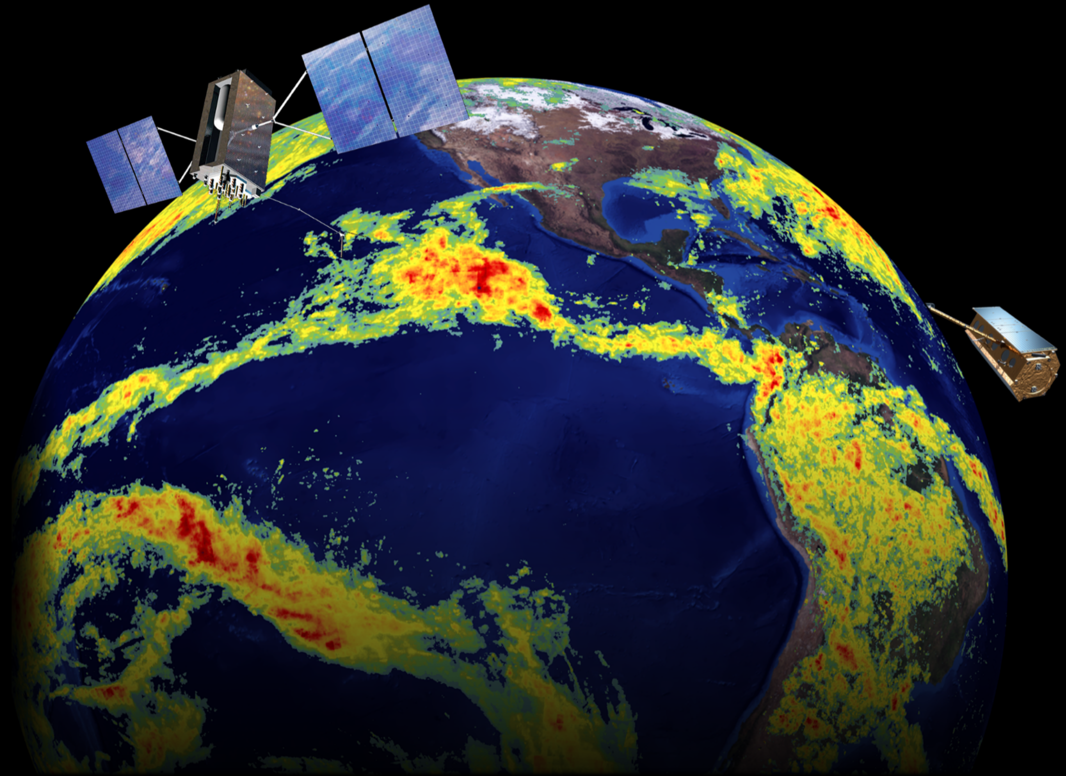

2019 Postdoc Seminar Series

Sensing heavy precipitation with GPS Polarimetric Radio Occultations:

A new view of precipitation and water vapor

Ramon Padullés[1*],

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Jet Propulsion Laboratory
California Institute of Technology

Outline

- Motivation
- GNSS Radio Occultations
- Polarimetric Radio Occultations concept
- Timeline
- Simulations and predicted performance
- ROHP PAZ experiment
    - Results after 9 months of operation
    - Calibration and Validation
    - Sensitivity to precipitation

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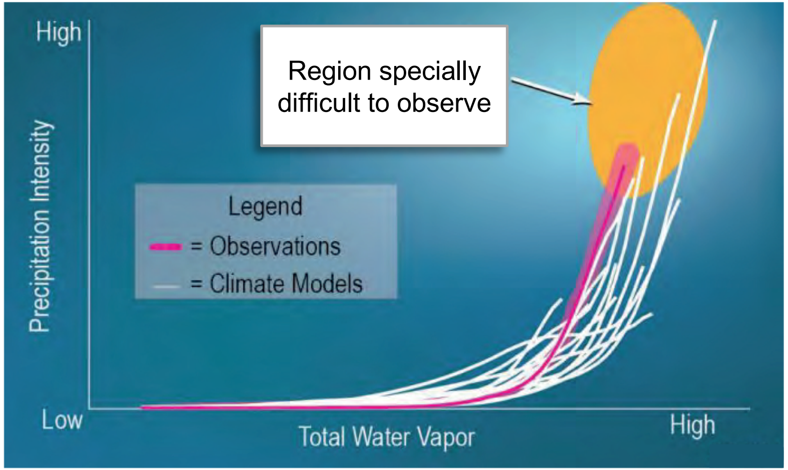
Motivation

To provide simultaneous observations of thermodynamics and heavy precipitation

Thermodynamics of heavy precipitation

- IR / MW sounders have problems penetrating clouds, surface calibration, vertical resolution
- Radiosondes remain fixed to certain locations
- Rely on collocated measurements for rain
- In the study of heavy precipitation and deep convection, this **lack of observations** results in uncertainties and discrepancies in modelling and predicting precipitation



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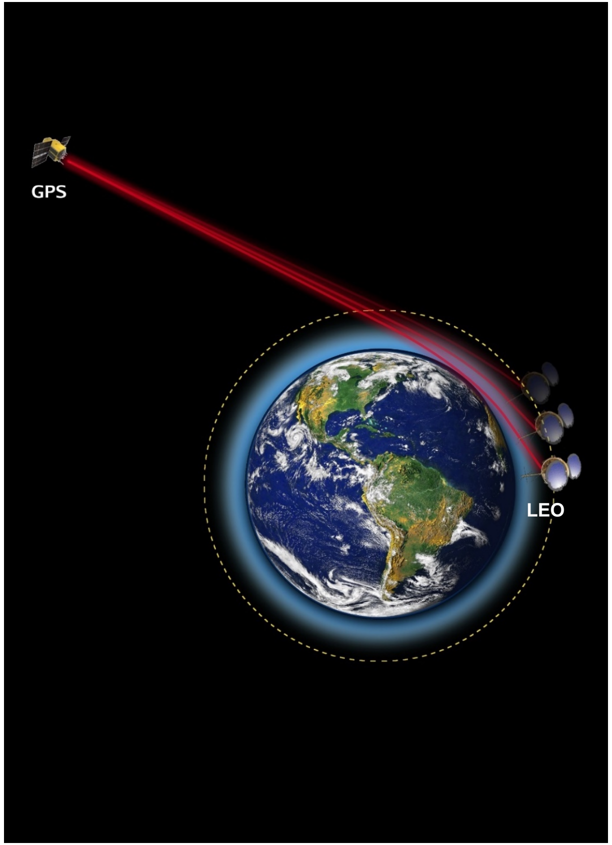
GNSS Radio Occultations



