Spaceborne G-band radar/radiometer: a leap forward for cloud and precipitation remote sensing from space.

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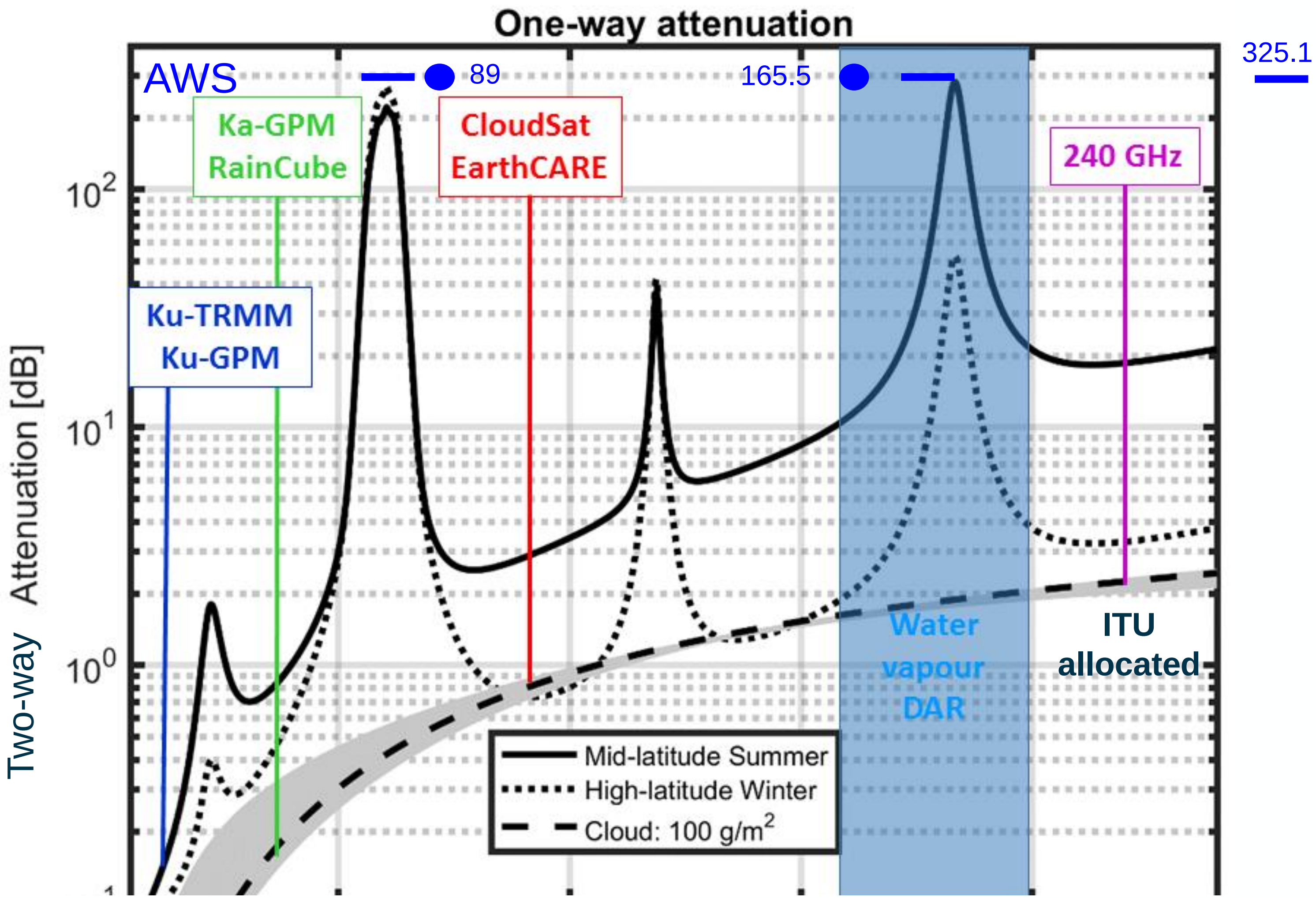
- ESA-funded study in progress to develop mission concepts for a G-band spaceborne radar mission (ref. ESA AO/1-11317)
- ESA-funded RainCast project, focused at assessing Scientific Value of G-band radar in synergy with radiometers (ref ESA AO/1-9324/18/NL/NA)

