Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

Advances in Remote Sensing Using the Polarimetric RO Technique

Ramon Padullés[1,2]

E. Cardellach[1,2], A. Paz[1,2], S. Oliveras[1,2]

F. Joe Turk[3], K.-N. Wang[3], C.O. Ao[3], M. de la Torre-Juárez[3], J. P. Weiss[4], D. Hunt[4], W. Kuo[4], S.-Y. Chen[5], J. Haase[6], M. Murphy[7], T. Burger[8], V. Nguyen[9], P. Jales[9], M. Talpe[9], D. Wu[10], G. Gong[10], K .Lonitz[11], S. Healy[11], D. Hotta[12]

[1]Institut de Ciències de l'Espai (ICE-CSIC), Barcelona
[2]Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona

[3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [4]University Corporation for Atmospheric Research (UCAR), [5]National Central University, Taiwan, [6]Scripps Institution of Oceanography, San Diego, CA, [7]NASA Global Modeling and Assimilation Office (GMAO), [8]European Space Agency (ESA), [9]Spire Global Inc., [10]NASA Goddard Space Flight Center, [11]ECMWF, [12]Japanese Meteorological Agency (JMA)

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Plan de Recuperación, Transformación y Resiliencia

AGENCIA ESTATAL DE INVESTIGACIÓN

Financiado por la Unión Europea NextGenerationEU

CSIC Institute of Space Sciences EXCELENCIA MARÍA DE MAEZTU IEEC Institut d'Estudis Espacials de Catalunya

Advances in Remote Sensing Using the Polarimetric RO Technique

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

- **The Polarimetric RO technique**
  - Basics
  - Processing, production and products
- **Status: what do we know?**
- **Current work on forward operator**

Advances in Remote Sensing Using the Polarimetric RO Technique

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

- **The Polarimetric RO technique**
  - Basics
  - Processing, production and products
- **Status: what do we know?**
- **Current work on forward operator**

Next talk by Estel Cardellach:

Roadmap towards full exploitation of PRO observations

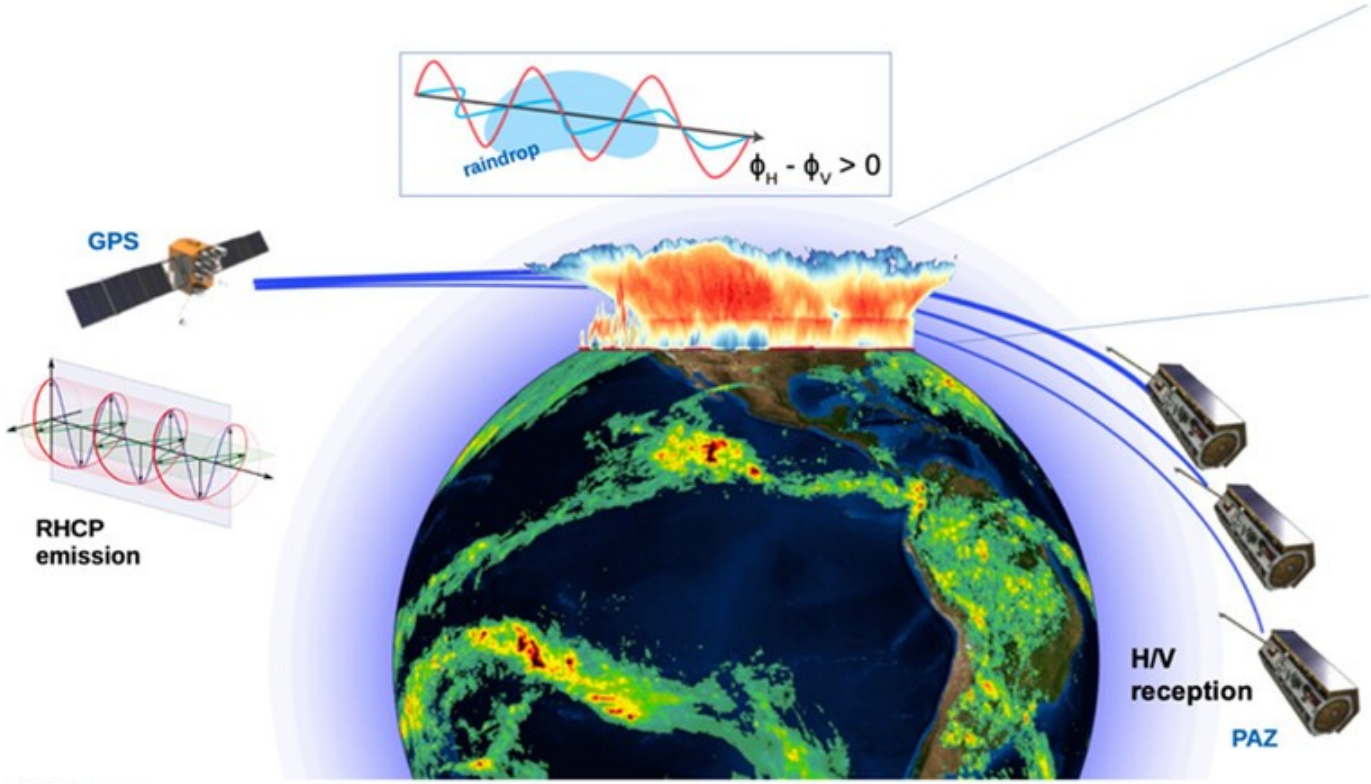
Advances in Remote Sensing Using the Polarimetric RO Technique

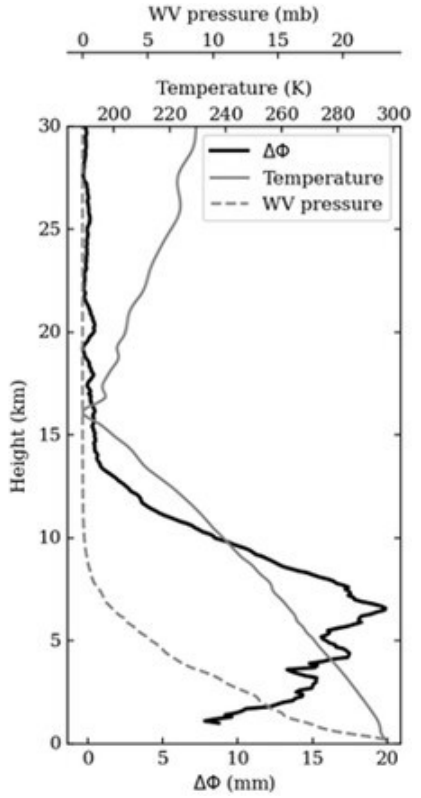
- **The Polarimetric RO technique**
  - Basics
  - Processing, production and products
- **Status: what do we know?**
- **Current work on forward operator**

Polarimetric RO Technique

- To collect the RO rays 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

ϕ: excess phase





Simultaneous retrieval of vertical profiles of thermodynamics (standard products) and differential phase shift ($\Delta\phi$, polarimetric products)

Polarimetric RO Technique

ROHP-PAZ experiment: proof of concept experiment aboard PAZ satellite (launched in 2018)

- 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 standard RO profiles be recovered from GNSS PRO data?

