Tutorial on GNSS Polarimetric Radio Occultations (GNSS PRO)

https://paz.ice.csic.es/outreach.php

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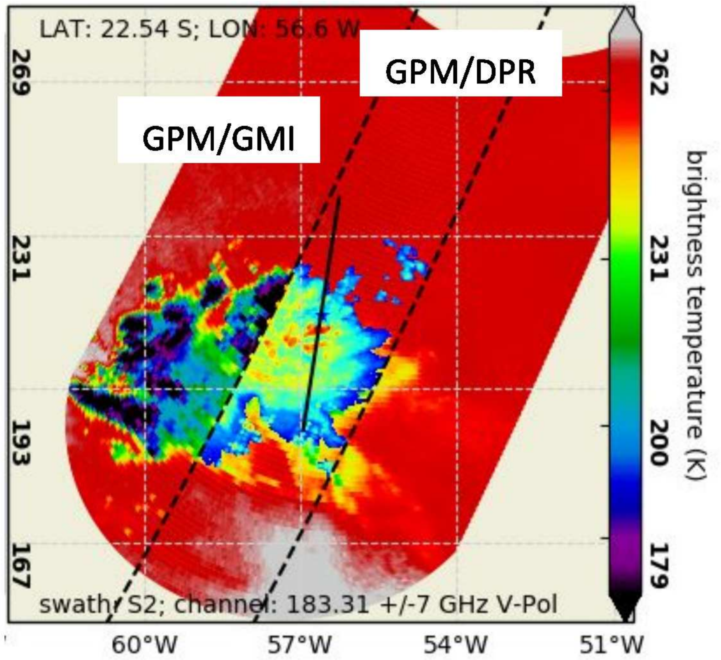
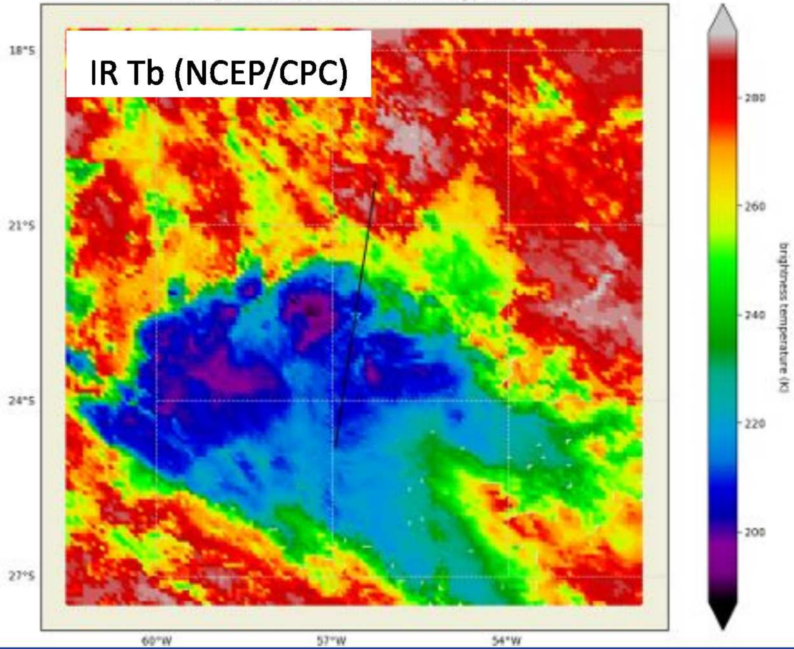
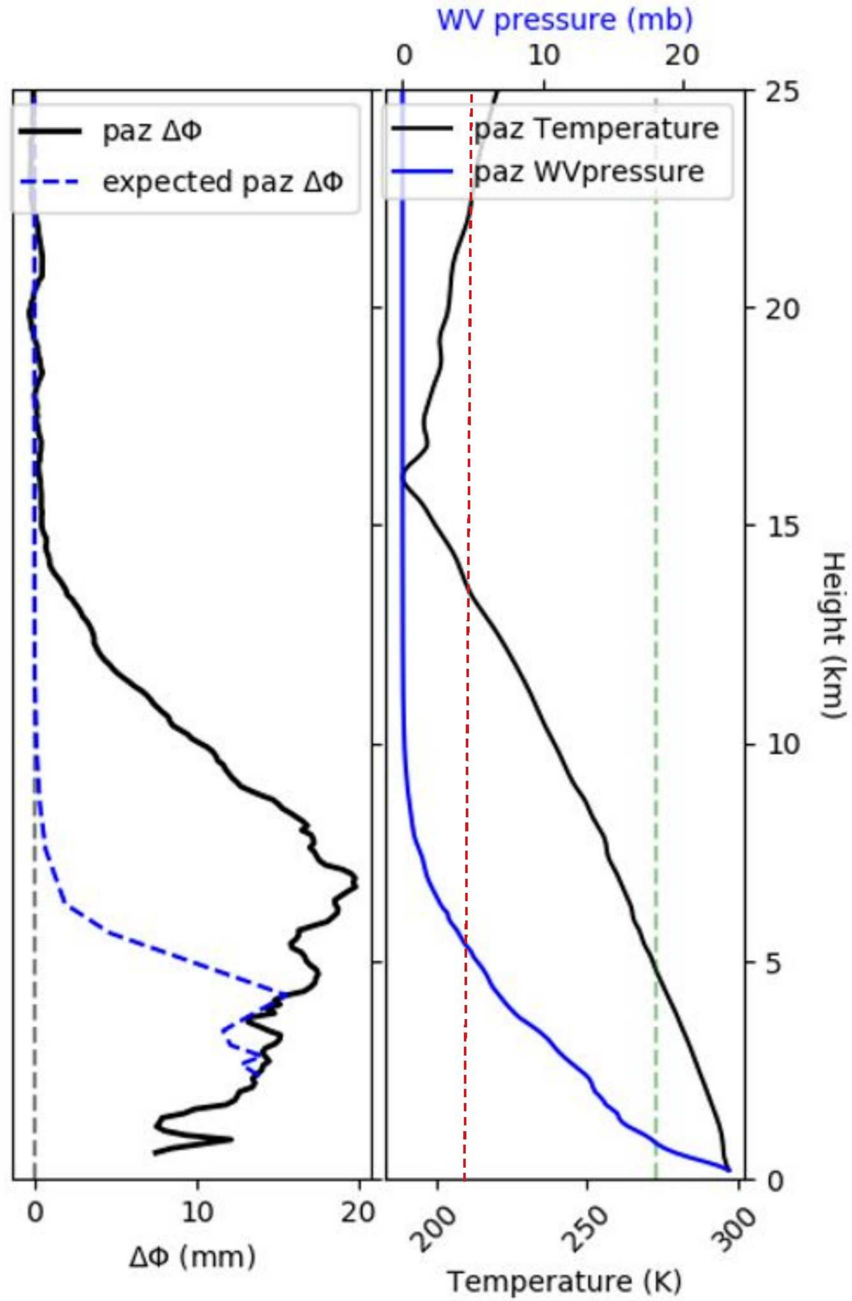
rohp-PAZ

https://paz.ice.csic.es


LAT: 22.54 S; LON: 56.6 W
GPM/DPR
GPM/GMI
269
231
193
167
262
231
200
179
brightness temperature (K)
swath: S2; channel: 183.31 +/-7 GHz V-Pol
60°W
57°W
54°W
51°W


IR Tb (NCEP/CPC)
18°S
21°S
24°S
27°S
60°W
57°W
54°W
280
260
240
220
200
brightness temperature (K)


paz ΔΦ
expected paz ΔΦ
0
10
20
ΔΦ (mm)
WV pressure (mb)
0
10
20
paz Temperature
paz WVpressure
200
250
300
Temperature (K)
0
5
10
15
20
25
Height (km)

Contents:

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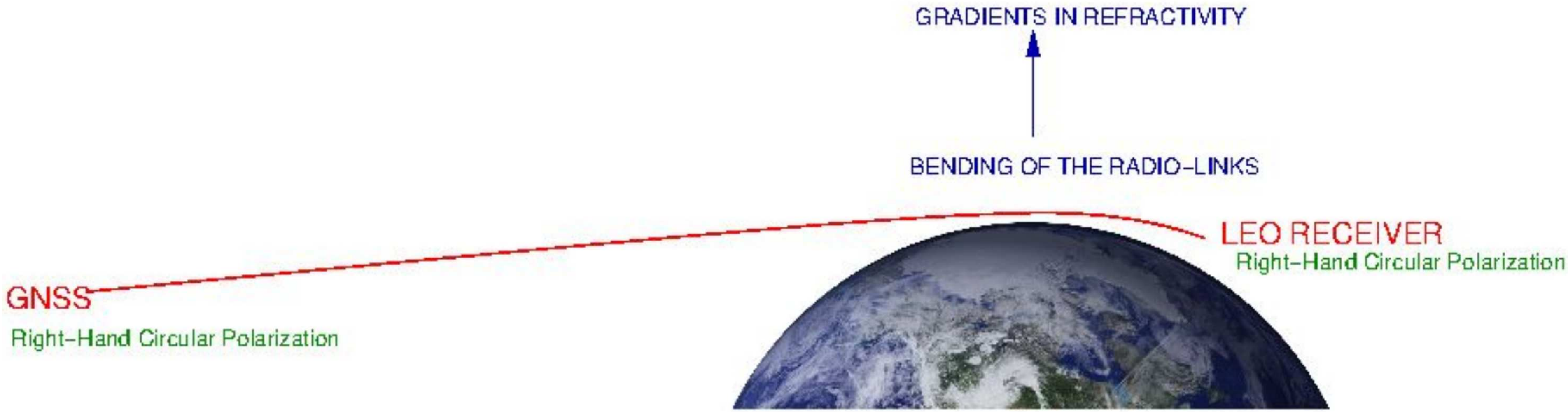
RO GEOMETRY:
propagation between a source of signal (GPS satellite) and a receiver (PAZ Low Earth Orbiter), when they are occulting from each other behind the horizon of a Planet (the Earth):

The EM signals cross the atmosphere in very slant geometry.
In this geometry, the vertical gradients in a medium refract EM signals, **bending** them.

RO GEOMETRY:
propagation between a source of signal (GPS satellite) and a receiver (PAZ Low Earth Orbiter), when they are occulting from each other behind the horizon of a Planet (the Earth):

The EM signals cross the atmosphere in very slant geometry.
In this geometry, the vertical gradients in a medium refract EM signals, **bending** them.
→ The Doppler effects of the bent signal are different than the ones for straight-line propagation. GNSS (GPS) can **measure the Doppler effects precisely**.



From Doppler measurements, it is possible to infer the bending of the 'ray'.

From the bending information, it is possible to infer **VERTICAL PROFILES OF THERMODYNAMIC VARIABLES** around the tangent point (typically temperature, pressure, humidity)

GNSS RO product!

Vertical resolution: a few hundred meters
Horizontal resolution: ~ hundred kilometers

COST-EFFECTIVE, MATURE AND VALUABLE TECHNIQUE!!

- First tested with Earth-planetary sounder radio links, when the sounders set below the planets (60s, 70s) → sounding other planets' atmospheres.

- First tested for Earth atmosphere: GPS-MET satellite (mid 90s).

- Mid 00s:
    - Several GPS RO missions orbiting the Earth.
    - GPS RO operationally assimilated into NWP models, strong positive impact (weather forecast error reduction).

Contents:

- Polarimetric RO (PRO) is a **NEW MEASUREMENT CONCEPT.**

- It combines **radio occultation links** of the GNSS with the **polarimetric properties** of the forward **scattering off big rain droplets** (and other hydrometeors).

- HYPOTHESIS: polarimetric information sensitive to **heavy precipitation**

- If successful, GNSS-PRO would represent the **only sensor** that can infer **both**

VERTICAL PROFILES OF ATMOSPHERIC THERMODYNAMICS

+

VERTICAL PROFILES OF HEAVY RAIN

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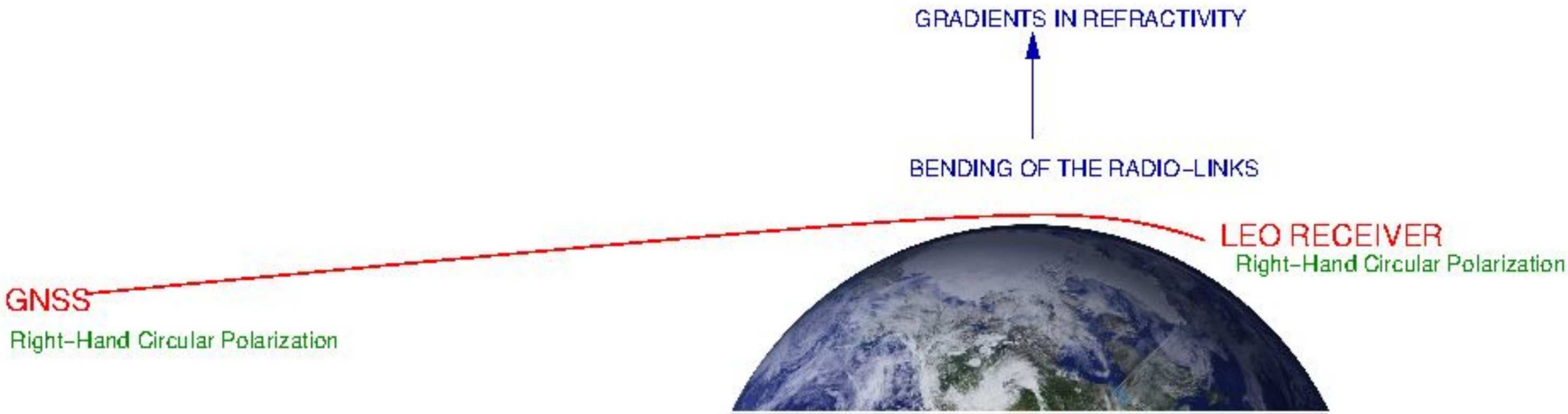
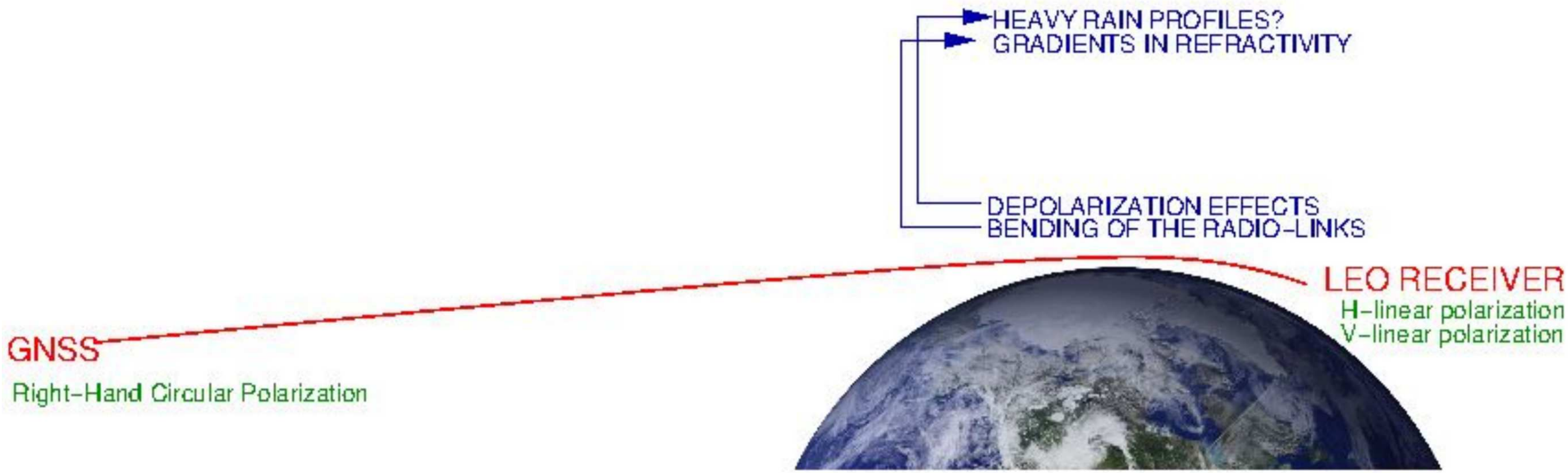
Why are coincident thermodynamic and precipitation vertical profiles required?

- They might help understanding the thermodynamic conditions underlying intense precipitation.
- This is relevant because extreme events **remain poorly predicted** with the current climate and weather model parametrization.
- A better understanding is necessary towards improving climate models and **quantifying the impact of climate variability** on precipitation.

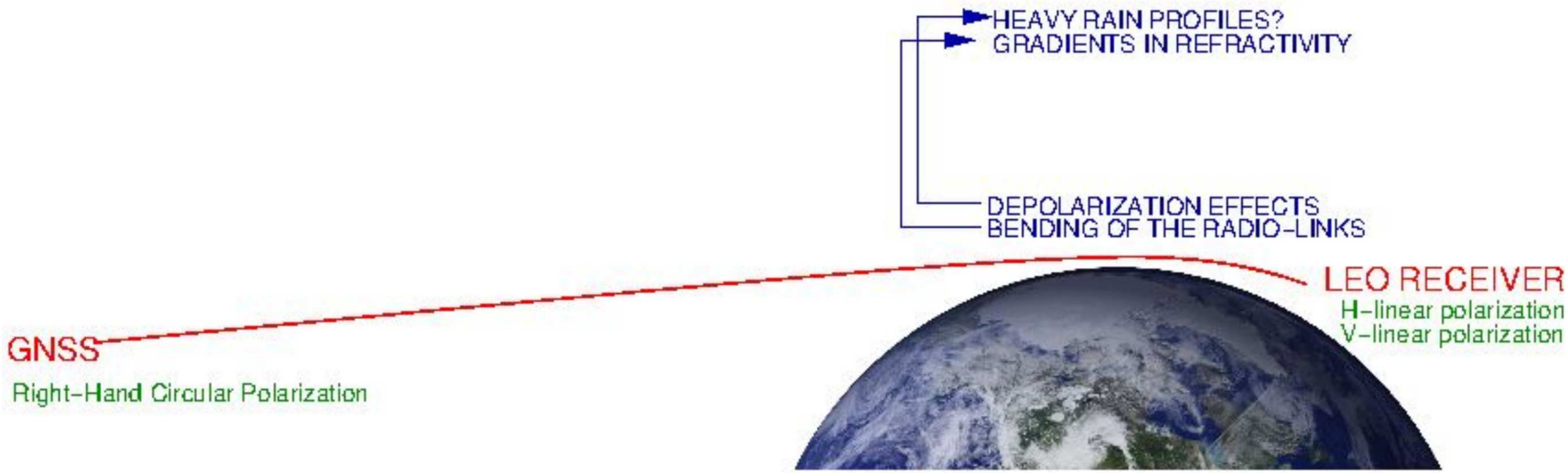
GNSS RO


GRADIENTS IN REFRACTIVITY
BENDING OF THE RADIO-LINKS
LEO RECEIVER
Right-Hand Circular Polarization
GNSS
Right-Hand Circular Polarization

GNSS PRO


HEAVY RAIN PROFILES?
GRADIENTS IN REFRACTIVITY
DEPOLARIZATION EFFECTS
BENDING OF THE RADIO-LINKS
LEO RECEIVER
H-linear polarization
V-linear polarization
GNSS
Right-Hand Circular Polarization

GNSS PRO

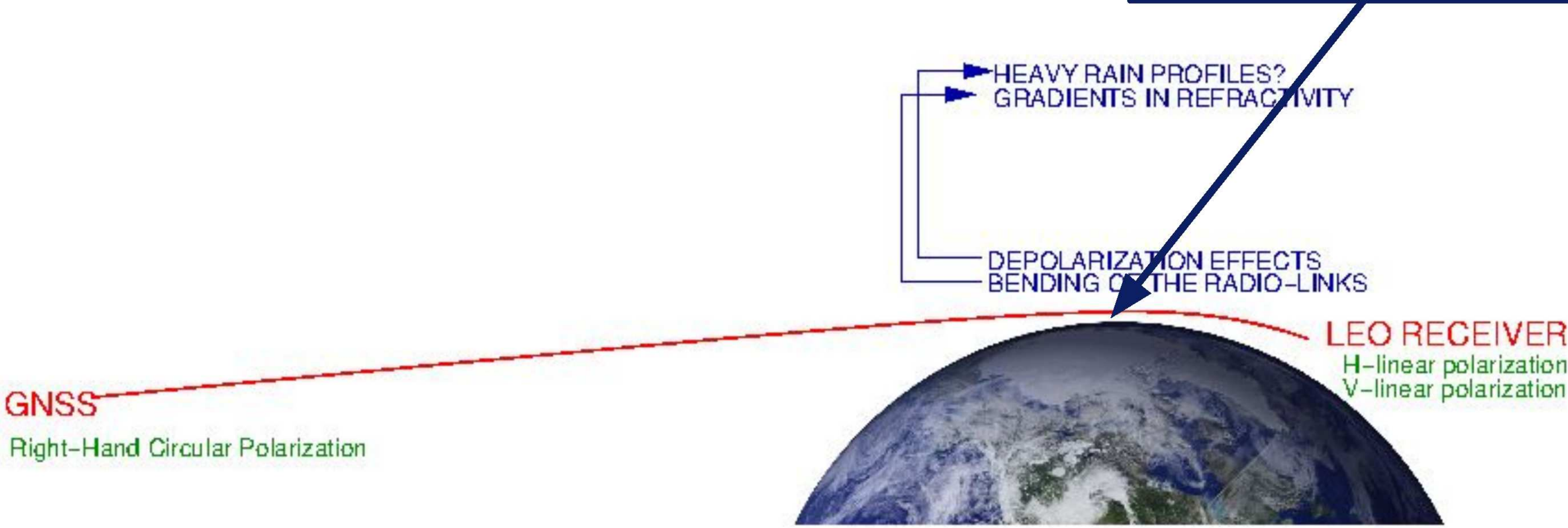


‘NEW’ GNSS-PRO PRODUCTS:

VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure, water vapor)

+ VERTICAL PROFILES OF INTENSE RAIN

Rain occurs at the lowest layers of the atmosphere: GNSS RO crossing along its **local horizontal direction**



'NEW' GNSS-PRO PRODUCTS:

VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure, water vapor)

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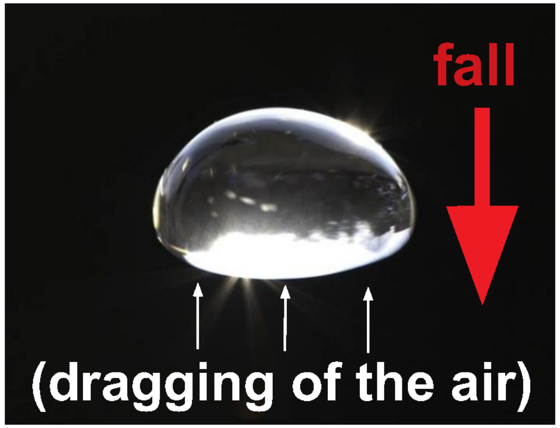
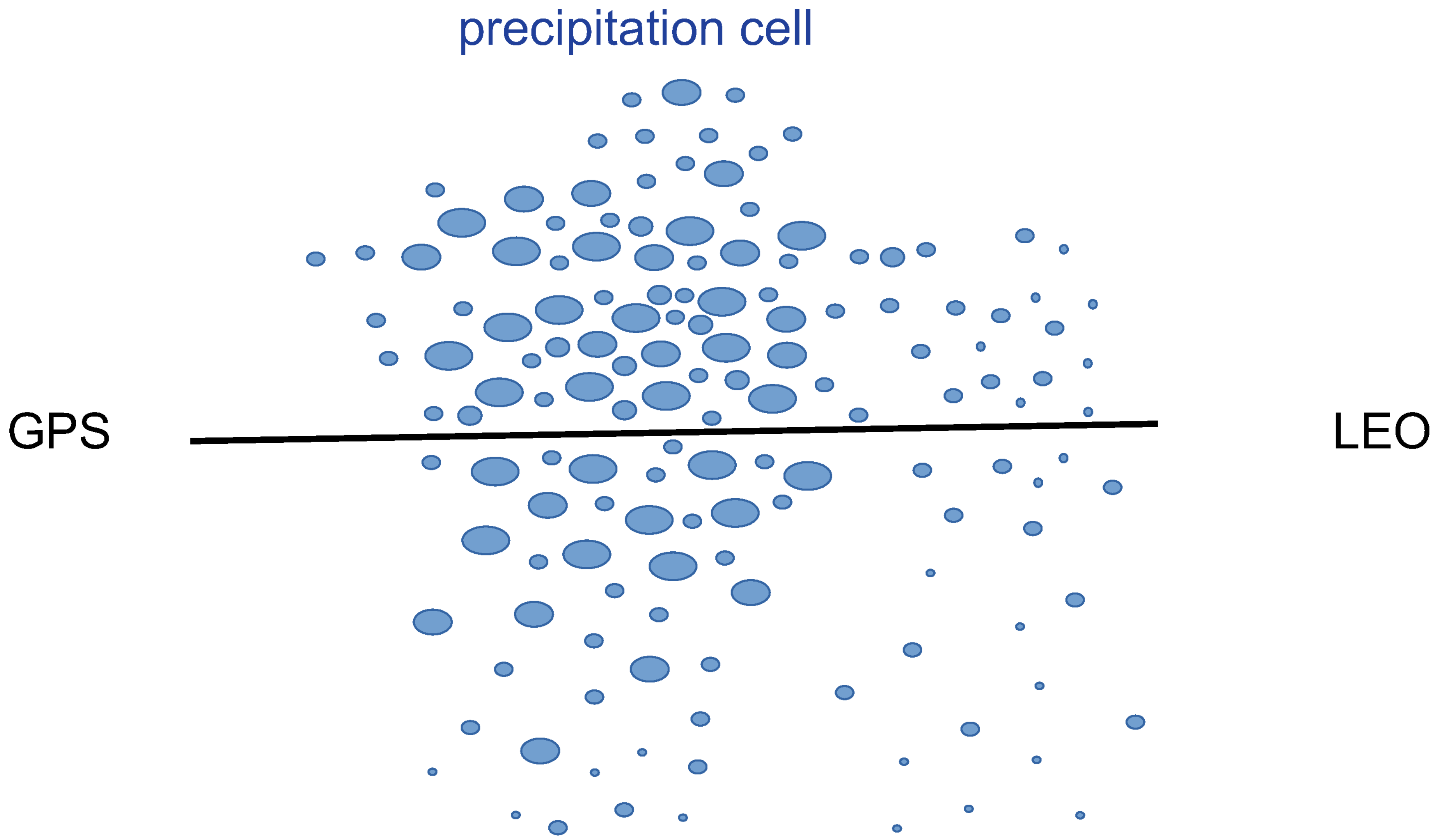
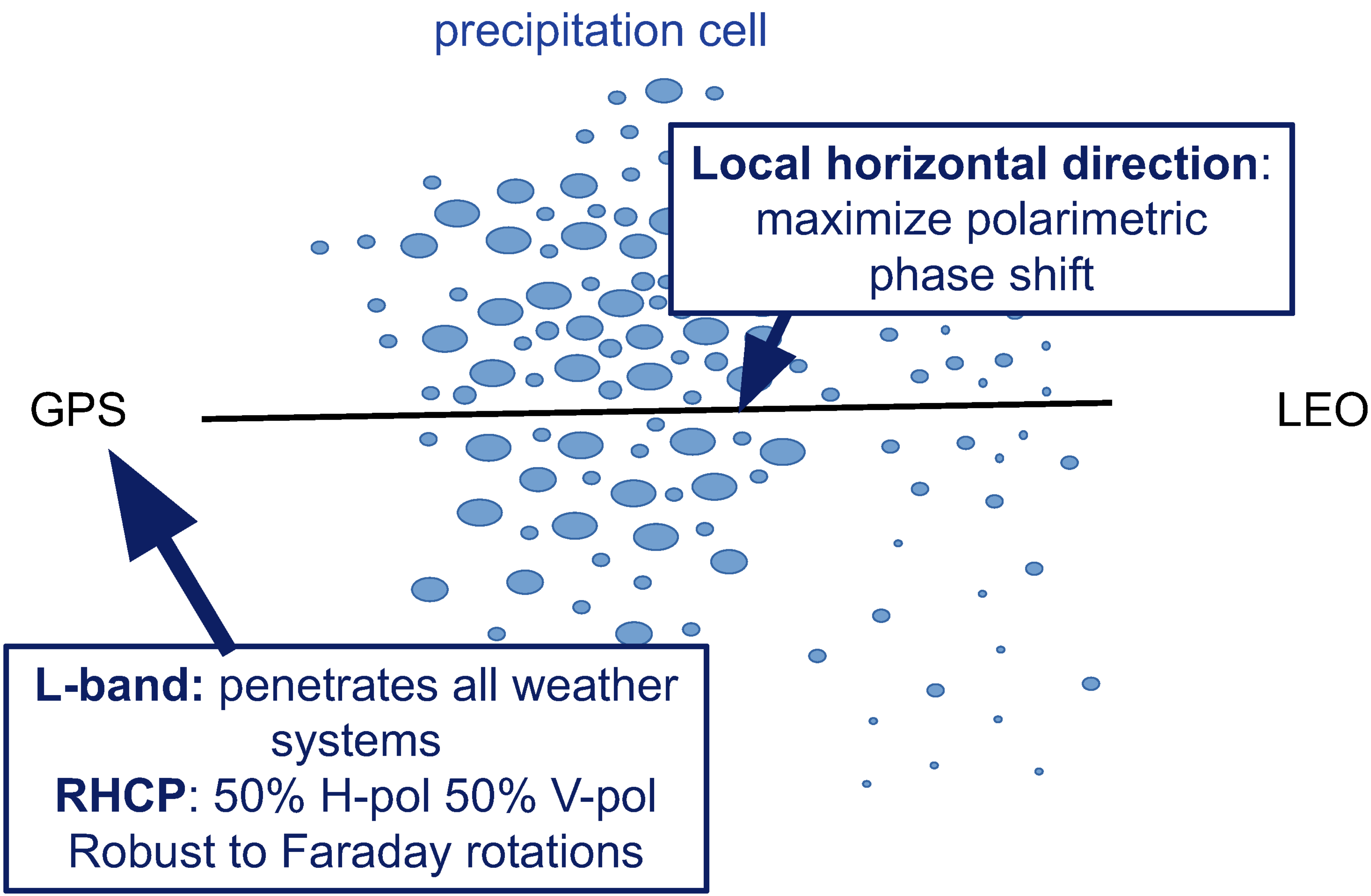
To understand this concept it is important to keep in mind that the big falling rain drops are not perfectly spherical, but flattened:

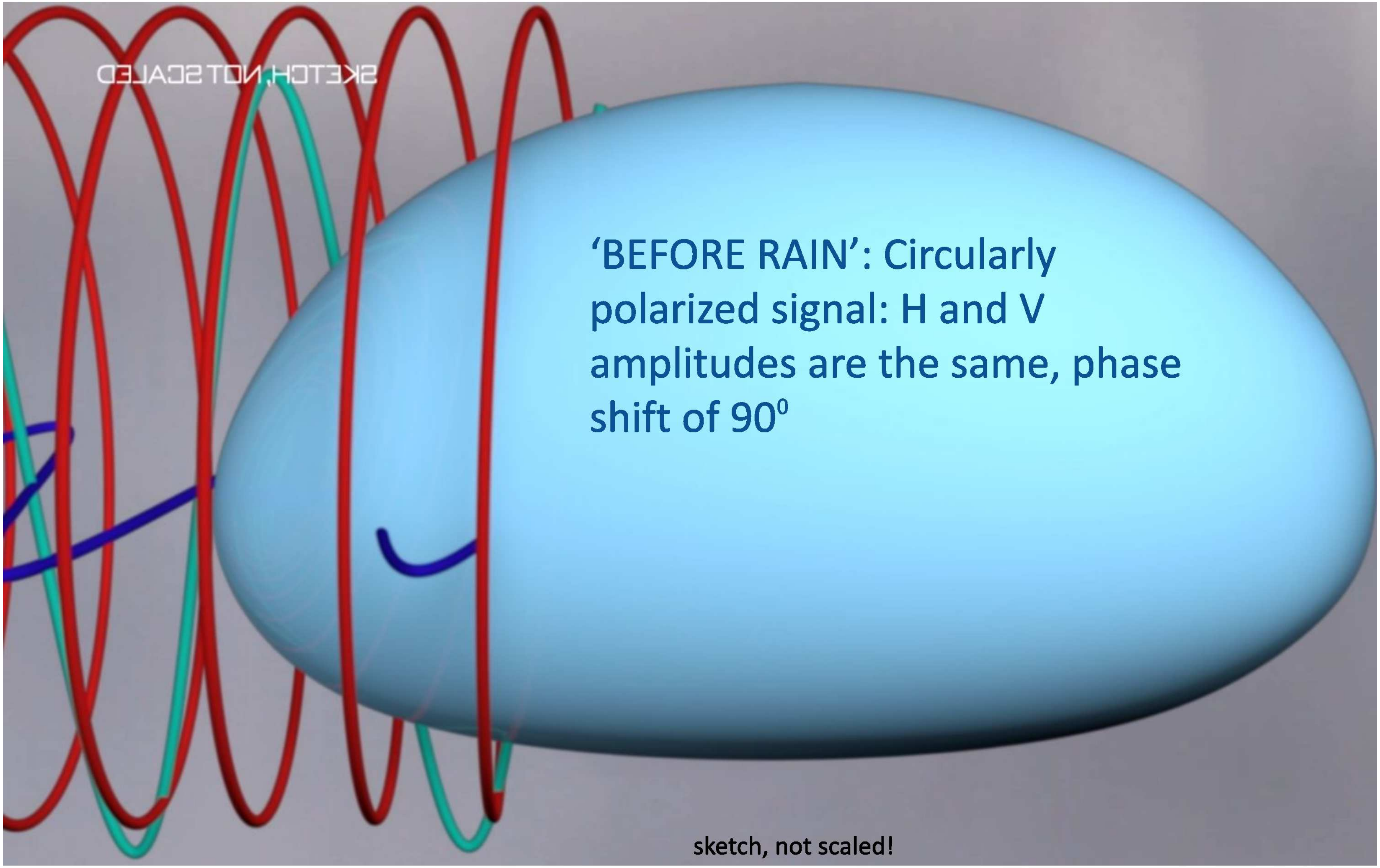


The bigger the drop, the larger the asymmetry effect.

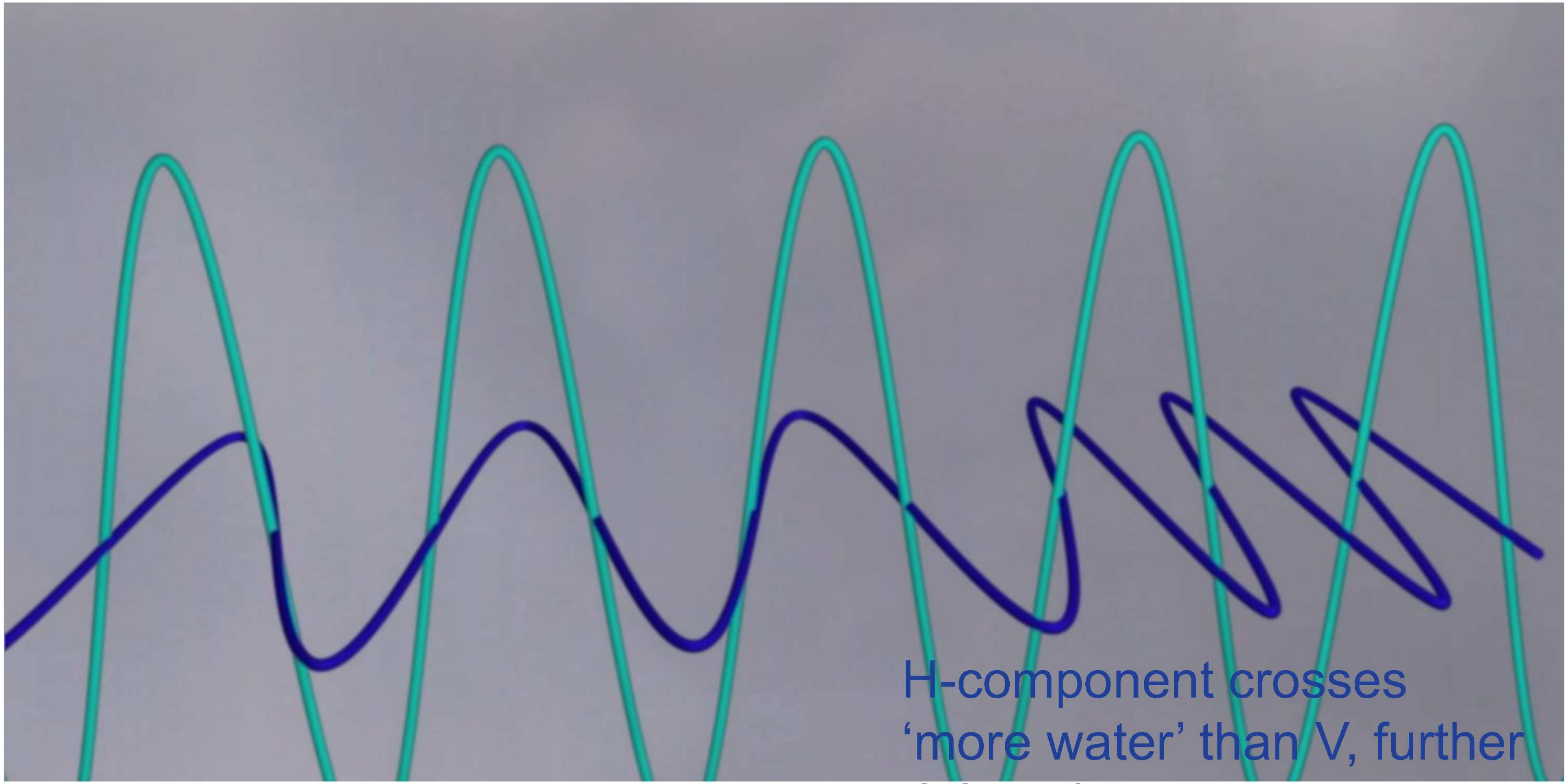
Heavier rain has more large drops.


precipitation cell
GPS
LEO


precipitation cell
Local horizontal direction: maximize polarimetric phase shift
GPS
LEO
L-band: penetrates all weather systems
RHCP: 50% H-pol 50% V-pol
Robust to Faraday rotations

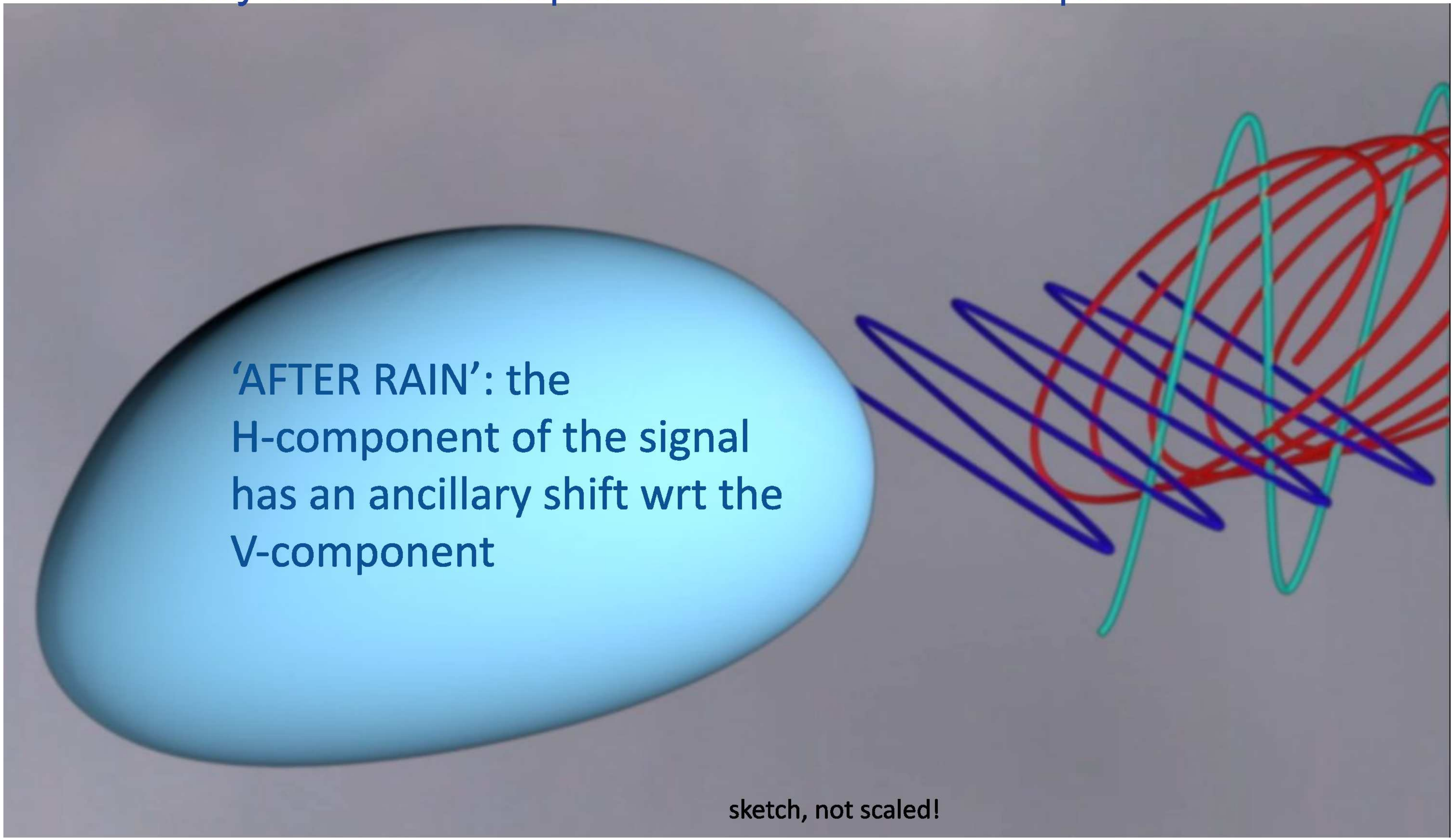

'BEFORE RAIN': Circularly polarized signal: H and V amplitudes are the same, phase shift of 90^0
sketch, not scaled!