G-band in the cloud&precipitation radar arena



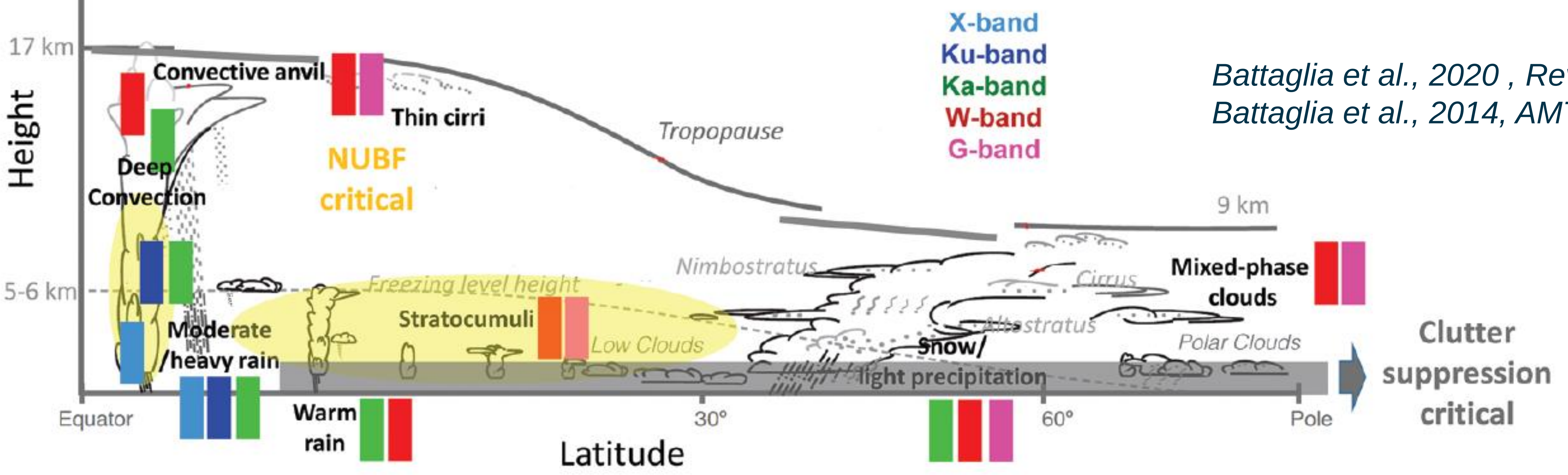
- Cloud radars at 140–215 GHz more than 30 years ago! (*Nemarich et al., 1988; Mead et al., 1989; Wallace, 1988*)
- Notional studies *(Lhermitte 1989, Hogan and Illingworth 1999, Battaglia et al., 2014).*

Game changer: mm- and sub-mm solid state power devices and low noise amplifiers have recently enabled higher frequency radar capable to achieve **sensitivities suitable**

240 GHz perfectly positioned to understand the physics of the next generation of high frequency MW radiometers

Science case for cloud&precipitation observations

Problem: limited understanding of cloud feedbacks is the major source of ***uncertainty in climate sensitivity*** (from 1.5 up to 4.5 K) ➔ better characterization of cloud&precipitation vertical structure and microphysics needed (benchmark for next generation of Earth System Models and for ML algorithms).



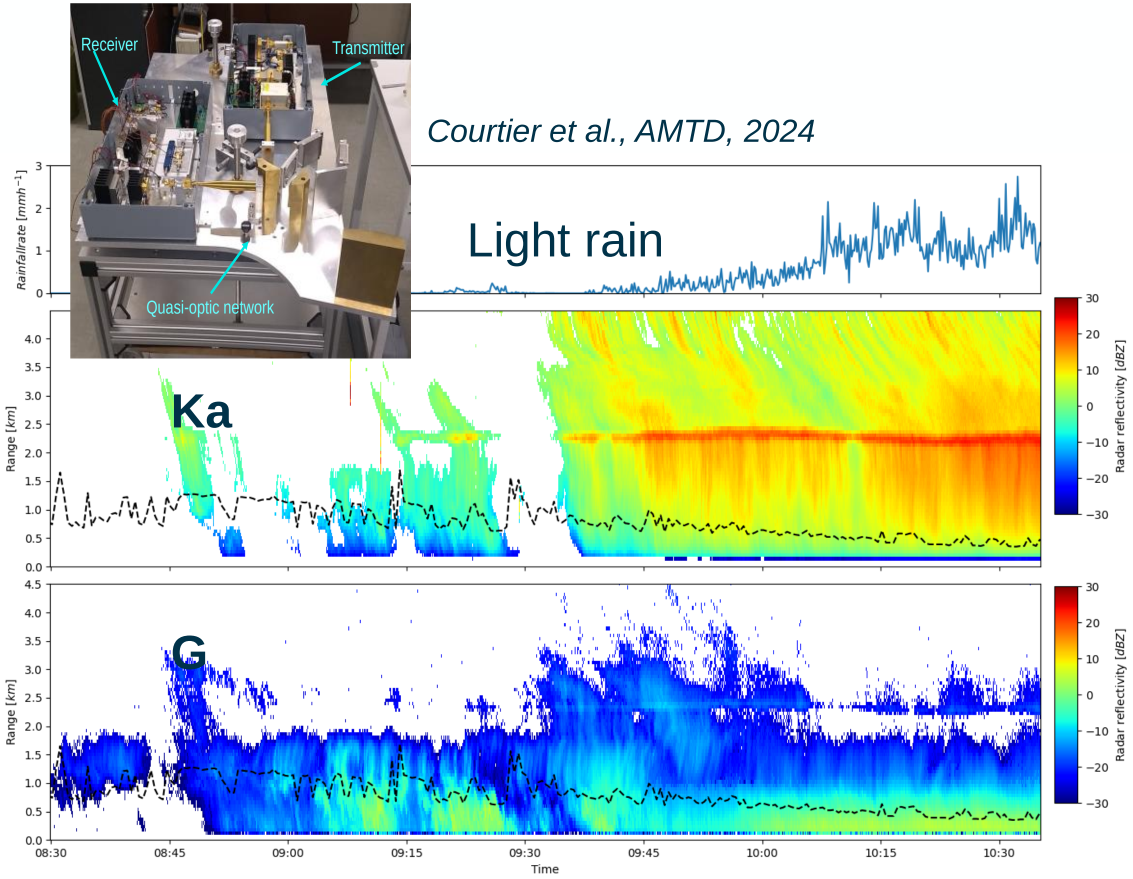
Battaglia et al., 2020 , Rev. of Geophysics
Battaglia et al., 2014, AMT