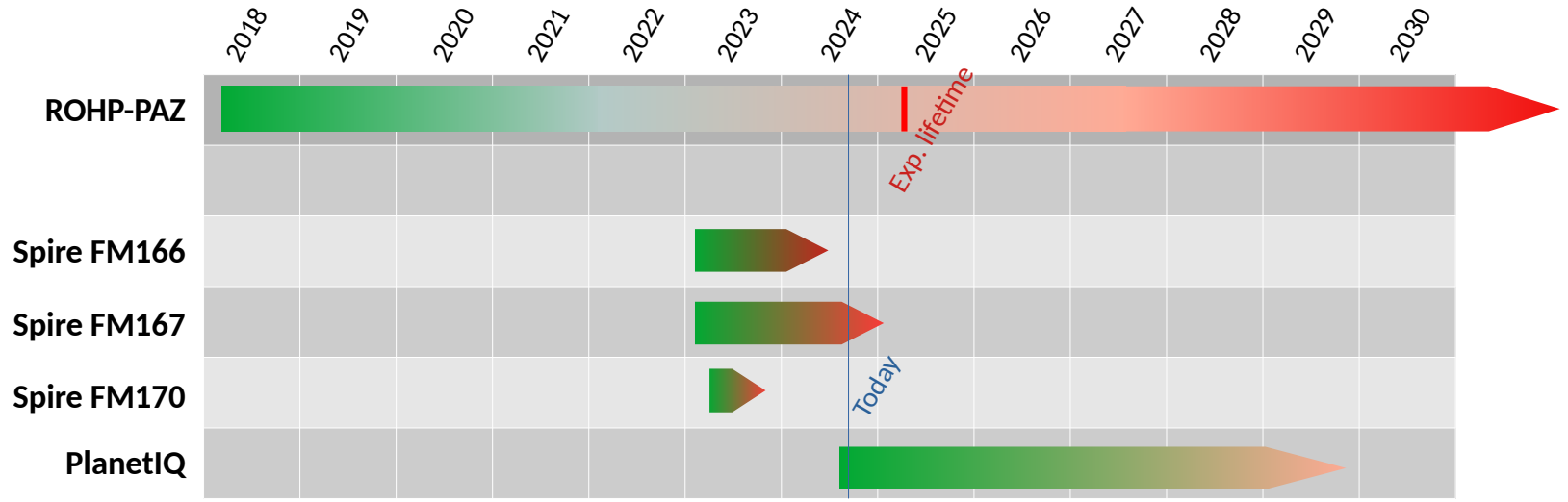
Polarimetric RO Technique

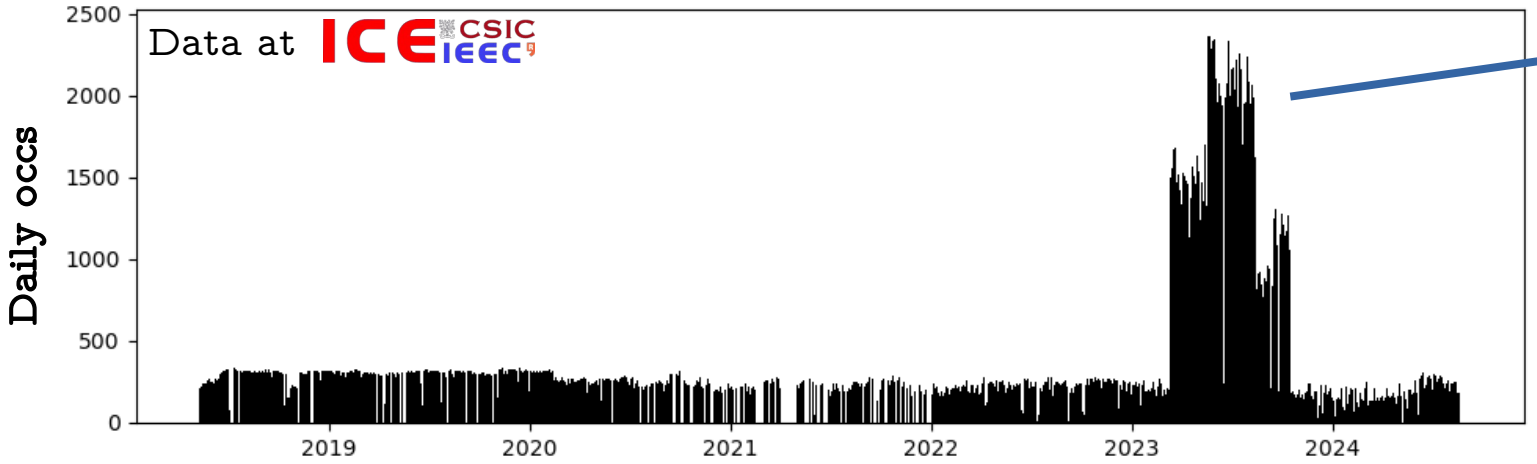
ROHP-PAZ experiment: proof of concept experiment aboard PAZ satellite (launched in 2018)

Soon after the launch

- 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 standard RO profiles be recovered from GNSS PRO data?

Polarimetric RO Technique

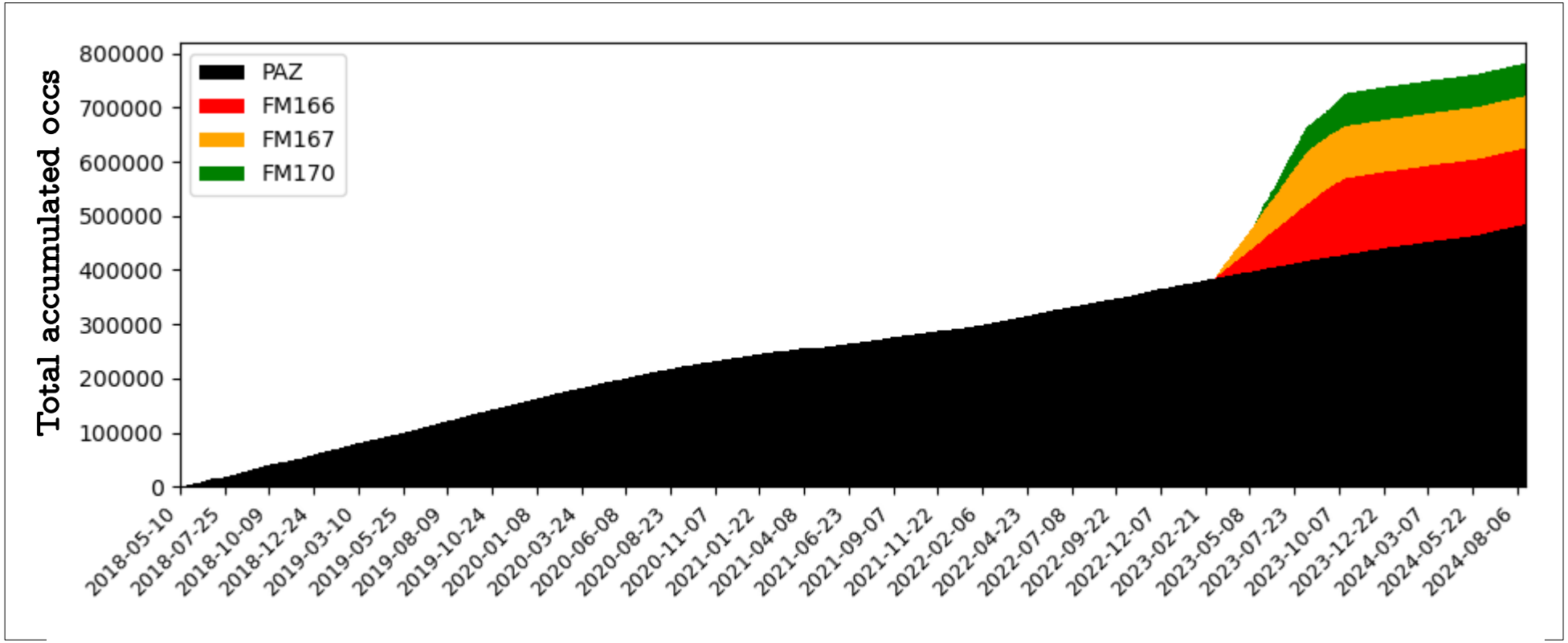




Spire data
(available to European researchers
through ESA third party mission (TPM))
(May – Nov 2023)

PAZ : ~200 occs/day
PAZ + 3 Spire nano-sats : ~2400 occs/day

Polarimetric RO Technique



Spire
>300.000 occs

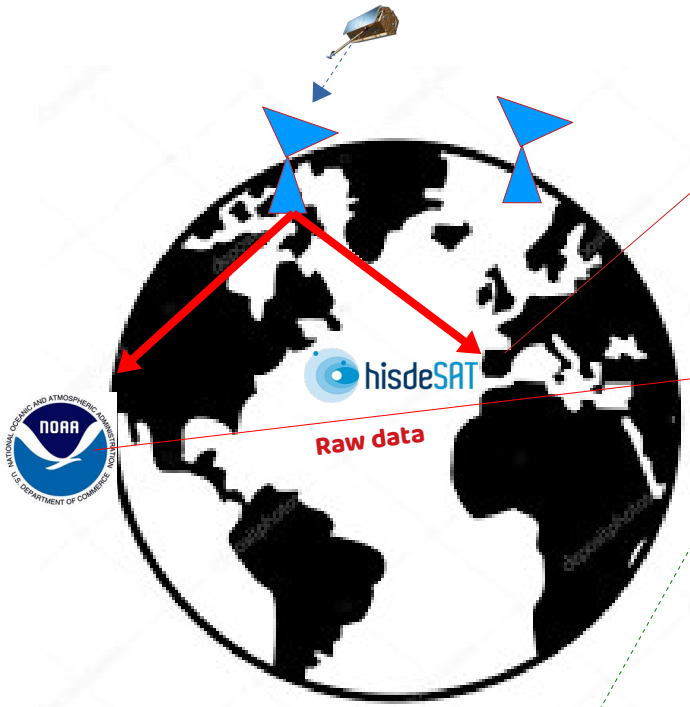
ROHP-PAZ
~500.000 occs

>800.000
pro obs

ROHP-PAZ data flow

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU



Raw data

ICE CSIC IEEC

Raw data

Level 1 data

NASA JPL Jet Propulsion Laboratory

Raw data processing:

data Level 1

Standard RO data Level 2:

H, V

separately

UCAR

Raw data processing:

data Level 1

Standard RO data Level 2

H,V → **combined**

conPhs

rohp-PAZ

polarimetric processing code

Global Telecommunication System

WMO

NRT assimilation into NWP

standard RO data (H, V combined) (data.cosmic.ucar.edu)

Polarimetric RO data (paz.ice.csic.es)

standard (H and V separately) and Polarimetric RO data (genesis.jpl.nasa.gov)

Polarimetric RO processing ICE-CSIC

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

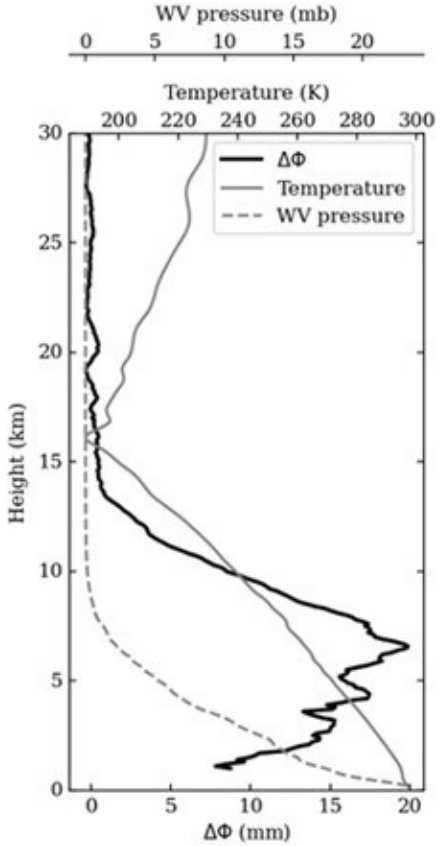
Filetype: resPrf
Processing version: V07
Available at *paz.ice.csic.es*.
DOI: https://doi.org/10.20350/digitalCSIC/16137

resPrf_PAZ1.YYYY.DOY.HH.MM.GXX_proc.vers_V07 {

- group: profiles
  - variables: height, dphi, temp, pres, vp, ref
- group: rays
  - variables: lat, lon, hei
- group: coll
  - group: precipitation
    - variables: precipitation
  - group: irtb
    - variables: irtemp
  - group: GPM radiometer
    - group Swaths
      - variables: channels