- LEO tracks the radio wave from GPS while occulting behind Earth
- The radio links bend as they penetrate into the atmosphere, due to changes in the refractive index (*n*)

- GPS RO receivers can track very precisely the phase. With very precise knowledge of the positions of the satellites we can infer the delay due to the atmosphere

Excess phase <-> Doppler shift

↓

Bending angle α*(h)*

↓

Refractivity profile N = N(*T,P,wv*)

↓

Thermodynamic vertical profiles

Temperature, Pressure, water vapor

- Globally distributed
- High vertical resolution
- No calibration required
- Over all surfaces
- Through all clouds

- **No precipitation**

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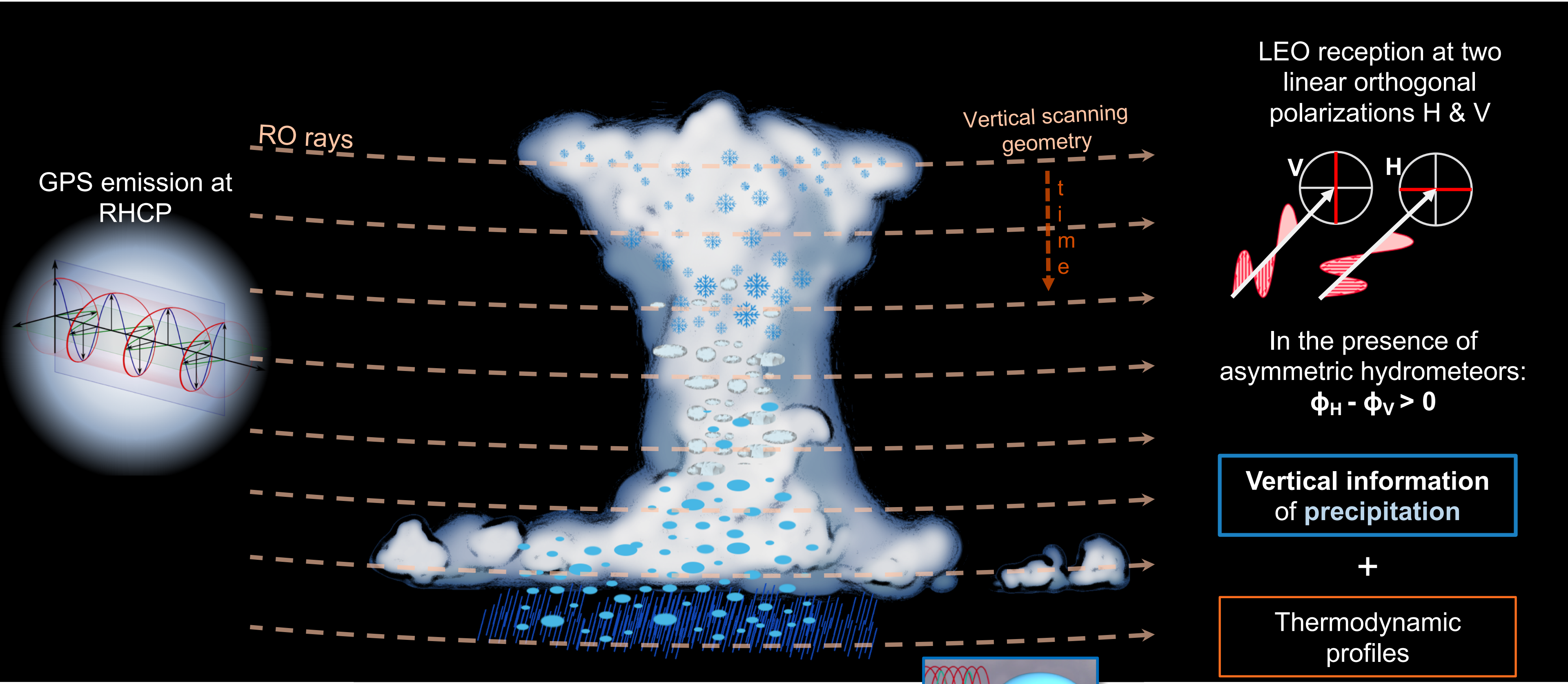
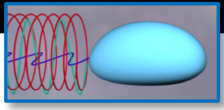
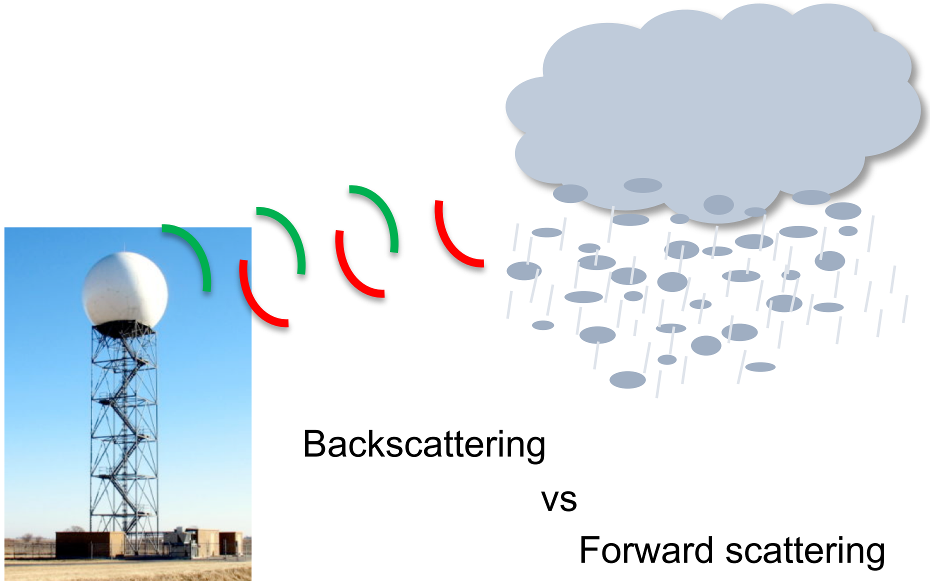
Polarimetric Radio Occultations (PRO)





Polarimetric Radio Occultations (PRO)

Fundamentals behind the concept have been extensively tested by Polarimetric Weather Radars
(e.g. modern NEXRAD)

