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Introduction to weather radar

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Pyrad course

Contents

1. Introduction

Definition

RADAR = **RA**dio **D**etection **A**nd **R**anging

Cambridge Dictionary : a device or system for finding the position or speed of objects, such as aircraft, that cannot be seen, by measuring the direction and timing of short radio waves that are sent out and reflect back from the objects

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Purpose of a weather radar

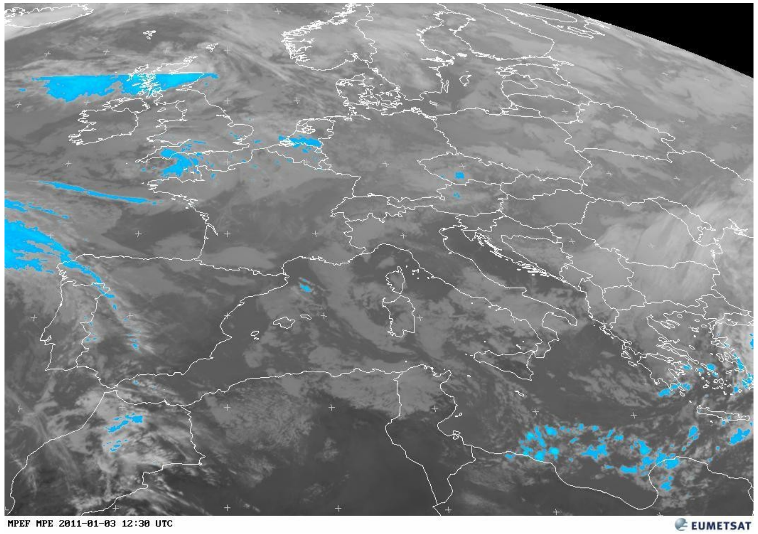
The main purpose of a weather radar is to locate precipitation, calculate its motion and intensity and estimate its type

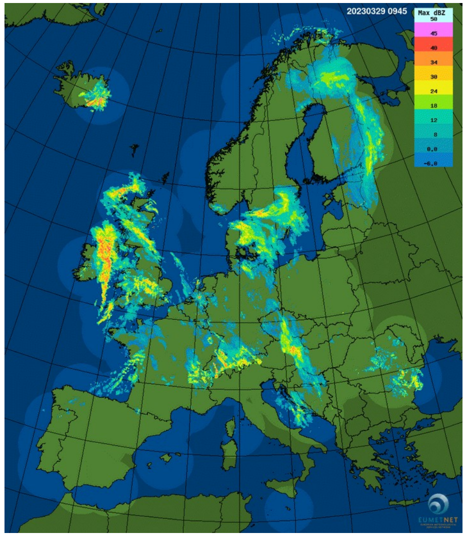


But other objects are also detected



Instruments for precipitation detection





MSG : Multi-Sensor Precipitation Estimate (MPE)

Continental scale

15 min, 5 km

Indirect measurement

Better at low latitudes and for convective precipitation

Radar networks:

Range up to 400 km

~5 min, ~1 km

Indirect measurement

e.g 33 radars in France

Rain gauges networks :

0.1m scale

~10 min, 1h, 24h

Direct measurement

e.g. 551 real time RG in France

Why weather radar ?

Weather radar only instrument that provides :

- Real time measurements
- 3D images of precipitation
- High temporal and spatial resolution
- For a wide range of precipitation intensity (from drizzle to hail)
- At a long range (up to 400 km)

BUT

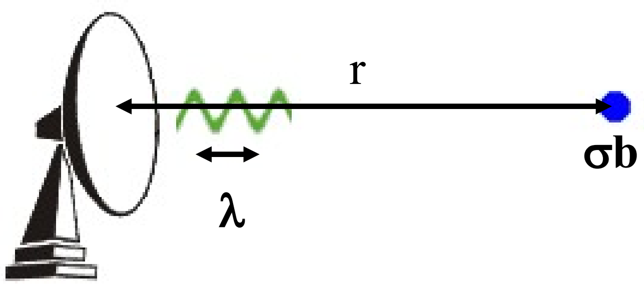
It is an indirect measurement and a lot of effort is required to go from measured voltage to mm/h

2. Principles of weather radar

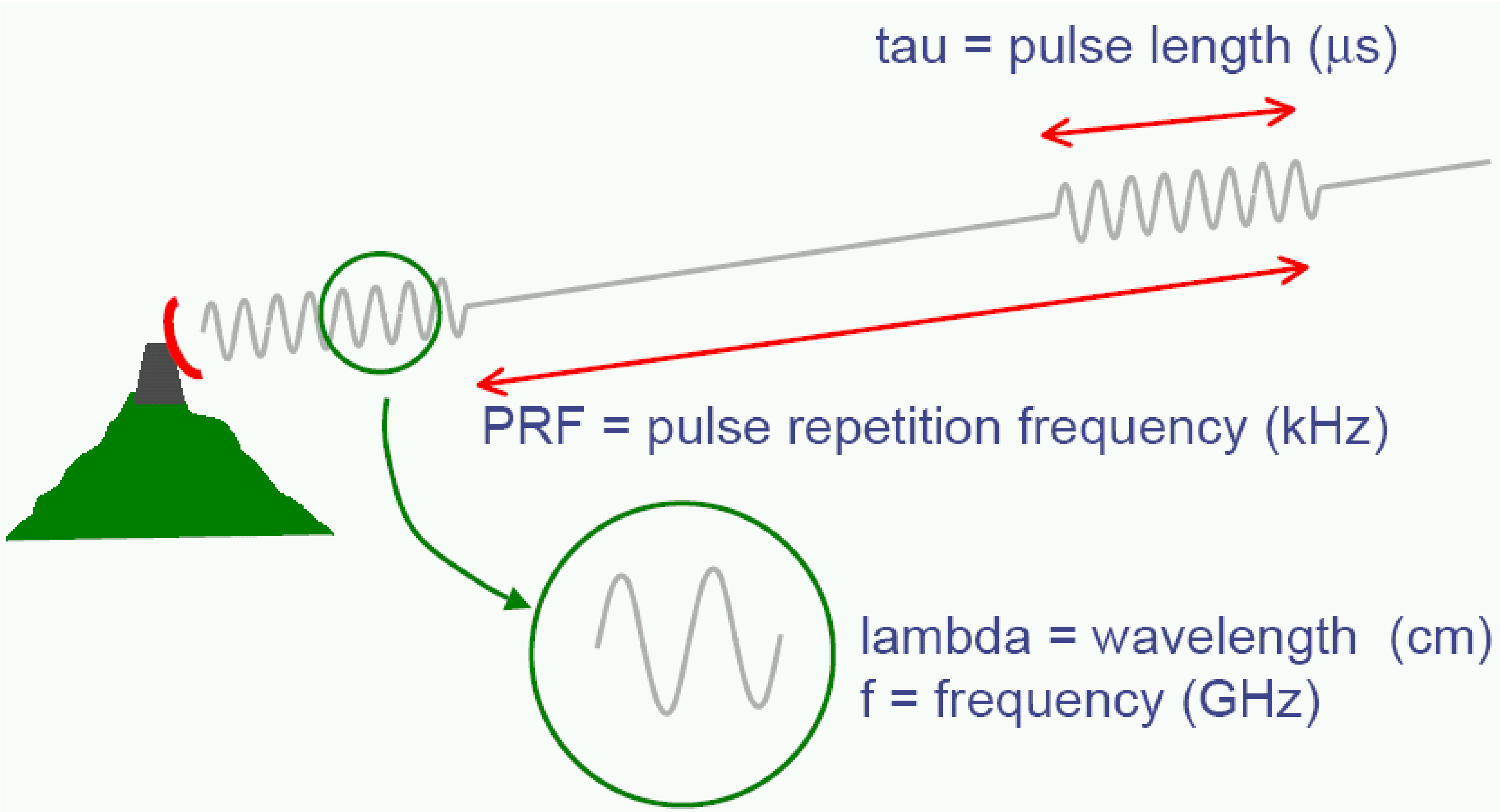
How it works (pulsed radar)

Emission to the atmosphere at regular intervals (PRT) of a pulse of energy of short duration (τ) and high power Pt and frequency (f, λ). The pulse is emitted by a directive antenna observing at a certain elevation (α) and azimuth (β) angles through a beam of angular size θ.

The scatterers at a particular range (r) absorb part of the energy and radiate in all directions. A small fraction of power (P_r) is sent back to the radar.



How it works


tau = pulse length (µs)
PRF = pulse repetition frequency (kHz)
lambda = wavelength (cm)
f = frequency (GHz)

How it works

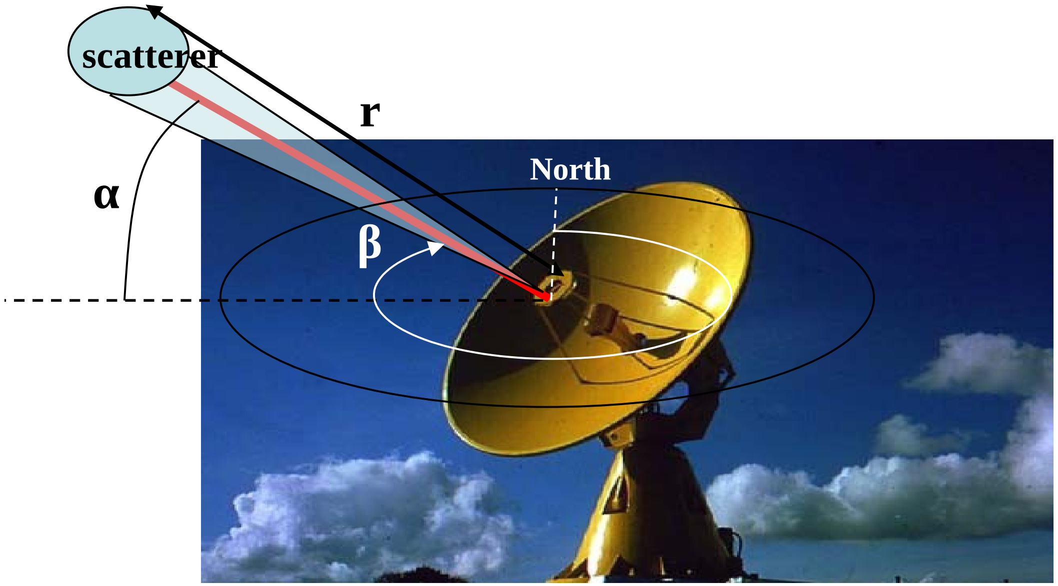
Geographical location

The scatterers are characterized with respect to the radar :