wetPf2
UCAR

Collocated vertical profiles of $\Delta\phi$ and thermodynamics



Polarimetric RO processing ICE-CSIC

Institute of Space Sciences

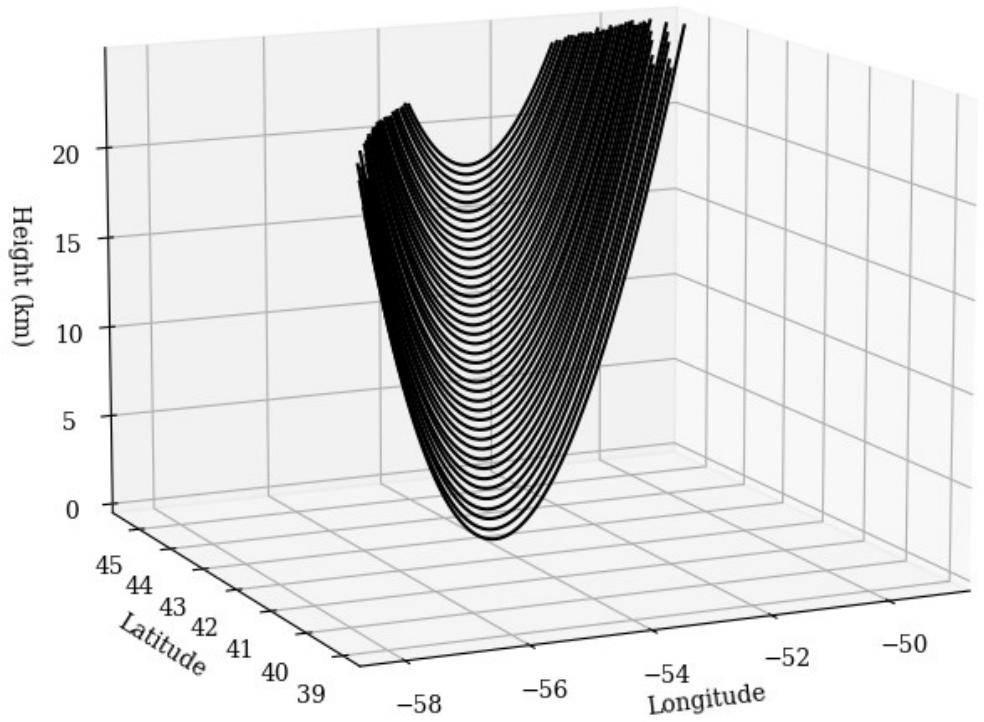
EXCELENCIA MARÍA DE MAEZTU

Filetype: resPrf
Processing version: V07
Available at *paz.ice.csic.es*.
DOI: https://doi.org/10.20350/digitalCSIC/16137

resPrf_PAZ1.YYYY.DOY.HH.MM.GXX_proc.vers_V07 {

- group: profiles
  - variables: height, dphi, temp, pres, vp, ref
- group: rays
  - variables: lat, lon, hei
- group: coll
  - group: precipitation
    - variables: precipitation
  - group: irtb
    - variables: irtemp
  - group: GPM radiometer
    - group Swaths
      - variables: channels

Ray trajectories obtained using ray-tracing technique



Polarimetric RO processing ICE-CSIC

Institute of Space Sciences

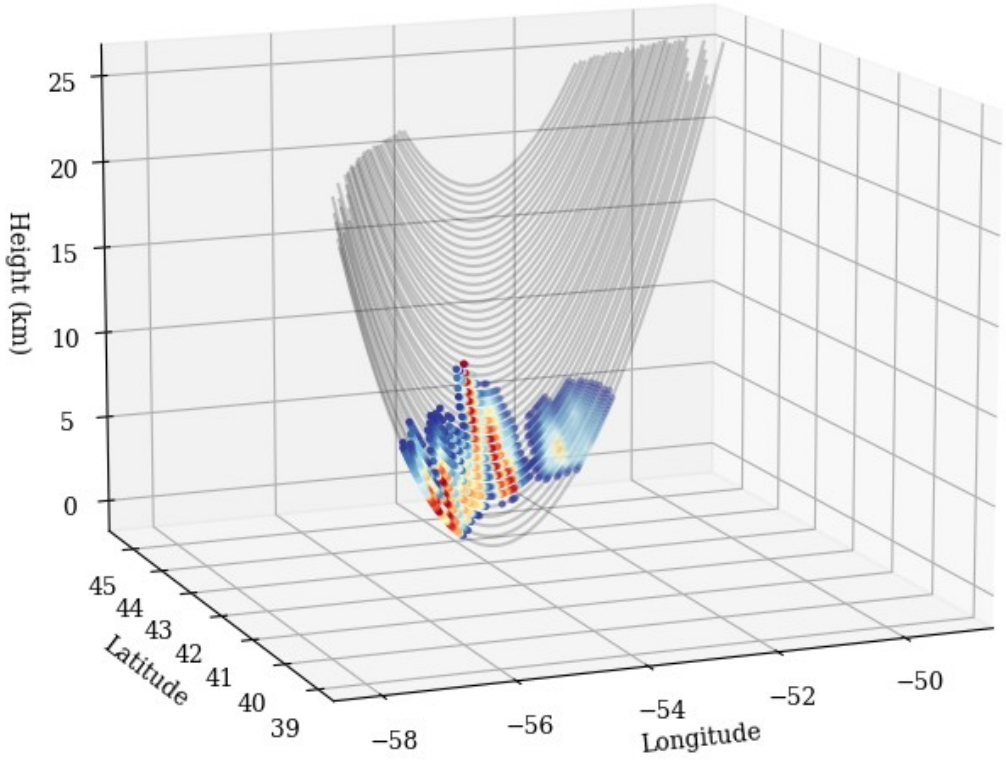
EXCELENCIA MARÍA DE MAEZTU

Filetype: resPrf
Processing version: V07
Available at *paz.ice.csic.es*.
DOI: https://doi.org/10.20350/digitalCSIC/16137

resPrf_PAZ1.YYYY.DOY.HH.MM.GXX_proc.vers_V07 {

- group: profiles
  - variables: height, dphi, temp, pres, vp, ref
- group: rays
  - variables: lat, lon, hei
- group: coll
  - group: precipitation
    - variables: precipitation
  - group: irtb
    - variables: irtemp
  - group: GPM radiometer
    - group Swaths
      - variables: channels

Ray trajectories obtained using ray-tracing technique



Interpolation of 3D model fields

Polarimetric RO processing ICE-CSIC

Institute of Space Sciences

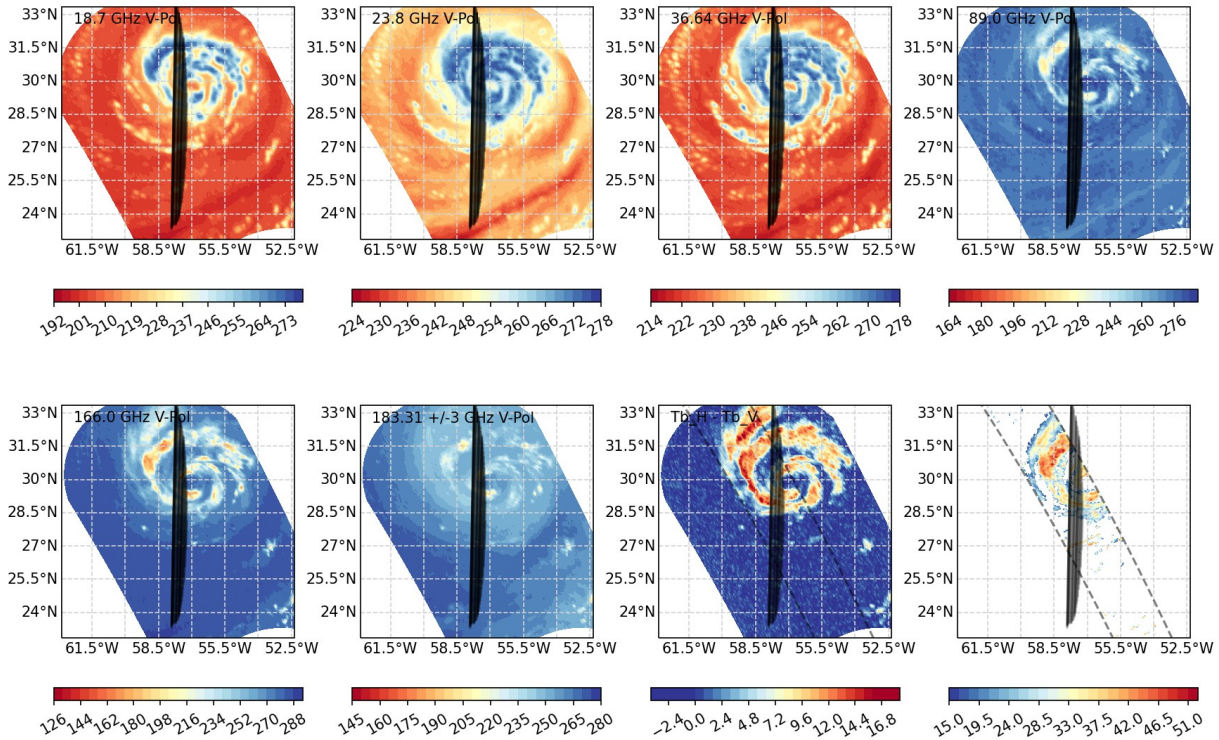
EXCELENCIA MARÍA DE MAEZTU

Filetype: **resPrf**
Processing version: V07
Available at *paz.ice.csic.es*.
DOI: https://doi.org/10.20350/digitalCSIC/16137

resPrf_PAZ1.YYYY.DOY.HH.MM.GXX_proc.vers_V07 {

- group: profiles
  - variables: height, dphi, temp, pres, vp, ref
- group: rays
  - variables: lat, lon, hei
- group: coll
  - group: precipitation
    - variables: precipitation
  - group: irtb
    - variables: irtemp
  - group: GPM radiometer
    - group Swaths
      - variables: channels

Context!