Solution: combination of multi-frequency (Doppler) radars with frequencies ranging from 10 to 300 GHz allows microphysical characterization from heavy precipitation particles to small-size ice crystals.
G-band highly beneficial in three areas: ***BL clouds, cirrus/mid-level ice clouds and precipitating snow***.

G-band ground-based systems

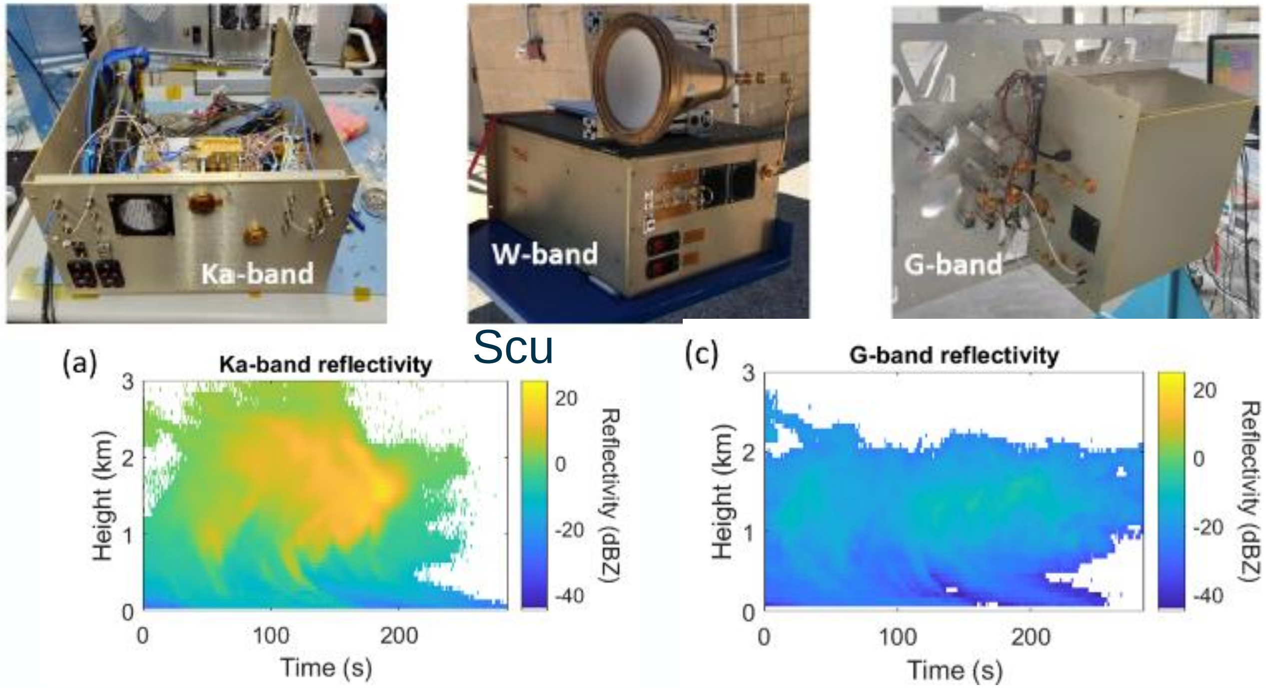
The UK-CEOI G-band Radar for Cloud Experiment (**GRACE**): **200 GHz,** Doppler, deployed at Chilbolton observatory.