Radial distance : $r = \frac{c\,\Delta t}{2}$

Azimuth : β

Elevation : α

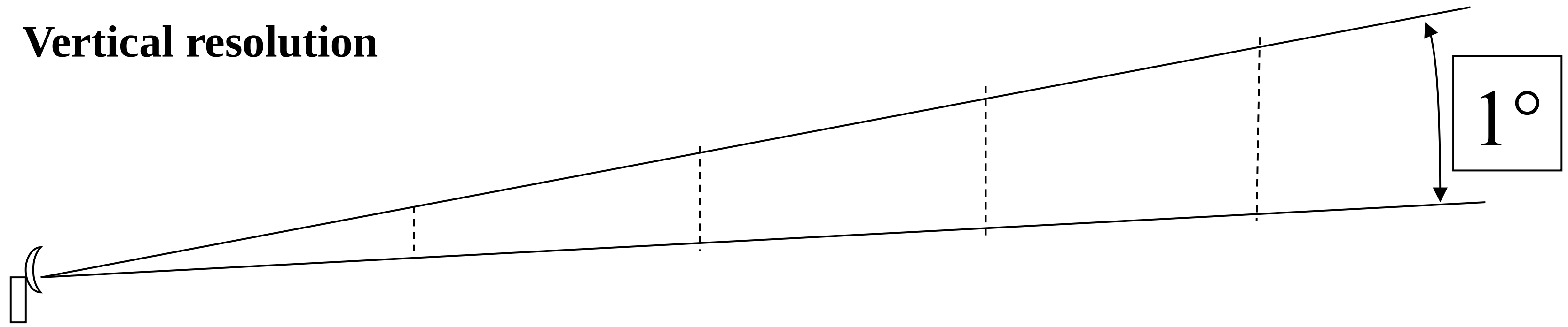


Physical properties

Received signal with respect to the distance of the scatterer

Resolution

Vertical resolution



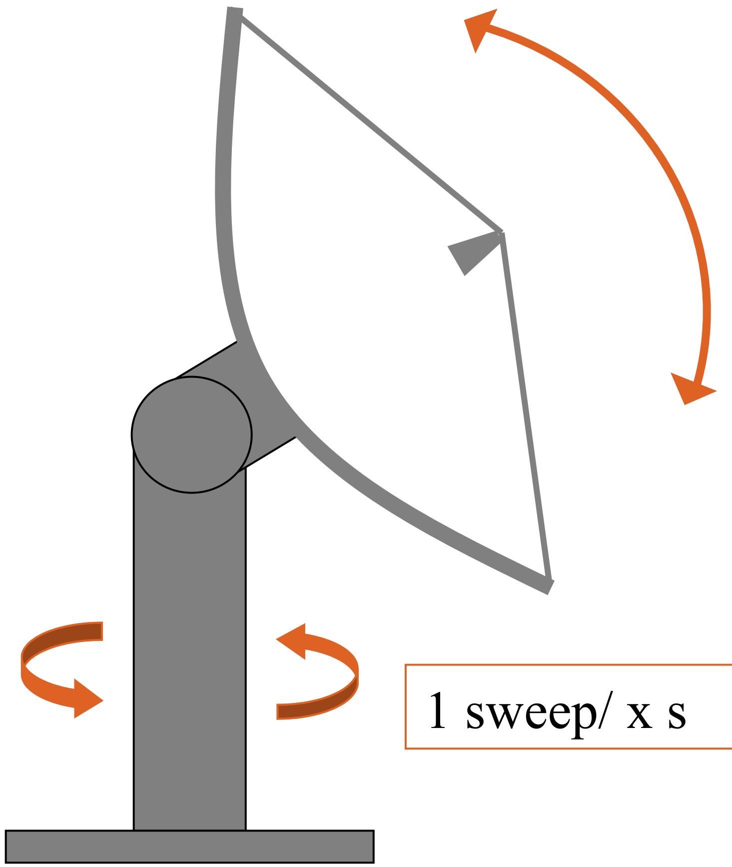
Range :	50 km	100 km	150 km	200 km
Vertical resolution :	0.9 km	1.8 km	2.6 km	3.5 km

Horizontal resolution in azimuth = vertical resolution
Horizontal resolution in distance: Depends on the speed of light and the pulse duration

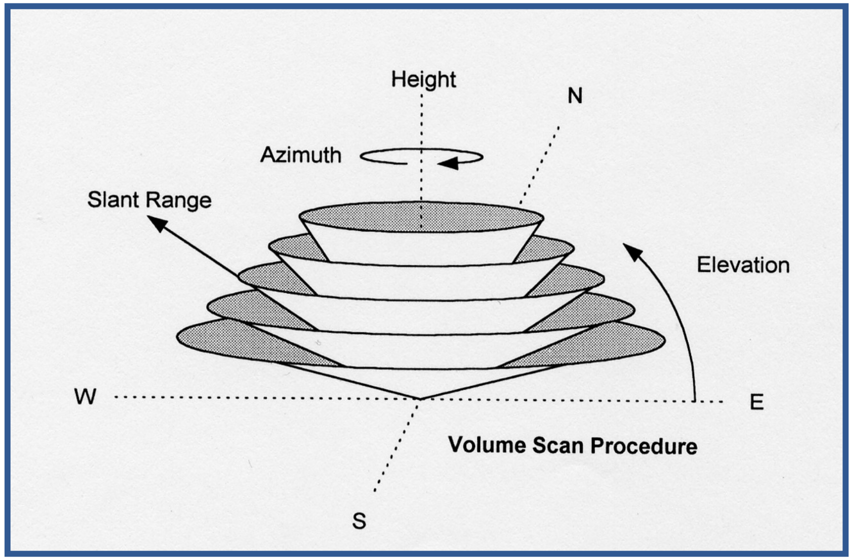
$$\Delta r = \frac{c\,\tau}{2}$$

Scanning strategy

x elevations / x min



1 sweep/ x s



Radar wavelength

The choice of the radar wavelength is determined by the size of the scatterer that has to be observed.

The wavelength should be an order of magnitude larger than the scatterer

Larger wavelength require larger antennas to obtain the same beamwidth

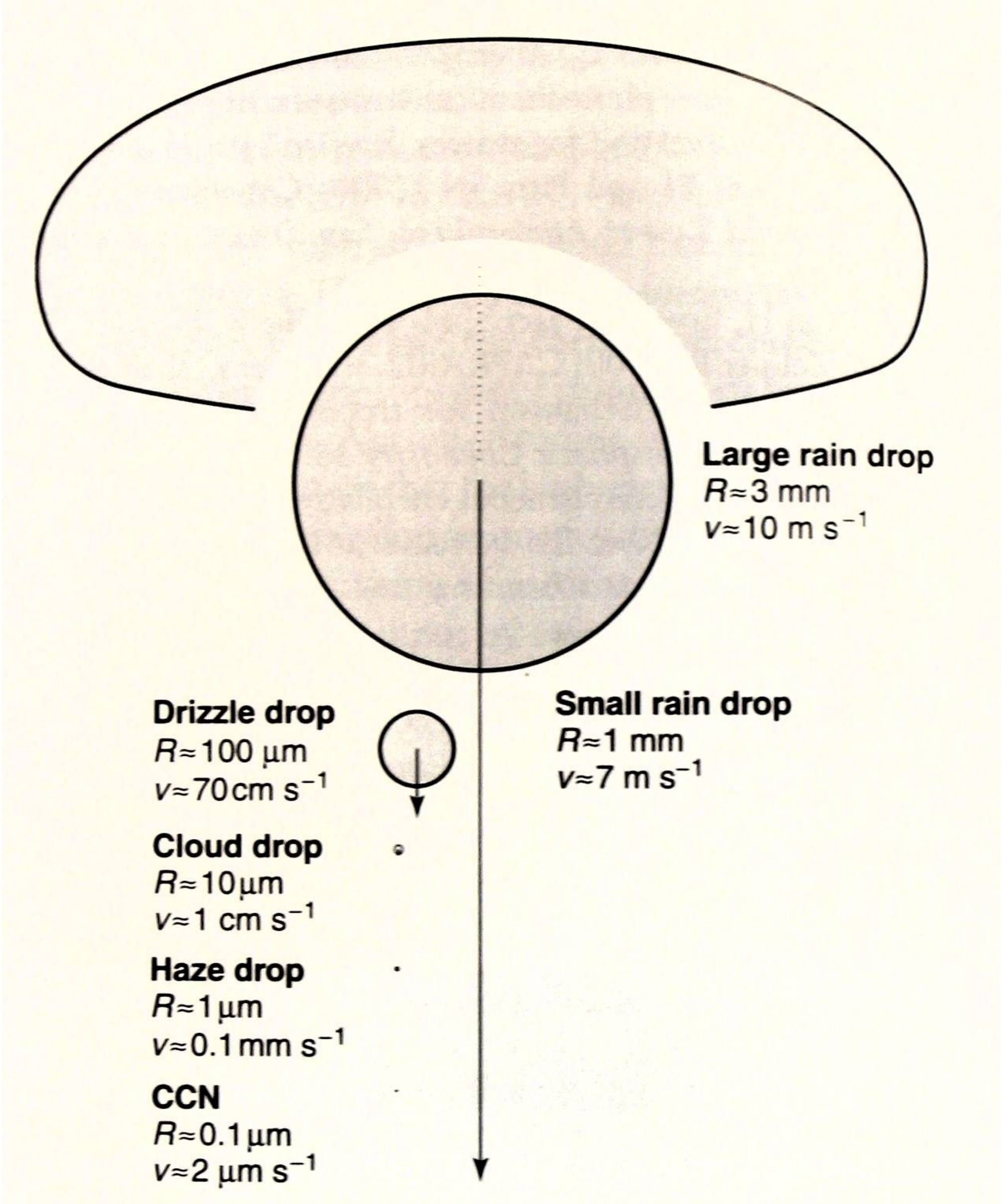
Typical hydrometeor sizes :

