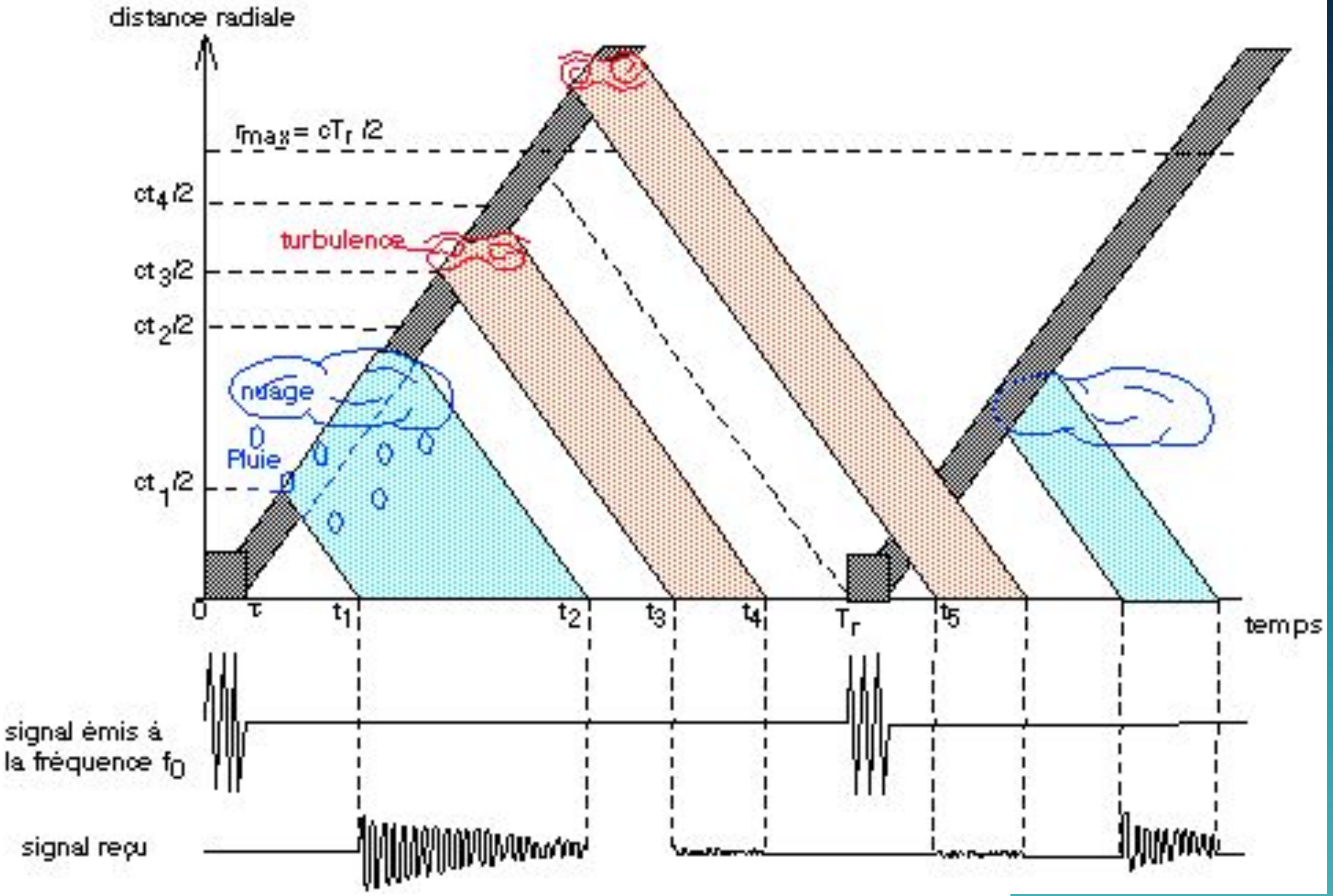
- Radars usually have high PRFs, to increase power output, enable coherent integration and improve doppler velocity estimates
  - For weather radars it can be of several hundred Hz to several kilohertz



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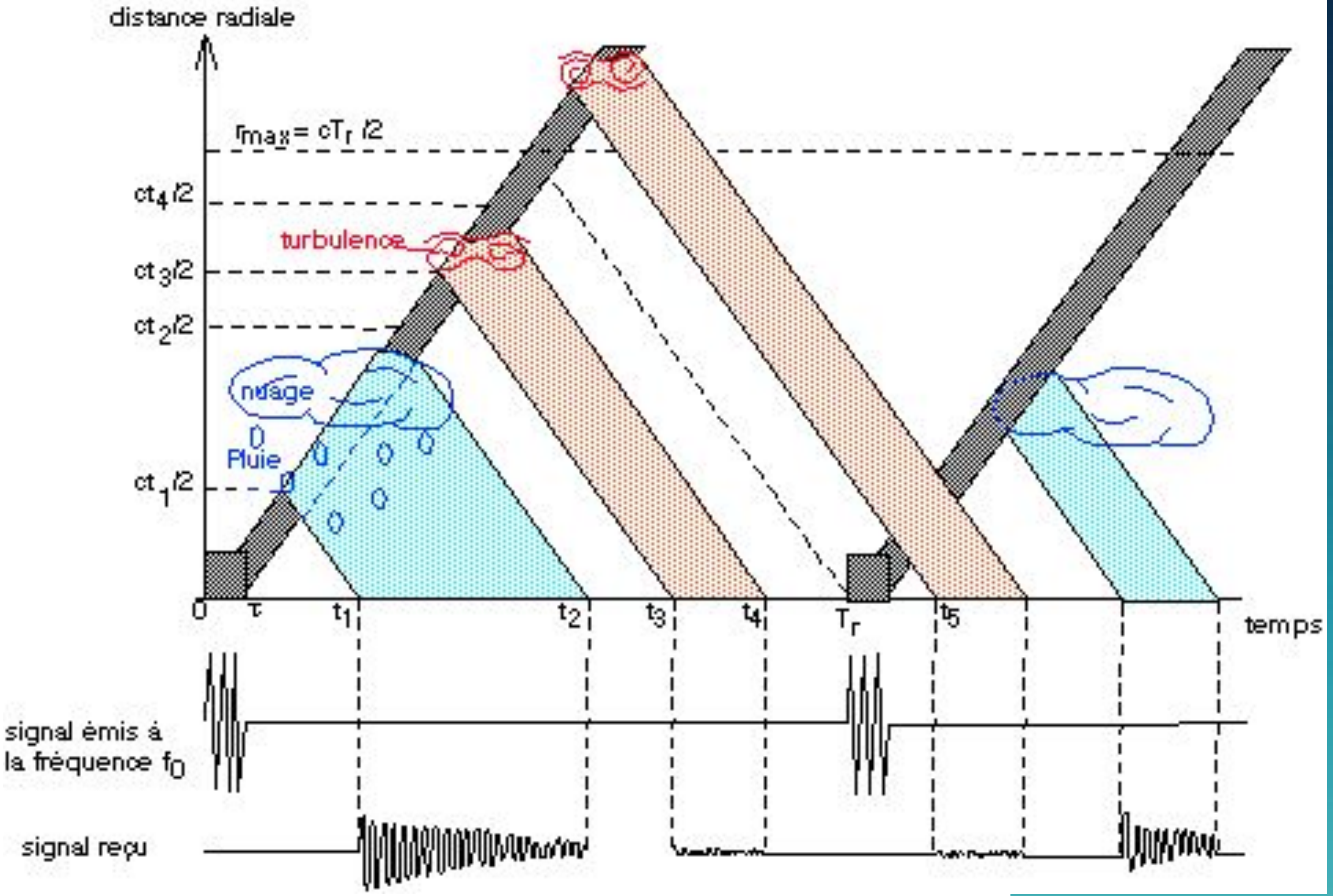
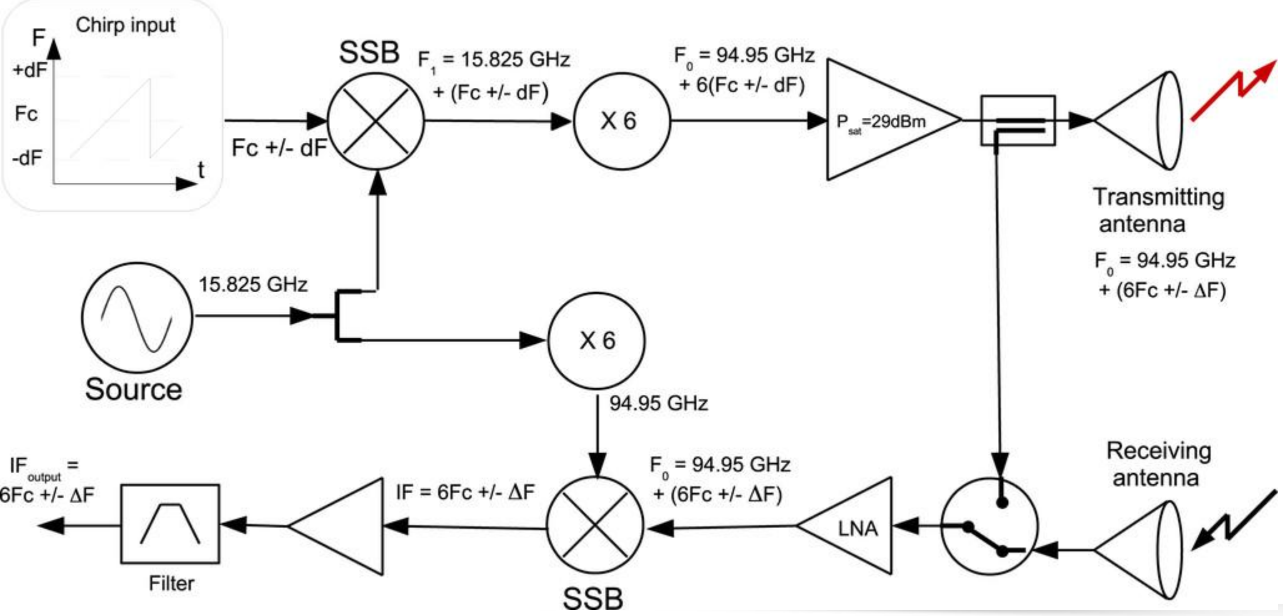
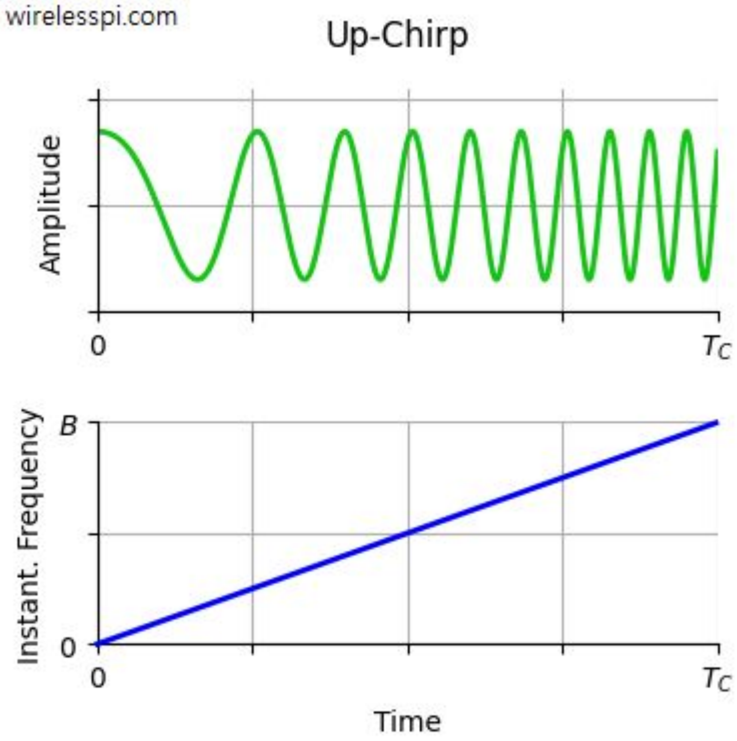


FMCW Radar Operation

- FMCW = Frequency Modulated Continuous Wave
- Instead of “pulses” it continuously transmits “chirps” of a signal modulated in frequency
- The **frequency** difference between the transmitted and received signal gives **range**
- The **phase** evolution from chirp gives **Doppler velocity**

Example of a FMCW radar architecture, BASTA radar, Delanoë et al. 2016.

