Institute of Space Sciences

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Advances in GNSS PRO forward model and sensitivity to NWP microphysics schemes

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With contributions from:
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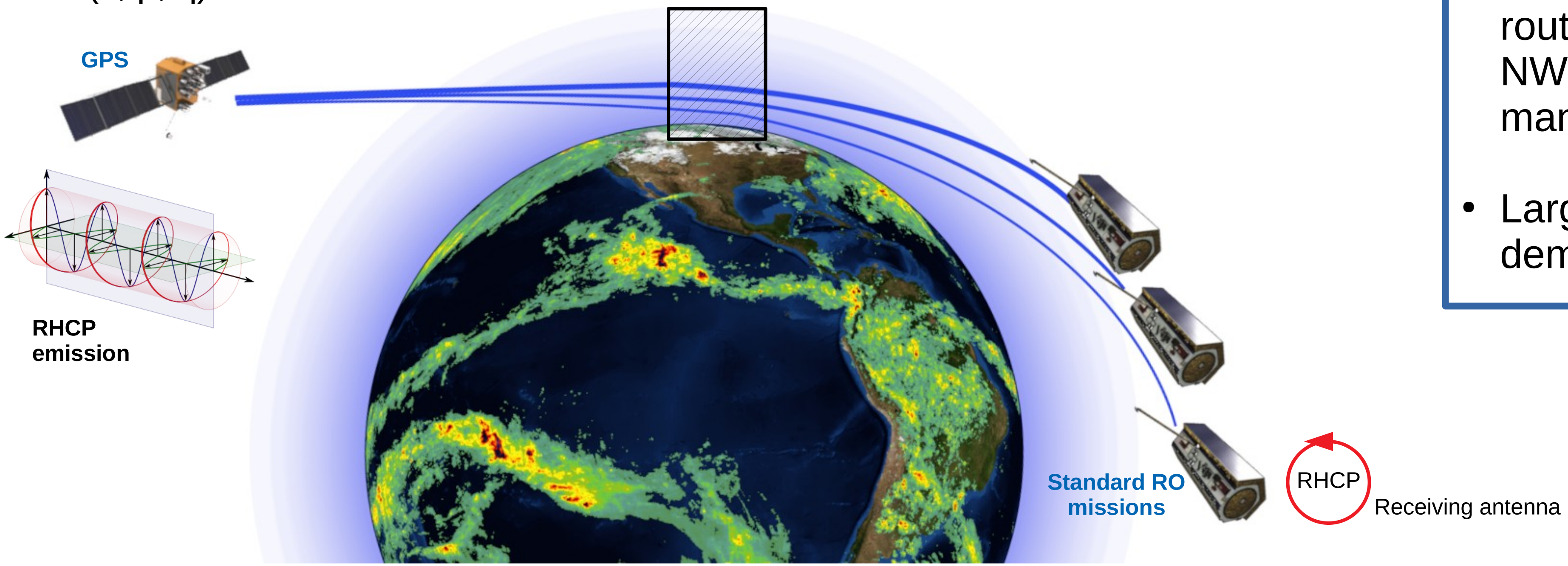
Traditional Radio Occultations (RO)

- GPS emitted electromagnetic waves cross the atmosphere before reaching a Low Earth Orbiter occulting behind the horizon
- **Observables:** Amplitude and phase (ϕ) of the received EM wave → Doppler measurements → bending angle
- The rays bend due to changes in the refractive index of the atmosphere. Such **bending angle** can be derived, and **refractivity vertical profiles** are retrieved → (T, p, q).



Data assimilation of RO

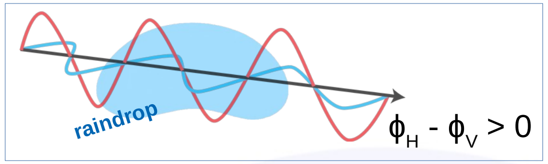
- RO- **Bending angle** profiles routinely assimilated into NWP prediction models for many years now
- Large Impact has been demonstrated

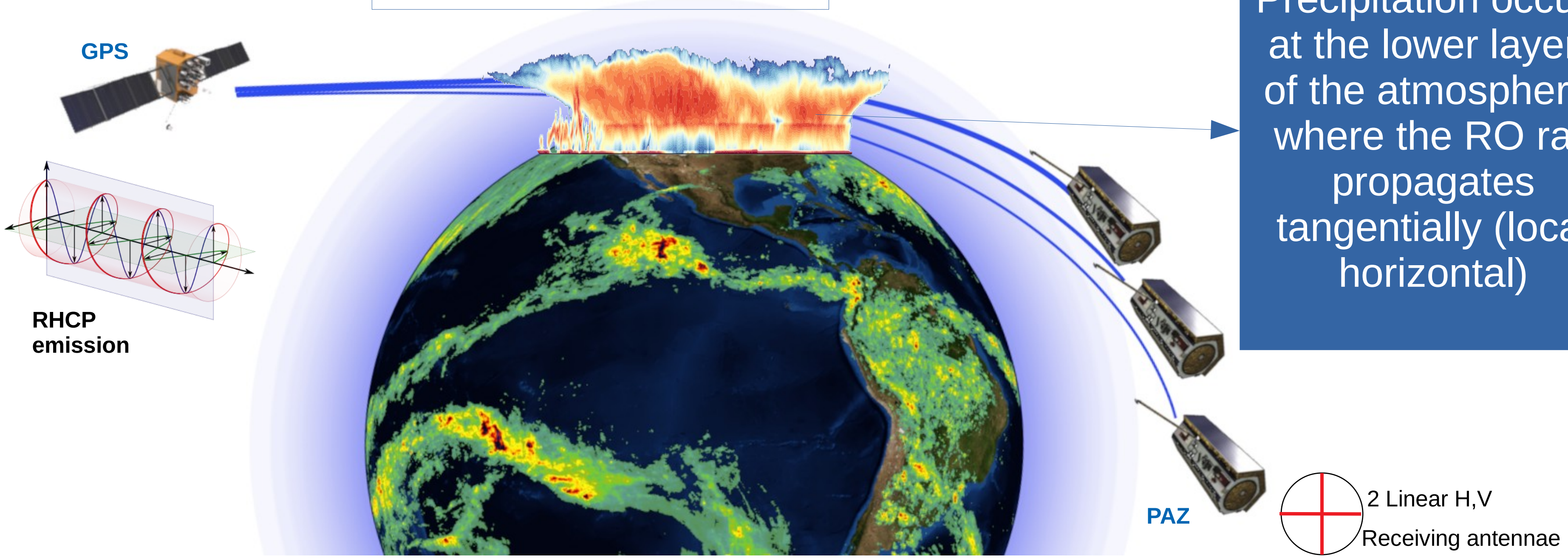
- Globally distributed
- Over all surfaces
- All weather conditions
- High vertical resolution
- Cost-effective

Polarimetric Radio Occultations (PRO)

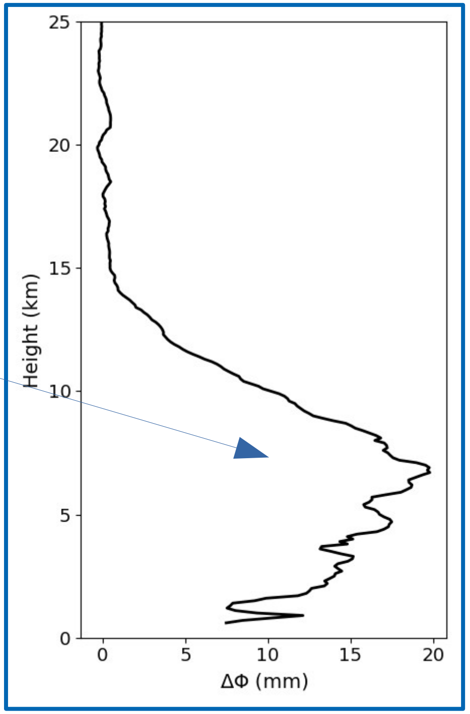
- Concept introduced in 2009
- RO rays are collected using a 2-linearly **polarized** antenna (H,V)

- If these rays happen to cross precipitation, a **positive differential phase** shift $\Delta\Phi = \Phi_H - \Phi_V$ is expected owing to the asymmetric shape of precipitating hydrometeors





Precipitation occurs at the lower layers of the atmosphere, where the RO ray propagates tangentially (local horizontal)



GNSS PRO aboard PAZ

- Is it technologically possible to measure the polarimetric RO?
- Are the GNSS PRO signatures sufficiently large to be measured?
- Do they relate to [heavy] precipitation?
- Can the ‘traditional’ (thermodynamics) profiles be recovered from GNSS PRO data?
- How can these measurements be used in meteorology and climate studies?

