Second year option 2604
Lecture 8: atmospheric radars

A. Battaglia

EOS-SRC, Dept. of Physics and Astronomy, University of Leicester, UK

Purpose of lecture

Atmospheric Radars

The purpose of lecture is the following:

- **Describe some atmospheric space-borne radars and applications**
- **Cloud vs precipitation radars**
- **Effect of attenuation**

Radar equation and radar reflectivity factor

Radar constant [W/m]

Target properties

$$\boxed{P_r = \frac{c}{1024\ln(2)}\frac{\pi^3|K|^2}{\lambda^2}\left[P_t\,\tau\,G^2\,\Phi_{3dB}\,\Theta_{3dB}\right]\frac{Z}{r^2}}$$

Reflected power

$|K|^2=0.93$ is always assumed

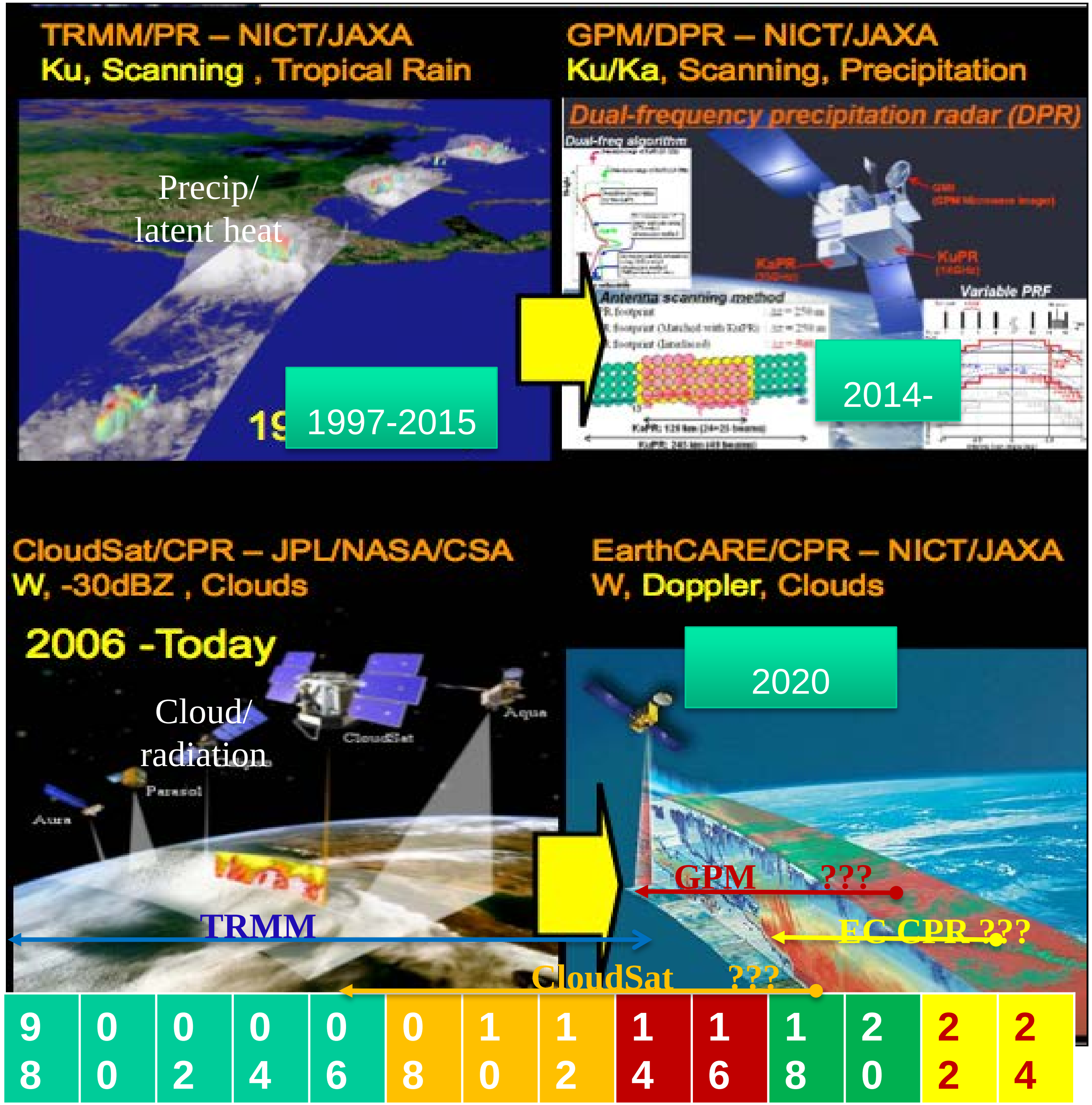
The quantity

$$\boxed{Z \equiv \frac{\sum_j D_j^6}{V_c} = \int N(D)D^6\,dD}$$

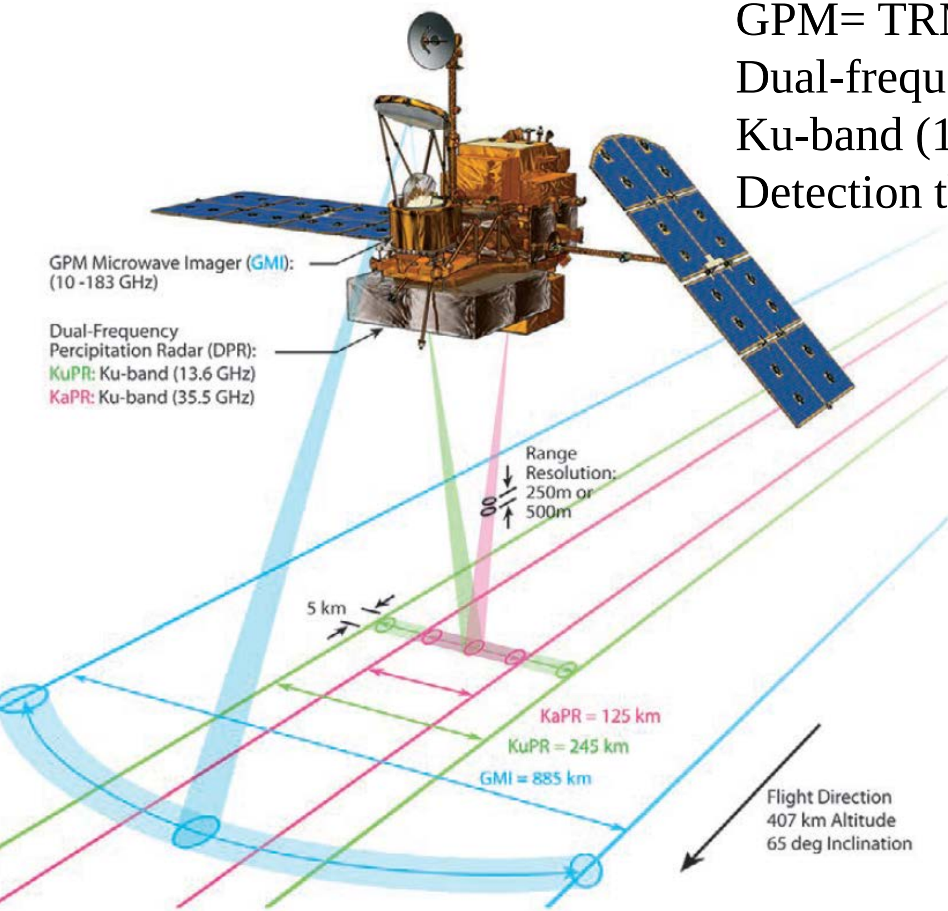
is of utmost importance in radar meteorology and is called the **radar reflectivity factor**