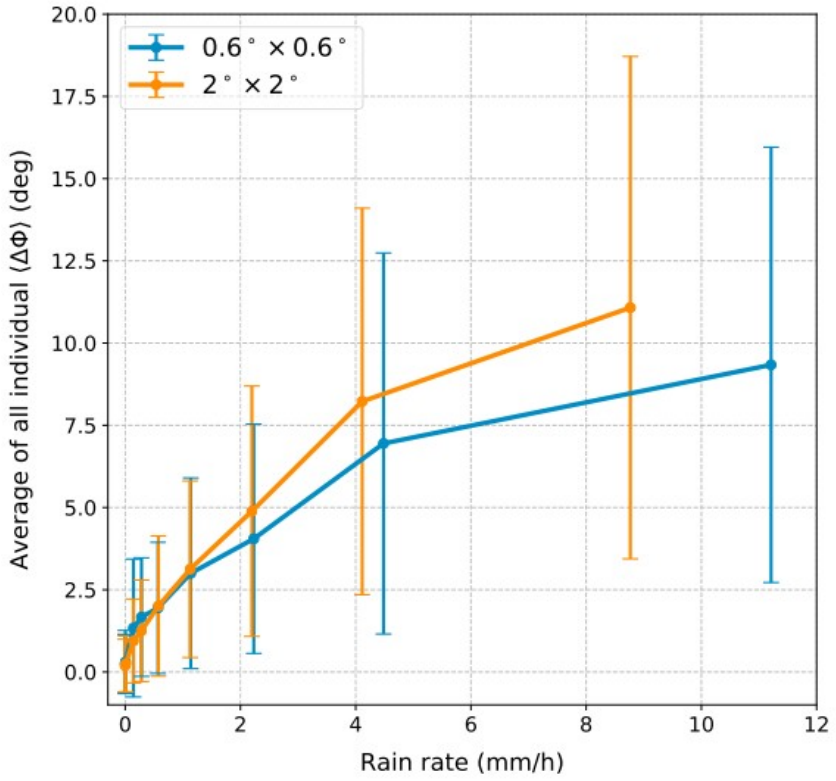
Advances in Remote Sensing Using the Polarimetric RO Technique

- The Polarimetric RO technique
  - Basics
  - Processing, production and products
- **Status: what do we know?**
- Current work on forward operator

Status: what do we know?

PRO is sensitive to precipitation, both presence and intensity

PAZ Δϕ increases with increasing R

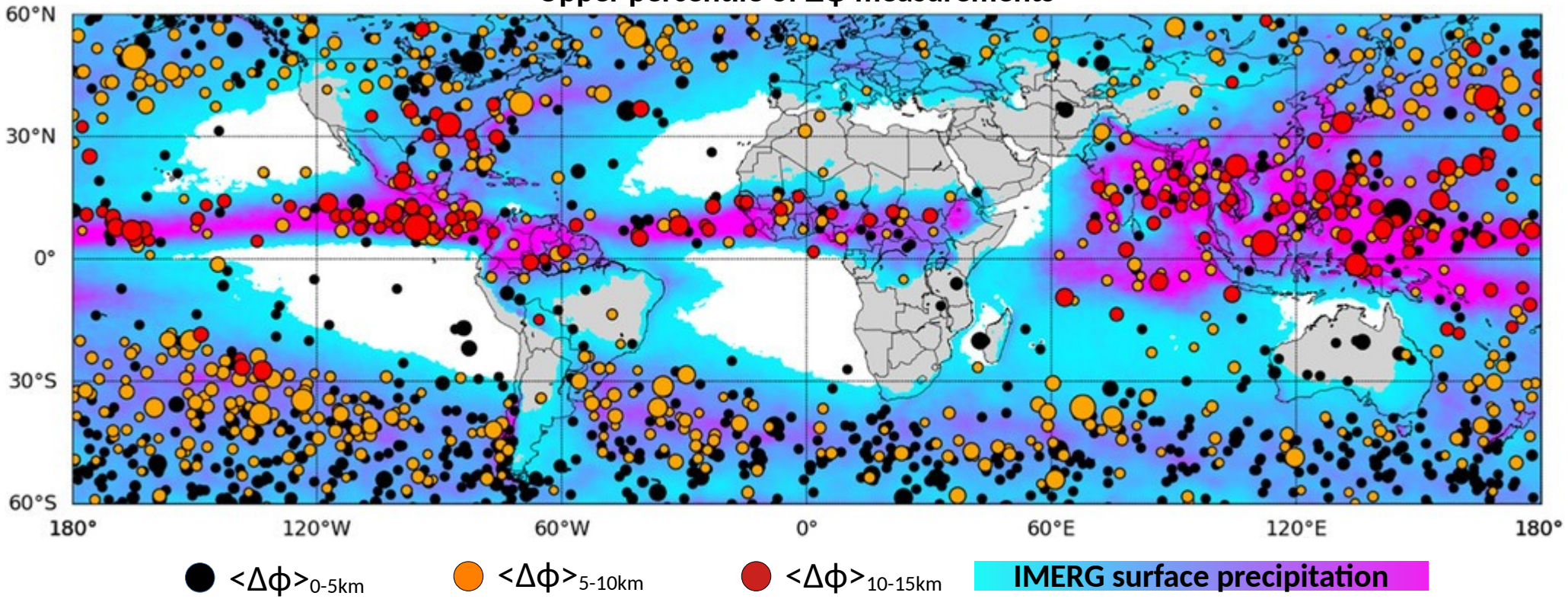


Cardellach et al. 2019, GRL, https://doi.org/10.1029/2018GL080412

Status: what do we know?

PRO captures **precipitation** patterns very well

Upper percentile of Δϕ measurements



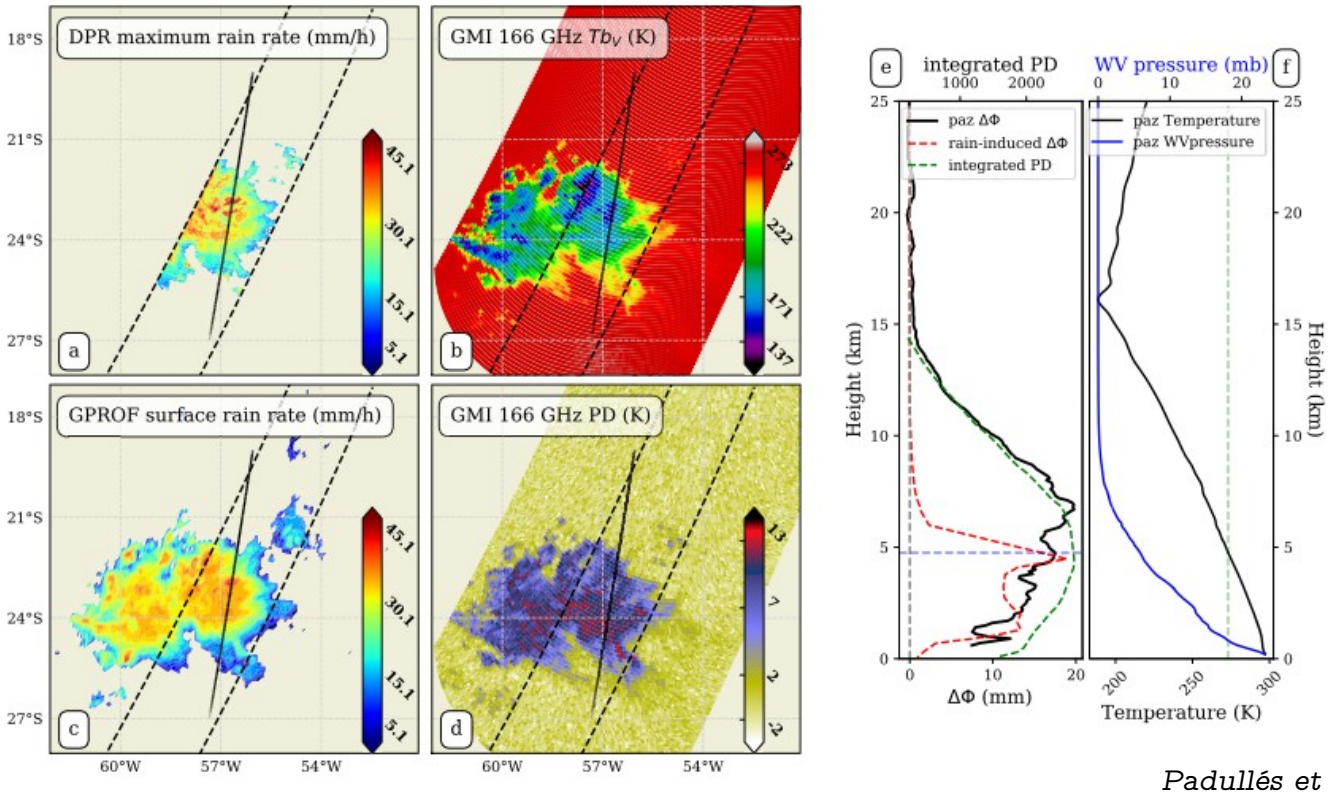
Turk et al. 2024, BAMS, https://doi.org/10.1175/BAMS-D-24-0050.1

Status: what do we know?