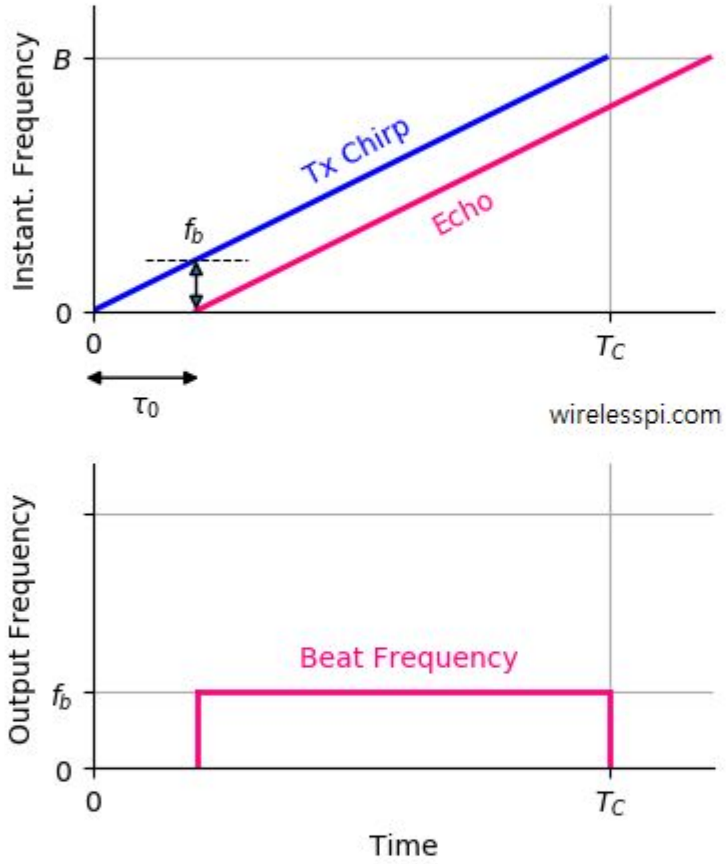




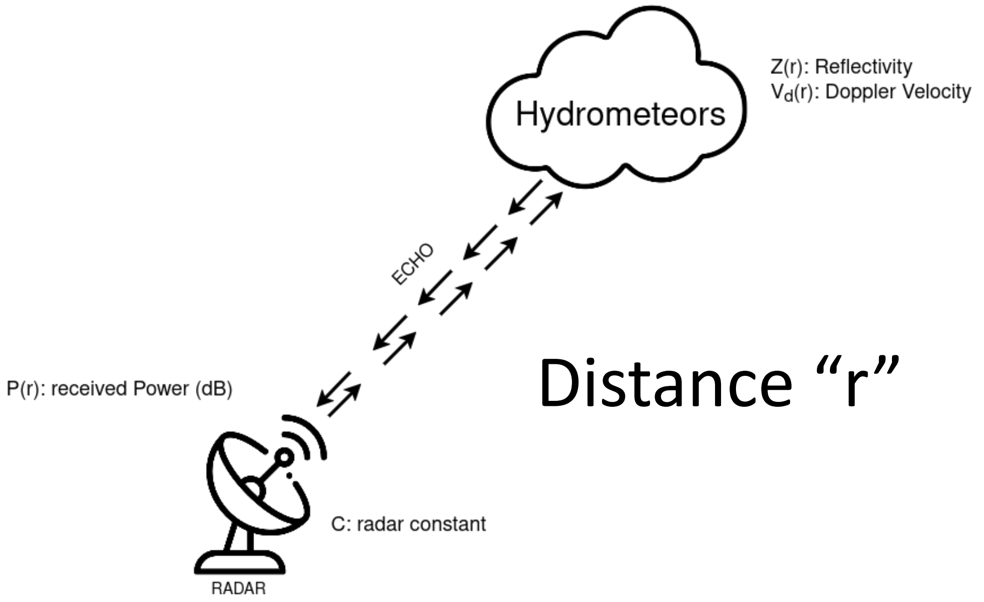
Single chirp: The emitted signal frequency increases

FMCW Radar Operation

- Travel time τ_0 : time it takes for a round trip.
- The travel time produces a frequency difference between transmitted and received signals → This is the "beat frequency" $\mathbf{f_b}$
- By **mixing** the transmitted and received signals we get a "beat signal". The frequency components will have information on range

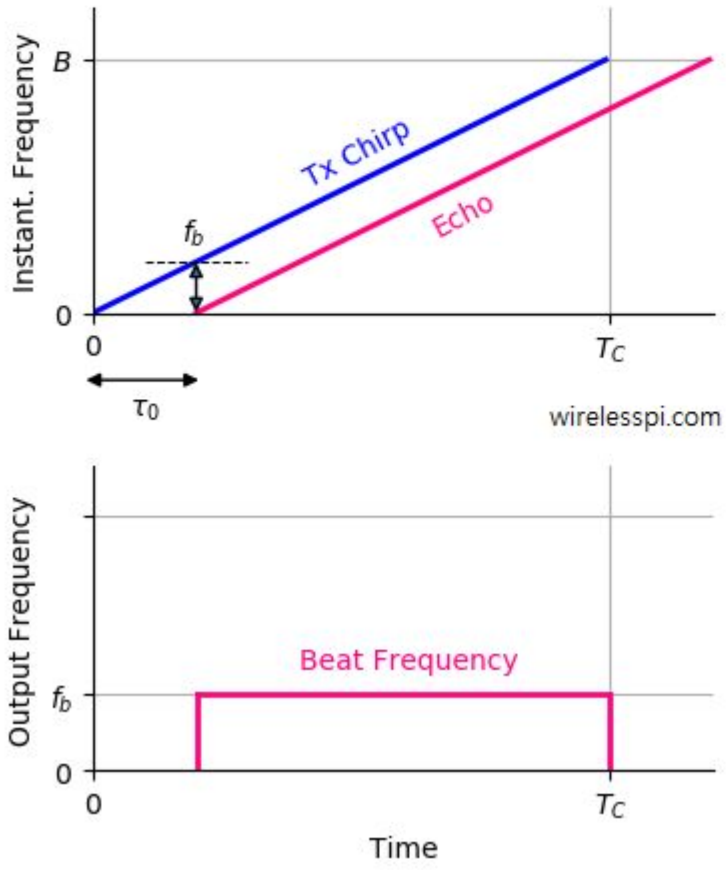


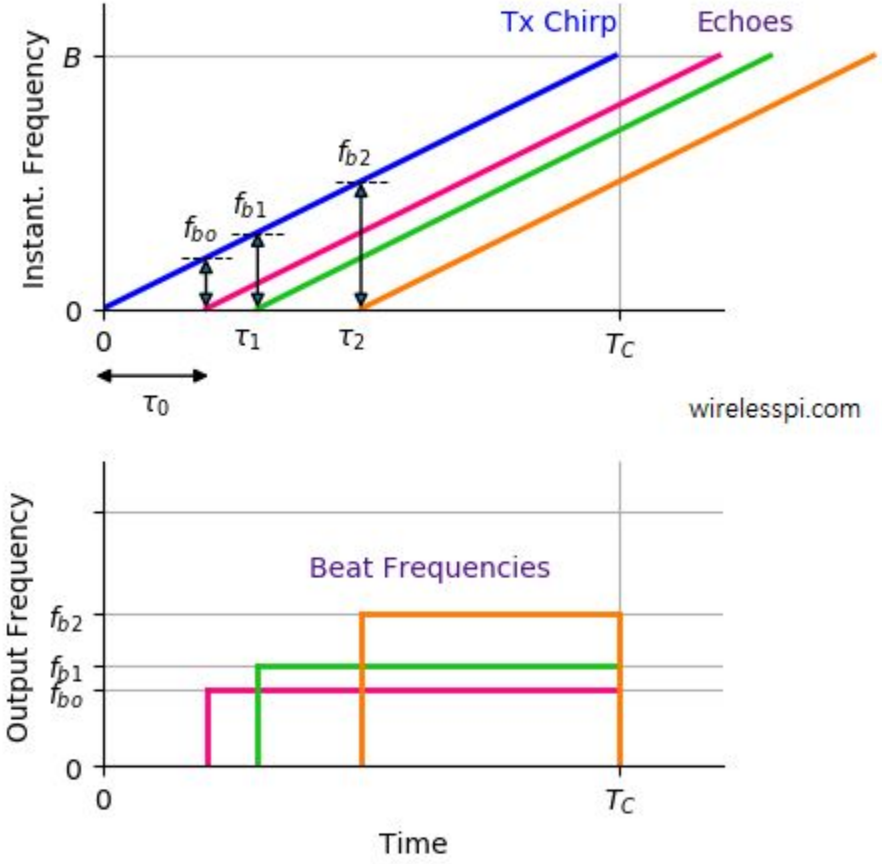
$$\tau_0 = \frac{2r}{c}$$



FMCW Radar Operation

- The time τ_0 it takes for the round trip will produce a frequency difference between the transmitted and received signals. This is the “beat frequency” f_b
- By mixing the transmitted and received signals we geat a “beat signal”. The frequency components can be extracted from filtering + FFT treatment





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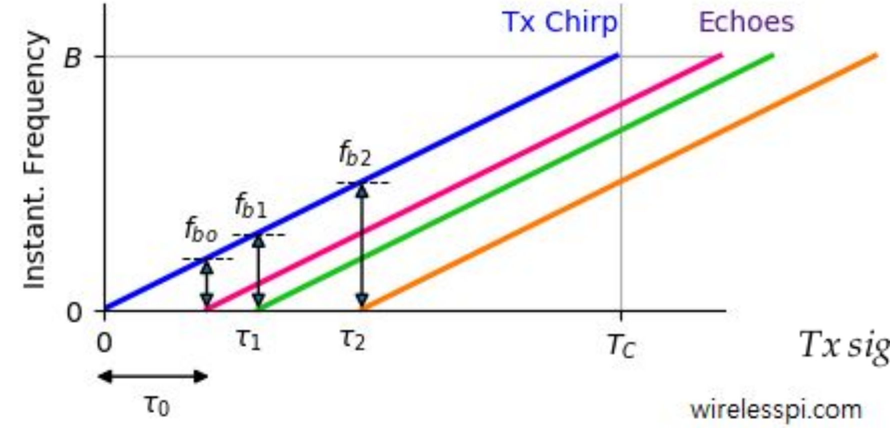
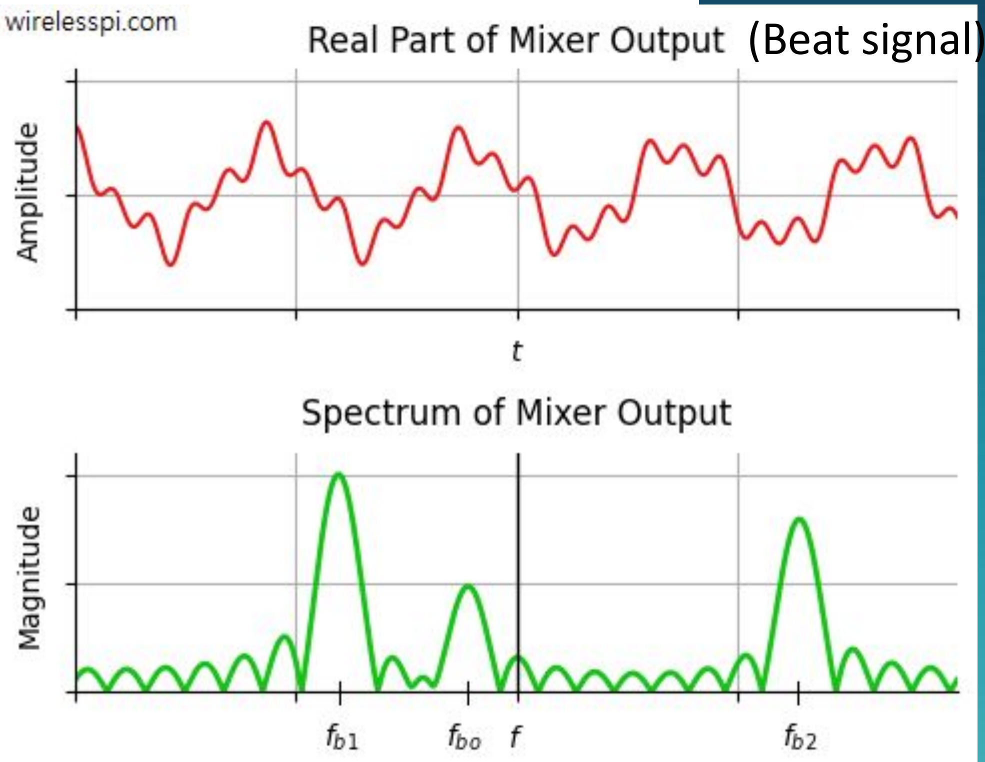


$$Tx\ signal\ (\mathbf{X})\ Echoes\ =\ beat\ signal$$



FMCW Radar range equations

- As with pulsed radars, many chirps are sent in cadence during operation

Key equations:

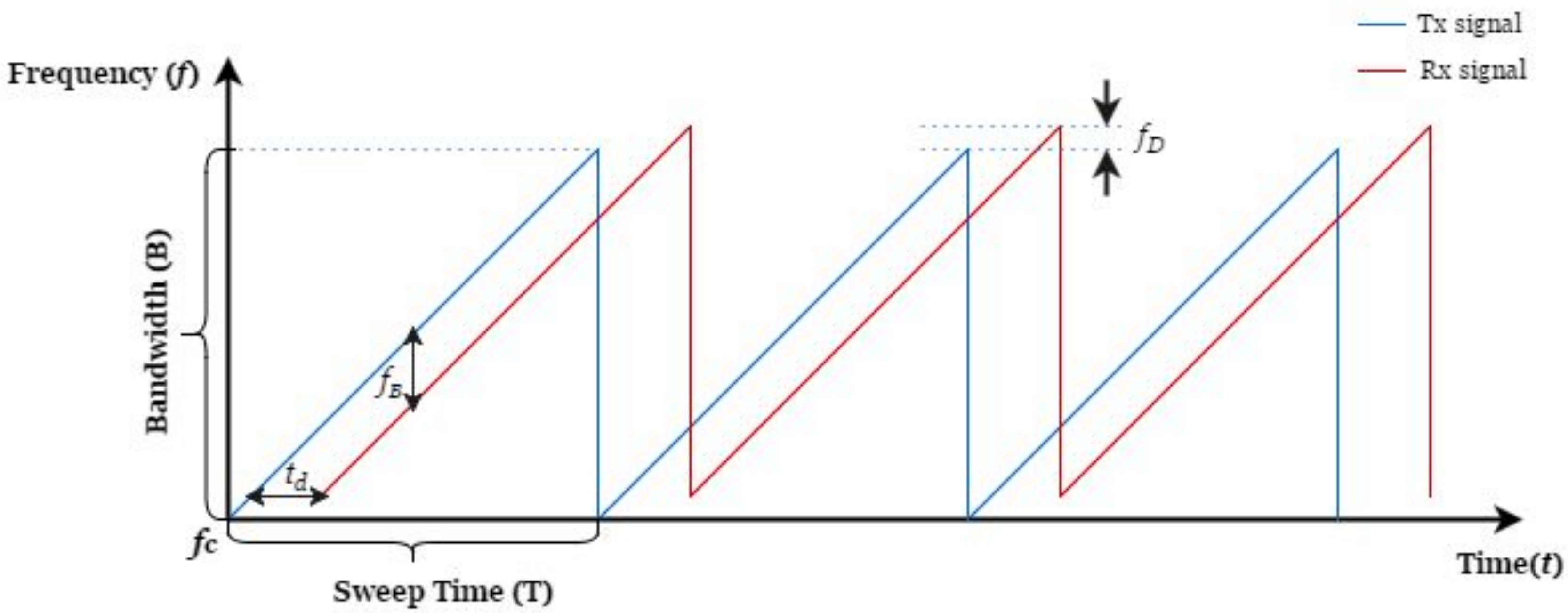
Chirp frequency slope $\alpha = \frac{B}{T}$

Unambiguous range $r_{max} = \frac{cT}{2}$

Blindzone? Depends on the radar hardware, “crosstalk”

Range $r = \frac{f_b c}{2\alpha}$

Range resolution $\Delta r = \frac{c}{2B}$



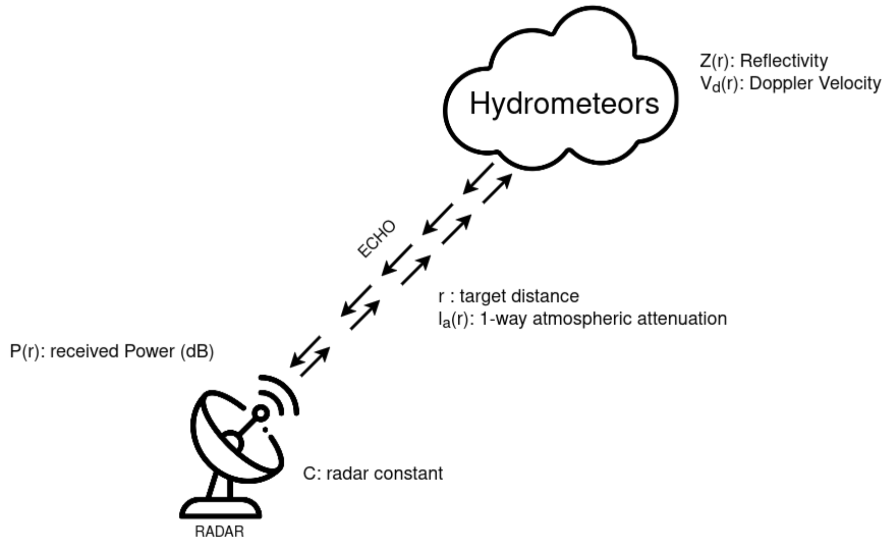
Suleymanov, S. (2016). *Design and Implement of an FMCW Radar Signal Processing Module for Automotive Applications* (Doctoral dissertation, Master Thesis, Aug. 31).

RADAR EQUATION

The Radar Equation

- The **radar equation** describes how **power scattered back** from atmospheric **hydrometeors** relates to their **physical properties** and **distance** from the radar

- In the case of **cloud radars**, we need it to calculate **key** radar **parameters** such as the **Radar Cross Section (RCS)** and the **Radar Equivalent Reflectivity (Z)**



ADD vertical reflectivity profile and a scan

The Radar Equation

- Power received at the target position $\vec{r}$:

$$P_{inci}(\vec{r}) = \frac{P_t G_a}{4\pi r^2 l_a(r)}$$

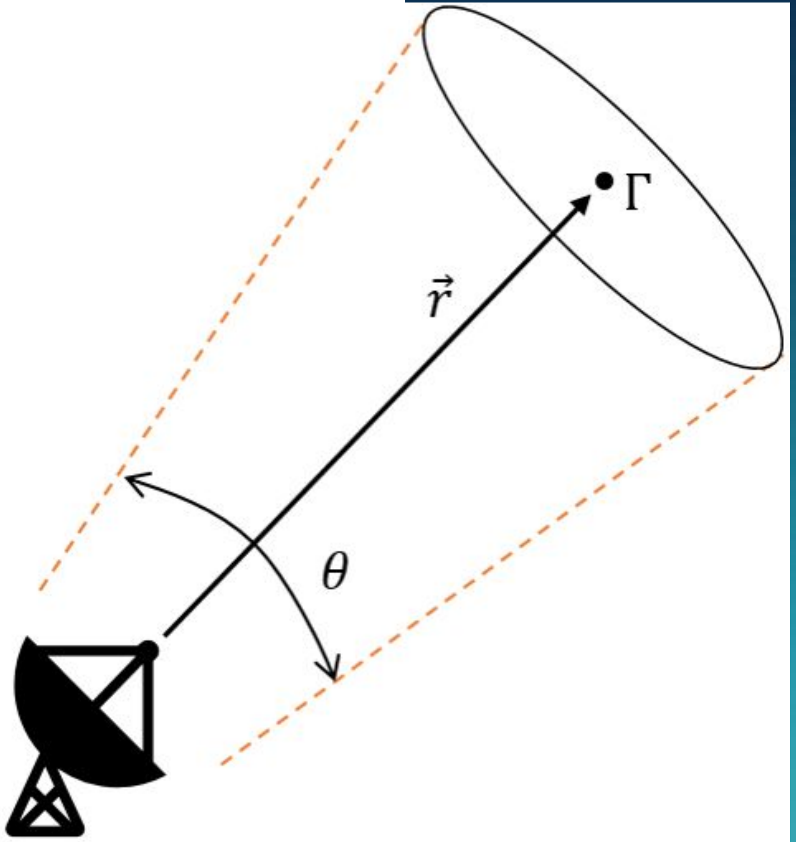
- Incident power : $P_{inci}(\vec{r})$ [mW] ; Transmitter power : P_t [mW]
- Max. antenna gain : G_a
- Atmospheric attenuation from the radar to $\vec{r}$: $l_a(r)$

- The target has a radar cross section Γ [m^2]

- Power scattered back and received by the radar, from the target at $\vec{r}$:

$$P_r(\vec{r}) = P_{inci}(\vec{r}) \frac{A_p}{4\pi r^2 l_a(r)} \Gamma = \frac{P_t G_a}{4\pi r^2} \frac{A_p}{4\pi r^2} \frac{\Gamma(r)}{l_a^2(r)}$$

- A_p is the effective antenna aperture for the receiver.



The Radar Equation

$$A_p = \frac{G_a \lambda^2}{4\pi}$$

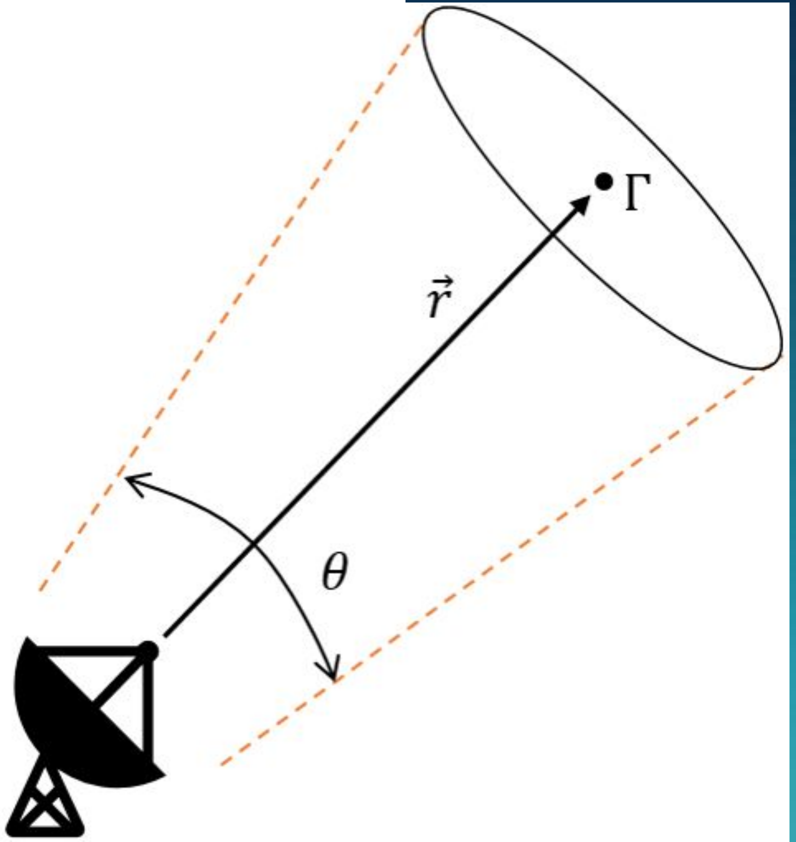
- λ [m] : Radar wavelength

- With this information we get the radar equation for point targets* :

$$P_r(\vec{r}) = \frac{G_a^2 \lambda^2 P_t}{(4\pi)^3 r^4 \, l_a^2(r)} \Gamma(r)$$

- By knowing the radar properties, we can measure the point target cross section from received power

- And what happens for distributed targets ?



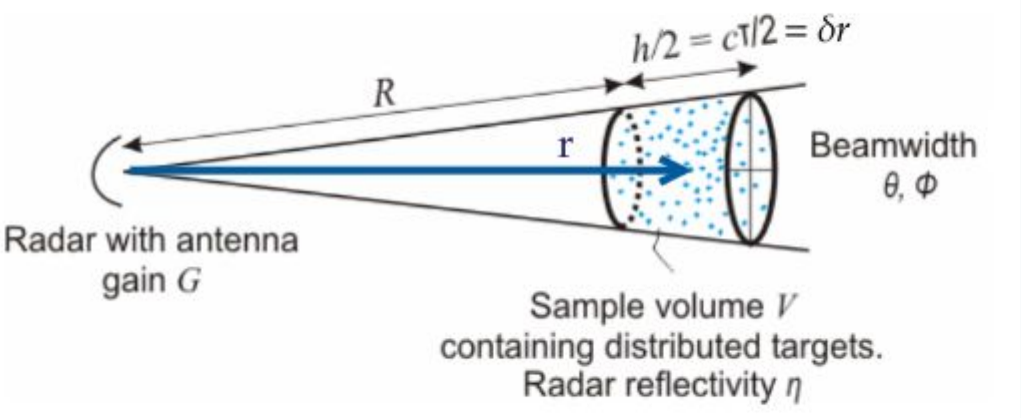
** The emitting and receiving antennas are assumed to have the same gain and axially symmetric beam lobes*

Sampling volume

- If we assume that for each sampling volume we have a uniform droplet distribution N(D) [number/m^3], then the total cross section would be :

$$\Gamma_v = V(r)\int_0^{\infty} N(D)\,\gamma_v(D)\,dD = V(r)\int_0^{\infty} \frac{\pi^5 K^2}{\lambda^4} N(D)\,D^6\,dD$$

- The effective sampling volume is calculated as:



$$V(r) = \int_{r-\delta r/2}^{r+\delta r/2}\int_0^{\pi}\int_0^{2\pi} f_a^2(\theta,\phi)\, r^2\, dr\, d\Omega \approx r^2\delta r \int_0^{\pi}\int_0^{2\pi} f_a^2(\theta,\phi)\, d\Omega$$

Where $f_a(\theta,\phi)$ is the normalized antenna pattern (antenna pattern divided by the maximum gain value). For symmetric antennas ($\theta = \varphi$) with Gaussian lobes :

$$V(r) = \frac{\pi r^2 \delta r}{2\ln 2}\left(\frac{\theta}{2}\right)^2$$

The radar Equation

- Definition of radar equivalent reflectivity from the Droplet Size Distribution (DSD):