Z can be derived from measurements of P_r

Space-borne cloud&precipitation radars: current state



Cloud and precipitation radars in space

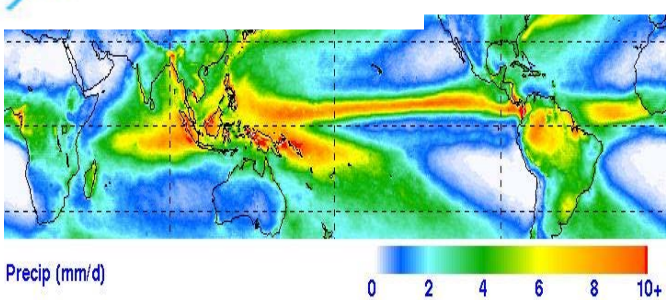


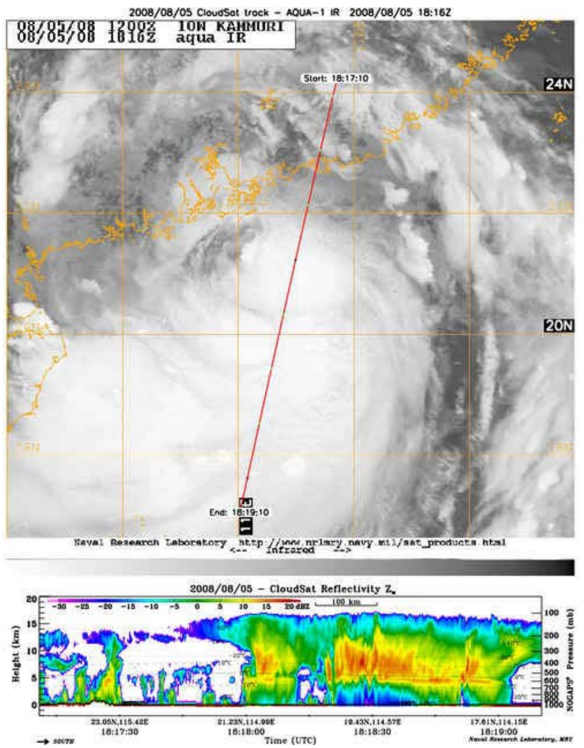
GPM= TRMM follow up
Dual-frequency precipitation radar (DPR)
Ku-band (13.6 GHz); Ka-band (35.5 GHz) 2.2 cm, 8 mm
Detection threshold: 0.2 mm/h.

3 mm

CloudSat carrying a high frequency (94 GHz) space-borne radar has now been in orbit since April 2006.

3 - December 2005

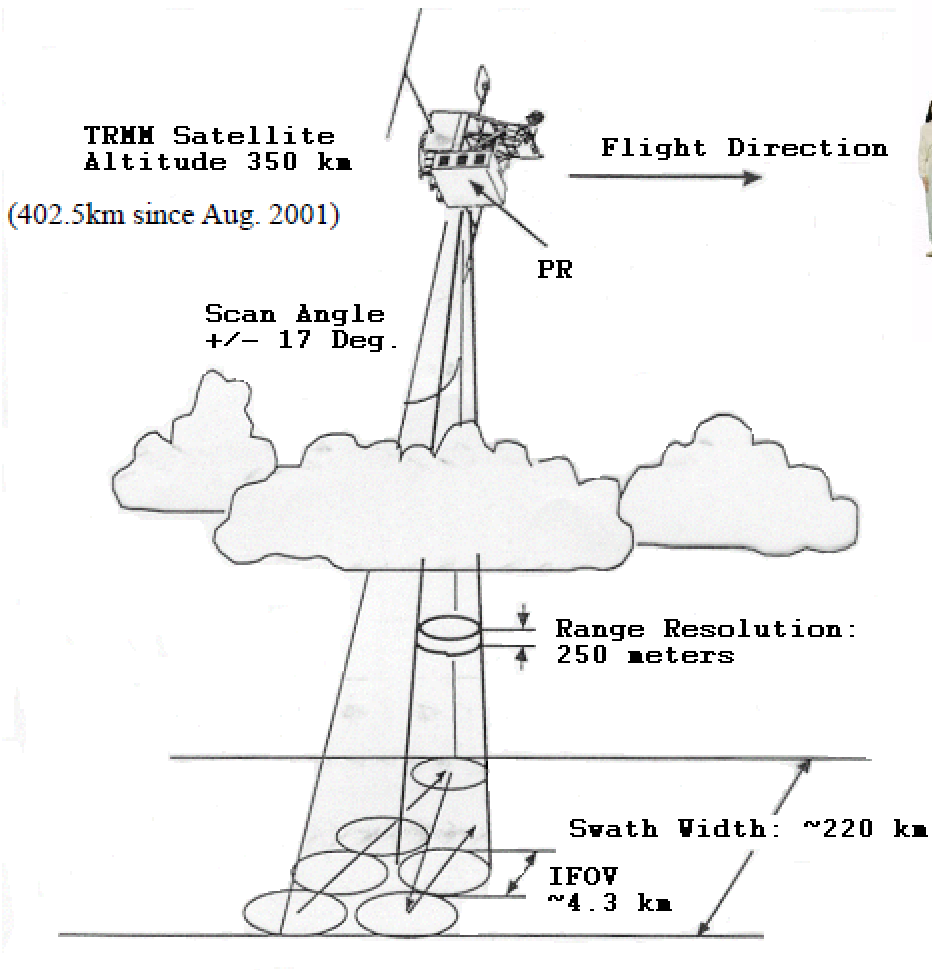




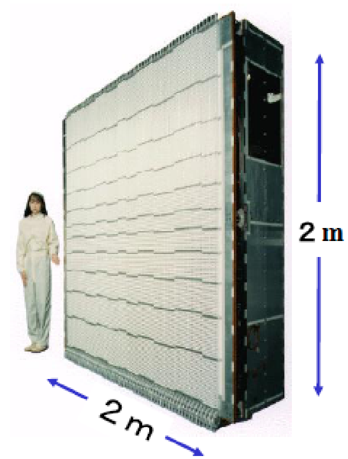
mainly intended for Precipitation STUDIES

mainly intended for CLOUD STUDIES

TRMM Precipitation Radar Characteristics (Ku-GPM)



Observation Concept of the PR



Radar type	Pulse radar
Antenna type	128-elem. WG slot array
Beam scanning	Active phased array
Frequency	13.796, 13.802 GHz
Polarization	Horizontal
TX/RX pulse width	1.57 / 1.67μsec
RX band width	0.6 MHz
Pulse rep. freq.	2776 Hz
Data rate	93.5 kbps
Mass	460 kg
Designed Life time	3 years
Sensitivity	< 0.5mm/h
Horizontal resolution	4.3 km (nadir)
Range resolution	250 m
# of indpdt samples	64 (fading noise < 0.7 dB)
Swath width	215km
Observable range	Surface to 15km

"Storm" Height

(Echo Top Height)

$$\Theta_{3dB} = 1.22\underbrace{\frac{\lambda}{D}}_{in\ radians} = 1.22\frac{2.2\bullet 10^{-2}}{2} = 0.013\,rad = 0.77^{o}$$

$$IFOV \approx H_{sat}\Theta_{3dB} = 4.5km$$

Surface Rainfall

Home thinking: figure out the relationship between pulse width and range resolution, antenna size and horizontal resolution

TRMM vs GPM sensitivity

TRMM Ku-radar has a sensitivity of 17 dBZ
GPM Ku-radar has a sensitivity of 12 dBZ
Compute the minimum detectable rain-rate.

$$\boxed{P_r = C_{radar} \frac{Z}{r^2}}$$

For stratiform rain at Ku we can use $Z = 292 R^{1.53}$

For convective rain at Ku we can use $Z = 146 R^{1.52}$

$$R_{strat} = \left(\frac{Z}{292}\right)^{1/1.53} = \begin{cases} 0.3 mm/h & Z = 17 dBZ \\ 0.15\, mm/h & Z = 12 dBZ \end{cases}$$

$$R_{conv} = \left(\frac{Z}{146}\right)^{1/1.52} = \begin{cases} 0.5\, mm/h & Z = 17 dBZ \\ 0.23\, mm/h & Z = 12 dBZ \end{cases}$$