Drizzle drop : 0.1 to 0.5 mm

Rain drop : 0.5 to 5 mm

Snowflake : 2 to 5 mm

Hailstone : 5 to 50 mm



Radar wavelength

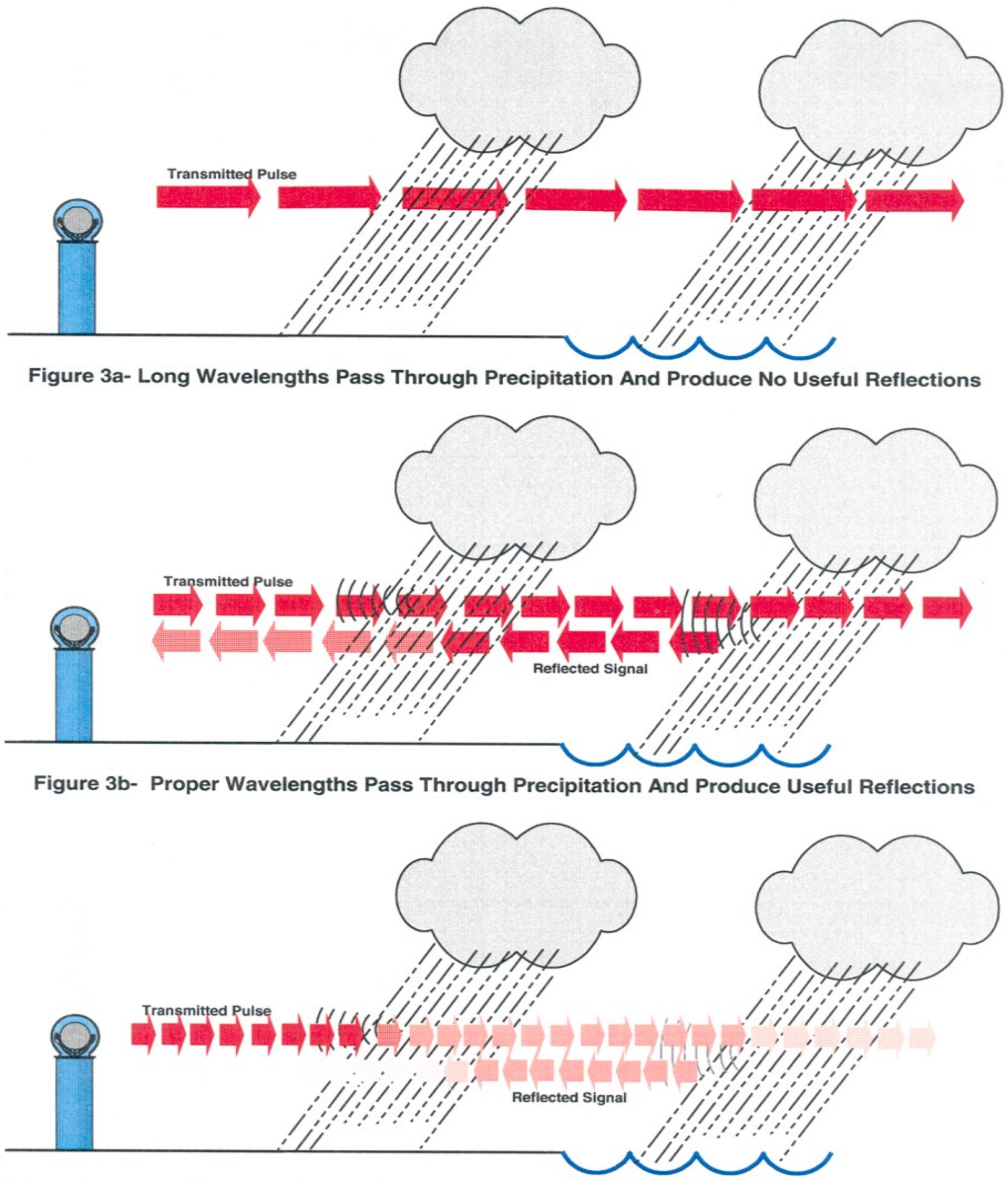


Figure 3a- Long Wavelengths Pass Through Precipitation And Produce No Useful Reflections

Figure 3b- Proper Wavelengths Pass Through Precipitation And Produce Useful Reflections

Figure 3c- Short Wavelengths Are Absorbed By Precipitation And Produce No Useful Reflections

Radar wavelength

wavelength (cm)	1	3	5	10	20
frequency (GHz)	30	10	6	3	1.5
Band	K	X	C	S	L
usage	clouds	precipitation	precipitation	precipitation	aeronautical

3. The weather radar equation

Radar equation for weather radar

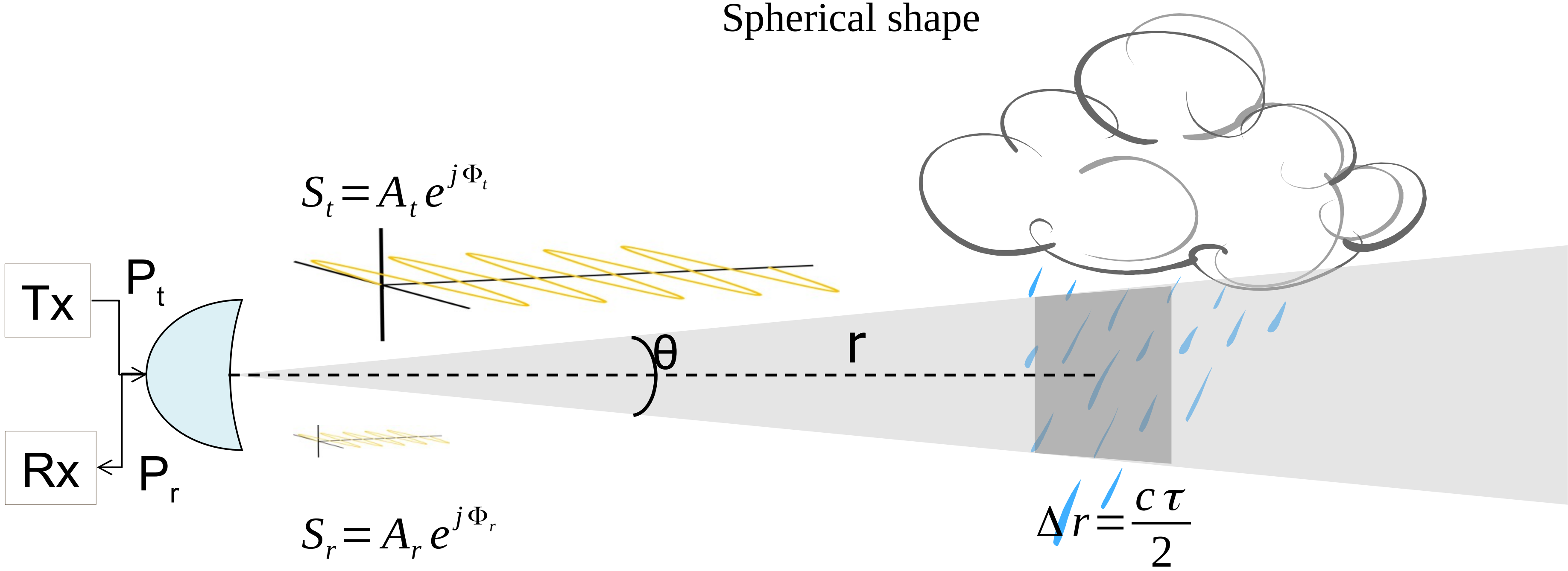
$$P_r(r)=\underbrace{\overbrace{\frac{P_t}{4\pi r^2}}^{\text{Power density incident on target}} G_t \frac{1}{4\pi r^2}\sigma(r)}_{\text{Power density at Rx antenna}}\underbrace{\frac{G_r\lambda^2}{4\pi}}_{\text{Rx antenna aperture}}$$

Uniform beam filling
Gaussian antenna pattern

$$\sigma(r)=V(r)\sum_{\forall i}\sigma_i(r)=\pi r^2\frac{\theta^2}{4}\frac{c\tau}{2}\frac{1}{2\ln 2}\sum_{\forall i\in V_{unit}}\sigma_i(r)$$

$$\sum_{\forall i\in V_{unit}}\sigma_i(r)=\sum_{\forall i\in V_{unit}}\frac{\pi^5|K_w|^2 D_i^6(r)}{\lambda^4}$$