Institute of Space Sciences — EXCELENCIA MARÍA DE MAEZTU

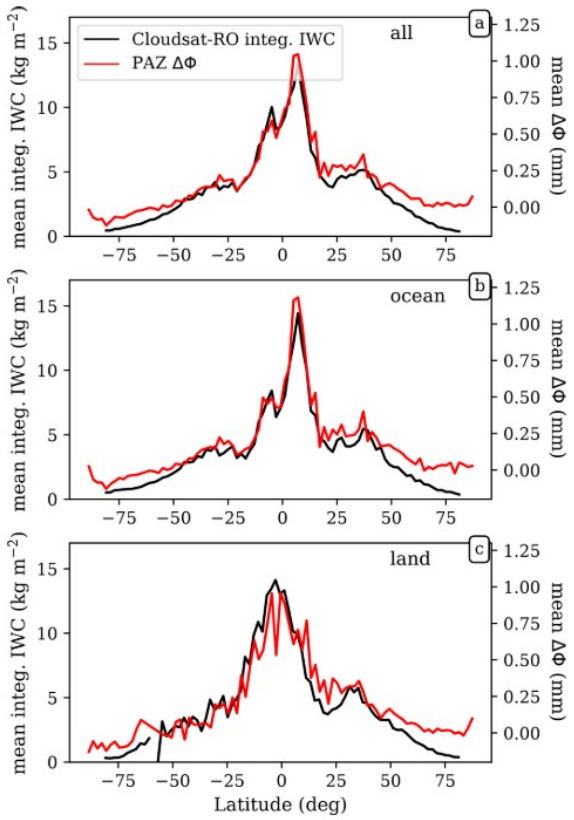
PRO is sensitive to **frozen hydrometeors** above freezing level

Coincidences with K-band radar cannot explain Δϕ measurements. Agreement is possible when we include ice/snow information



Agreement between Cloudsat IWC climatology and PAZ

@ 7km



Padullés et al. 2021, IEEE-TGRS, https://doi.org/10.1109/TGRS.2021.3065119

Padullés et al. 2023, ACP, https://doi.org/10.5194/acp-23-2199-2023

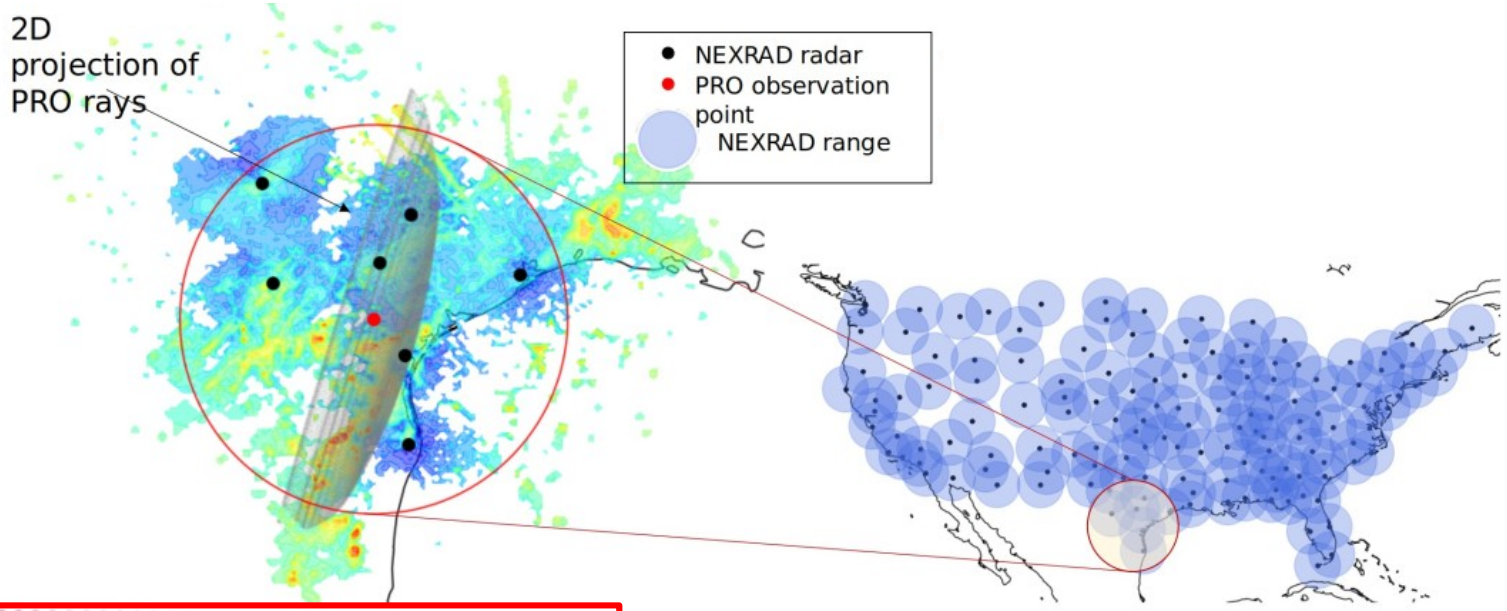
Status: what do we know?

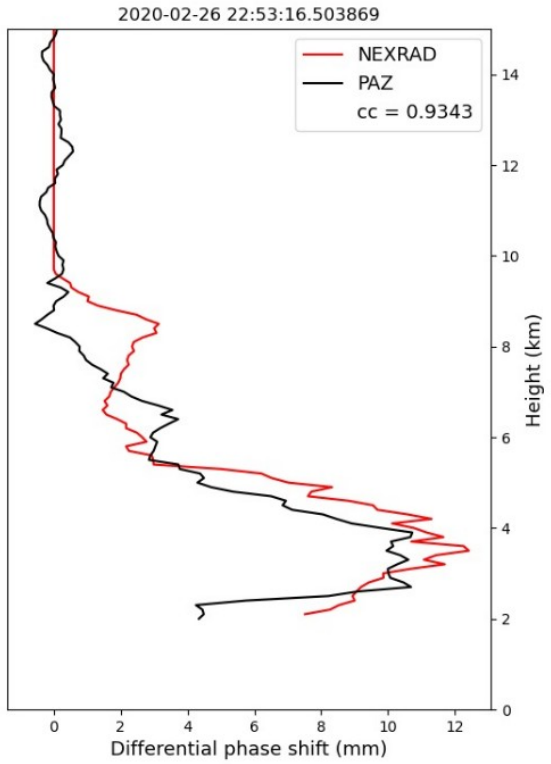
Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

Validation of **PRO vertical structure** using NEXRAD polarimetric radars

Agreement between vertical profiles of Δϕ obtained with PAZ and Δϕ recreated from K_{dp} measurements from NEXRAD polarimetric radars





*Poster by **Antía Paz**, **#20-A**:*
Validation and sensitivity analysis of the Polarimetric Radio Occultation technique

Paz et al. 2024, Remote Sensing, https://doi.org/10.3390/rs16071118

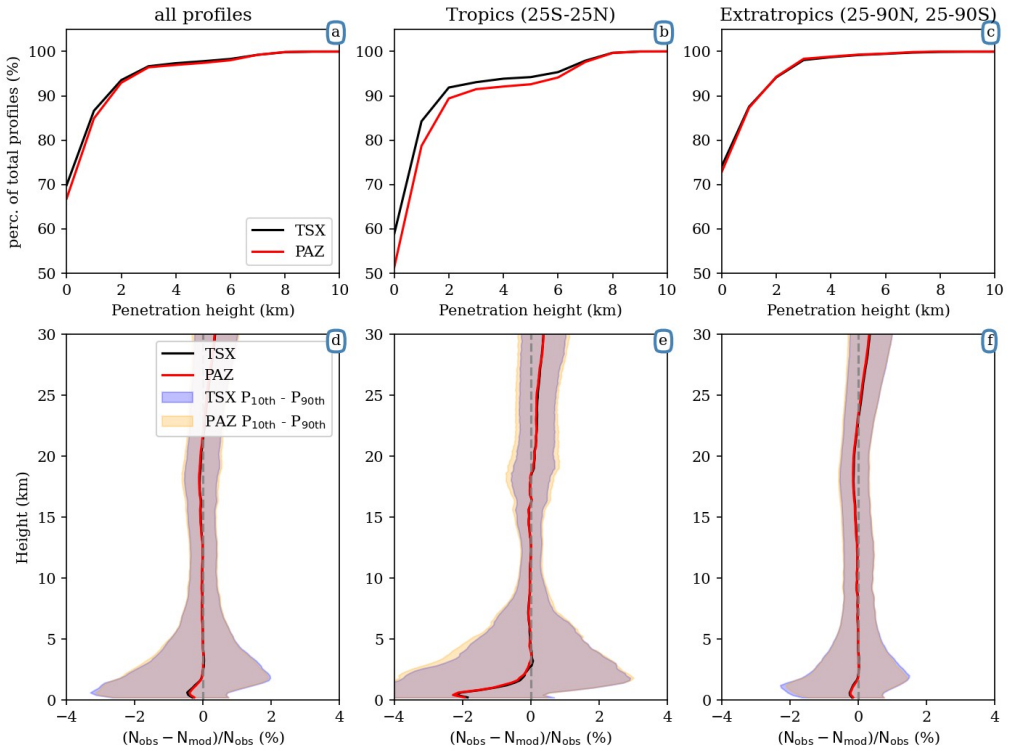
Status: what do we know?