Looking inside Hurricanes

https://pmm.nasa.gov/articles/gpm-captures-hurricane-harveys-rainfall

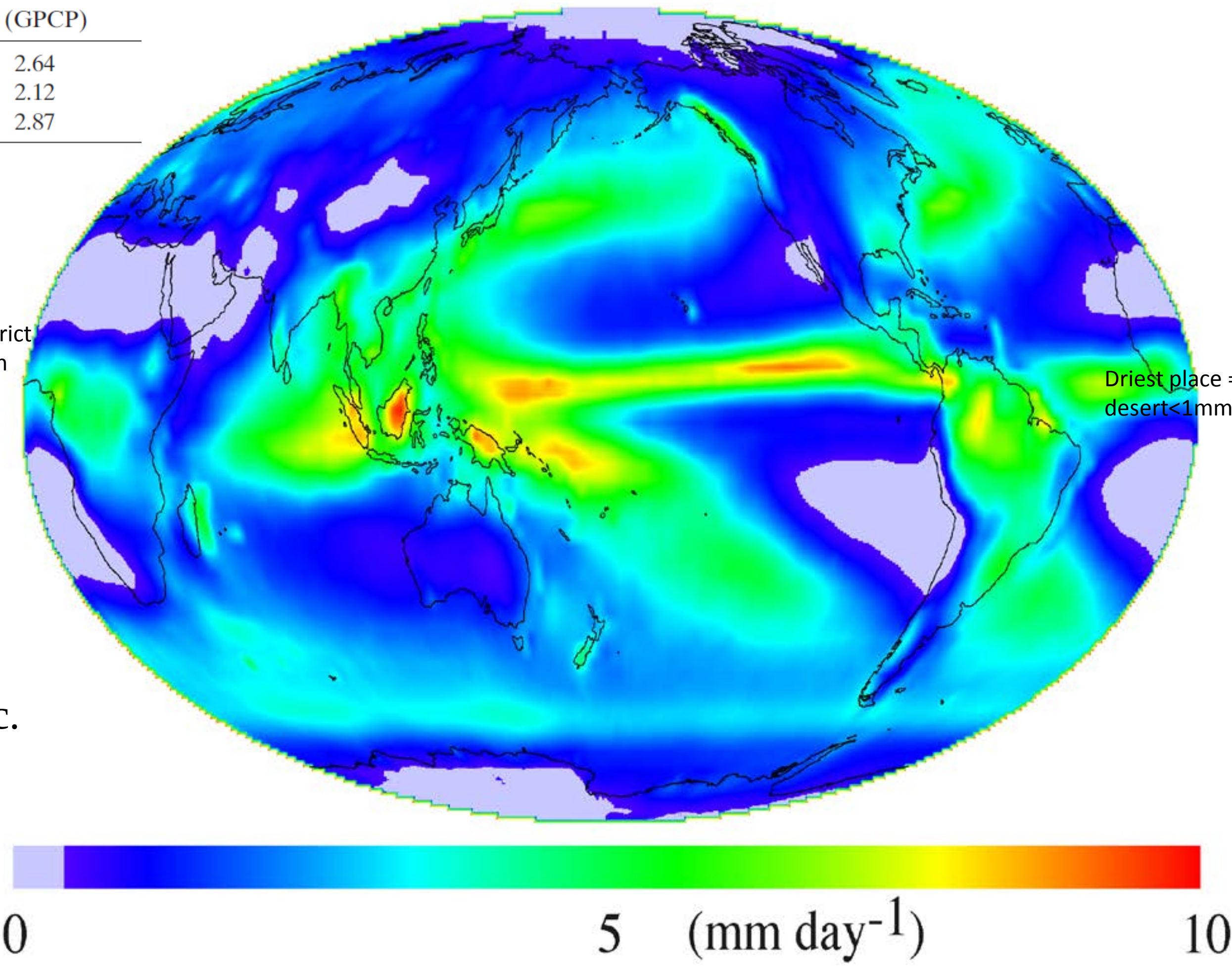
Hurricane Harvey movie

How much does it rain? The present

<RR>=2.6 mm/day~1m/year

	μ (GPCP)
Land and ocean	2.64
Land	2.12
Ocean	2.87

Wettest place = East Khasi Hills district of Meghalaya state in north-eastern India,11.8 m/year

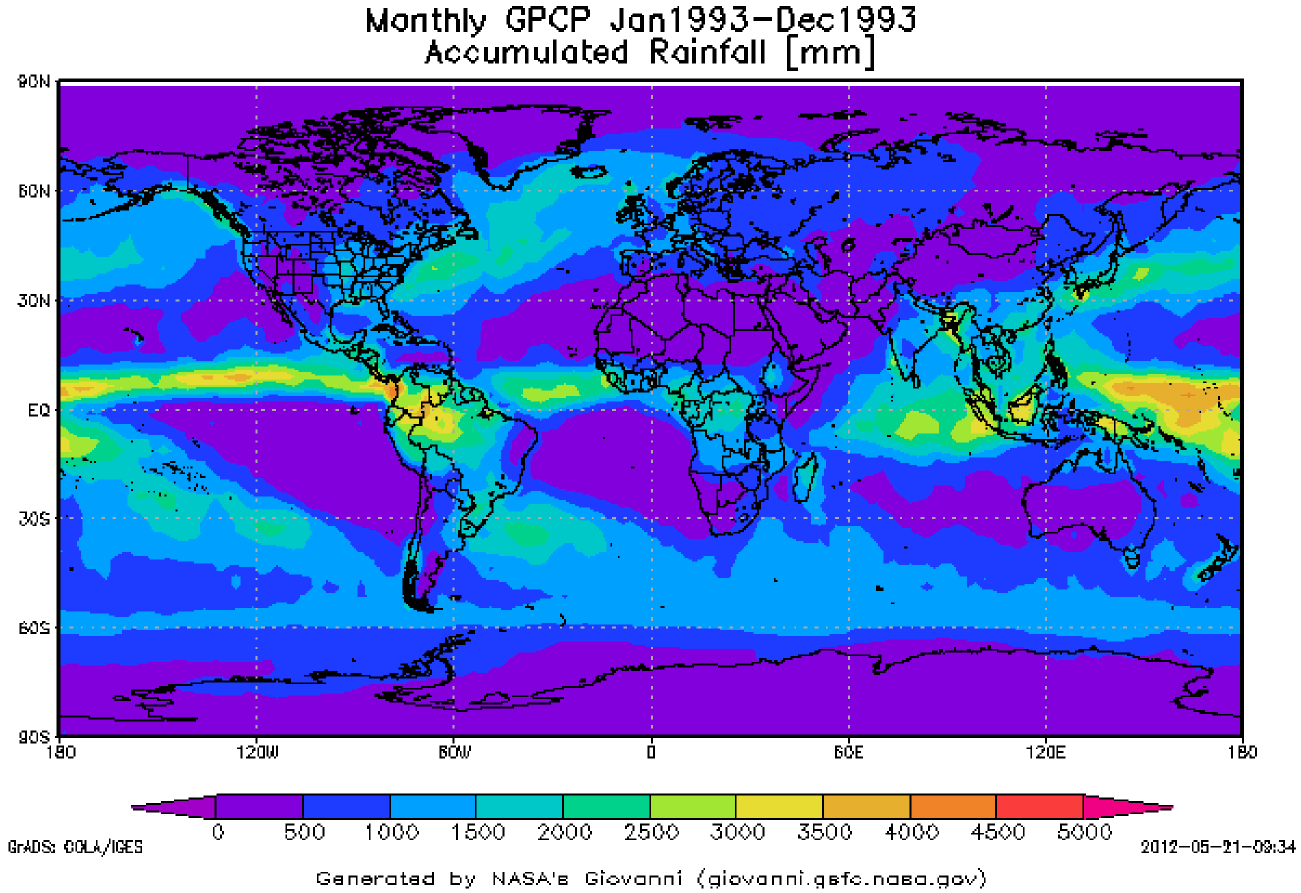


Driest place = Atacama desert<1mm/year

Source=Global Prec. Clim. Proj.