Rayleigh scattering
Spherical shape



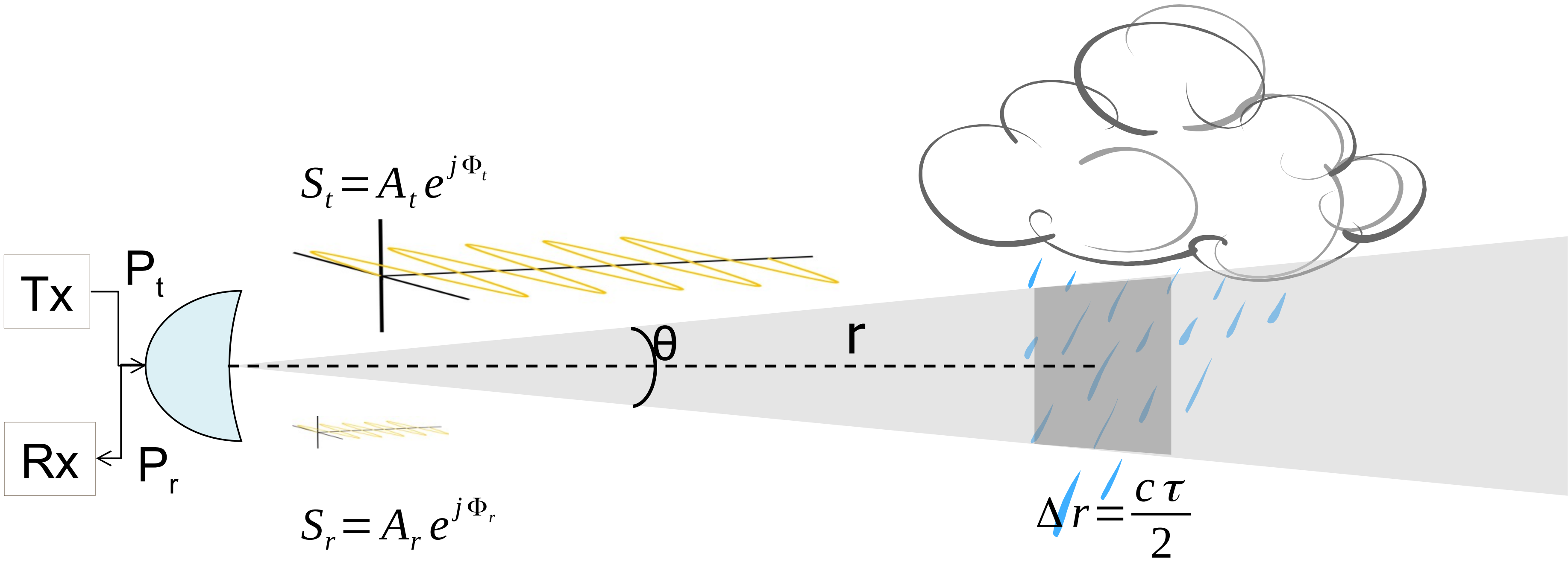
Radar equation for weather radar

$$P_r(r) = \frac{P_t}{4\pi r^2} G_t \frac{1}{4\pi r^2} \sigma(r) \frac{G_r \lambda^2}{4\pi} = \frac{\pi^3 P_t G_t G_r \theta^2 \tau c}{1024 \ln 2 \lambda^2} \frac{1}{r^2} |K_w|^2 z(r) = \frac{|K_w|^2}{Cr^2} z(r); [W]$$

$$z(r) = \sum_{\forall i \in V_{unit}} D_i^6 = \int_0^\infty N(D,r) D^6 dD; \left[\frac{mm^6}{m^3}\right]$$

$$LWC(r) = \int_0^\infty N(D,r) V_d(D) dD; \left[\frac{mm^3}{m^3}\right]$$

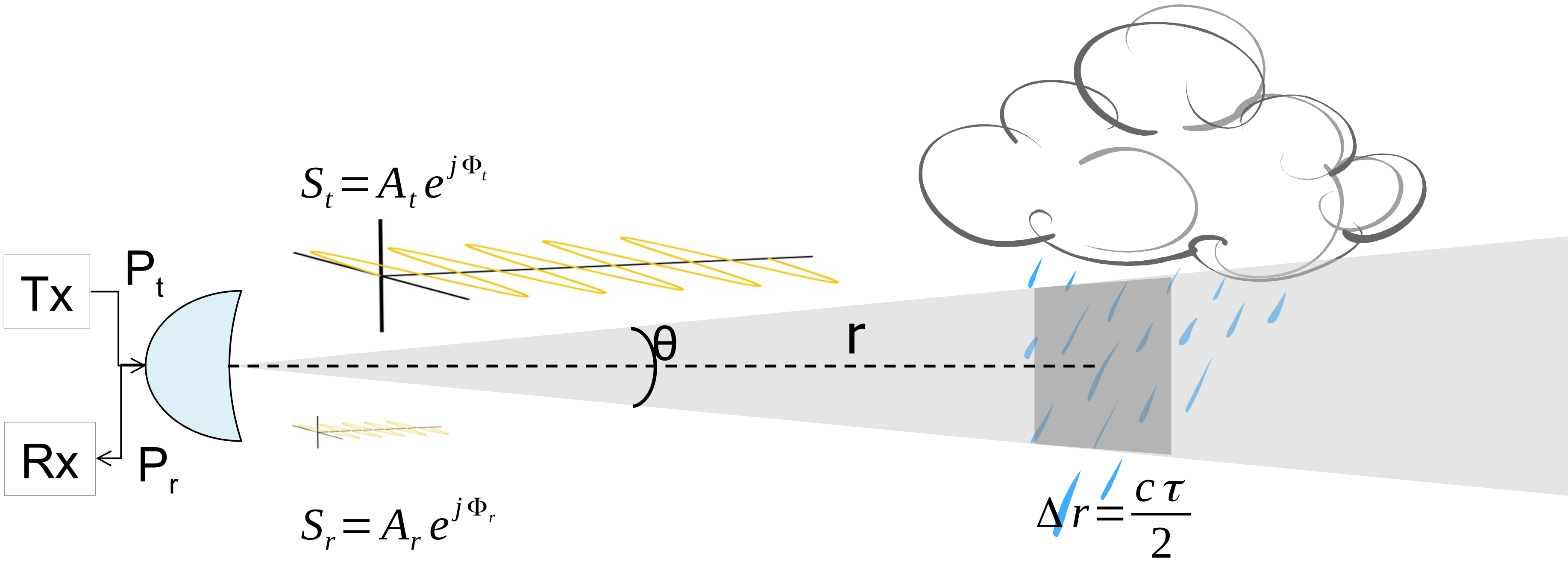
$$R(r) = \int_0^\infty N(D,r) V_d(D) v_t(D) dD; \left[\frac{mm}{h}\right]$$



Radar equation for weather radar

$$P_r(r) = \frac{|K_w|^2}{Cr^2} z(r) \qquad P_r^{obs}(r) = P_r(r) + P_n$$

$$\boxed{z(r) = C\left(P_r^{obs}(r) - P_n\right)\frac{L_{atm}^2(r)}{|K_w|^2} r^2}$$



Relationship reflectivity - rainfall rate

$$z(r)=\int_0^\infty N(D,r)D^6 dD = a\left(\int_0^\infty \underbrace{N(D,r)}_{\text{Depends on type of precip}} V_d(D)\underbrace{v_t(D)}_{\text{Empirically derived}} dD\right)^b = aR^b$$

Parameters a and b depend on knowledge of Particle Size Distribution PSD N(D, r)

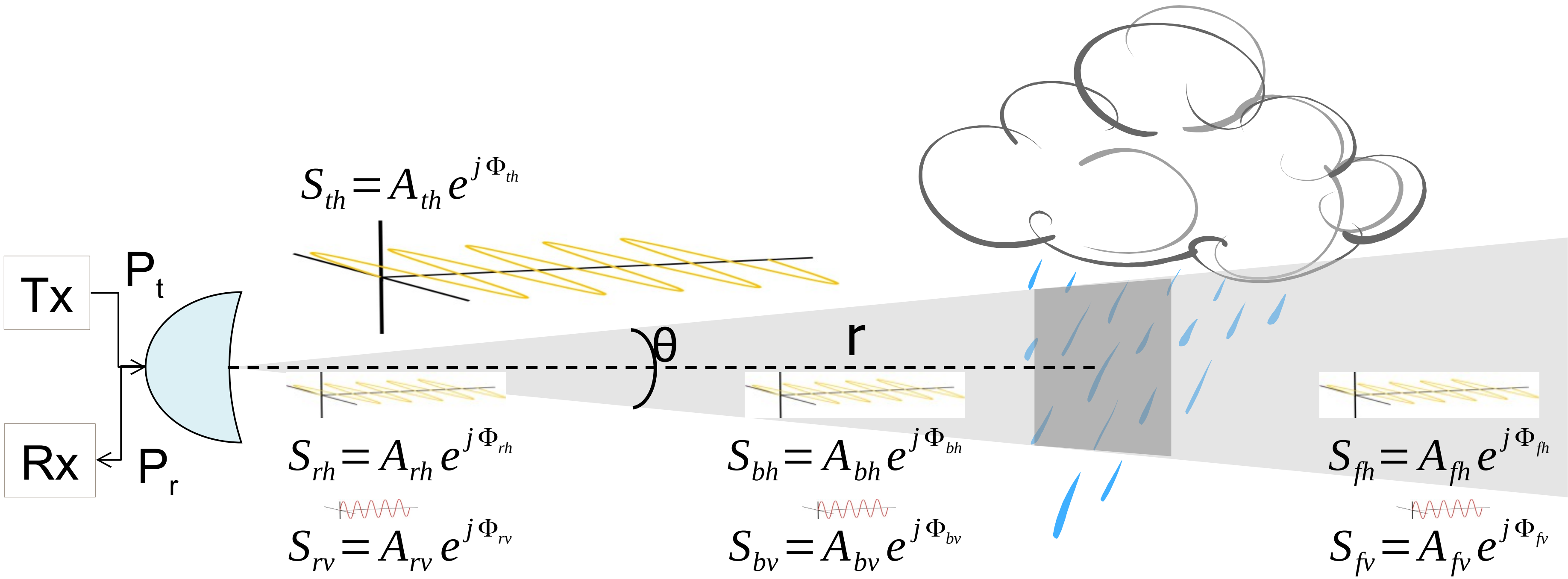
Most likely a and b can be derived statistically using long-term observations

However, individual precipitation events may deviate significantly from the average relationship