Interaction with the drop



H-component crosses 'more water' than V, further delayed

Delay of the H-component wrt to the V-component



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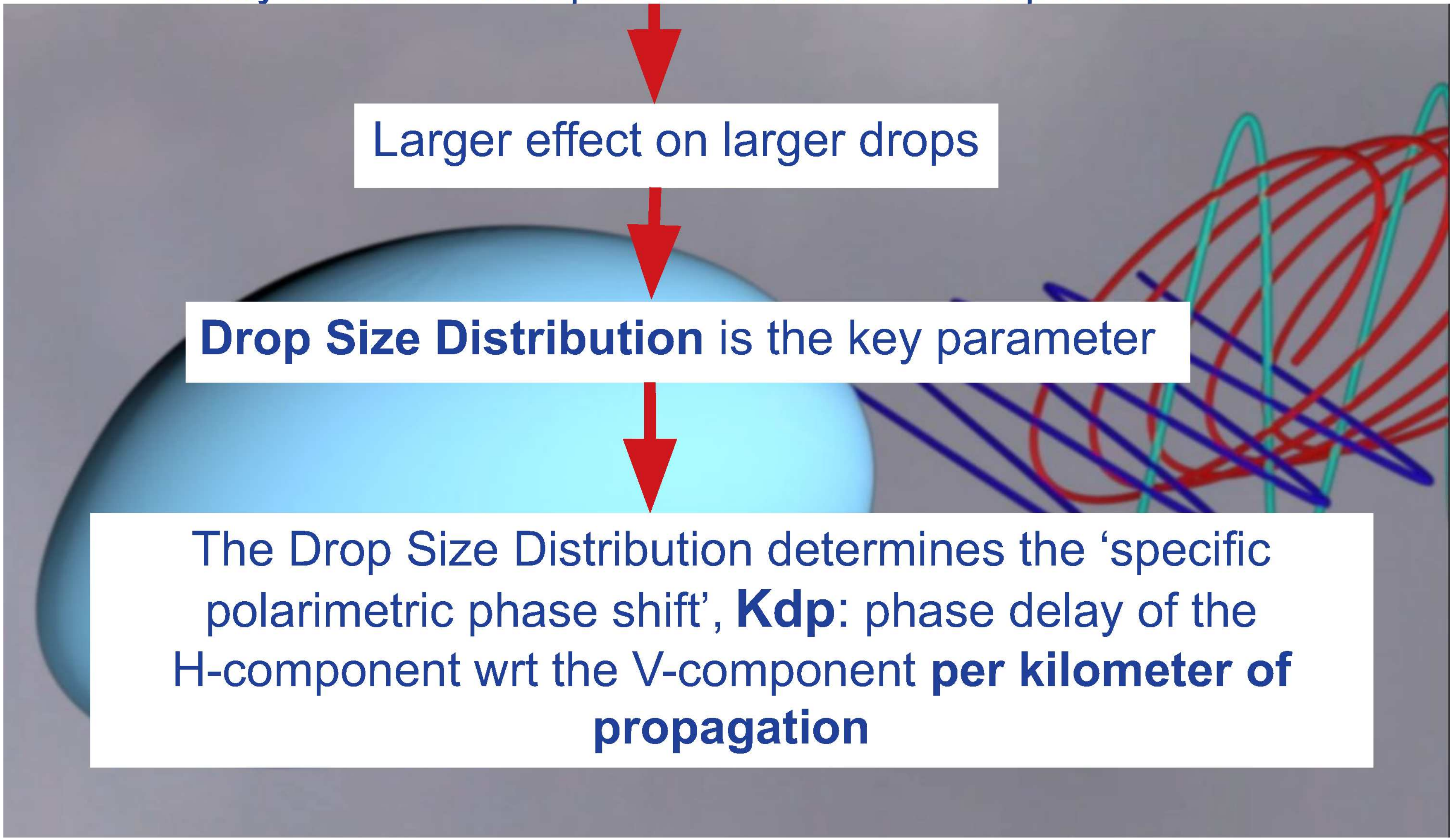
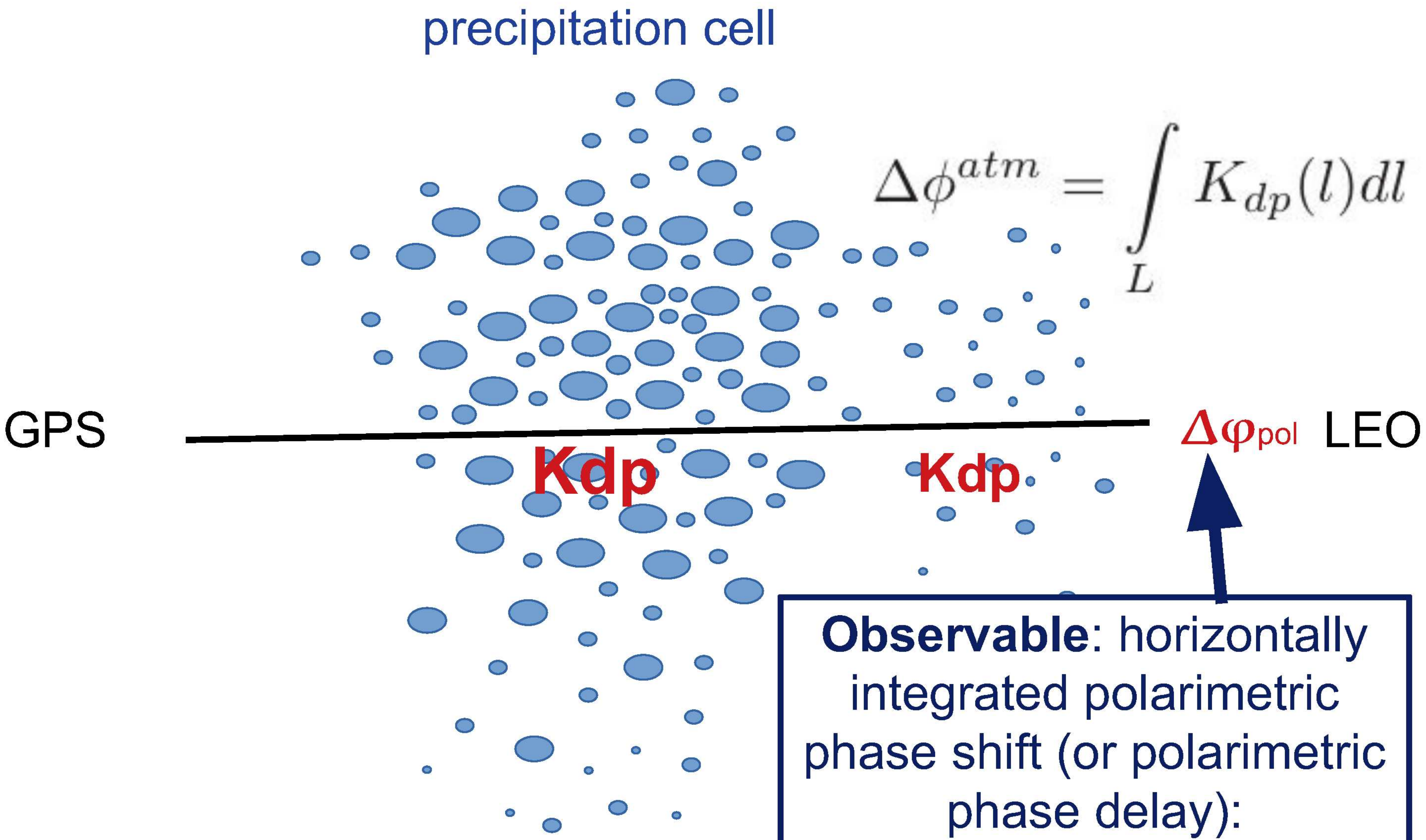
Delay of the H-component wrt the V-component



Larger effect on larger drops

Drop Size Distribution is the key parameter

The Drop Size Distribution determines the ‘specific polarimetric phase shift’, **Kdp**: phase delay of the H-component wrt the V-component **per kilometer of propagation**



$$\Delta\phi^{atm} = \int_L K_{dp}(l)dl$$

Observable: horizontally integrated polarimetric phase shift (or polarimetric phase delay):

$\Delta\varphi_{pol} = \varphi_H - \varphi_V$

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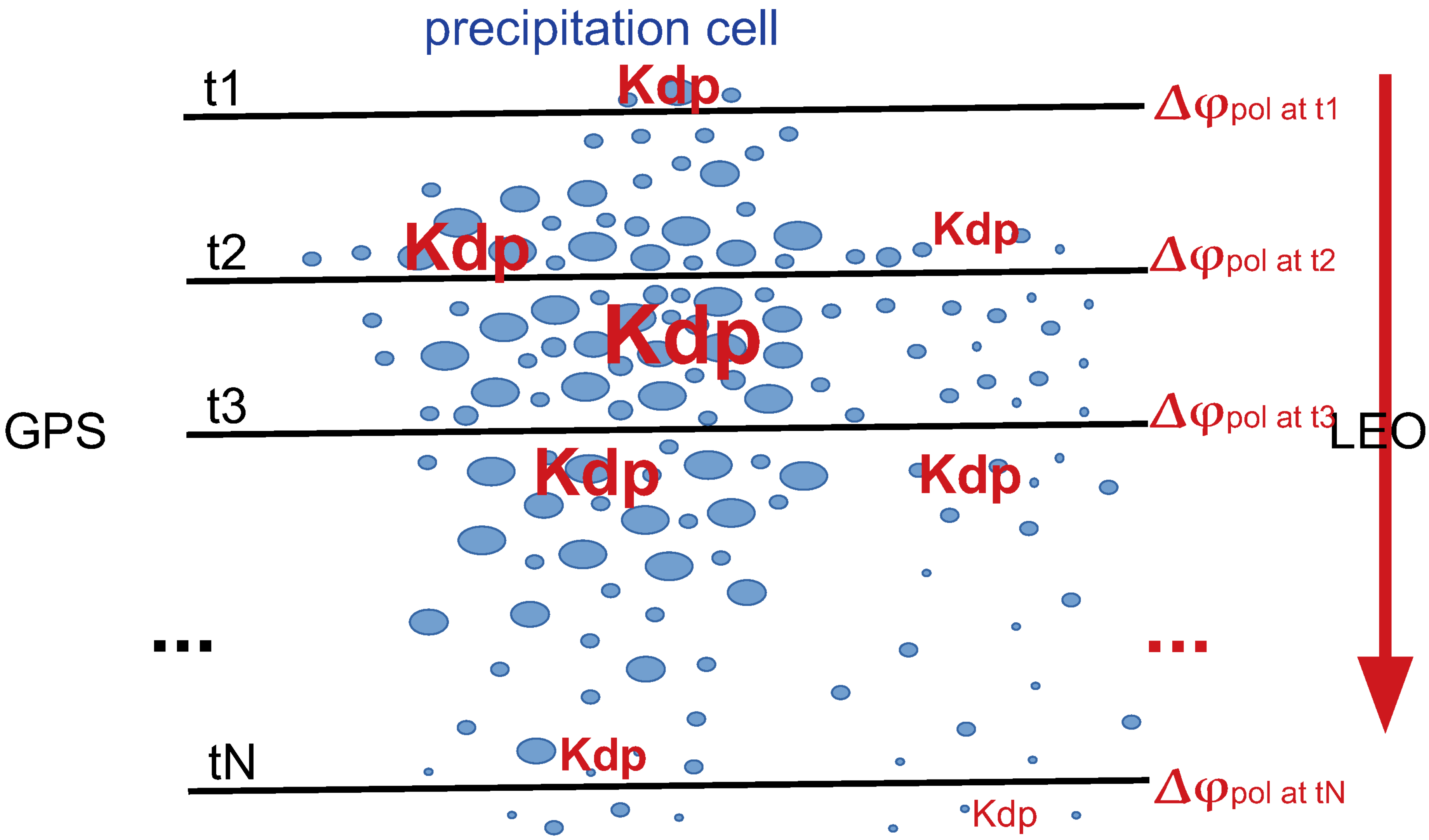

Vertical scanning, Δh ~ 200 m

GNSS RO:

Main observable: **excess phase $\Delta\varphi$**

$$\Delta\phi = \int_{GPS}^{LEO} N(l)\, dl$$

N: refractivity (non-vacuum effects in refractive index, n)

N(T, p, q) **simple analytical** function

Thermodynamic parameters

GNSS PRO:

Main observable: polarimetric phase shift $\Delta\varphi_{pol}$

$$\Delta\phi_{pol} = \Delta\phi_H - \Delta\phi_V = \int_{GPS}^{LEO} K_{dp}(l)\, dl$$

Kdp: specific polarimetric shift

Kdp(DSD) **complicated numerical** integrations → tabulated solutions

Hydrometeors

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Kdp: specific polarimetric shift

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tions

Hydrometeors

Note for RO experts: the mathematical structure is the same. Abel-like retrievals to infer Kdp(h) would be possible, but the problem is the number and small scale of inhomogeneities of the precipitation field.

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GNSS RO:

Main observable: **excess phase $\Delta\varphi$**

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N: ref…
refr…

N(T, p…

Thermodynamic parameters

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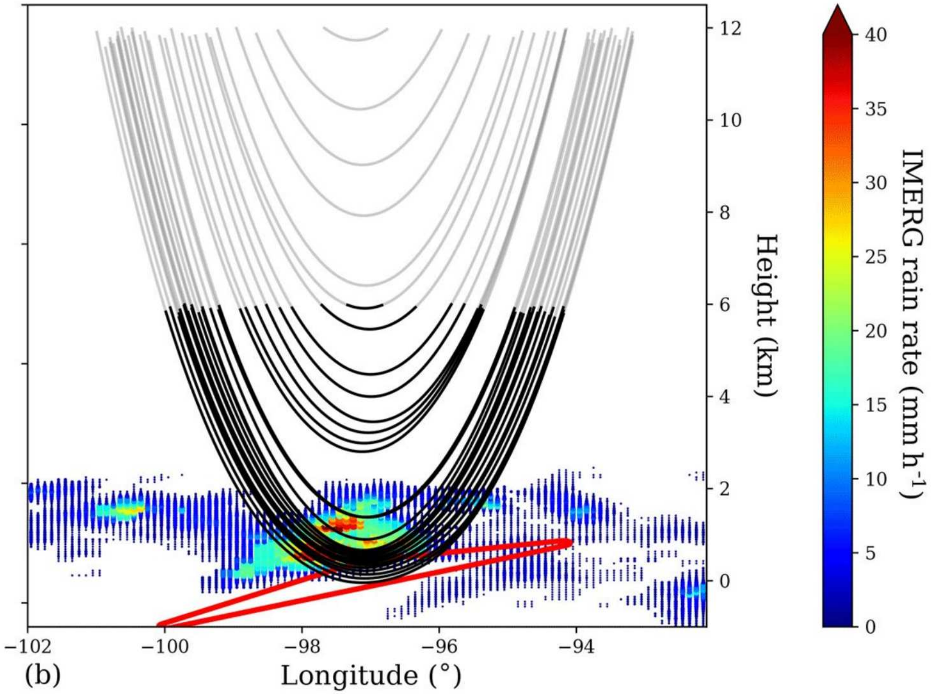
…rical
…utions

Hydrometeors

GNSS PRO data is based on excess phases (at H and V), so the **GNSS RO Thermodynamic** parameters are **also** retrieved!

Same data set, two different observables, two different measurement concepts, both synchronous products.

The rays are not fully horizontal: tangent point is at the minimum altitude. Altitude of the ray points increasing on both sides of it:



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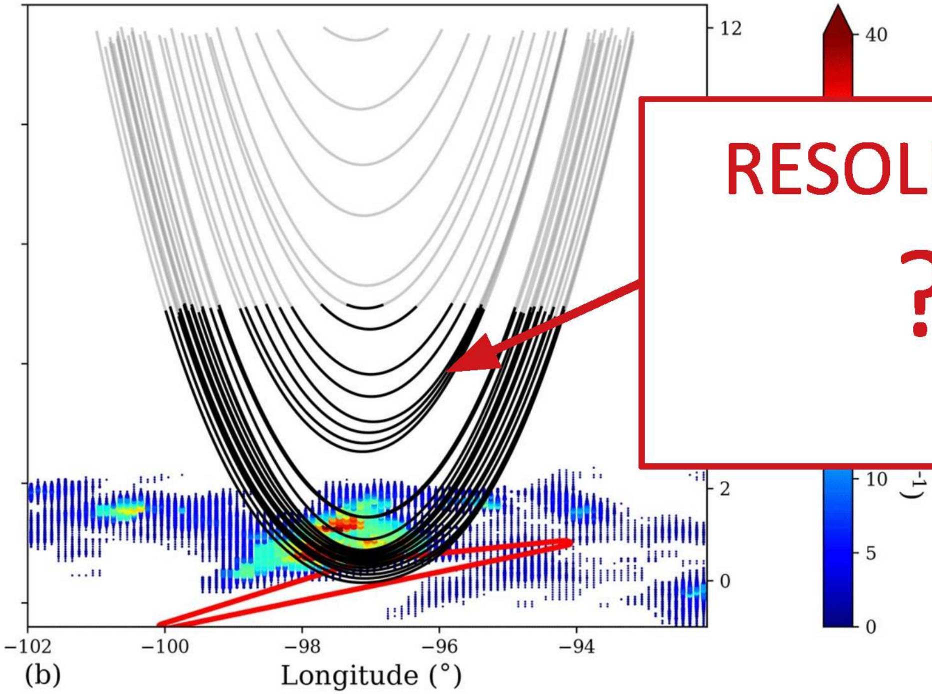


RESOLUTION

?