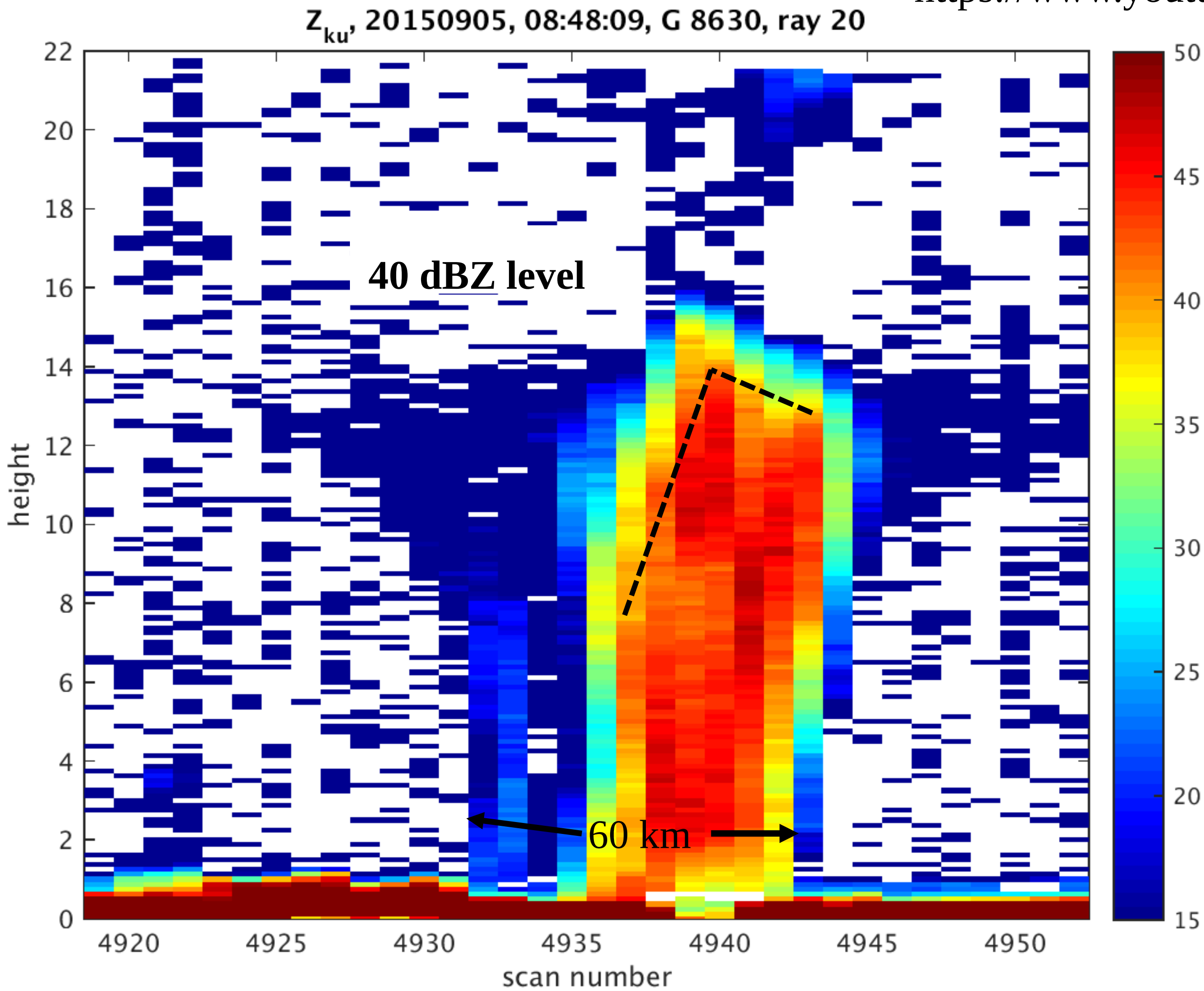
A 25-Year Precipitation Climatology (1979-2003) Based on Observations from Multiple Satellites

Rainfall climatology



Ku-band radar observations for the Naples event

https://www.youtube.com/watch?v=242rbAzUsgs

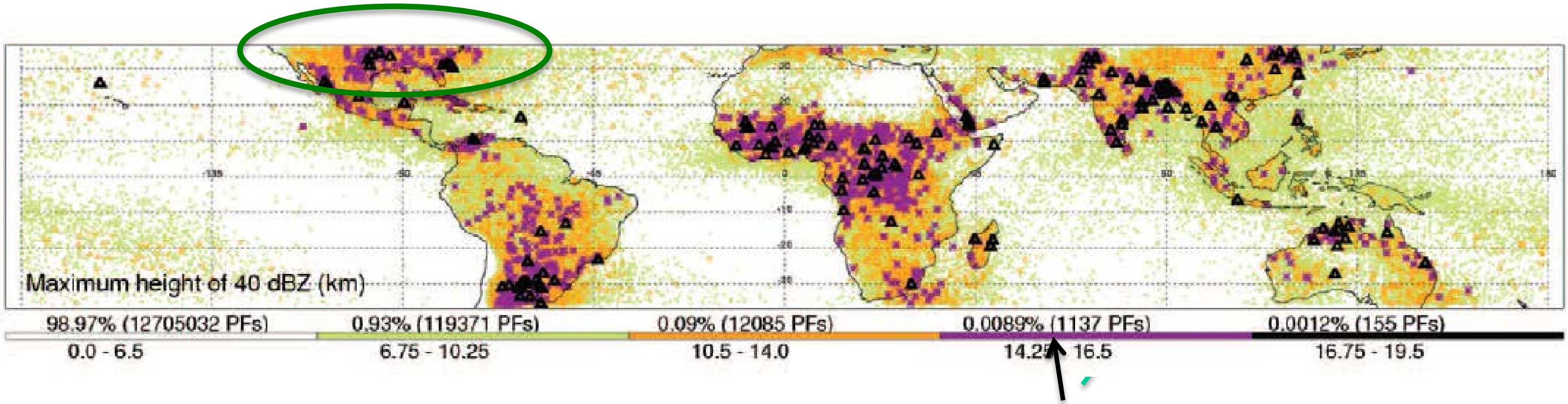


A cumulonimbus tower

$$R_{conv} = \left(\frac{Z}{146}\right)^{1/1.52} = \begin{cases} 16\,mm/h & Z = 40dBZ \\ 73\,mm/h & Z = 50dBZ \end{cases}$$

Where are the strongest storms?

PROXY: the higher the height attained by the 40-dBZ level in a Precipitation Feature, the more intense the storm



1. Preference for extreme events to be located over land or adjacent to land;
2. the strongest convective storms often found in semiarid regions, while the heavy rains of the oceanic ITCZ, western Amazonia, and much of SE Asia and Indonesia have relatively few intense storms;
3. the equatorial land areas of Amazonia and Indonesia have many moderately intense but fewer extreme storms than those of equatorial Africa

CloudSAT Profiling Radar

The CPR (in orbit since 4/2006) provides the first mm-radar designed to regularly see precipitation on the planet at latitudes higher than the subtropics

Goal: vertical structure of cloud systems, distribution rain, interrelationship between cloud and precip.

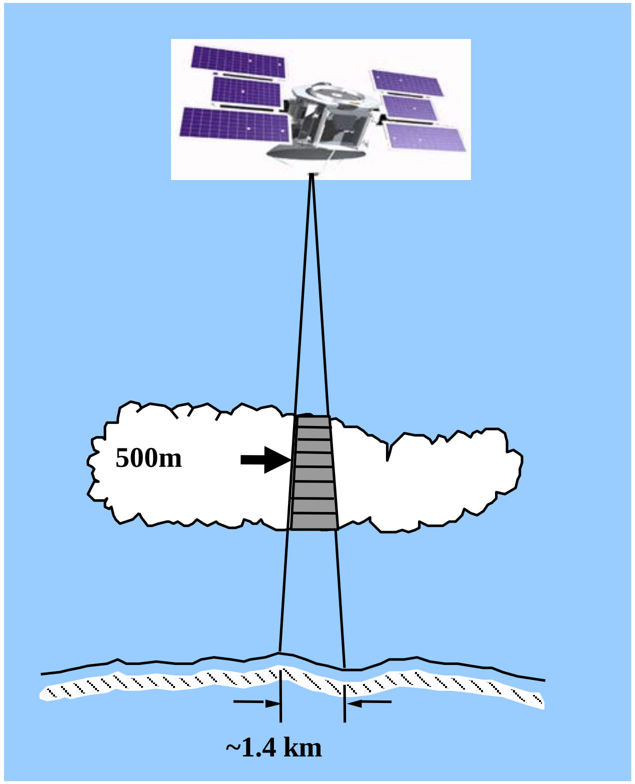


Table 1. Cloud Profiling Radar Instrument and Performance Parameters

Parameter	Proposed Performance
Frequency	94.05 GHz
Altitude	705 – 730 km
Range resolution (6 dB)	485 m
Cross-track resolution	1.4 km
Along-track resolution	1.8 km
Pulse width	3.3 μs
Peak power (measured)	32.6 dBW
PRF	3700–4300 Hz
Antenna diameter	1.85 m
Antenna gain	63.1 dBi
Antenna sidelobes	-50 dB @ $\theta > 7°$
Integration time (single-beam)	0.16 s
Data window	30 km
Minimum detected reflectivity (measured)	-30 dBZ

Example I: Radar reflectivity factor of a continental cloud

Diameter (μm)	Number/cm^3	$N D^6$ (mm^6/m^3)
5 $=5 \times 10^{-3}$ mm	100 $=10^8$ m^{-3}	$1.56 \cdot 10^{-6}$
10	100	$1.00 \cdot 10^{-4}$
15	50	$5.69 \cdot 10^{-4}$
20	25	$1.60 \cdot 10^{-3}$
25	10	$2.44 \cdot 10^{-3}$
30	5	$9.19 \cdot 10^{-3}$
35	1	$4.01 \cdot 10^{-3}$
		Total $= 1.80 \cdot 10^{-2}$ => -17.4 dBZ

This can be detected by a cloud radar (CloudSat) but not by a rain radar (TRMM). We need log scale because of the D^6 dependence!!!