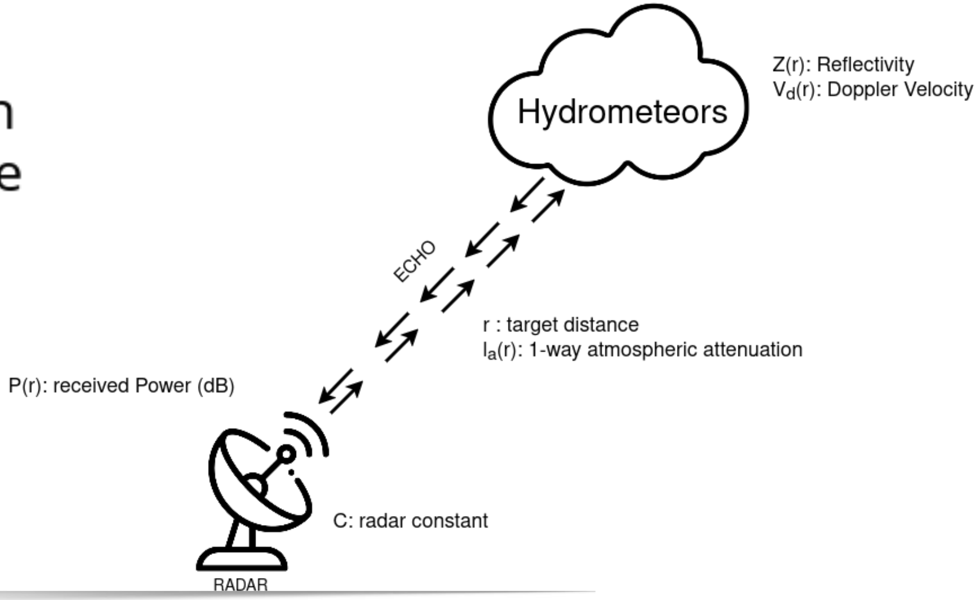
$$Z = \int_0^\infty N(D)\, D^6\, dD\ [m^6 m^{-3}] = 10^{18} \int_0^\infty N(D)\, D^6\, dD\ [mm^6 m^{-3}]$$

- The change to mm units is because these values are more commonly found in DSD measurements for precipitation

- Using the definition of Z and Γ_v, we can replace the RCS in the point target equation to get the radar equation for the **reflectivity** of distributed targets :

$$P_r(\vec{r}) = \frac{G_a^2 \lambda^2 P_t}{(4\pi)^3 r^4\, l_a^2(r)} \Gamma_v = \frac{10^{18} \pi^3 \theta^2 G_a^2\, P_t \delta r}{512\, \lambda^2 \ln 2} \frac{K^2}{l_a^2(r)\, r^2} Z(\vec{r})$$

Z in mm^6/m^3



The Radar Equation : Real Situation

- For real radars, the emitter and receiver can have different gains and losses that must be accounted for.

In reality $P_t = P_t^{nom}/L_t$; P_t^{nom} : nominal transmitted power ; L_t : Transmitter losses

Example from the BASTA radar system Delanoë et al. 2016

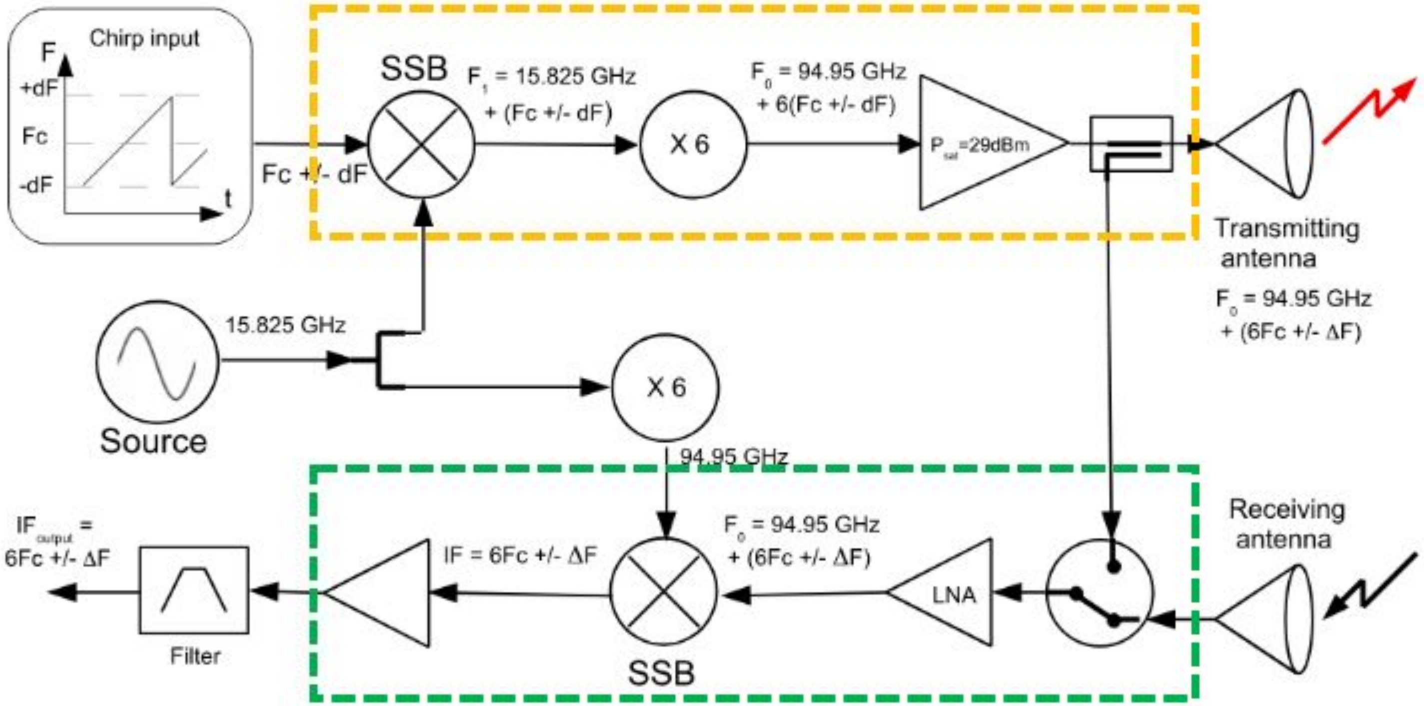


FIG. 8. Radar block diagram.

And similarly $P_r^{meas}(r) = G_r\ P_r(r)$; $P_r^{meas}(r)$: measured received power ; G_r : Receiver gain

Note: $\text{gain} = \frac{1}{\text{loss}}$

The Radar Equation : Real Situation

- Considering radar gain and losses, the radar equation for point target becomes :

$$P_r^{meas}(\vec{r}) = \frac{G_a^2 \lambda^2 G_r P_t}{(4\pi)^3 L_t \; l_a^2(r) r^4} \Gamma = \frac{1}{c_\Gamma} \frac{\Gamma(r)}{l_a^2(r)\, r^4} \quad \Rightarrow \quad \Gamma(r) = c_\Gamma \; l_a^2(r)\, r^4 \; P_r^{meas}(\vec{r})$$

- And for reflectivities :

$$P_r^{meas}(\vec{r}) = \frac{10^{18} \pi^3 \theta^2 G_a^2 P_t^{nom} \delta r \; G_r}{512 \; \lambda^2 \ln 2 \; L_t} \frac{K^2}{l_a^2(r)\, r^2} Z_e(\vec{r}) = \frac{1}{c_z} \frac{Z_e(\vec{r})}{l_a^2(r)\, r^2} \Rightarrow Z_e(\vec{r}) = c_z \; l_a^2(r)\, r^2 \; P_r^{meas}(\vec{r})$$

- By knowing c_Γ and c_z we can calculate Γ and Z_e from radar measurements!

$\rightarrow$ Radar calibration

The Radar Equation : Real Situation

- Considering radar gain and losses, the radar equation for point target becomes :

$$P_r^{meas}(\vec{r}) = \frac{G_a^2 \lambda^2 G_r P_t}{(4\pi)^3 L_t\, l^2(r) r^4}\, \Gamma = \frac{1}{c_\Gamma} \frac{\Gamma(r)}{l^2(r)\, r^4} \quad \Rightarrow \quad \Gamma(r) = c_\Gamma\, l_a^2(r)\, r^4\, P_r^{meas}(\vec{r})$$

- And for reflecti

$$P_r^{meas}(\vec{r}) = \frac{10^{18} \pi^3 \theta^2}{512\, \lambda} \quad \ldots \quad {}_a^2(r)\, r^2\, P_r^{meas}(\vec{r})$$

Hands on Training on Radar Calibration this afternoon

- By knowing c_Γ and c_z we can calculate Γ and Z_e from radar measurements!

$\rightarrow$ Radar calibration

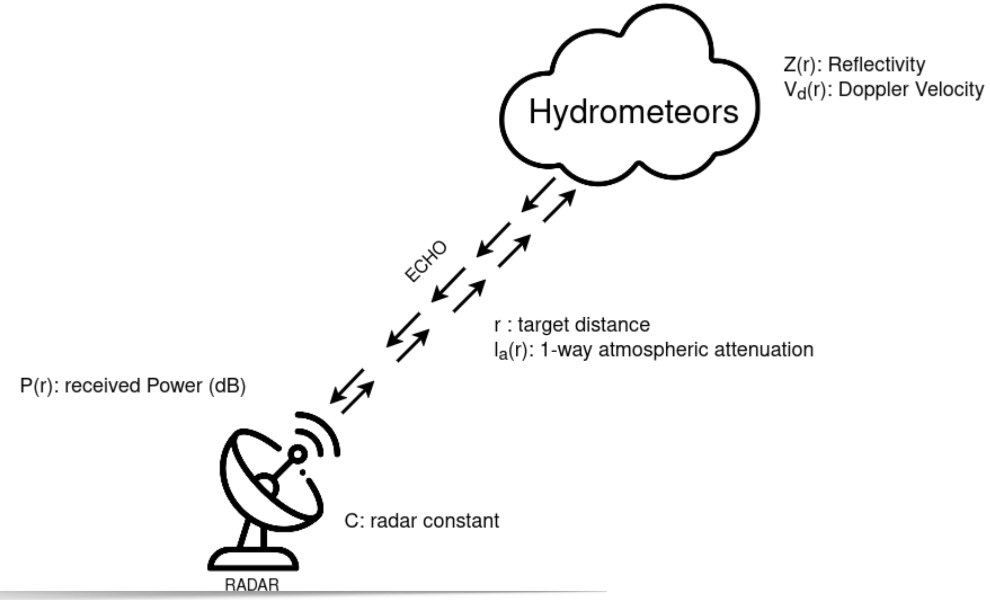
The Radar Equation : dB form

- To finalize, usually the radar equations are presented in dB form. Applying $10\log_{10}(\cdot)$ at both sides of the equation we get:

$$\Gamma(r)[dBm^2] = C_\Gamma + 2L_a(\mathbf{r}) + 40\,log_{10}(r[m]) + P_r^{meas}(\vec{r})\ [dBm]$$

$$\mathbf{Z}(\vec{\mathbf{r}})[\mathbf{dBZ}] = C_z + 2\mathbf{L_a}(r)\ + 20\,log_{10}(r[m]) + P_r^{meas}(\vec{\mathbf{r}})\ [\mathrm{dBm}]$$

- With :
  - $\mathbf{L}_a(\mathbf{r}) = 10\log_{10}(\mathrm{l}_a(\mathrm{r}))$
  - $\mathbf{P_r^{meas}}(\vec{\mathbf{r}}) = 10\log_{10}(\mathrm{P_r^{meas}}(\vec{\mathrm{r}}))$
  - $\mathbf{\Gamma(r)} = 10\log_{10}(\Gamma(\mathrm{r}))$
  - $\mathbf{Z}(\vec{\mathbf{r}}) = 10\log_{10}(\mathrm{Z}(\vec{\mathrm{r}}))$



Doppler velocity

Doppler velocity

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- Goal: measure the radial velocity of hydrometeors
- Based on the Doppler effect: a shift in frequency due to motion of target relative to the radar
- In meteorological radars, the motion is relatively slow (~0-10m/s for cloud droplets, up to 30-40m/s for graupel/hail in convective clouds)
- The frequency shift is very small (few Hz/kHz), due to high transmitted frequency and low target speeds
- The classical Doppler frequency is hard to detect directly
- Radars detect phase changes between successive pulses backscattered from the same volume (pulse-pair method)
- Same approach on pulsed and FMCW radars. Phase shifts are used on the raw signal for pulsed, and on the beat signal for FMCW

Doppler velocity estimation

- Only works if the radar is coherent, i.e. if it keeps track of the phase of emitted pulses
- The pulse has a wavelength λ_0, frequency f_0, starting phase of φ_0
- The target has a radial velocity V_r
- Pulse repetition period of T_r