Use of auxiliary information to better characterize the PSD

4. Polarimetry

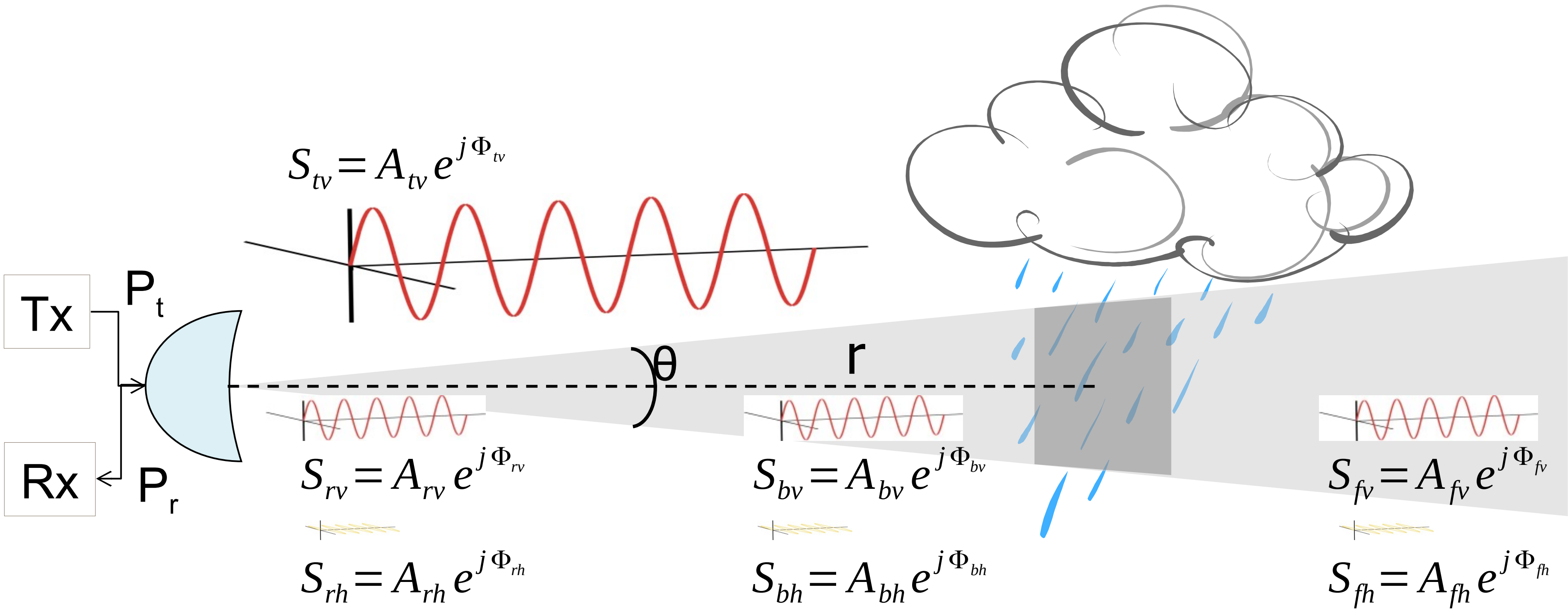
Polarimetry



Polarimetry

$$S_b=\begin{pmatrix} S_{b_{vv}} & S_{b_{vh}} \\ S_{b_{hv}} & S_{b_{hh}} \end{pmatrix} \qquad \sigma_{b_{xx}}=4\pi|S_{b_{xx}}|^2$$

$$S_f=\begin{pmatrix} S_{f_{vv}} & S_{f_{vh}} \\ S_{f_{hv}} & S_{f_{hh}} \end{pmatrix} \qquad \sigma_{e_{xx}}=2\cdot 10^{-3}\Im\{S_{f_{xx}}\}$$



Polarimetric variables

$$z_{e_{xx}} = \frac{\lambda^4}{\pi^5} \frac{1}{|K_w|^2} 10^6 \int_0^\infty N(D) \sigma_{b_{xx}}(D) dD \quad \Rightarrow \quad Z_{dr} = 10 \log\left(\frac{z_{hh}}{z_{vv}}\right)$$

$$LDR_h = 10 \log\left(\frac{\int_0^\infty N(D) |S_{b_{hv}}(D)|^2 dD}{\int_0^\infty N(D) |S_{b_{hh}}(D)|^2 dD}\right)$$

$$\rho_{hv} = \frac{4\lambda^4}{\pi^4} \frac{1}{|K_w|^2} 10^6 \frac{\left|\int_0^\infty N(D) S_{b_{hh}}(D) S^*_{b_{vv}}(D) dD\right|}{\sqrt{z_{hh} z_{vv}}}$$

$$A_{xx} = 4.34 \cdot 10^3 \int_0^\infty N(D) \sigma_{e_{xx}}(D) dD$$

$$\underbrace{\delta_{co} = \frac{180}{\pi} arg\left[\int_0^\infty N(D) S_{b_{hh}}(D) S^*_{b_{vv}}(D) dD\right]}_{\text{Backward scattering}}$$

$$\underbrace{KDP = \frac{180}{\pi} \lambda \int_0^\infty N(D) \Re\{S_{f_{hh}}(D) - S_{f_{vv}}(D)\} dD}_{\text{Forward scattering}}$$

STAR polarimetric measurements

$$z_{ehh}(r)=C_{hh}\left(P_{r_{hh}}(r)-P_{n_{hh}}\right)\frac{L_{atm_{hh}}{}^{2}(r)}{|K_w|^2}r^2$$

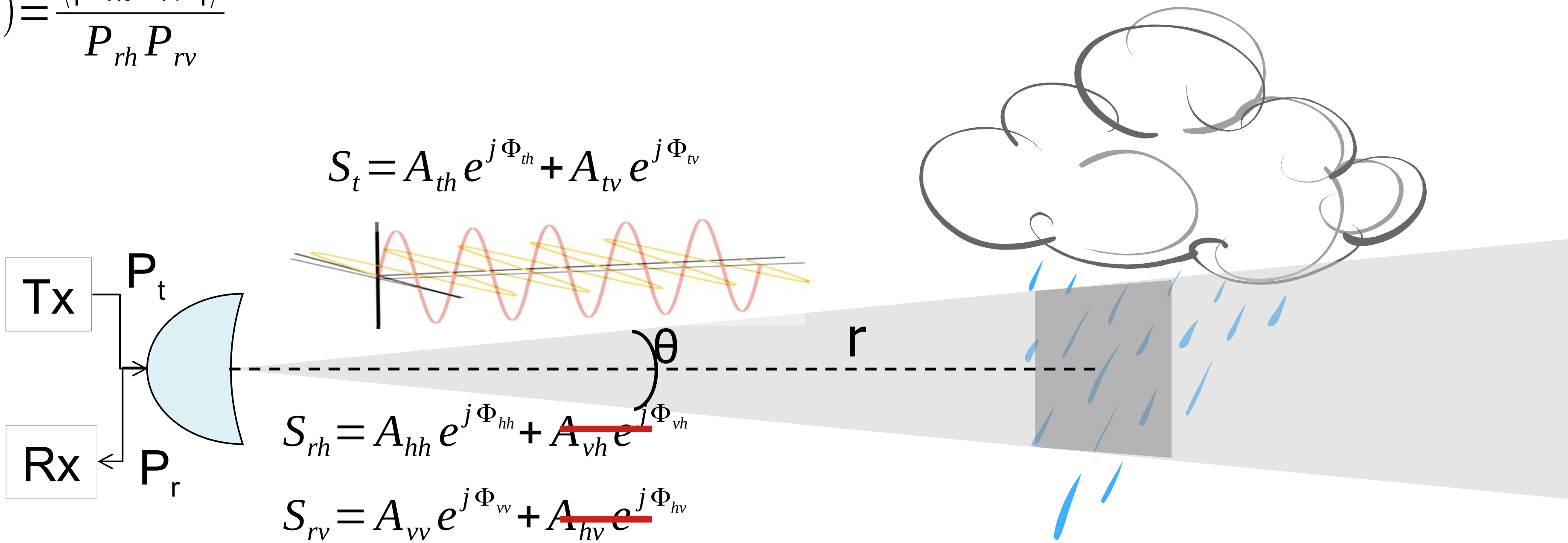
$$z_{evv}(r)=C_{vv}\left(P_{r_{vv}}(r)-P_{n_{vv}}\right)\frac{L_{atm_{vv}}{}^{2}(r)}{|K_w|^2}r^2$$

$$Z_{dr}=10\log\left(\frac{z_{hh}}{z_{vv}}\right)$$

$$\Phi_{dp}(r)=\Phi_{hh}(r)-\Phi_{vv}(r) \Rightarrow K_{dp}(r)=\frac{1}{2}\frac{d\Phi_{dp}(r)}{dr}=\frac{\Phi_{dp}(r_2)-\Phi_{dp}(r_1)}{2\Delta r}$$

$$\rho_{hv}(r)=\frac{\left\langle\left|S_{rh}S_{rv}{}^{*}\right|\right\rangle}{P_{rh}P_{rv}}$$

$$S_t=A_{th}e^{j\Phi_{th}}+A_{tv}e^{j\Phi_{tv}}$$



$$S_{rh}=A_{hh}e^{j\Phi_{hh}}+\cancel{A_{vh}e^{j\Phi_{vh}}}$$

$$S_{rv}=A_{vv}e^{j\Phi_{vv}}+\cancel{A_{hv}e^{j\Phi_{hv}}}$$

Polarimetric radar observations

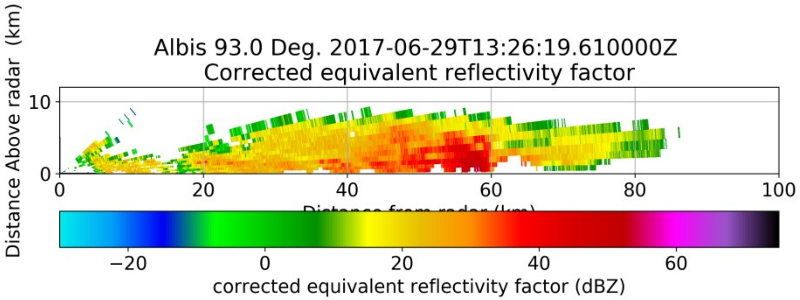
$$z_{hh}^{obs}(r) = z_{hh}(r) - 2\int_0^r a_h(r)\,dr - 2\,a_h^{radome} + \Delta Z_{hh} + \sigma_{z_{hh}}$$

