Illustrative examples of GNSS PRO studies

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[3]Jet Propulsion Laboratory, California Institute of Technology (JPL), Pasadena CA, U.S.A.
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rohp-PAZ

https://paz.ice.csic.es

Contents:

PURPOSE OF THIS PRESENTATION

UNDERSTANDING PAZ DATA

APPLICATIONS RELEVANT TO CLIMATE

APPLICATIONS RELEVANT TO NWP

PURPOSE OF THIS PRESENTATION

To show illustrative examples of

- studies conducted,
- studies going on,
- ideas for potential studies

based on GNSS PRO / PAZ data.

DISCLAIMER: Please note different degree of maturity of them, some are nearly concluded, some are purely 'speculative'.

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Contents:

PURPOSE OF THIS PRESENTATION

UNDERSTANDING PAZ DATA

- **Thermodynamic profiles**
- **Understanding the polarimetric signatures; Co-locations DB**

APPLICATIONS RELEVANT TO CLIMATE

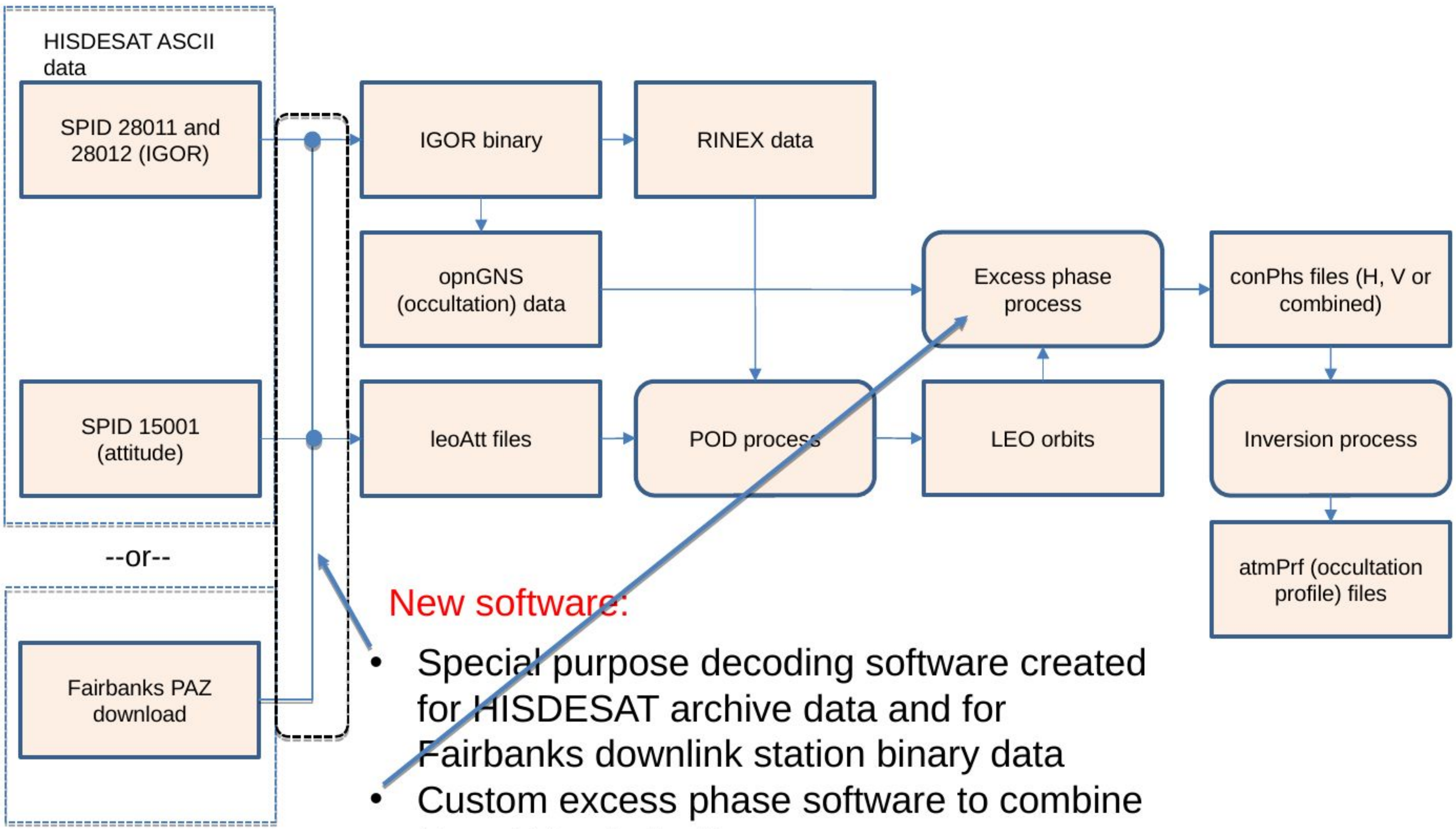
APPLICATIONS RELEVANT TO NWP

Contents

Some quick slides to discuss ‘normal’ Radio Occultation processing for Paz at UCAR.

- CDAAC dataflow
- Single polarization processing
- Combining polarizations
- Results
- Conclusion

PAZ data flow at CDAAC



New software:

- Special purpose decoding software created for HISDESAT archive data and for Fairbanks downlink station binary data
- Custom excess phase software to combine H and V polarizations

Single-polarization processing

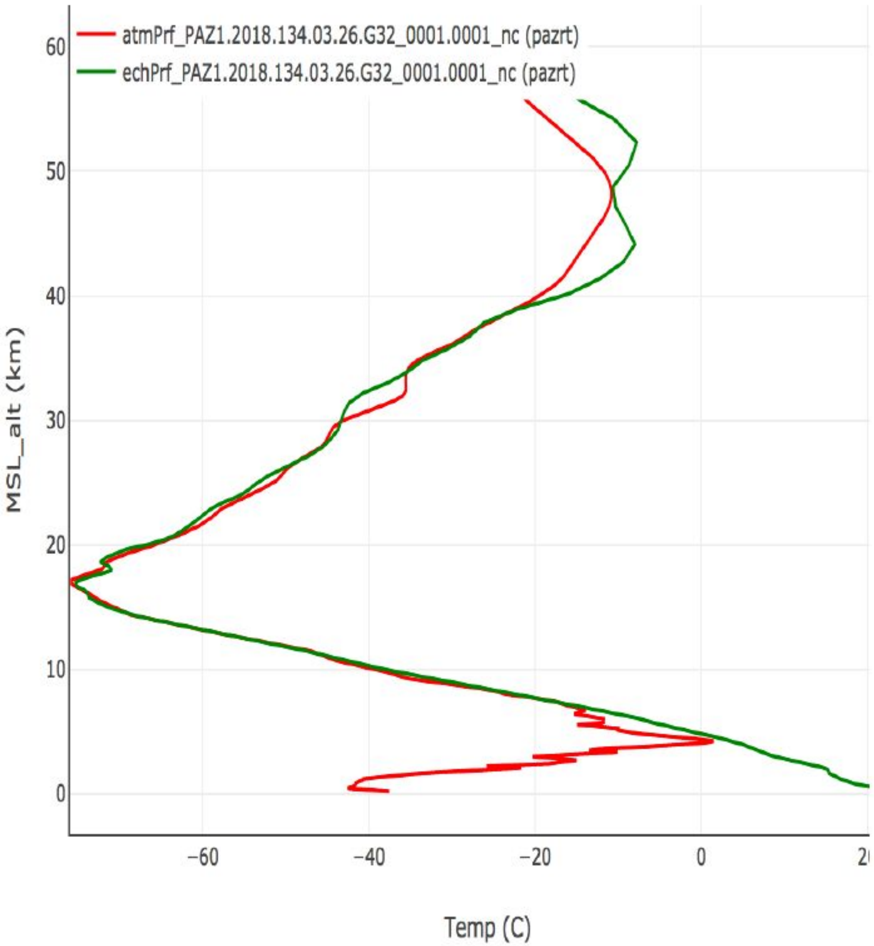
Normal RO processing

1. Start with high rate opnGns occultation data
2. Remove orbital motion (LEO and GNSS POD data), GNSS clocks (e.g. IGS products), and LEO clocks (via differencing with a high elevation (reference) satellite)
3. Compute an atmospheric Doppler model from climatology
4. Integrate this model to get a phase model, then difference it with the observed (excess) phase computed above
5. This phase angle $\Delta\theta$ is now rotating slowly enough to generate meaningful I and Q components: $I = SNR \ast \cos(\Delta\theta), Q = SNR \ast \sin(\Delta\theta)$
6. Apply navigation bits to the open-loop portion of I and Q
7. Stitch open- and closed-loop I's and Q's together
8. Compute phase via $atan2(Q, I)$
9. Fix full cycle slips by adding or subtracting 2π to minimize the difference between samples
10. Add the phase model back in to get connected excess phase
11. These connected L1 and L2 phases are then submitted to the *inversion process* to compute bending angle, refractivity, and finally temperature and pressure profiles. This same inversion process is used by all other missions.

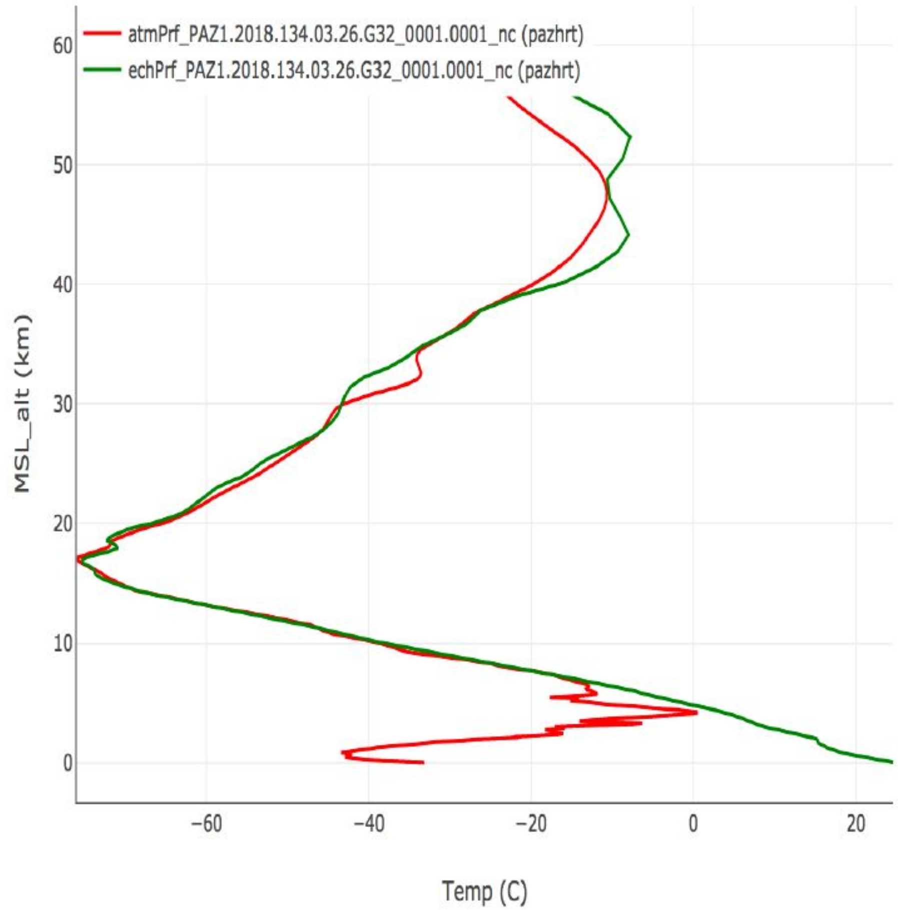
V and H compared

Single-polarization processing generates reasonable results

Vertical

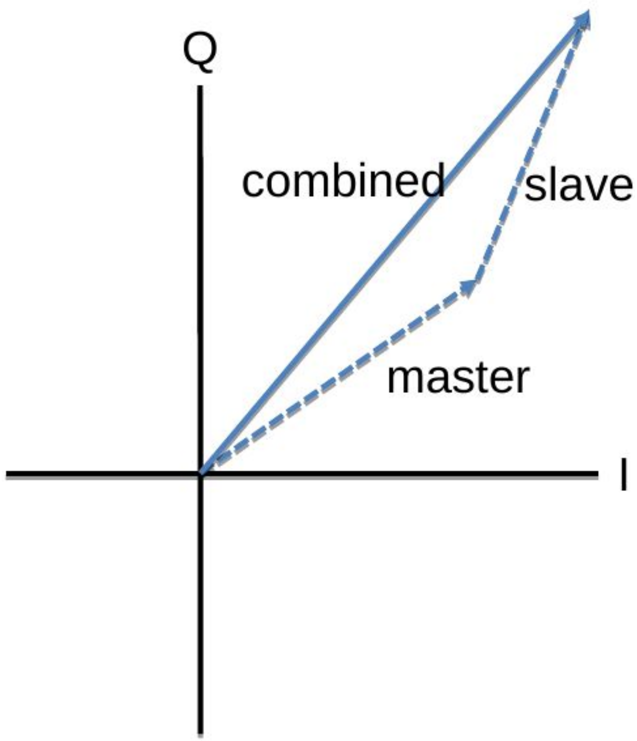


Horizontal



Dual polarization processing via vector sum of I and Q

1. Determine a 'master' polarization for this occultation. We use higher SNR to choose between H and V
2. Compute separate Horizontal and Vertical I and Q values as in the single-polarization example
3. Determine the phase alignment between H and V
4. Line the I's and Q's up and use the 'master' to fix ½ cycle slips in the 'slave'
5. Find the point at which the slave polarization signal descends into noise. This is the point at which to stop the vector combination
6. Perform a vector sum of the lined up I and Q values from the master and slave: $I = I_s + I_m$, $Q = Q_s + Q_m$
7. Assemble the combined excess phase (as in steps 9-11 in the single polarization processing)
8. Compute the SNR of the combined signal as $\frac{\sqrt{I^2+Q^2}}{\sqrt{2}}$ (assumes equal noise on H and V channels)

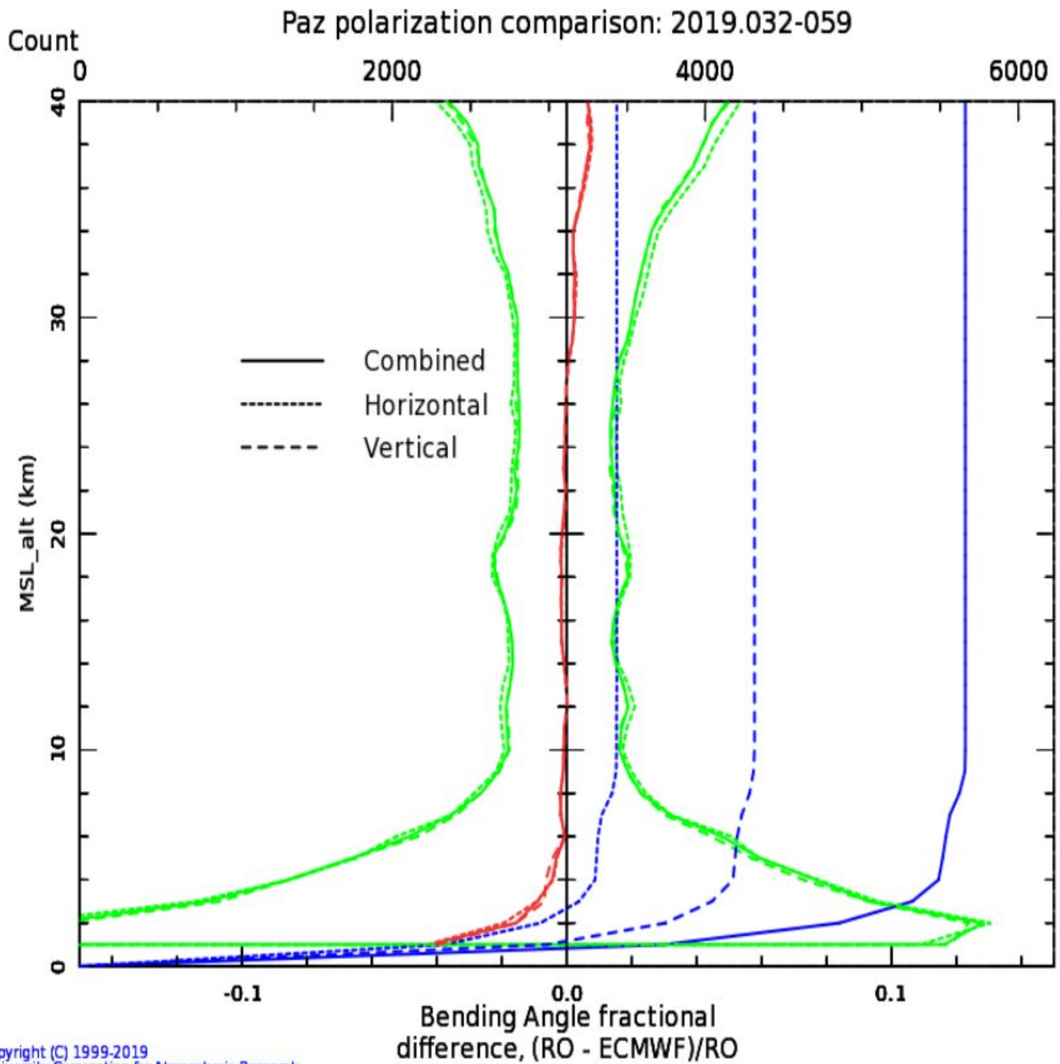


V/H combination results

Combined processing results in good statistics compared with ECMWF.

The combination results in much higher occultation counts compared with processing H or V polarization separately.

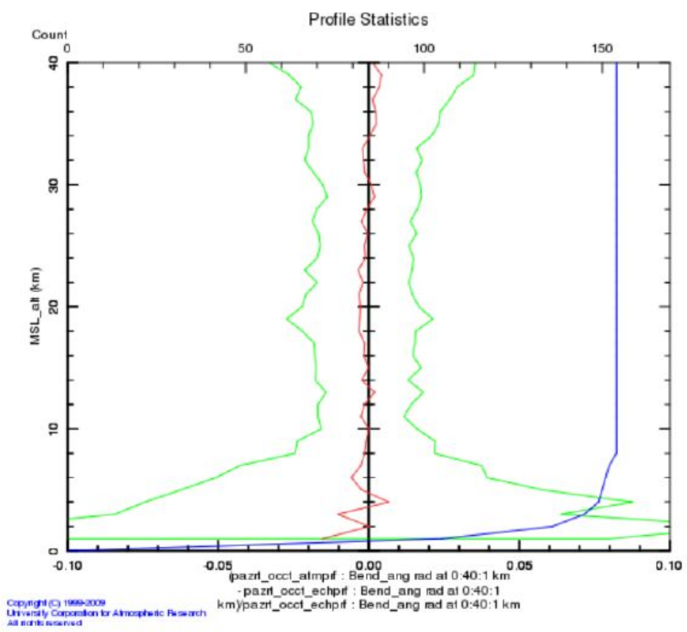
Polarization	Good occultation count
Vertical	4390
Horizontal	3493
Combined	5750



Operational Paz processing

- Fairbanks data for PAZ downlinked and processed at CDAAC since March 2019
- Near real-time processing implemented
- Leveraging COSMIC-2 data processing center infrastructure
- UCAR/CDAAC PAZ products are being provided to the NOAA Product Distribution and Access (PDA) system since July 2019
- PAZ products now on GTS

Constraints applied: (pazrt_occt_atmprf.bad = 0) AND (pazrt_occt.yrdoy = 2020100)



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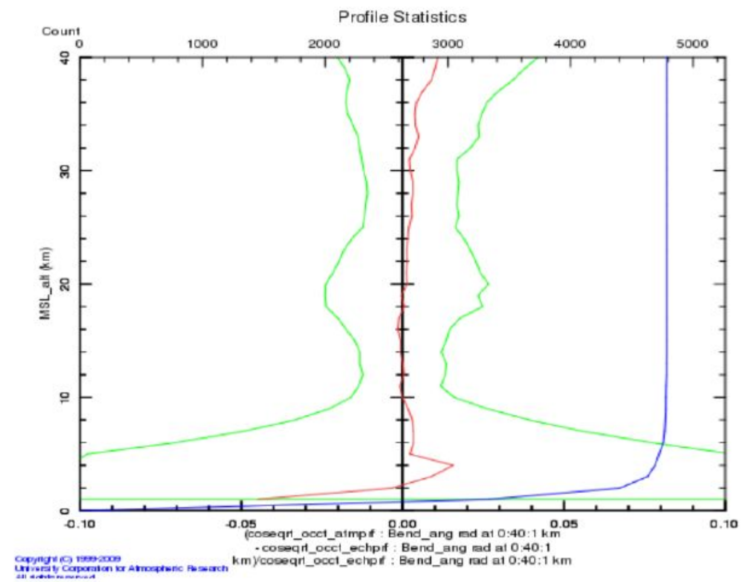

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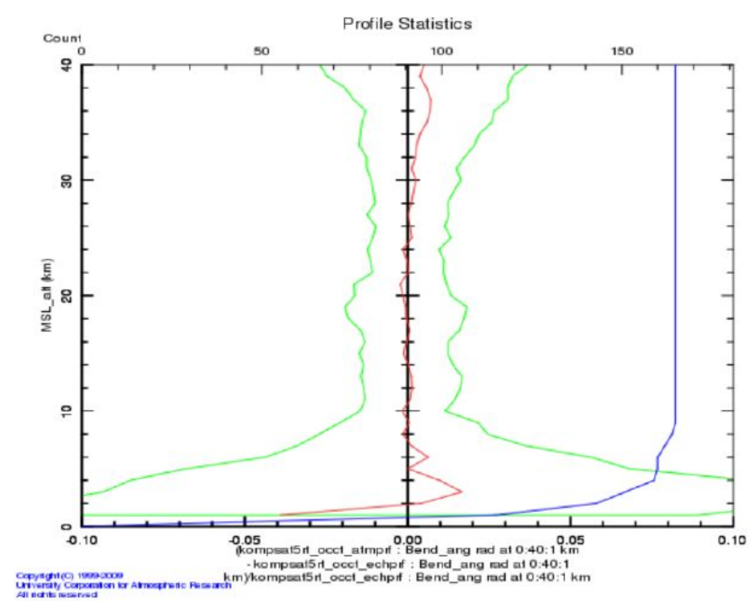


Paz real-time statistics vs other missions

- Paz (upper left) compares well with COSMIC-2 (upper right) and KOMPSAT-5 (lower right)
- All three plots: Bending angle statistics for day 2020.100
- UCAR/CDAAC real-time processing
- ECMWF data used for comparison

Conclusion

- PAZ data processed at UCAR since May 2018
- H and V processed separately for sanity check
- Several approaches tried for combining H and V
- Current approach yields similar statistics to independent H or V processing, but results in much higher quality checked data counts
- Results from Paz compare favorably with other real-time RO missions processed at UCAR/CDAAC.
- PAZ data on PDA and on GTS