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- A **proof-of-concept experiment** aboard the Spanish **PAZ satellite: Radio Occultation and Heavy Precipitation with PAZ (ROHP-PAZ)**
- Modified IGOR receiver
- Agreements with **NOAA** and **UCAR** for dissemination in **NRT of ‘traditional’ RO** profiles
- Close collaboration with **NASA/JPL** for **scientific investigations**

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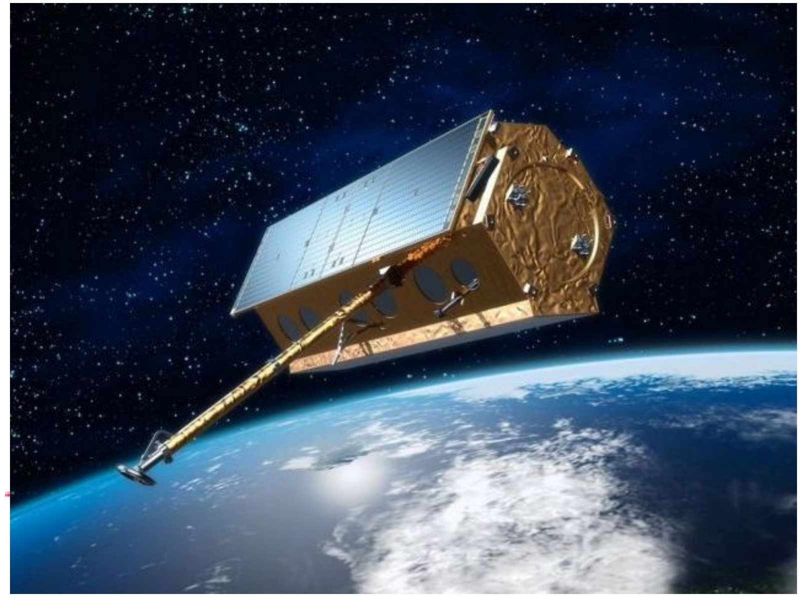
- PAZ launched in 02/2018
- ROHP-PAZ activated in 05/2018
- Continuous data acquisitions since then…
- Validation with NEXRAD polarimetric weather radars (see Poster!)

Power Flex issue fixed last week >240 daily profiles



Visit **https://paz.ice.csic.es**

GNSS PRO aboard PAZ

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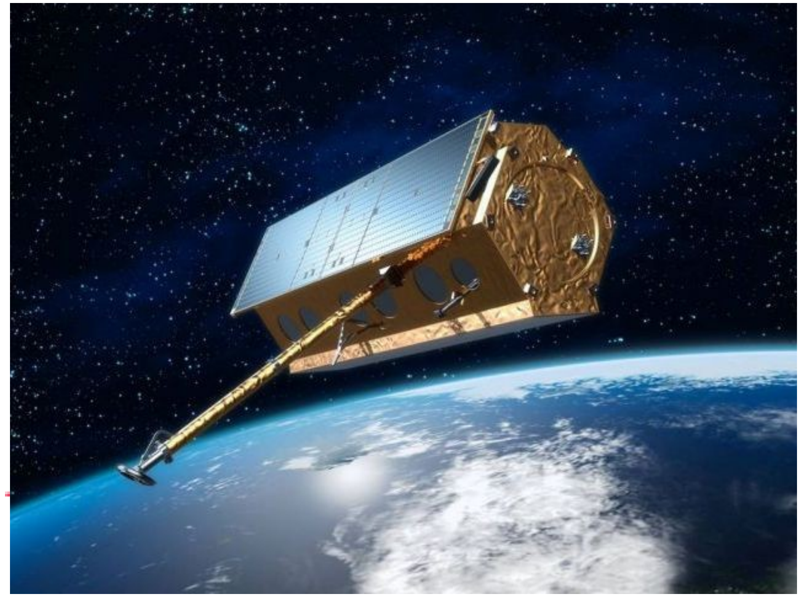

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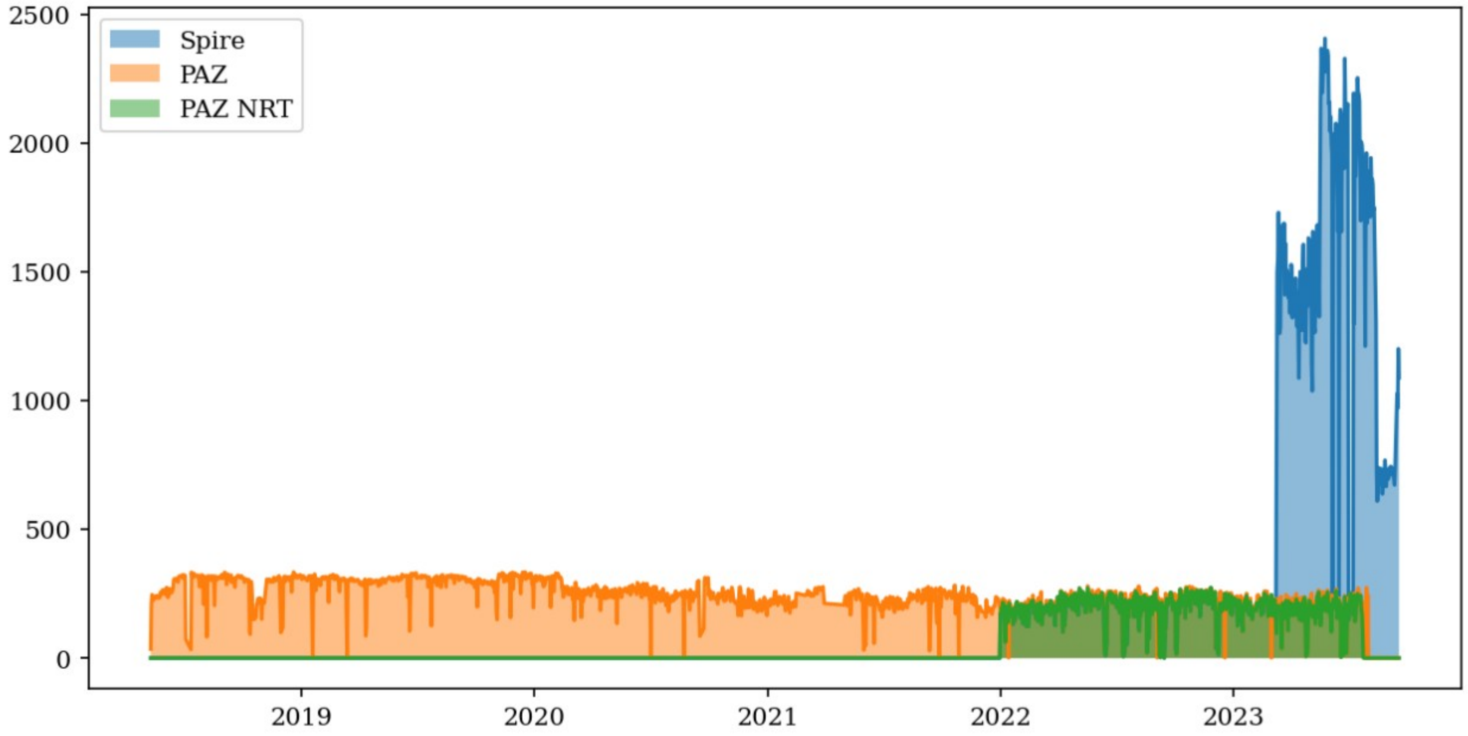
Commercial GNSS PRO