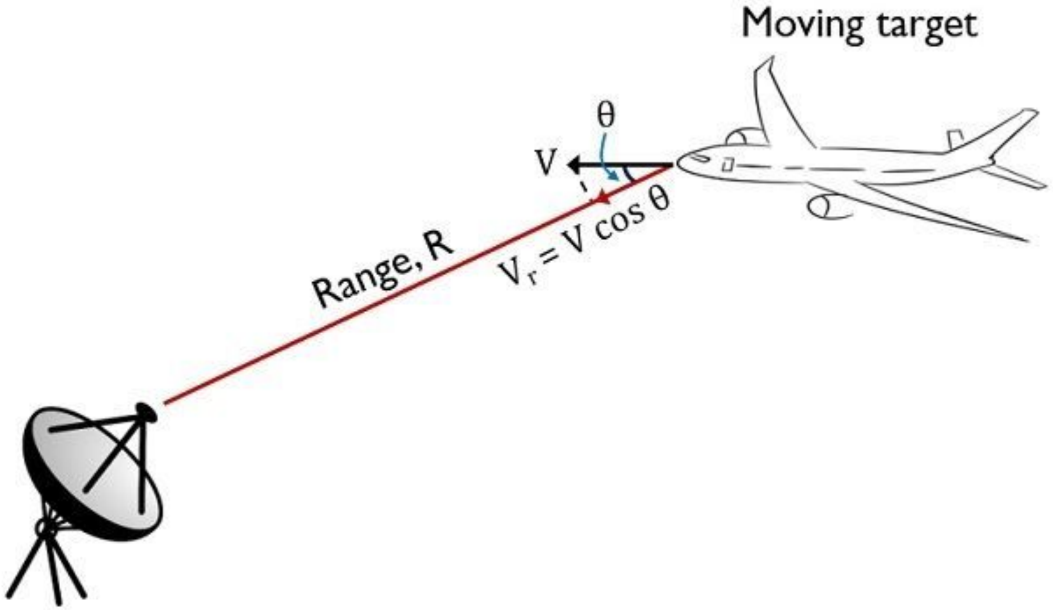
The angular excursion of a wave traveling between the radar and the target is of:

$$\Theta = 2\pi \cdot \frac{2R}{\lambda_0} = \frac{4\pi R}{\lambda_0}$$

The received signal would have the form:

$$s(t) = A(t)\cos(2\pi f_0 t + \varphi)$$

With $\varphi = \Theta + \varphi_0$



Geometry of radar and target in deriving doppler frequency shift

Roshni Y., **Doppler Effect in Radar**, Electronics Desk

Doppler velocity estimation

If the target moves, the phase at the receiver changes with time:

$$\varphi(t) = \frac{4\pi R(t)}{\lambda_0} + \varphi_0$$

Assuming that acceleration of the target is negligible at the radar time scale:

$$\frac{d\varphi(t)}{dt} = \frac{4\pi}{\lambda_0}\frac{dR(t)}{dt} \approx \frac{4\pi V_r}{\lambda_0}$$

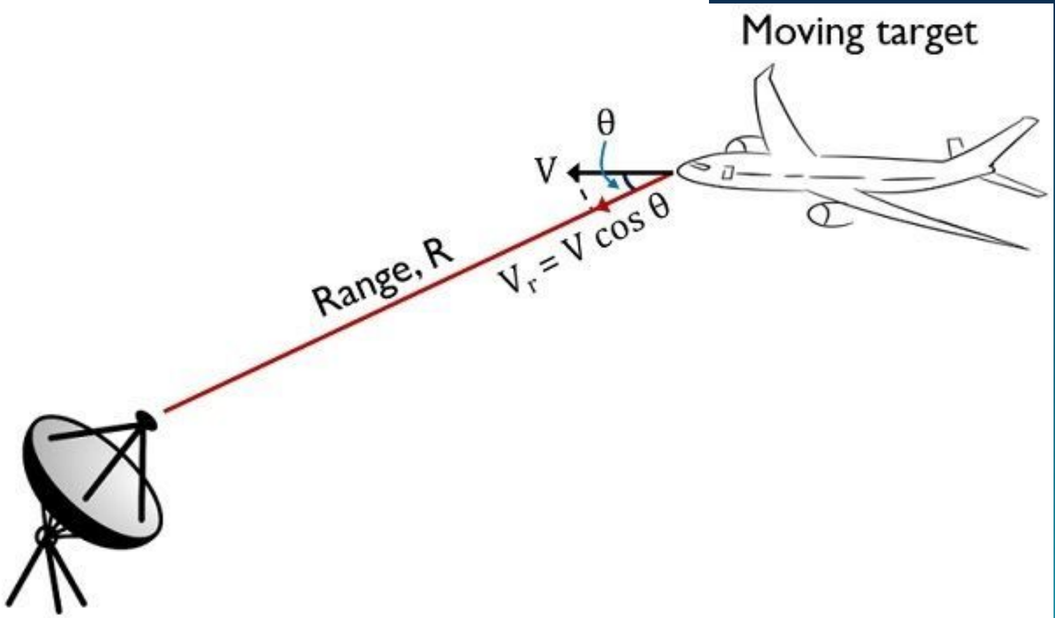
Hence, by sampling successive phase shifts we can estimate V_r :

$$V_r = \frac{\lambda_0}{4\pi}\frac{\Delta\varphi}{\Delta t} = \frac{\lambda_0}{4\pi T_r}\Delta\varphi$$

It can also be shown that, under these assumptions:

$$s(t) = A(t)\cos\left(2\pi\left(1 + \frac{2V_r}{c}\right)f_0 t + \varphi_0'\right)$$

Doppler freq. shift



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Electronics Desk

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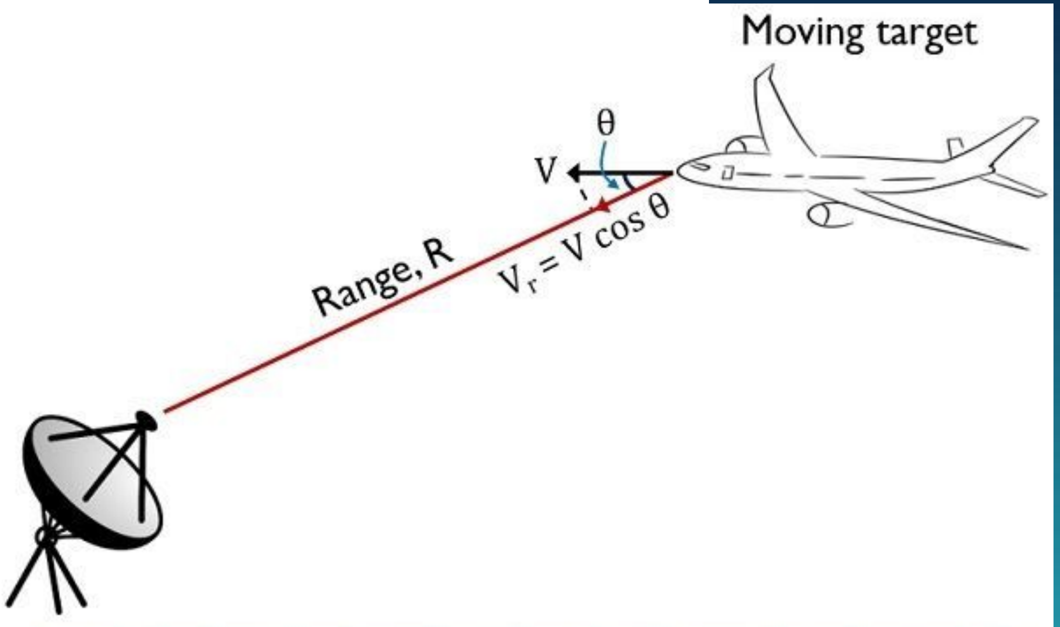


Geometry of radar and target in deriving doppler frequency shift

Note: Notice the sign convention in the radial velocity! Weather radar conventions usually have this sign flipped, positive velocity means moving away from the radar.

Doppler velocity estimation

Unambiguous velocity

Sine waves are periodic, phase shift can be positive or negative ⇒ $\Delta\varphi \equiv \Delta\varphi \pm \pi$

Thus, only phase shifts smaller than ± π give **unambiguous** results

If $|\Delta\varphi| < \pi$

$$\Rightarrow |V_r| < \frac{\lambda_0}{4T_r}$$

This is the unambiguous velocity limit.

Example: A target velocity inducing a phase shifts $\Delta\varphi = \pi + \varepsilon$ will be observed as a negative shift with $\Delta\varphi = -\pi + \varepsilon$ to remain in the ± π range.

This changes the sign and magnitude of the associated velocity → **Folding**

Pulse-pair processing

After each beam, at each range gate we get an amplitude and phase sample (phasor notation*):

$$S_i = a_i + jb_i = A_i e^{j\varphi_i}$$

*To recover the original sine wave:

$$s(t_i) = \mathrm{Re}\left\{S_i\, e^{j2\pi f_0 t_i}\right\} = A_i \cos\left(2\pi f_0 t_i + \varphi_i\right)$$

Integrating N pulses, we get for each gate:

Power (lag-0 autocorrelation) :

$$P = \frac{1}{N}\sum_{i=0}^{N-1} S_i S_i^* = \frac{1}{N}\sum_{i=0}^{N-1} A_i^2$$

Phase shift (lag-1 autoccorrelation) :

$$\Delta\varphi = -\arg\left\{\frac{1}{N-1}\sum_{n=0}^{N-2} S_i S_{i+1}^*\right\} = -\arg\left\{\frac{1}{N-1}\sum_{n=0}^{N-2} A_i A_{i+1} e^{j(\varphi_i - \varphi_{i+1})}\right\}$$

Note: Doppler velocity resolution improves with the number of integrated pulses:

$$\Delta V_r = \frac{\lambda_0}{2NT_r}$$

From DSD to Moments

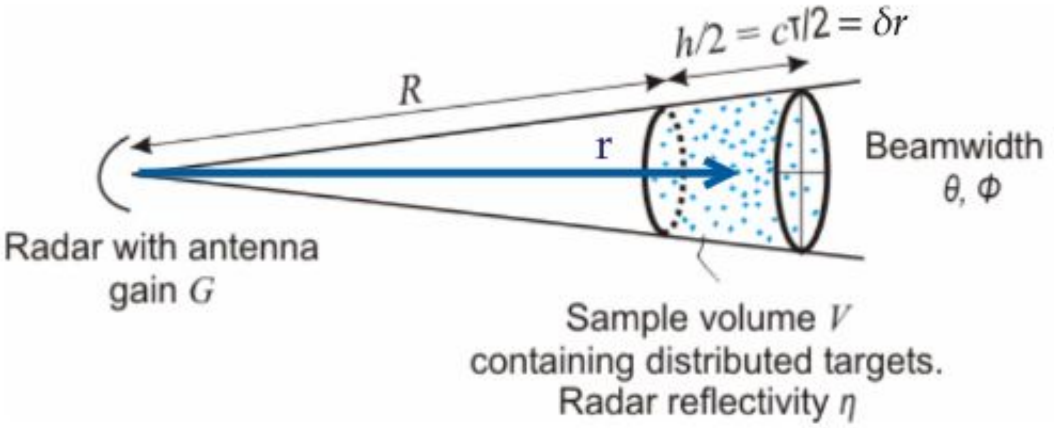
Drop Size Distribution (DSD)

The radar samples a **volume** defined by a **beamwidth** and **“pulse” length**

A **radar measurement** integrates the **backscatter** of droplets within a **sampled volume** (e.g. thousands to millions !)