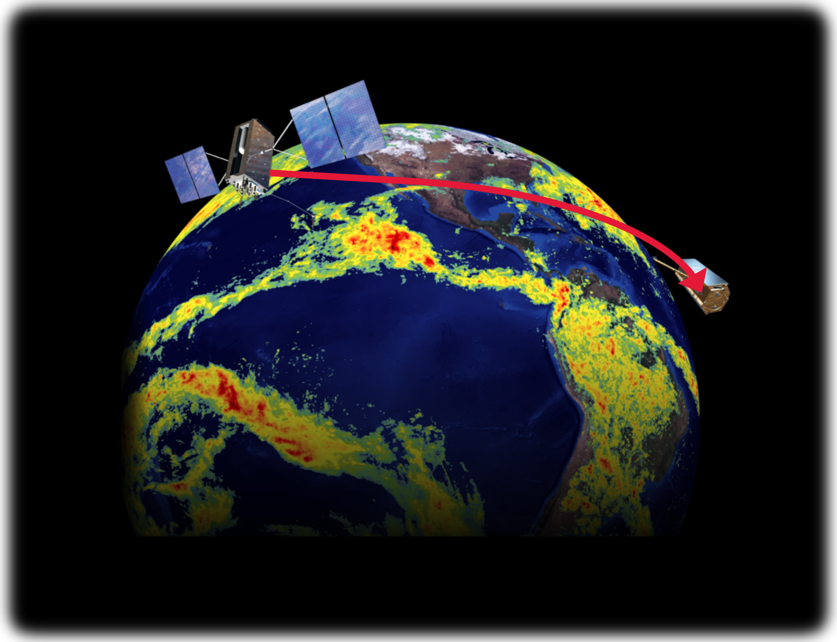


Backscattering

vs

Forward scattering

PRO are being tested for the **first time** with the Spanish PAZ satellite



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Timeline

- **~2006 –** Opportunity to include a scientific payload using the GPS receiver in a Spanish satellite to be launched in 2012.
- **2009 –** Spanish Ministry for Science and Innovation approves a proposal to include a Polarimetric RO (PRO) payload in PAZ satellite. PI: Estel Cardellach (ICE,CSIC, IEEC)
- **2012-2014 –** Theoretical sensitivity analyses show that PRO should be able to detect heavy precipitation *(Cardellach et al. IEEE TGRS)*
- **2013-2015 –** Field Campaign in Barcelona: first GNSS signals acquired with a 2-pol antenna for rain detection. First results suggest sensitivity to rain *(Padullés et al. ACP)*
- **2018 –** PAZ launch
- **2018 –** First PRO collected from space. First evidences that PRO is sensitive to heavy precipitation *(Cardellach et al. GRL)*

Timeline

- **~2006 –** Opp … eiver in a
  Spanish satelli …
- **2009 –** Spanis … include a
  Polarimetric R … SIC, IEEC)
- **2012-2014 –** T … e to detect
  heavy precipita …
- **2013-2015 –** F … ith a 2-pol
  antenna for rai … *al. ACP)*
- **2018 –** PAZ la …
- **2018 –** First P … e to heavy
  precipitation *(C …*

JPL involvement in the mission and technique:

- Chi Ao, Manuel de la Torre, and Joe Turk in the Science team of the PAZ mission since the beginning
- NASA ROSES (2)
- USPI
- NPP

- IGOR+ receiver designed at JPL and modified by BroadReach (same as in Terrasar X, similar to COSMIC)

- Current proposals using PRO concept

- Processing RO data from PAZ satellite
- Full involvement in the Cal/Val phase of the PAZ mission

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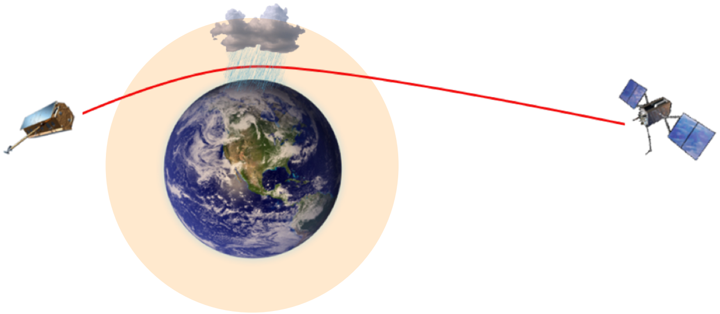
Simulations and Predicted Performance

End to End propagation effects

$$\Delta\Phi = \Delta\Phi\left(E, K_{dp}, L, n_e, \vec{B}, A, R\right)$$

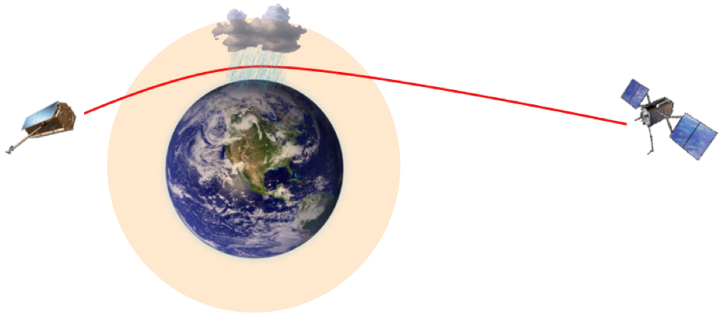


Simulations and Predicted Performance

End to End propagation effects

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

$$\Delta\Phi = \Delta\Phi\left(E,\, K_{dp},\, L,\, n_e,\, \vec{B},\, A,\, R\right)$$



Simulations and Predicted Performance

End to End propagation effects

Observed field

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

Emitted field

Propagation terms → Not important for differential measurements

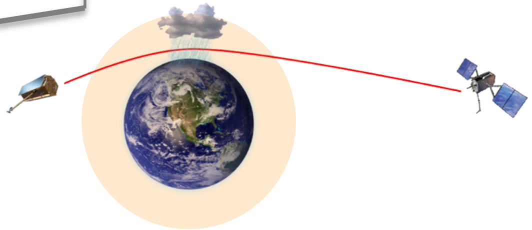
Receiver effects
constant

Antenna pattern
calibration

Ionosphere Faraday rotation
Rotation matrix

Precipitation transmission matrix

Described in linear basis



Simulations and Predicted Performance

Propagation through precipitation introduces a differential phase delay between the H and V components

$$\Phi_H - \Phi_V = \Delta\Phi_{precip} = \int_L K_{dp}(l)dl$$

$$K_{dp} = \frac{\lambda^2}{2\pi}\int_{D_{min}}^{D_{max}} \Re\{S_h - S_v\}N(D)dD$$