PURPOSE OF THIS PRESENTATION

UNDERSTANDING PAZ DATA

Thermodynamic profiles

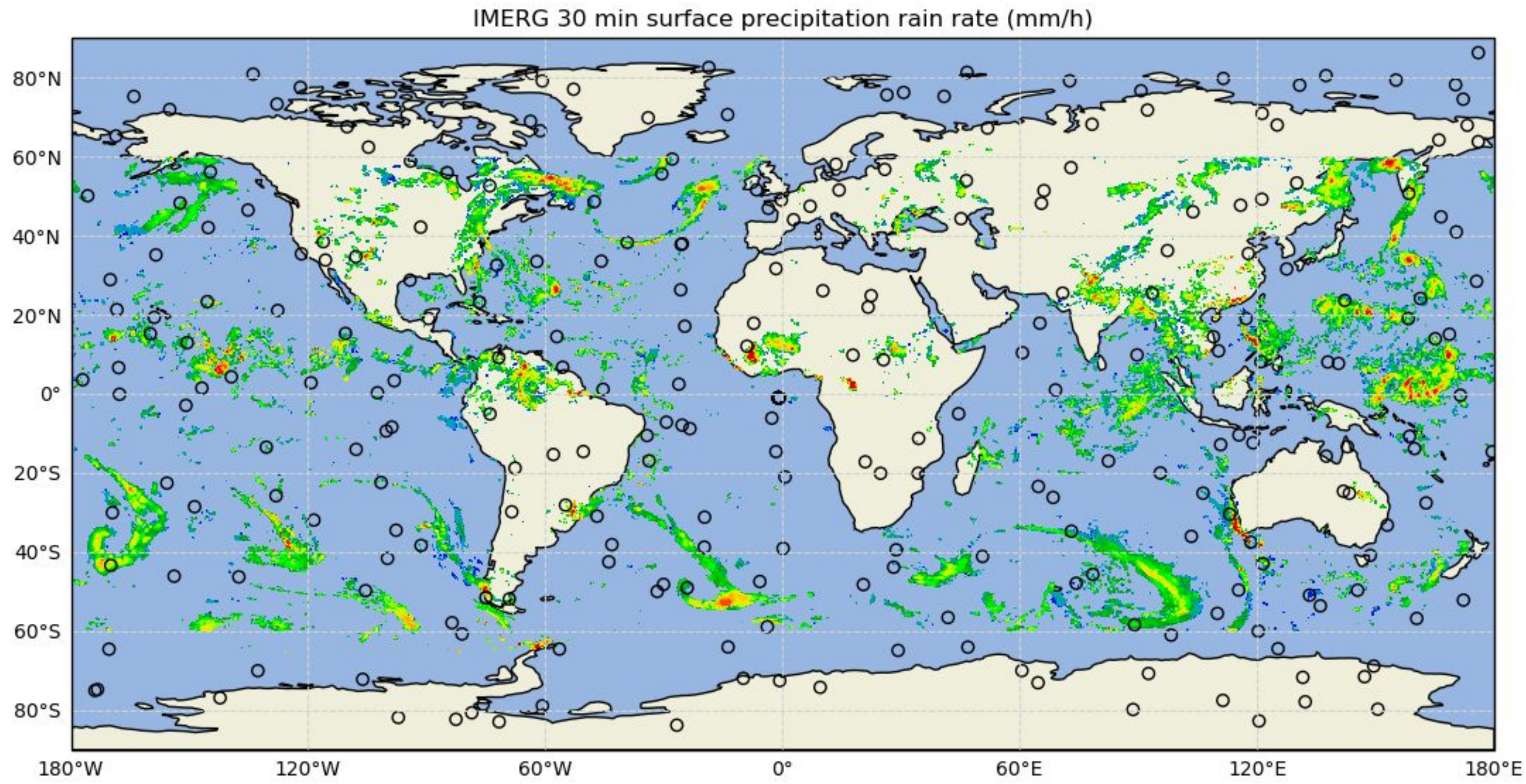
Understanding the polarimetric signatures; Co-locations DB

APPLICATIONS RELEVANT TO CLIMATE

APPLICATIONS RELEVANT TO NWP

UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

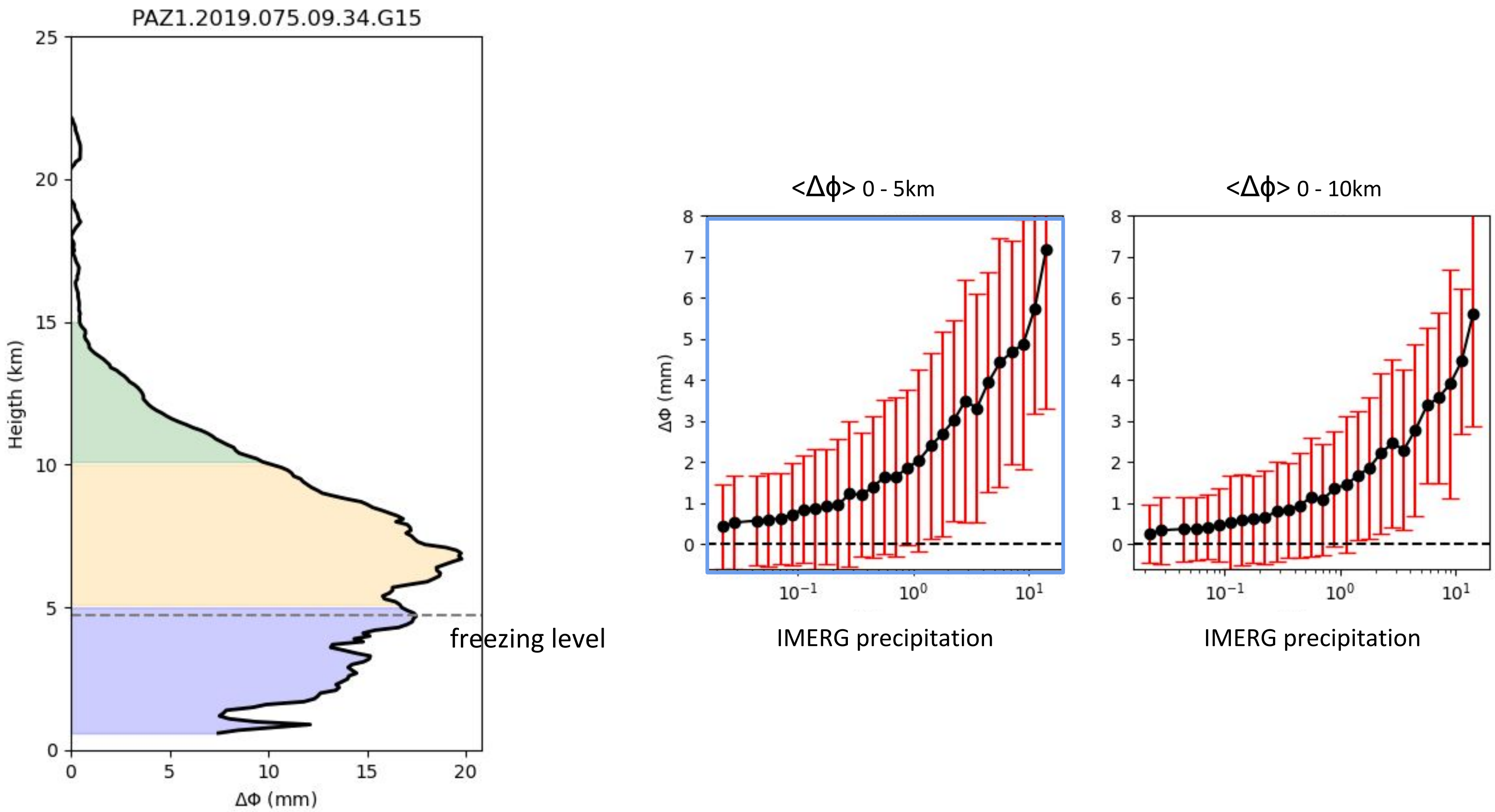
Differential phase shift vs precipitation:



○ → PAZ RO locations for one day

UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

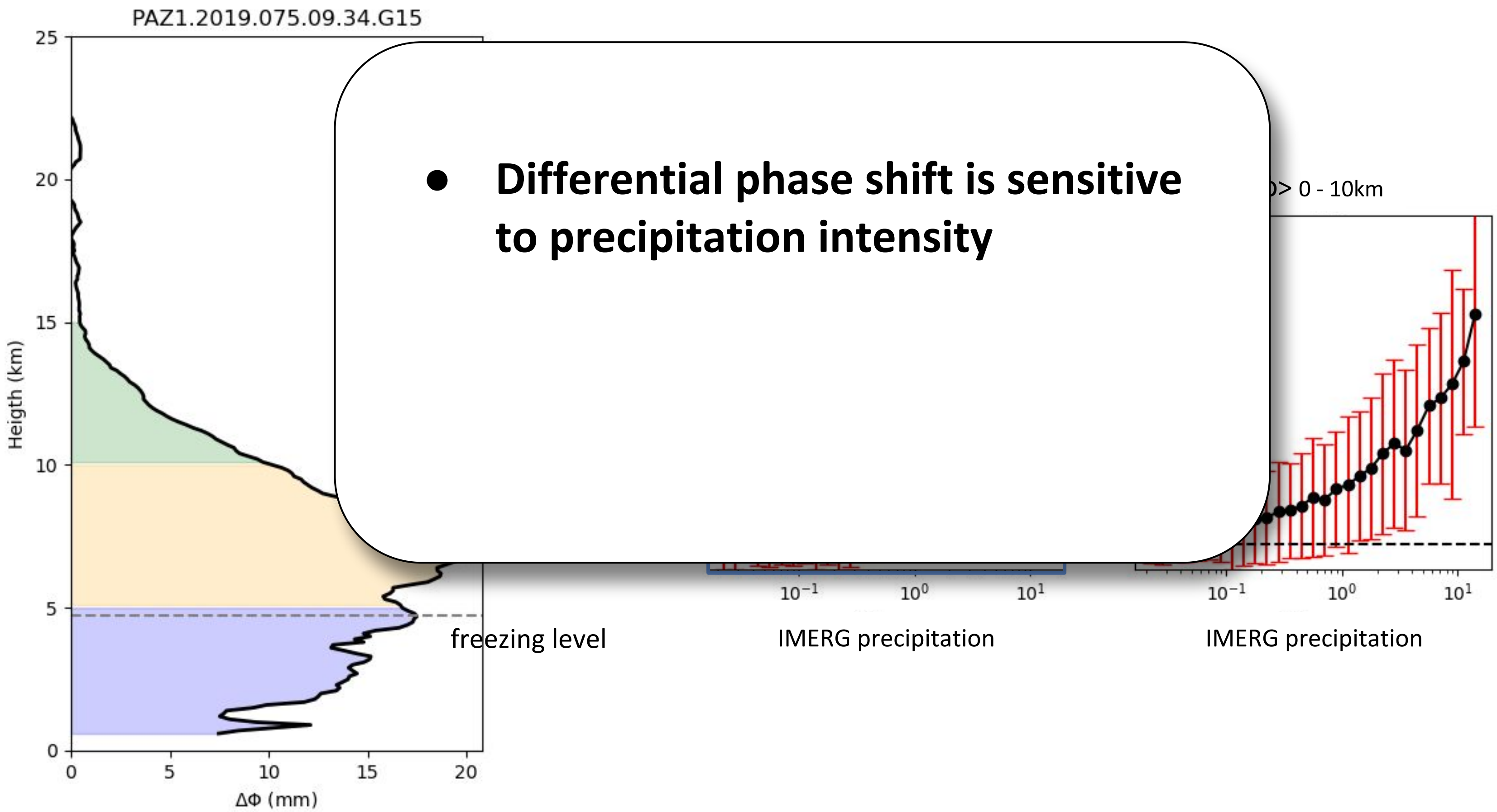
Differential phase shift vs precipitation:



UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

Differential phase shift vs precipitation:

- **Differential phase shift is sensitive to precipitation intensity**



UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

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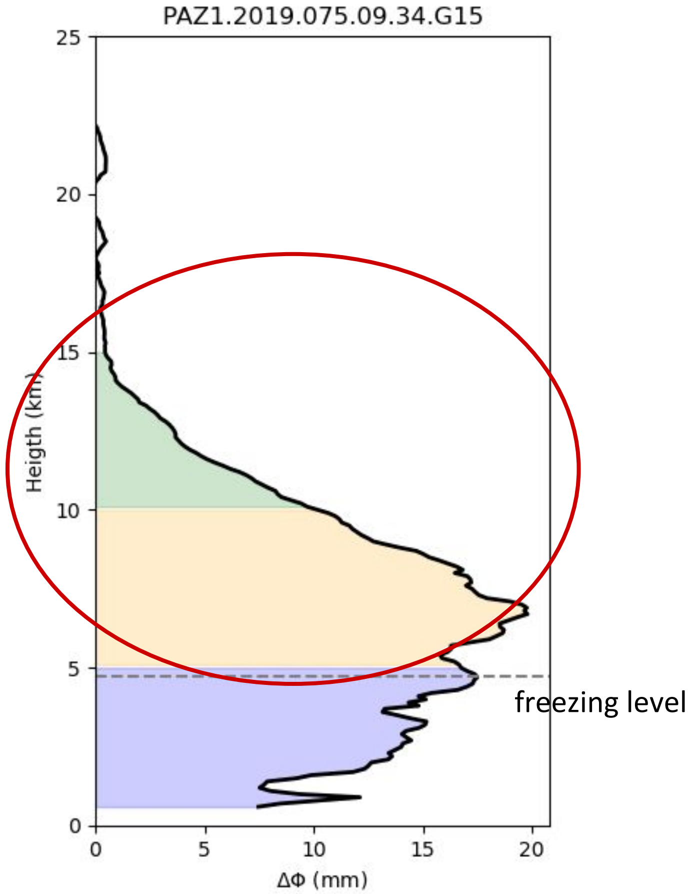

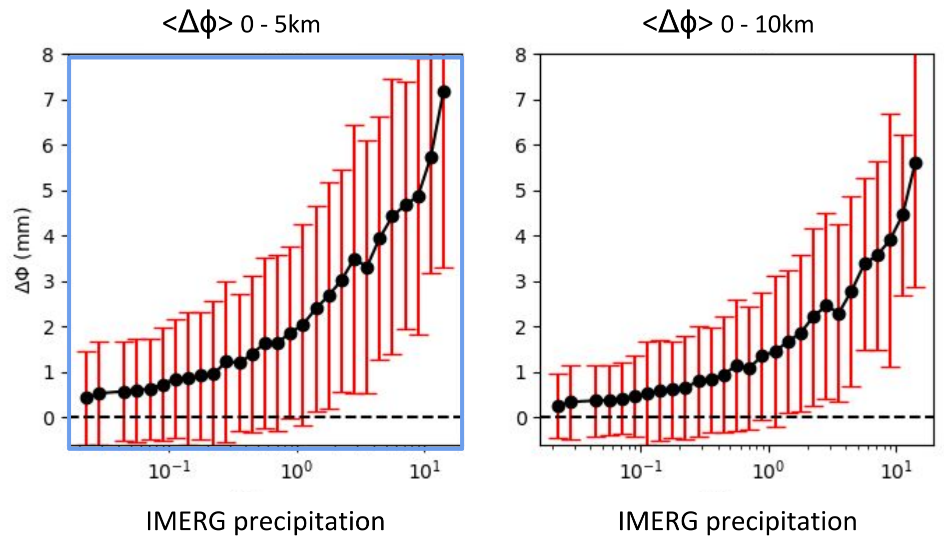

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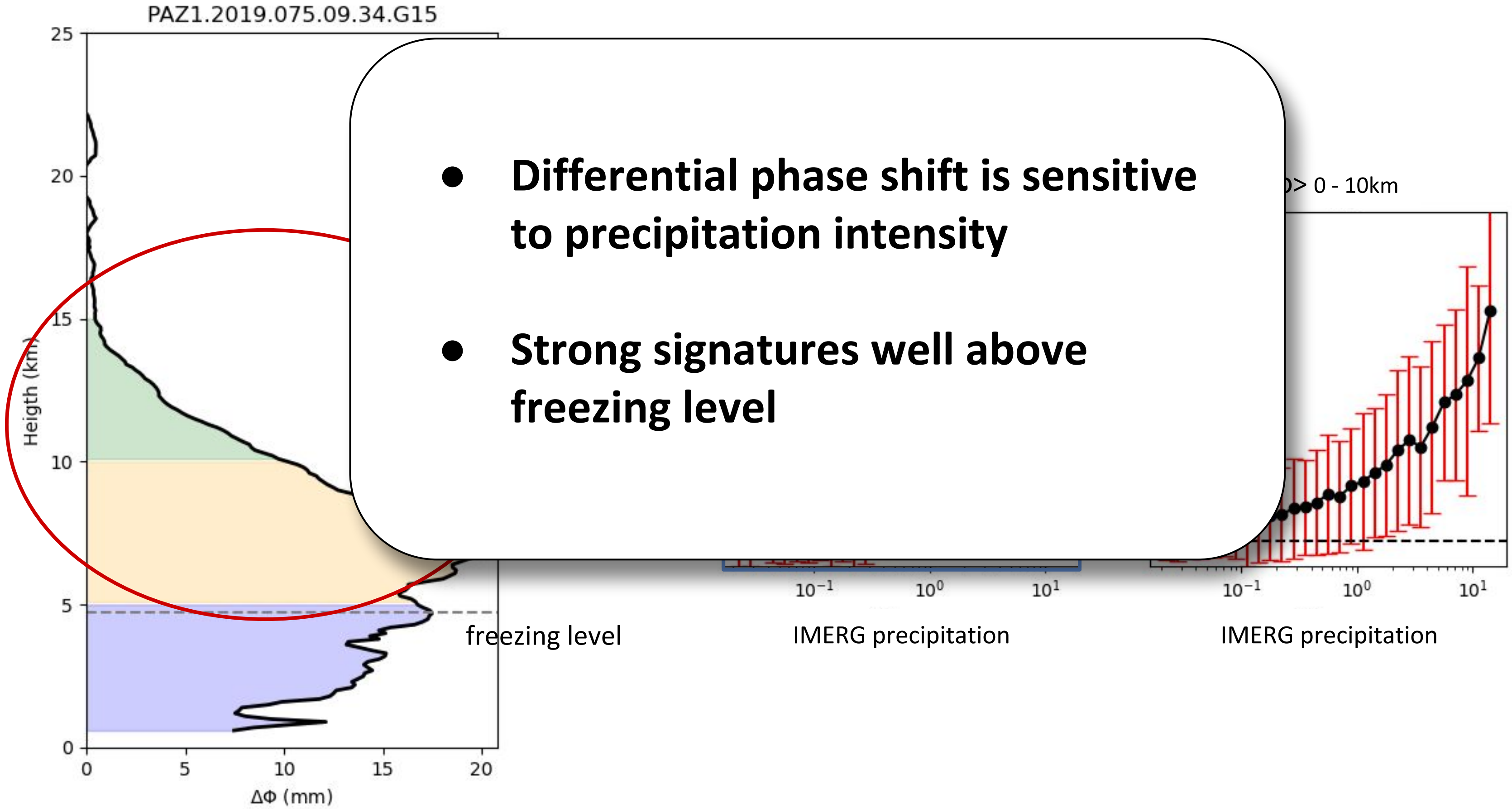
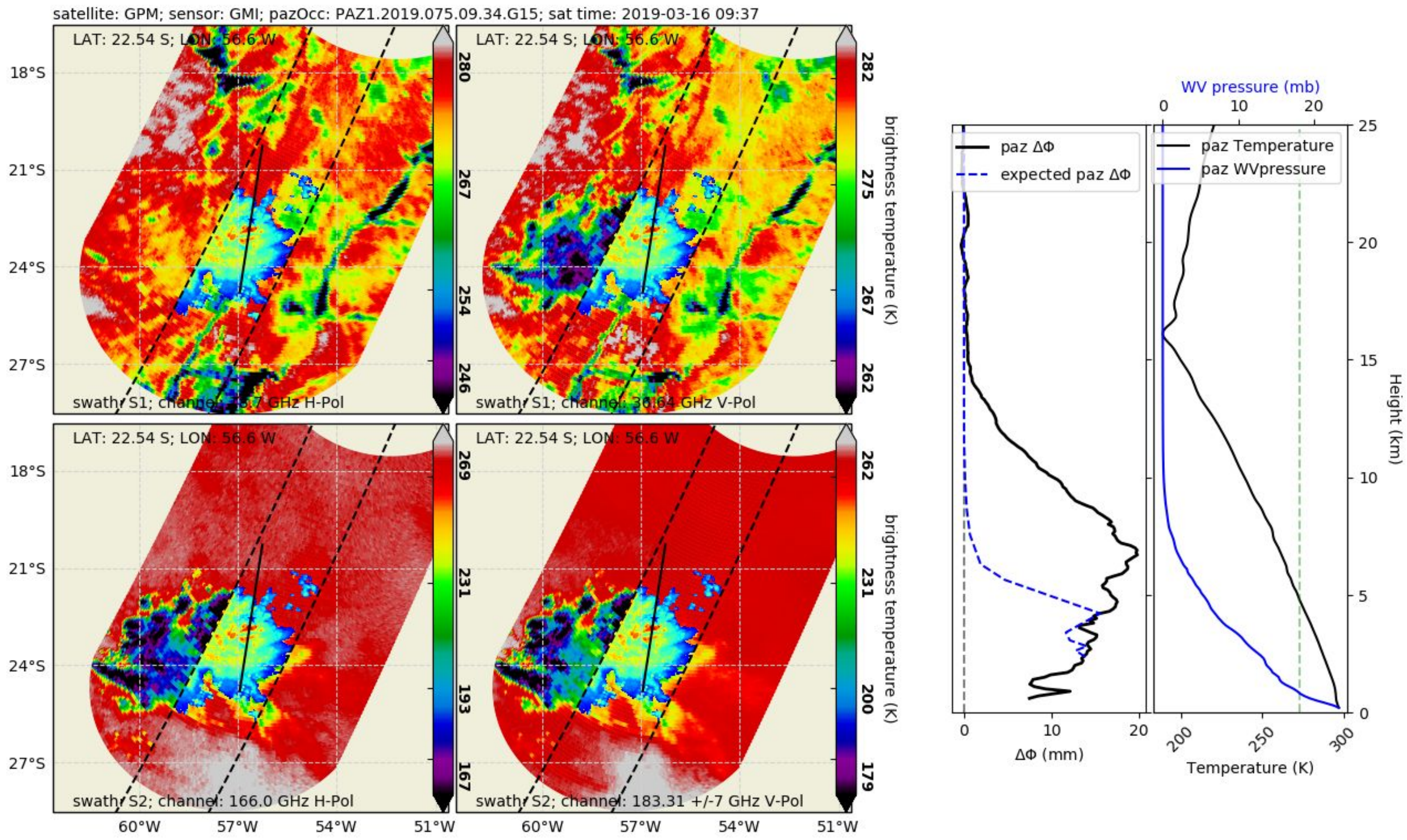


- Differential phase shift is sensitive to precipitation intensity
- Strong signatures well above freezing level

UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

What are we sensing?