Courtier et al., AMTD, 2024



The JPL Ka-W-G band **CloudCube,** 238.8 GHz, Doppler. EPCAPE campaign conducted in March/April 2023 in California (marine clouds and light precipitation)

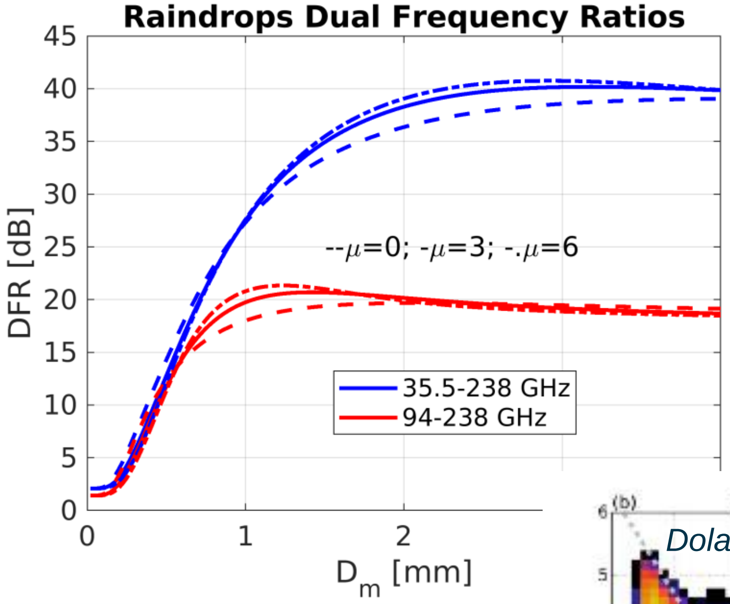
Socuellamos et al., Earth Syst. Sci. Data, 2024

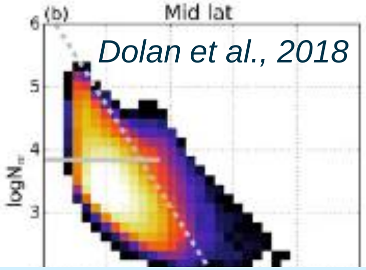


The differential signal between the two frequencies can be exploited for microphysics retrievals

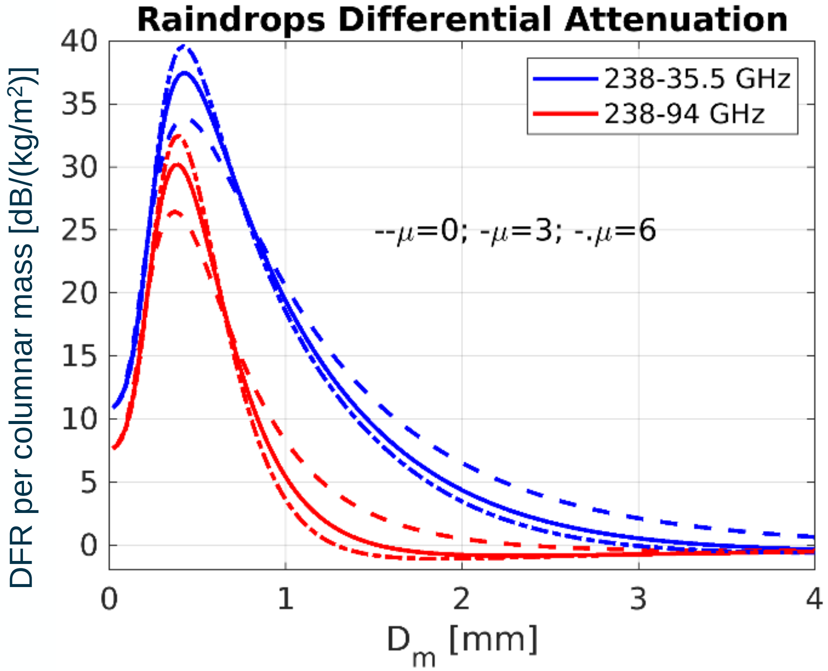
Why a multi-frequency approach? Liquid cloud case

$$DFR(f_1, f_2, r)[\mathrm{dB}] \equiv Z_m(f_1, r) - Z_m(f_2, r) = \overbrace{Z_e(f_1, r) - Z_e(f_2, r)}^{\text{Non-Rayleigh}} + \overbrace{2\int_0^r [k_e(f_2, r) - k_e(f_1, r)]\, dr}^{\text{Differential attenuation}}$$