Simulations and Predicted Performance

Propagation through precipitation introduces a differential phase delay between the H and V components

Intensity of precipitation

Scattering amplitude matrix

Drop Size Distribution

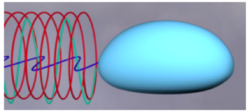
$$\Phi_H - \Phi_V = \Delta\Phi_{precip} = \int_L K_{dp}(l)dl$$

Extension of precipitation

$$K_{dp} = \frac{\lambda^2}{2\pi}\int_{D_{min}}^{D_{max}} \Re\{S_h - S_v\} N(D) dD$$

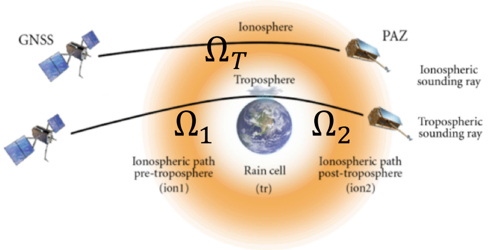
- Distribution of sizes
- Higher rain rate implies larger rain drops

- Size of precipitation particles
- Axis ratio (how asymmetric particles are)
- Composition of the particles (water, ice, …)



Simulations and Predicted Performance

Is the **ionosphere** affecting the differential phase shift?



Faraday Rotation Ω

RHCP: $\begin{bmatrix}1\\0\end{bmatrix}_{\{e_R,e_L\}} \longrightarrow \frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ i & -i\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\i\end{bmatrix}_{\{e_H,e_V\}}$

1): $X = \frac{E_V}{E_H} = i \longrightarrow \arg(i) = 90°$

2): $\begin{pmatrix}\cos(\Omega) & -\sin(\Omega)\\ \sin(\Omega) & \cos(\Omega)\end{pmatrix}\frac{1}{\sqrt{2}}\begin{bmatrix}1\\i\end{bmatrix}_{\{e_H,e_V\}} =$

$$\frac{1}{\sqrt{2}}\begin{pmatrix}\cos(\Omega) - i\sin(\Omega)\\ \sin(\Omega) + i\cos(\Omega)\end{pmatrix} \longrightarrow X = \frac{E_V}{E_H} =$$

$$\frac{\sin(\Omega) + i\cos(\Omega)}{\cos(\Omega) - i\sin(\Omega)} = \frac{i\,(sin^2(\Omega) + (cos^2(\Omega))}{(sin^2(\Omega) + (cos^2(\Omega))} = i$$

$\longrightarrow \arg(i) = 90°$

For RCHP, the ionosphere (FR) does not induce any differential phase shift

What if non-RHCP?

1) - After rain, the EM wave is no longer RHCP:

$$\Delta\phi_{measured} \approx [1 - 2\Omega_2^2(t)]\Delta\phi_{rain}(t)$$

2) - The GPS transmission is not perfectly RHCP:

$$\Delta\phi_{measured} \approx 2m\,sin(\Omega_{Total}(t)) + [1 - 2\Omega_2^2(t)]\Delta\phi_{rain}(t)$$

* non-RHCP emitted wave: $\begin{bmatrix}1\\ m\,e^{i\Delta}\end{bmatrix}_{\{e_R,e_L\}}$

Tolerance up to 10% of the orthogonal component according to official GPS documentation

Simulations and Predicted Performance

Is the **ionosphere** affecting the differential phase shift?

Faraday Rotation Ω

RHCP: $\begin{bmatrix}1\\0\end{bmatrix}_{\{e_R,e_L\}} \longrightarrow \frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ i & -i\end{pmatrix}\begin{pmatrix}1\\0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\i\end{bmatrix}_{\{e_H,e_V\}}$

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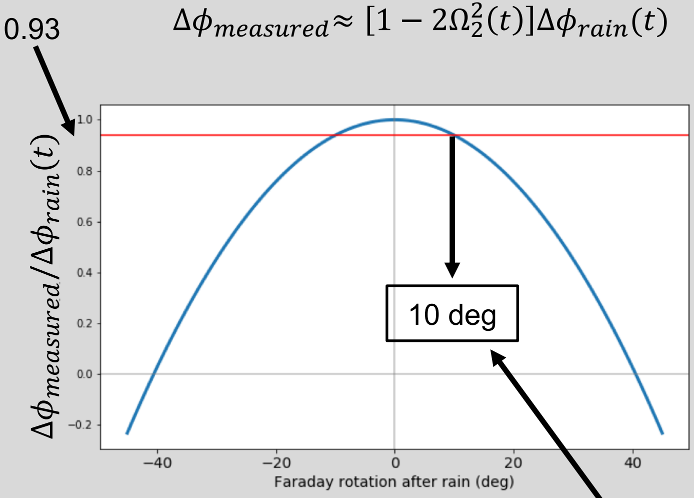
$\frac{\sin(\Omega) + i\cos(\Omega)}{\cos(\Omega) - i\sin(\Omega)} = \frac{i\,(sin^2(\Omega) + (cos^2(\Omega))}{(sin^2(\Omega) + (cos^2(\Omega))} = i$

$\longrightarrow \arg(i) = 90°$

For RCHP, the ionosphere (FR) does not induce any differential phase shift

simulations

$$\Delta\phi_{measured} \approx [1 - 2\Omega_2^2(t)]\Delta\phi_{rain}(t)$$



Maximum observed Faraday Rotation Ω_2 : 10 degrees

Simulations and Predicted Performance

End to End propagation effects

Observed field

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

Emitted field

We are confident that:

- We are able to correct most of the effects
- The residual ionospheric effect is small

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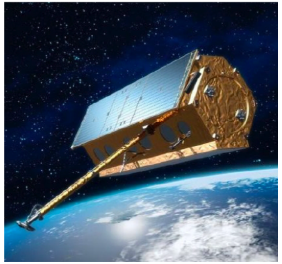
  - **Sensitivity to precipitation**