Example II: radar equation for CloudSat

$$\boxed{P_r = \frac{c}{1024\ln(2)}\frac{\pi^3|K|^2}{\lambda^2}\left[P_t\,\tau\,G^2\,\Phi_{3dB}\,\Theta_{3dB}\right]\frac{Z}{r^2} = C_{radar}\frac{Z}{r^2}}$$

Radar constant [W/m]

λ=3 mm

$$\Phi_{3dB} = \Theta_{3dB} = 1.22\frac{\lambda}{D} = 0.02\ \ rad = 0.11^0$$

$|K|^2$=0.93

$$G \approx \frac{16}{(\Theta_{3dB})^2} = 4.1x10^6 = 66\,dB$$

$$P_t = 32.6\,dBW = 1.8\,kW$$

$$C_{CloudSat} = 5.4\times10^{19}\ \frac{W}{m}$$

$$Z = -17.4\ dBZ = 1.8\times10^{-2}\ \frac{mm^6}{m^3} = 1.8\times10^{-20}\ m^3$$

$$P_r = C_{radar}\frac{Z}{r^2} = 2\times10^{-12}\ W$$

r=710 km

still detectable by the radar receiver!

Note the advantage of employing short wavelength (also for achieving large G)➔ improving the sensitivity.

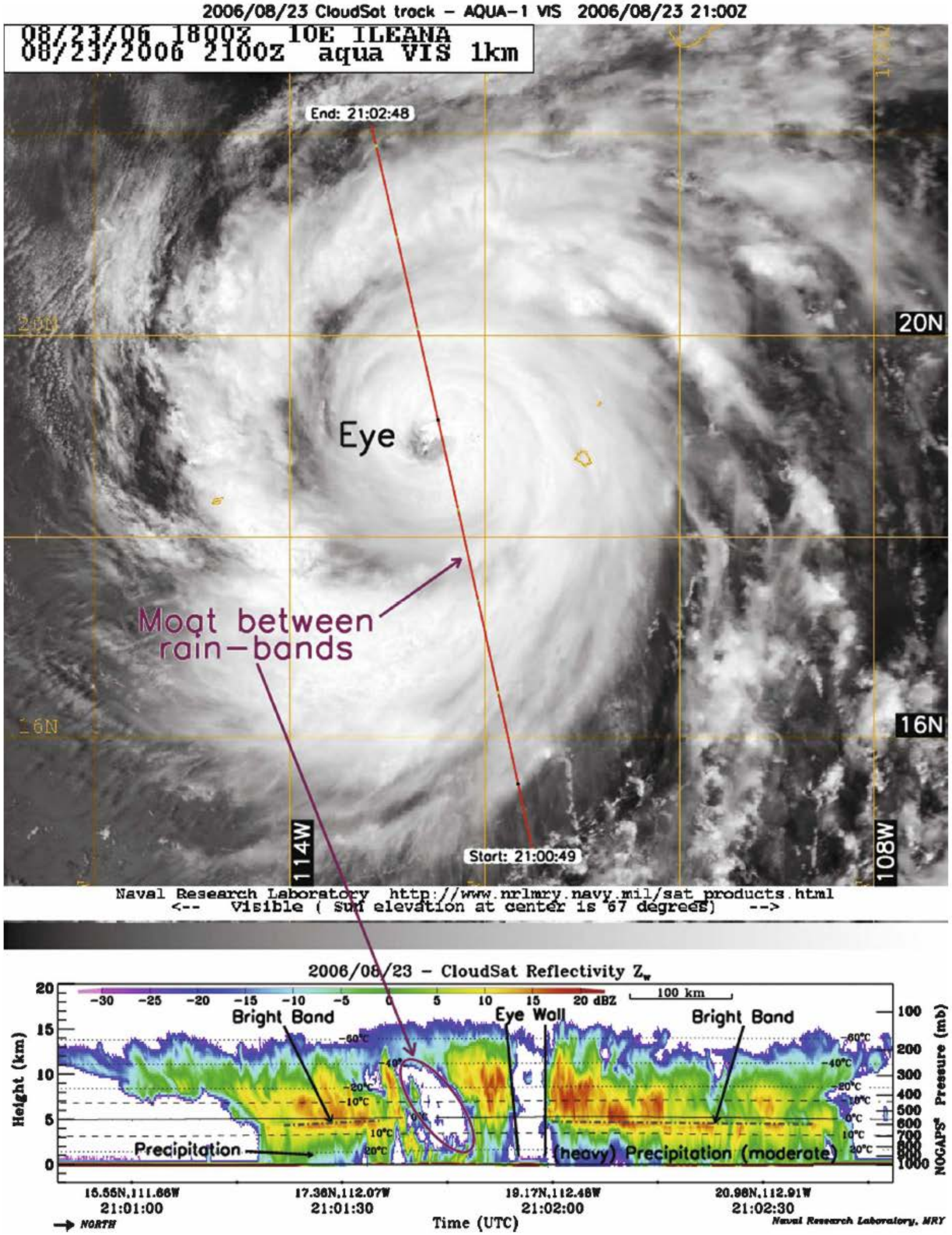


FIG. 2. The A-Train (*Aqua*-VIS and *CloudSat*) view of Hurricane Ileana at 2100 UTC 23 Aug 2006. See text for explanations.