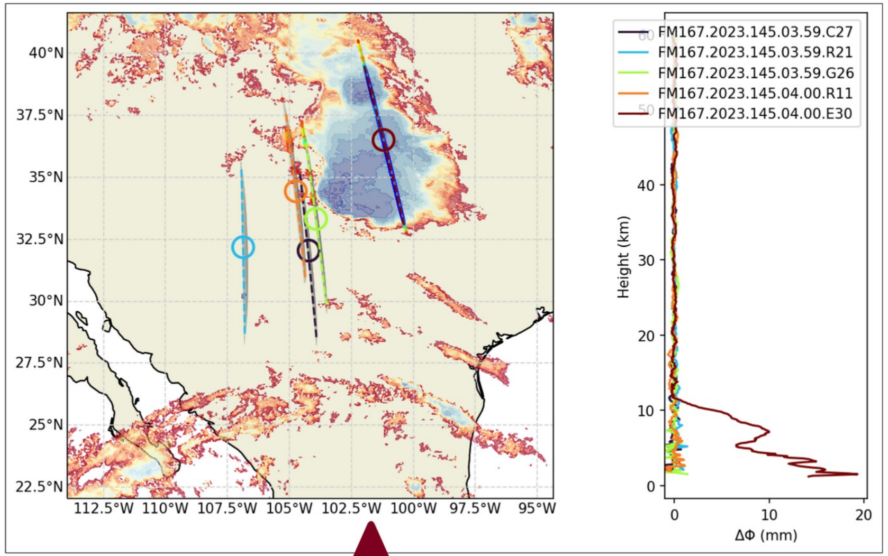
- In addition to PAZ, since 2023 there are **3 other LEOs** equipped with GNSS PRO payload: Spire Global, **commercial GNSS PRO**



Clusters of GNSS PRO

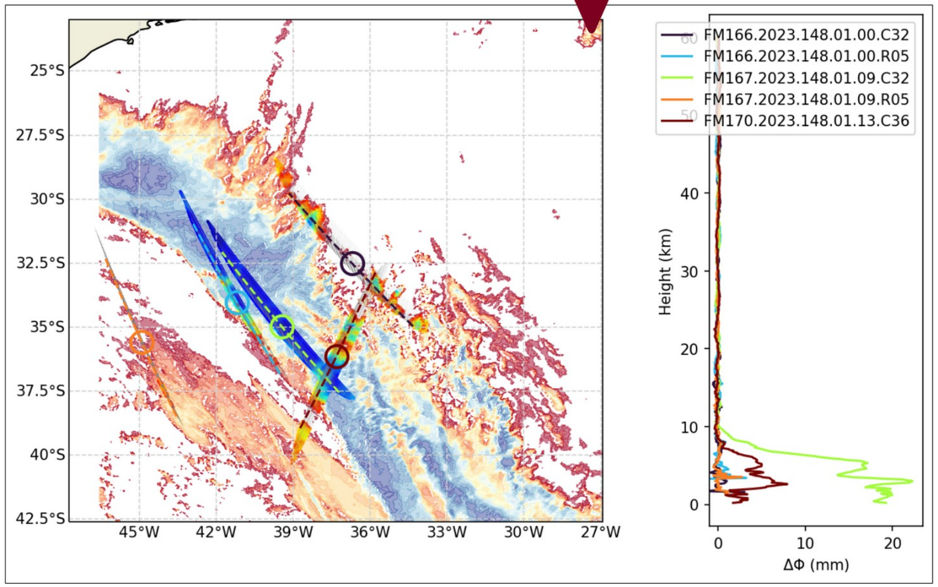
- Given the capacity for multiple simultaneous GNSS PRO profiles, **clusters of measurements** are possible across interesting events
- **3-LEO** system also permits **clusters**

Clusters of observations



Cluster of observations from only one FM

Cluster of observations from several FMs



Hundreds of clusters across precipitation systems found during the few months of data available

GNSS PRO in NWP

- How can these measurements be used in NWP?
  - **Data Assimilation** → need of a **Forward Operator**
  - **Diagnosis Tool** → check assumptions made by the NWP models (microphysics, particles...)

Contribution to ROMSAF

GNSS PRO in NWP

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First part of this talk

See also Poster

Second part of this talk

GNSS PRO Forward Operator

CURRENT STATUS

The GNSS PRO observable is the accumulated polarimetric phase shift:

$$\Delta\Phi = \int_L K_{\mathrm{dp}} \mathrm{d}L$$

Where **Kdp** is the specific differential polarimetric phase shift (per km)

Kdp comes from the **forward scattering** off **non-spherical hydrometeors** along the radio-link.

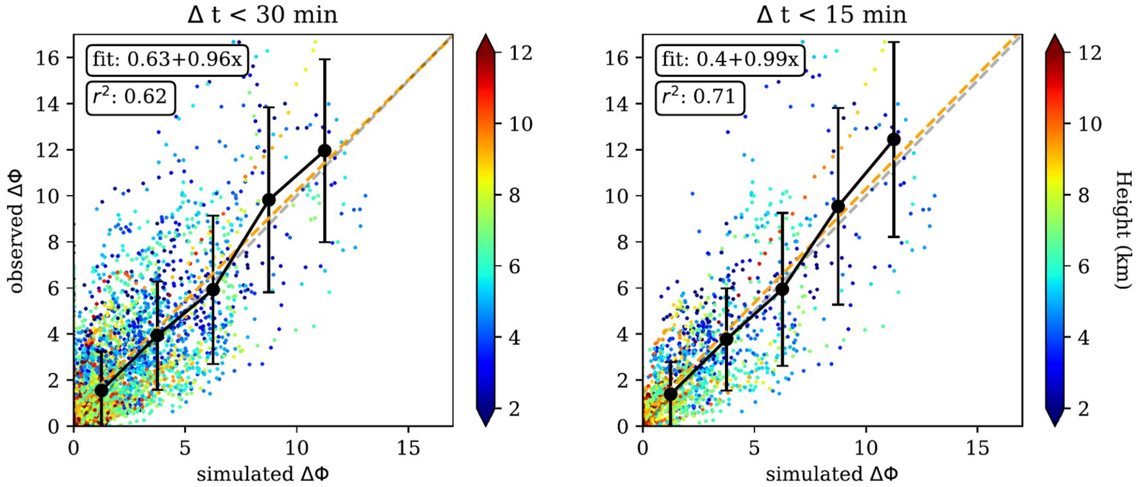
Bringi & Chandrasekar 2001, for polarimetric weather radars, suggested:

$$K_{dp} = \kappa \; WC \; \rho_{eff} \; (1 - ar)$$

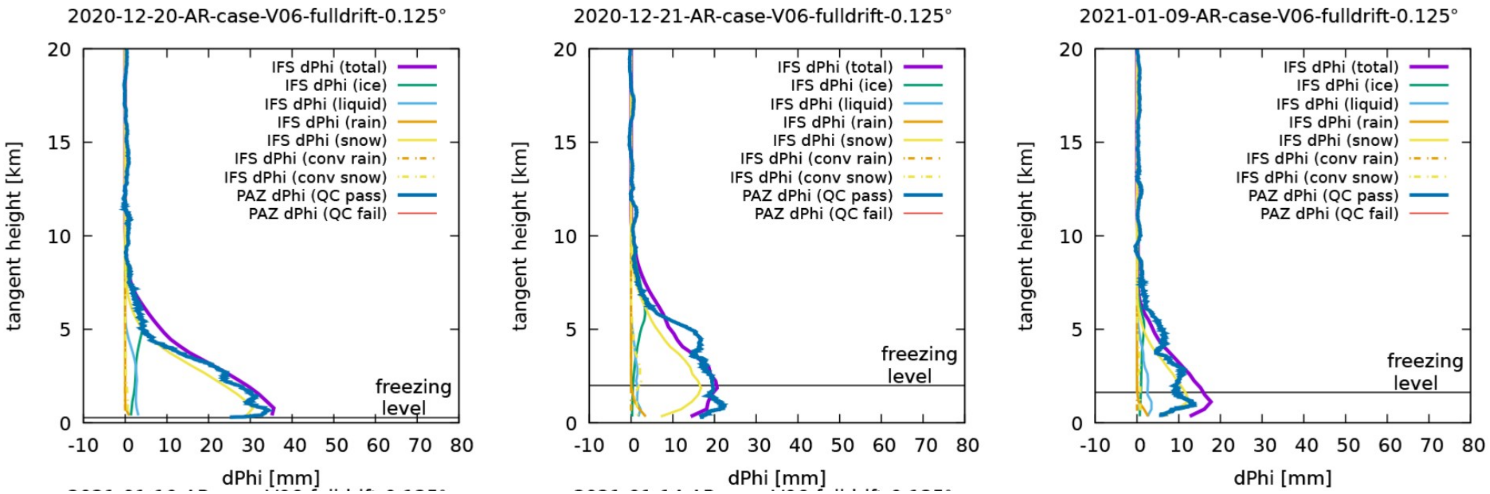
GNSS PRO Forward Operator

CURRENT STATUS

Approach validated in *Padullés et al., 2021* doi: 10.1109/TGRS.2021.3065119



And also used in *Hotta et al., 2024* doi:10.5194/amt-17-1075-2024



ar = 0.5
rho = 0.2 gr/cm³

GNSS PRO Forward Operator

CURRENT STATUS

What are the right values for ρ_{eff} and ar in $K_{dp} = \kappa \; wc \; \rho_{eff} \; (1 - ar)$?

- ‘EFFECTIVE’ APPROACH: a set of values for type of hydrometeor (rain/snow/ice/...)
- PARTICLE APPROACH: compute the forward scattering solution for each hydrometeor particle shape, then one obtains

$$K_{dp}^{part.} = X^{part.} \; wc^{part.}$$

GNSS PRO Forward Operator

CURRENT STATUS

What are the right values for ρ_{eff} and ar in $K_{dp} = \kappa \; wc \; \rho_{eff} \; (1 - ar)$?

- ‘EFFECTIVE’ APPROACH: a set of
  (rain/snow/ice/...)

- PARTICLE APPROACH: compute th ch
  hydrometeor particle shape, then on

$$K_{dp}^{part.} = X^{p}$$

ADVANTAGES:
Less dependent on assumptions

DISADVANTAGES:
Is it accurate enough?
Is it consistent with other NWP modules?

GNSS PRO Forward Operator

CURRENT STATUS

What are the right values for ρ_{eff} and

- 'EFFECTIVE' APPROACH: a set of (rain/snow/ice/...)

- PARTICLE APPROACH: compute th... hydrometeor particle shape, then one ...n

ADVANTAGES:
Consistent with other modules of the NWP model (RTTOVS/CRTM...)

DISADVANTAGES:
More dependent on assumptions

$$K_{dp}^{part.} = X^{part.}\ wc^{part.}$$

Particle scattering

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- RTTOVS is based on particles' shapes as given by ARTS
- Under ROM SAF CDOP4, we are computing **$X^{part.}$** for each of the **ARTS**/**RTTOVS hydrometeor particles**
- GOAL: to provide a LUT to forward model GNSS PRO **consistently** with other modules of the NWP modules

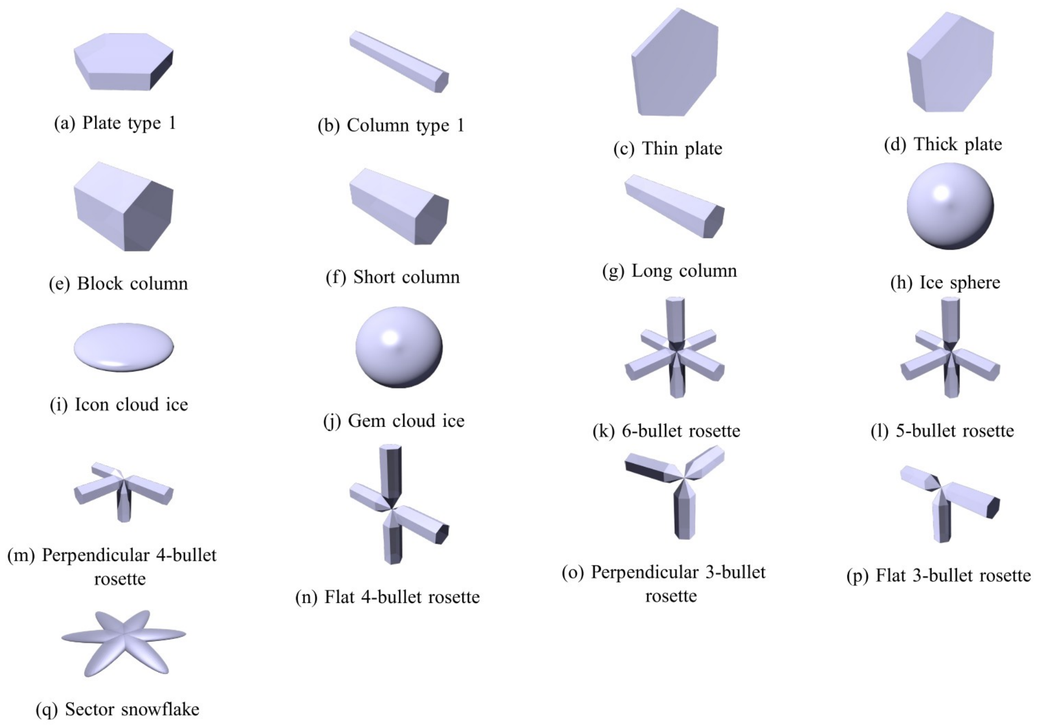
ARTS Microwave Single Scattering Properties Database

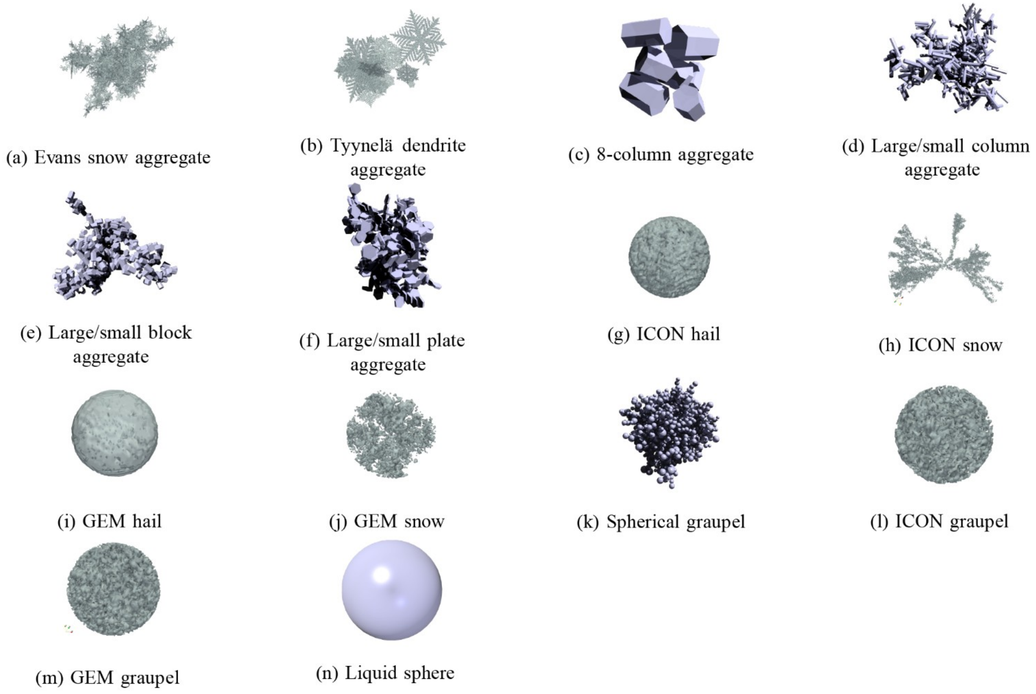
Eriksson, et al., 2018 doi:10.5194/essd-10-1301-2018

Ekelund et al., 2020 doi:10.5281/zenodo.4646605

What does it contain?