GNSS PRO:

Main observable: polarimetric phase shift $\Delta\varphi_{pol}$

$$\Delta\phi_{pol} = \Delta\phi_H - \Delta\phi_V = \int_{GPS}^{LEO} K_{dp}(l)\, dl$$

...cific polarimetric shift

...) **complicated numerical** integrations → tabulated solutions

Hydrometeors

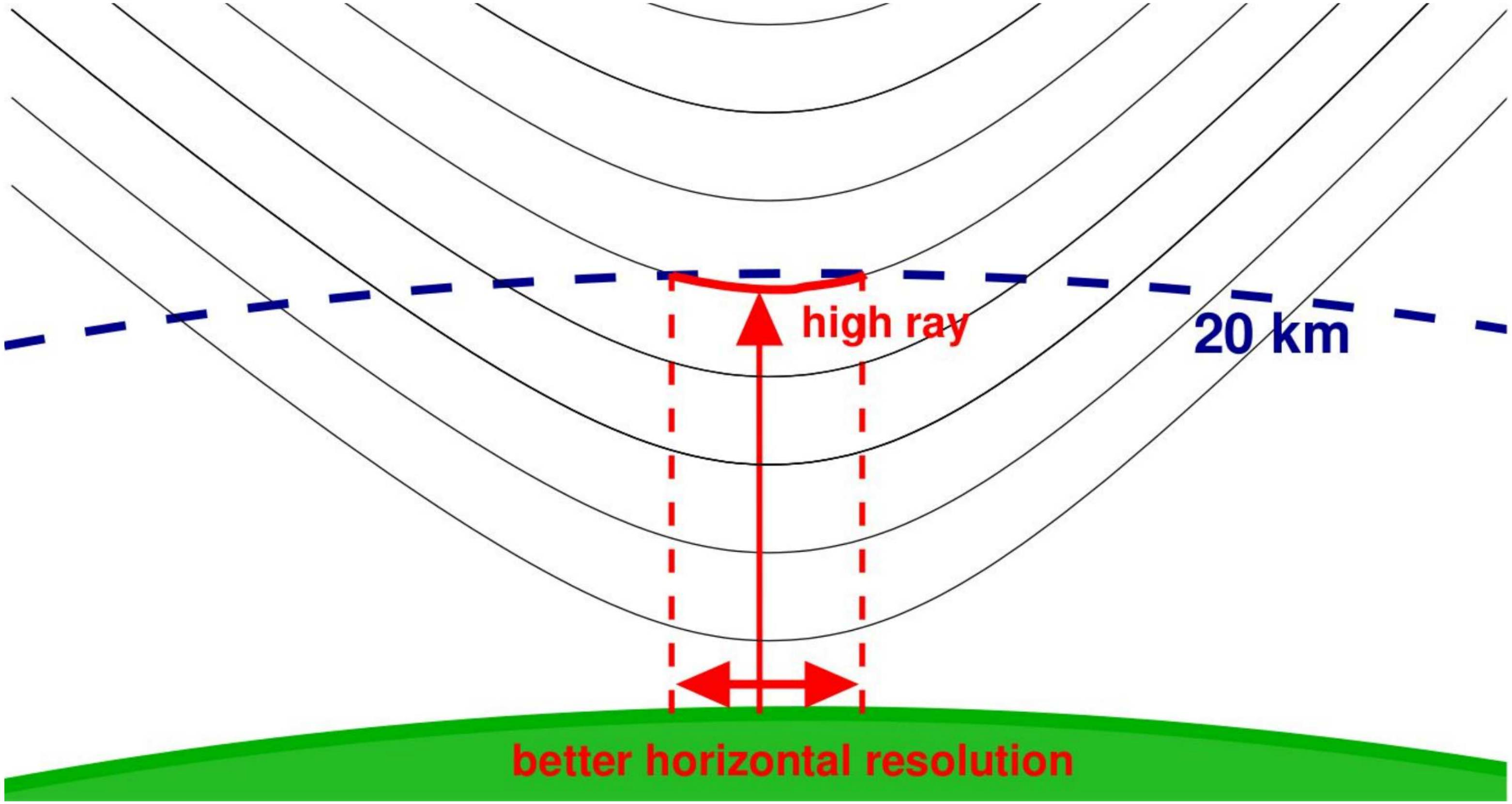
Contents:

HORIZONTAL RESOLUTION:

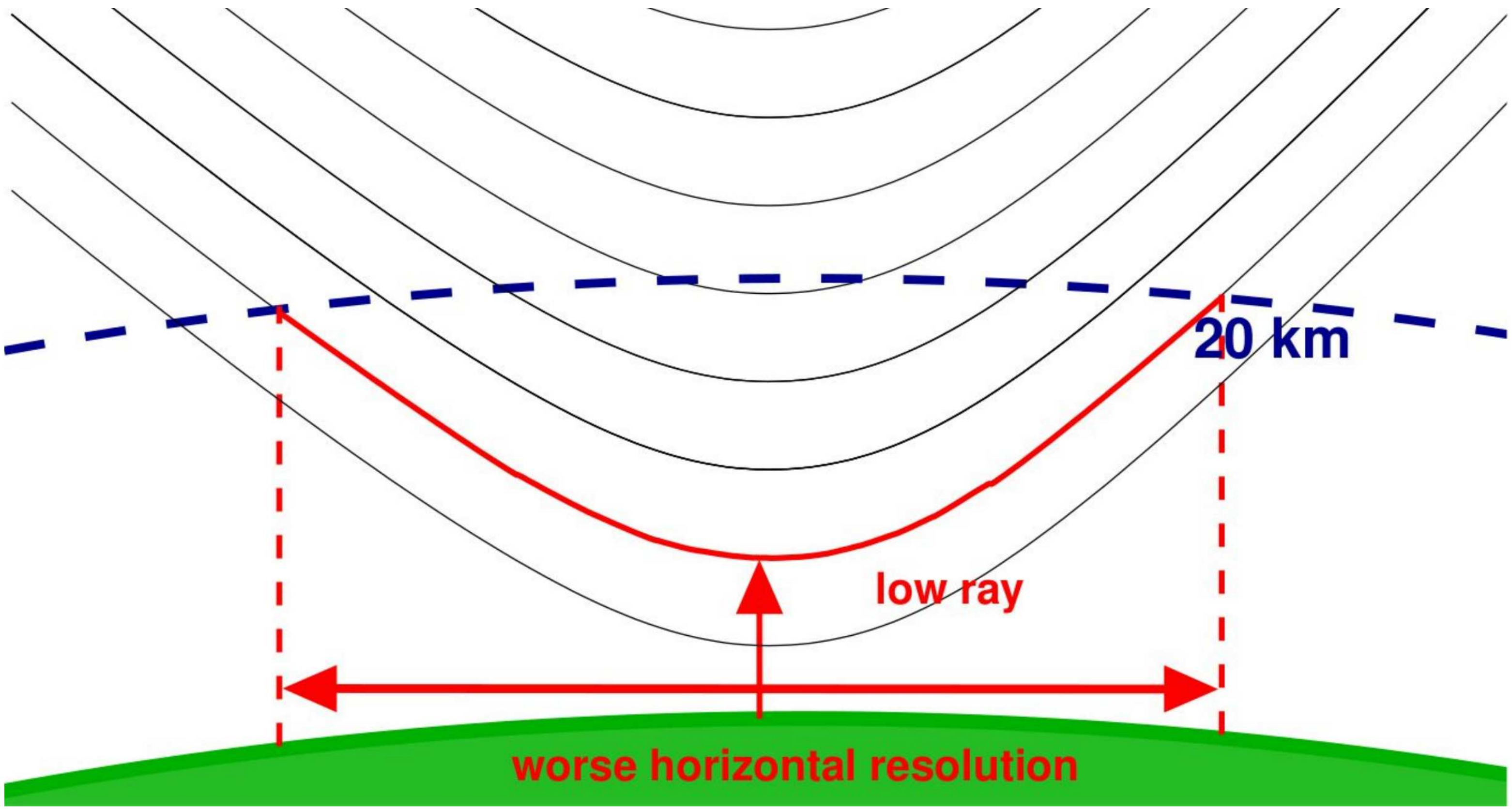
- The observation is integrated along very long path.

- The final resolution will depend on different aspects:
  - **processing strategy**: e.g. variational analysis or tomographic retrievals could break down the integrated values;
  - **cloud extension:** if ancillary images inform about the size of the cloud, the resolution can be constrained;
  - **altitude of the tangent point**: the lower the ray, the longer the integration within zones where hydrometeors can be expected; and
  - **altitude of the cloud top** (or top of the polarimetric signal): if the polarimetric signal vanishes at a given altitude, one could assume the part of the ray integral with hydrometeors happens only under that altitude.

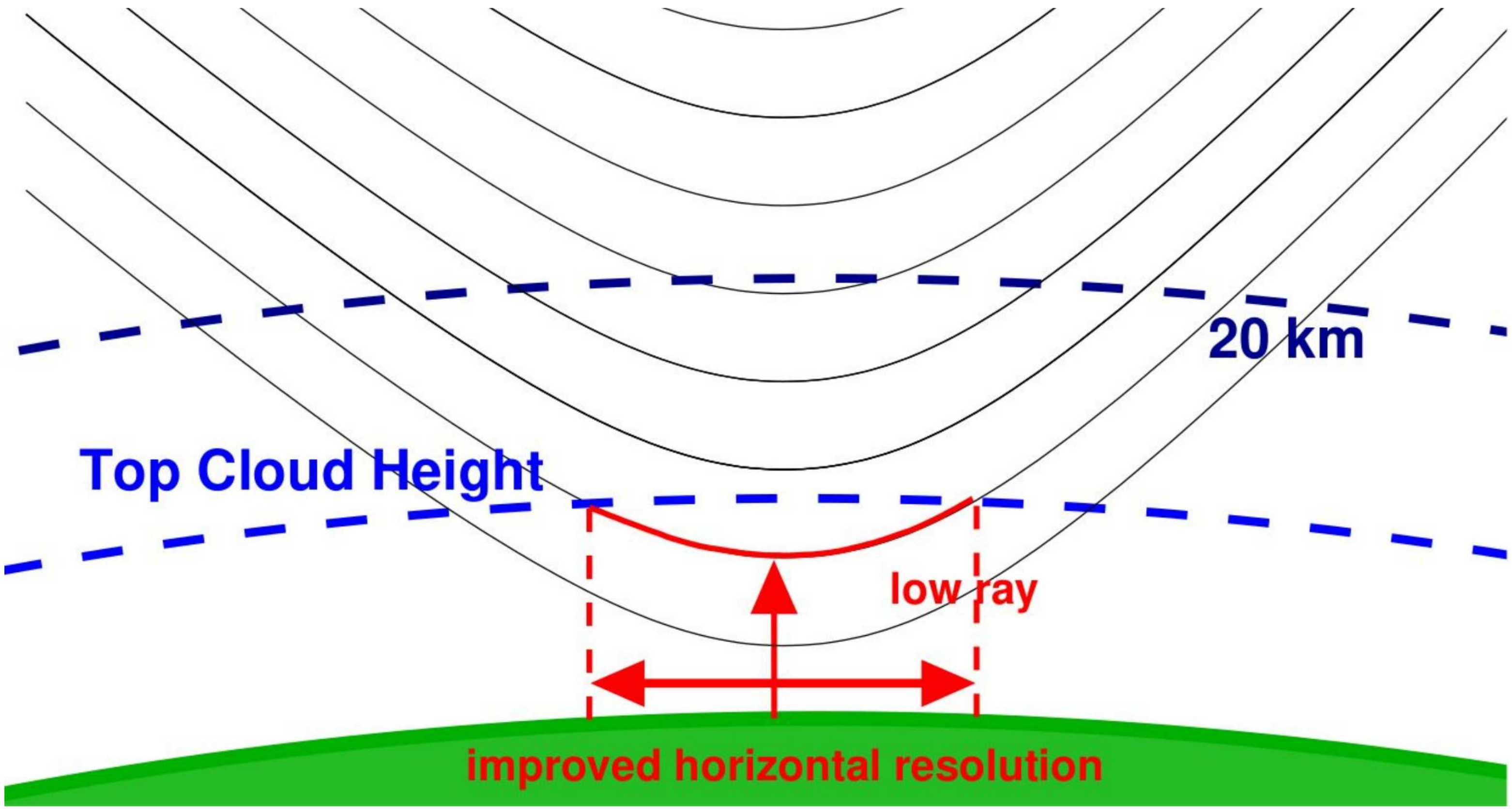
HORIZONTAL RESOLUTION:



HORIZONTAL RESOLUTION:



HORIZONTAL RESOLUTION:



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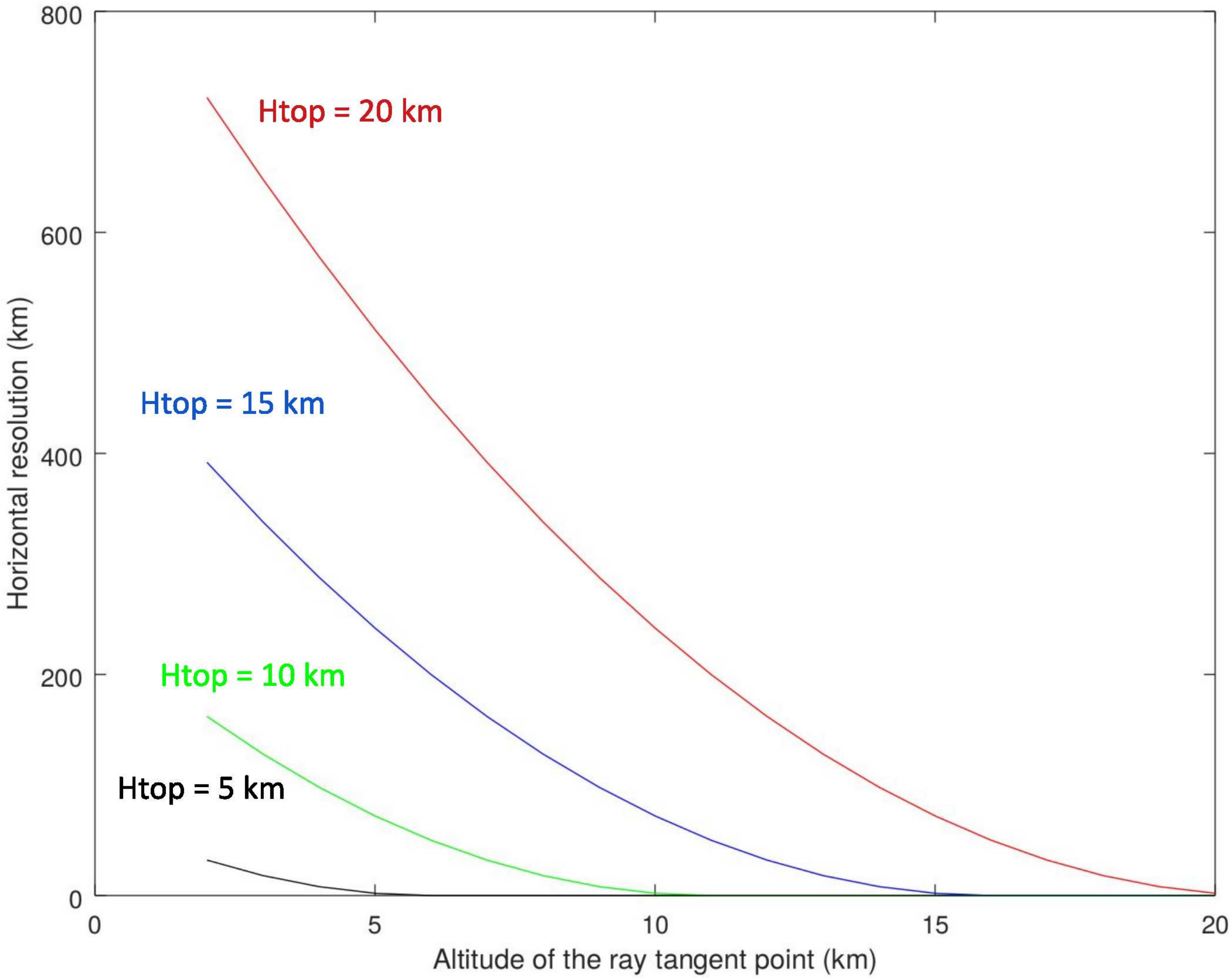
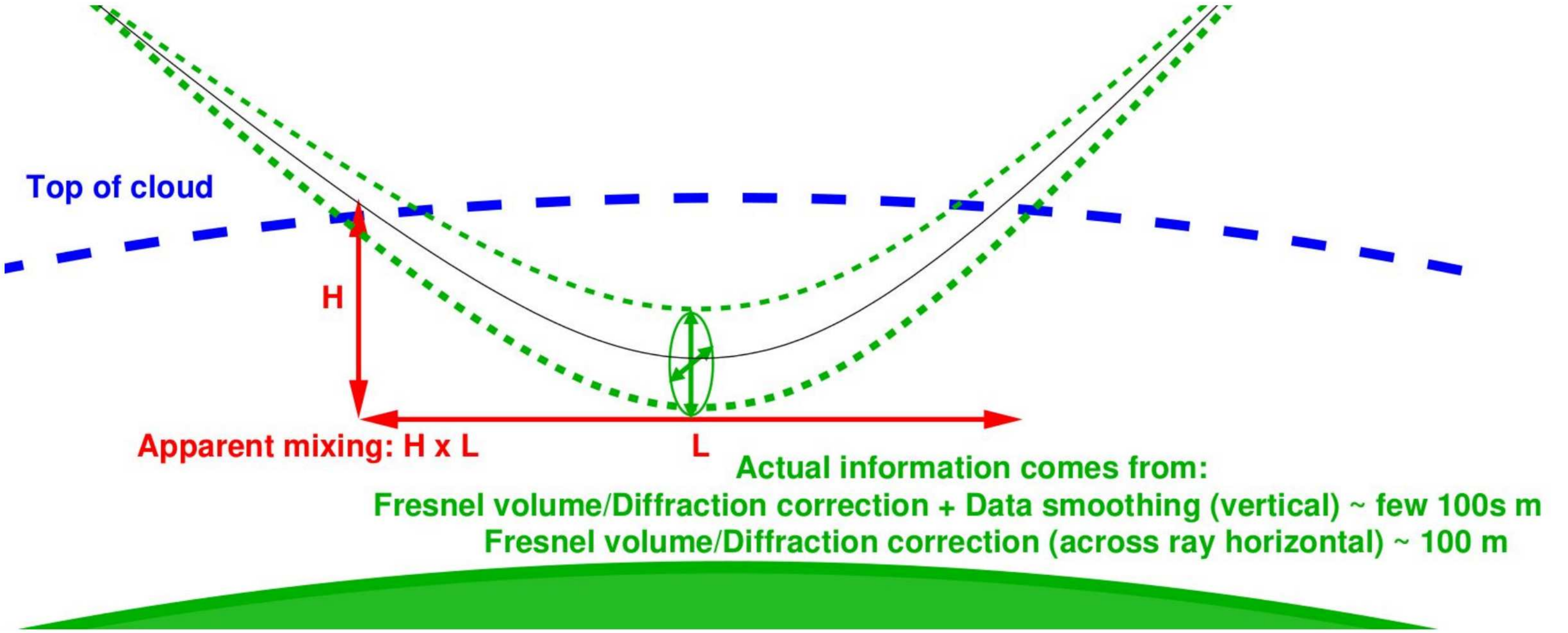
APPROX. HORIZONTAL RESOLUTION: simplified equations (straight propagation)



As a matter of fact, GNSS PRO presents
MIXED but LOCALIZED RESOLUTION:
vertical extent from tangent point to top of the cloud



VERTICAL RESOLUTION:

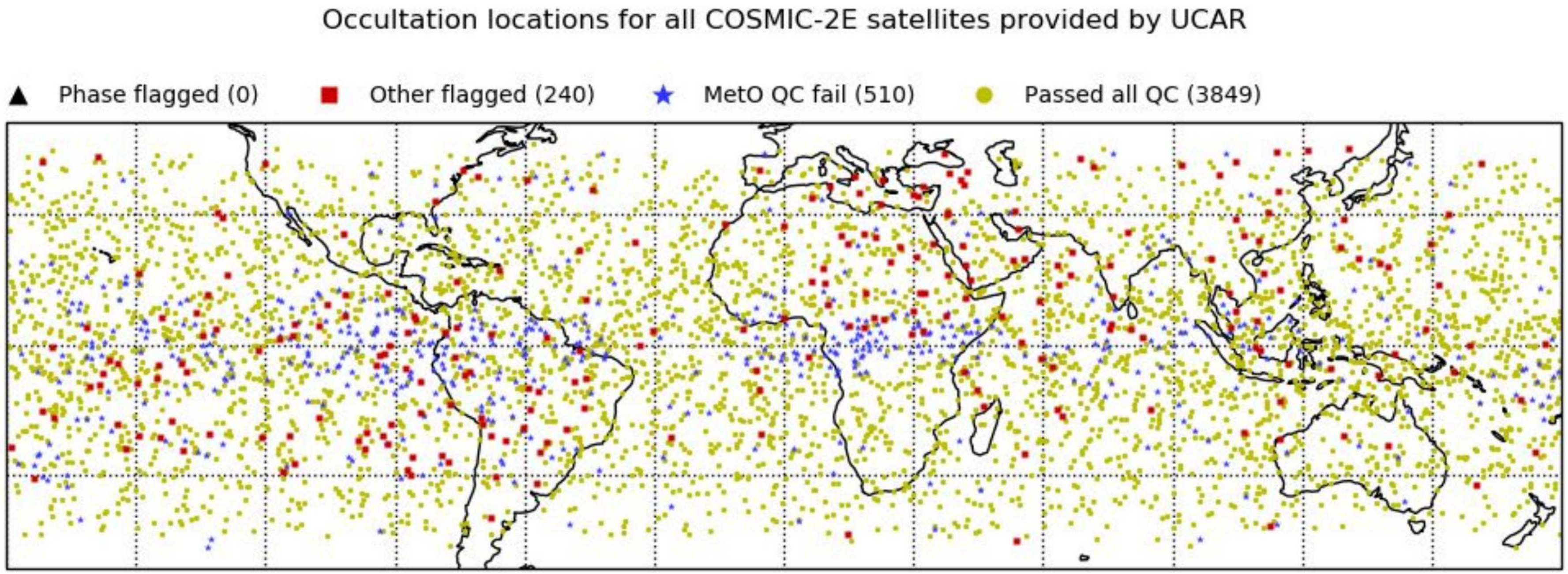
A combination of several aspects:

- The Fresnel volume of the propagation path (~1 km).
- Defocusing by the atmosphere (reduces to ~500 m).
- Processing technique (diffraction correction methods can improve the vertical resolution to **~100 m**).
- Data smoothing: excursion of the tangent point during the time averaging/filtering → 1 Hz filtering lowers to **a few 100s m in the troposphere**.

COVERAGE:

- For some applications, coverage also determines the spatial resolution.
- A LEO with 1 single RO antenna (like PAZ), obtains ~ 200 profiles per day, globally distributed (if near-polar orbit).
- Two antennas (setting/rising occultations) double the amount of daily profiles.
- Receiver/satellite capabilities can further increase the number of daily profiles (e.g. MetOp GRAS RO obtain more daily profiles per satellite).
- Like GNSS RO, GNSS PRO is small and relative cheap technology, easily scalable and **suitable for constellations of small (even cubesat) satellites** → coverage scales up.

QC applied
No. of occultations: 4599 (4599 after QC)
Data from 08/04/20 to 09/04/20



Example 24h coverage COSMIC-2, April 8, 2020
(non polarimetric, but illustrative of potential coverage)

Plotted at 09:42, 09 Apr 2020

Contents:

Elements of the modelling:

$$\Delta\phi_{pol} = \Delta\phi_H - \Delta\phi_V = \int_{GPS}^{LEO} K_{dp}(l)\, dl$$

1.GEOMETRY: where are the two satellites?