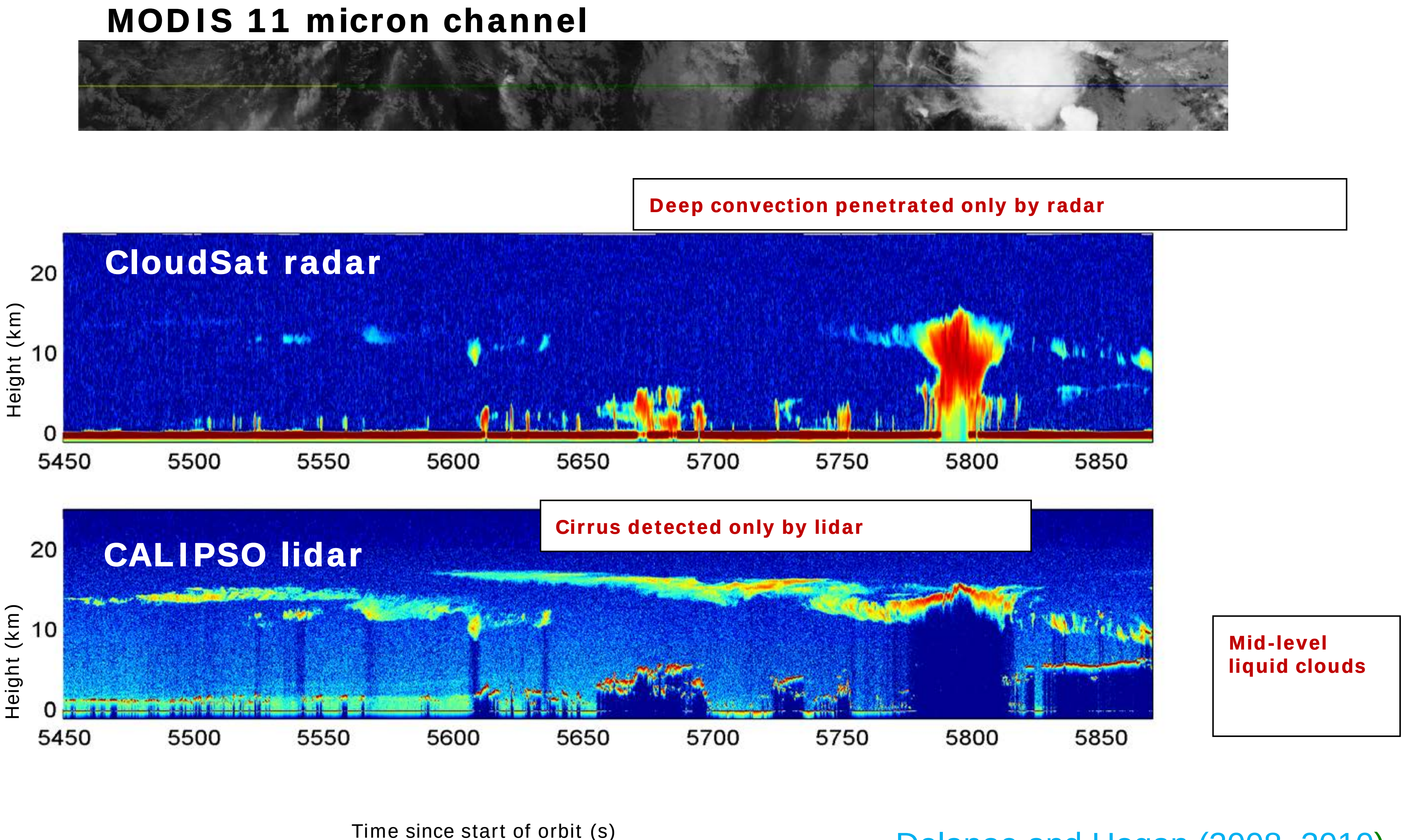
Tropical cyclone

Vertical structure is not resolved by optical/IR/MW-spectrum passive instruments. Radars, on the other hand, can penetrate deep into the dense cloud/precipitation structure before being totally attenuated providing a better understood vertical slice of TC structure

1) upward sloping of cloud tops toward the TC eye or storm center;
2) a rain-free region associated with both the eye and a moat-like region to the south located between the inner eyewall and an outer rain band;
3) ready identification of intense rain areas along the radar's nadir-only ground track;
4) cloud-base measurements to the south as the cirrus cloud bases get progressively higher away from the convective source region;
5) mapping of the upward sloping bright band.

Radar-lidar: synergies and complementarities

- **Lidar:** backscattering~D^2, more sensitive to thin cirrus and liquid clouds but attenuated
- **Radar:** backscattering~D^6, detects whole profile, surface echo provides integral constraint

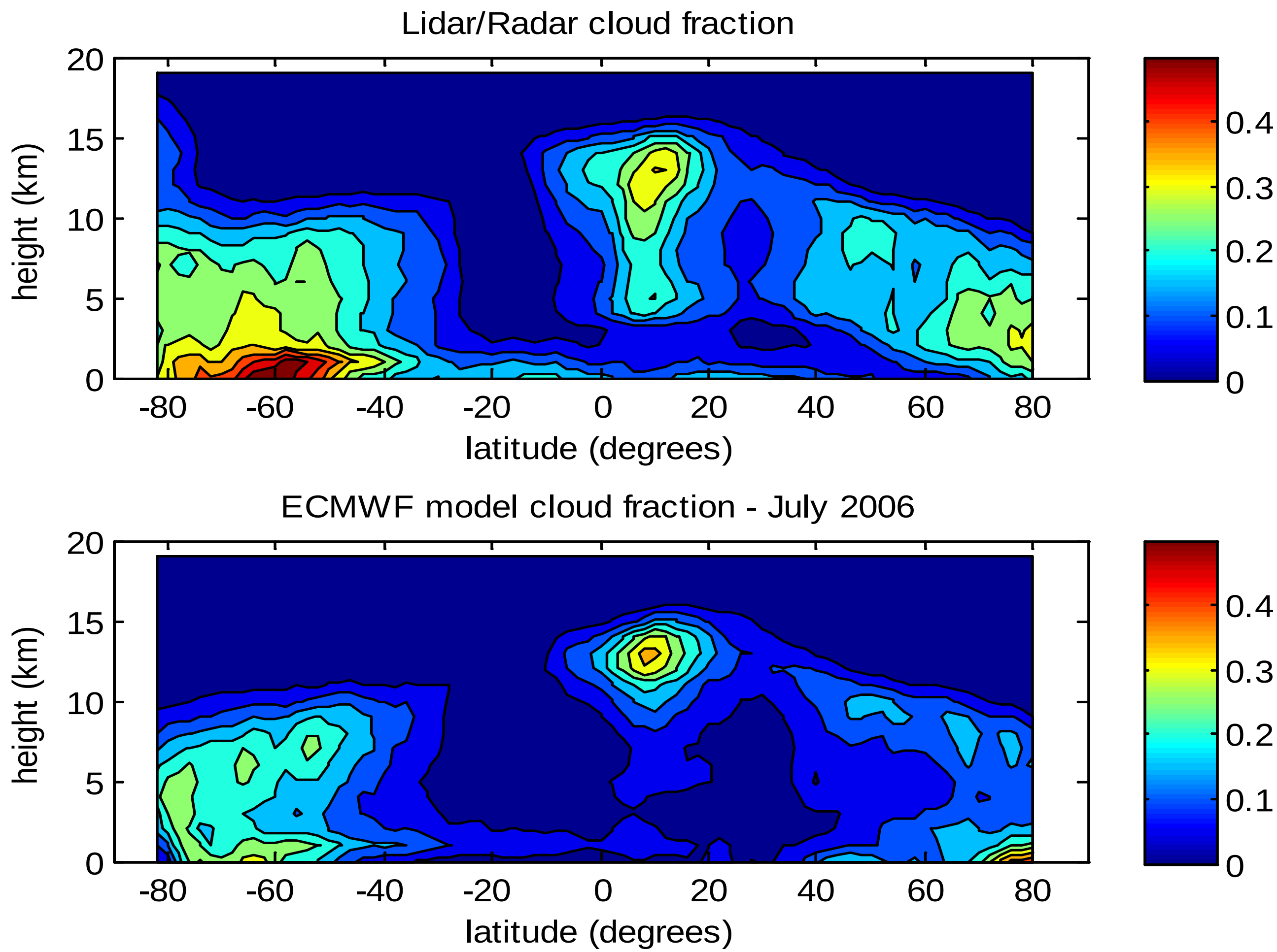


Delanoe and Hogan (2008, 2010)

Radar-lidar model evaluation

Helene Garcon, MSc dissertation (2011)

- ECMWF model underestimates mid- and low-level cloud
- Notice polar stratospheric clouds in observations