- Particle shapes (both pristine and aggregates)





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Eriksson, et al., 2018 doi:10.5194/essd-10-1301-2018

Ekelund et al., 2020 doi:10.5281/zenodo.4646605

What does it contain?

- Particle shapes (both pristine and aggregates)
- Single scattering properties of those particles for different frequencies: (in GHz) 1, 1.4, 3, 5, 7, 8, 9, 10, 13.4, 15, 18.6, 24, 31.5, 50.1, 57.6, 88.8, 94.1, 115.3, 122.2, 164.1, 166.9, 175.3, 191.3, 228.0, 247.2, 314.2, 336.1, 439.3, 456.7, 657.3, 670.7, 862.4, 886.4
- Scattering matrix, absorption vector and extinction matrix.
- Interface to extract other parameters and interact with RTTOV

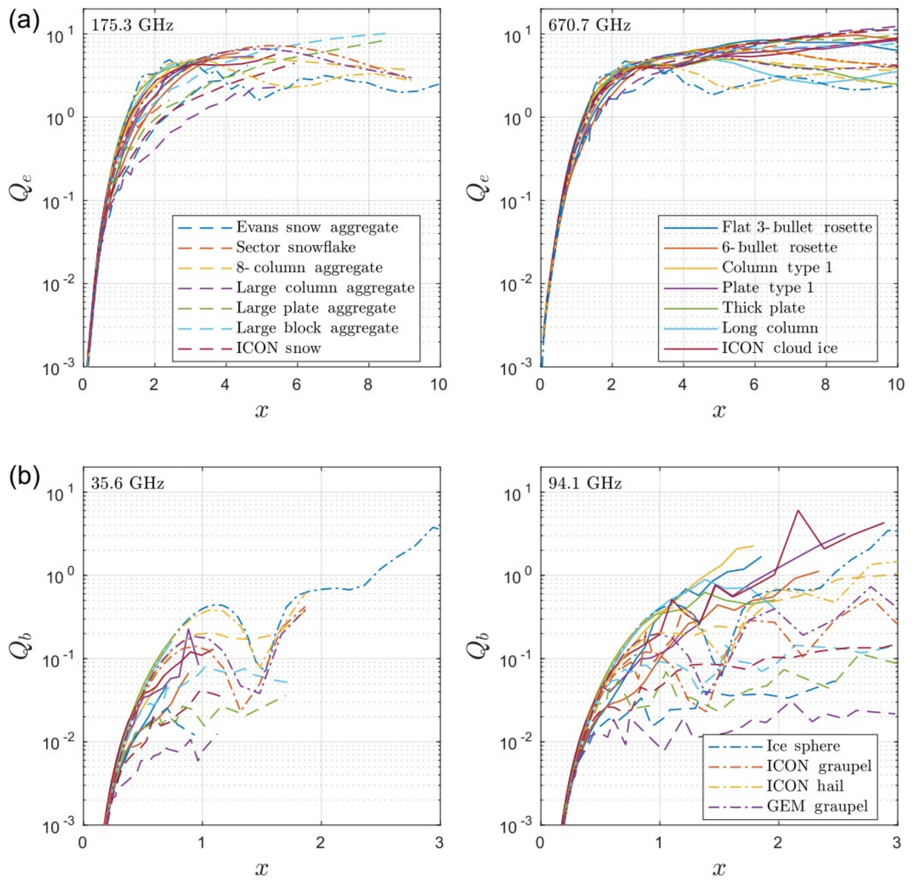

Figure 12. Example extinction **(a)** and backscattering **(b)** efficiencies (Eq. 19) as a function of the size parameter (Eq. 4). Legends are valid across all panels.

From *Eriksson et al., 2018*

ARTS Microwave Single Scattering Properties Database

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Eriksson, et al., 2018 doi:10.5194/essd-10-1301-2018

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What does **NOT** contain?

- The scattering amplitude matrix (**f**) at forward and tangential to Earth surface geometry (i.e. **RO geometry**)
- f is needed for computing the specific differential phase shift (**Kdp**) to obtain the PRO observable Δϕ

$$K_{dp} = \frac{\lambda^2}{2\pi} \int \Re\{f_H(D) - f_V(D)\} N(D) dD$$

ARTS Microwave Single Scattering Properties Database

What we have done:

- Particle shapes from ARTS database:
  - Force maximum possible horizontal orientation
  - Run Discrete Dipole Approximation (DDA), using ADDA implementation, for horizontal orientation and averaging over azimuthal rotation, using forward scattering geometry, and L-band frequency → this provides **f**
  - Store the **f** for every shape and every size of the different particles
- Once we have the **f**, and using the mass of each particle and particle size, we can compute the bulk properties:
  - Using the particle size distribution N(D), we can obtain Kdp and WC
  - We have used a set of realistic gamma sized N(D) to generate all possible plausible **Kdp – WC relationships**

ARTS Microwave Single Scattering Properties Database

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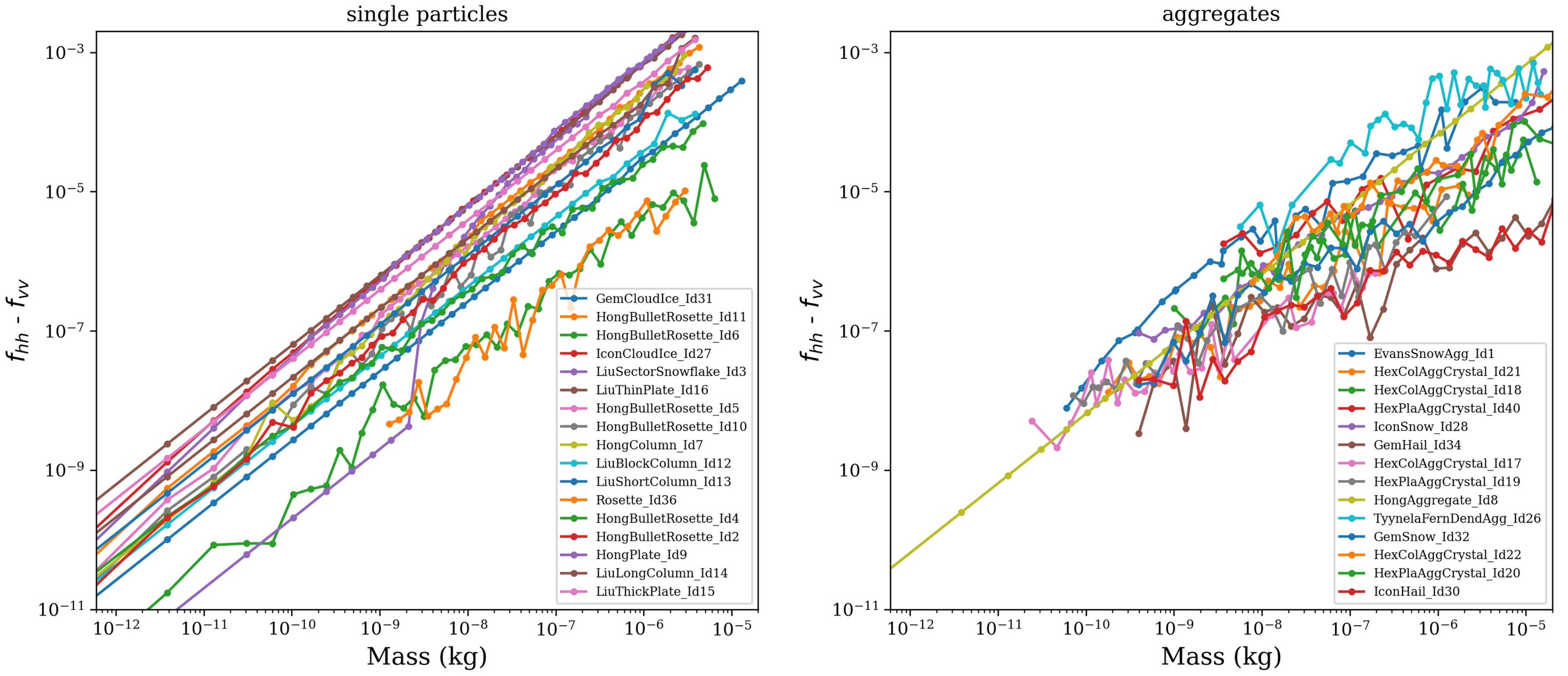
What we have done: SINGLE PARTICLE/AGGREGATE RESULTS for ‘f’