Most of rain mean mass-weighted diameter range between 0.7 and 1.5 mm



Huge differential signal

Similar reasoning applies to ice particles

Earth Explore-class Baseline Miss

Frequency of operation	G-band (238 GHz) & Ka-band (35 GHz)
Antenna	2m solid reflector (G-band) 7.5m deployable reflector (Ka-band)
Polarisation	Single, circular
Instrument modes	Radar Mode 1: High sensitivity Radar Mode 2: High vertical resolution Radiometric Noise Mode
Transmitter	EIKA at G-band, ~100W EIKA at Ka-band, ~2kW
Pointing	Nadir + 10 km swath
Launcher	Vega-C

Enabling Technologies

Deployable reflector antenna (Large Space Structures GmbH, others): *7.5 m reflector diameter for Ka-band radar (CIMR heritage)*

Antenna feed network (Thomas Keating Ltd): *linear-to-circular polarisation conversion with high isolation between Tx/Rx. Necessary for single-antenna radar instruments.*

Tx/Rx Hardware (RAL Space, others): *Schottky & MMIC based components operating up to 238 GHz (e.g. SSPA, High-power multiplier, RF LNA, Waveguide switch, Noise source)*

Extended Interaction Klystrons (CPI Inc): *Vacuum electronics technology for high-power applications (heritage CloudSAT, EarthCARE)*

250-276 GHz EIK (courtesy CPI Inc)

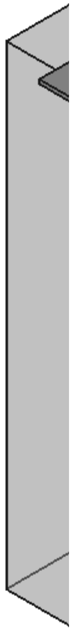


Table 4-2 EE Instrument Performance Analysis

Radar Parameter	Value		Value	
Frequency (GHz)	238		35	
Band	G		Ka	
Altitude (km)	450		450	
Ground-track speed (ms^{-1})	7137		7137	
Transmitter information				
Transmitter type	EIKA		EIKA	
Transmitter power (W)	100		2000	
Duty cycle (%)	4.9		4.9	
Transmit Loss (dB)	0.7		0.5	
Antenna information				
Antenna size (m)	2.0		7.0	
Antenna efficiency	0.5		0.5	
Antenna Gain (dB)	70.9		65.2	
3dB beamwidth (°)	0.044		0.086	
Instantaneous FOV (km)	0.35		0.67	
Receiver information				
Noise Figure (dB)	6		2.5	
Receive Loss (dB)	2.0		1.0	
System temperature (K)	290		290	
Sampling and integration				
$\sigma_{D,ground-track}$ (ms^{-1})	1.65		3.2	
t_{coh} (µs)	132.8		464.9	
PRF_{MIN} (kHz) for Doppler	7.53		2.15	
PRF (kHz)	2.25		2.25	
Radar Mode				
Pulse scheme	Pulse Frequency diversity 1.66 µs unmodulated (ref)	Chirp Max pulse 20µs NLFM pulse with B = 0.6 MHz	Pulse Frequency diversity 1.66 µs unmodulated (ref)	Chirp Max pulse 20µs NLFM pulse with B = 0.6 MHz
Range resolution (m)	250	250	250	250
MDS no integration (dBZ)	-14.8	-22.6	-10.1	-17.9
Integration length (km)	0.5		0.5	
Number of samples (#)	158		158	
Independent samples	158		158	
MDS with integration (dBZ)	-25.8	-33.6	-21.0	-28.9
Random error after Integration assuming 20 dBZ target return level (dB)	0.346	0.346	0.346	0.346
Radiometric Mode				
Pre-detection Bandwidth (MHz)	95		95	
Integration Time per PRI (us)	420		420	
# PRI integration periods	8192		16384	
Scene Integration Time (s)	3.44		6.88	
Calibration Integration Time (s)	0.05		0.05	
Calibration Sample Averaging	4		4	
Receiver Gain Stability	0.0001		0.0001	
NeDT at max scene temp (K)	0.48		0.18	