The backscatter signal is not from individual drops but from their statistical distribution

Knowing the **DSD allows to relate radar variables to cloud microphysics** (Liquid Water Content, rain rate, …)

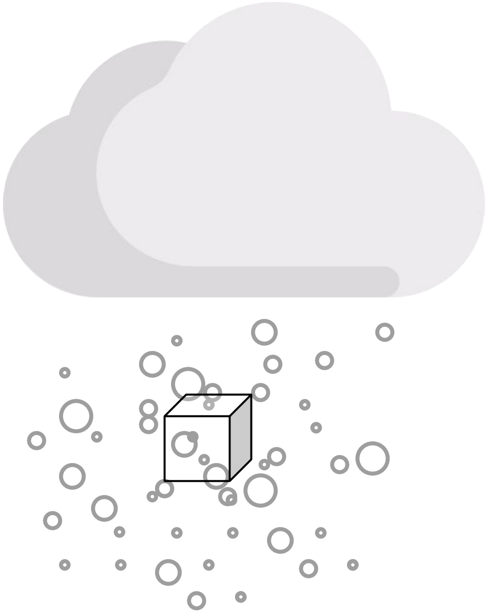


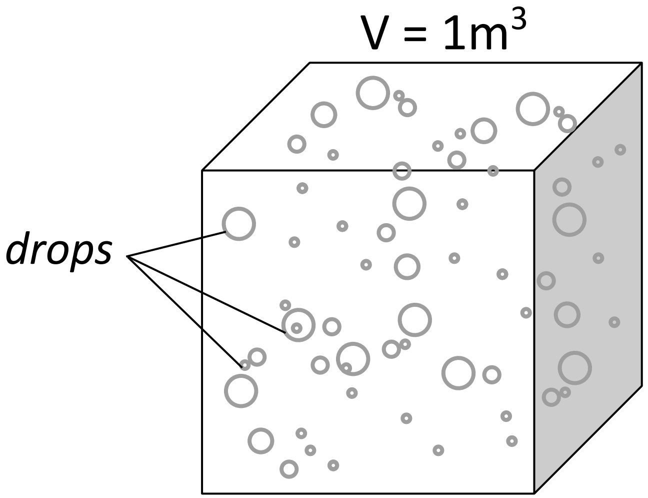
Drop Size Distribution (DSD)

DSD: N(D), number, per unit of volume, of drops for which size is between D and d+dD

$N(D) = N_0 e^{-\lambda D}$ [$m^{-3}.mm^{-1}$] (Marshall-Palmer)

The total number of drops, per unit of volume, **N_t** is:





$$N_t = \int_{D_{\min}}^{D_{\max}} N(D)\, dD$$

Moments of the DSD

The **DSD** is described by its **moments**:

$$M_n = \int N(D).\,D^n\,dD$$

Order n	Moment Mn	Physical meaning	Units
0	M0	Total number of drops	m^{-3}
1	M1	Mean Drops size	$mm.m^{-3}$
2	M2	Extinction coeff (optical)	$mm^2.m^{-3}$
3	M3	Liquid Water Content (LWC)	$mm^3.m^{-3}$
6	M6	Reflectivity factor (Z)	$mm^6.m^{-3}$

Instrument and their sensitivity to DSD moments:

- Radar → reflectivity Z ($mm^6.m^{-3}$) → M6
- Raingauge → rainfall rate R ($mm.h^{-1}$) → M3.67 (Marshall-Palmer)
- Microwave radiometer → $\propto$ M3 (LWP)
- Lidar → M0 & M2 (α)

Importance of knowing dropsizes

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- Radar reflectivity **$Z \propto D^6$** → a few **large drops** can **dominate Z**
- **Water volume $\propto D^3$** → doesn't grow as fast as Z with drop size

Drop Size	Concentration [#.m^{-3}]	Reflectivity Z	Water volume per cubic meter
1 mm	4096	36 dBZ	2144.6 mm^3
4 mm	1	36 dBZ	33.5 mm^3

Radar reflectivity is highly sensitive to large drops
Two clouds can have the same Z but very different water content

→ **Be cautious when using Z to estimate liquid water content!**

Tomorrow

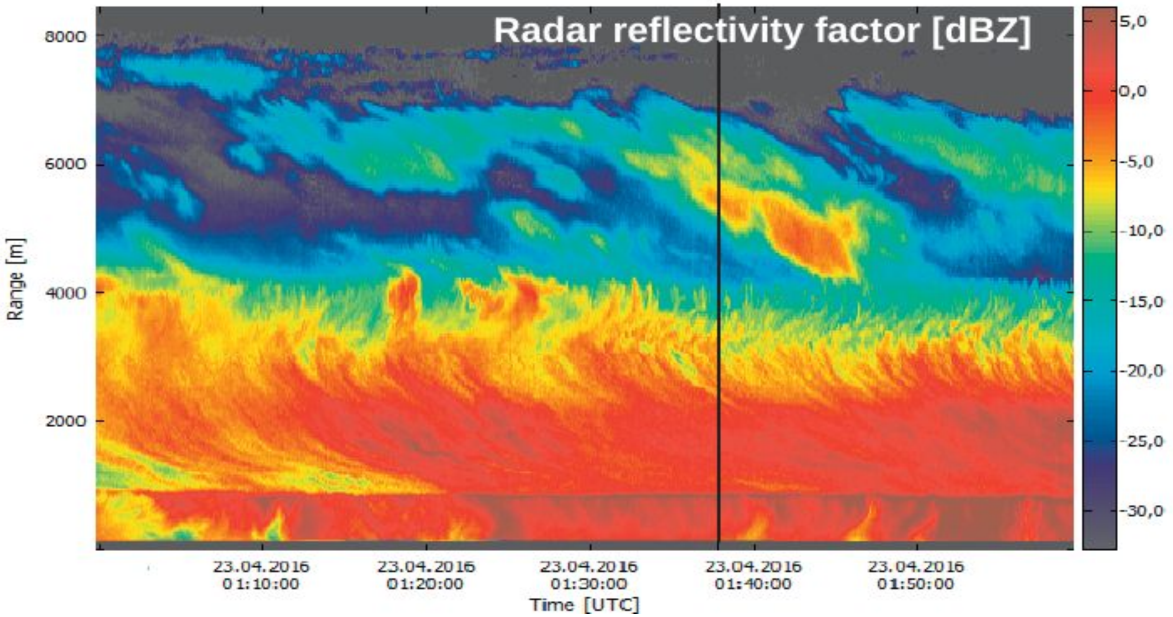
Lecture : Visualization and interpretation of radar doppler spectra 9:00 - 10:30, S. Kneifel (LMU)

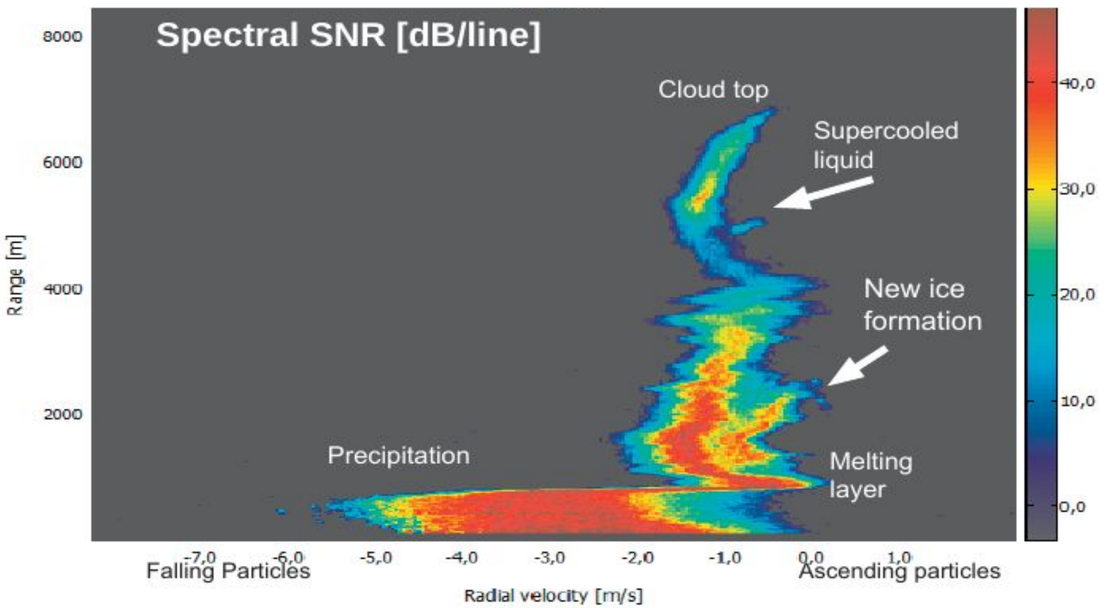
Hands-on : Cloud radar doppler spectra analysis with peako and peaktree, 14:00 - 17:30, M. Radenz (TROPOS)

Doppler Spectra

Doppler Spectra

- **Doppler spectra** provide **more information** than just mean velocity: they show the **full distribution** of **particle fall speeds** in the **radar sampling volume**.
- Because **larger particles** typically **fall faster**, the **Doppler spectrum** helps to infer the **Particle Size Distribution (PSD)**.
- This is especially **useful** for **microphysical retrievals**, such as **distinguishing** between **cloud droplets, raindrops, or snowflakes**.





From RPG documentation, sept 2017

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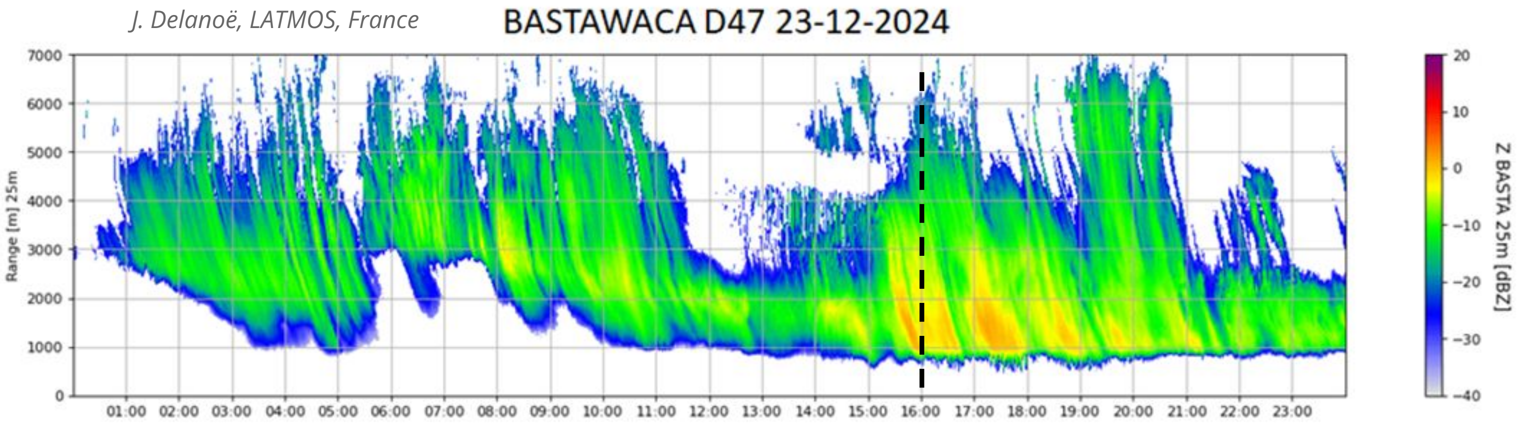
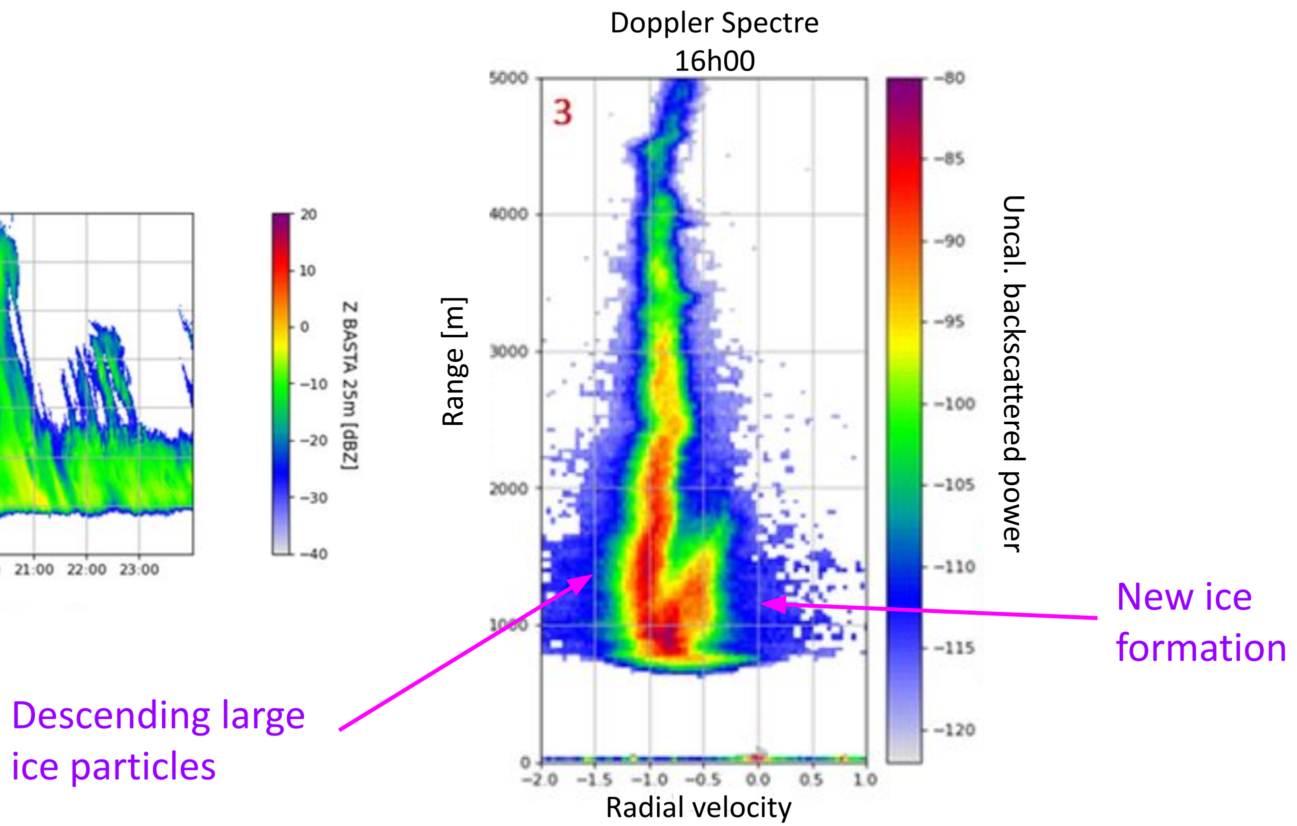