Co-location with GPM-core satellite: DPR radar provides 3D information about precipitation



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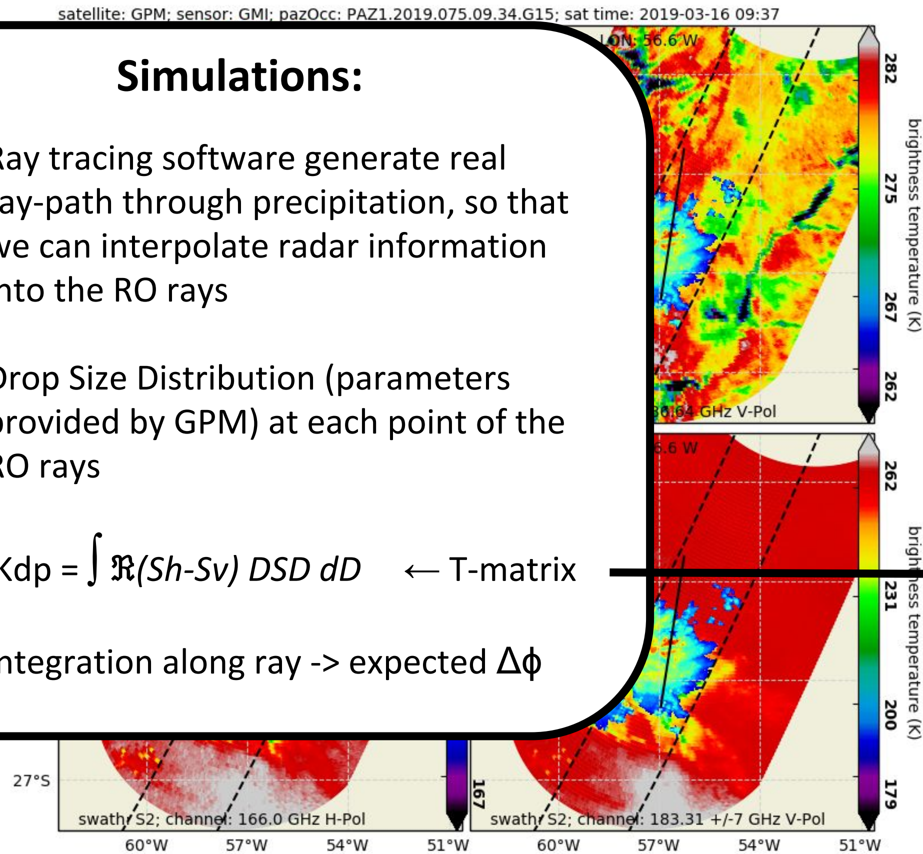
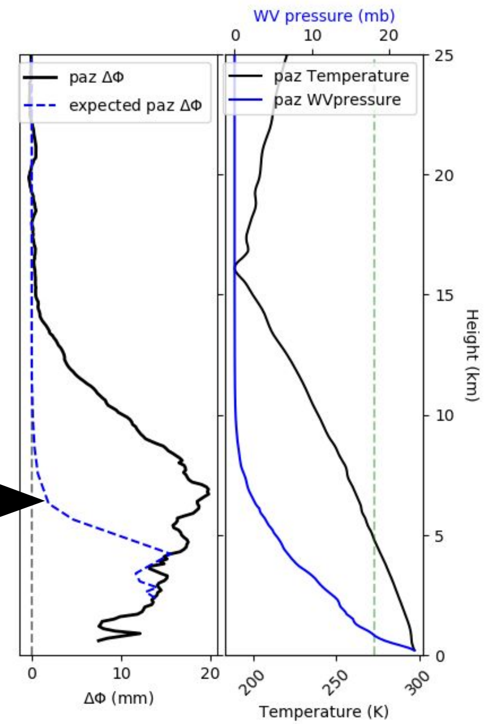


Simulations:

1. Ray tracing software generate real ray-path through precipitation, so that we can interpolate radar information into the RO rays
2. Drop Size Distribution (parameters provided by GPM) at each point of the RO rays
3. Kdp = $\int \Re(Sh\text{-}Sv)\ DSD\ dD$ ← T-matrix
4. Integration along ray -> expected $\Delta\phi$



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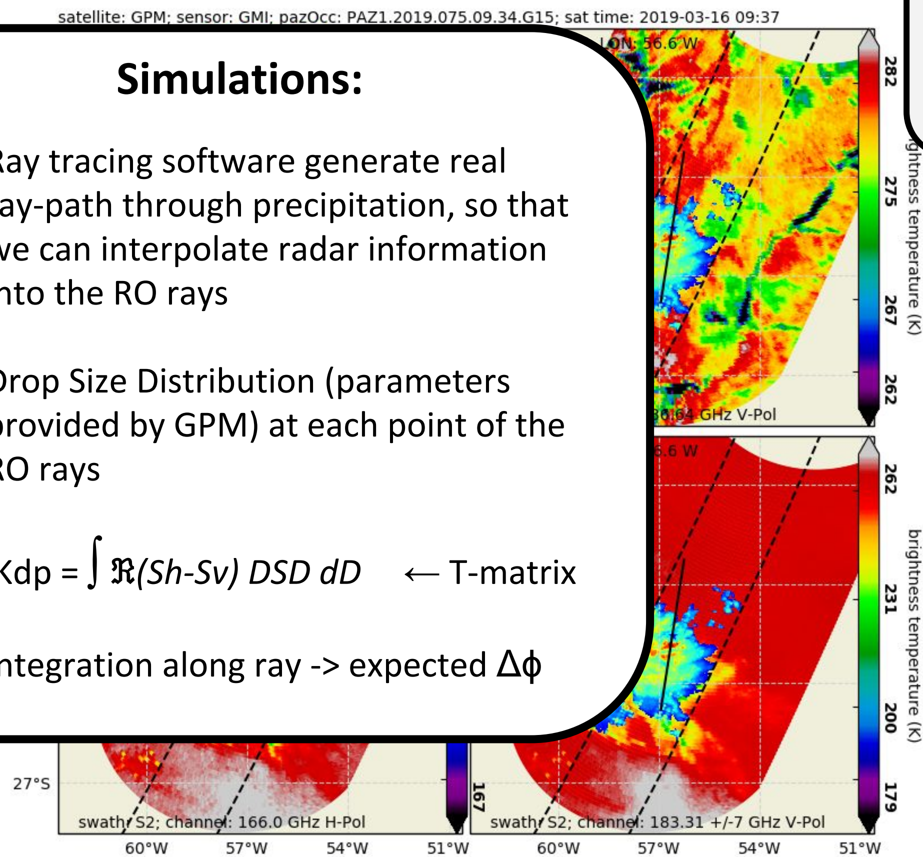

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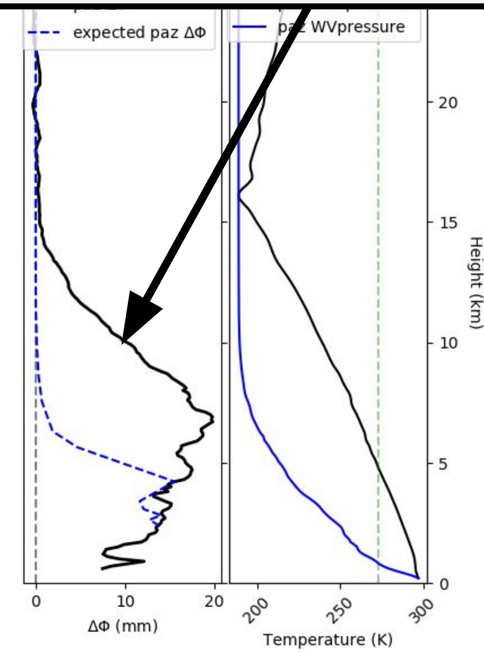

What are we missing here?

UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

What are we sensing?

- **GPM-core satellite: (DPR; 13.6GHz, 35.5GHz) mostly sensitive to liquid phase precip**
- **TRMM satellite (1997-2015): (PR; 13.6 GHz) similar radar with only 1 frequency**

- **Cloudsat: High frequency radar (94 GHz): sensitive to smaller particles**

full picture:

simultaneous observation of the same scene by Cloudsat and GPM/TRMM

Database of co-located observations with >20,000 cases for 2006-2019 period

UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

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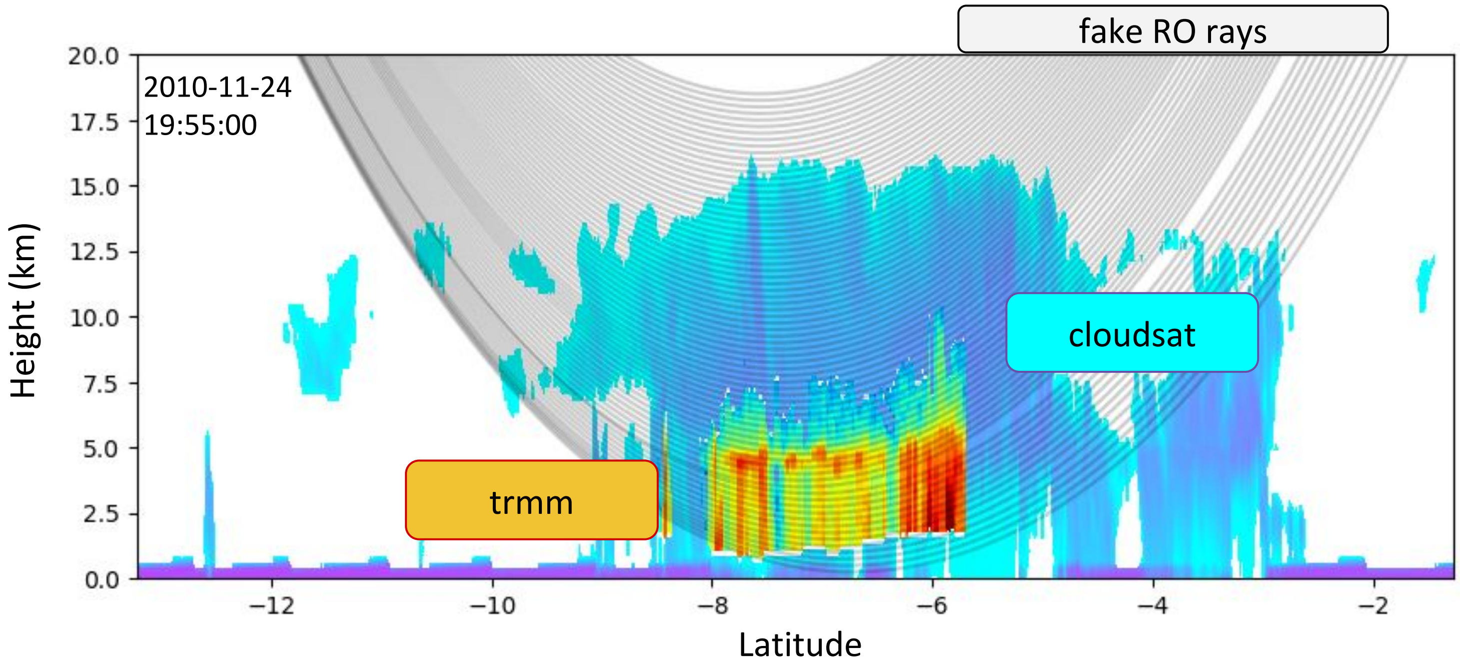

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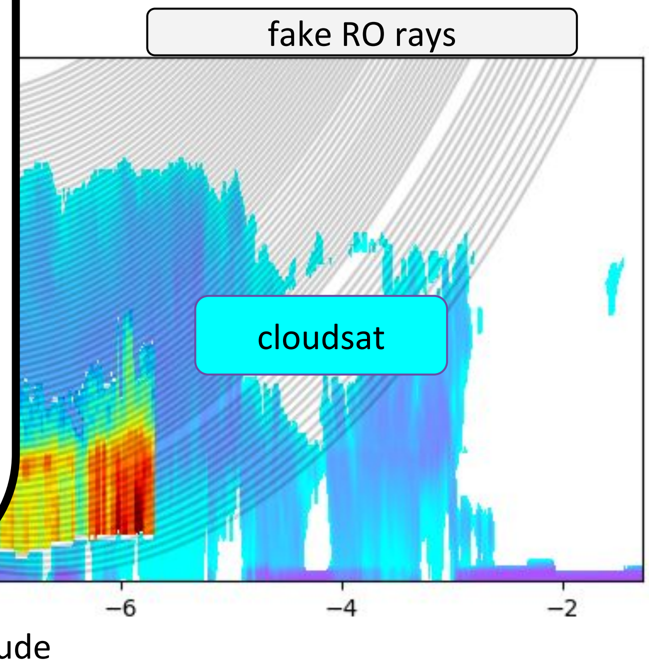
Simulations:

1. **Fake RO rays** (but realistic) to interpolate radar information into the RO rays
2. Drop Size Distribution (parameters provided by Cloudsat) at each point of the RO rays
3. Kdp ← **DDA** using: 
4. Integration along ray -> expected $\Delta\phi$



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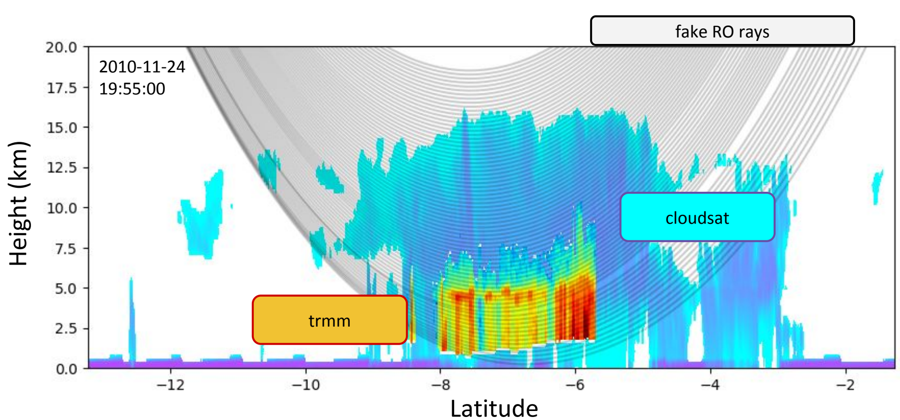
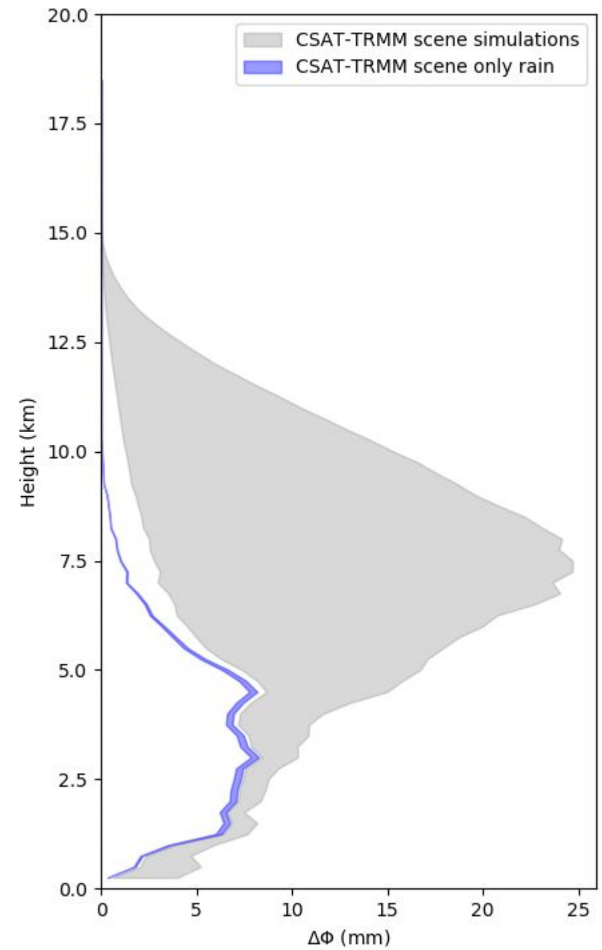
UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

What are we sensing?

<u>Assumptions:</u>

- Particles randomly oriented +
  a variable % of fully Horizontally Oriented
- The % of Horizontally Oriented increases linearly with height from 1% at the top to:
  - 10 % at the Freezing Level (left gray)
  - 75 % at the Freezing Level (right gray)





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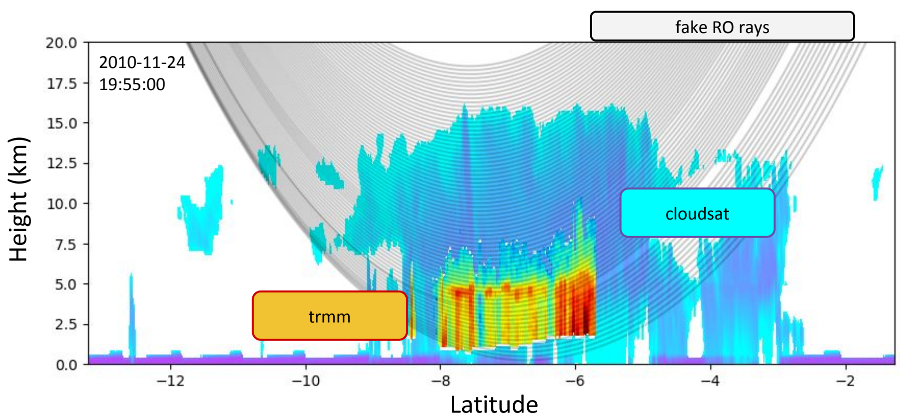
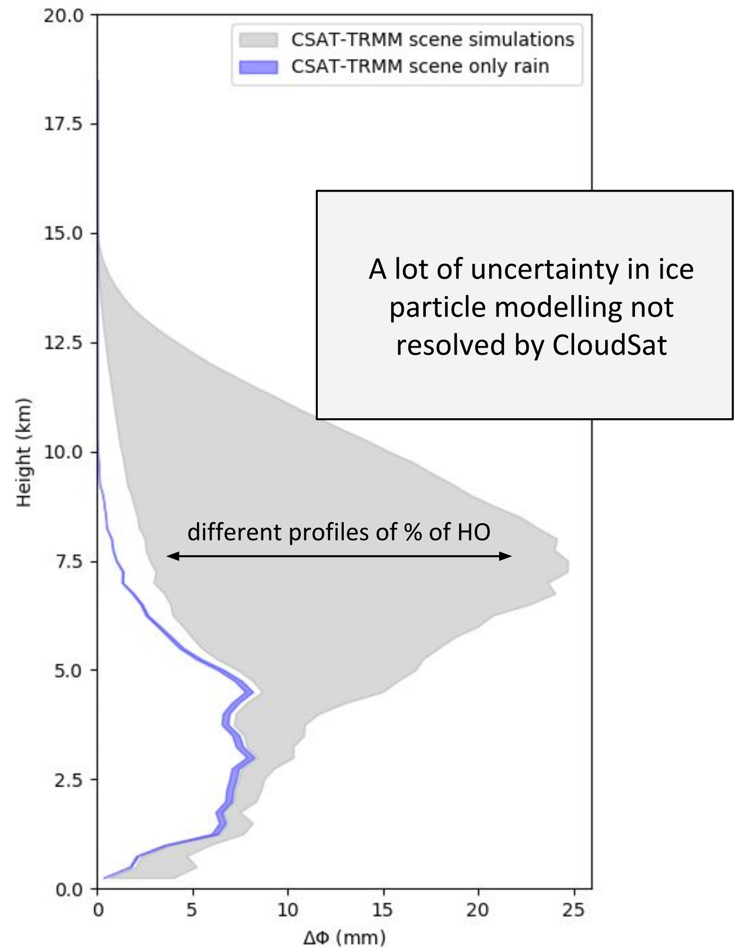


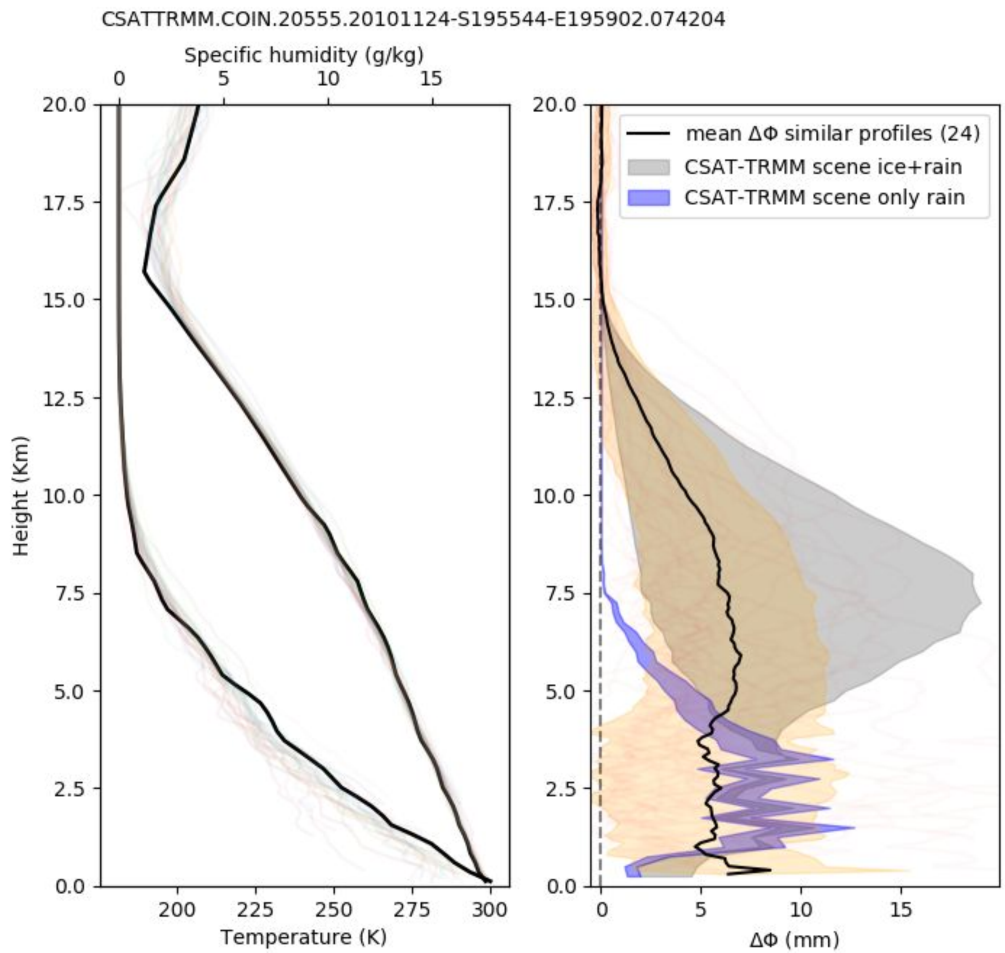


UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

What are we sensing?