ROHP – PAZ experiment

Radio Occultations and Heavy Precipitation with PAZ

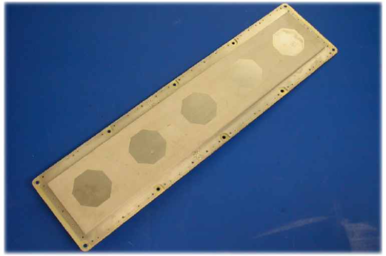
- Proof of concept mission on the Spanish PAZ satellite
- Main PAZ payload: SAR
- PAZ launched **Feb 22, 2018**, from VAFB
- Sun-synchronous dusk/dawn polar orbit
- **Polarimetric experiment** activated on May 10, 2018

PAZ artistic view



Credit: Hisdesat

PAZ PRO antenna



Credit: Hisdesat

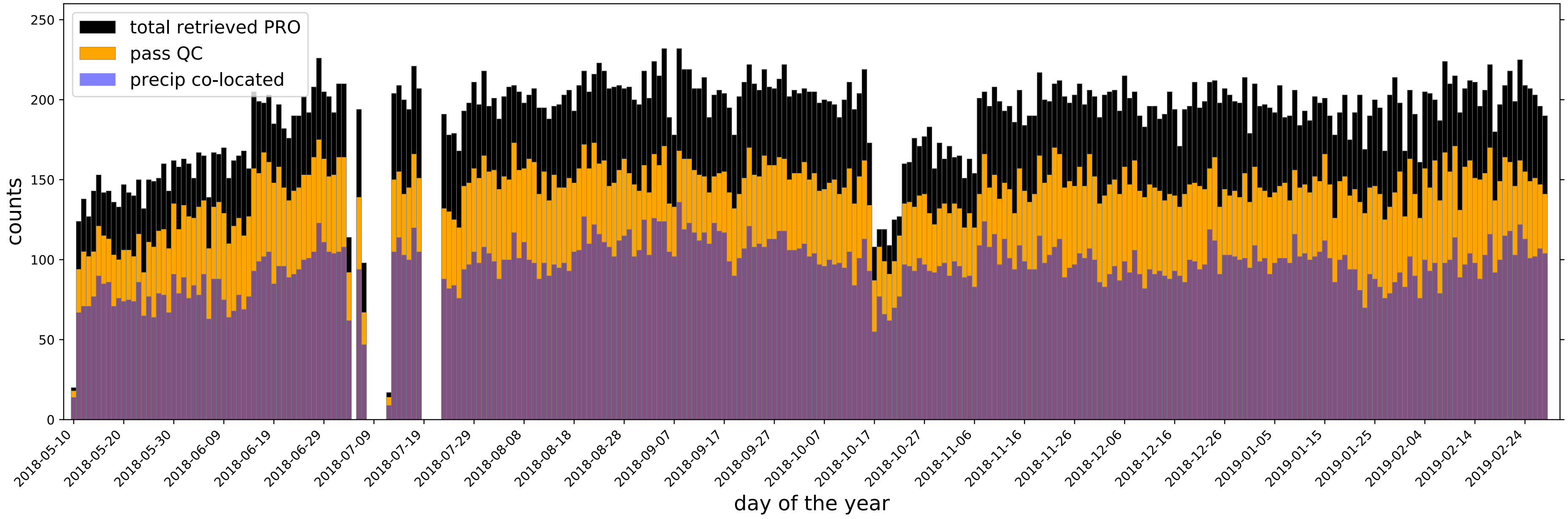
PAZ satellite deployment

Credit: SpaceX

Credit: SpaceX

ROHP – PAZ experiment

Number of collected PROs

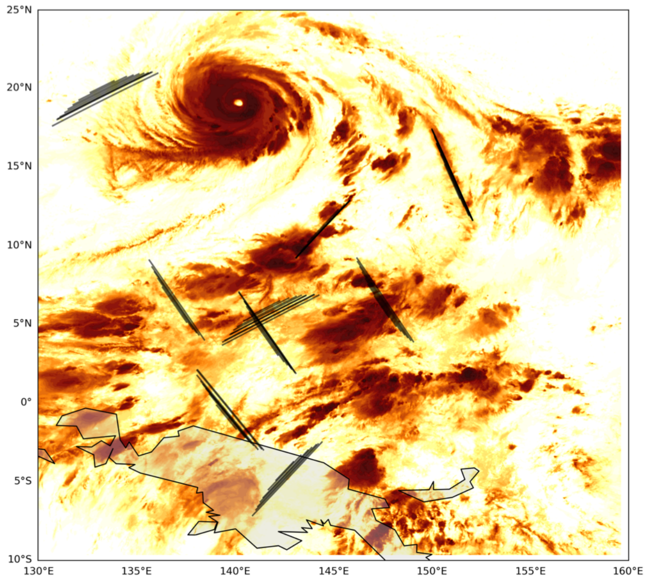


ROHP – PAZ experiment

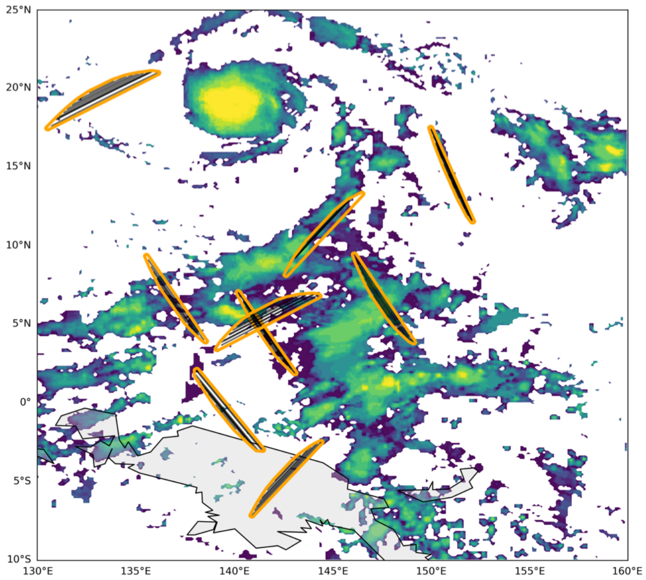
Validation using GPM constellation products

- Each RO is linked to a T_{min} and R_{mean}
- Precipitation values:
  Precip in the region sensed by PRO
- Coverage between +-60 deg latitude