Institute of Space Sciences

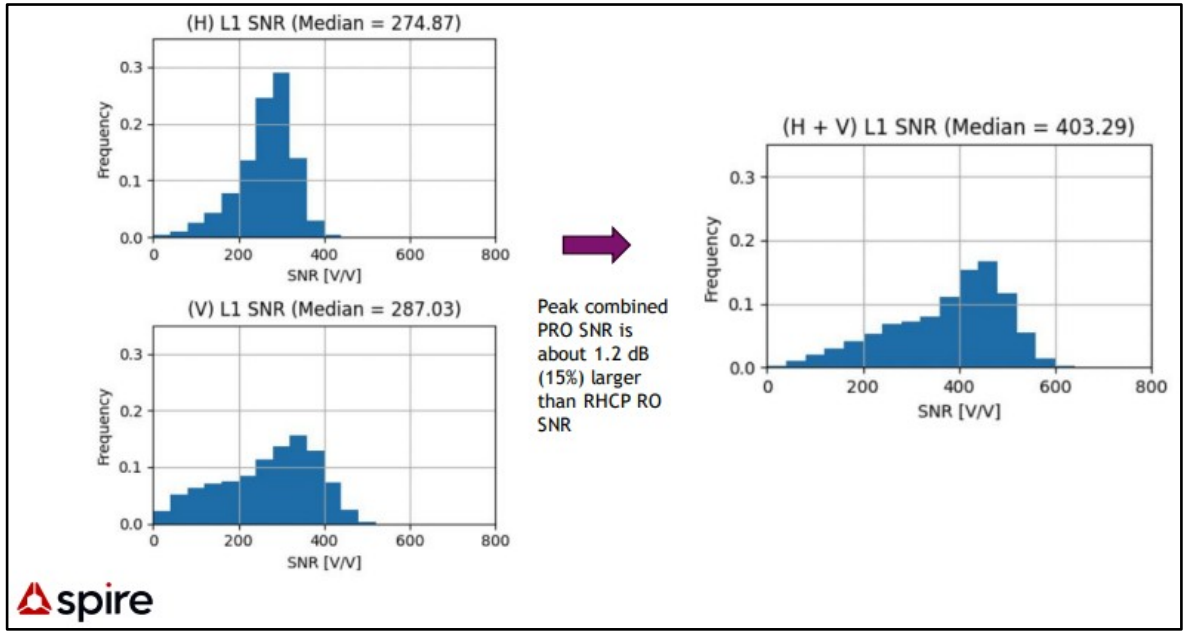
EXCELENCIA MARÍA DE MAEZTU

Standard RO products from PRO antennae are of **equivalent quality**

Comparison with ECMWF of refractivity profiles obtained with PAZ and those from TSX for the same time period



Combined H + V SNR from Spire's PRO antenna is larger than Spire's RO RHCP antenna SNR



Nguyen, V., et al. 2023, 2nd PAZ Polarimetric Radio Occultations User Workshop

Padullés et al. 2024, ESSD, https://doi.org/10.5194/essd-2024-150

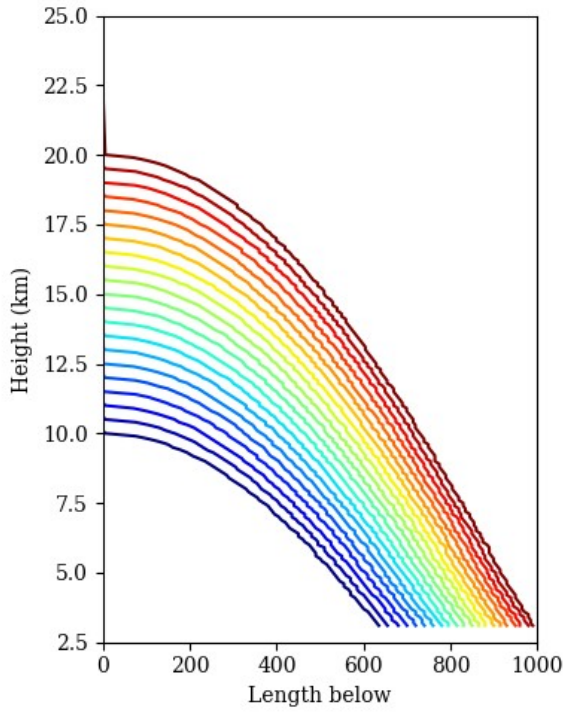
Status: what do we know?

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

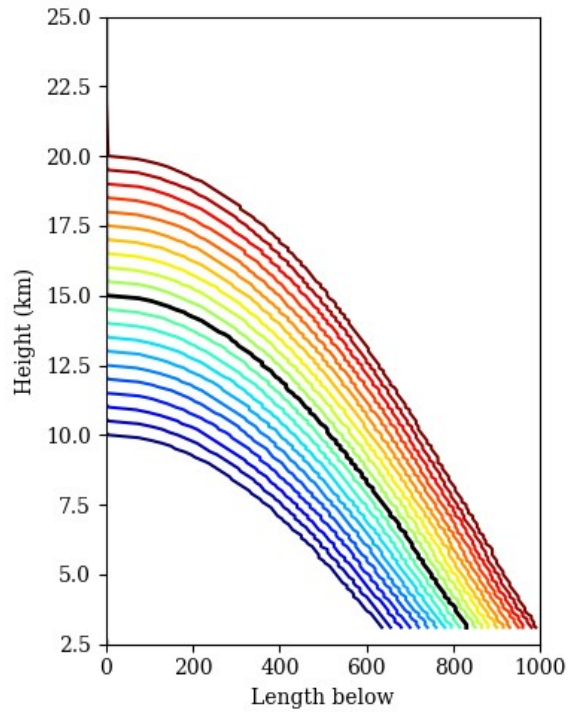
PRO Δϕ products have large along-track **horizontal resolution**

Everything present along the ray-path contributes equally to Δϕ



Assuming a height at which clouds may be present, we can compute the theoretical (maximum) horizontal resolution

If we can know the cloud top height (using Δϕ or external information), we can reduce the maximum horizontal resolution



Padullés et al. 2024, ESSD, https://doi.org/10.5194/essd-2024-150

Advances in Remote Sensing Using the Polarimetric RO Technique

- The Polarimetric RO technique
  - Basics
  - Processing, production and products
- Status: what do we know?
- **Current work on forward operator**

Forward operator

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

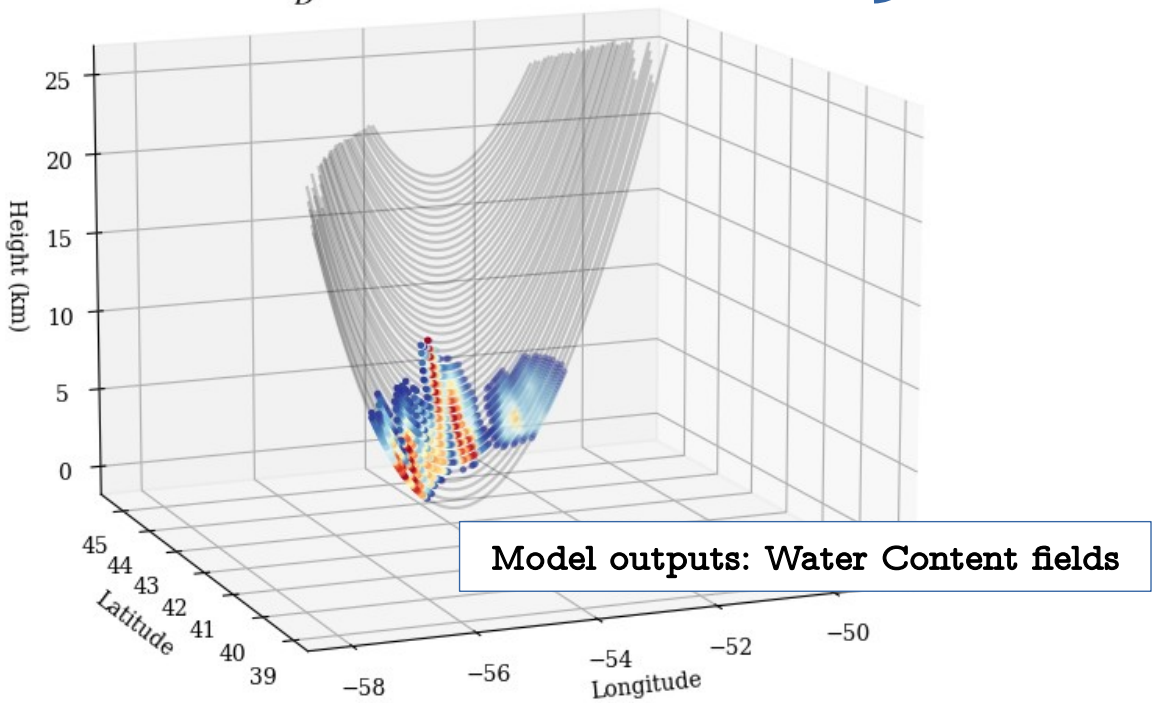
$$\Delta\phi^{atm} = \int_L K_{dp}(l)dl$$

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

$$\mathrm{WC} = \frac{\pi}{6}\rho_{w,i} \int_D D^3 N(D)\mathrm{d}D$$

Simplified approximation: K_{dp} = ½ C ρ (1-ar) WC

(e.g. Padullés et al. 2021, IEEE-TGRS
Hotta et al. 2024, AMT)



Model outputs: Water Content fields

Study that uses this approximation

Poster by Shu-Ya Chen, #18-B:
Comparison of WRF simulations and Polarimetric RO Data for Hydrometeors around Tropical Cyclones

Padullés et al. 2021, IEEE-TGRS, https://doi.org/10.1109/TGRS.2021.3065119
Hotta et al. 2024, AMT, https://doi.org/10.5194/amt-17-1075-2024