ARTS Microwave Single Scattering Properties Database

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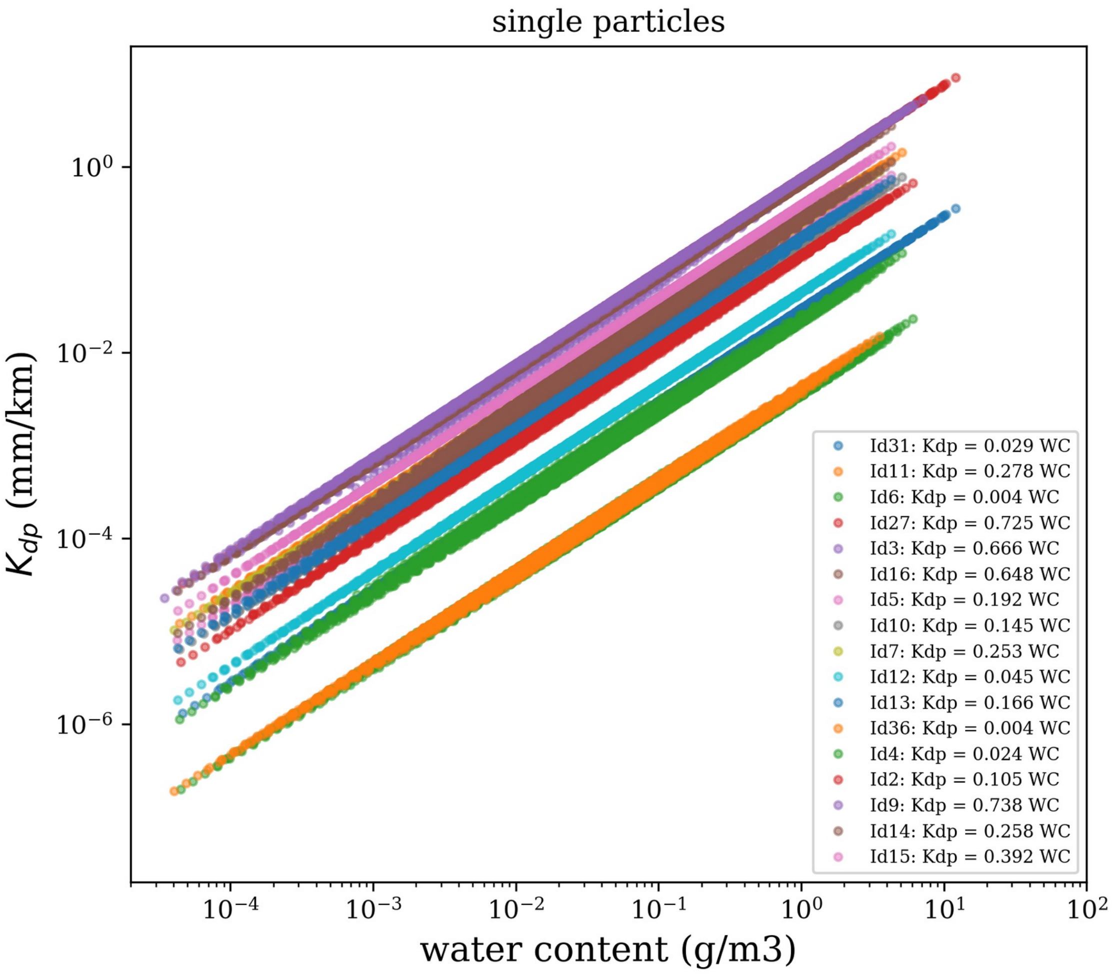
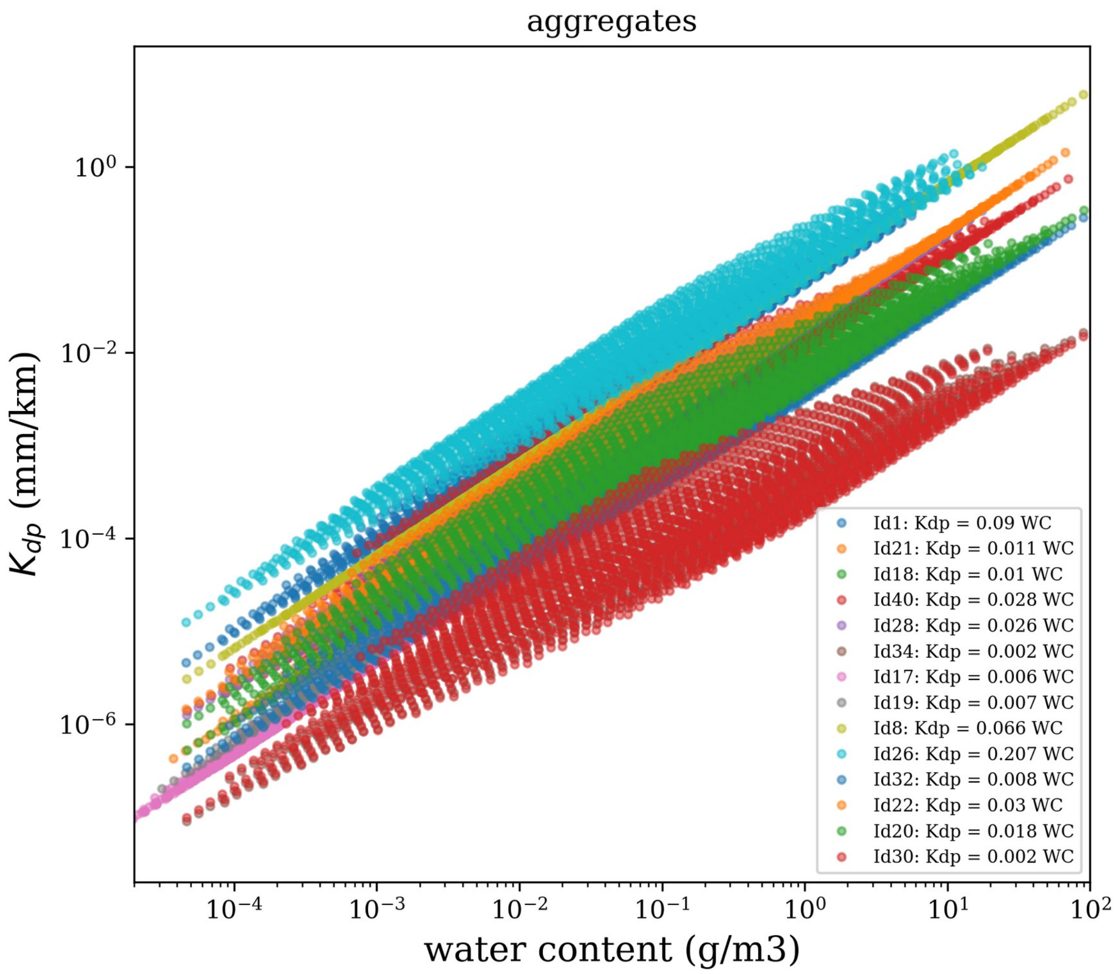
What we have done: wc to Kdp relationship -- using sets of realistic ~100k N(D)