NCEP / CPC Brightness Temperature



IMERG precipitation



ROHP – PAZ experiment

Validation using GPM constellation products

- Each RO is linked to a T_{min} and R_{mean}
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  Precip in the region sensed by PRO
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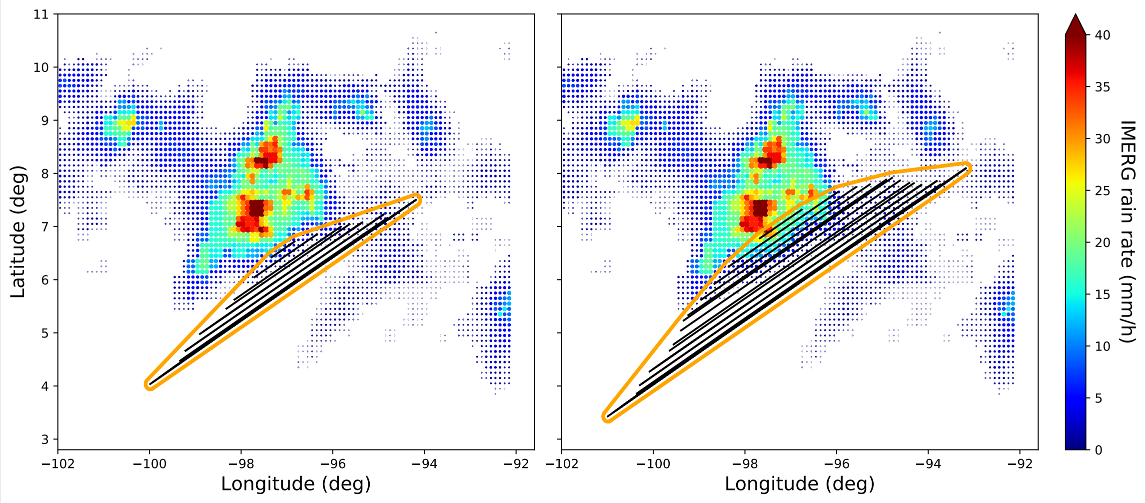
Region sensed defined by the portion of the rays below 6 km

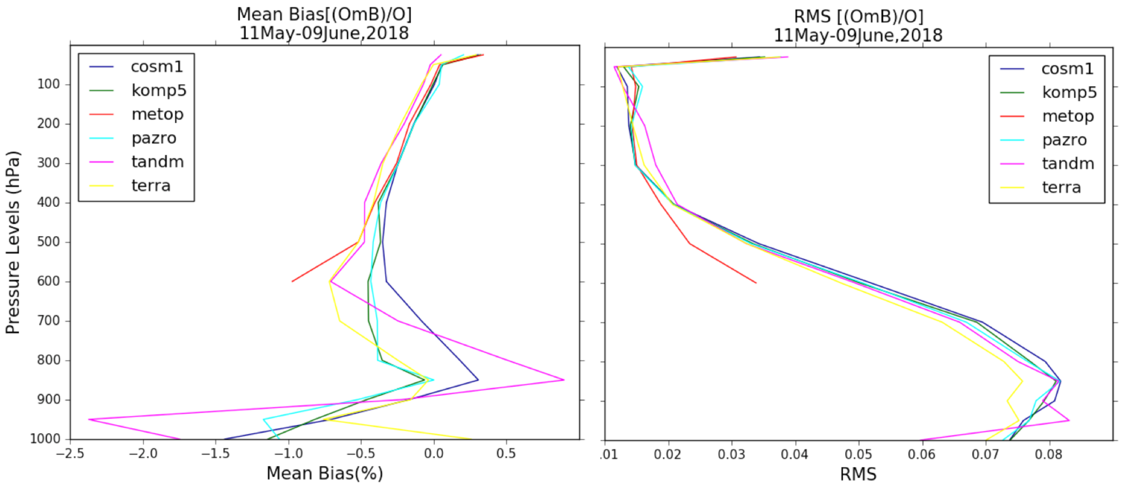
Region sensed defined by the portion of the rays below 12 km

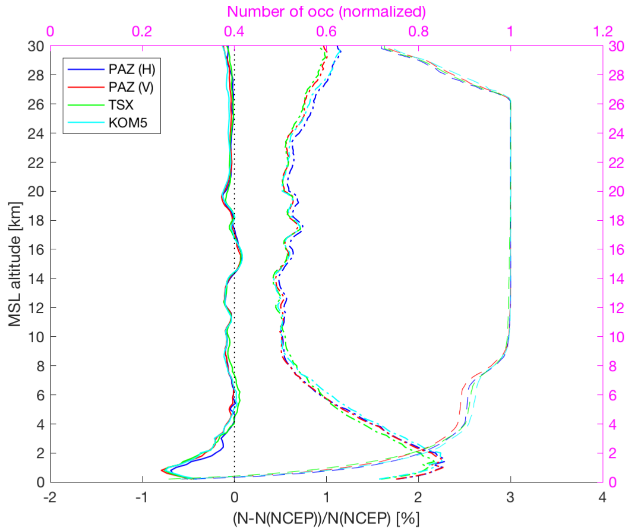


ROHP – PAZ experiment

Standard products quality

- Comparable to TerraSar-X and Kompsat-5 (similar satellite, similar receiver)
- **Good news** => using a 2-pol antenna does not impact quality of standard products