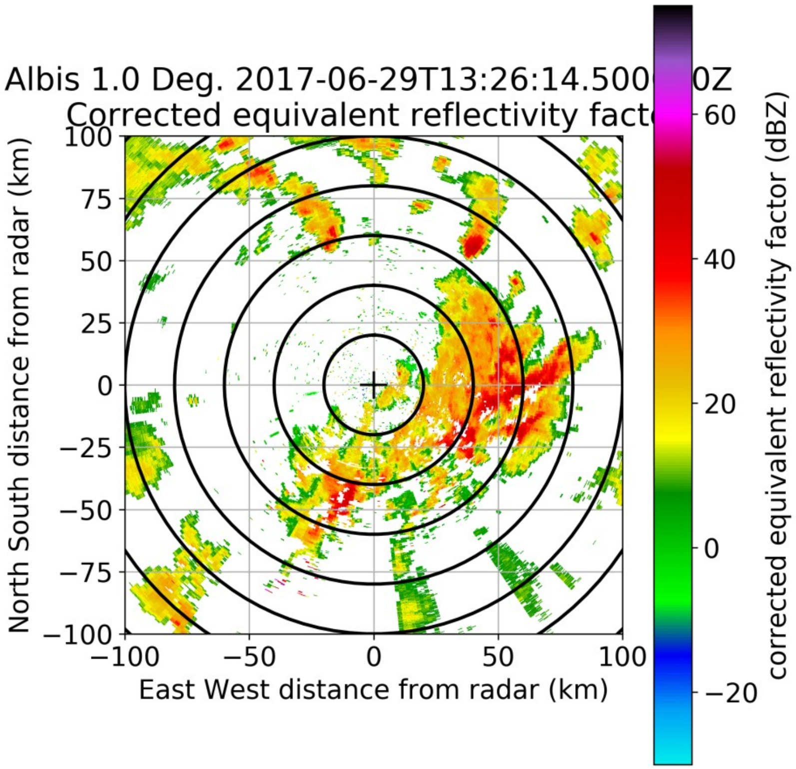
$$z_{dr}^{obs}(r) = z_{dr}(r) - 2\int_0^r a_{dp}(r)\,dr - 2\,a_{dp}^{radome} + \Delta Z_{dr} + \sigma_{z_{dr}}$$

$$\Psi_{dp}^{obs}(r) = 2\int_0^r K_{dp}(r)\,dr + \delta_{co}(r) + \Phi_{dp_0} + \sigma_{\Phi_{dp}}$$

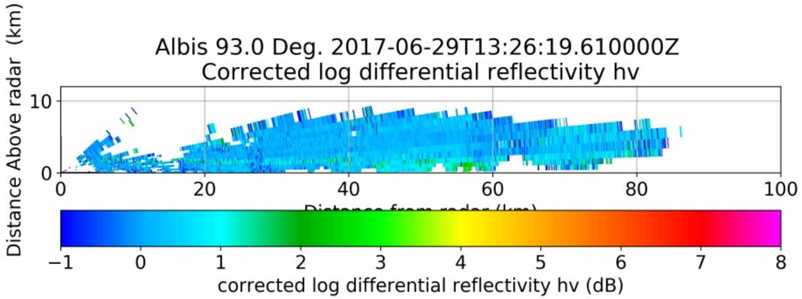
$$\rho_{hv}^{obs}(r) = \rho_{hv}(r) + \sigma_{\rho_{hv}}$$