Forward operator

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

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

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

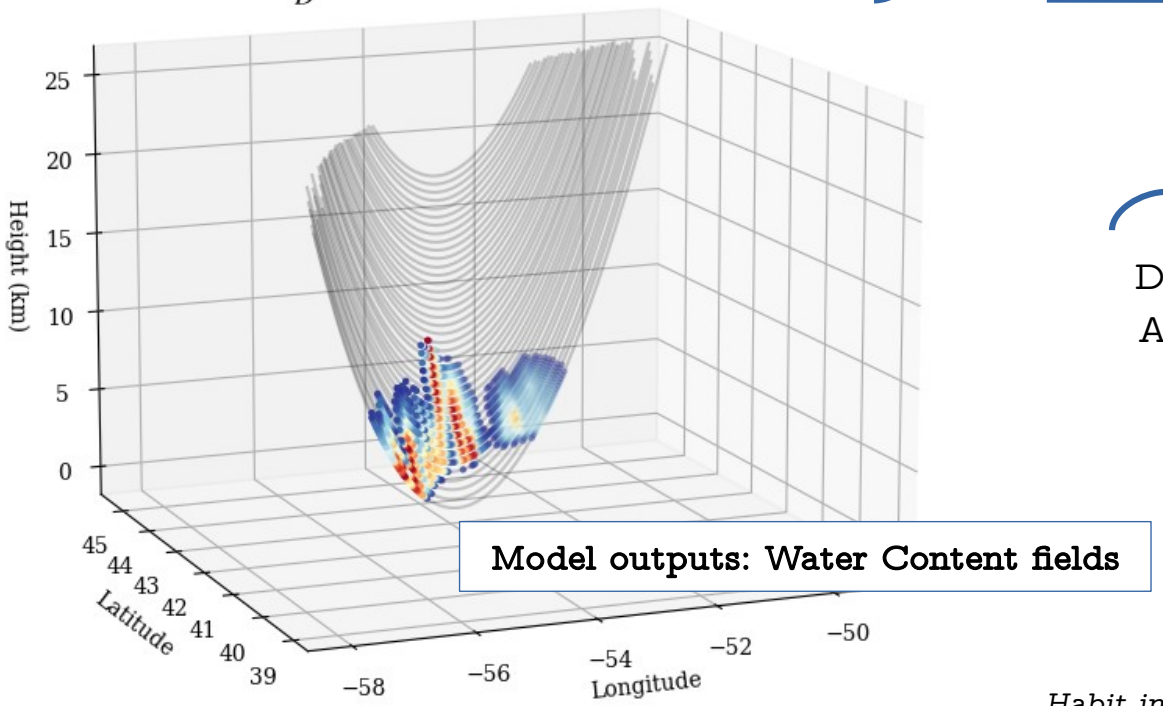
$$\mathrm{WC} = \frac{\pi}{6}\rho_{w,i}\int_D D^3 N(D)\mathrm{d}D$$

Simplified approximation: K_{dp} = ½ C ρ (1-ar) WC

(e.g. Padullés et al. 2021, IEEE-TGRS
Hotta et al. 2024, AMT)

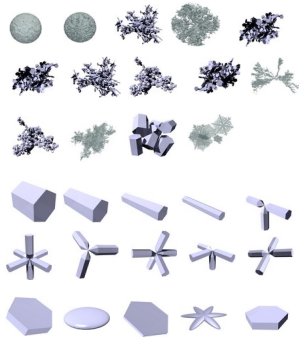
$$K_{dp} = \frac{\lambda^2}{2\pi}\int \Re\{f_H(D) - f_V(D)\}\, N(D)dD$$

$$\mathrm{WC} = \frac{\pi}{6}\rho_{w,i}\int_D D^3 N(D)\mathrm{d}D$$



Model outputs: Water Content fields

Discrete Dipole Approximation Forward scattering

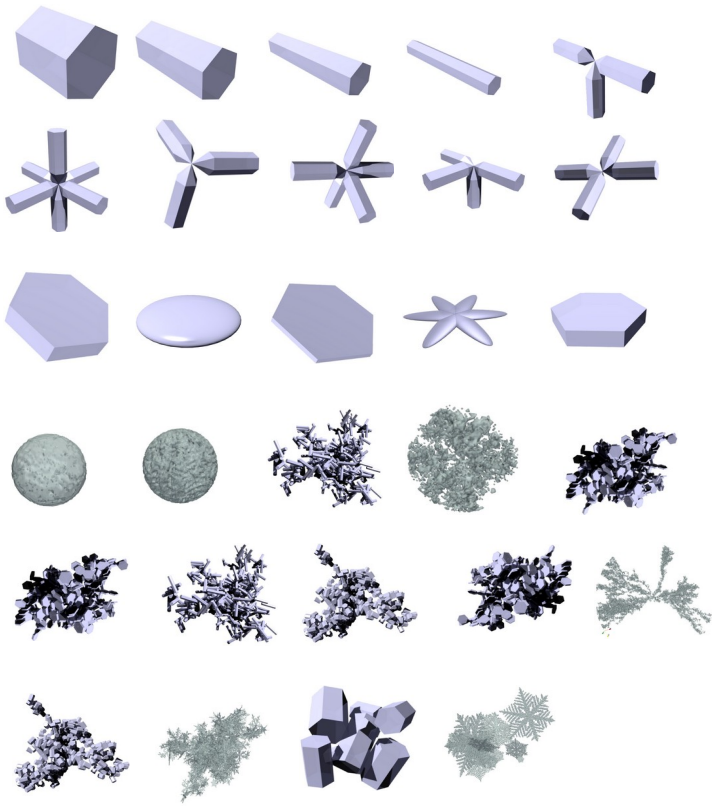


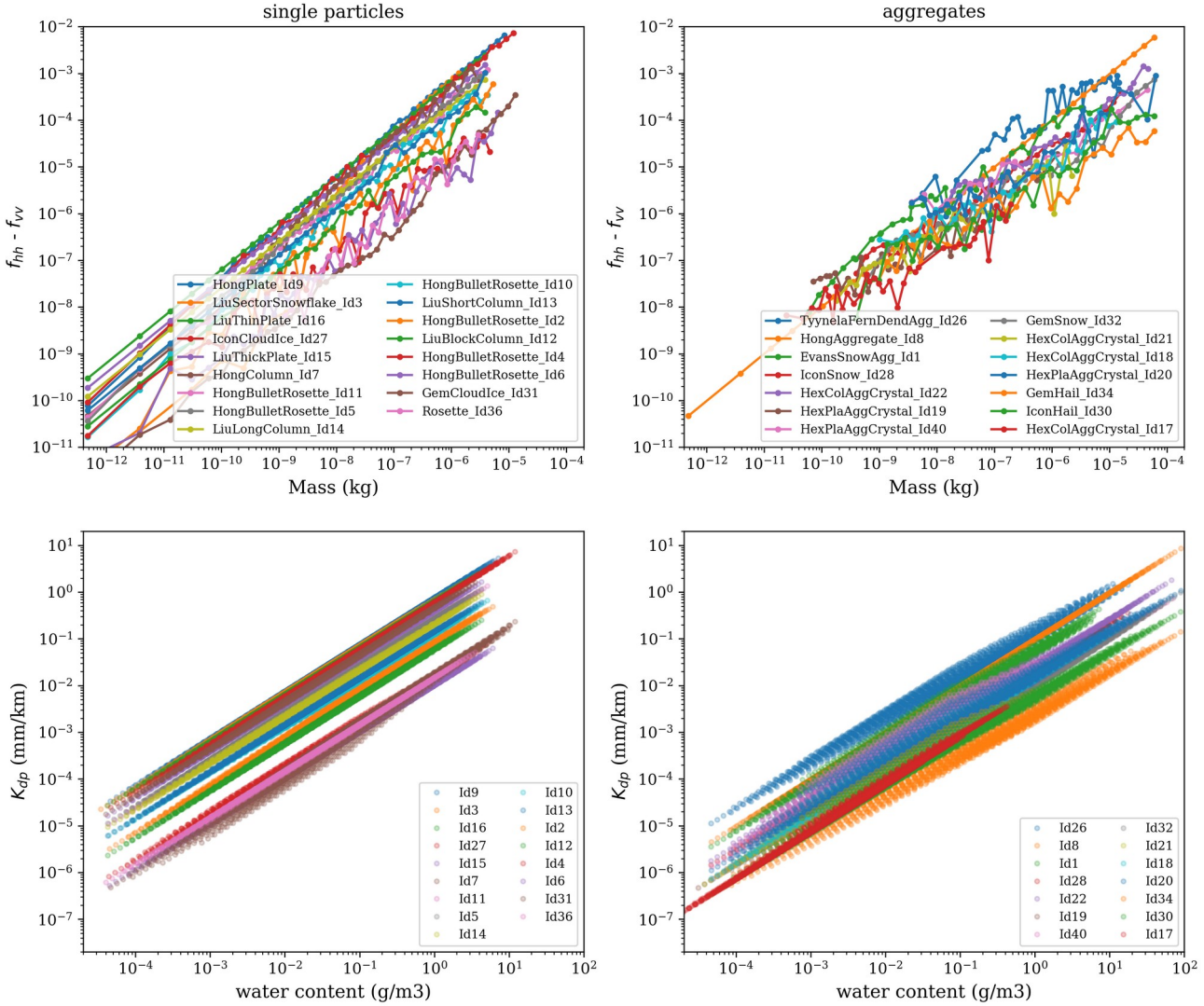
- Realistic shapes
- Consistent with Radiative Transfer approaches like RTTOV an CRTM

Habit images from: Eriksson et al. 2018, ESSD, https://doi.org/10.5194/essd-10-1301-2018