François Vandenberghe et al., AMS 2019

JPL

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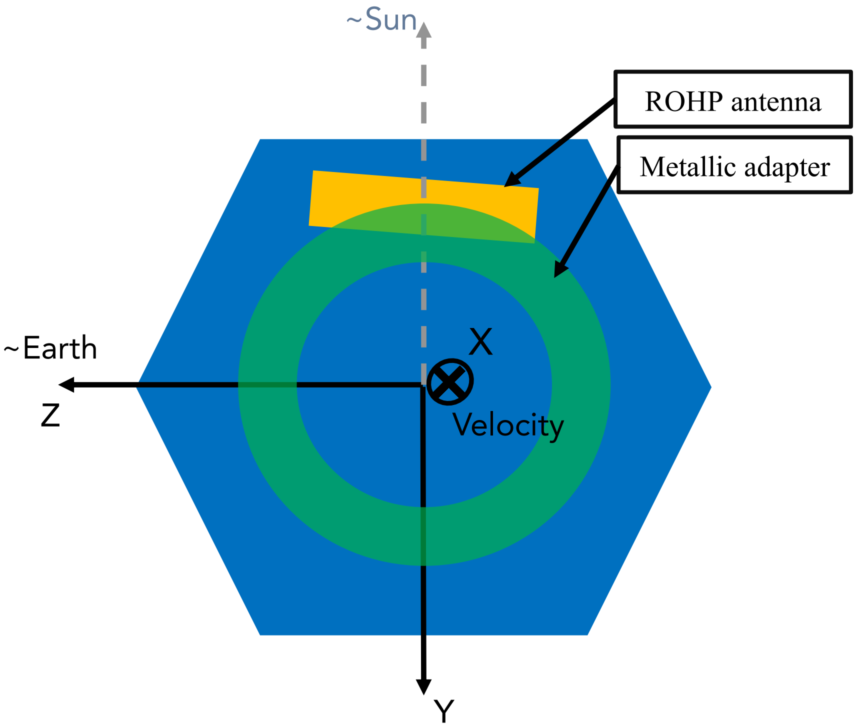
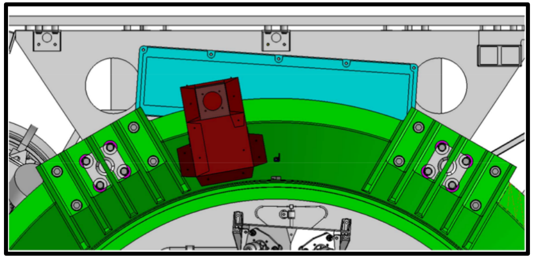
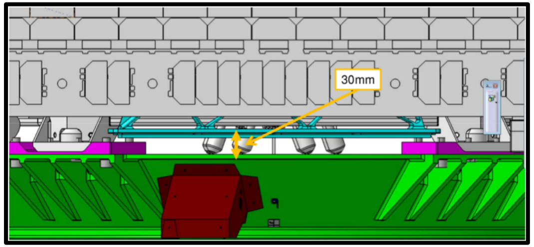
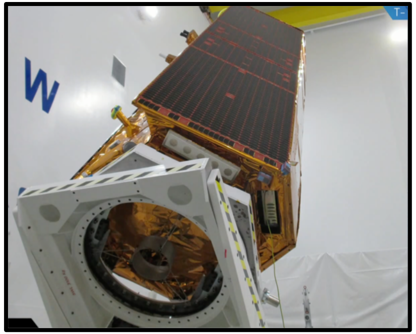
ROHP – PAZ experiment