reflectivity

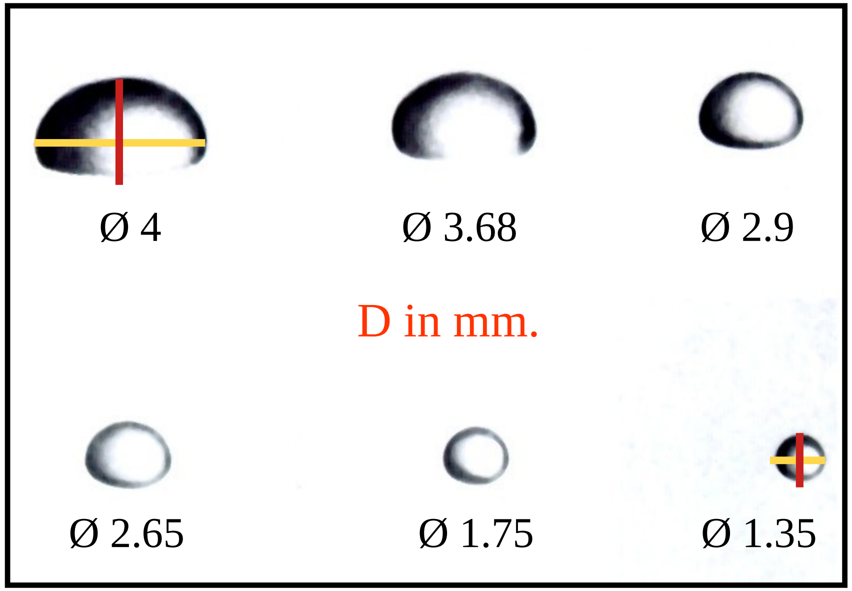


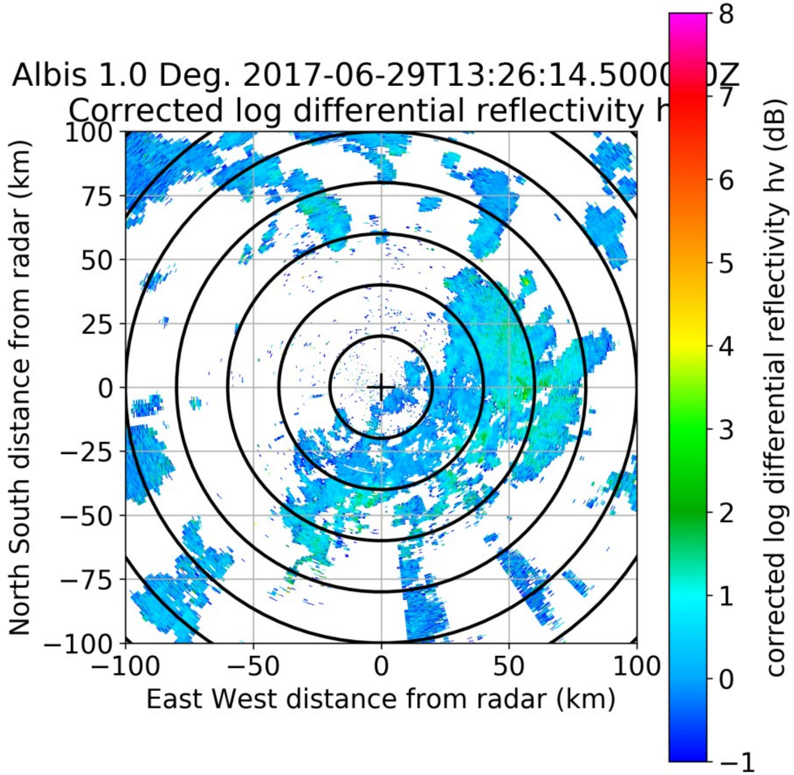


Differential reflectivity

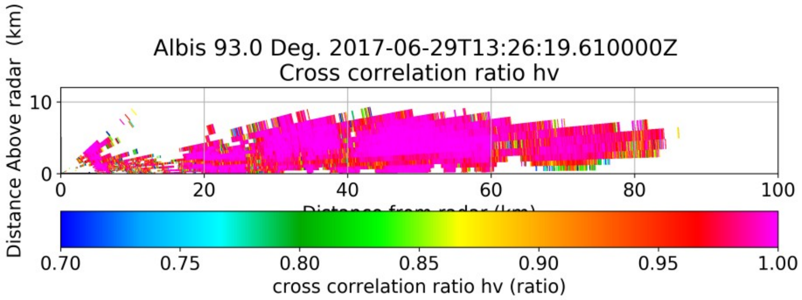


Linked to hydrometeor shape
Raindrop size

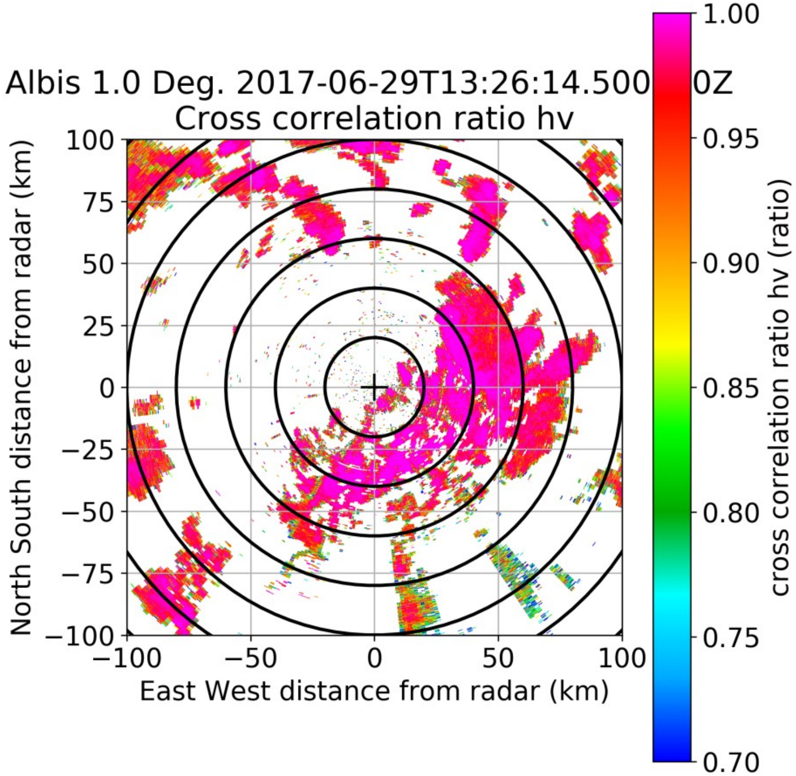




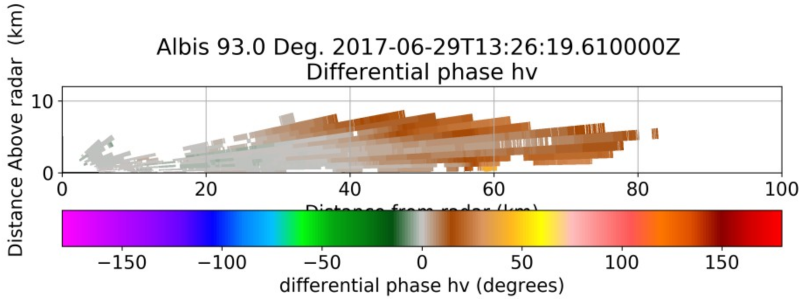
Co-polar correlation coefficient



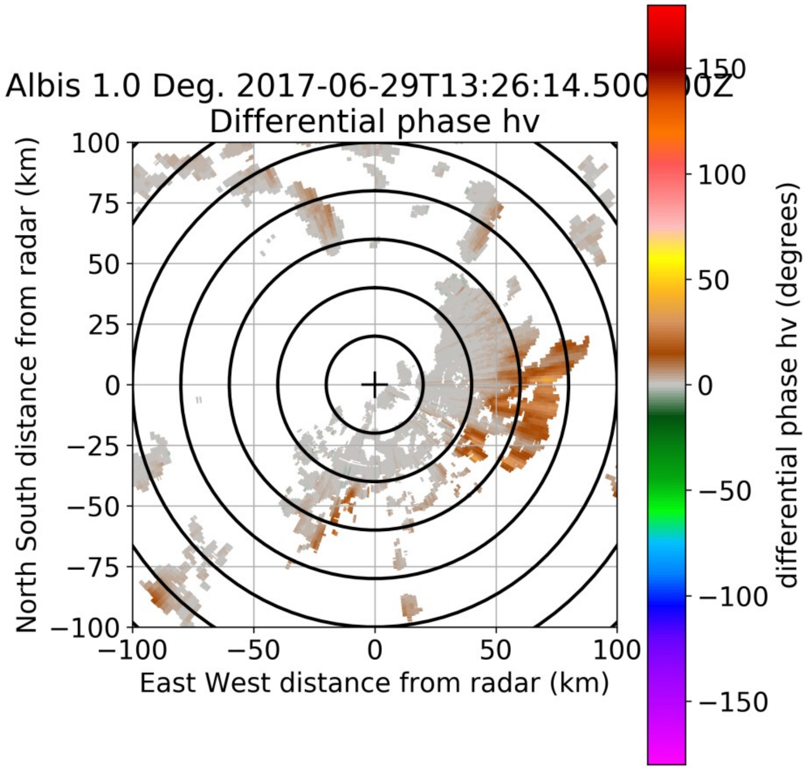
Linked to heterogeneity of the scatterers
Hydrometeor phase
Antenna quality



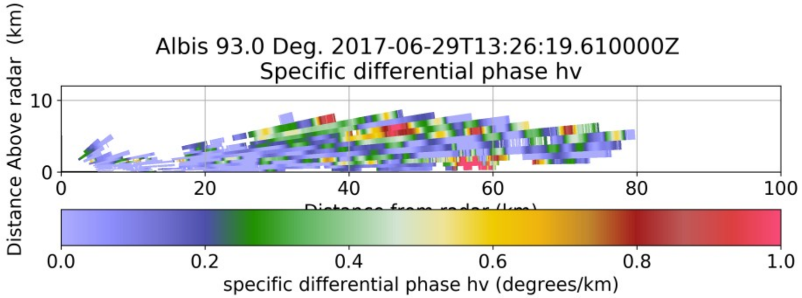
Differential phase



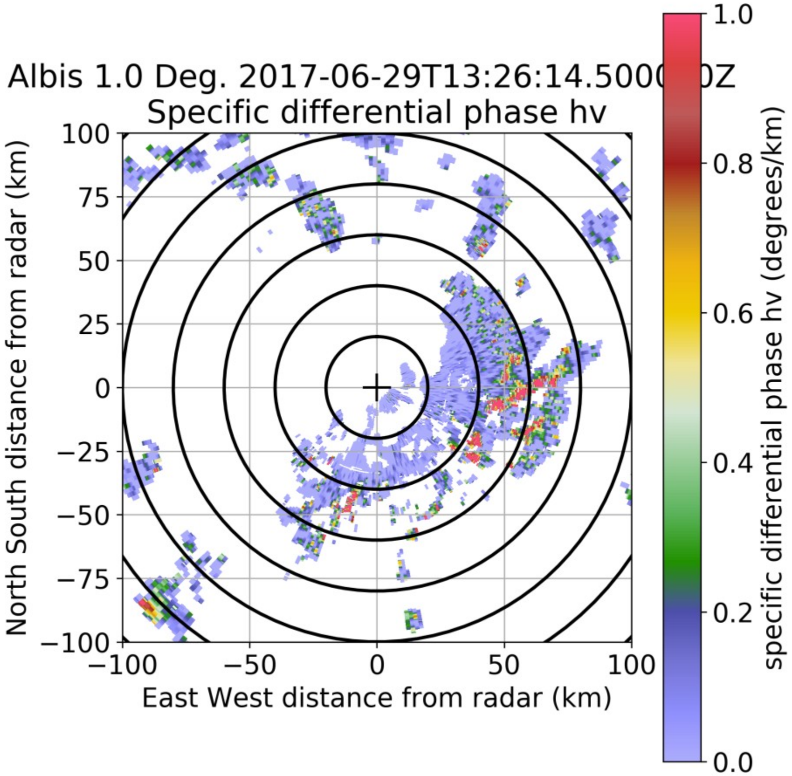
Linked to attenuation



Specific differential phase



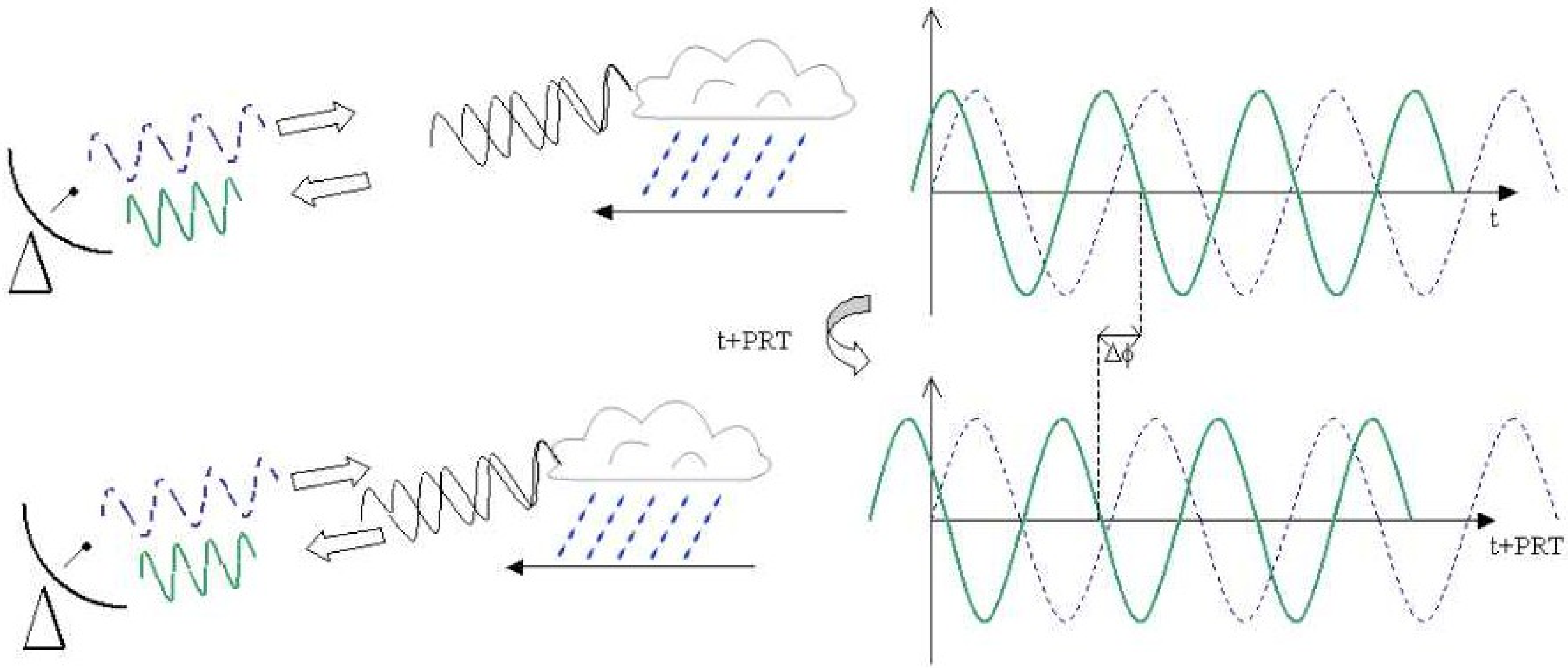
Linked to liquid water content



5. Doppler moments

The Doppler effect

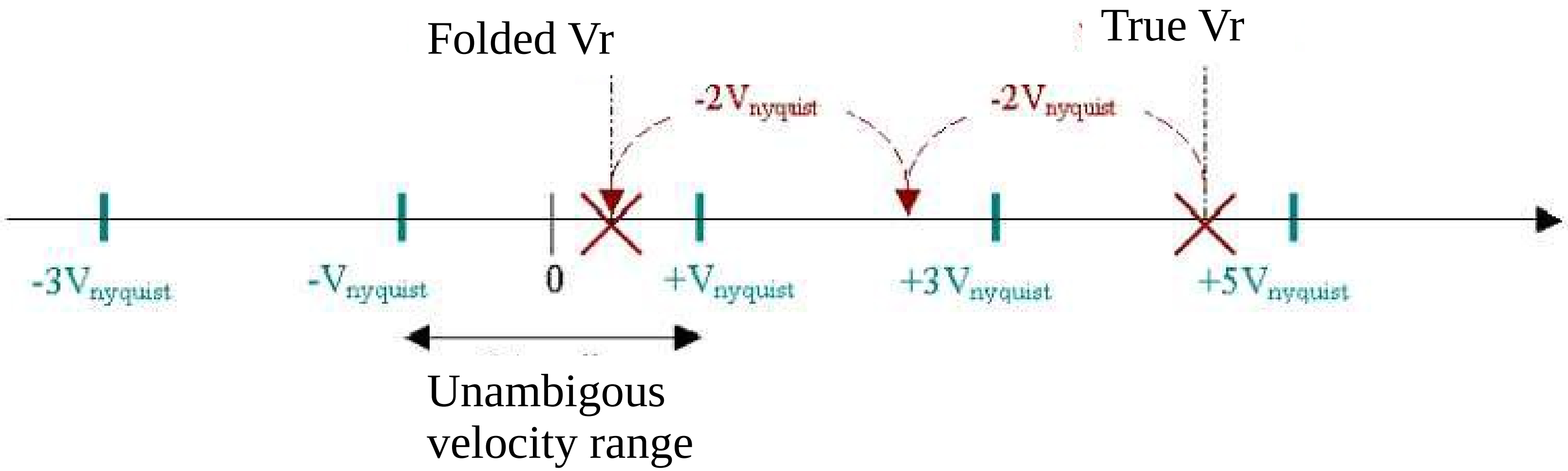
Discovered by Christian Doppler in 1842



$$V_r = \frac{\lambda}{4\pi\, PRT} \Delta\Phi$$

Nyquist velocity

$$\Delta\Phi \in]-\pi, \pi] \Rightarrow V_r \in]-V_{Nyquist}, +V_{Nyquist}]; V_{Nyquist} = \frac{\lambda}{4\,PRT}$$