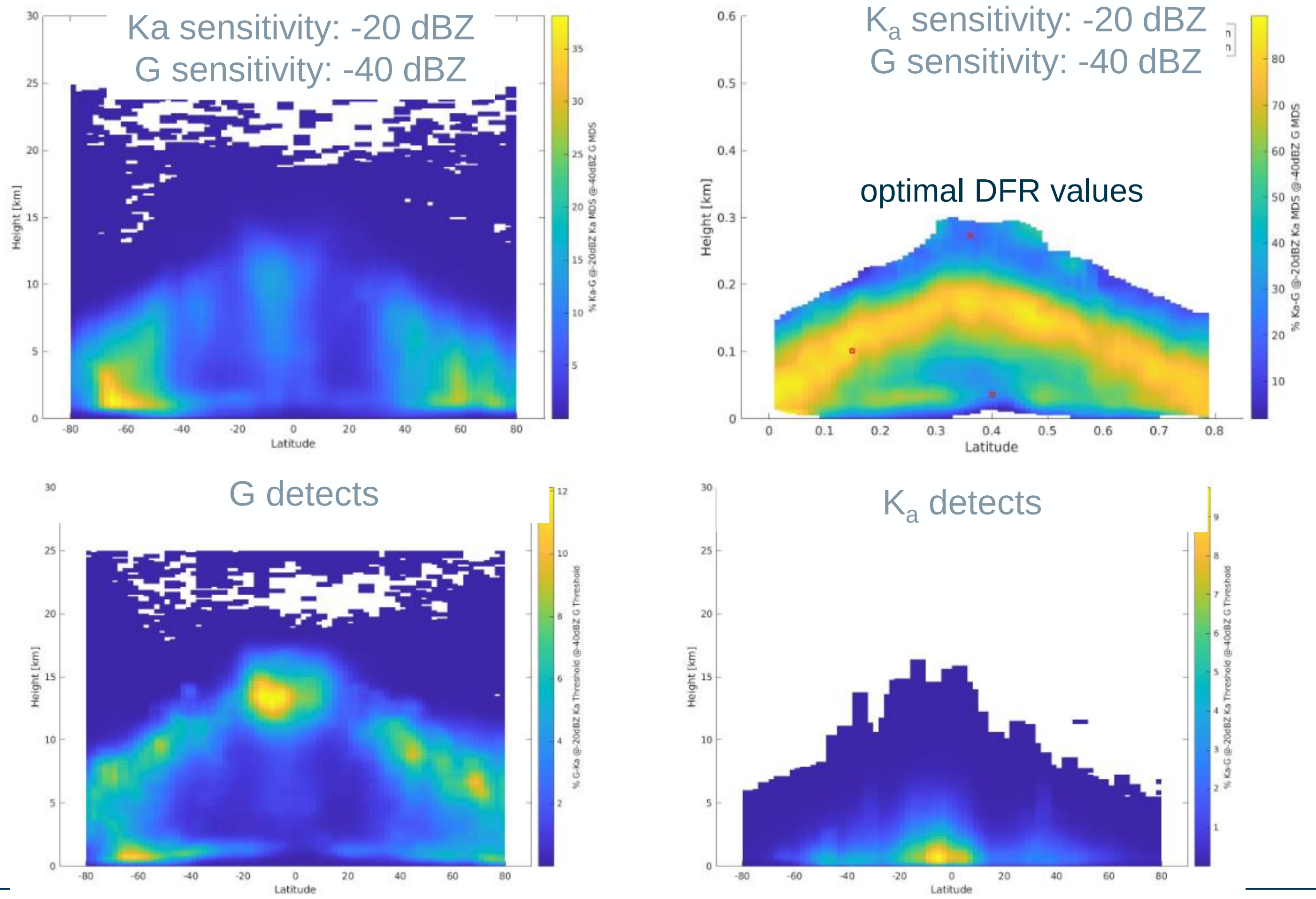
K_a-G band radar: synergy and complementarity

From a database of microphysical profiles derived from 1500 A-Train orbits via CAPTIVATE algorithm (Mason et al., 2024) K_a and G band radar reflectivities and radiometer T_Bs are simulated➔ samples of all thermodinamic, atmospheric and surface conditions we are interested in.