2.SIGNAL PROPAGATION: which is the actual ray-path followed by the signal?

Function of the geometry and the thermodynamic state of the atmosphere.

3.SCATTERING OFF HYDROMETEORS: which meteors are found along the ray path? How do they interact with the GNSS L-band signals at H and V polarization?

Function of the number, size and shape of the hydrometeors along the ray path.

Elements of the modelling:

$$\Delta\phi_{pol} = \Delta\phi_H - \Delta\phi_V = \int_{GPS}^{LEO} K_{dp}(l)\, dl$$

1.GEOMETRY: where are the two satellites?

INFORMATION AVAILABLE, PROVIDED BY THE SAME RECEIVER AND EXTERNAL SERVICED (e.g. IGS PRECISE GNSS ORBITS).

2.SIGNAL PROPAGATION: which is the actual ray-path followed by the signal?

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Function of the geometry and the thermodynamic state of the atmosphere.

GIVEN BY RAY TRACERS or 2D-RO OPERATORS IN NWP. ATMOSPHERIC STATE (refractive index) PROVIDED BY THE SAME GNSS PRO PROFILE.

3.SCATTERING OFF HYDROMETEORS: which meteors are found along the ray path? How do they interact with the GNSS L-band signals at H and V polarization?

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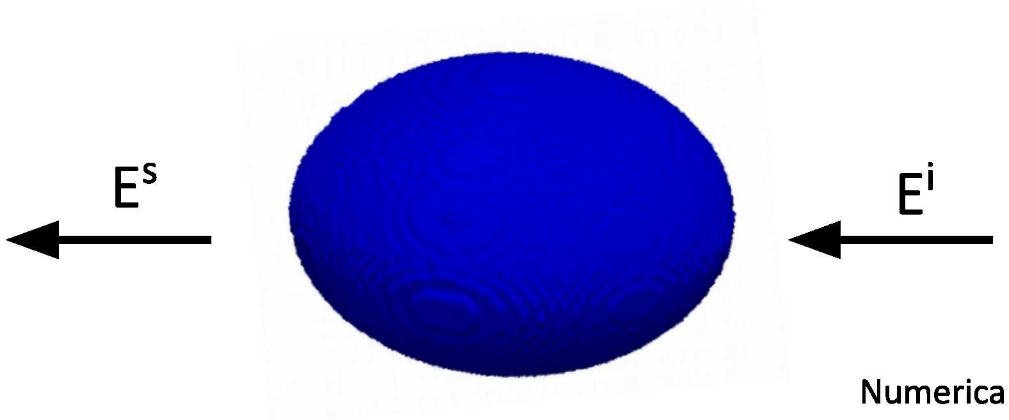
A BIT MORE COMPLEX…

BUT SEVERAL MODELS ALREADY EXIST (T-matrix, Discrete Dipole Approximation…)

AND IT MIGHT BE TABULATED, IF NEEDED.

Scattering models:

1) FORWARD scattering off 1 single particle (rain droplet, ice particle)
   - given by scattering matrix amplitude (S)



Numerical computations

$$\begin{bmatrix} E_{\rm h}^{\rm s} \\ E_{\rm v}^{\rm s} \end{bmatrix} = \frac{e^{-ik_0 r}}{r} \mathbf{S} \begin{bmatrix} E_{\rm h}^{\rm i} \\ E_{\rm v}^{\rm i} \end{bmatrix} \qquad \mathbf{S} = \begin{bmatrix} S_{\rm hh} & S_{\rm hv} \\ S_{\rm vh} & S_{\rm vv} \end{bmatrix}$$

- For **FORWARD** geometry!
- For each **polarization**
- For each drop **size/shape**

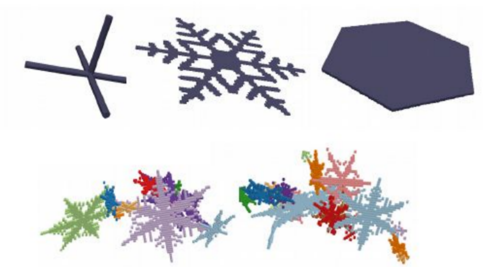
Scattering models:

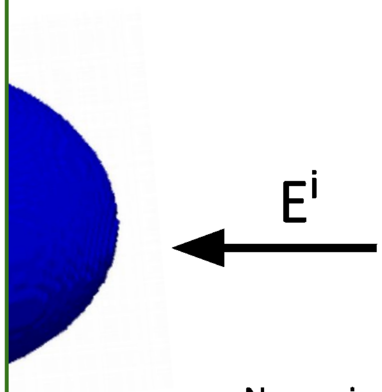
1) FORWARD scattering off 1 single particle (rain droplet, cloud ice particle)

Different raindrop size/shape/axis ratio models, e.g.:

- Oblate spheroid drop shape
- Beard and Chuang model for drop shape
- Pruppacher–Beard drop size relationship
- Axis Ratio as function of drop Diameter relationships: AR(D)

Larger complexity for ice particles!!!





Numerical computations

$$\mathbf{S} = \begin{bmatrix} S_{\text{hh}} & S_{\text{hv}} \\ S_{\text{vh}} & S_{\text{vv}} \end{bmatrix}$$

- For **FORWARD** geometry!
- For each **polarization**
- For each drop **size/shape**

Scattering models:

2) Effect on **one** polarization, when crossing a media filled with a given distribution of sizes (Drop/Particle Size Distribution = N(D)) → '*specific phase shift at p-polarization*' **Kp** (shift per km propagation)

$$K_p = \frac{2\pi}{k_0} \int \Re\{S_{pp}\} N(D) \mathrm{d}D$$

- For a given polarization p
- S_{pp} is function of D, too: $S_{pp}(D)$

3) Difference between **two polarizations** → '*specific polarimetric phase shift*' Kdp (polarimetric shift per km propagation)

$$K_{\mathrm{dp}} = \frac{2\pi}{k_0} \int \Re\{S_{\mathrm{hh}} - S_{\mathrm{vv}}\} N(D) \mathrm{d}D$$

Scattering models:

Different **models for drop/particle size distribution** N(D), too (e.g. Marshall Palmer, Gamma function).

4) Relationship with other variables:

water content

$$\mathrm{WC} = \frac{\rho\pi}{6} \int N(D)\, D^3\, \mathrm{d}D \quad [\mathrm{g\ m^{-3}}]$$

rain rate

$$R = 0.6\,\pi\, 10^{-3} \int v(D)\, N(D)\, D^3\, \mathrm{d}D \quad [\mathrm{mm\ h^{-1}}]$$

5) Relationship with other measurements, e.g. radar reflectivity Z, and equivalent reflectivity Ze:

$$Z = \int N(D)\, D^6\, \mathrm{d}D \quad [\mathrm{mm^6\ m^{-3}}]$$

$$Z_{\mathrm{e}} = \frac{\lambda^4}{\pi^5 |K_{\mathrm{w}}|^2} \int \sigma_{\mathrm{bk}}(D) N(D) \mathrm{d}D$$

σ_{bk}: backscattering cross section

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Summary of scattering models:

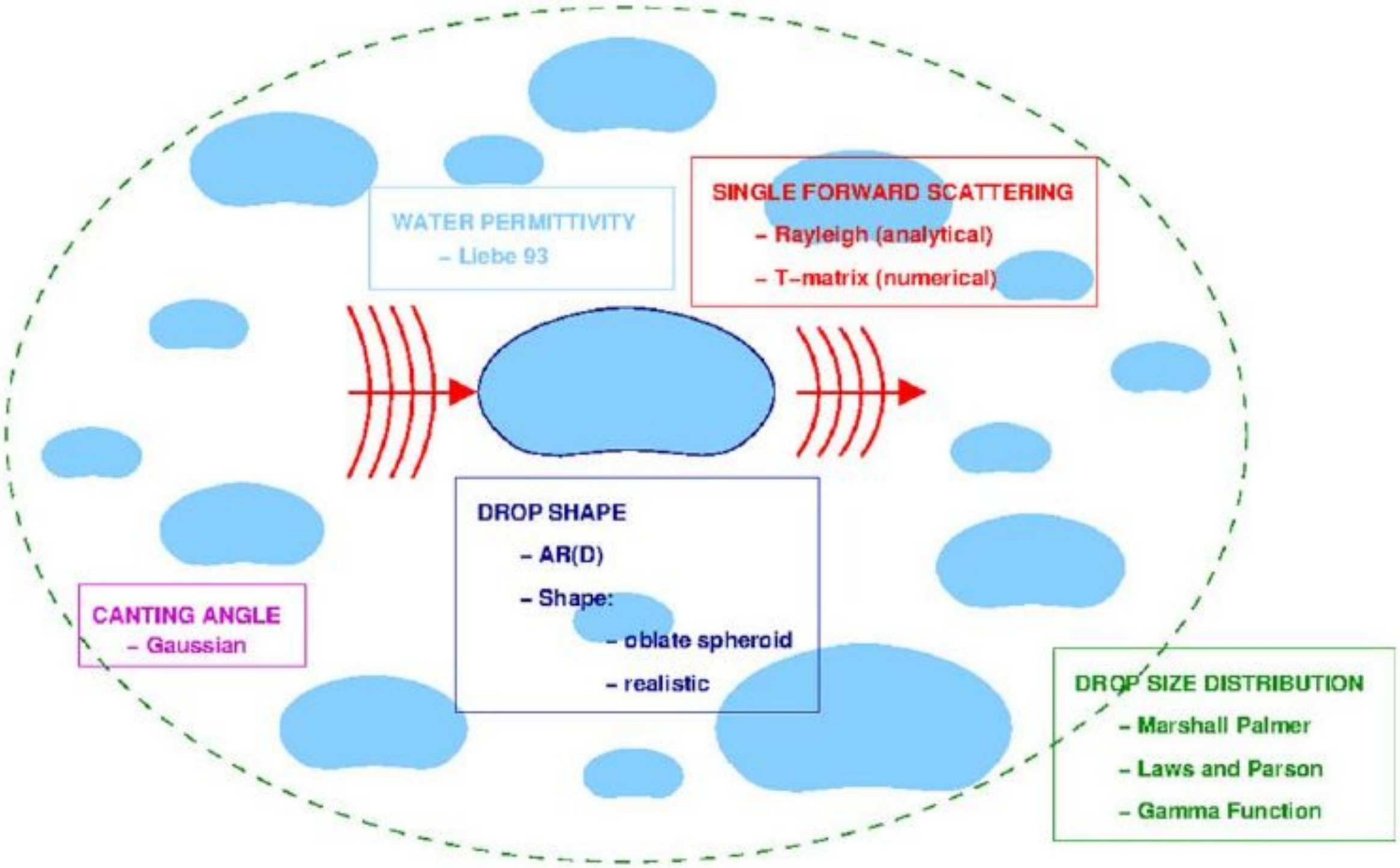


Figure from doi: 10.1109/TGRS.2014.2320309

Relationship with radar backscattering:

Figure from Padullés, PhD Dissertation, 2017

$K_{dp} - Z_e$ relationship

All mathematically possible PSDs

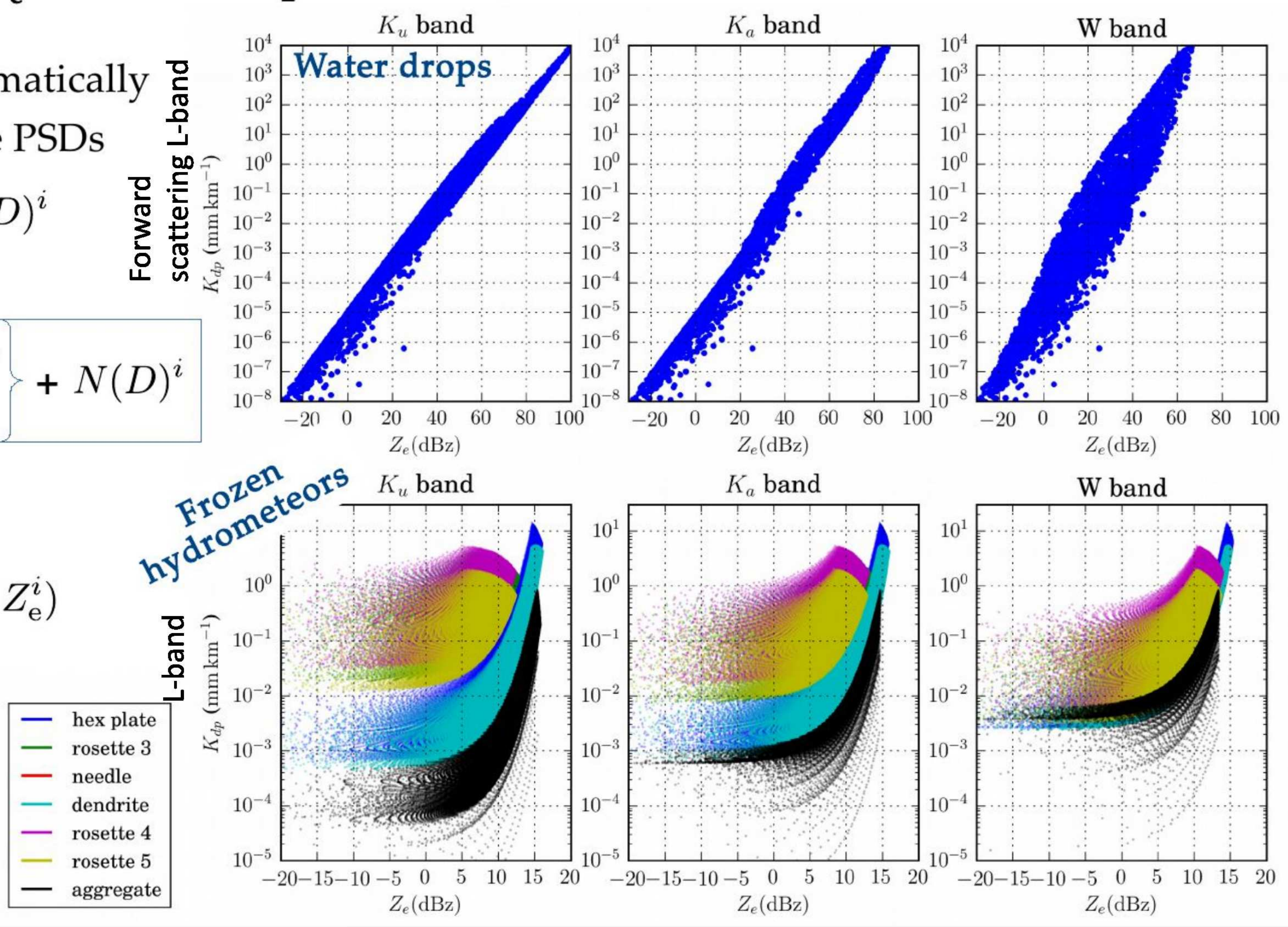
$N(D)^i$

↓

$$\left.\begin{array}{c}\Re\{S_{hh} - S_{vv}\}\\ \sigma_{bk}\end{array}\right\} + N(D)^i$$

↓

$$(K^i_{dp}, Z^i_e)$$



Contents:

The observable modelled as:

$$\Delta\phi_{pol} = \Delta\phi_H - \Delta\phi_V = \int_{GPS}^{LEO} K_{dp}(l)\, dl$$

assumes there are no other effects altering $\Delta\varphi_{pol}$.

This is not true. The equation above can only be applied once the observables have been corrected for the systematic effects:

- transmitter polarization purity;
- ionospheric effects (Faraday rotations);
- receiver antenna pattern and other inter-channel delays.

DOI: 10.1109/TGRS.2018.2831600: contains a detailed theoretical frame for the full propagation (all systematic effects).

DOI: 10.5194/amt-13-1299-2020: analyzes in detail residual systematic effects found in PAZ GNSS-PRO data.

Actual observed field includes:

Figures from Padullés, PhD Dissertation, 2017

Signal propagation

Observed field

$$\mathbf{E} = \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi_{arc}} \end{bmatrix}}_{\text{receiver}} \underbrace{\begin{bmatrix} a_{\text{hh}} & 0 \\ 0 & a_{\text{vv}} e^{i\phi_{\text{ant}}} \end{bmatrix}}_{\text{antenna}} \overbrace{\mathbf{R}(\Omega_2)}^{\text{ionosphere}} \underbrace{\begin{bmatrix} e^{-ik_h} & 0 \\ 0 & e^{-ik_v} \end{bmatrix}}_{\text{hydrometeors}} \overbrace{\mathbf{R}(\Omega_1)}^{\text{ionosphere}} \mathbf{E}^{\text{i}}{}_{\{\hat{e}_h, \hat{e}_v\}}$$

emitted field

$$\mathbf{E} = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi_{arc}} \end{bmatrix} \begin{bmatrix} a_{\mathrm{hh}} & 0 \\ 0 & a_{\mathrm{vv}} e^{i\phi_{\mathrm{ant}}} \end{bmatrix} \mathbf{R}(\Omega_2) \begin{bmatrix} e^{-ik_h} & 0 \\ 0 & e^{-ik_v} \end{bmatrix} \mathbf{R}(\Omega_1) \underbrace{\mathbf{E}^{\mathrm{i}}_{\{\hat{e}_h, \hat{e}_v\}}}$$

emitted field

Normalized Jones representation of RHCP: $\mathbf{E} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}_{\{\hat{e}_R, \hat{e}_L\}}$ circular basis

Real case:

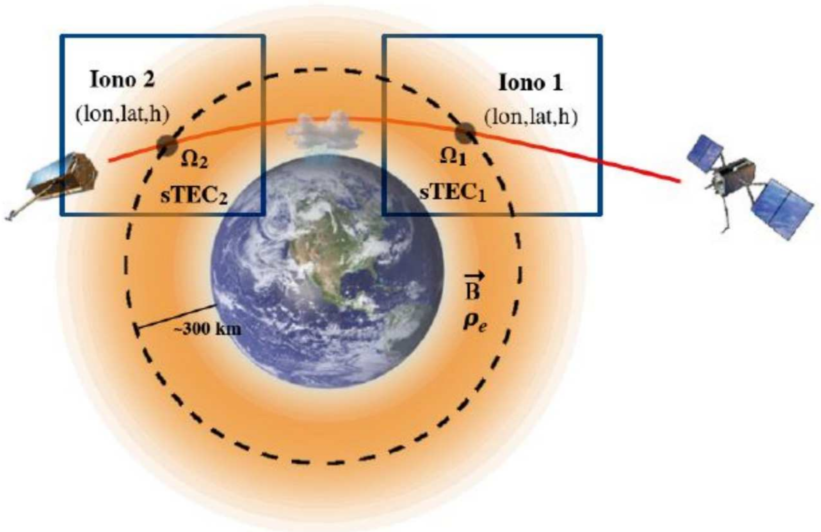
$$\mathbf{E} = E_0 \begin{bmatrix} 1 \\ m e^{i\Delta} \end{bmatrix}_{\{\hat{e}_R, \hat{e}_L\}}$$

At the emission: $\Delta\Phi_{\mathrm{h-v}} \neq 90^\circ$

m : tolerance term
Δ : random phase

Figures from Padullés, PhD Dissertation, 2017

$$\mathbf{E} = \begin{bmatrix}1 & 0\\ 0 & e^{i\phi_{arc}}\end{bmatrix}\begin{bmatrix}a_{\mathrm{hh}} & 0\\ 0 & a_{\mathrm{vv}}e^{i\phi_{\mathrm{ant}}}\end{bmatrix}\underbrace{\overbrace{\mathbf{R}(\Omega_2)}^{\text{ionosphere}}}\begin{bmatrix}e^{-ik_h} & 0\\ 0 & e^{-ik_v}\end{bmatrix}\underbrace{\overbrace{\mathbf{R}(\Omega_1)}^{\text{ionosphere}}}\,\mathbf{E}^{\mathrm{i}}{}_{\{\hat{e}_h,\hat{e}_v\}}$$



The signal crosses **twice** the ionosphere

Ionosphere induces a rotation:
Faraday rotation

induces depolarization to
non-circular EM waves

$$d\Omega_{\mathrm{F}} = \frac{2.36 \cdot 10^4}{f^2} n_{\mathrm{e}}(\vec{l})\,\vec{B}(\vec{l}) \cdot \hat{l}\ \mathrm{d}l$$

electron density & Magnetic field

Figures from Padullés, PhD Dissertation, 2017

Figure from Padullés, PhD Dissertation, 2017

$$\mathbf{E} = \underbrace{\begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi_{arc}} \end{bmatrix} \begin{bmatrix} a_{\mathrm{hh}} & 0 \\ 0 & a_{\mathrm{vv}} e^{i\phi_{\mathrm{ant}}} \end{bmatrix}} \mathbf{R}(\Omega_2) \begin{bmatrix} e^{-ik_h} & 0 \\ 0 & e^{-ik_v} \end{bmatrix} \mathbf{R}(\Omega_1)\, \mathbf{E}^{\mathrm{i}}{}_{\{\hat{e}_h, \hat{e}_v\}}$$

Receiver instrumental effects:

- Antenna pattern at H-pol and V-pol can introduce polarimetric shift.
- The receiver sets an arbitrary phase to each channel (H- and V-pol) at the beginning of tracking that satellite (phase offset at each arch of data).
- Receiver induced ‘cycle-slips’ (jumps in the phase) also occur.
- Other elements in the receiving system can add slightly different delays at H- and V-pol.