Forward operator

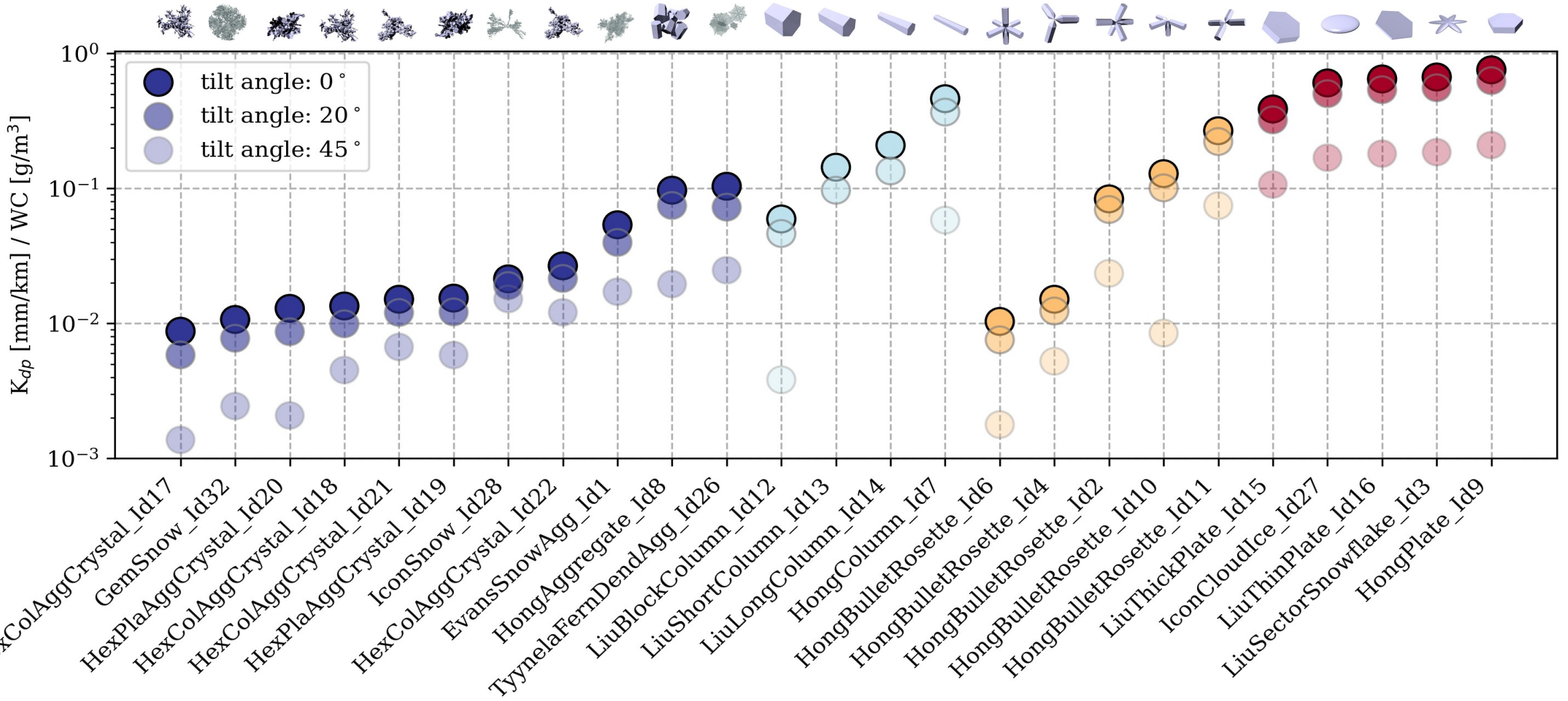
Particles from the ARTS database





Habit images from: Eriksson et al. 2018, ESSD, https://doi.org/10.5194/essd-10-1301-2018

Forward operator



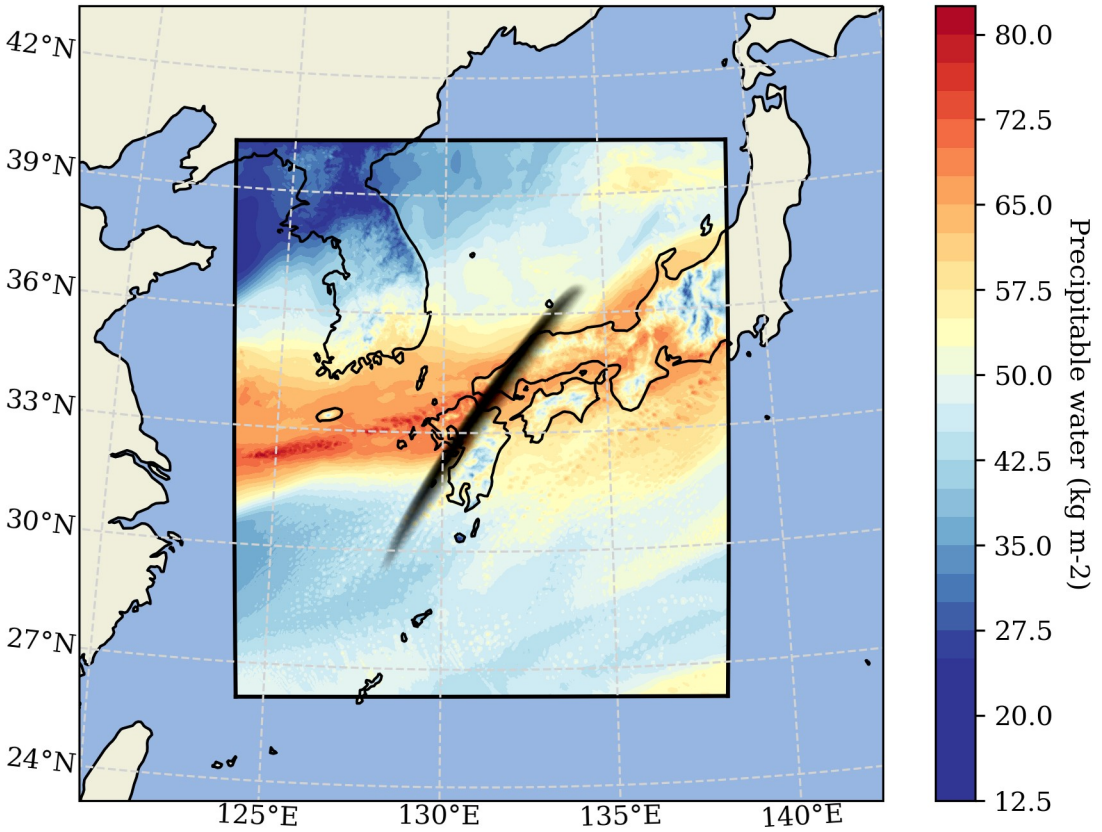
Habit images from: Eriksson et al. 2018, ESSD, https://doi.org/10.5194/essd-10-1301-2018

Forward operator

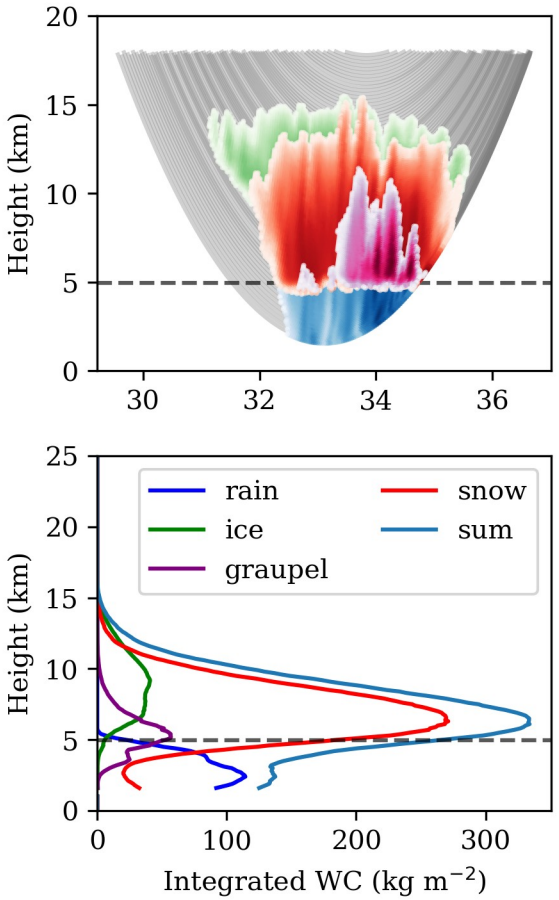
Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

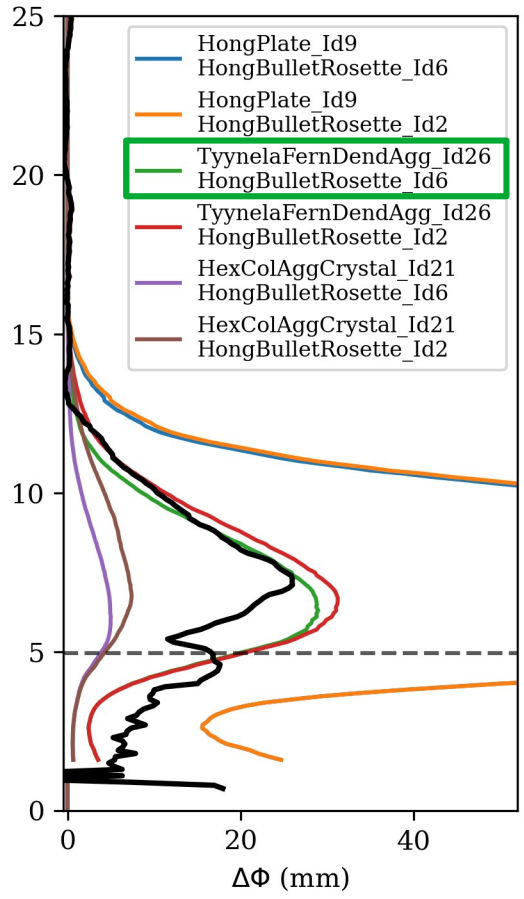
WRF simulation: inner domain
Goddard microphysics scheme, 3 km x 3 km
2019-08-27 23:00



Interpolation of WC into RO rays and integration along the rays



Simulated vs observed $\Delta\phi$



Conclusions

- **The very basics of Polarimetric RO technique**: collect GNSS signals using two linearly polarized antennae (H, V) →

  Bending + $\Delta\phi$ → Precipitation information + thermodynamics

- **Status:**
  - PRO works, even 'better' than hypothesized
  - Sensitivity to heavy rain, to frozen hydrometeors, with no (or little) degradation of standard products
  - More missions collecting PRO, more products being released

- **Current work on forward operator:**
  - Approximations and simplifications provide reasonable results
  - More sophisticated methods should allow for consistency with other RT (e.g. PMW)

Thanks!

padulles@ice.csic.es

Funding: RYC2021-033309-I, PID2021-1264436OB-C22, and CEX2020-001058-M from MCIN/AEI (10.13039/501100011033), and EUMETSAT ROM SAF CDOP4. The work by authors KNW, FJT, COA and MTJ was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Plan de Recuperación, Transformación y Resiliencia

AGENCIA ESTATAL DE INVESTIGACIÓN

Financiado por la Unión Europea NextGenerationEU

CSIC

Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

IEEC Institut d'Estudis Espacials de Catalunya