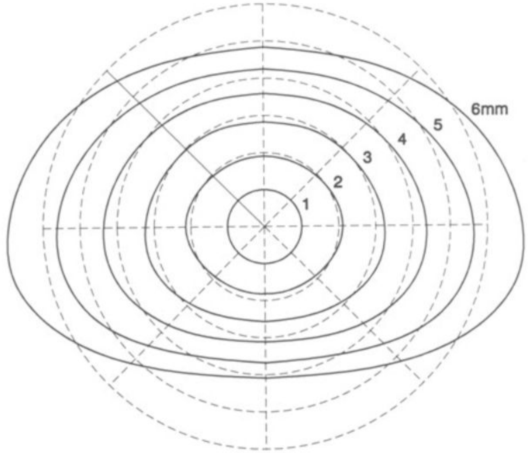
The spectre allows to separate (TBC)



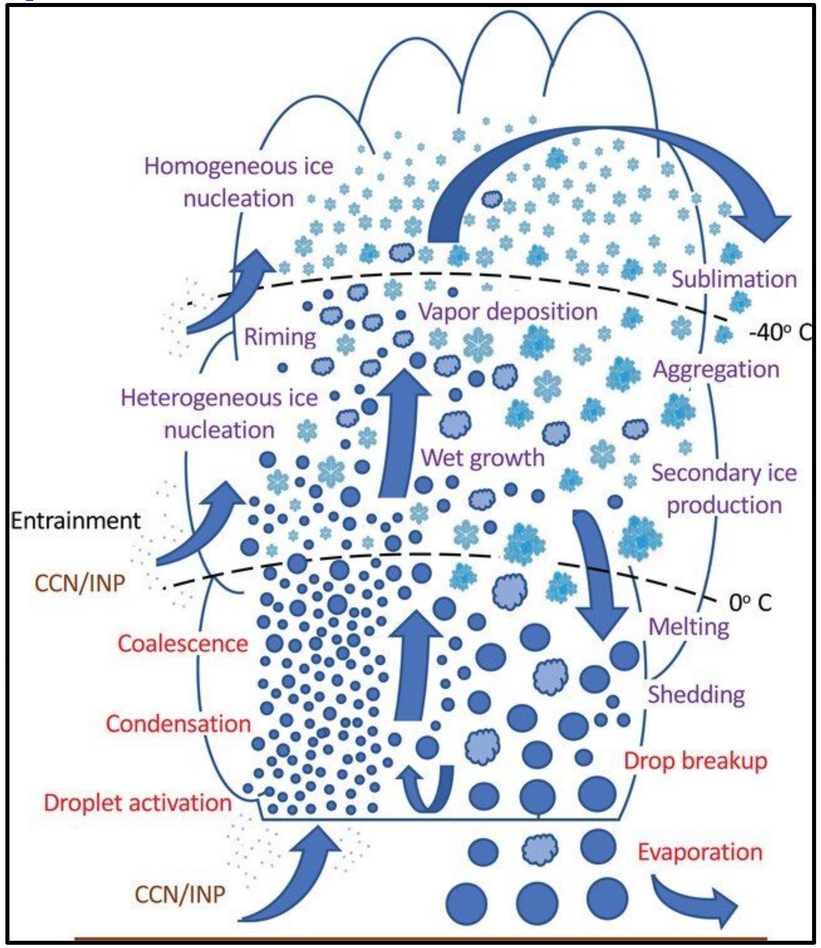
Polarimetry

Can polarimetry add information ?

Yes, because **hydrometeors are not spheres**



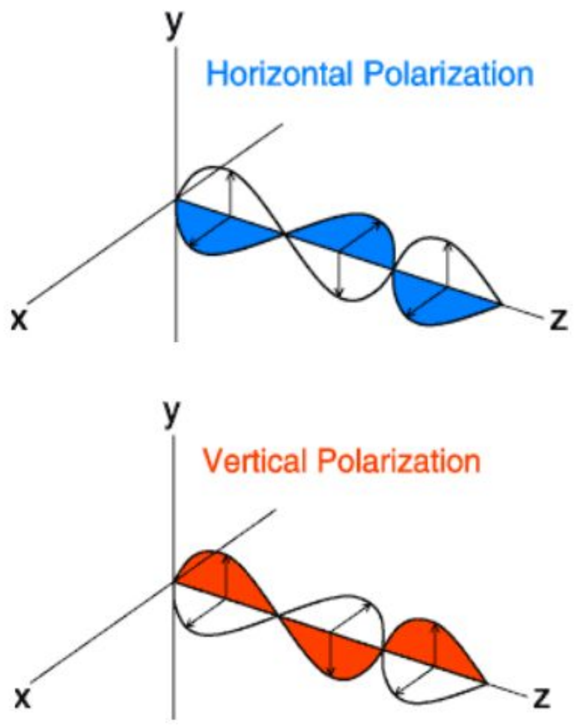
From Beard and Chuang, 1987

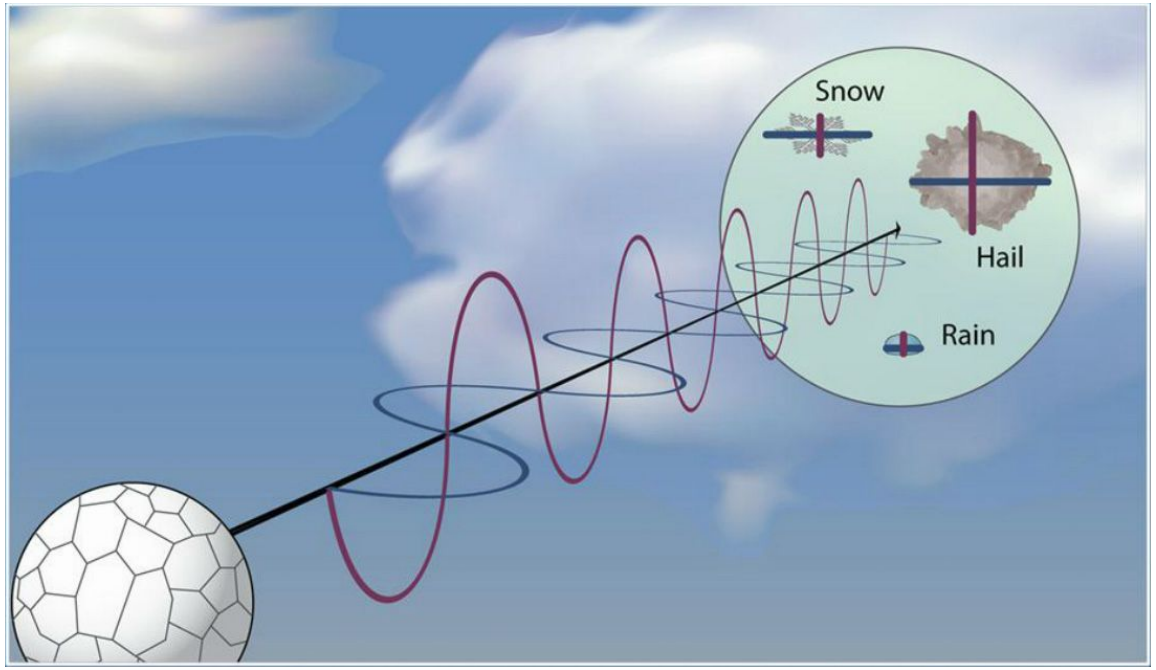


Morrison et al., 2020
https://doi.org/10.1029/2019MS001689

Dual polarization principles

When the **particle** becomes **oblate or prolate**, the backscattering becomes **polarization dependent**





Credit: National Weather Service

Also improves clutter removal, melting layer detection, lightning activity identification, and hail detection, …

Polarimetric operation modes and their implications

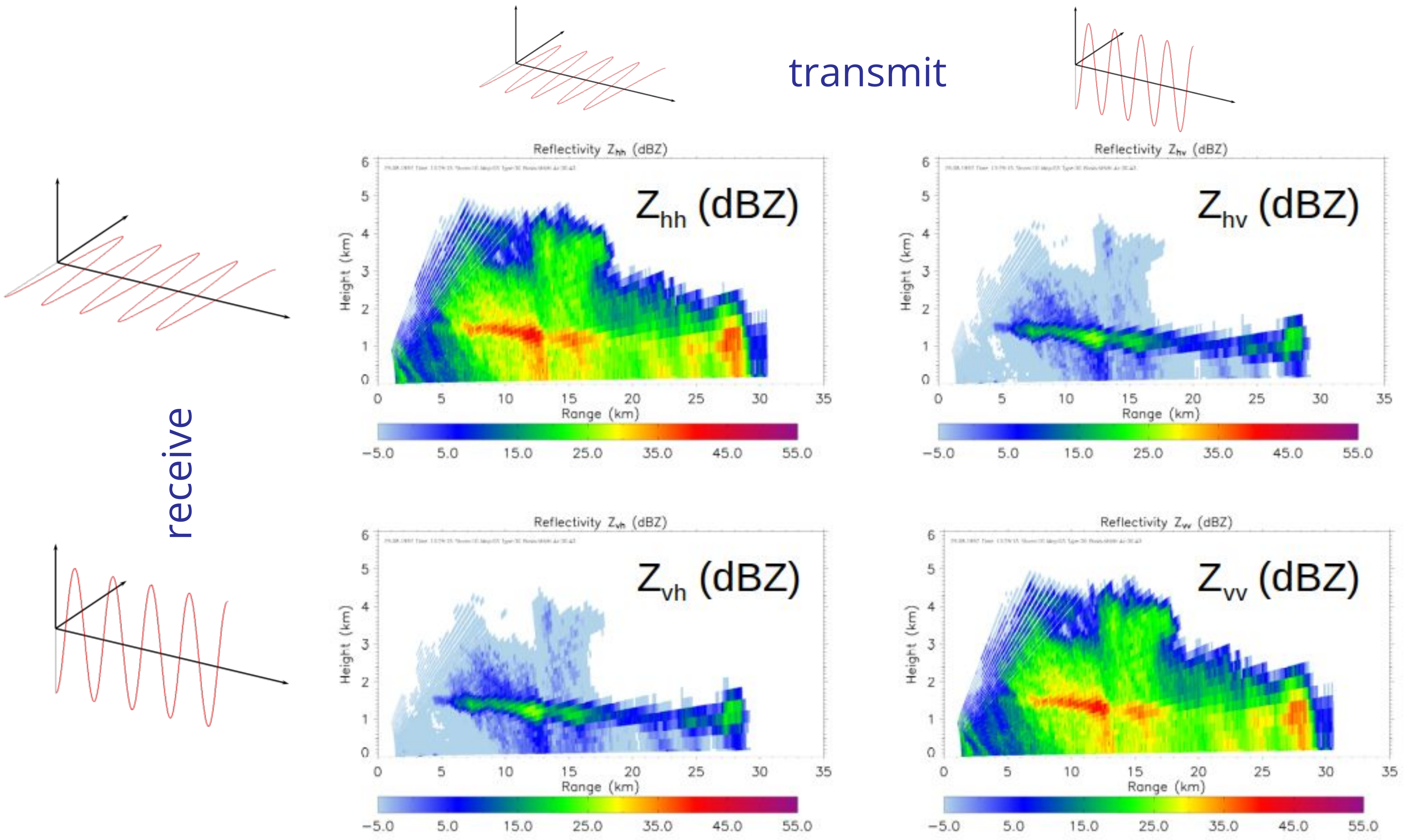
1. **STAR Mode — Simultaneous Transmit and Receive (e.g. Météo-France weather radar)**
    a. Transmit simultaneously in H and V (co-polar).
    b. Receive simultaneously in H and V.
    c. Measures: Z_{DR}, ρ_{HV}, Φ_{DP}, K_{DP}.
    d. Advantage: fast, no switching needed (good time resolution).
    e. Limitation: does not provide pure cross-pol (no LDR or HV→VH).

2. **Alternating H/V Mode (Pulse Switching)**
    a. Transmit alternately H and V pulses.
    b. Receive in same polarization as transmit pulse (H→H, V→V).
    c. Good estimates of Z_{DR}, ρ_{HV}, sometimes LDR.
    d. Common in precipitation radars (e.g. USA NEXRAD).

3. **Cross-Polar/LDR Mode**
    a. Transmit in H (or V), receive in orthogonal polarization (V or H).
    b. Allows measurement of LDR and cross-polar correlation.
    c. Requires dedicated or sequential setup.
    d. Typical for **cloud radars**, to study depolarization and phase.

Access to **DPOL variables depends** on the chosen **polarimetric mode**.