$$V_r^{true} = V_r^{obs} + 2kV_{Nyquist}$$

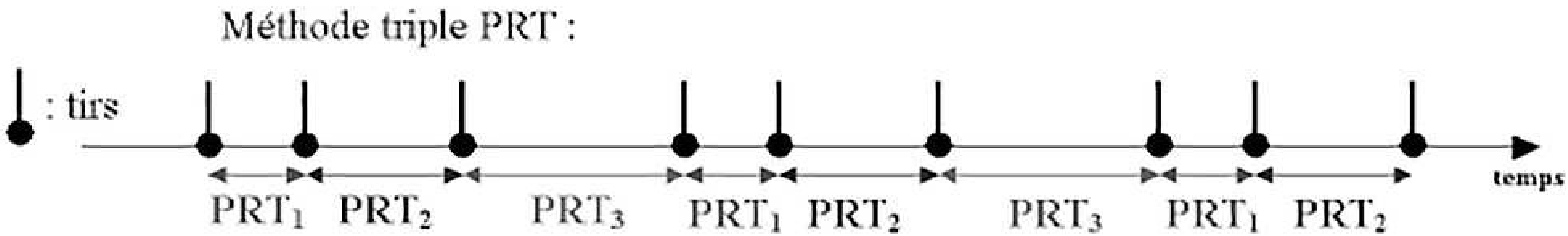
Doppler dilemma

$$V_{Nyquist} = \frac{\lambda \, PRF}{4}$$

$$r_{max} = \frac{c}{PRF}$$

$\uparrow$PRF => $\uparrow$ $v_{Nyquist}$ **BUT** $\downarrow$ r_{rmax}

Solution : **MULTIPLE PRF**



We get 2 or more Vr potentially folded in 2 or more $\pm V_{nyquist}$
Combining them properly we can extend the Nyquist interval

Doppler spectrum

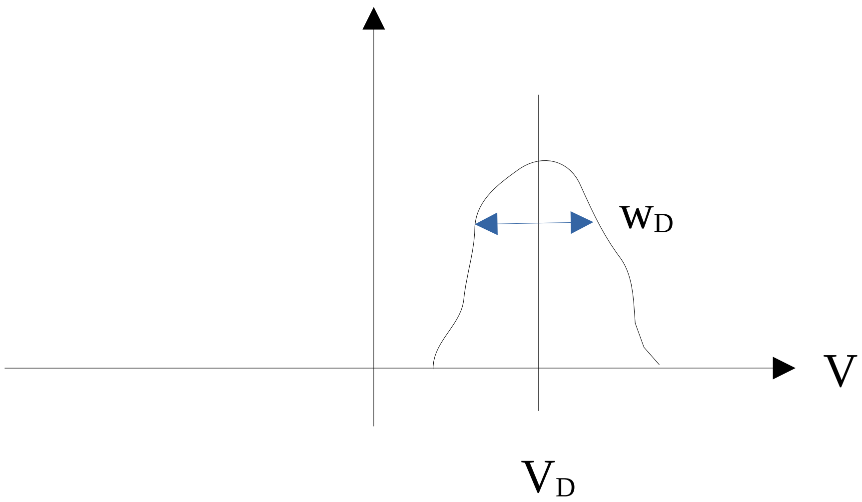
The received signal phase will be a combination of multiple single scatterer returns

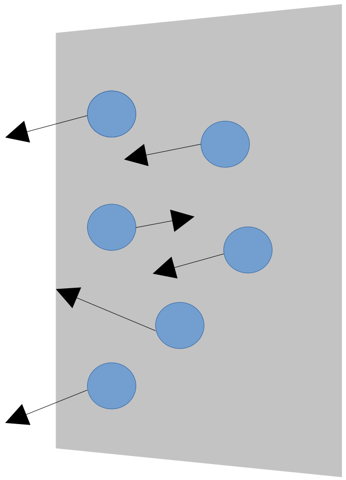
Combining several pulses we can obtain the **Doppler spectrum**

The averaged velocity is the Doppler velocity representative of the global displacement (with respect to the radar) within the radar volume

We can compute higher order moments such as the **Doppler spectrum width W_D**

W_D is related to the turbulence within the radar volume

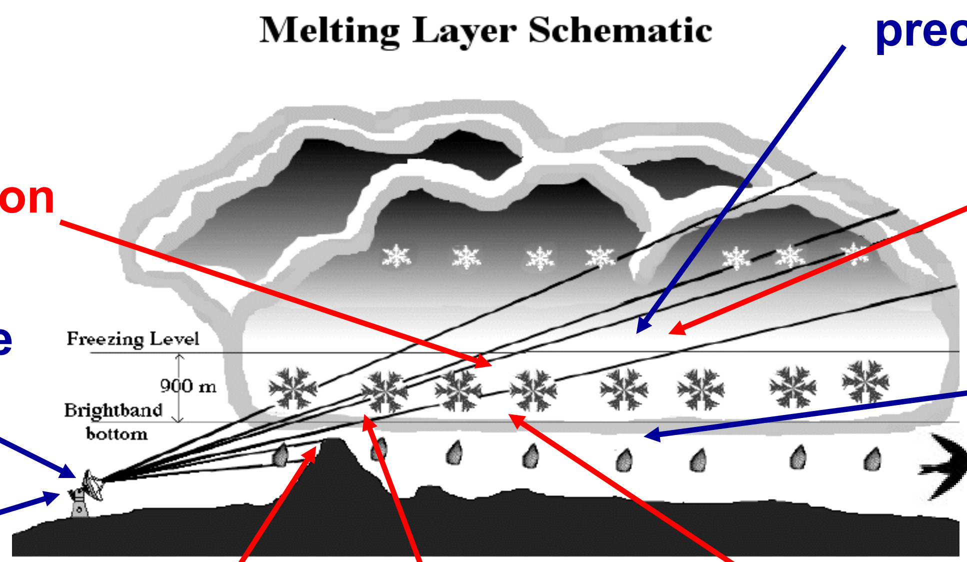




Ground clutter is centered around 0 m/s

6. Sources of uncertainty

Sources of uncertainty



Attenuation by precipitation

VPR correction

Attenuation by gases

Calibration of the radar system

Conversion of Z_H into R

(wet) radome attenuation

Artefacts

Ground-clutter identification

Partial beam blocking correction

Revisit time reduction using the advection field

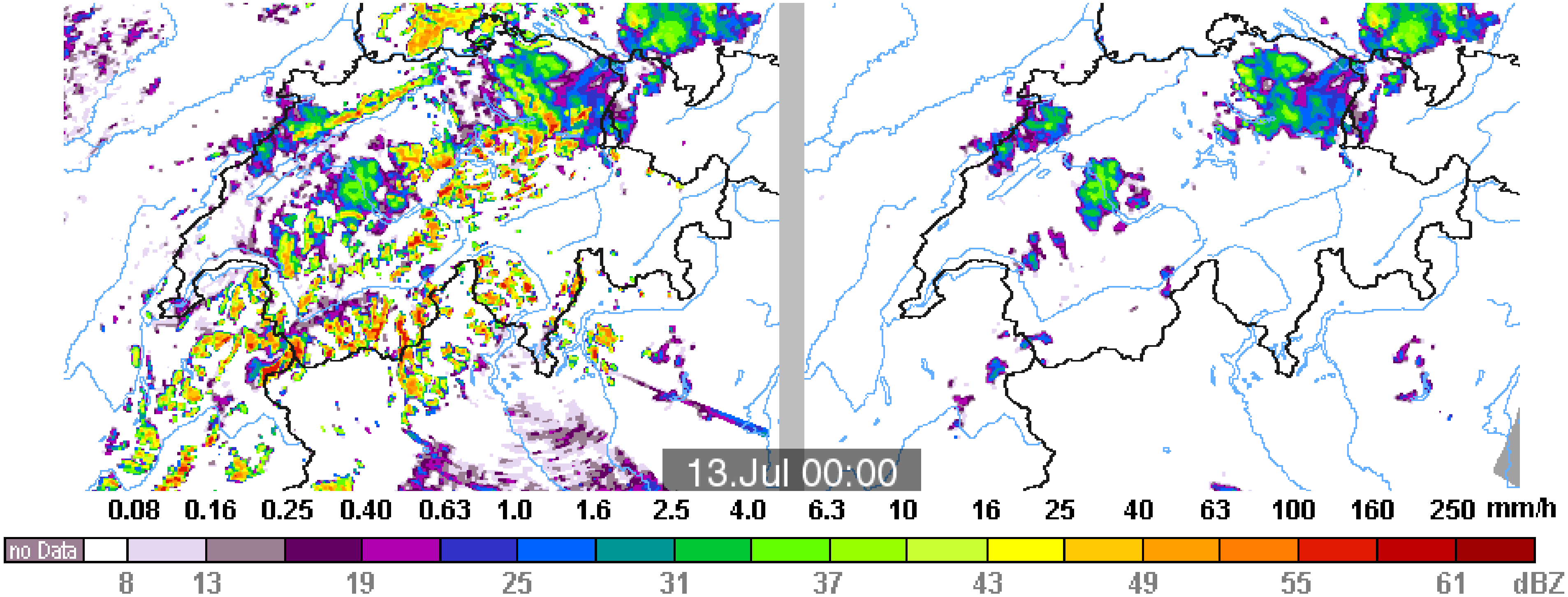
Secondary lobe reception

Secondary trip echoes

Anomalous Propagation

...

Clutter identification



Calibration

Calibration: In measurement technology and Metrology is the comparison of measurement values delivered by a device under test with those of a calibration standard of known accuracy (reference). Such a standard could be another measurement device of known accuracy, a device generating the quantity to be measured, etc.

References: internal signal generator, metallic sphere, sun, light rain, precipitation when pointing at the vertical, ground clutter, etc.


Thank you!
Grazie mille!
Moltes Gràcies!
Merci!