Multi-frequency observation of a precipitating system

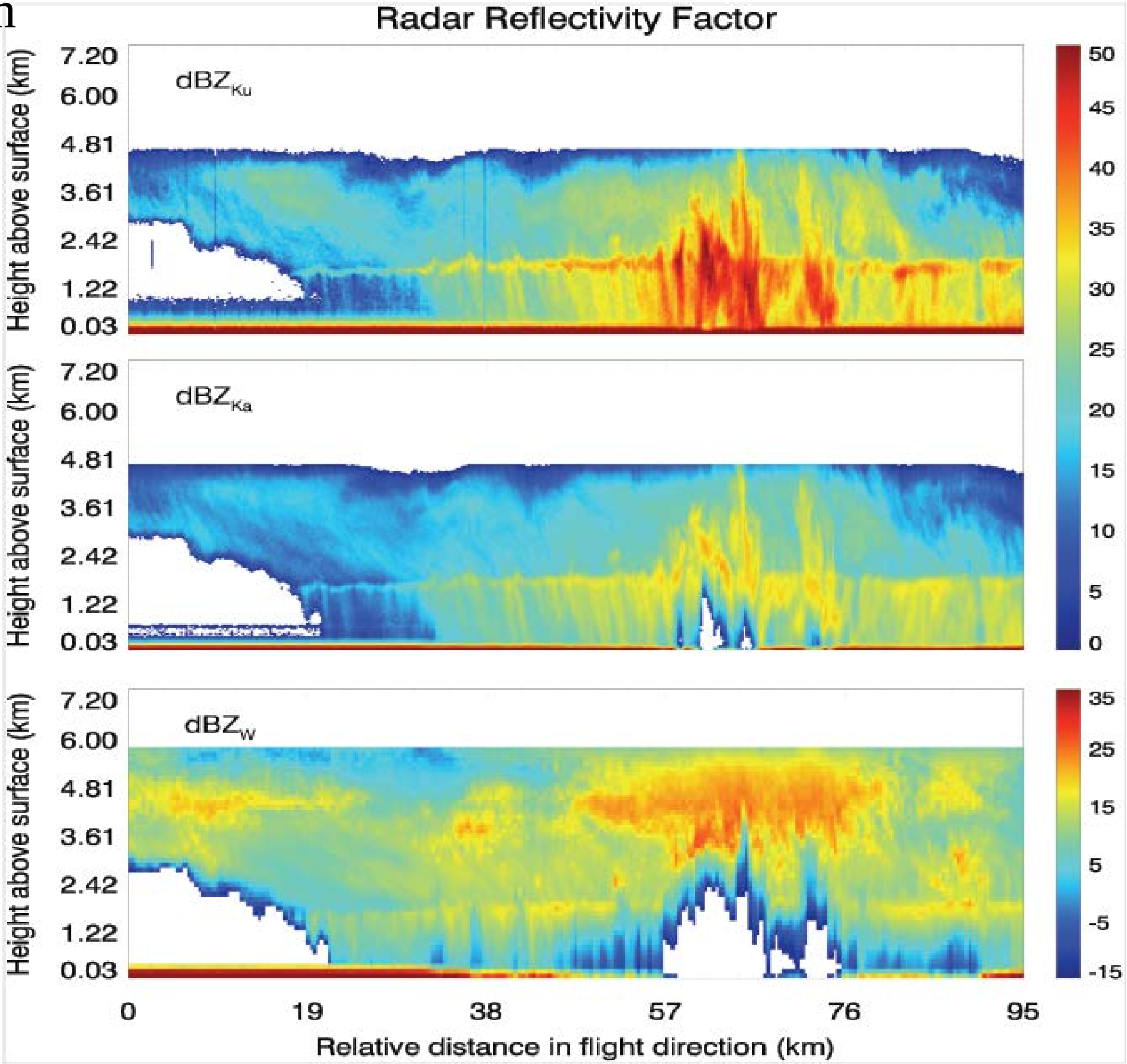
Note increasing levels of attenuation when increasing frequency

Airborne system

13 GHz

35 GHz

94 GHz



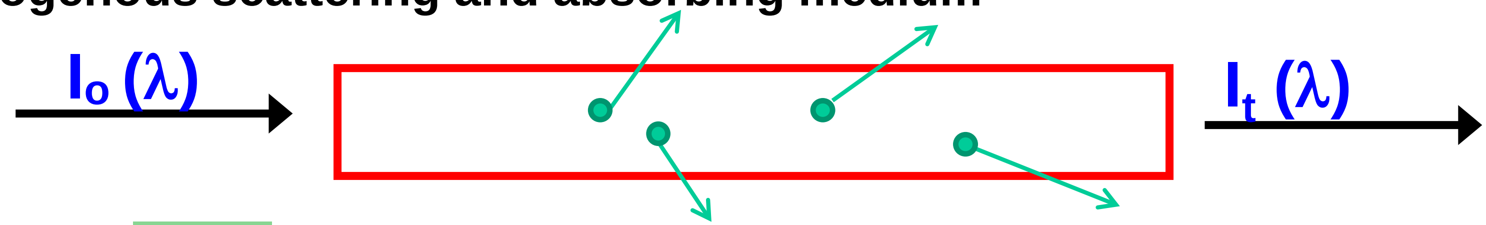
2.3 cm

8 mm

3 mm

Attenuation from Beer-Lambert law

Homogenous scattering and absorbing medium



$dI(\lambda) = -\, k_a(\lambda)\, I\, dL$ **loss due to absorption**

$dI(\lambda) = -\, k_s(\lambda)\, I\, dL$ **loss due to scattering**

Experimentally observed

both dimensionally L^{-1}

and, by integrating:

$$I_t(\lambda) = I_0(\lambda)\, e^{-\int_0^r [k_a(r)+k_s(r)]dr} = I_0(\lambda)\, e^{-\int_0^r k_e(r)dr} = I_0(\lambda)\, e^{-\tau}$$

with extinction coefficient: $k_e = k_s + k_a$

No attenuation

$$\boxed{P_r = C_{radar} \frac{Z_e}{r^2}}$$

With attenuation

$$\boxed{P_r = C_{radar}\, e^{-2\int_0^r k_e(r)dr} \frac{Z_e}{r^2}}$$

The factor 2 accounts for the 2-way attenuation

Effective and measured reflectivities

$$P_r = \frac{C_{radar}}{r^2} \underbrace{e^{-2\int_0^r k_e(r)\,dr} Z_e}_{Z_m}$$

What is measured by the radar is the combined effect of:

- the intrinsic reflectivity of the target at range r, Z_e
- the total attenuation from the radar to the target and backwards.

$$Z_m\left[\frac{mm^6}{m^3}\right] = Z_e\left[\frac{mm^6}{m^3}\right] \quad e^{-2\int_0^r k_e(r)\,dr}$$

<u>in linear units</u>

$$Z_m[dBZ] = Z_e[dBZ] - 2\overbrace{\int_0^r k_e(r)\,dr \times \underbrace{10\log_{10}(e)}_{4.343}}^{A_{one-way}} = Z_e[dBZ] - 2A_{one-way}[dB]$$

<u>in dB units</u>

N.B. A layer with τ=1 reduces the measured reflectivity by 8.7 dB

Attenuation coefficient

$$A_{one-way}[dB] = 4.343 \times \underbrace{\int_0^r k_e(r)\,dr}_{\tau}$$

Extinction coefficient is affected by different sources:

- Atmospheric gases
- Hydrometeors (**cloud droplets, raindrops**, ice crystals, graupel/hailstones, melting hydrometeors)

$$\boxed{k_e = k_e[gases] + k_e[hydro]}$$

All of these bulk properties are:

- <u>strongly dependent on the radar frequency</u>
- intrinsically <u>related to the atmospheric composition or the hydrometeor microphysics</u>

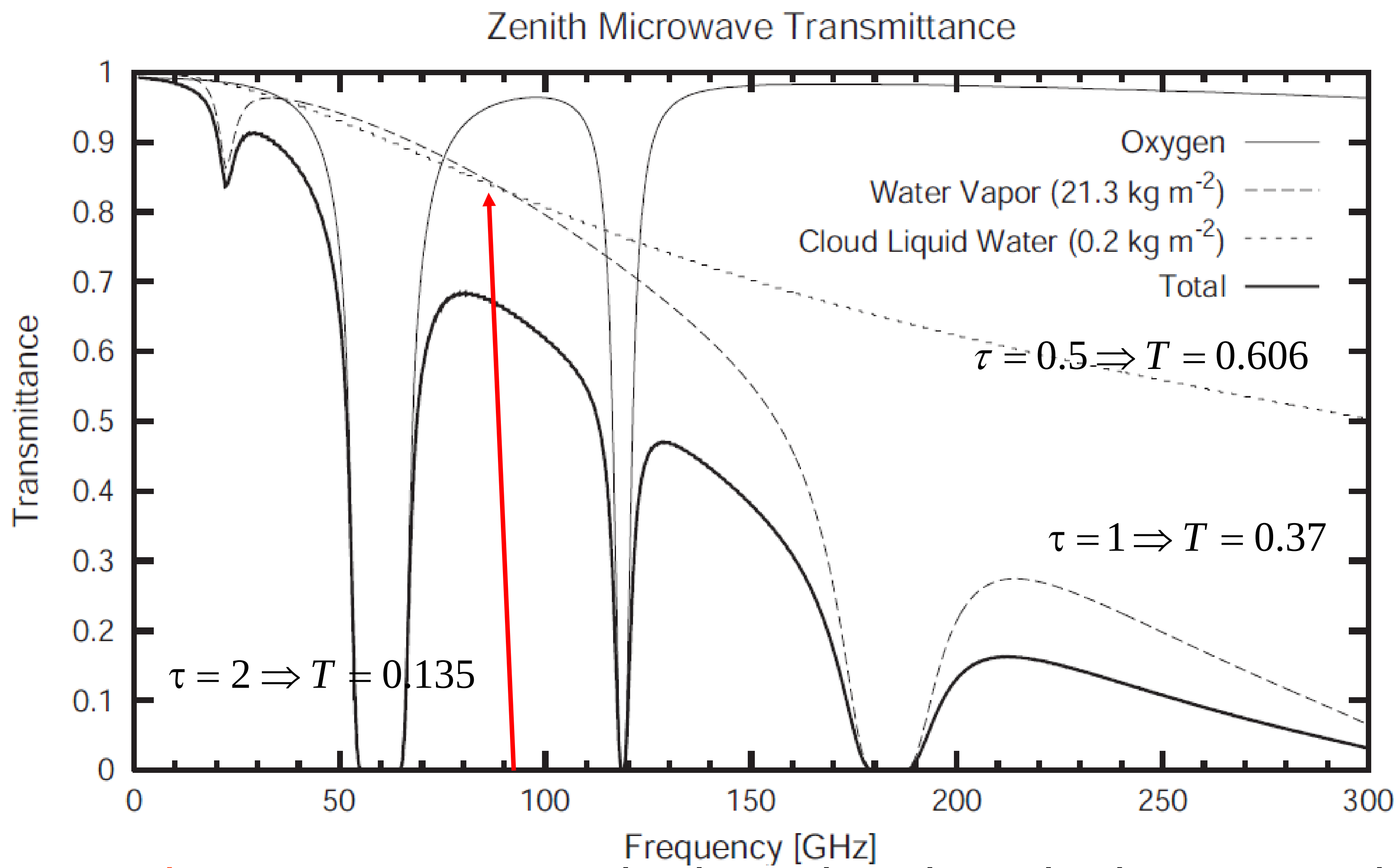
$$k_e[hydro] = \int_{PSD} \sigma_e(D)\ N(D)\ dD$$