DPOL observations



NB: capability here to receive the co- and cross-polar component

From H. Russchenberg, TU Delft Master lesson on cloud radar 2015
Data: POLDIRAD (DLR, Oberpfaffenhofen, Germany), Prof. Madhu Chandra

Dual Polarization variables : STAR mode

Z_{DR}: Differential reflectivity [dB]

- $Z_{DR} = Z_H - Z_V$ [dB]
- Indicates particle shape/orientation (oblate raindrops vs spherical ice crystals)

ϕ_{DP} : Differential Phase [°]

- $\phi_{DP} = \phi_H - \phi_V$ [°]
- Sensitive to particle shape and concentration. Useful for identifying liquid water content and melting layers

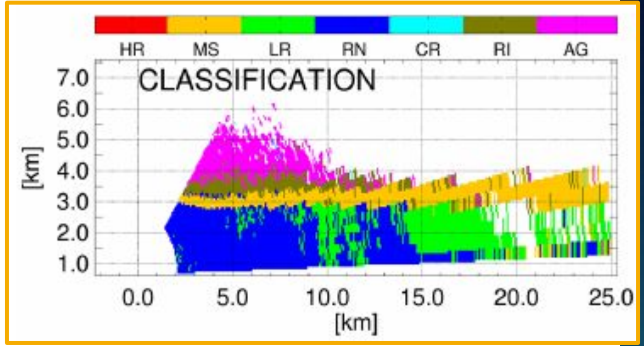
K_{DP}: Specific differential phase [°.km^{-1}]

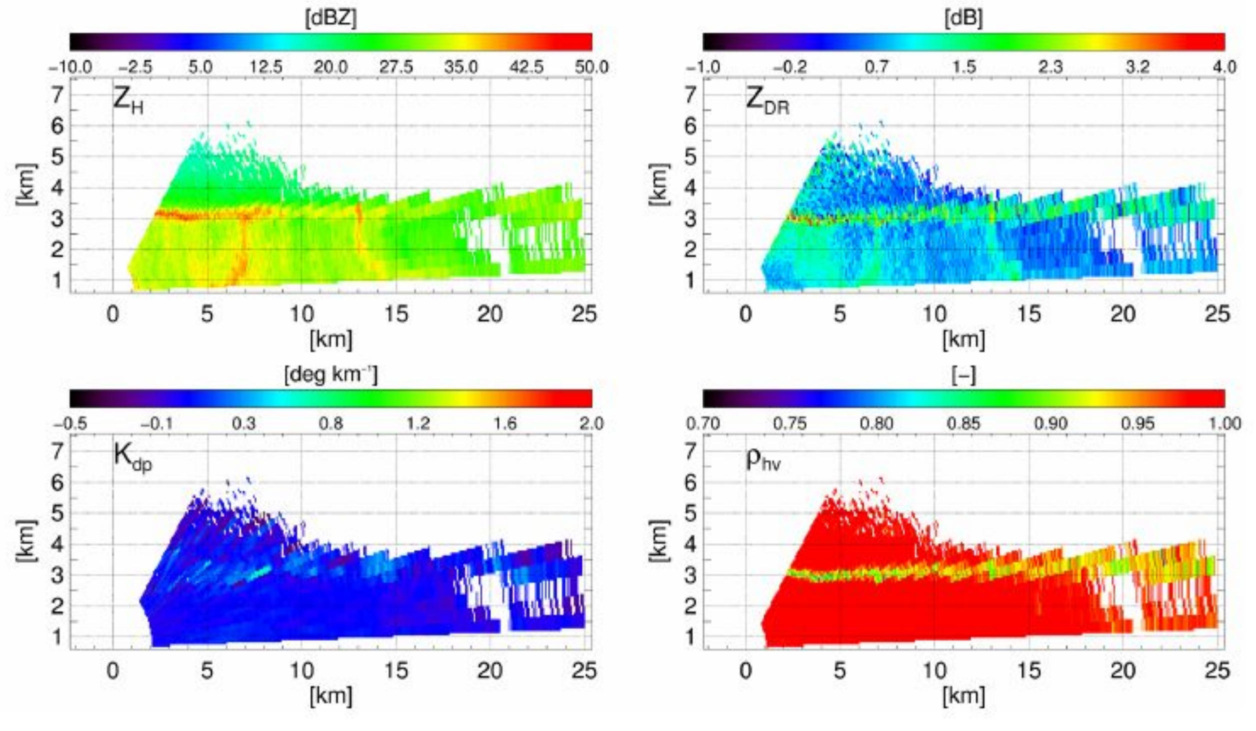
$$K_{DP} = \int_{r}^{r+\delta r} \left(\frac{d\Phi_{DP}}{dr} \right) [^\circ \cdot \mathrm{km}^{-1}]$$

- Independent of radar calibration
- ~ unaffected by attenuation/blocking

ρ_{HV} : Correlation coefficient [-]

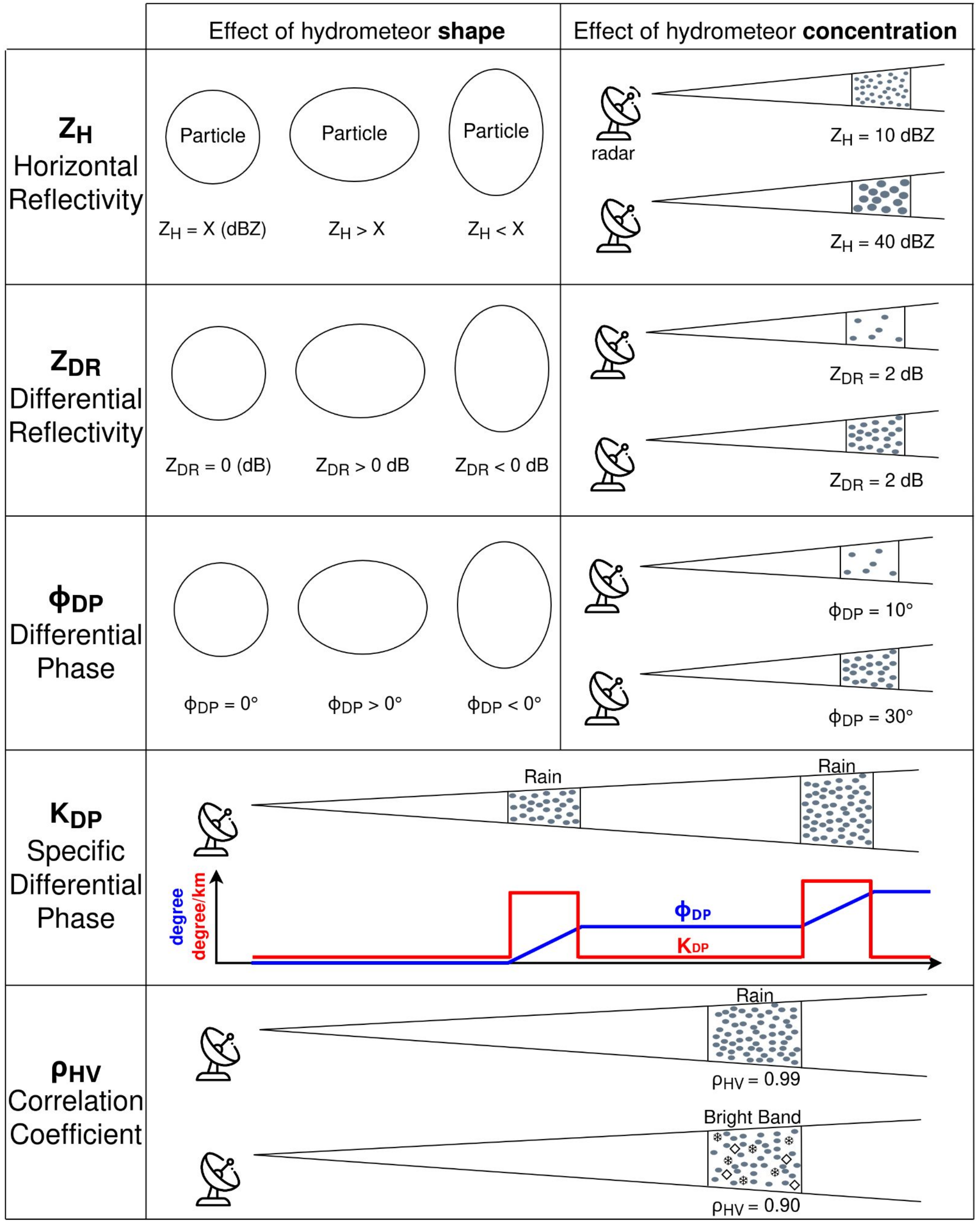
- Cross-correlation between horizontally/vertically polarized returned signals
- Measures similarity between the 2 polarization channels.
- High values indicate uniform particle type/shape
- Useful for detecting melting layer, hail





From Grazioli et al., 2015
X-band DPOL radar

Dual Polarization variables: STAR mode



Dual Polarization variables: cross-polar mode

LDR: Linear Depolarization Ratio [dB]

- Ratio of cross-polarized power to co-polarized power (typically horizontal transmission and vertical reception)
- Indicates particle shape irregularities, nonsphericity, and orientation diversity

Co-Cross Channel Correlation Coefficient [-]

- Correlation between co-polarized and cross-polarized channels
- Provides additional discrimination of particle types and helps identify complex scattering mechanism
- Usually low values [0.4-0.8]

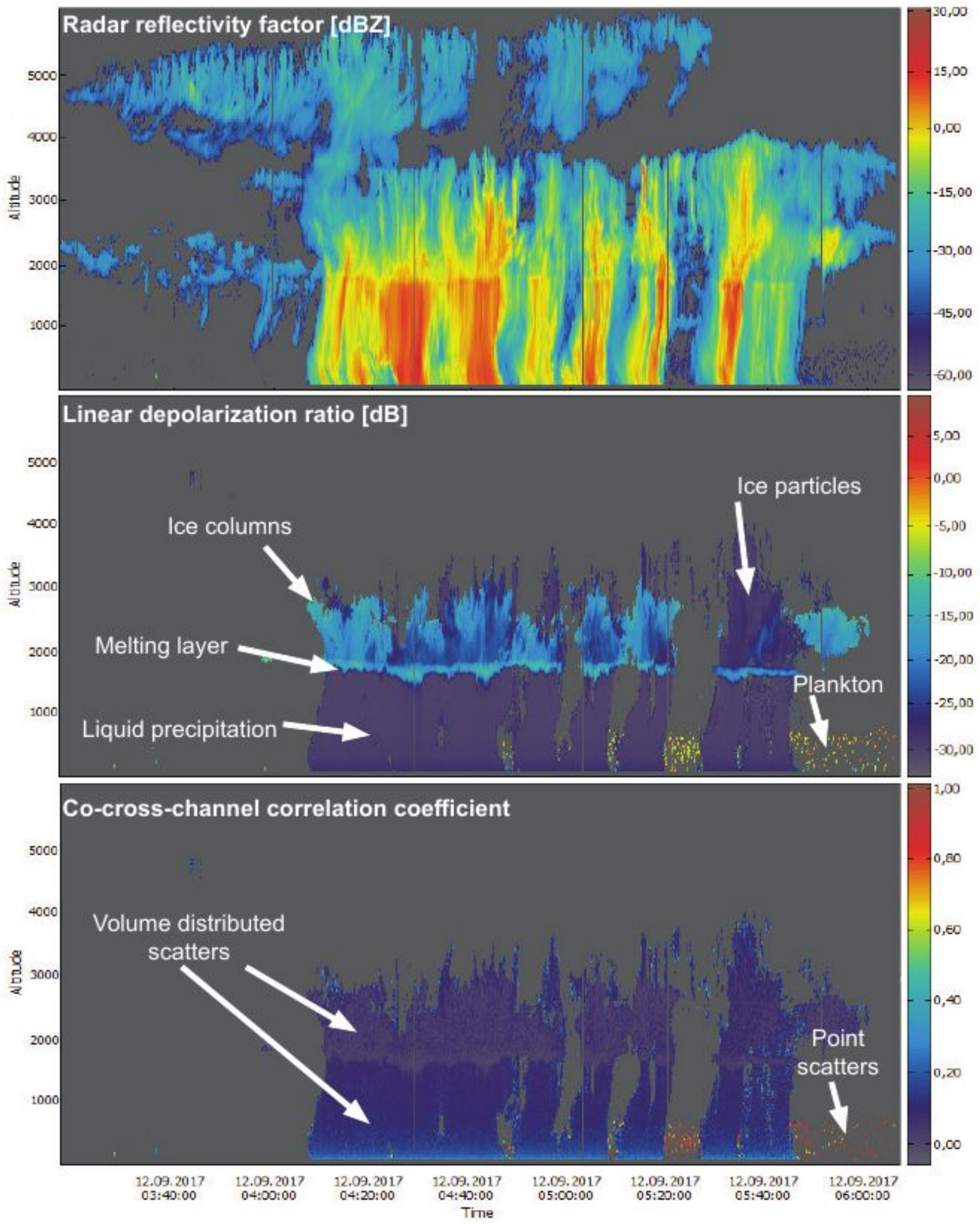


Fig. 10. Example of polarimetric observations in the LDR-mode. Time-height cross-sections of the radar reflectivity (upper panel), linear depolarization ratio (middle panel), and co-cross-channel-correlation coefficient (lower panel). During the measurements the radar was pointed vertically. Measurements were taken at the RPG site, Meckenheim, Germany.

From RPG documentation, sept 2017

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Thank you !