$$K_{dp} = \frac{\lambda^2}{2\pi}\int \Re\{f_H(D) - f_V(D)\}\, N(D)\, dD$$





$$\mathrm{WC} = 10^{-3}\frac{\pi}{6}\rho\int_D D^3 N(D)\,\mathrm{d}D$$

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So, now we have:

- Single scattering properties of those particles for different frequencies: (in GHz) 1, 1.4, 3, 5, 7, 8, 9, 10, 13.4, 15, 18.6, 24, 31.5, 50.1, 57.6, 88.8, 94.1, 115.3, 122.2, 164.1, 166.9, 175.3, 191.3, 228.0, 247.2, 314.2, 336.1, 439.3, 45[illegible]70.7, 862.4, 886.4

e.g., RTTOV

- Scattering matrix, absorption vector, extinction matrix at nadir looking geometry, and **f** at **L-band, forward scattering** in **RO geometry, for the same particles**.

GNSS PRO FO

- This ensures consistency among different DA / RT / GNSS PRO communities

- This ensures **consistency among RT and GNSS PRO modules in NWP models**

GNSS PRO in NWP

- How can these measurements be used in NWP?
  - **Data Assimilation** → need of a **Forward Operator**
  - **Diagnosis Tool** → check assumptions made by the NWP models (microphysics, particles...)

First part of this talk

Second part of this talk

PRO as Diagnosis Tool

Work with UCAR and NCU/Taiwan to use **WRF with different microphysics** → Forward Model $\Delta\phi$ → Compare to PAZ profiles (presented at *2nd PAZ GNSS PRO User Workshop, Pasadena, Nov'23*)

FO using 'effective' values of hydrometeor density and axis ratio (not particular ice particles)

$$K_{dp} = \kappa \; wc \; \rho_{eff} \; (1 - ar)$$

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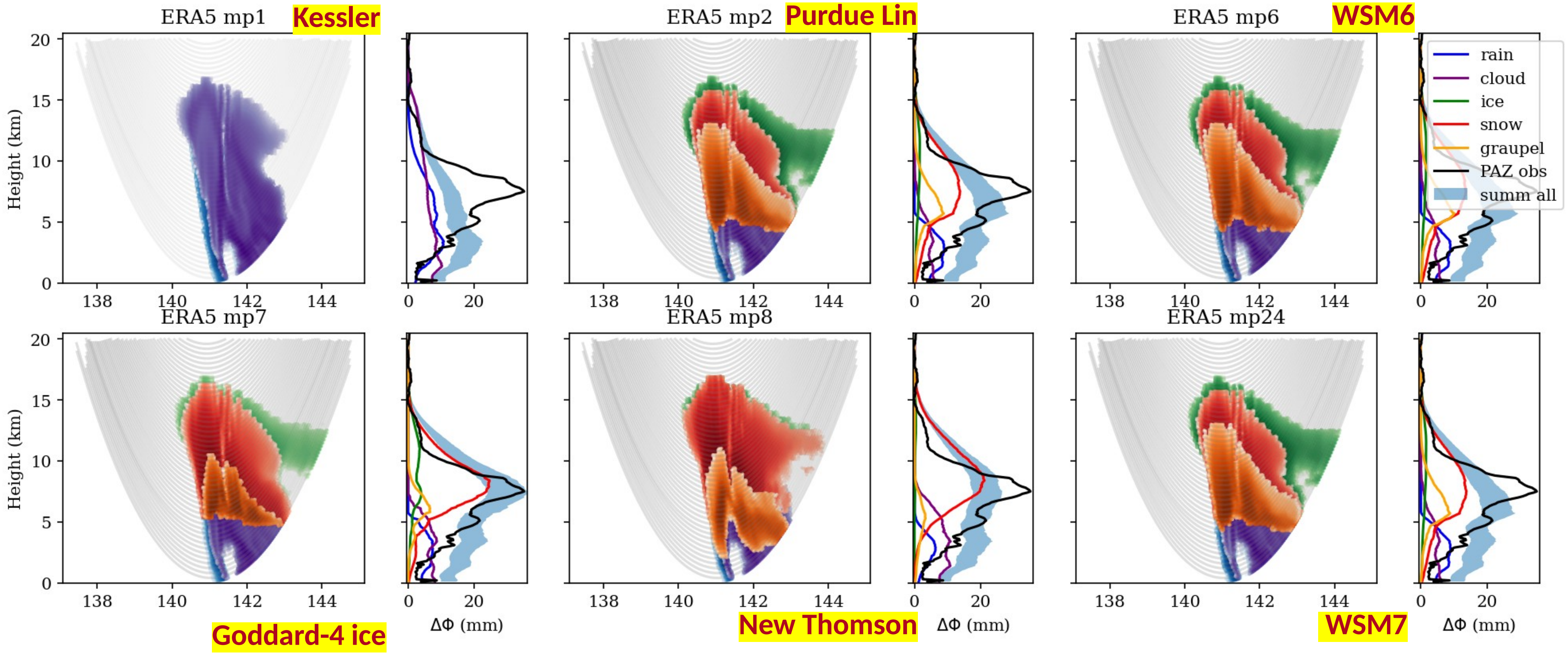