Most similar PAZ RO observations to that CSAT-TRMM scene

- Similar IR brightness temperature
- Similar Temperature profile
- Similar specific humidity profile



Results point towards a good agreement between the presence and the simulated effect of frozen particles and the PAZ observations

DATABASE OF CO-LOCATED OBSERVATIONS

PAZ co-locations (2018-05-10 -- 2019-12-31)

Coincident observations with other satellites, within 30 min

Satellite	Sensor	Number of coincidences
GPM	*DPR (radar)*	1618
GPM	*GMI*	6306
NPP	*ATMS*	10739
NOAA-20	*ATMS*	10727
NOAA-19	*MHS*	30202
GCOM-W1	*AMSR-2*	6370
MEGHA-TROPIQUES	*SAPHIR*	7164
METOP - A / B / C	*MHS*	24536
CLOUDSAT	*PR (radar)*	1573
TERRA	*MODIS*	10559
AQUA	*MODIS*	10738

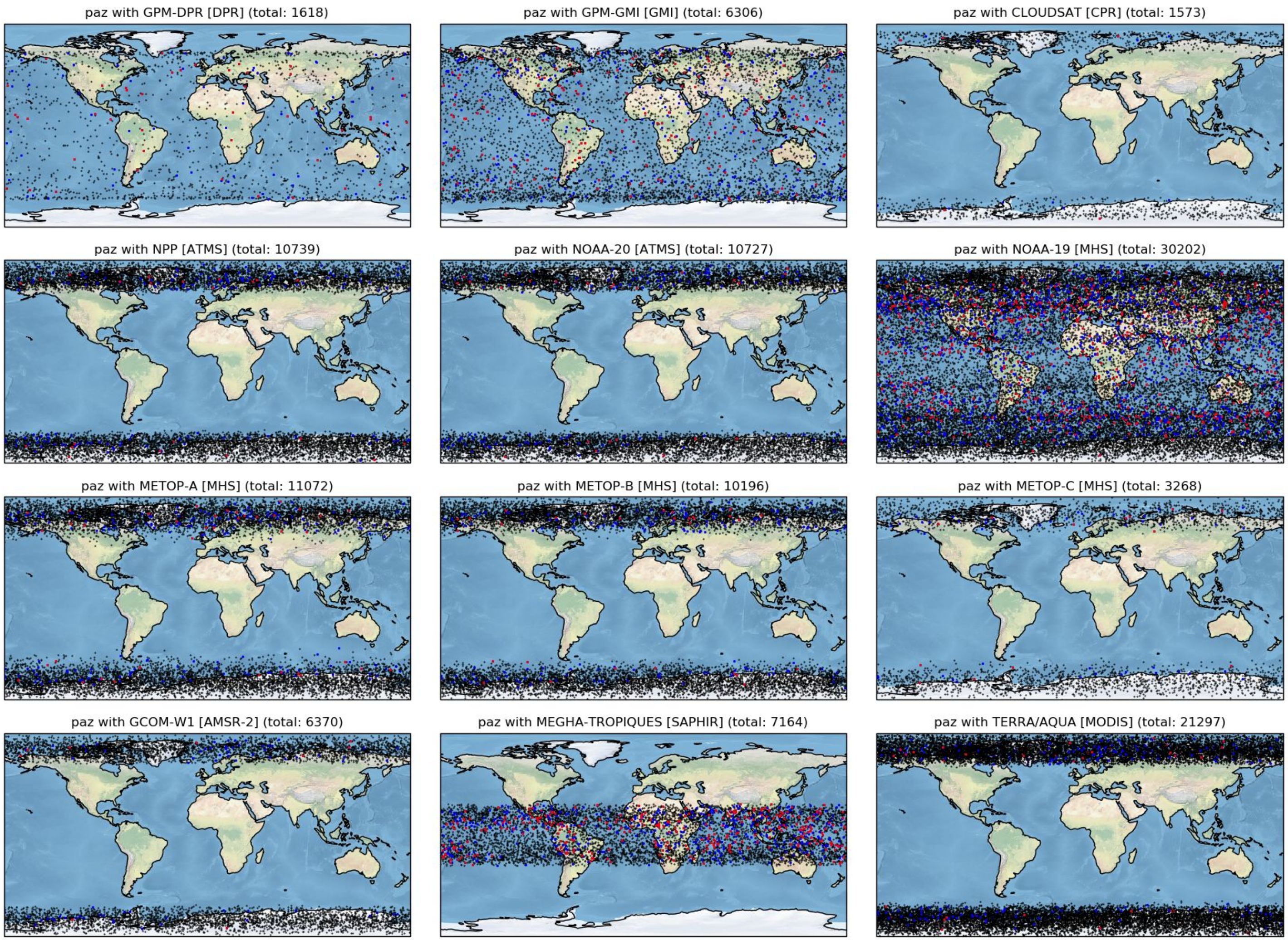
Coincident observations with NEXRAD (within 200 km), Tropical Cyclones (within 400 km)

nexrad	tropical cyclones
2832	924

These databases will be updated regularly and can be made available upon request

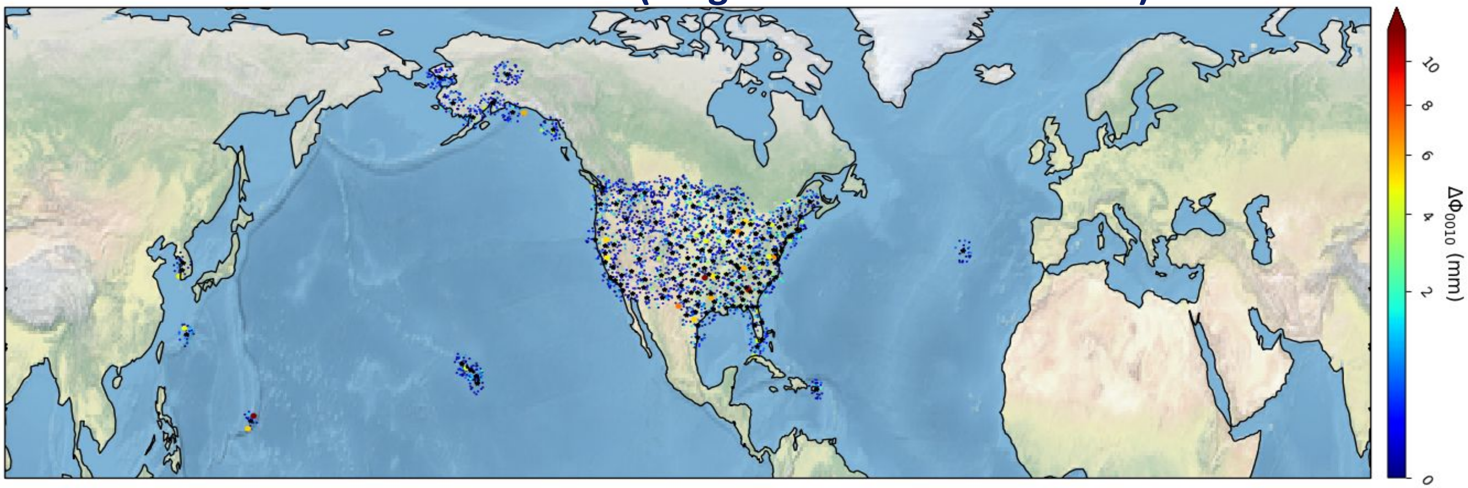
DATABASE OF CO-LOCATED OBSERVATIONS

PAZ with Satellites with radars and MW radiometers

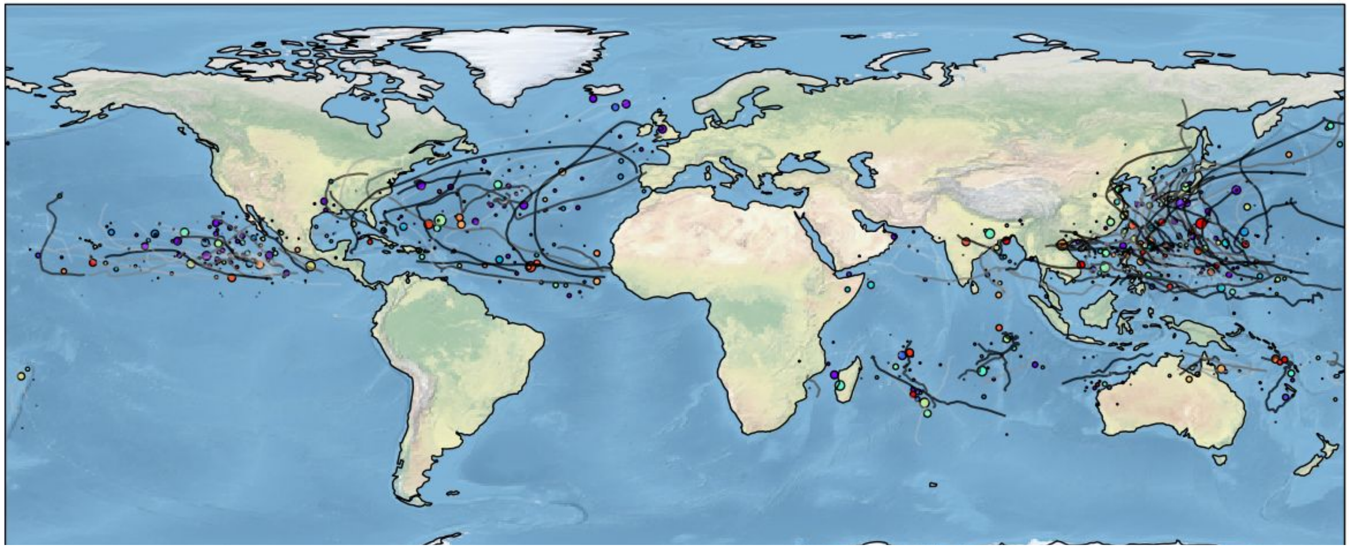


DATABASE OF CO-LOCATED OBSERVATIONS

PAZ with NEXRAD (US ground - weather radars)



PAZ with Tropical Cyclones



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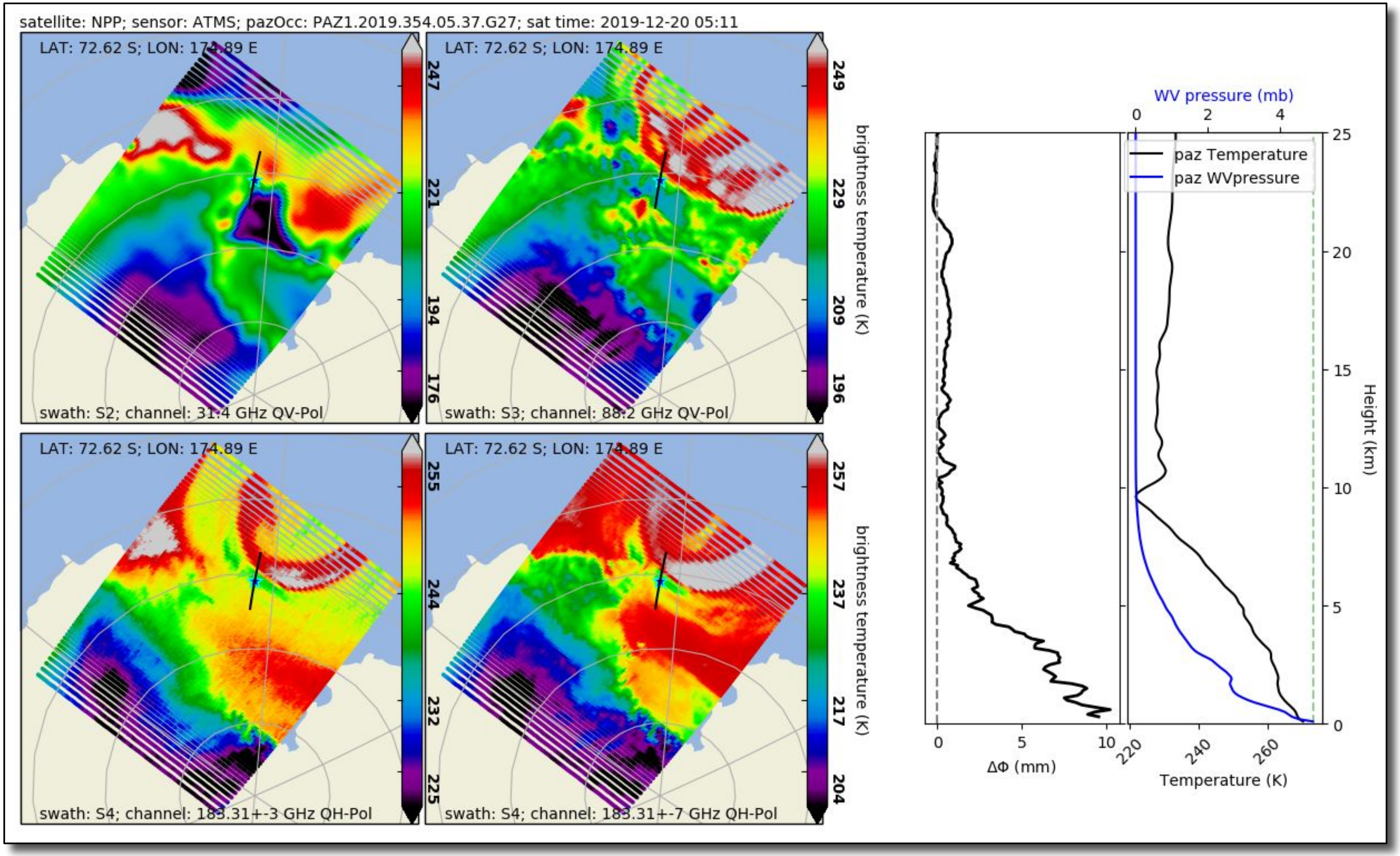

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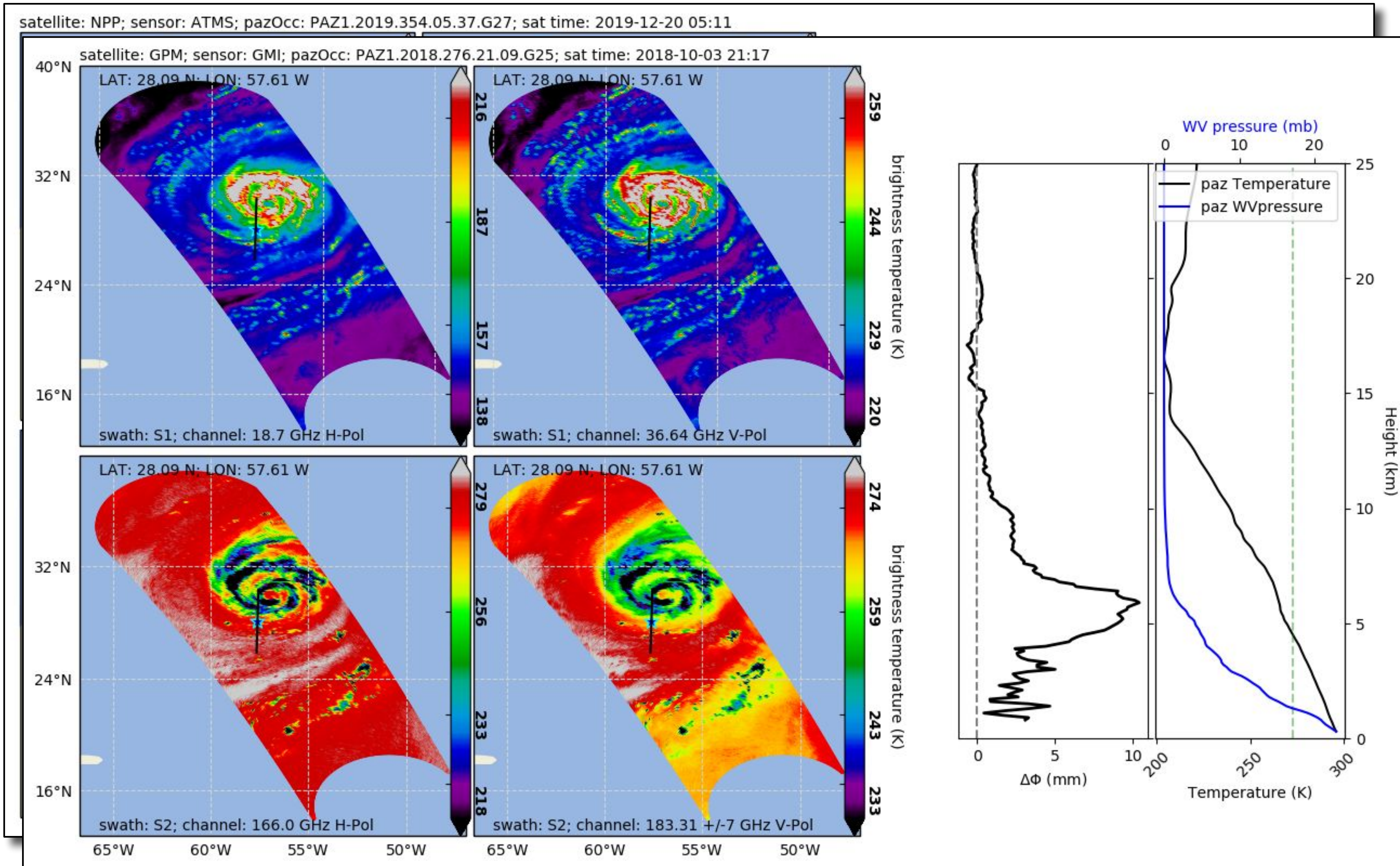

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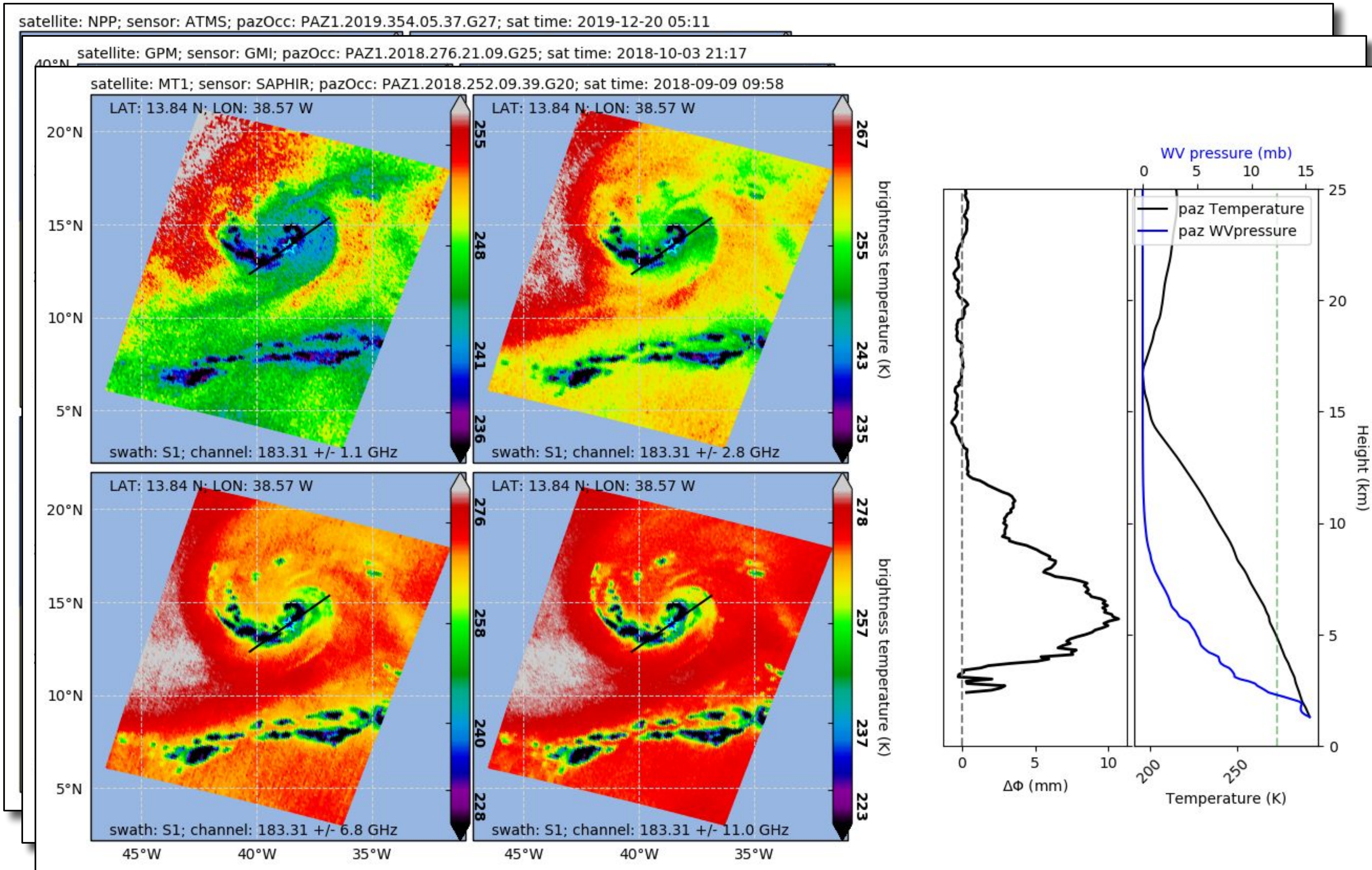

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What scientific questions can be tackled regarding climate studies?
Large scale convective systems: heavy rain and moisty free troposphere
Ideas for constellation observing system

APPLICATIONS RELEVANT TO NWP

Scientific questions relevant to climate studies:

- Convective transition statistics: Model diagnostics
  - Use PRO to characterize the “pickup” of precipitation as a function of CWV, and the dependence of the moisture–precipitation relation on tropospheric temperature
  - The moisture–precipitation relation is representative of the relation between observed deep convection and the buoyancy available for deep convection

Kuo, Y., J.D. Neelin, C. Chen, W. Chen, L.J. Donner, A. Gettelman, X. Jiang, K. Kuo, E. Maloney, C.R. Mechoso, Y. Ming, K.A. Schiro, C.J. Seman, C. Wu, and M. Zhao, 2020: Convective Transition Statistics over Tropical Oceans for Climate Model Diagnostics: GCM Evaluation. *J. Atmos. Sci.*, **77**, 379–403, https://doi.org/10.1175/JAS-D-19-0132.1

- Use PRO to more directly examine (rely less on ancillary data) model biases in precipitation

Juárez, Manuel de la Torre, R. Padullés, F. J. Turk, and E. Cardellach. “Signatures of Heavy Precipitation on the Thermodynamics of Clouds Seen From Satellite: Changes Observed in Temperature Lapse Rates and Missed by Weather Analyses.” *Journal of Geophysical Research: Atmospheres* 123, no. 23 (2018): 13,033-13,045. https://doi.org/10.1029/2017JD028170.

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UNDERSTANDING PAZ DATA

APPLICATIONS RELEVANT TO CLIMATE

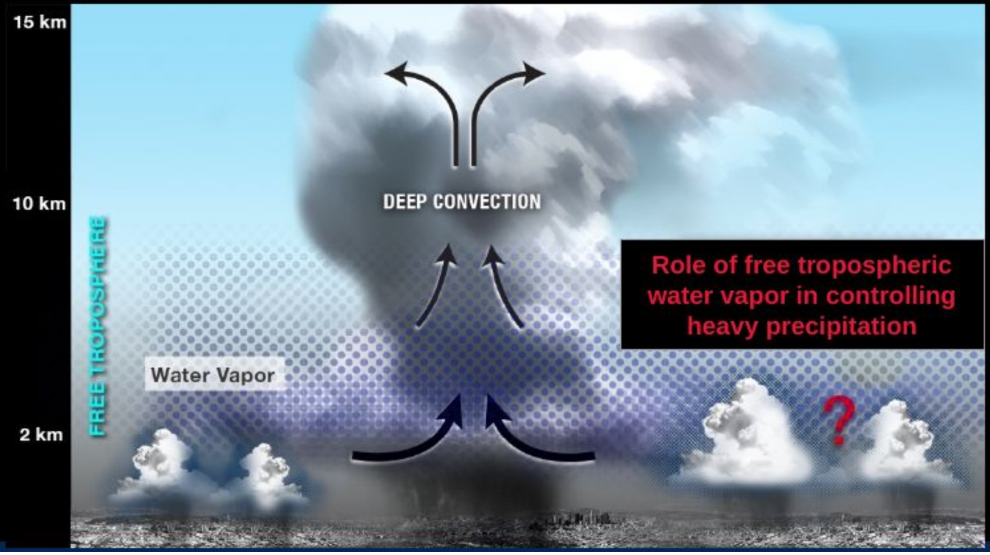
- What scientific questions can be addressed regarding climate studies?
- **Large scale convective systems: heavy rain and moist free troposphere**
- Ideas for a PRO constellation observing system

APPLICATIONS RELEVANT TO NWP

Padullés et al., AGU 2018:

Vertical Thermodynamic Structure of Precipitation

- Convection drives the most intense precipitation events
- There is a lack of observations in deep convection
- This results in uncertainties in modeling and predicting precipitation



- Increasing evidence points to control of convection by the free tropospheric water vapor

Neelin, J.D., et. al, 2009: "The Transition to Strong Convection." *J. Atmos. Sci.* https://doi.org/10.1175/2009JAS2962.1.