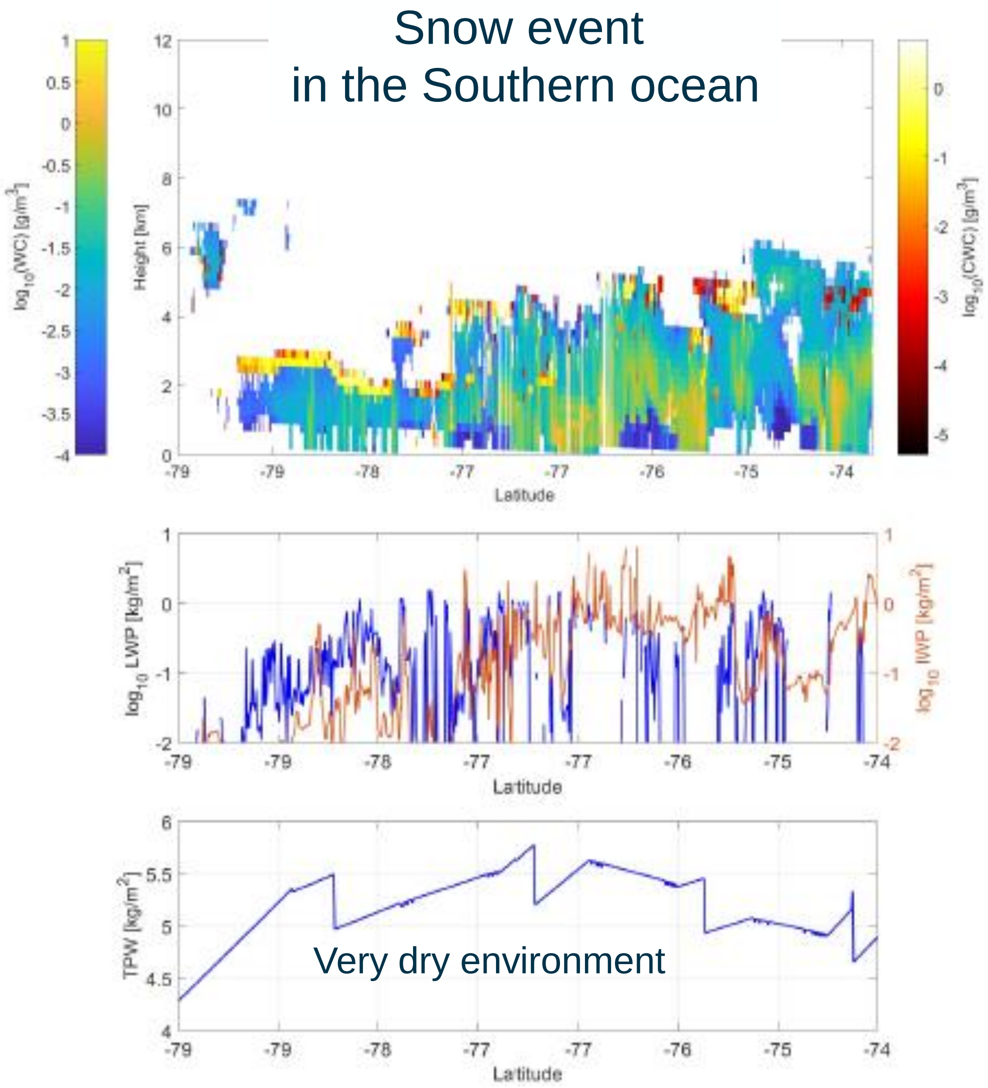
For instance frequency of when:

both systems detect clouds
(SYNERGY)

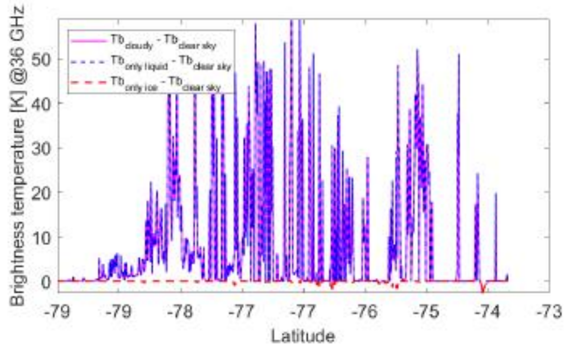
only one system detects clouds
(COMPLEMENTARITY)



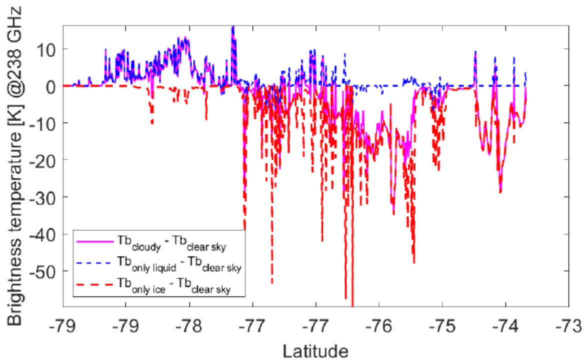
Brightness temperature value (radiometric mode)



Supercooled layers are ubiquituous (both at cloud top and embedded).
They are invisible to conventional radars (amounts >30-50 g/m^2 can be seen by G-band attenuation)



35 GHz T_Bs are driven by the liquid component



238 GHz T_Bs are the result of a «tug of war» between ice scattering and supercooled water emission

T_Bs can be used to constrain integrated ice and liquid cloud amounts.

Outlook and Recommendations

G-band cloud radars are now a reality with levels of sensitivities to levels appropriate for cloud studies ➔ thanks to their increased dynamic range of DFR when operated in synergy with a lower frequency, they have great potential for **sizing sub-millimeter ice crystals and rain droplets and for quantifying light rain and snowfall** (focus on clouds at high latitude/high altitude).