Need of some sort of calibration to isolate the hydrometeor contribution $\Delta\varphi \rightarrow \Delta\varphi^{\mathrm{hydro}}$

Contents:

Two main steps:

1) **CORRECTION** of residual cycle slips

2) **CALIBRATION** of the residual systematic effects. Two calibration strategies implemented:

   a) **Linear fit** above 20 km

   b) Removal of an **in-orbit antenna pattern**

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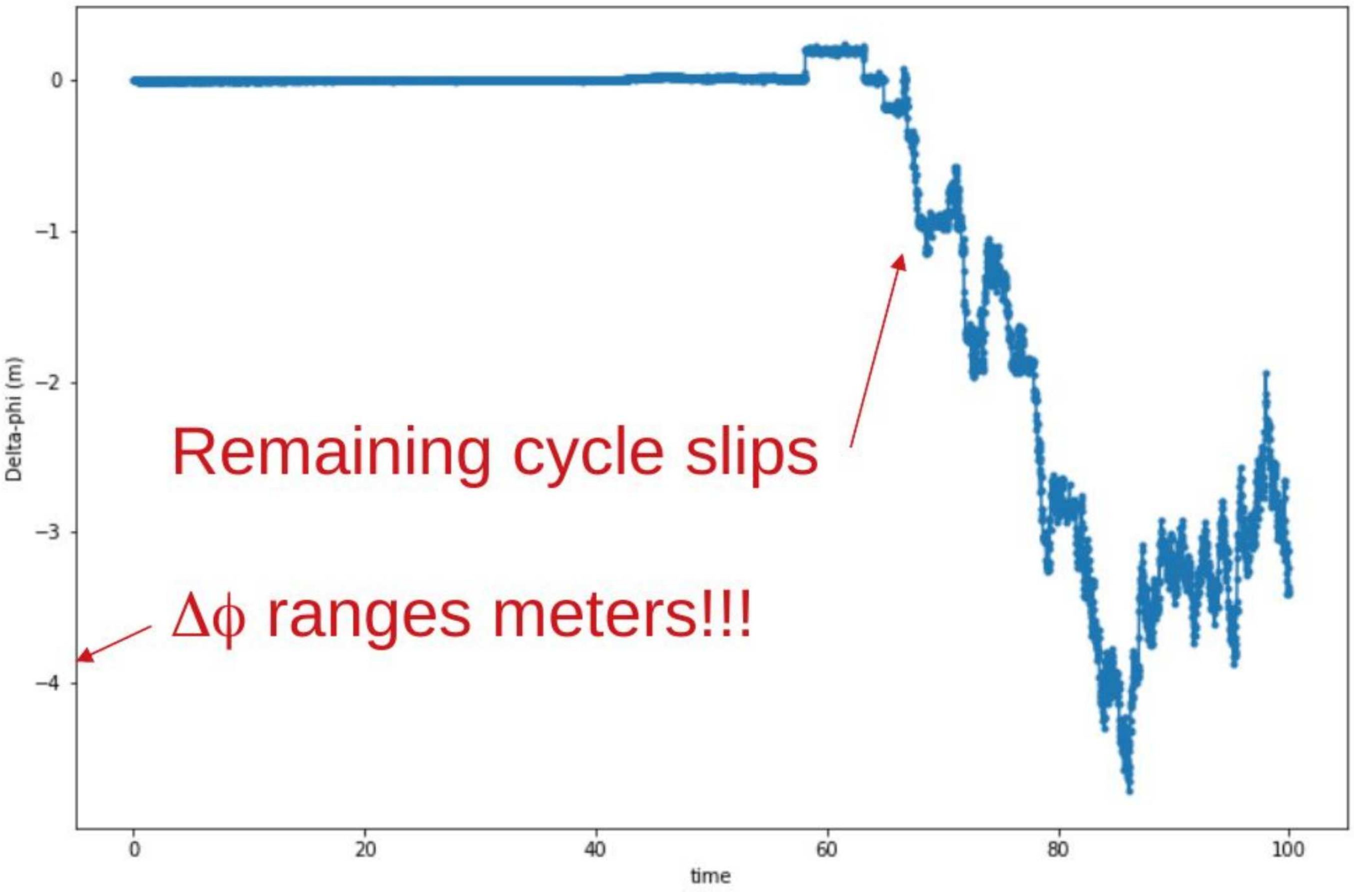
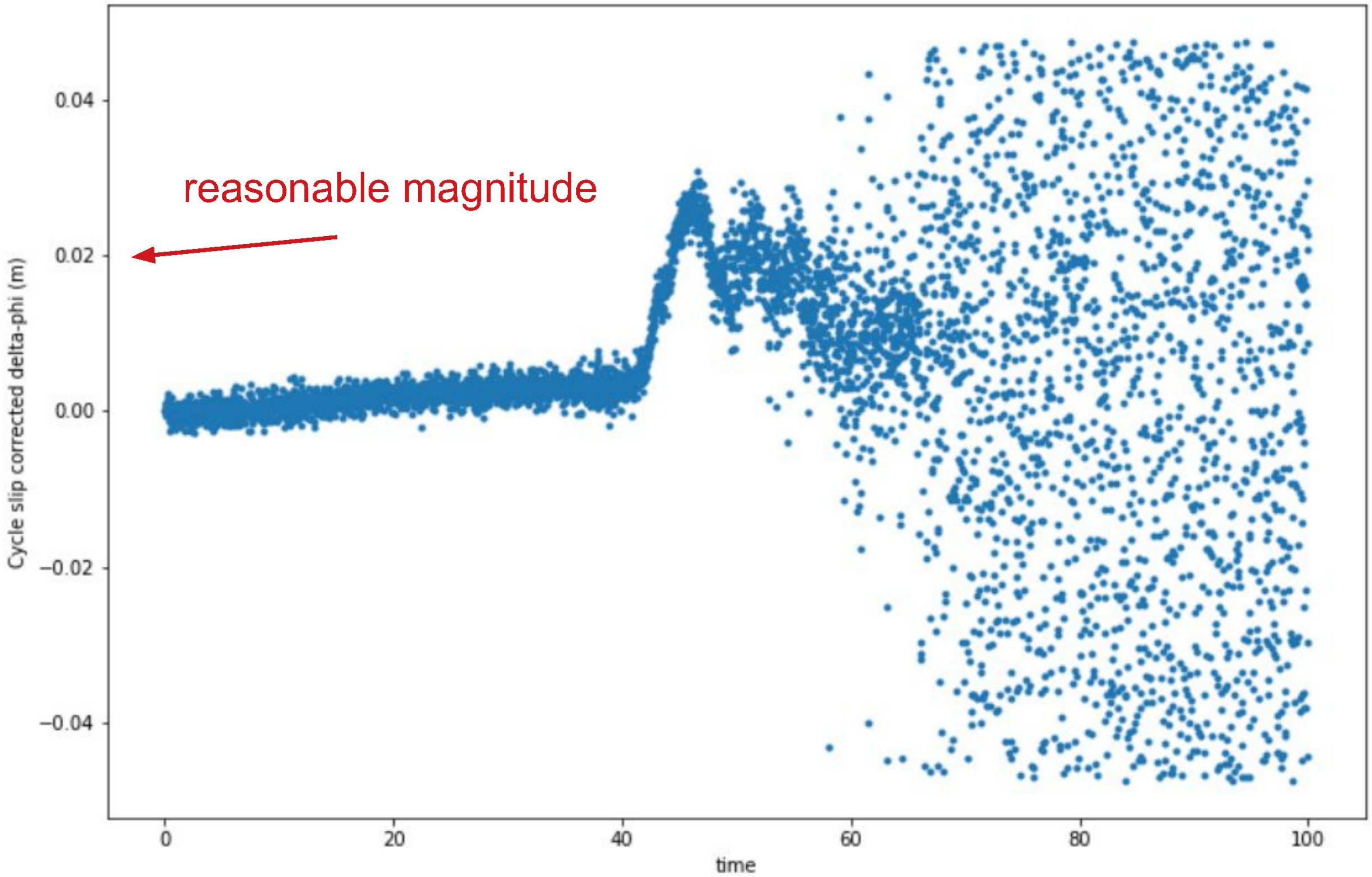
How do the data look like?

ϕH-ϕV without further processing looks wrong (h_exL1 - v_exL1):



How do the data look like?



Cycle-slips corrected

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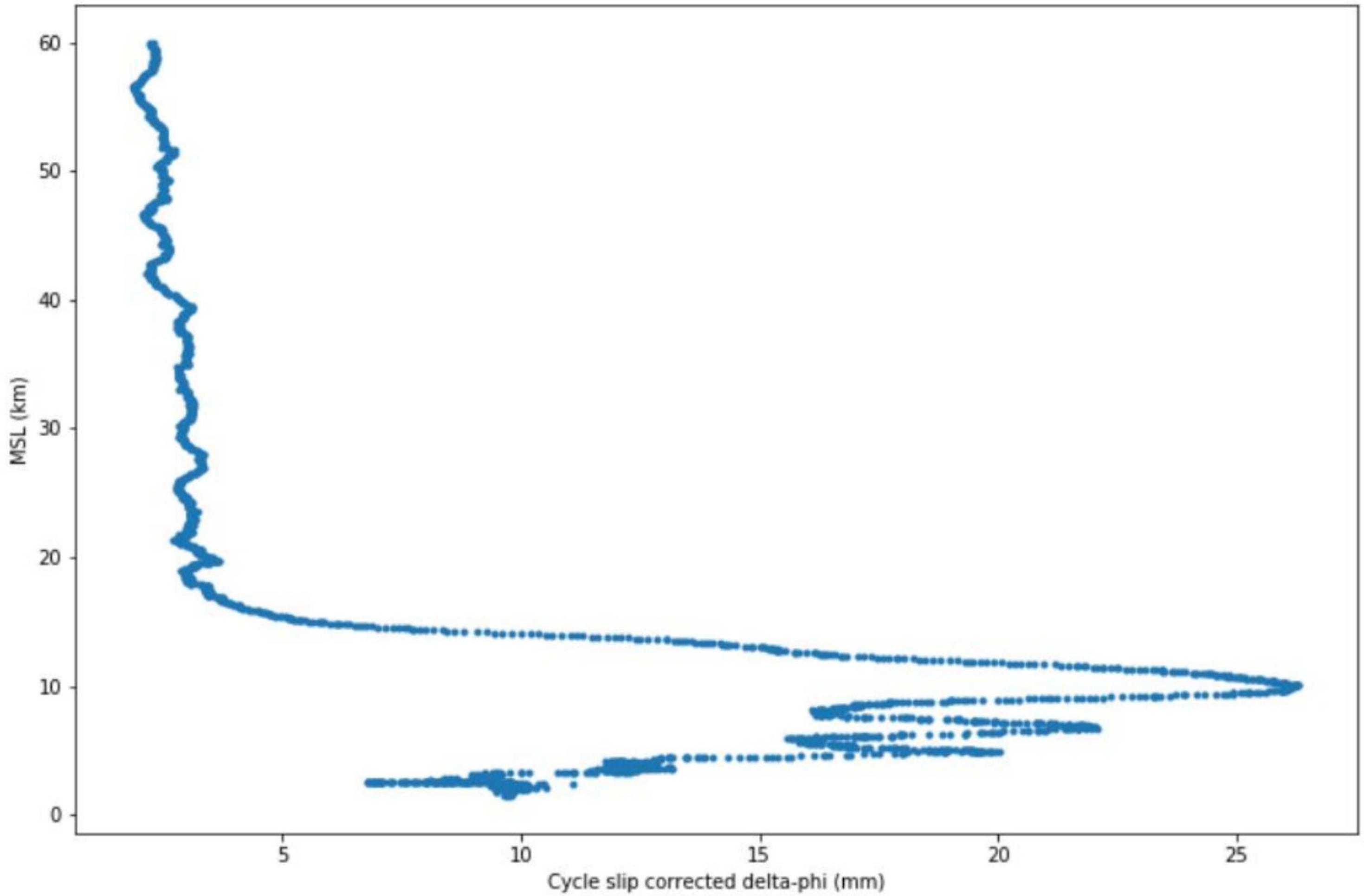
How do the data look like?



time → altitude & 1Hz filter

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Two main steps:

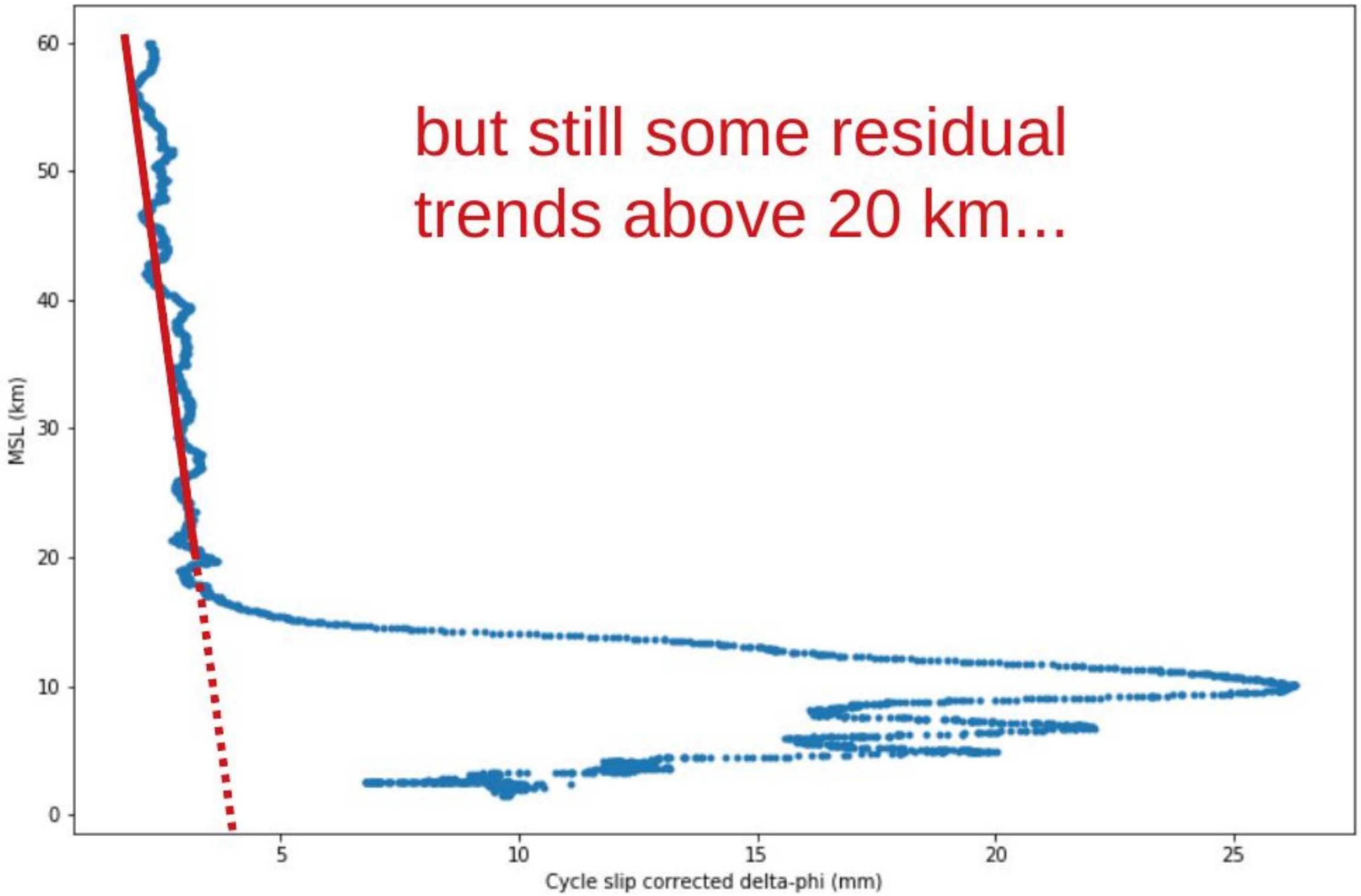
1) **CORRECTION** of residual cycle slips ✓

2) **CALIBRATION** of the residual systematic effects. Two calibration strategies implemented:

   a) **Linear fit** above 20 km (explained in doi:10.1029/2018GL080412)

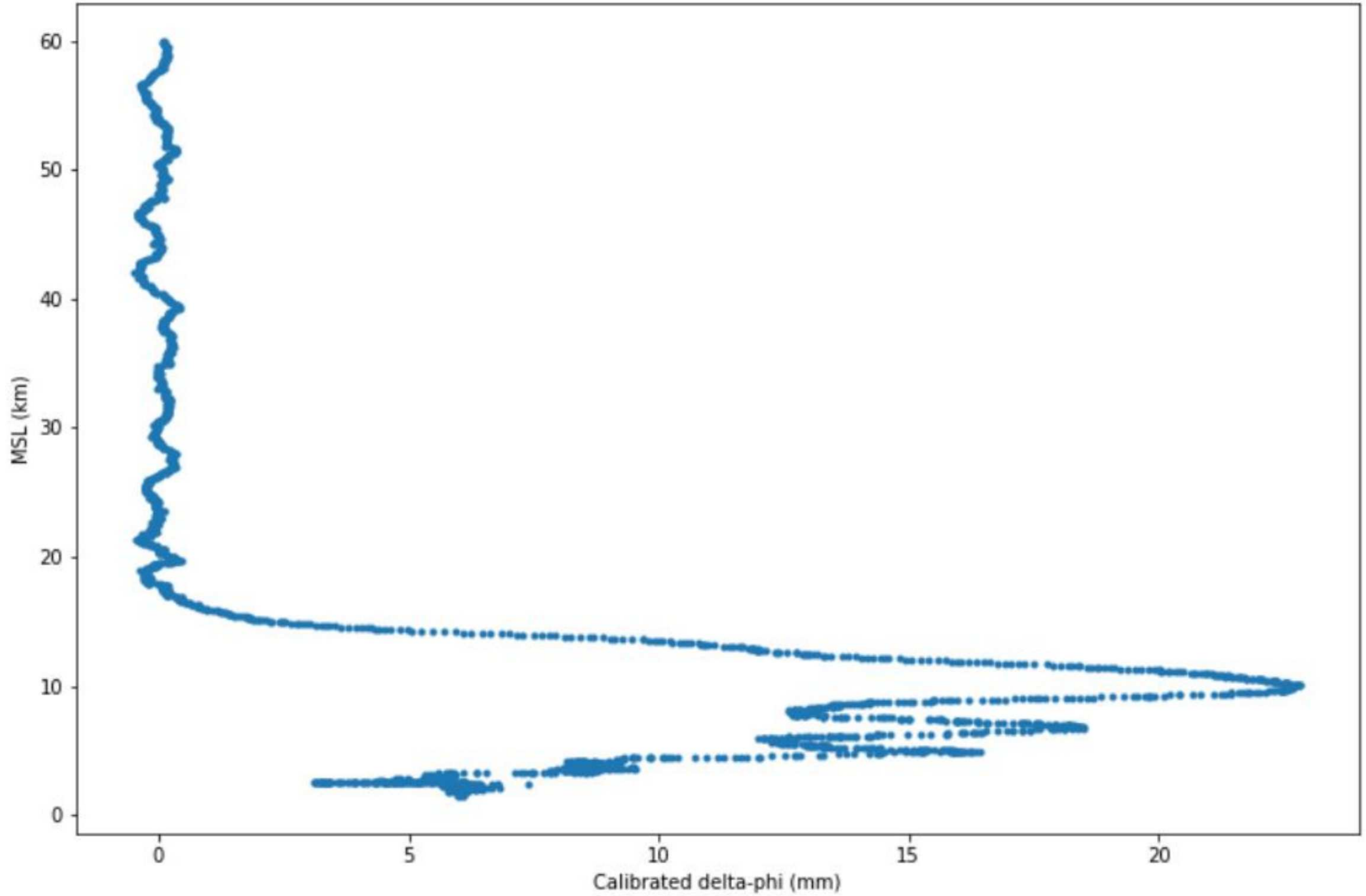
   b) Removal of an **in-orbit antenna pattern** (explained in doi:10.5194/amt-13-1299-2020)

Calibration: linear fit



LINEAR FIT CALIBRATION: linear fit above 20 km → subtract it to the whole profile

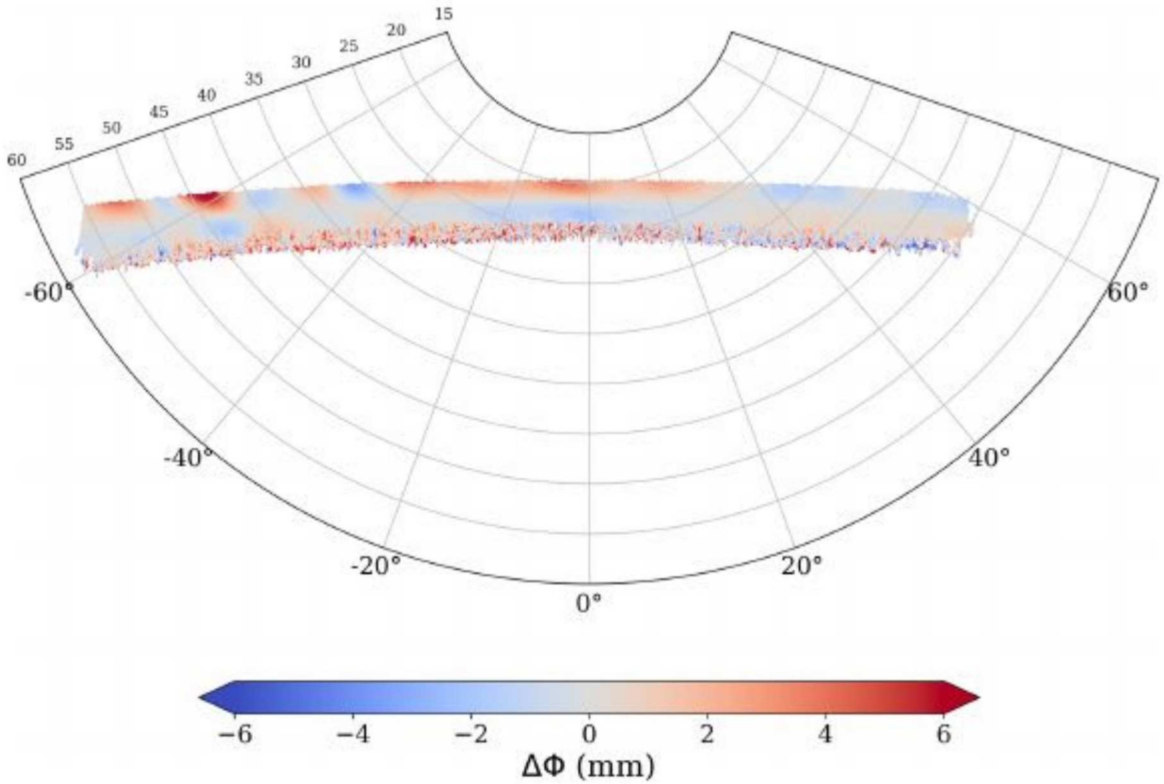
How do the data look like?