The bulk effect is obtained by summing up the extinction of all particles present in the backscattering volume

Gas attenuation in the microwave region

$$Transmittance = e^{-\tau}$$

Separation of different contributions



Oxygen and water vapour are the key absorbers in the MW region

Example: attenuation by cumulus clouds at 94 GHz

A 0.5 km thick Sc with a mean LWC=0.8g/m³ is lingering over Leicester. Compute the two-way attenuation produced by the layer for the CloudSat radar (94 GHz).

Solution

1. LWP=0.5x0.8=0.4 kg/m^2

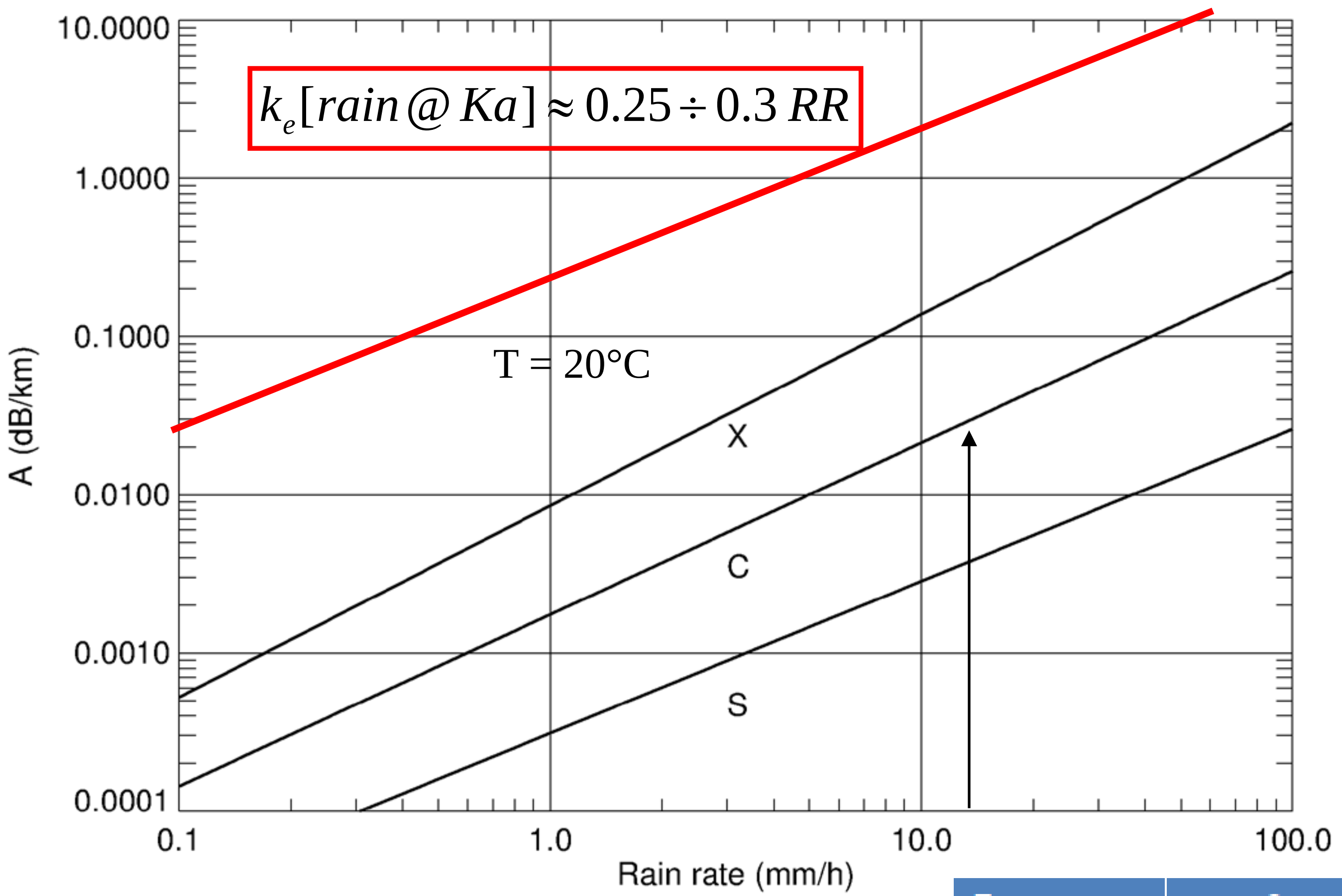
2. From the previous table T [0.2 kg/m^2]=0.85 ➔ T [0.4 kg/m^2]=0.85^2=0.72

Then the two way transmissivity

T_{2way} [0.4 kg/m^2]=0.72^2 =0.52 ➔ 3 dB attenuation

$10\log_{10}(1/2)=-10\log10(2)=-3\text{dB}$

Attenuation-rainfall rate relationship



Best fitting A-RR curves

RR almost linearly related to attenuation at Ka-band (but also in other bands), much better than Z ➔ rainfall attenuation algorithms

Temperature	S	C	X
0°C	$5.37\ 10^{-4}\ R^{0.96}$	$2.90\ 10^{-3}\ R^{1.06}$	$1.14\ 10^{-2}\ R^{1.13}$
10°C	$4.07\ 10^{-4}\ R^{0.96}$	$2.25\ 10^{-3}\ R^{1.08}$	$1.00\ 10^{-2}\ R^{1.17}$
20°C	$3.11\ 10^{-4}\ R^{0.96}$	$1.75\ 10^{-3}\ R^{1.09}$	$8.51\ 10^{-3}\ R^{1.21}$
30°C	$2.46\ 10^{-4}\ R^{0.96}$	$1.38\ 10^{-3}\ R^{1.09}$	$7.16\ 10^{-3}\ R^{1.25}$

Example: rain attenuation at 35 GHz

A layer of 3 km of rain is producing an attenuation of 24 dB in a Ka-band radar. Estimate the rain rate. What would be the attenuation at C-band?

6 km of two way path ➔ 24/6= 4 dB/km attenuation

$$k_e[rain@Ka\ in\ dB/km] \approx 0.28\,RR\left[mm/h\right]$$

$$RR\left[mm/h\right] \approx 3.6\,k_e[dB/km] = 14.4mm/h$$

From the previous Table with such rain rate at C-band

$$k_e[rain@C\ in\ dB/km] \approx 0.02dB/km$$

$$A_{2-way}[rain@C] \approx 6\times 0.02 = 0.12dB$$ Negligible!

What do you need to know?

- Space-borne radars for the characterization of the vertical structure of cloud and precipitation.
- Be able to use the radar equation to compute received power
- Cloud vs rain radars: advantages and disadvantages. Role played by attenuation.
- Missions: TRMM, GPM, CloudSat (topics for essay)