Schiro, K.A., et. al, 2016: "Deep Convection and Column Water Vapor over Tropical Land versus Tropical Ocean: A Comparison between the Amazon and the Tropical Western Pacific." *J. Atmos. Sci.* https://doi.org/10.1175/JAS-D-16-0119.1.

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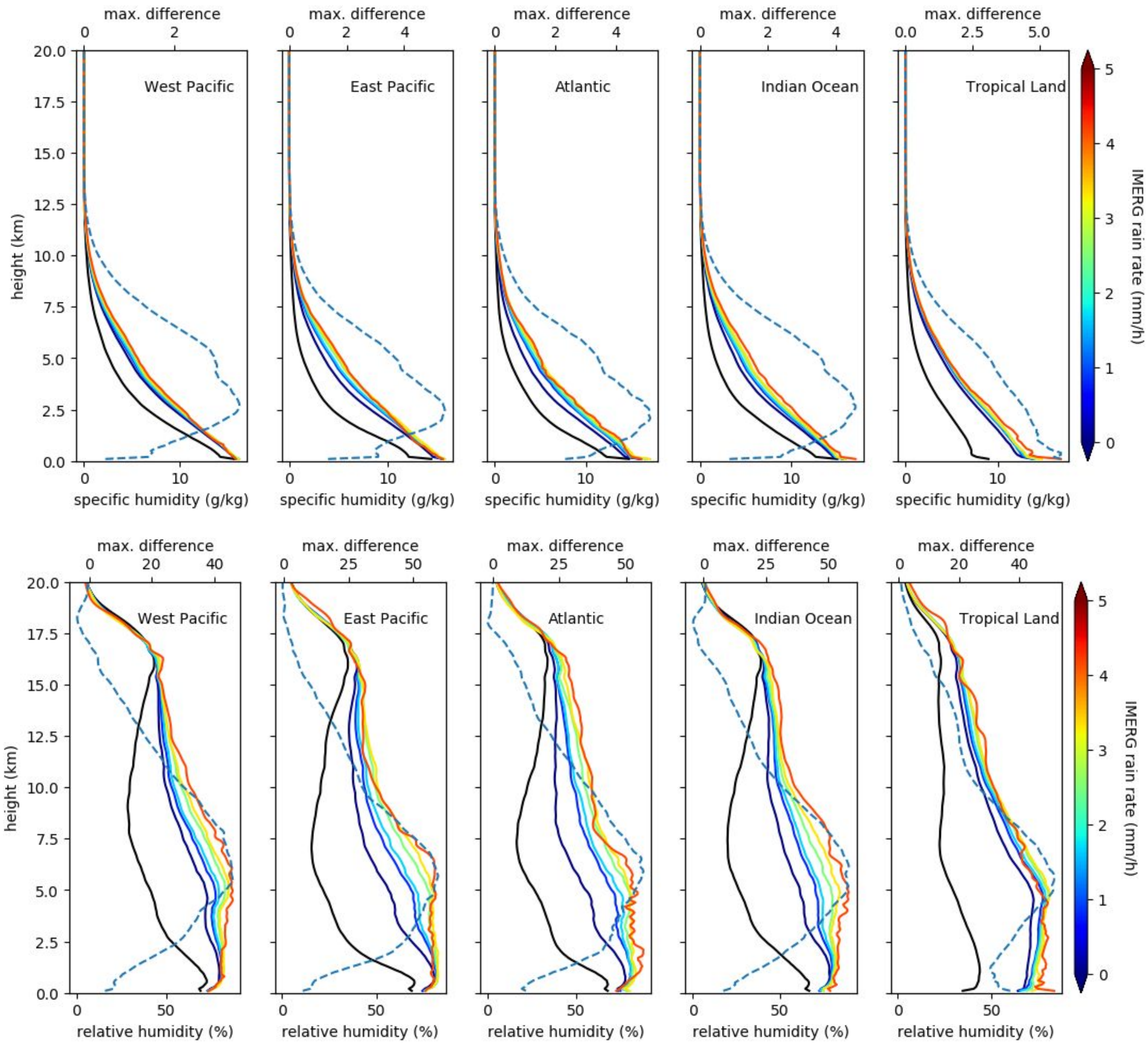
VERTICAL STRUCTURE OF PRECIPITATION



Co-located PAZ and IMERG data

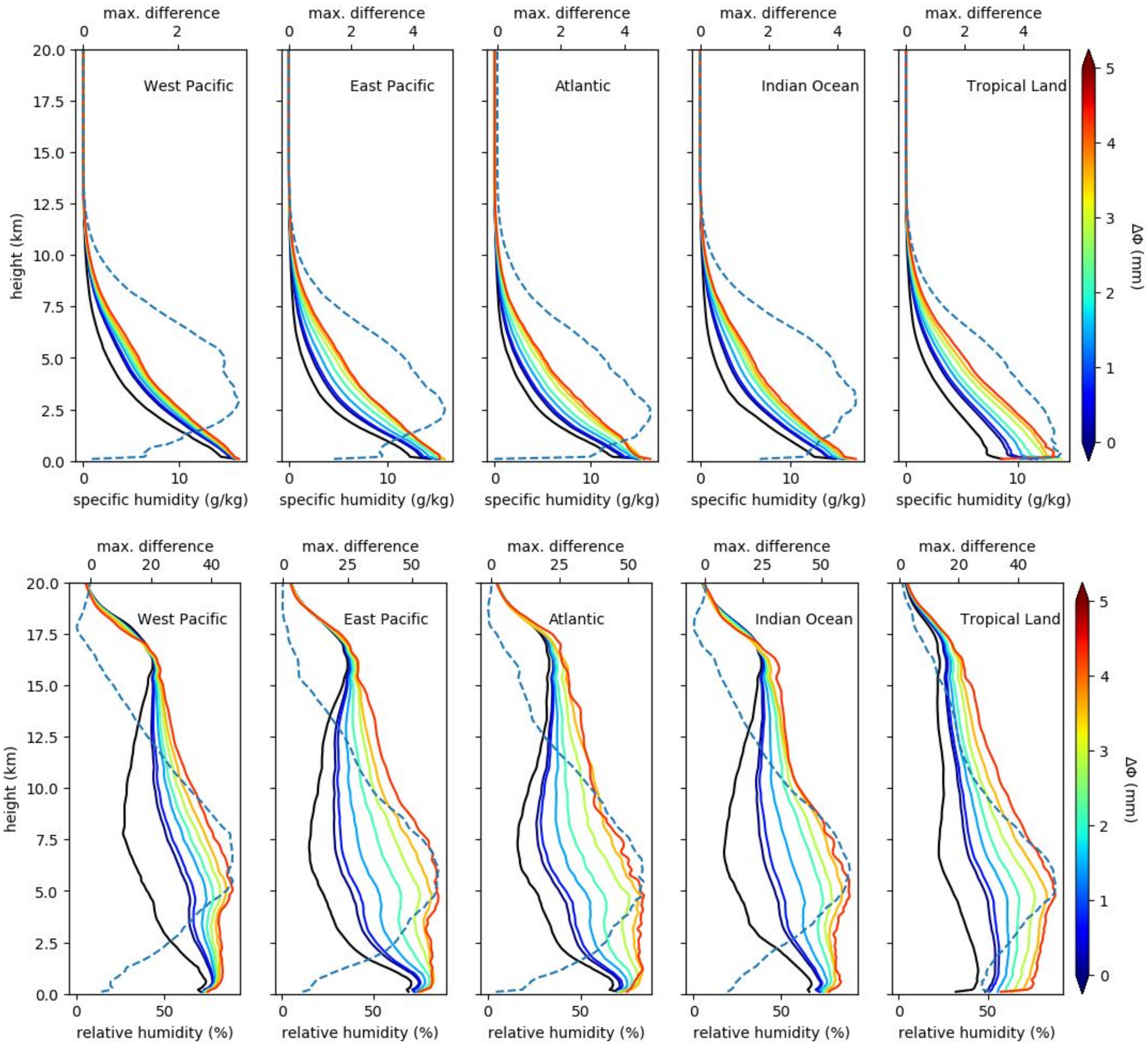
Specific humidity (top)
Relative humidity (bottom)

Each region as a function of height (0-20 km)

Averaged on different IMERG **precipitation ranges** (solid colored lines, according to color scale)

Dashed line shows the difference between those profiles averaged when there is no precipitation, and those in the maximum precipitation bin, as a function of height.

VERTICAL STRUCTURE OF PRECIPITATION



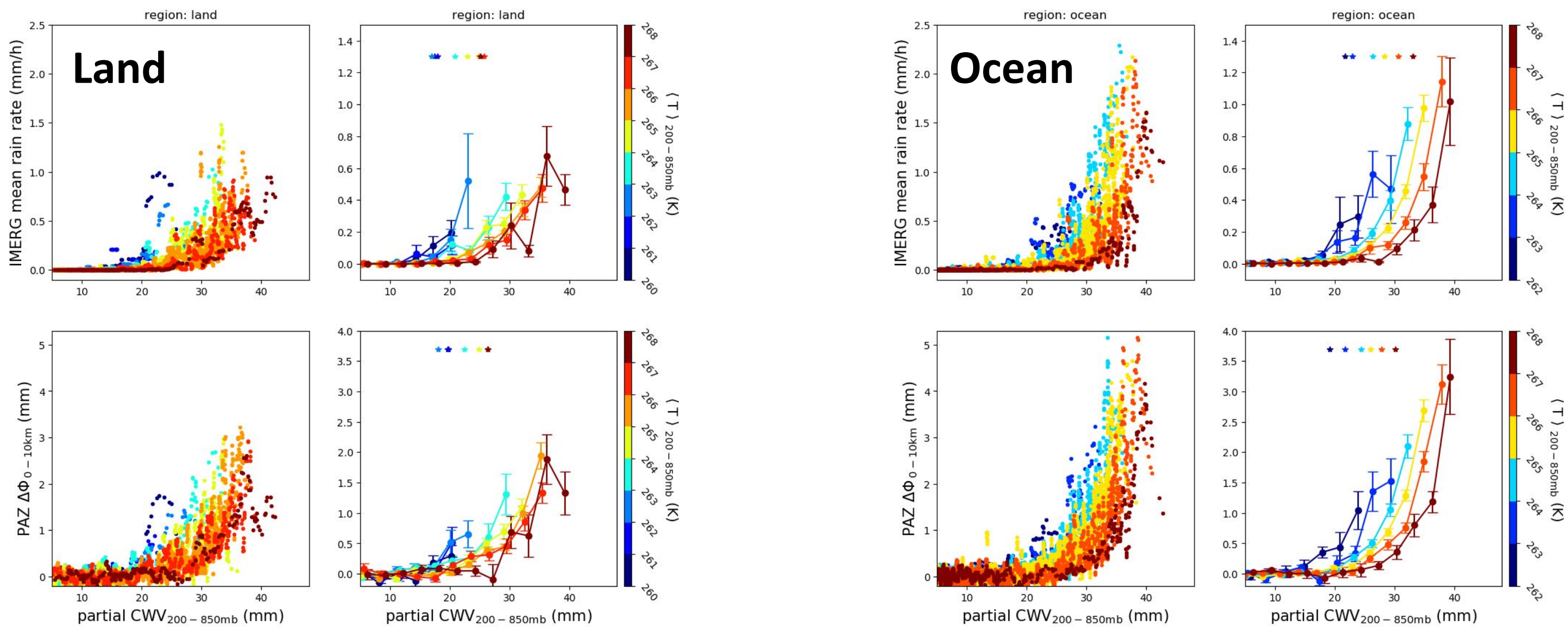
Co-located PAZ and IMERG data

Specific humidity (top)
Relative humidity (bottom)

Each as a function of height (0-20 km)

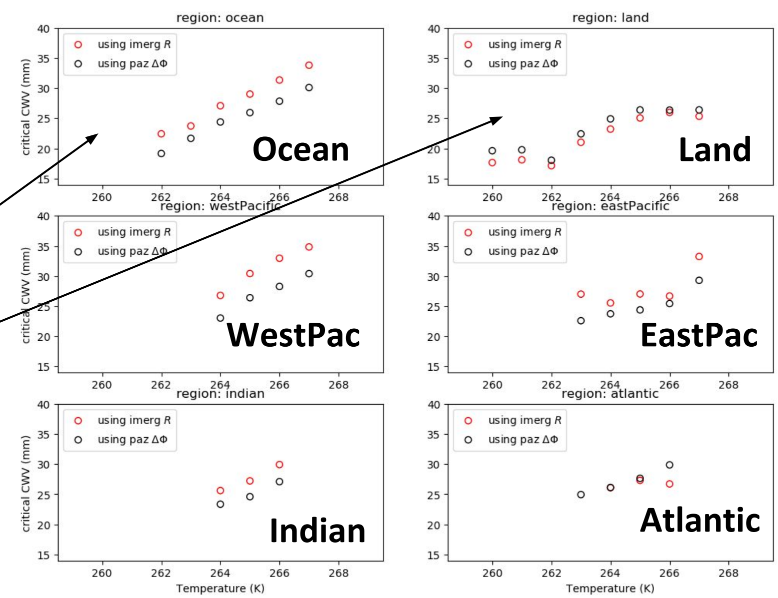
Averaged on different **Δφ** ranges (solid colored lines, according to color scale)

Importance of the free tropospheric water vapor controlling the onset of deep convection



Top row: IMERG precip vs column vapor 200-850 hPa

Bottom row: PAZ **Δϕ** vs column vapor 200-850 hPa



PAZ Δϕ is a good diagnostic for precipitation that would be brought in from another source: **All data from the same PAZ observation**

PURPOSE OF THIS PRESENTATION

UNDERSTANDING PAZ DATA

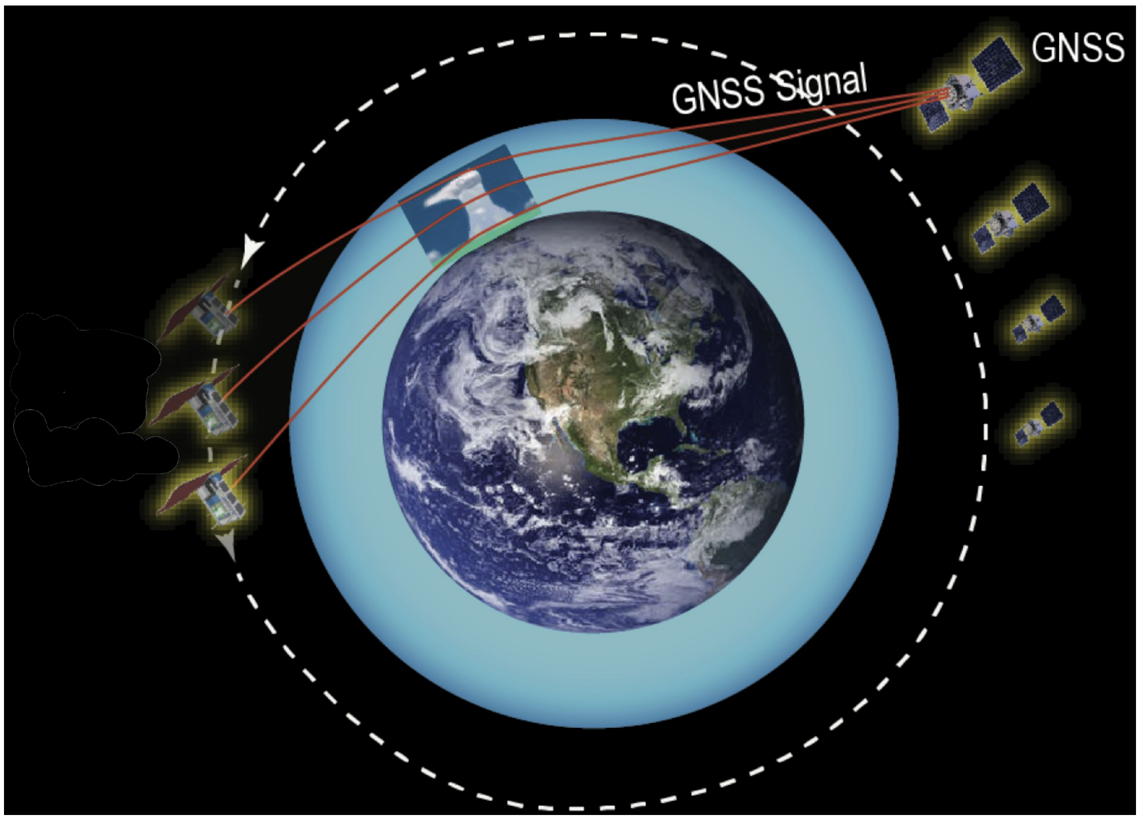
APPLICATIONS RELEVANT TO CLIMATE

- What scientific questions can be tackled regarding climate studies?
- Large scale convective systems: heavy rain and moist free troposphere
- **Ideas for a closely-spaced constellation observing system**

APPLICATIONS RELEVANT TO NWP

Benefits of a Closely-Spaced Satellite Constellation of Atmospheric Polarimetric Radio Occultation Measurements

Turk et. al., Remote Sens. **2019**, *11*(20), 2399
https://doi.org/10.3390/rs11202399

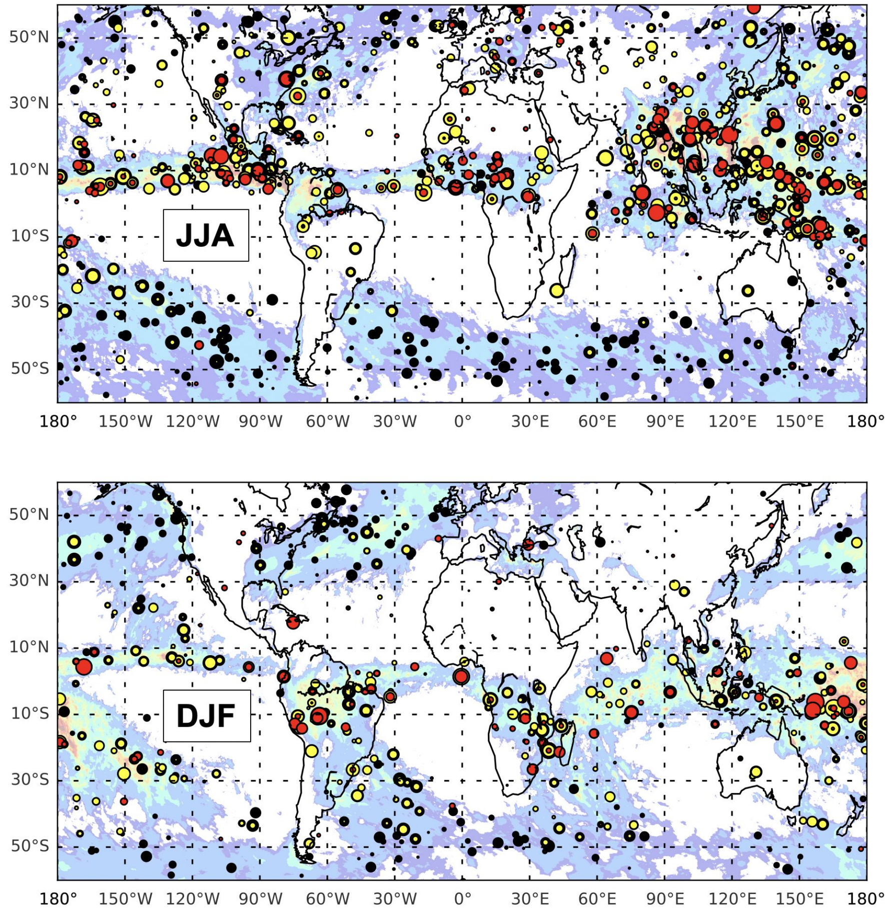


The PRO ray path may traverse and detect a region of heavy precipitation, but there is no way contrast the T/q profile with the surrounding environment

A closely spaced “train” of PRO data may open up new perspectives on convective cloud processes

Some PRO traverse the external environment, at the (almost) same time as its neighbor traverses the heavy precipitation

Benefits of a Closely-Spaced Satellite Constellation of Atmospheric Polarimetric Radio Occultation Measurements



The color background map depicts the average rain rate during these months derived from the GPM IMERG precipitation product.