CALIBRATRATED PROFILE

Calibration: In-orbit Antenna Pattern

- pattern of $\Delta\varphi_{pol}$ generated with PAZ profiles for which IMERG rain products indicate NO-RAIN



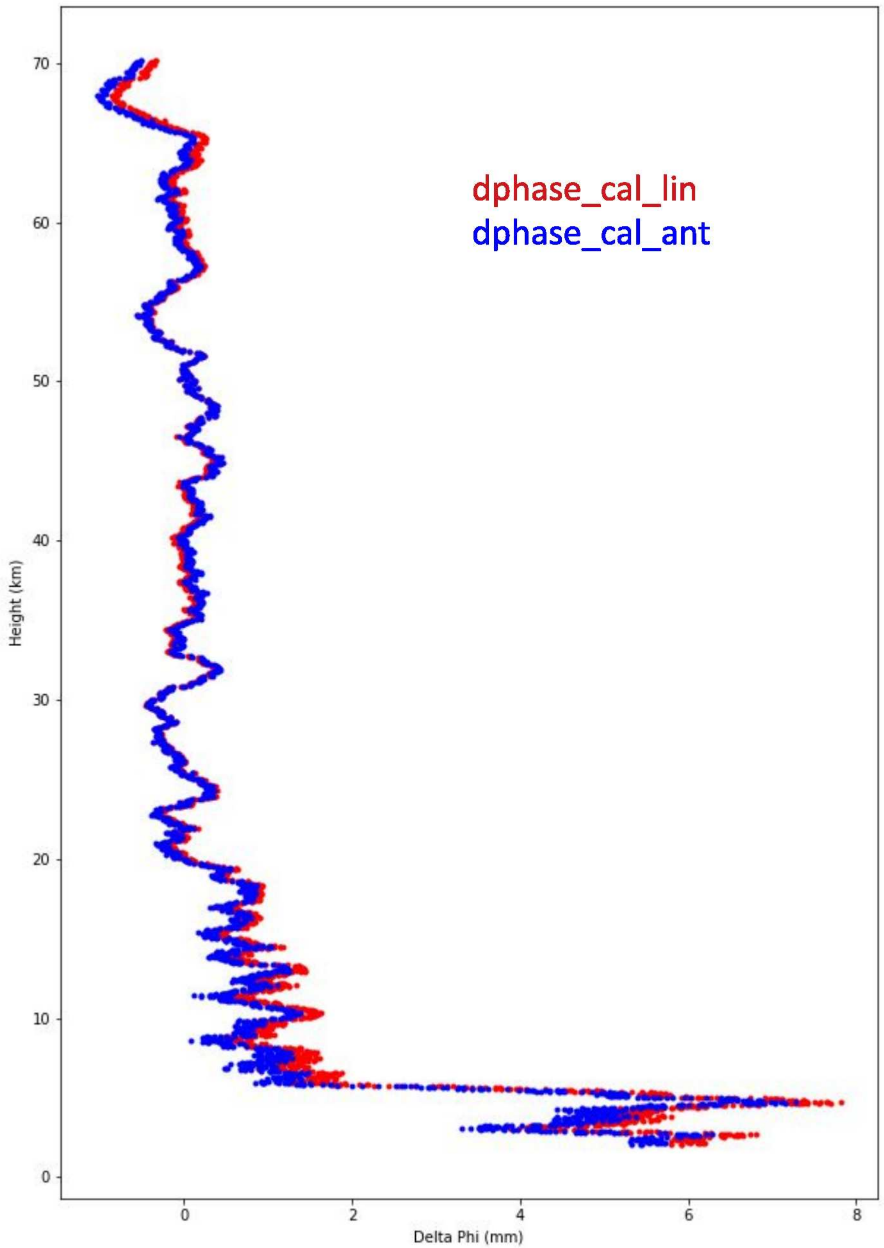
doi:10.5194/amt-13-1299-2020

In-orbit Antenna Pattern Calibration:

- Pattern subtracted to each file

- Residual trend above 20 km also subtracted (residual **ionospheric** effects?)

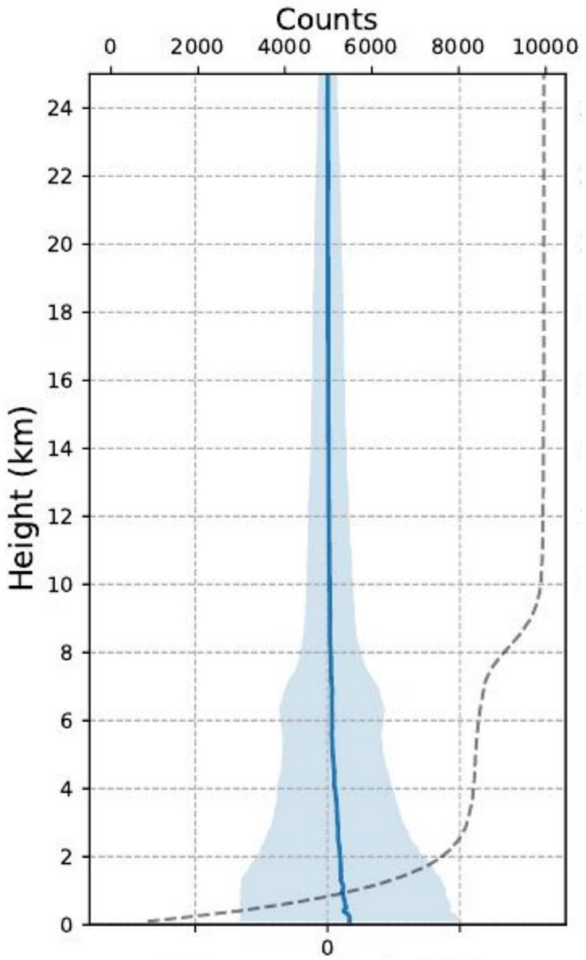
→ CALIBRATED PROFILE!



Statistics of PAZ profiles FREE of RAIN:

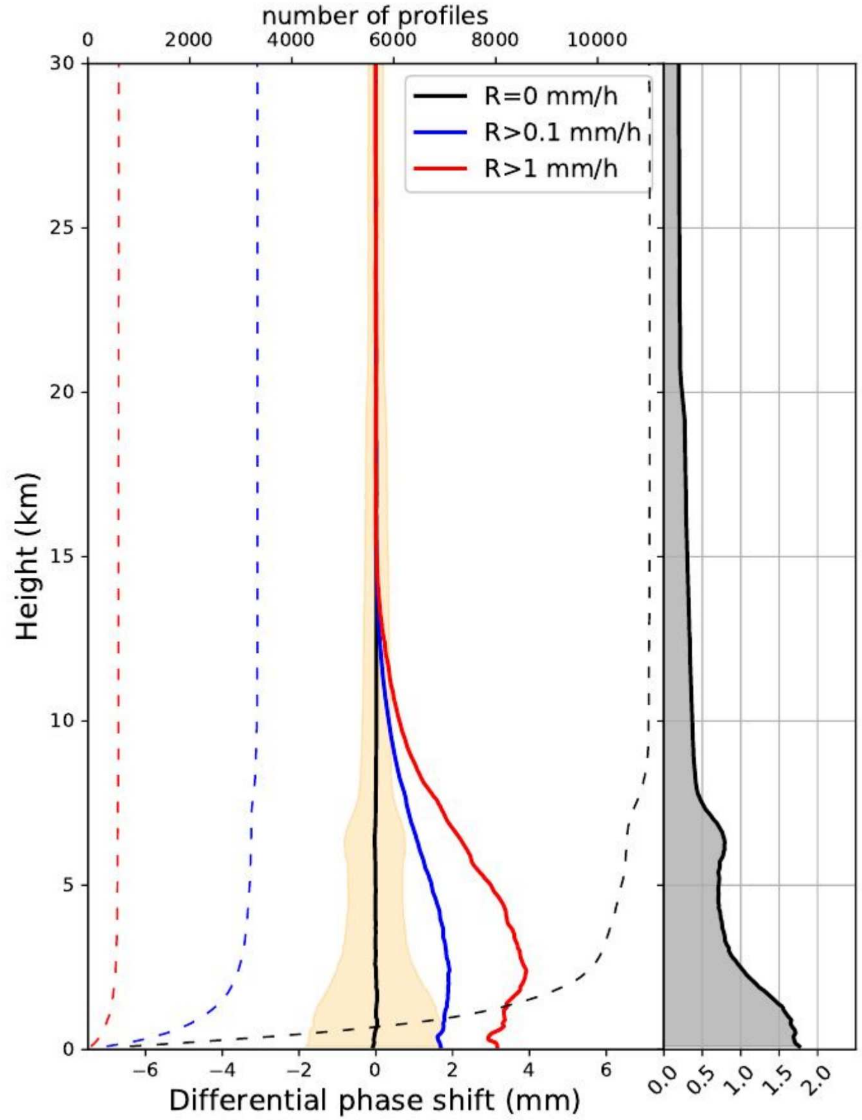
Antenna calibration, doi:10.5194/amt-13-1299-2020

Linear fit calibration, doi:10.1029/2018GL080412



-2.64 mm

2.64 mm



This new measurement concept is being proved aboard the Spanish PAZ LEO

→ the Radio Occultation and Heavy Precipitation aboard PAZ experiment

(ROHP-PAZ)

https://paz.ice.csic.es

ROHP-PAZ:

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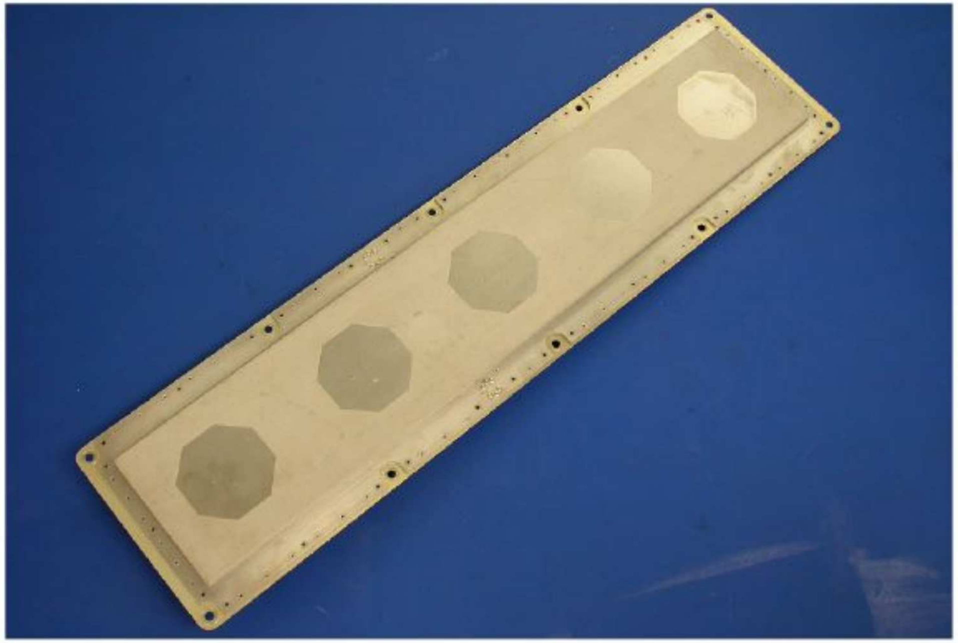
Spanish PAZ satellite:

- Main payload, X-band SAR
- Polar orbit (97.4 deg) at ~514 km altitude, sun-synchronous dusk/dawn
- GPS receiver
- One 2-pol (H/V) RO antenna
- **Expected lifetime: 7-10 years** (TSX 13 yr and still operational)



The ROHP-PAZ experiment is led by ICE-CSIC IEEC: concept, experiment design, technological requirements, funding responsibilities…

But it has only been possible because of the committed support, collaboration and agreements with:

- **Hisdesat**: company owner of PAZ
- **NASA/Jet Propulsion Laboratory**: scientific interest in products and post-processing algorithms, NASA grants for their participation
- **NOAA**: near-real time ground-segment operations, NRT data dissemination of the 'standard' products to weather services worldwide
- **UCAR**: generation of the NRT 'standard' products for NOAA

Successful launch on **February 22, 2018**, by SpaceX (Falcon9).
GNSS RO experiment **activated on May 10**, 2018.

ROHP-PAZ:

Sucessful launch on **February 22, 2018**, by SpaceX (Falcon9).
GNSS RO experiment **activated on May 10**, 2018.

Thermodynamic GNSS RO products being disseminated through GTS since Dec 2019

Do GNSS PRO sense heavy rain? doi:10.1029/2018GL080412

- Results using **first 5 months** of data: May 10 to October 10 2018
- Co-located with IMERG 2D rain products + successful QC: **14,297** with **4,338 rainy cases**
- **IMERG provides 2D rain rate** combined from different sources, in 30 minute interval, but ~14% detection failures
- Co-location by **averaging wide areas of IMERG** rain around the GNSS-PRO central point

IMERG co-location not perfect, invalid set of data for one-to-one validation, but valid approach to **statistically check the response of GNSS-PRO to hydrometeors**

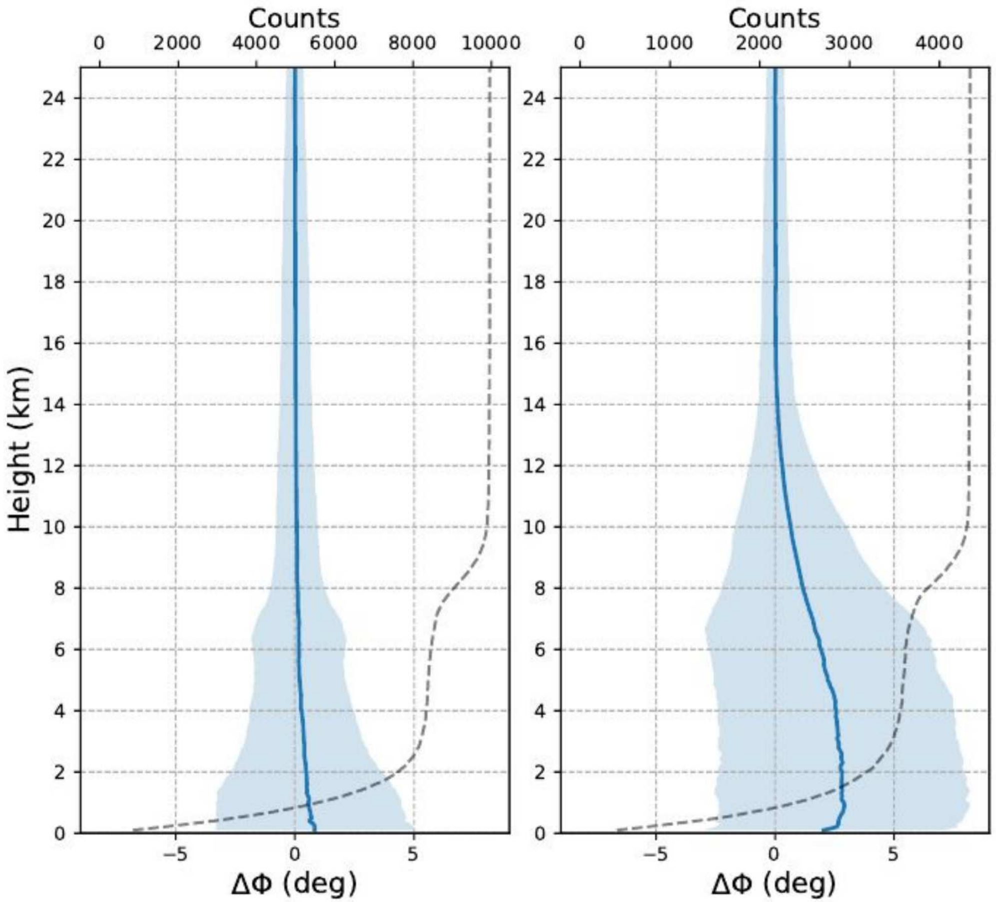
- After linear-fit calibration:

GRL 2019
doi:10.1029/2018GL080412

RAIN FREE:
- average → 0
- bias ~ 1^0 (bottom)
- dispersion:
  - $<2^0$ @ h>4.5km
  - $<4^0$ @ surface

RAIN EVENTS:
- clear positive mean (<~10km)
- mean > rain-free dispersion (except bottom)
- dispersion larger:
  - diversity of rain rate
  - inaccuracy co-location

Rain-free: Rain:



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$<\Delta\varphi>_{0km\text{-}20km}$ for each individual profile → histograms:

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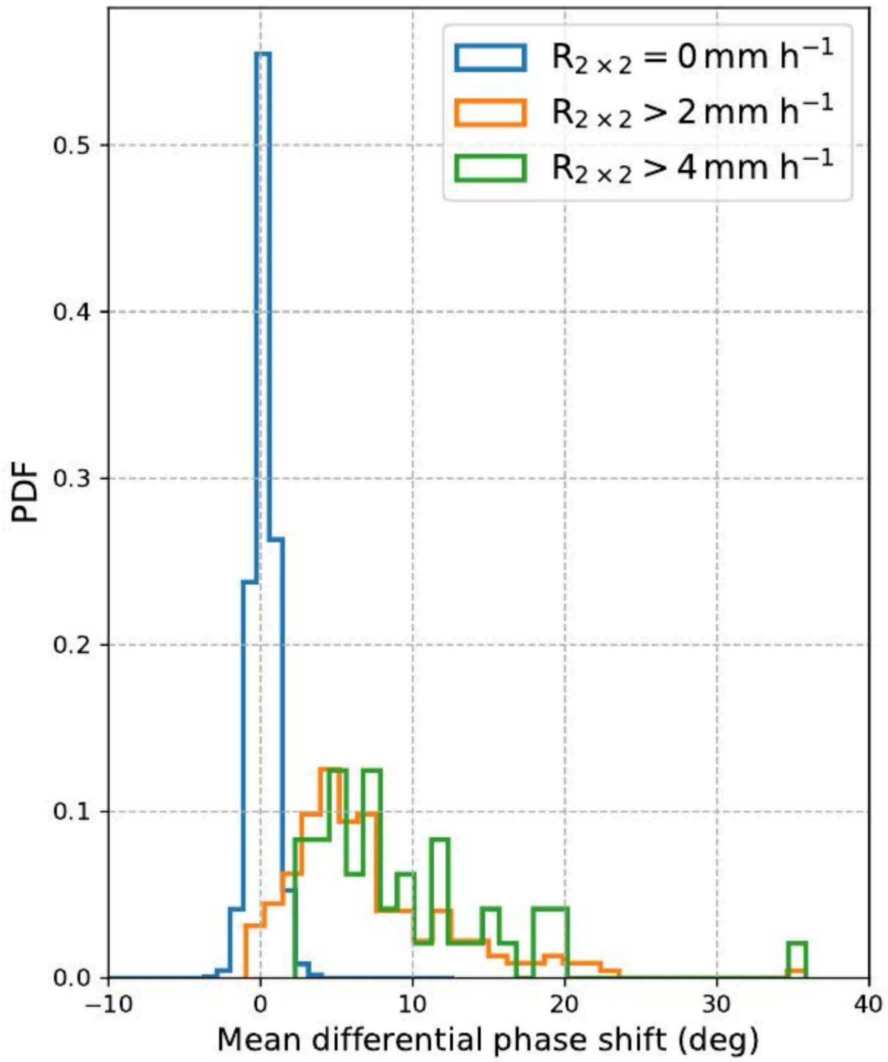
doi:10.1029/2018GL080412



RAIN-FREE events:
98.4% with $<\Delta\varphi>_{0km\text{-}20km} <2^0$
99.97% with $<\Delta\varphi>_{0km\text{-}20km} <4^0$

'false intense rain positives':
for $<\Delta\varphi>_{0km\text{-}20km} >4^0$ → 0.96%

NOTE: not a detection algorithm, yet
Exercise to check meaning of the signals, to understand the observables, link to hydrometeors...