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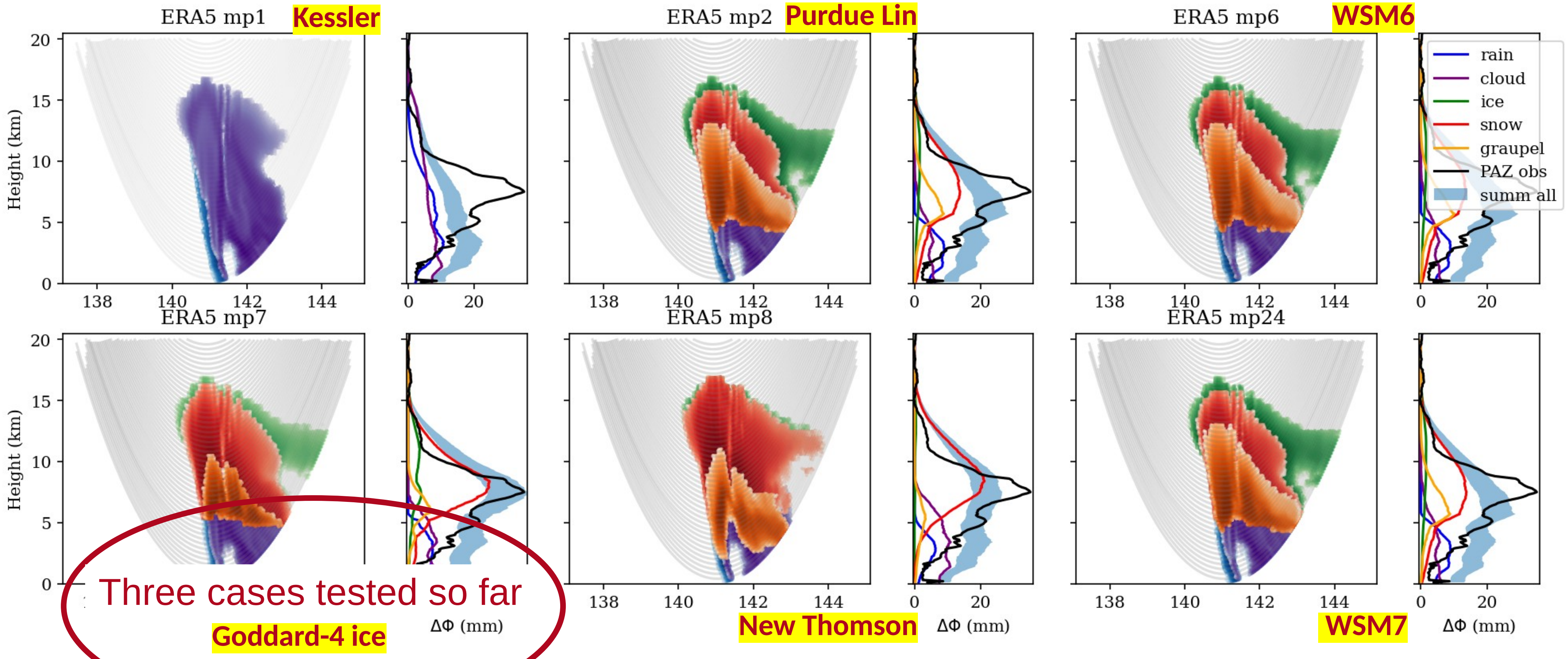

PRO as Diagnosis Tool

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We are now trying to implement a similar approach but **using particle-scattering derived Kdp** instead of effective density and axis ratio values

PRO as Diagnosis Tool

WRF is being run for a series of RO events in the northern-east Pacific

- Regions where Atmospheric Rivers tend to happen
- Phenomena with larger part of stratiform rain than Tropical Cyclones
- More spatial homogeneity, less sensitive to exact positioning of the weather events than Tropical Cyclones

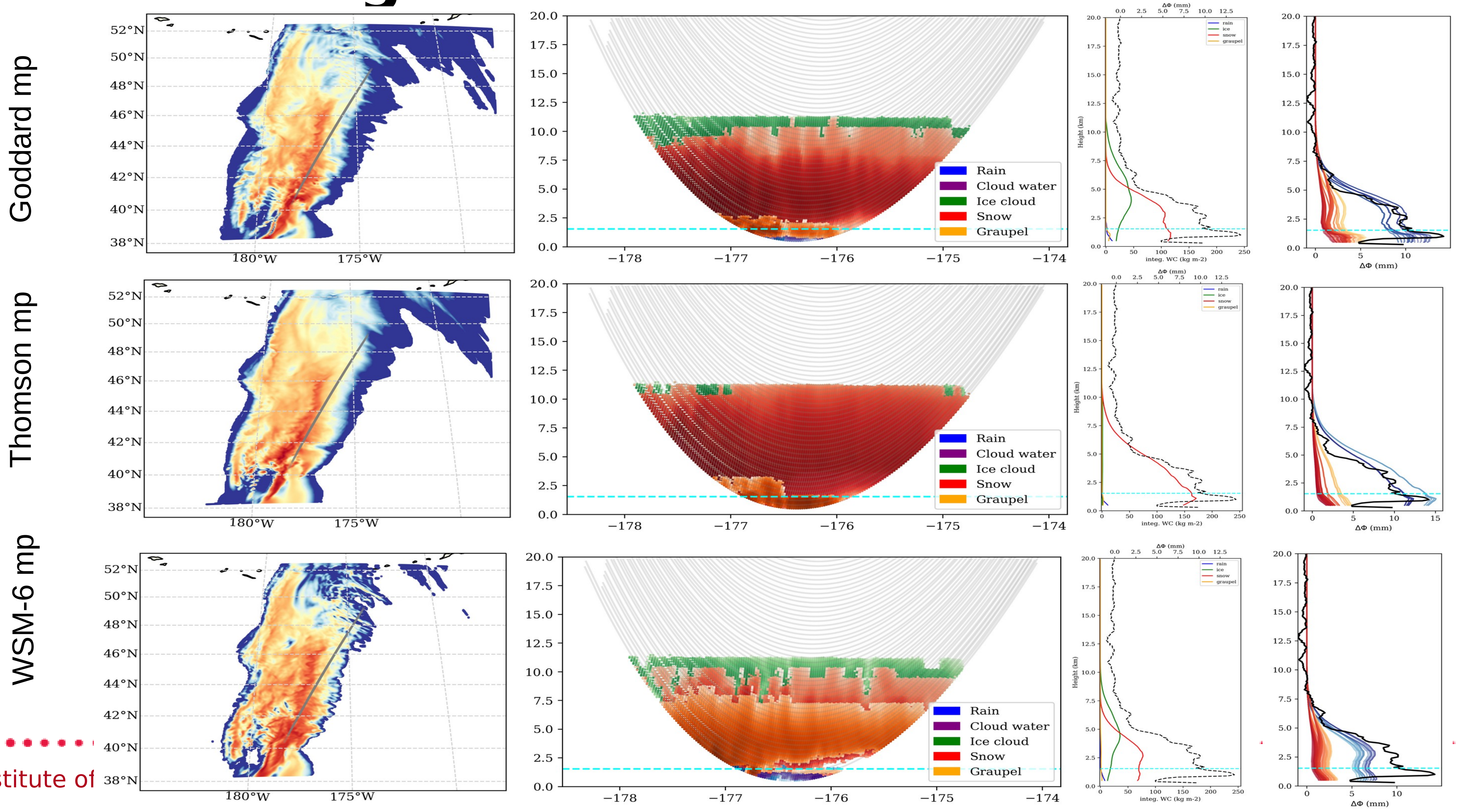
For each case, four different microphysics schemes are used: Goddard, Thomson, WSM-6, Morrison

Different set of particles for each kind of hydrometeor, e. g.:

- **Snow**: 'IconSnow_Id28', 'GemSnow_Id32', 'EvansSnowAgg_Id1', 'HongAggregate_Id8', 'TyynelaFernDendAgg_Id26', 'HexPlaAggCrystal, 'LiuThickPlate_Id15', 'LiuThinPlate_Id16', 'HongPlate_Id9', 'LiuSectorSnowflake_Id3'
- **Ice**: 'GemCloudIce_Id31', 'IconCloudIce_Id27', 'HexColAggCrystal_Id21'
- **Graupel**: 'LiuBlockColumn_Id12', 'LiuShortColumn_Id13', 'LiuLongColumn_Id14', 'HongColumn_Id7'

Work in progress, a case example shown: PAZ1.2021.071.18.28.G27

PRO as Diagnosis Tool



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Conclusions

- **Polarimetric RO** experiment aboard PAZ + 3 commercial (Spire) CubeSats
- Ongoing studies to exploit the use of **GNSS PRO for and in NWP**:
  - **DA** → **forward operator**:
    - Already tested using hydrometeor 'effective' density and axis ratio: Kdp(wc; rho, ar)
    - Developing relationships based on L-band forward scattering off ARTS particles: Kdp(wc; particle, N(D)) → consistency between RT modules in NWP (e.g., RTTOVS)
  - **DIAGNOSIS** → Examples shown based on WRF simulations
    - **Sensitivity to microphysics** schemes: Goddard scheme gets best agreements with PAZ in a few TC studied cases
    - **Sensitivity to microphysics** schemes and **particle shapes**: one AR-like case shown, Goddard scheme gets best agreement for a particular combination of particles.

Thanks!

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