Geographical distribution of the upper percentile (top 2%) of the measured $\Delta\phi$ from ROHP observations

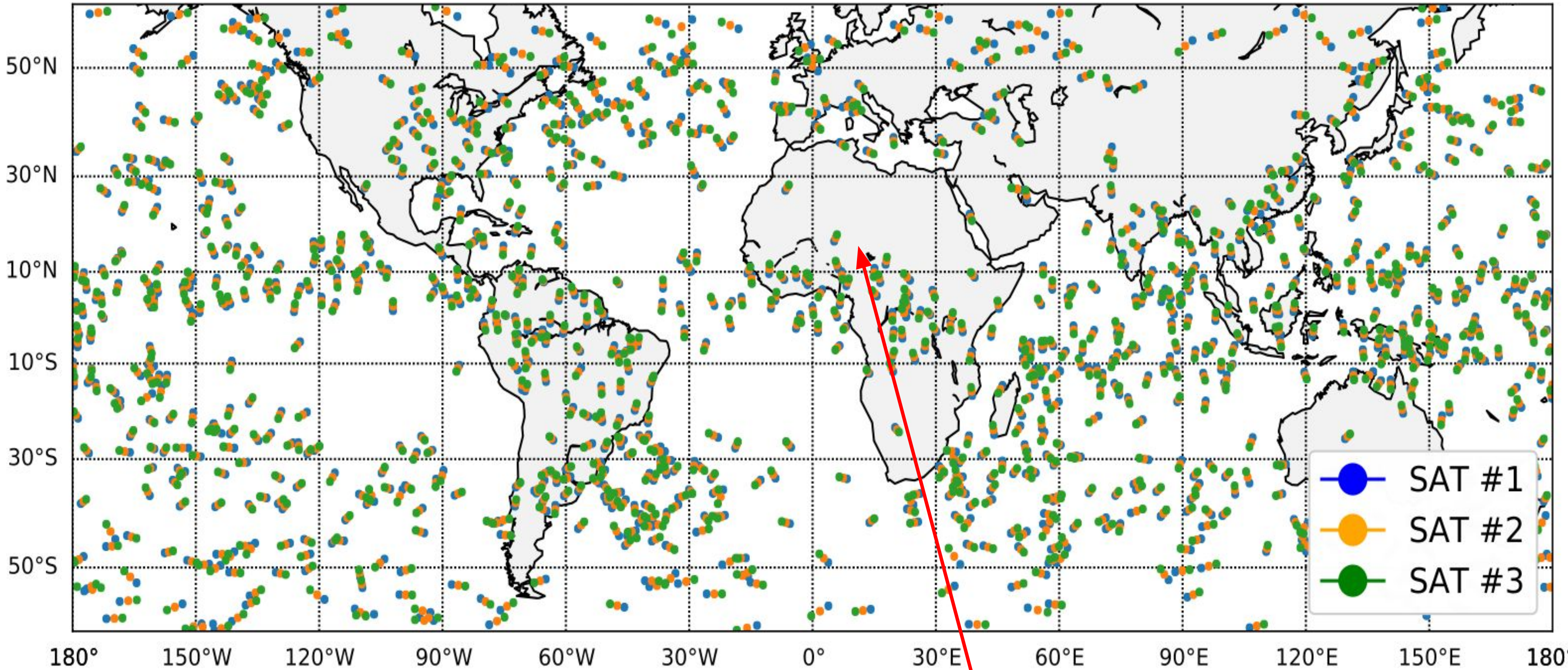
Each color denotes a vertical region where the $\Delta\phi$ from all rays were averaged

Symbols represent cases where the average $\Delta\phi$ was obtained by averaging all RO rays whose tangent point lies between:

0–5 km (black)
5–10 km (orange)
10–15 km (red)

Benefits of a Closely-Spaced Satellite Constellation of Atmospheric Polarimetric Radio Occultation Measurements

3 satellites, 45-deg inclination, each with PRO capability
2-minute time separation between each satellite

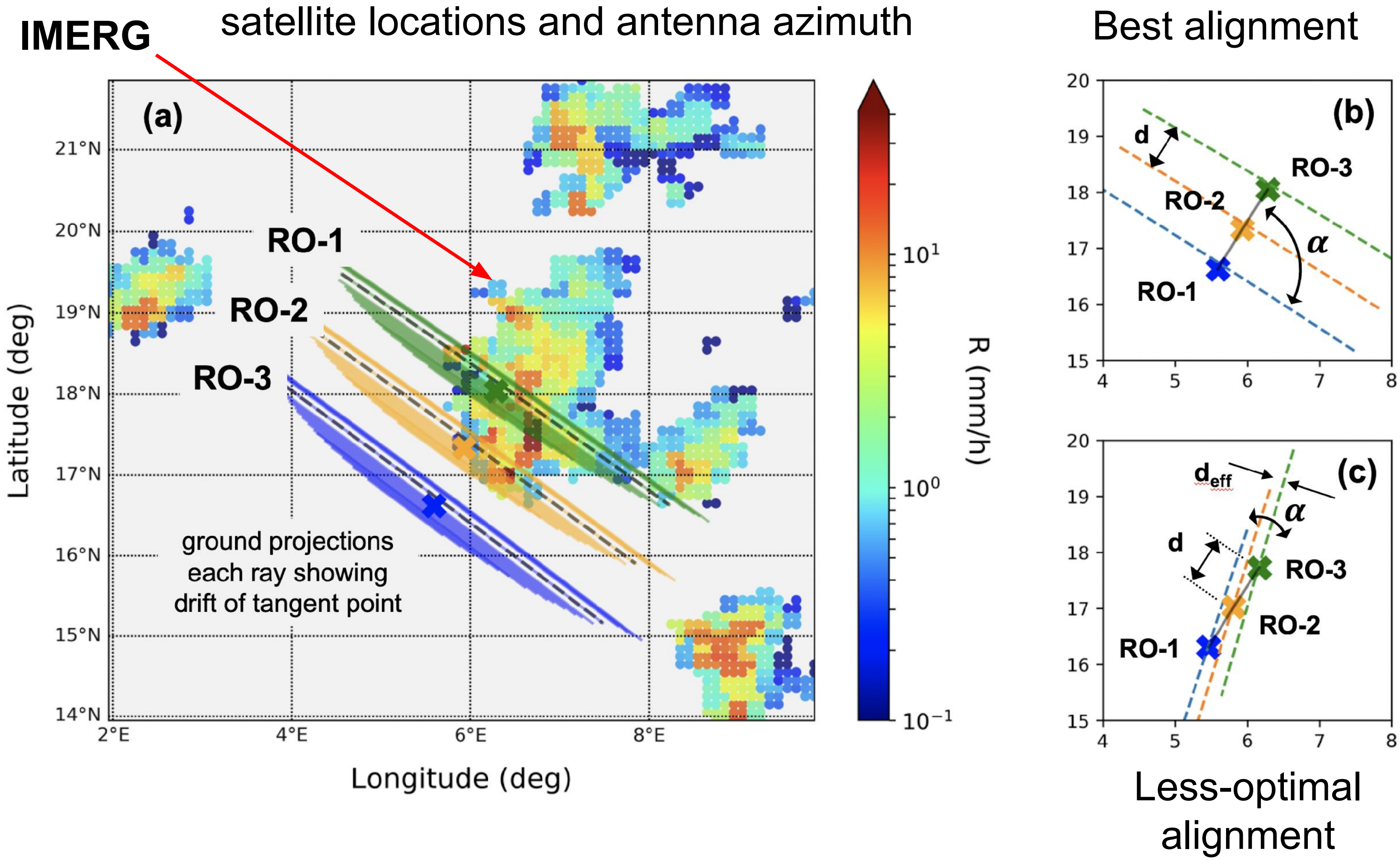


Note that the PRO tangent point locations tends to clump (triplicates), rather than being more equally distributed

Zoom into some specific cases (next slide)

Benefits of a Closely-Spaced Satellite Constellation of Atmospheric Polarimetric Radio Occultation Measurements

Rays align differently depending upon relative satellite locations and antenna azimuth



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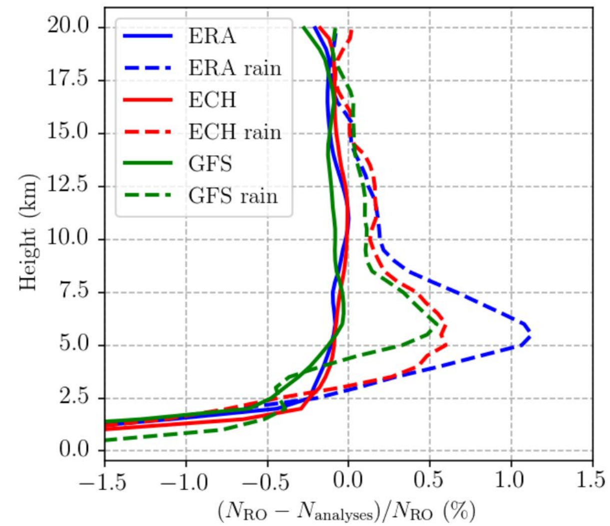
- **Biases under heavy rain**
- Sensing convective systems
- Polarimetry in the bending angle
- Potential for data assimilation

Several studies have reported **Obs-NWPmodel biases when RO occurs under heavy rain**:

- doi:10.1175/2009MWR2986.1
- doi:10.1029/2011JD016452
- doi:10.1175/JAS-D-11-0199.1,
- doi:10.1007/s10291-016-0541-1
- doi:10.5194/acp-18-11697-2018



Hypothesis-1:

scattering terms in the refractivity equation should not be neglected

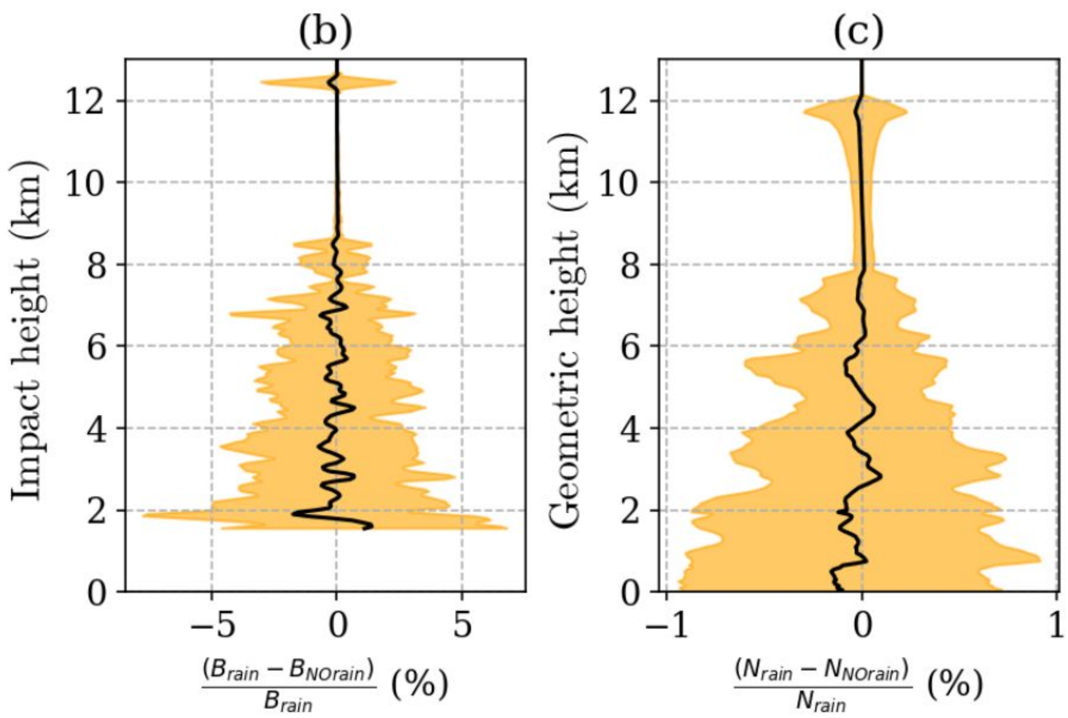
$$N(h) = (n(h) - 1) \times 10^6 = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} - 40.3 \times 10^6 \frac{n_\mathrm{e}}{f^2} + O\left(\frac{1}{f^3}\right) + 1.4W_\mathrm{w} + 0.6W_\mathrm{i},$$

Padulles et al. 2018 (doi:10.5194/acp-18-11697-2018):

Hypothesis-1 tested with simulated rain-induced phase delays from collocated RO and TRMM PR observations:

- compute phase delay from rain;
- subtract this from observed phase to get "rain-free" phase;
- retrieve BA and N from "rain-free" phase;
- compare "rain" and "rain-free" retrievals;

→ **No appreciable bias**.

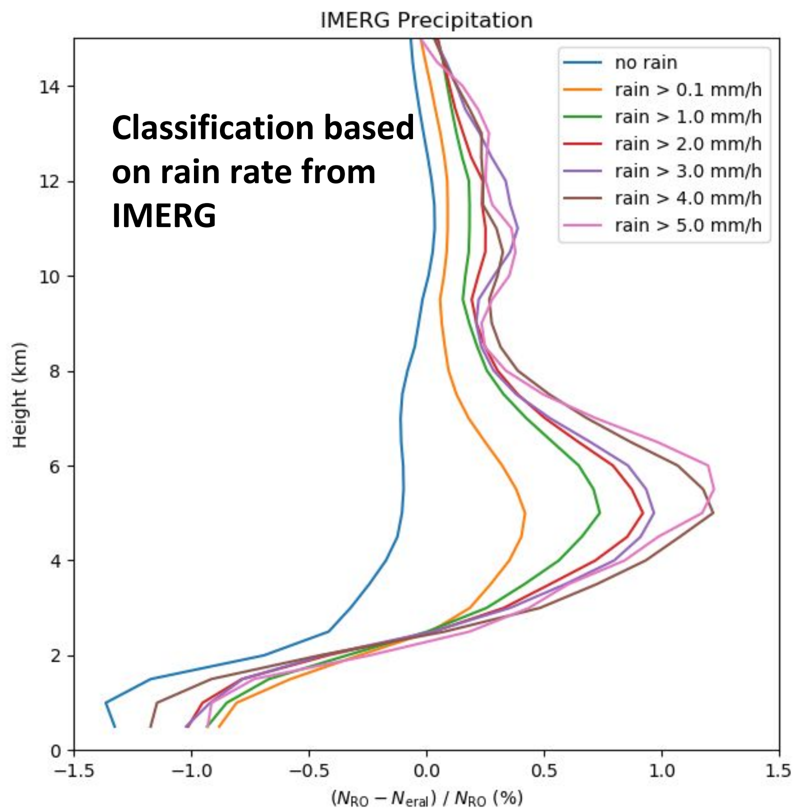


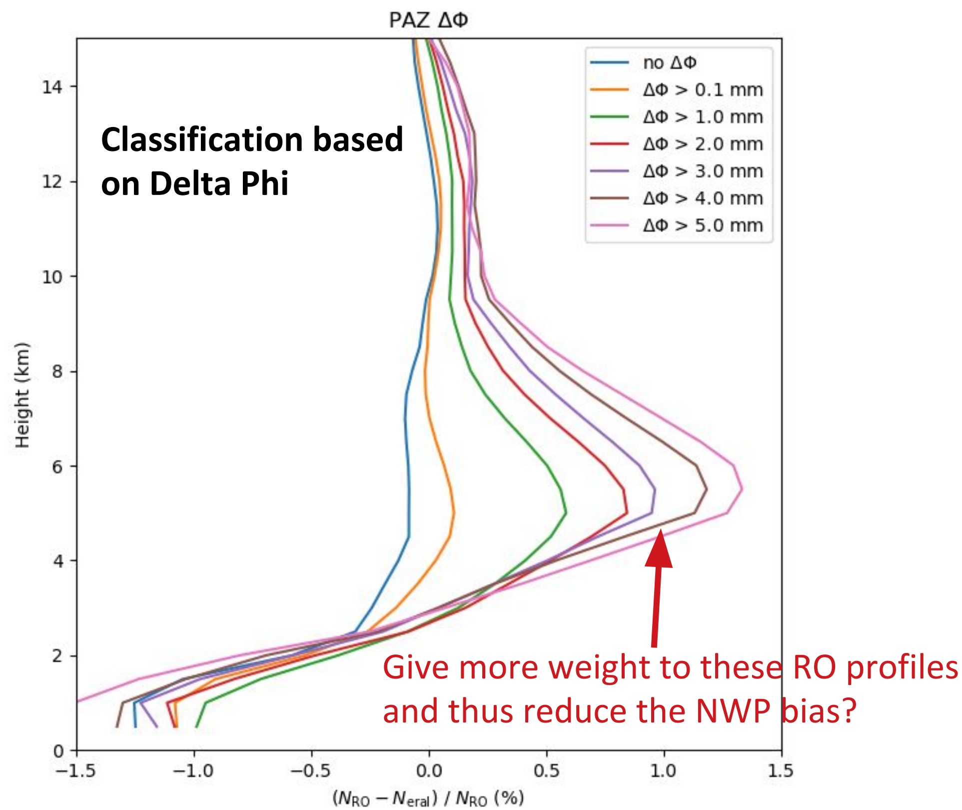
→ **Hypothesis-2: bias mostly due to NWP model**

NWP:

- Could PAZ data help better assess NWP bias under heavy precip conditions? Could identification of these conditions help improve NWP DA (e.g., more weighting to RO obs)?

Unpublished figures, done with PAZ data:





PURPOSE OF THIS PRESENTATION

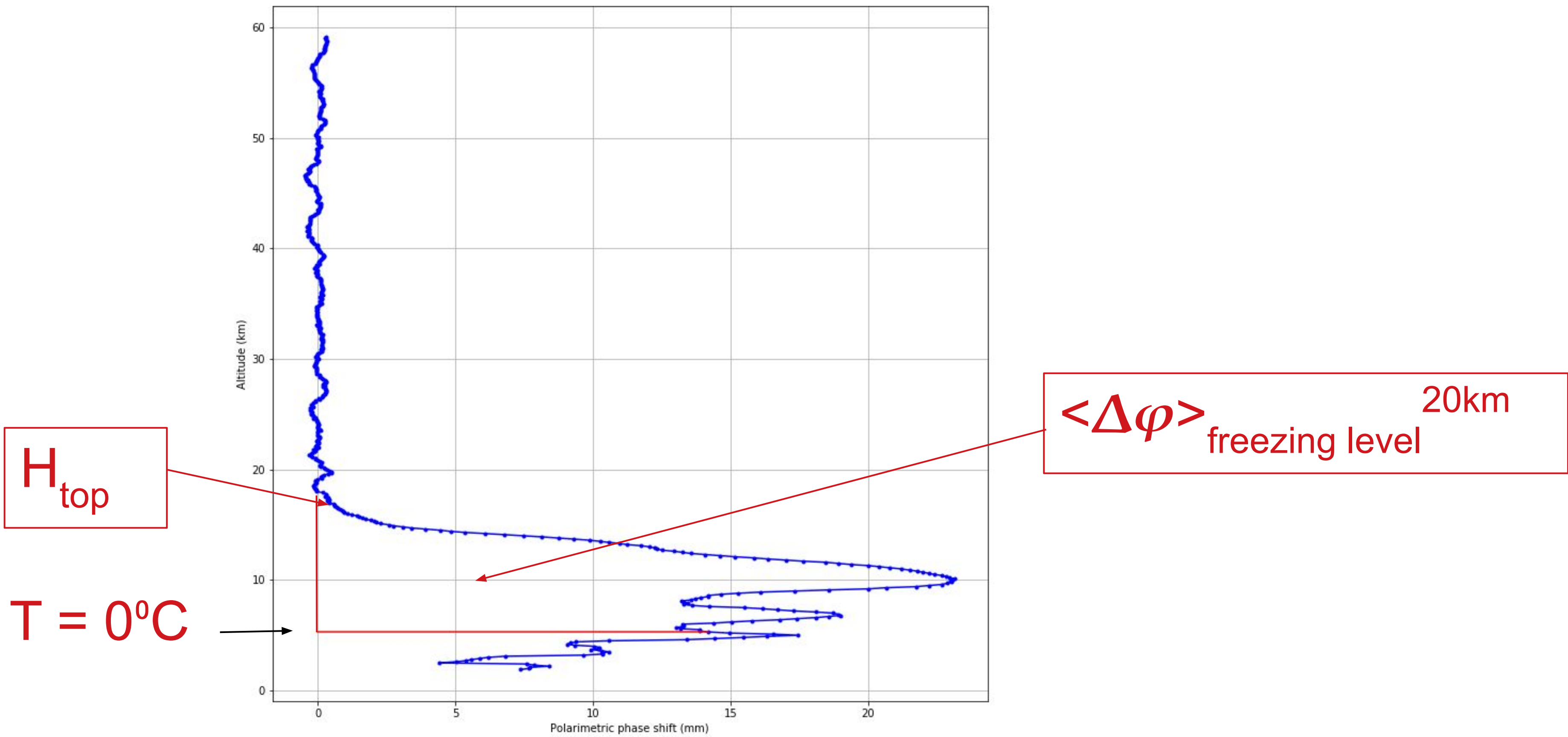
UNDERSTANDING PAZ DATA

APPLICATIONS RELEVANT TO CLIMATE

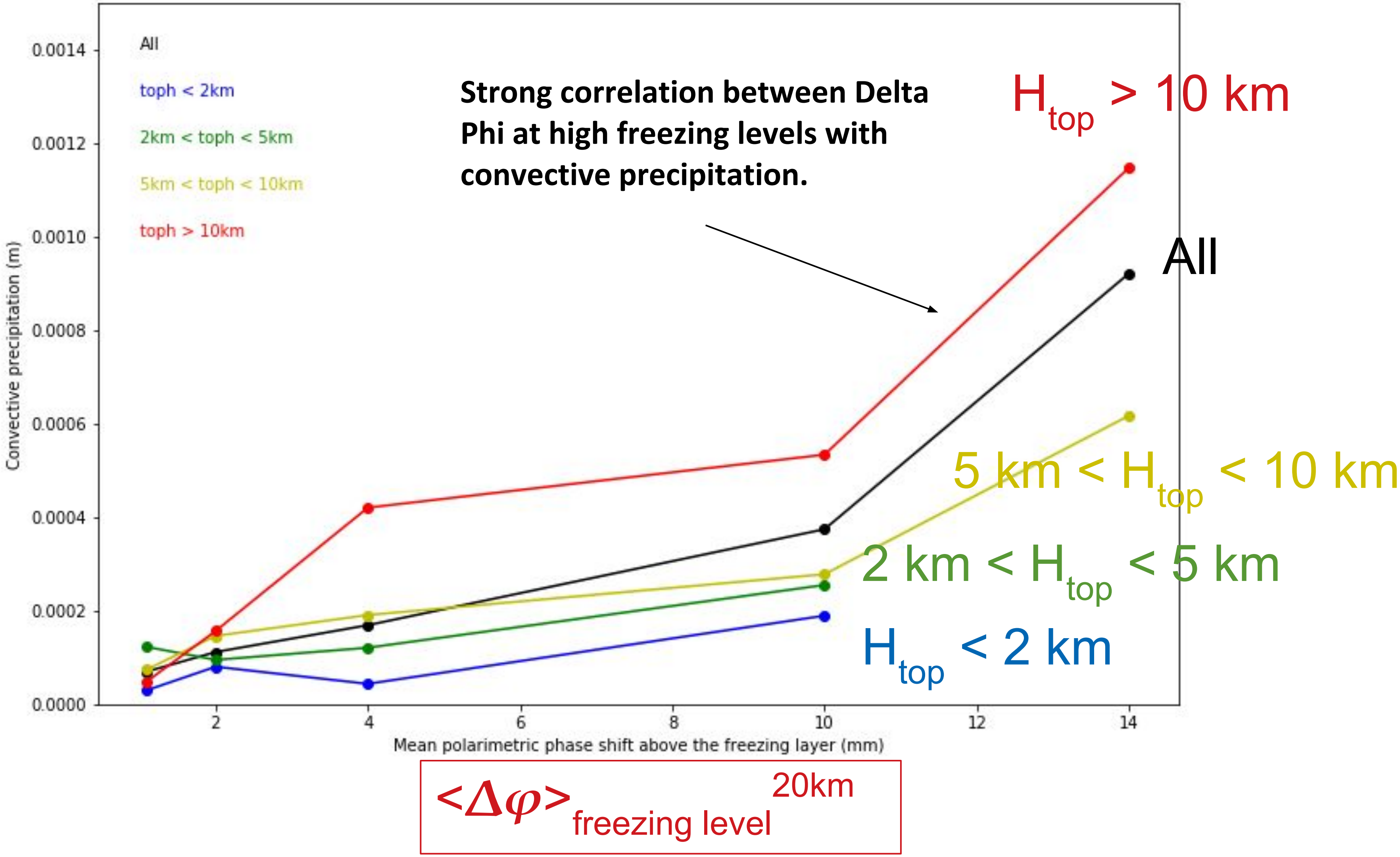
APPLICATIONS RELEVANT TO NWP

- Biases under heavy rain
- **Sensing convective systems**
- Polarimetry in bending angle
- Potential for data assimilation