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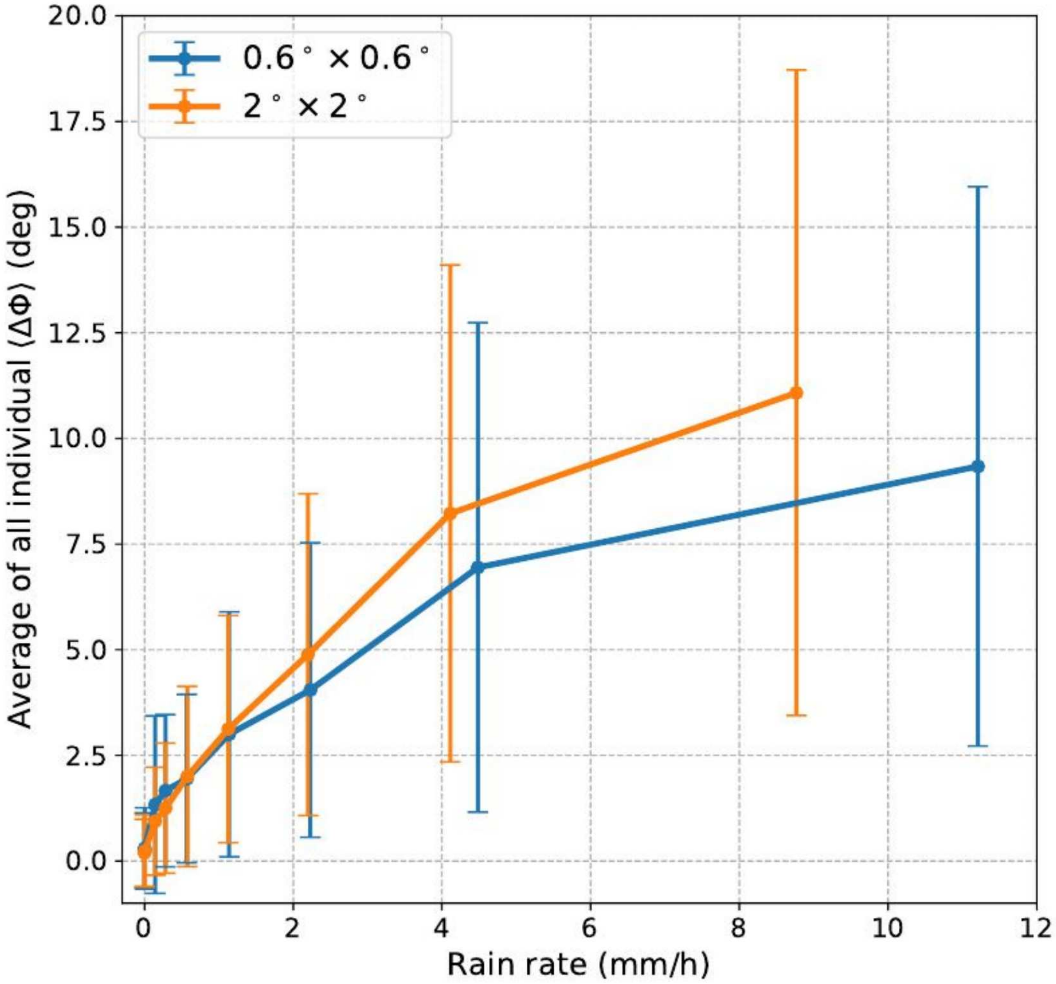
$<\Delta\varphi>_{0km\text{-}20km}$ for each individual profile → link to rain rate:



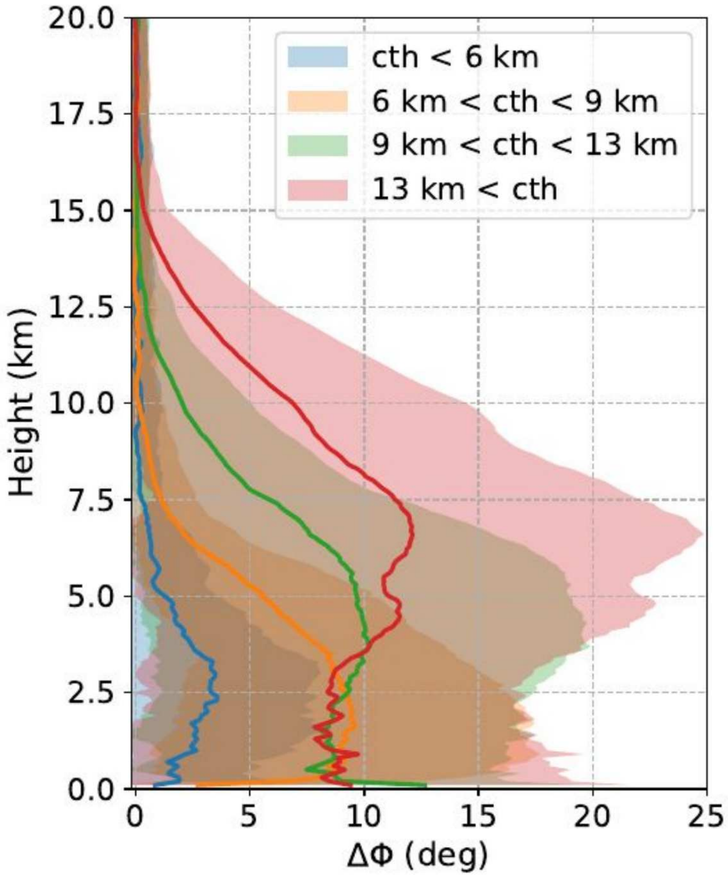
GRL 2019

doi:10.1029/2018GL080412

Validation of the vertical structure of $\Delta\varphi_{pol}(h)$:

GRL 2019

doi:10.1029/2018GL080412

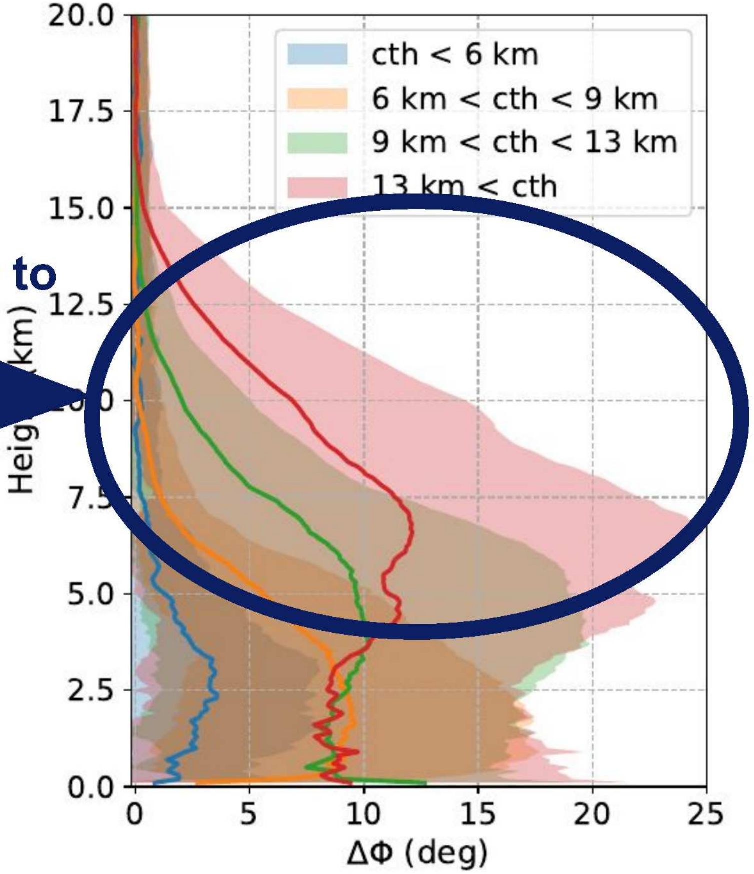


All cases with R_{2^0}>1mm/h

Validation of the vertical structure of $\Delta\varphi_{pol}(h)$:

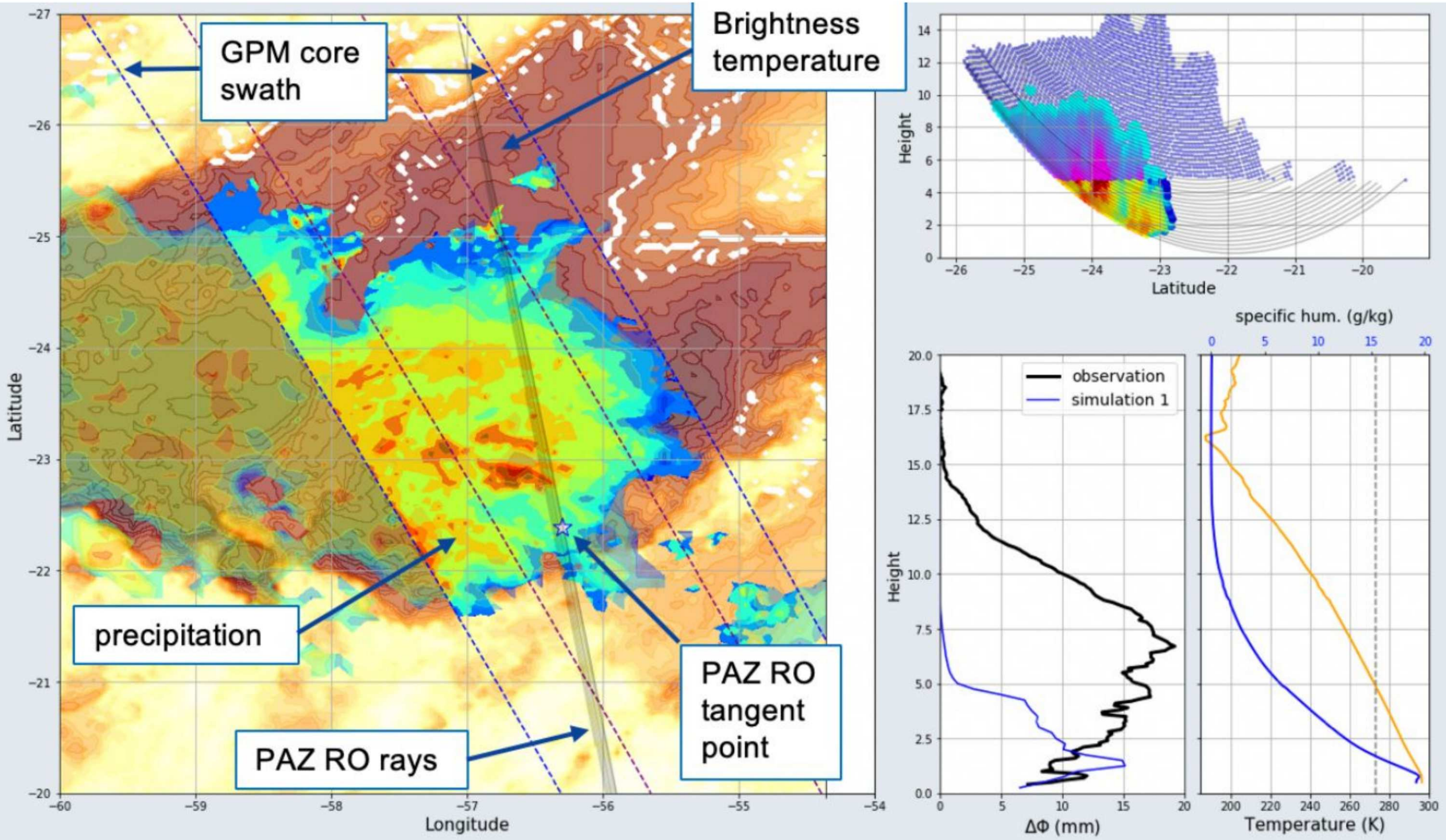
GRL 2019

doi:10.1029/2018GL080412

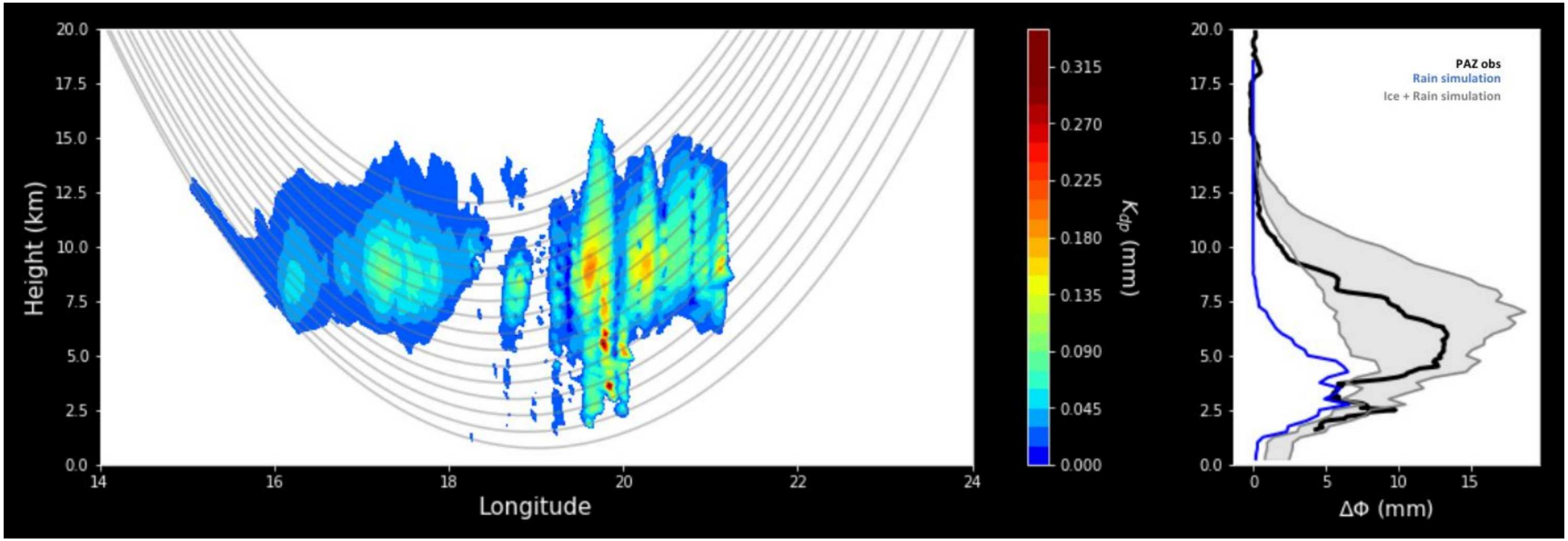


All cases with $R_{2^{\circ}}$>1mm/h

- **Rain vs Frozen particles and mixed phase?**



- **Rain vs Frozen particles and mixed phase?**
  - Simulations along vertical planes where TRMM + CloudSat co-located observations
  - TRMM → insensitive to ice aloft
  - CloudSat → adds this information



Expected products:

- Statistical **algorithms to retrieve vertical profiles of rain** were developed before the launch of PAZ.

- Based on simulated GNSS PRO data across GPM 3D rain estimates.

- PRODUCT: **percentiles of rain probabilities** at different altitudes + **thermodynamic profiles**

(described in doi:10.1002/qj.3161)

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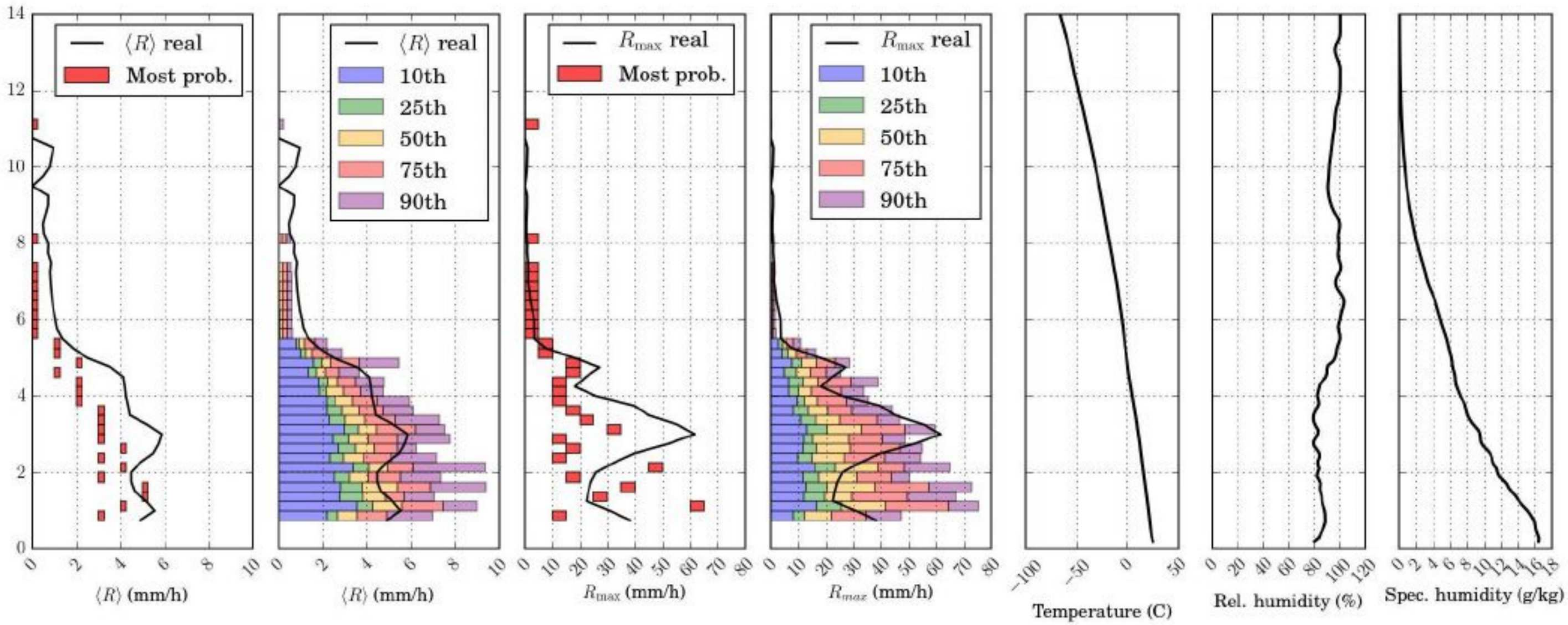
EXPECTED PRODUCTS

QJRMS 2018 doi:10.1002/qj.3161



These products are not ready → **effect of frozen particles** at high altitudes was not considered when developing the retrieval algorithm.

Contents:

UCAR/CDAAC: https://cdaac-www.cosmic.ucar.edu/cdaac/

- level 1: excess phase, SNR for H, V separately (and combined-polarization, combined-polarization bending angles) → $\Delta\varphi_{pol}$ can be obtained, but needs to be corrected and calibrated.
- level 2 thermodynamic profiles

ICE-CSIC/IEEC: https://paz.ice.csic.es/

- level 1: excess phase, SNR for H, V separately, polarimetric phase shift, $\Delta\varphi_{pol}$ corrected, $\Delta\varphi_{pol}$ corrected and calibrated
- in-orbit $\Delta\varphi_{pol}$ antenna pattern

NASA/JPL: https://genesis.jpl.nasa.gov [Target release date: July 1, 2020]

- level 1: excess phase, SNR, bending angle for H, V separately; calibrated $\Delta\varphi$pol
- level 2: refractivity, temperature, water vapor profiles for H, V separately; layer-averaged $\Delta\varphi$pol

rohp-PAZ

More info and data access:
https://paz.ice.csic.es