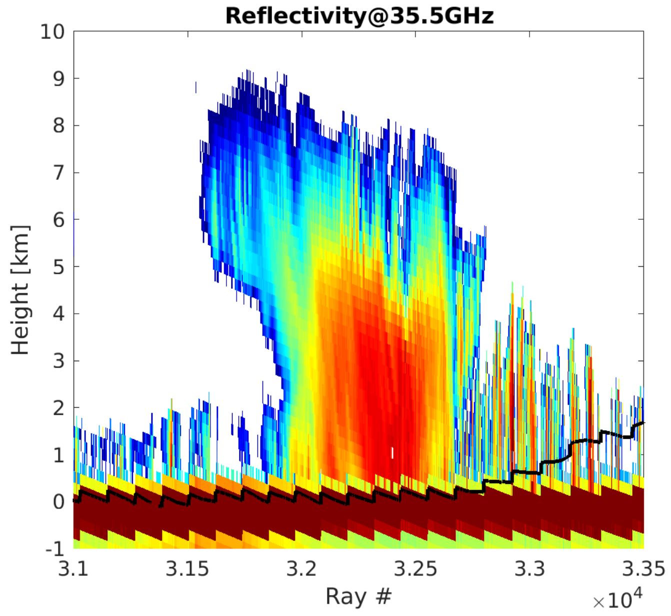
1. More **field campaigns needed** in synergy with lower frequency (X-Ka-W) to confirm science merit in improving microphysics of light rain and ice/snow ➔ground-based systems operated continuously, air-borne coming up soon (ESA ITT announced).

2. **Advance SRL and TRL** (definition of science requirements, E2E simulator, L2 retrievals, synergy with high-freq radiometers, deployable antennas, SSPA, EIK, antenna feed network) to be ready for next Earth Explorer call.

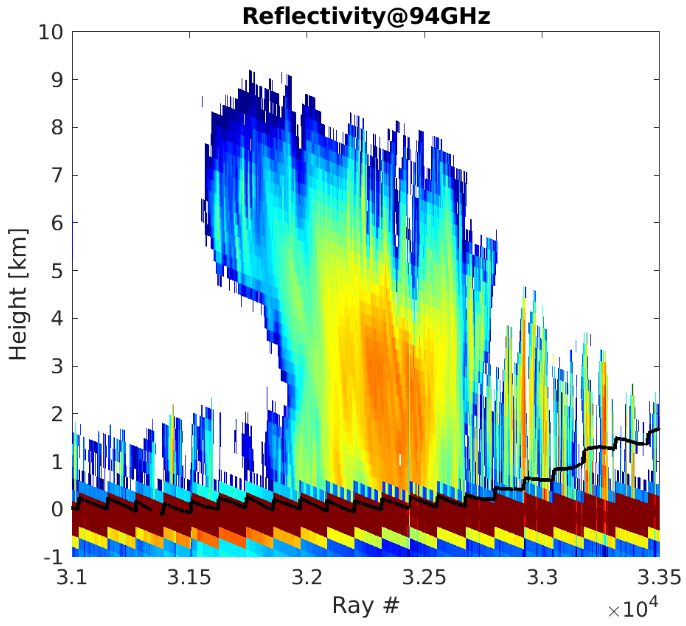
3. **Liaise with other agencies** (e.g. NASA and JAXA) because multi-frequency is expensive.

Thanks for the attention

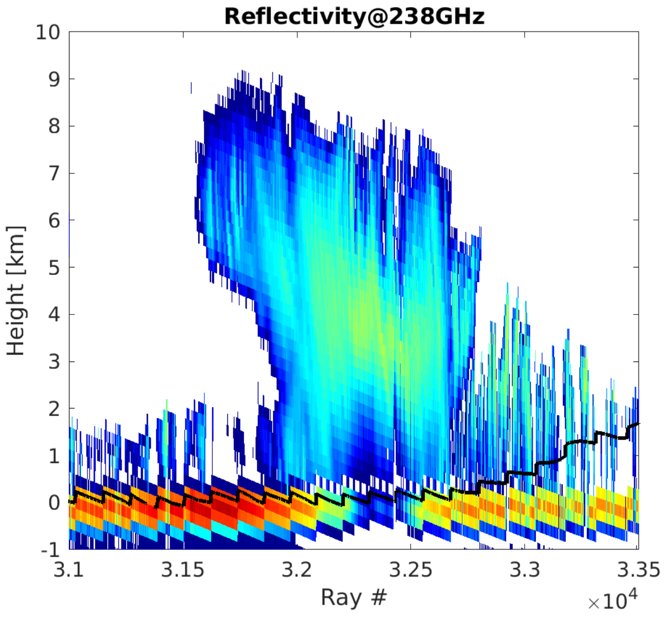
A mid-latitude frontal system as seen by a 35.5 (GMP-like) a 94 GHz (CloudSat and EarthCARE-like) and 238 GHz radar



GMP-like



CloudSat and EarthCARE-like



The missing arrow in the quiver!