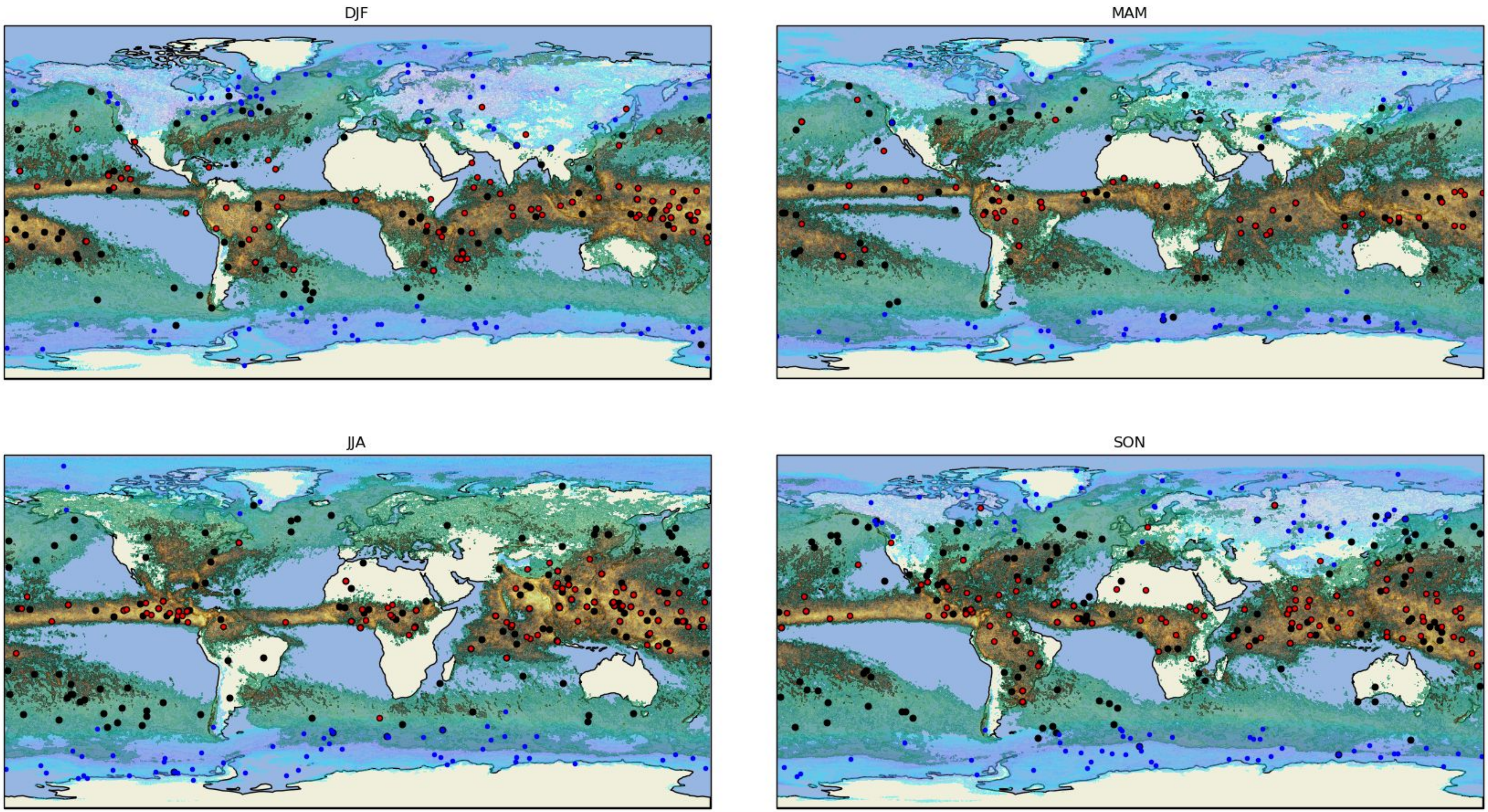
- **Vertical structure of Delta Phi could provide additional information on the type of precipitation system.**



- # Convective precipitation from ERA-5:



Preliminary study: 4.5 months of PAZ data



seasonal avg. from GPM constellation

- Convective precipitation
- Surface precipitation
- Frozen precipitation

- PAZ occs with <Δϕ> between 10 - 15 km > 1 mm
- PAZ occs with <Δϕ> between 0 - 10 km > 4 mm
- PAZ occs with <Δϕ> between 0 - 5 km > 2.5 mm and max(T) < 273K

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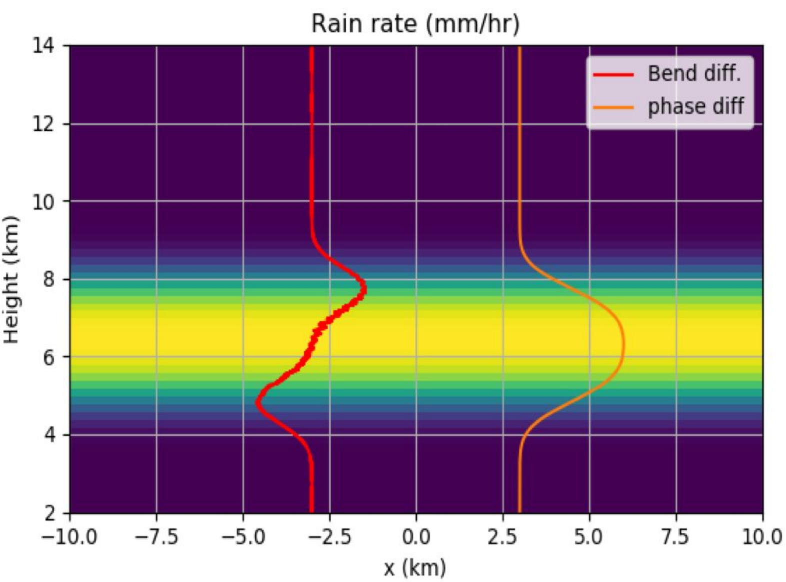
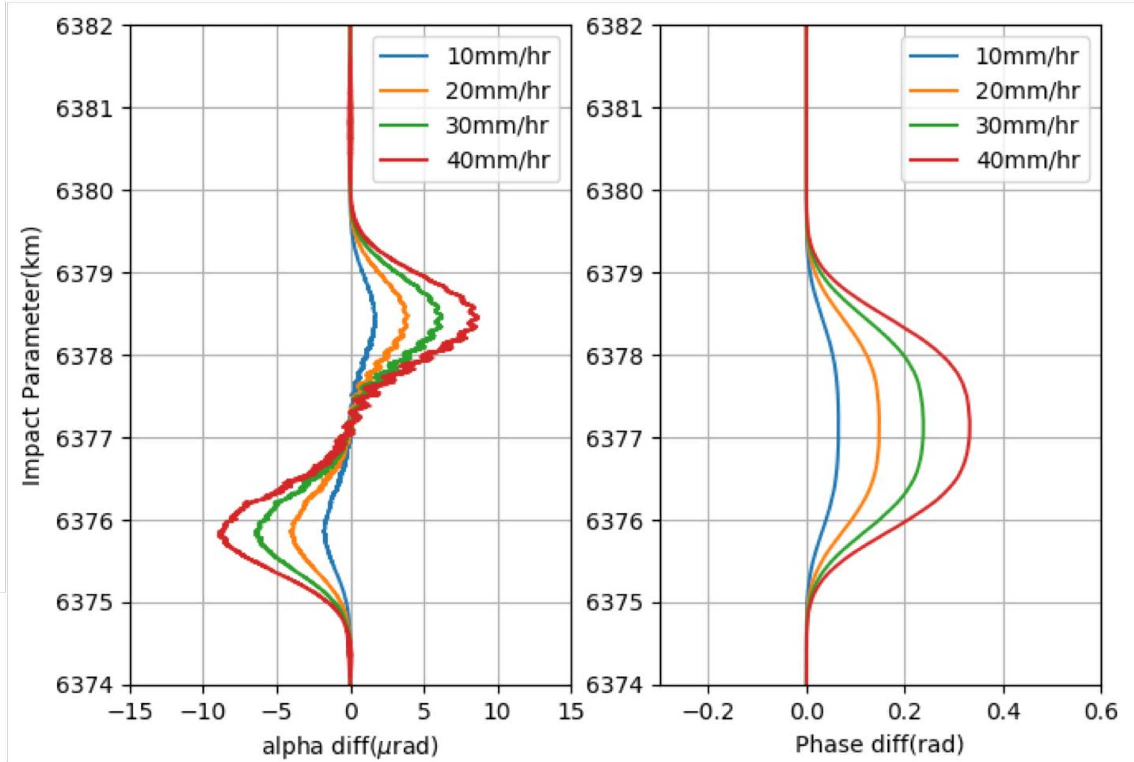
NWP:

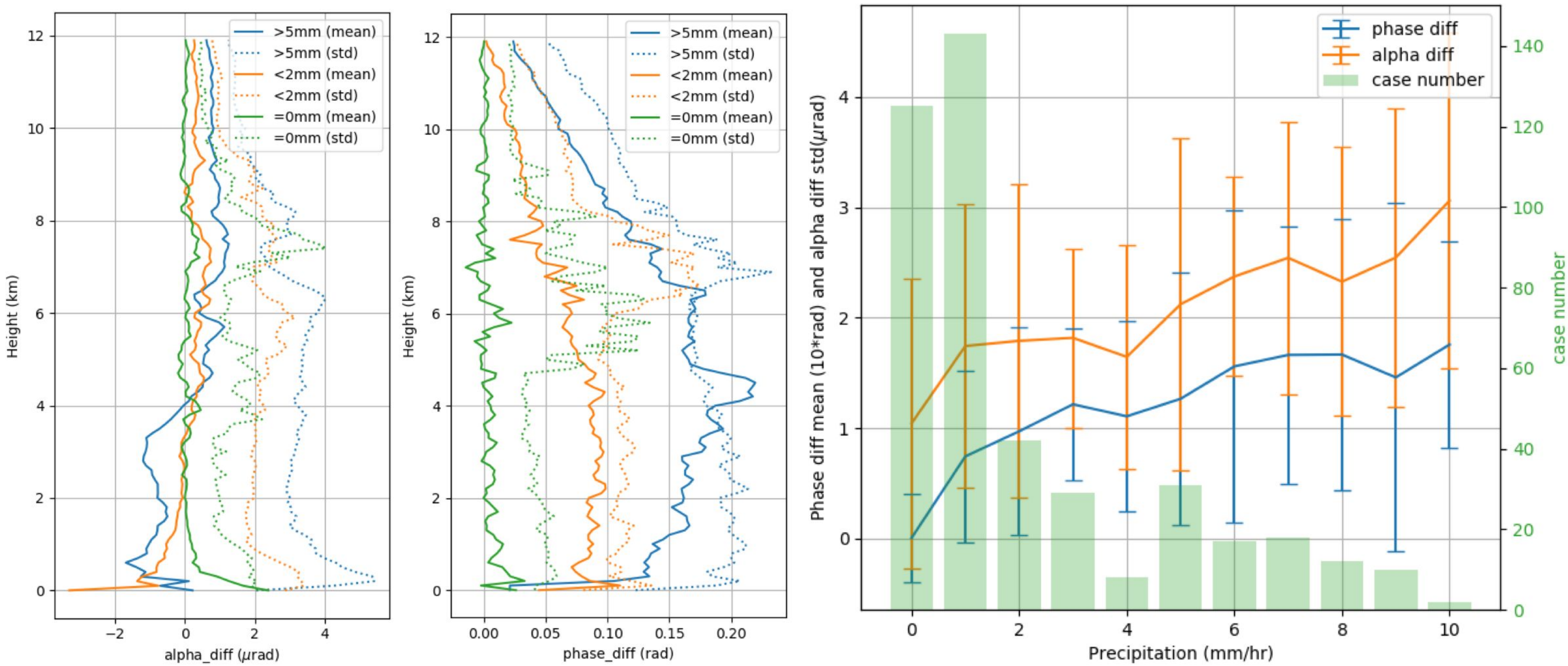
- Bending angle (BA) is an intermediate retrieval parameter commonly used in NWP RO data assimilation.
- Similar to H-V phase, H-V BA is sensitive to precipitation. Unlike phase, the effect on H-V BA can be either positive or negative.

Simulation Results





PAZ statistical results show that the **mean of H-V phase** and **stdev of H-V bending angle** increase with increasing precipitations in a similar way.



Could PAZ H-V BA be more suitable for NWP DA?

PURPOSE OF THIS PRESENTATION

UNDERSTANDING PAZ DATA

APPLICATIONS RELEVANT TO CLIMATE

APPLICATIONS RELEVANT TO NWP
- Biases under heavy rain
- Sensing convective systems
- Polarimetry in the bending angle
- **Potential for data assimilation**

- Assimilation of polarimetric RO into NWP models?
  - Forward operators implementation:
    - Along-ray trajectory for integral evaluation as in RO 2D operators $$\Delta\phi_{pol} = \Delta\phi_H - \Delta\phi_V = \int_{GPS}^{LEO} K_{dp}(l)\, dl$$
    - K_{dp} for integration could be tabulated given rain DSD and parameters of the other hydrometeors.
    - **What is the link between water and cloud ice parameters in NWP model and K_{dp}?**

QUESTION POSED BY SEVERAL PARTICIPANTS IN THE GOOGLE-FORM, TO BE DISCUSSED AFTER THE BREAK

- Would any impact be expected?

Sensitivity to microphysics schemes

[Presentation by Murphy/Haase after the break]

- Murphy et al., 2019 (doi:10.3390/rs11192268): Simulations of GNSS polarimetric RO aboard an aircraft during an Atmospheric River event.
- Two numerical experiments were run using a mesoscale model configured with **two different microphysical parameterizations**.
- The $\Delta\varphi_{pol}$ **due to hydrometeors differed significantly** in the two experiments, suggesting that PRO observations have the potential in <u>validating and improving the representation of microphysical processes in numerical weather forecasts</u>.

rohp-PAZ

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

Backup slides

Paz Background

- Launched Feb 22 2018
- Spanish SAR satellite based on TerraSAR-X
- Radio Occultation Heavy Precipitation (ROHP) IGOR instrument a secondary payload
- JPL heritage instrument
- Special purpose multiple patch antenna has separate outputs for Horizontal and Vertical polarizations
- These outputs are processed by the IGOR as separate antenna inputs, similar to fore and aft antennas on other spacecraft
- This approach is a simple change to IGOR firmware, but adds complexity to ground data processing due to separate time stamps for each polarization
- The separate H and V channels are intended for rain detection, but can use this extra information to enhance normal radio occultation (RO) processing.

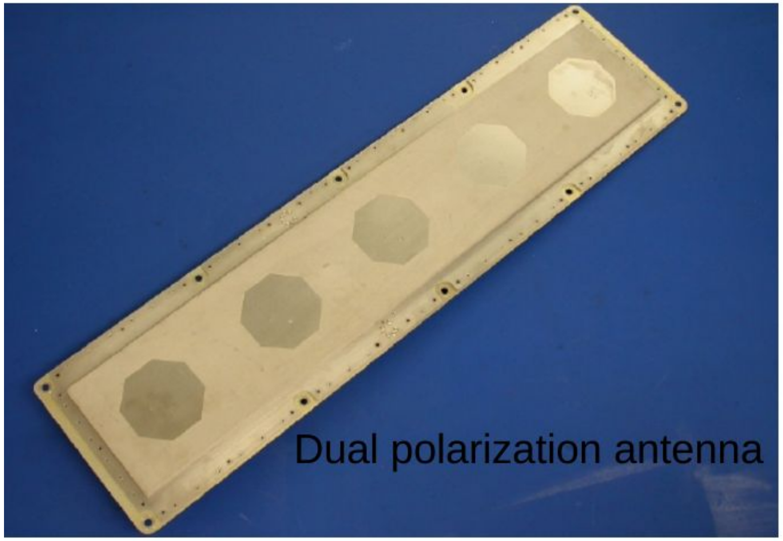
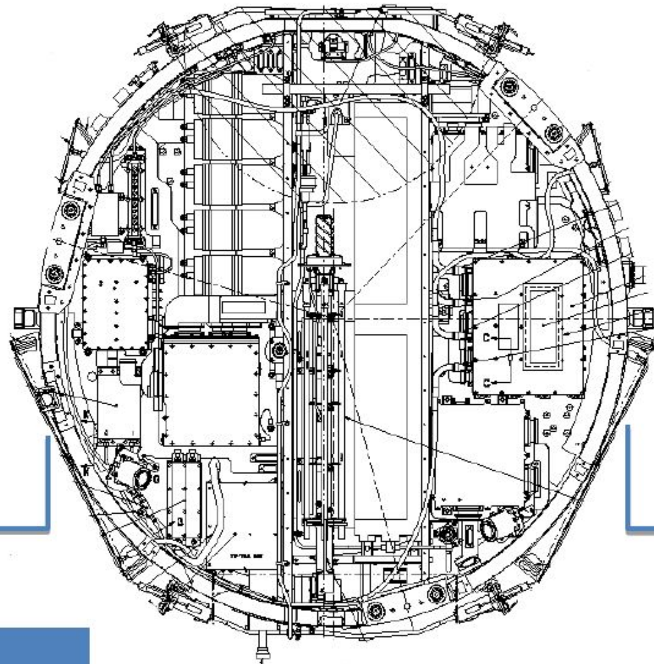


Photo credit: Estel Cardellach, ICE CSIC

Multi-antenna High Rate Data Packaging



COSMIC-1

Antenna 3
(Occultation)

Antenna 2
(Occultation)

High rate data, antenna 3	
Time	1233014435 .0000254
PRN	23
Phase	...
SNR	...

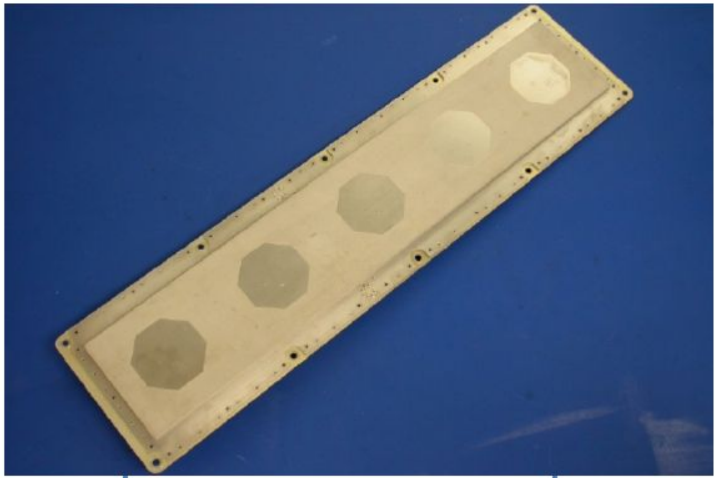
Separate data packets per antenna

Different times

Different PRNs

High rate data, antenna 2	
Time	1233014435 .0000255
PRN	24
Phase	...
SNR	...

Paz High Rate Data Packaging



Paz

H polarization antenna input

V polarization antenna input

High rate data, antenna 2	
Time	1233014435 .0000254
PRN	23
Phase	...
SNR	...

Separate data packets per polarization, same antenna

Different times

Same PRN

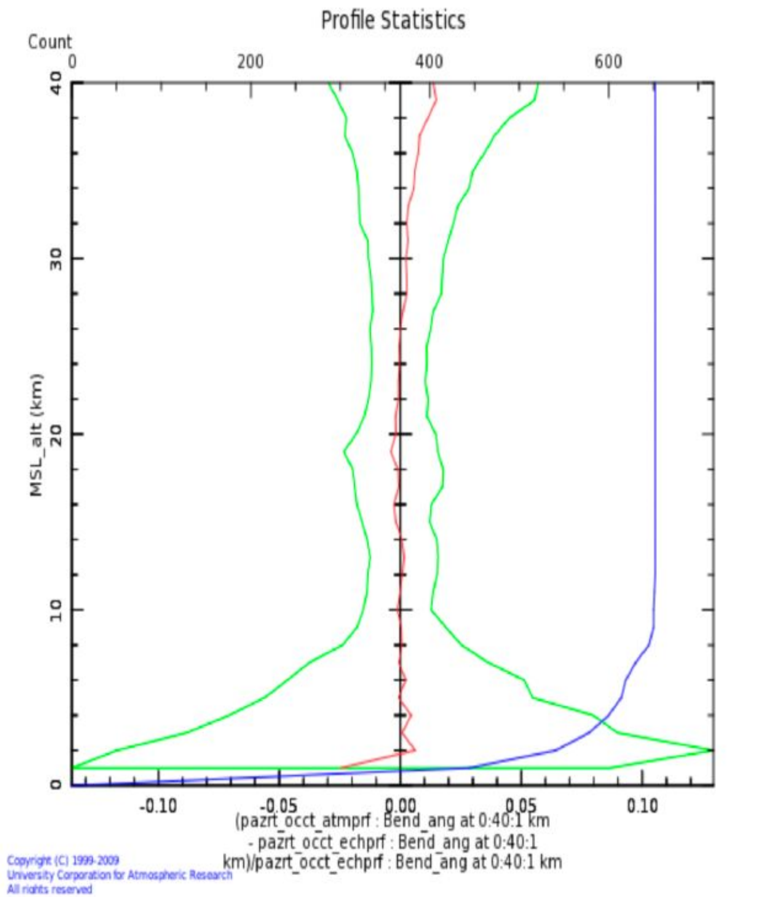
High rate data, antenna 3	
Time	1233014435 .0000255
PRN	23
Phase	...
SNR	...

V and H compared

Single-polarization statistics similar

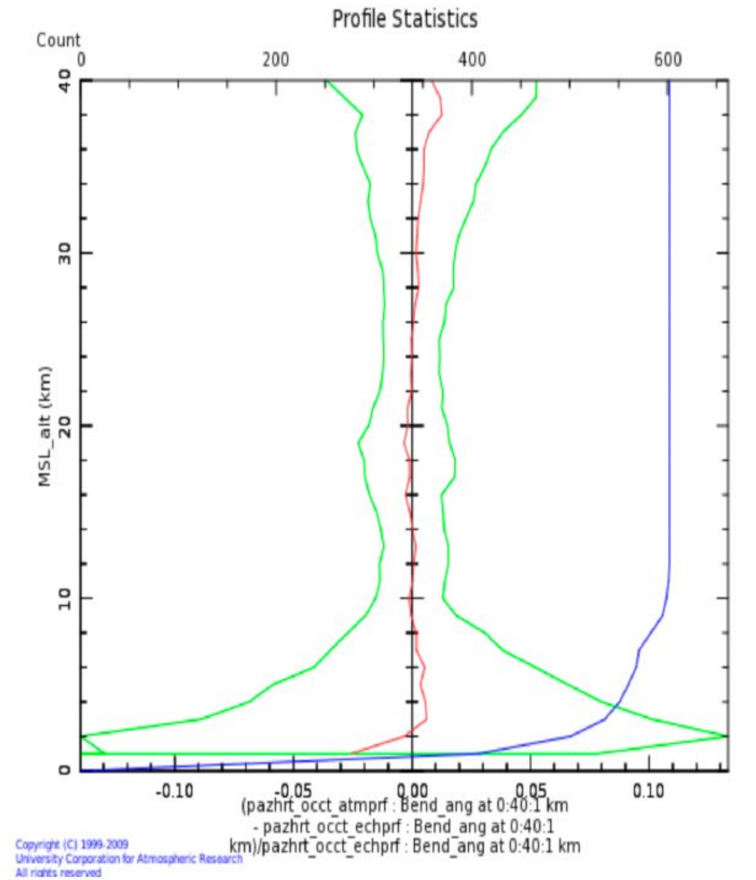
Vertical

Constraints applied: (pazrt_occt_atmprf.bad = 0) AND ((pazrt_occt.yrdoy <= 2018137) AND (pazrt_occt.yrdoy >= 2018130))



Horizontal

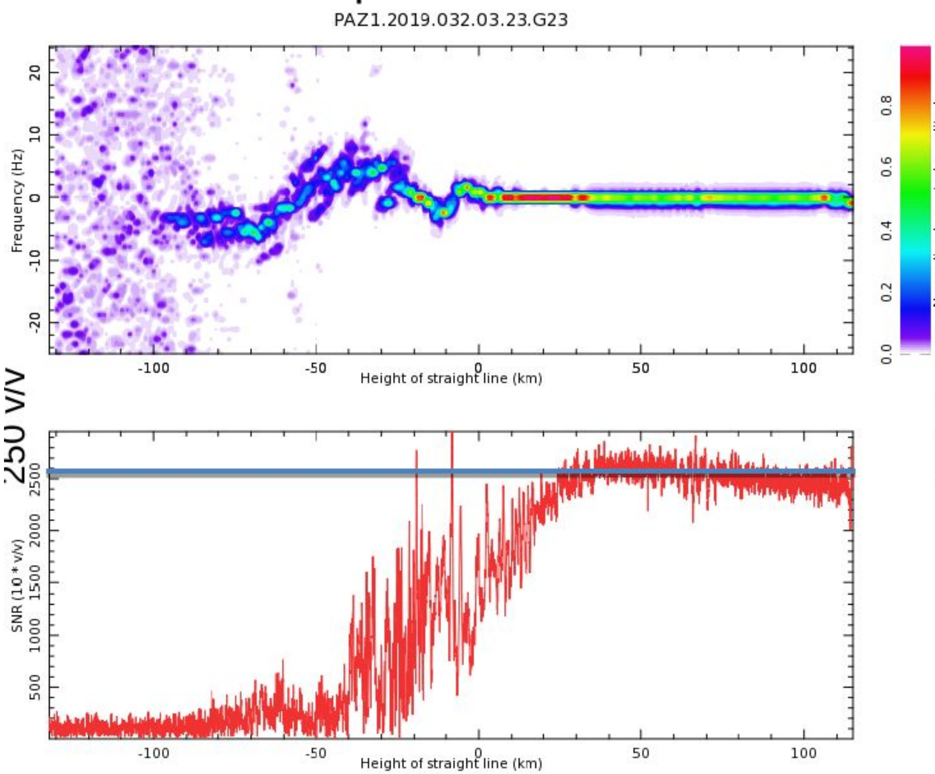
Constraints applied: (pazhrt_occt_atmprf.bad = 0) AND ((pazhrt_occt.yrdoy <= 2018137) AND (pazhrt_occt.yrdoy >= 2018130))



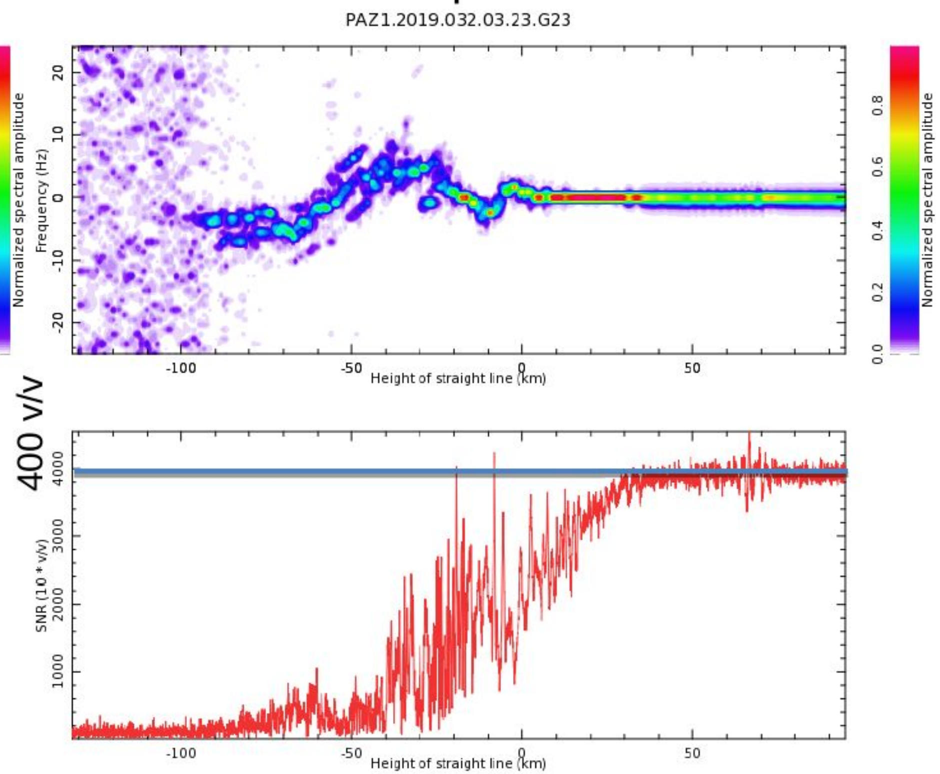
Spectrogram comparison

Note the larger SNR for the horizontal polarization case. In other cases, vertical polarization has higher SNR. Both can be combined to yield higher SNR.

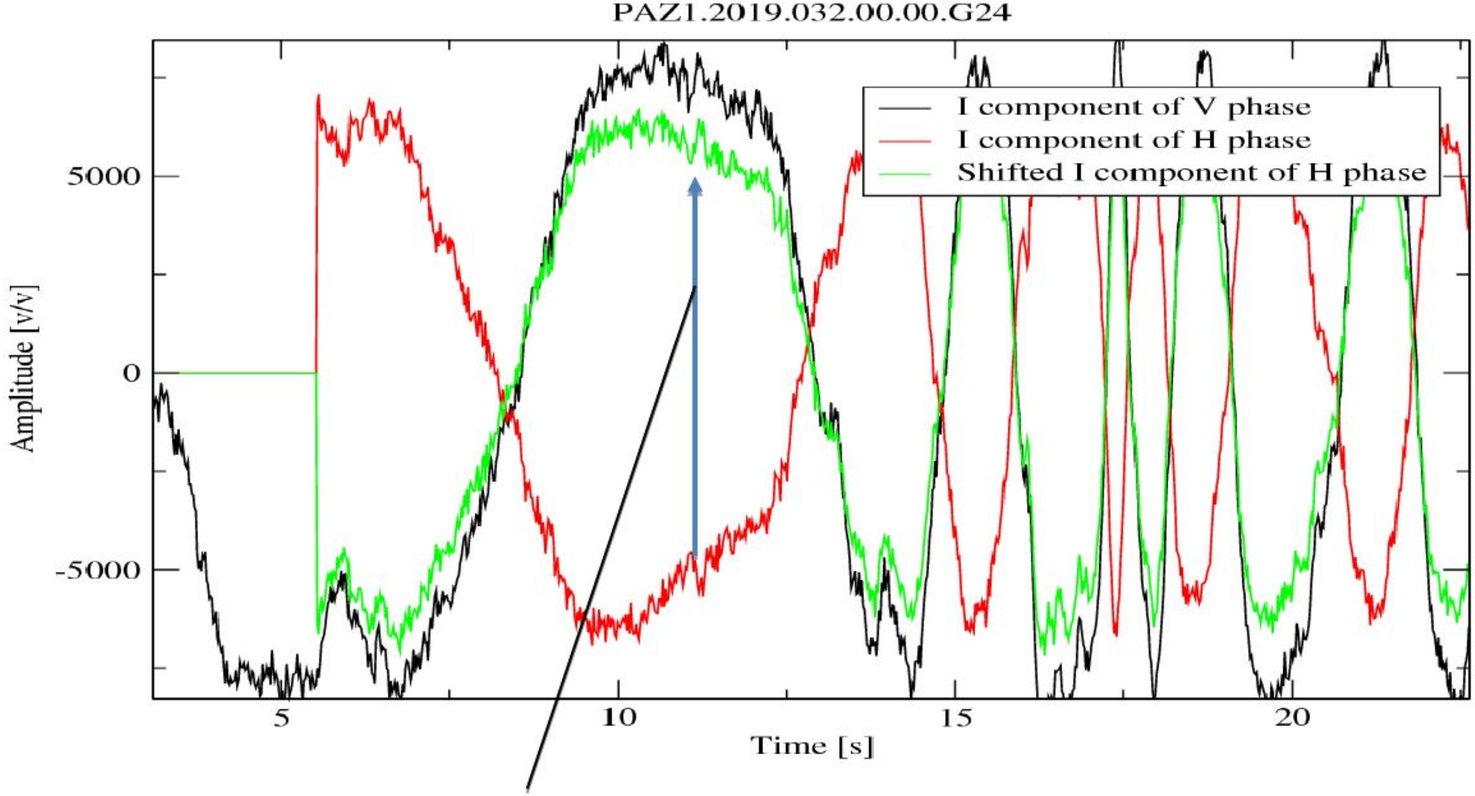
Vertical polarization



Horizontal polarization



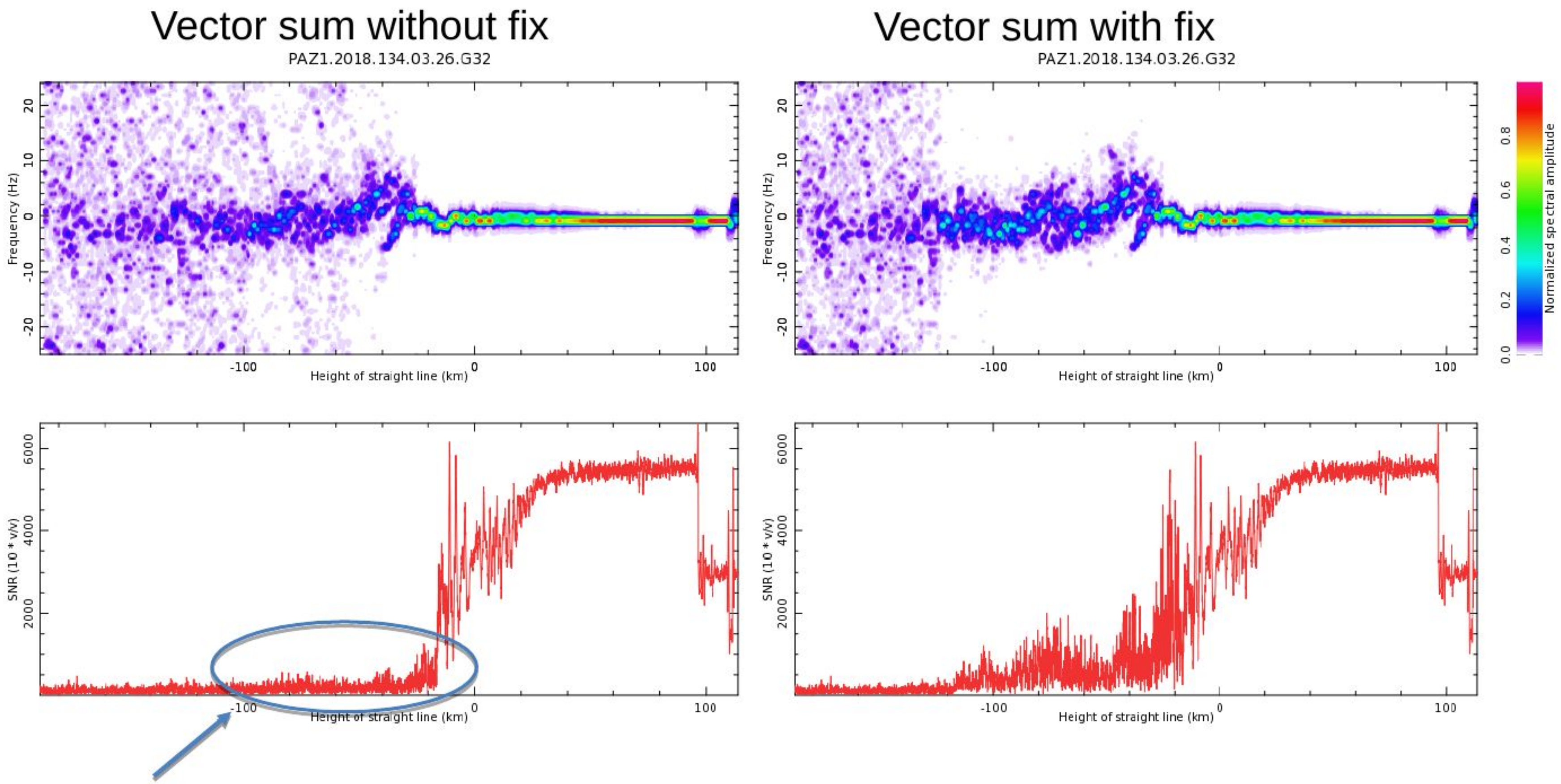
Aligning V and H polarization phases



H phase is shifted 2.9 radians to align with V phase

Now I and Q components of H and V can be added constructively

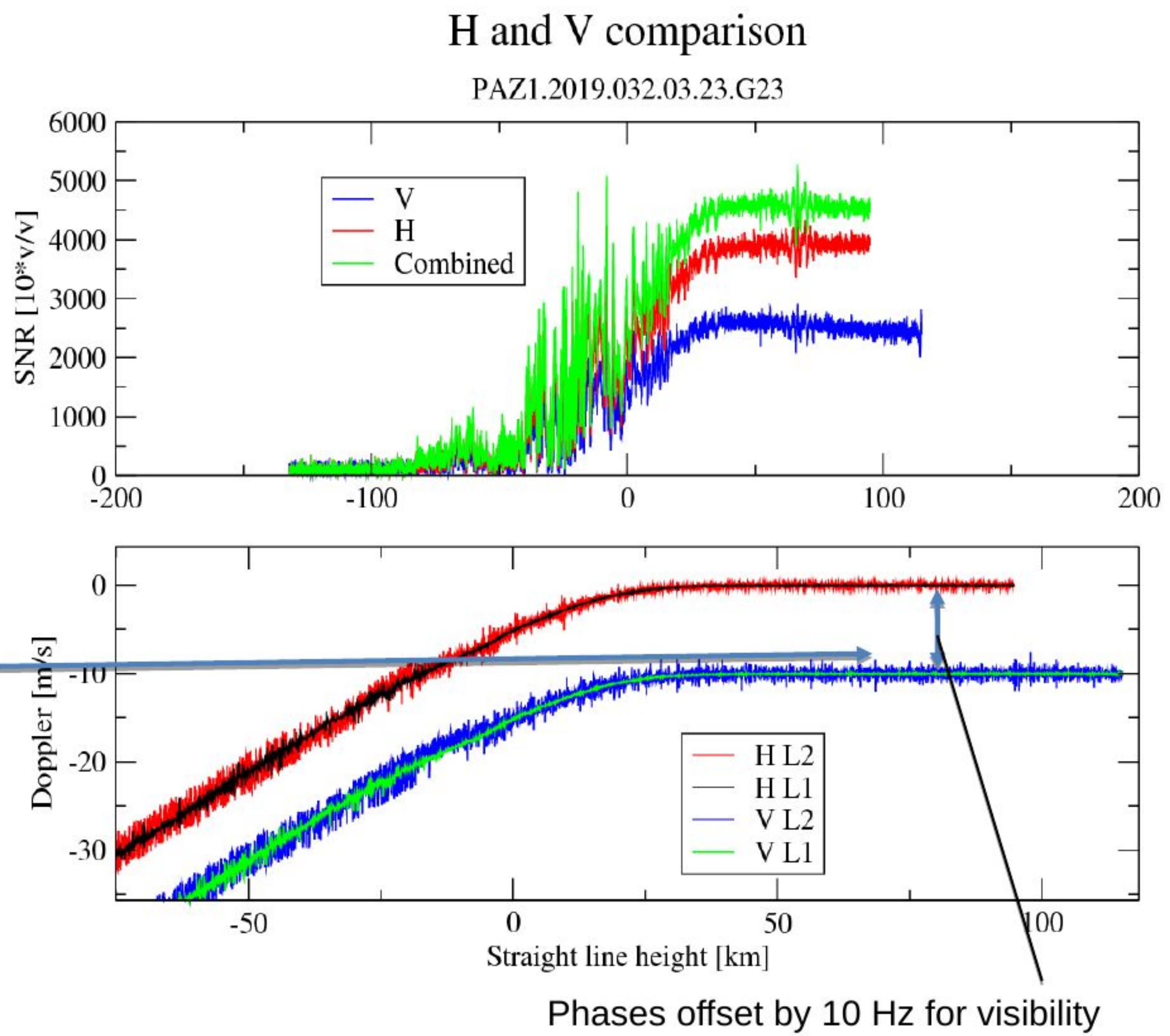
Fixing ½ cycle slips in the slave by comparison with the master



If ½ cycle slips are not fixed in the slave polarization, then there is substantial cancellation when the two are added, as shown at left.

Choosing V or H for master polarization

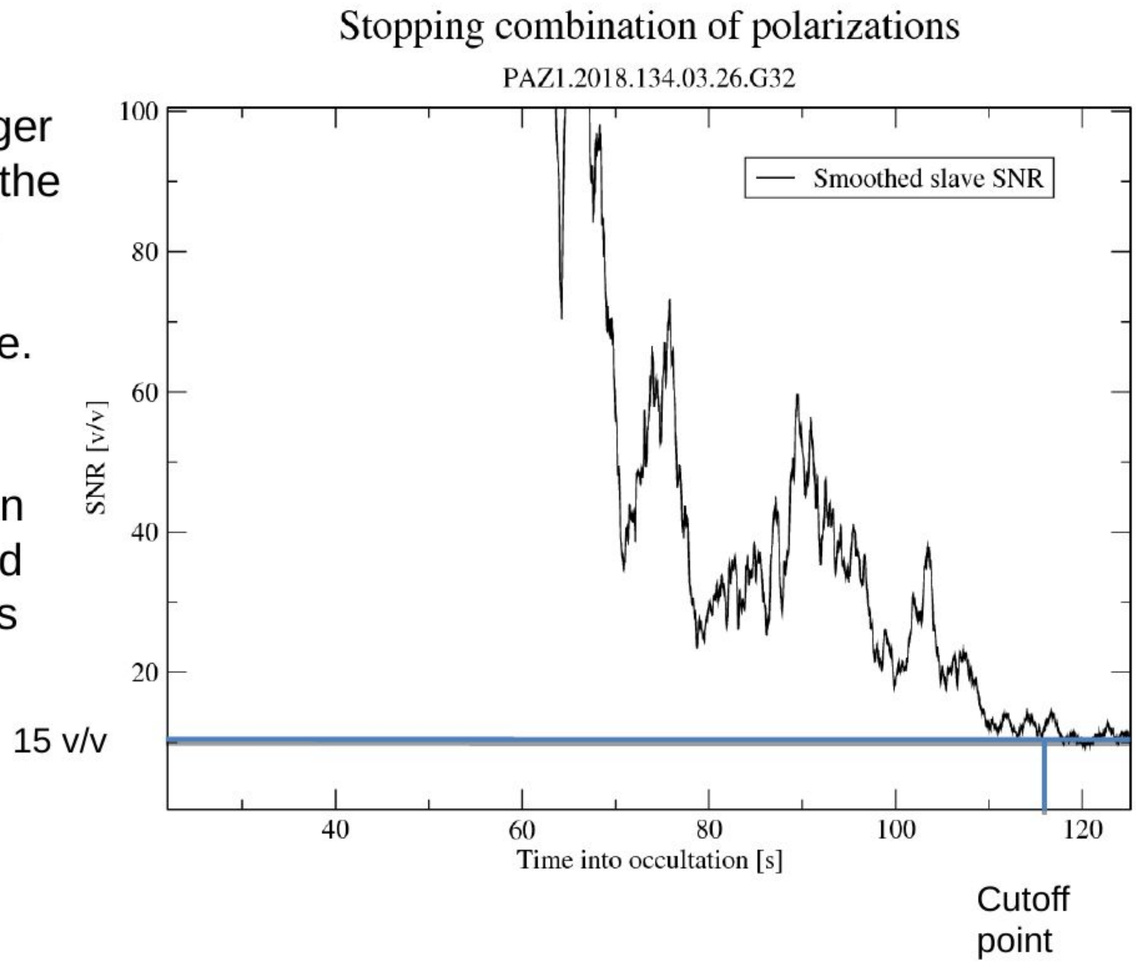
- Originally I always chose V for the 'master' polarization, but found that in many cases H worked better
- In this occultation, the single-polarization H processing passed QC, whereas the V processing did not.
- Note the higher L2 Doppler noise for V
- Master polarization is chosen by higher average SNR, so for this occultation H is chosen over V



Determining when to stop combination

The combination of polarizations no longer makes sense when the SNR gets too low—this can result in an amplification of noise.

We cut the combination off when the boxcar-smoothed slave SNR descends below 15 v/v



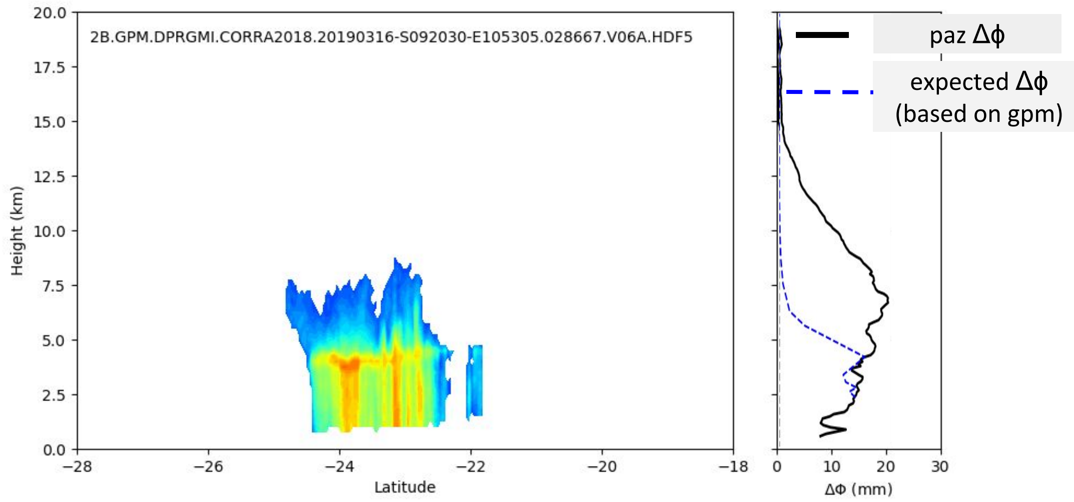
UNDERSTANDING POLARIMETRIC SIGNATURES ON PAZ DATA

What are we sensing?

The other way around:

Look for similar cases based on real PAZ Δϕ profiles:

- PAZ Δϕ within margins of simulated profiles
- Similar latitudes



The TRMM - CSAT coincidence show an scene quite similar to that observed by GPM. The part that GPM misses and cloudsat would see could explain the signatures above 5 km