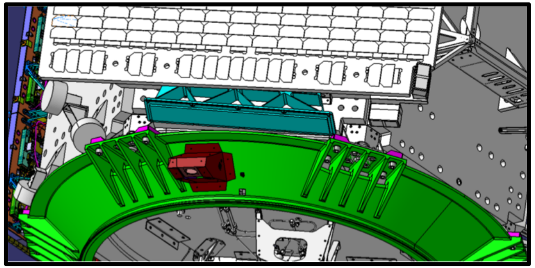
Antenna obstruction





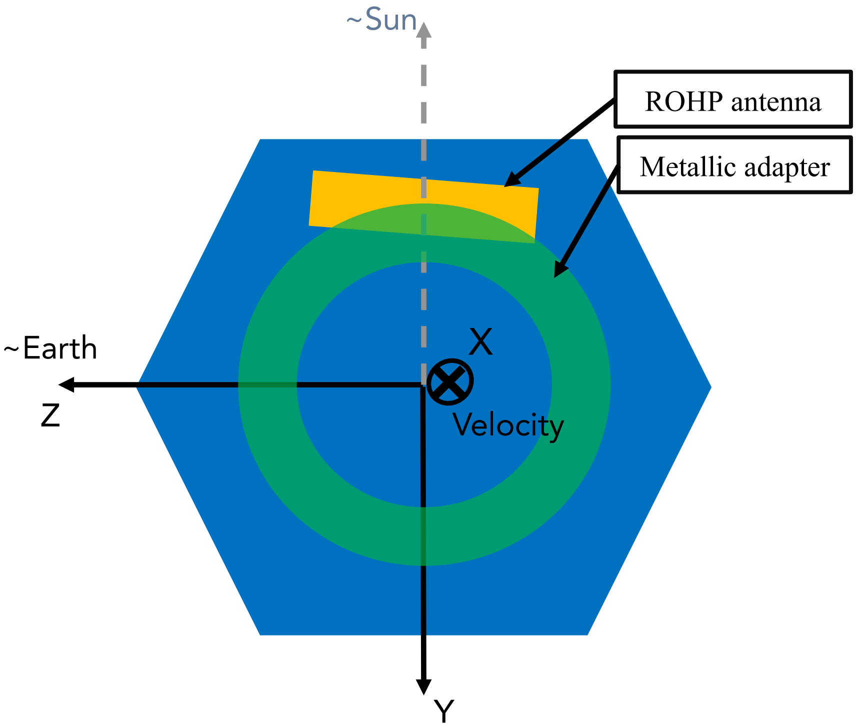


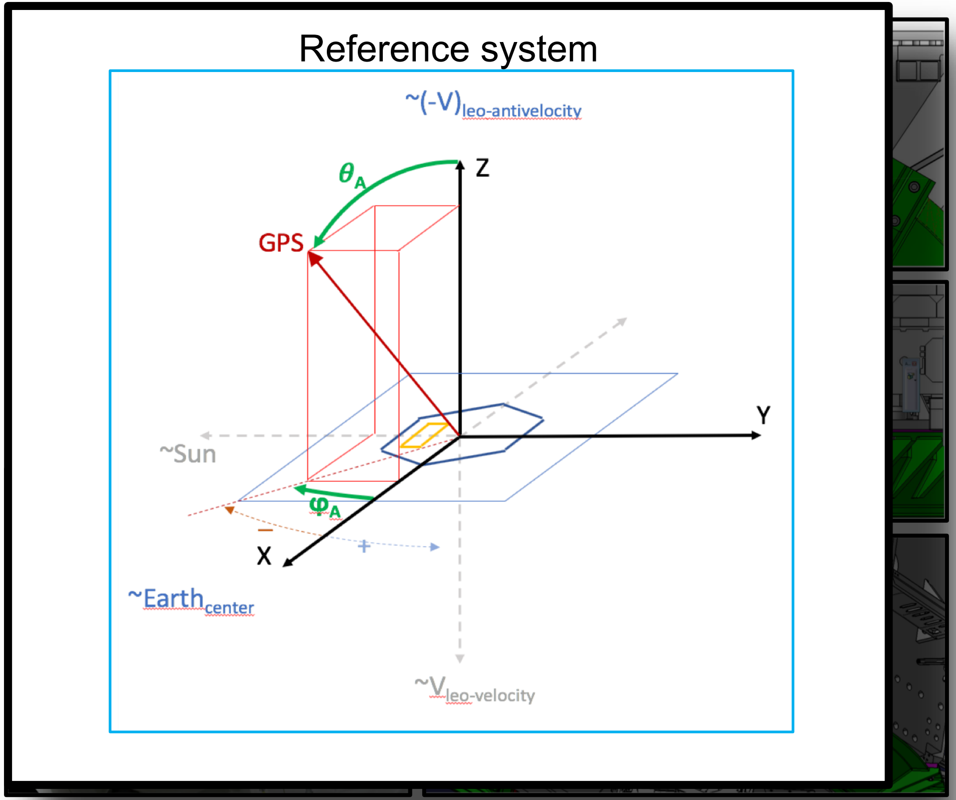




ROHP – PAZ experiment

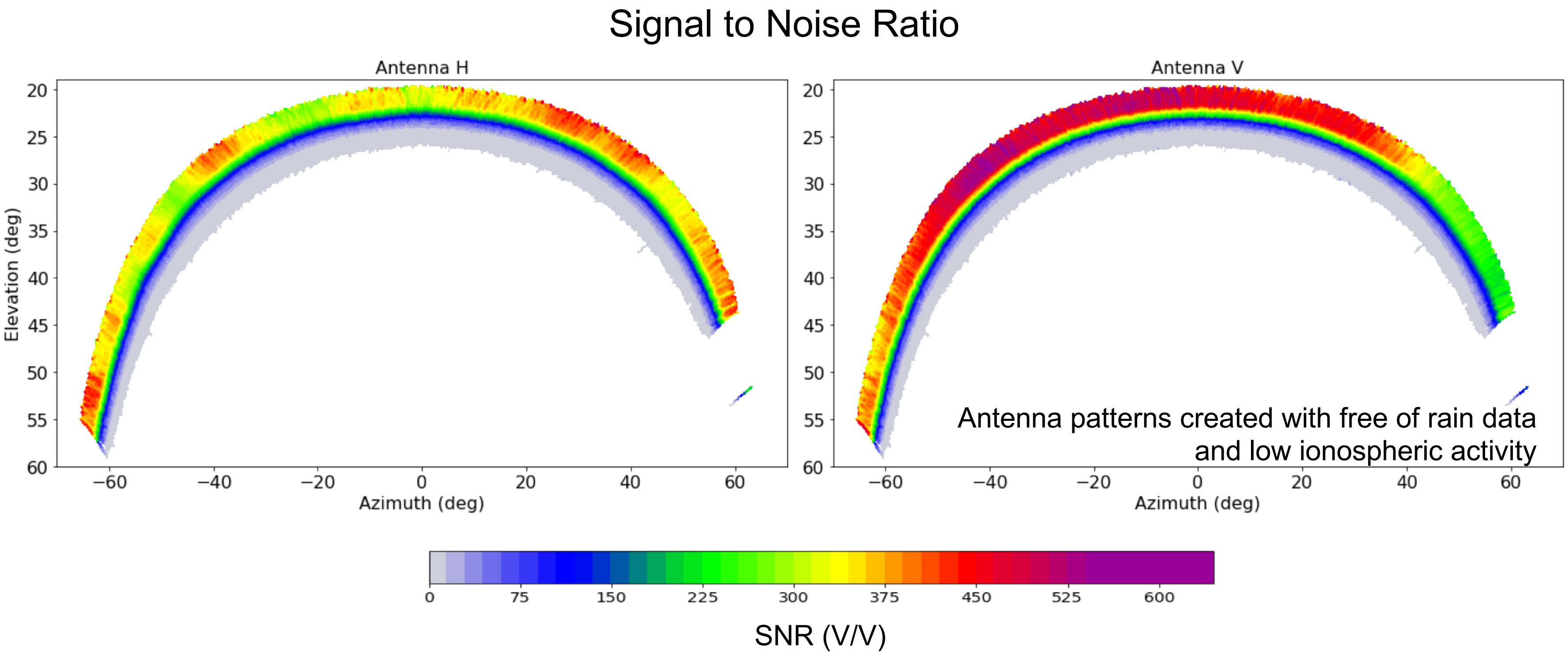
Antenna obstruction





ROHP – PAZ experiment

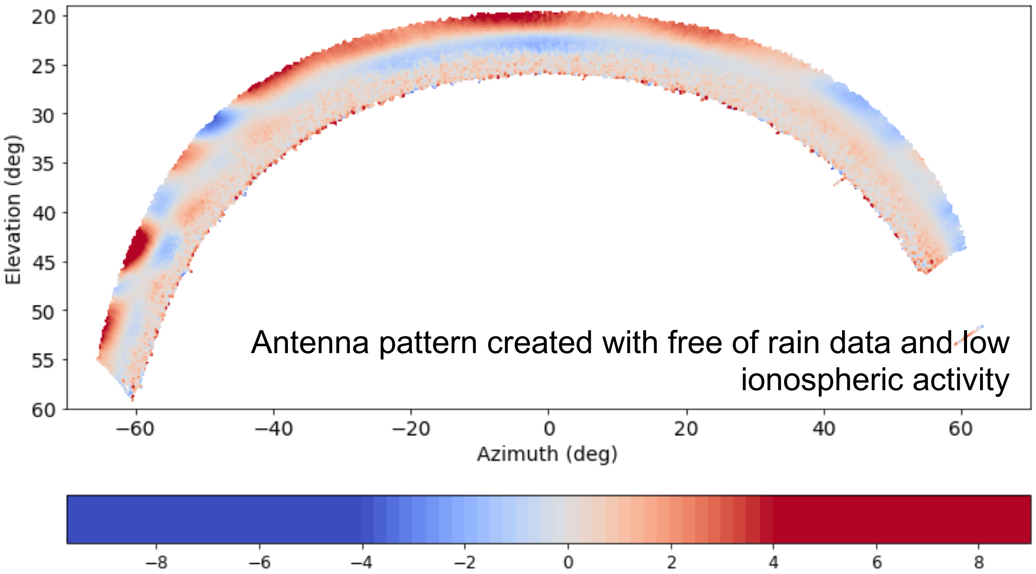
Antenna pattern



ROHP – PAZ experiment

Antenna pattern

Differential phase shift

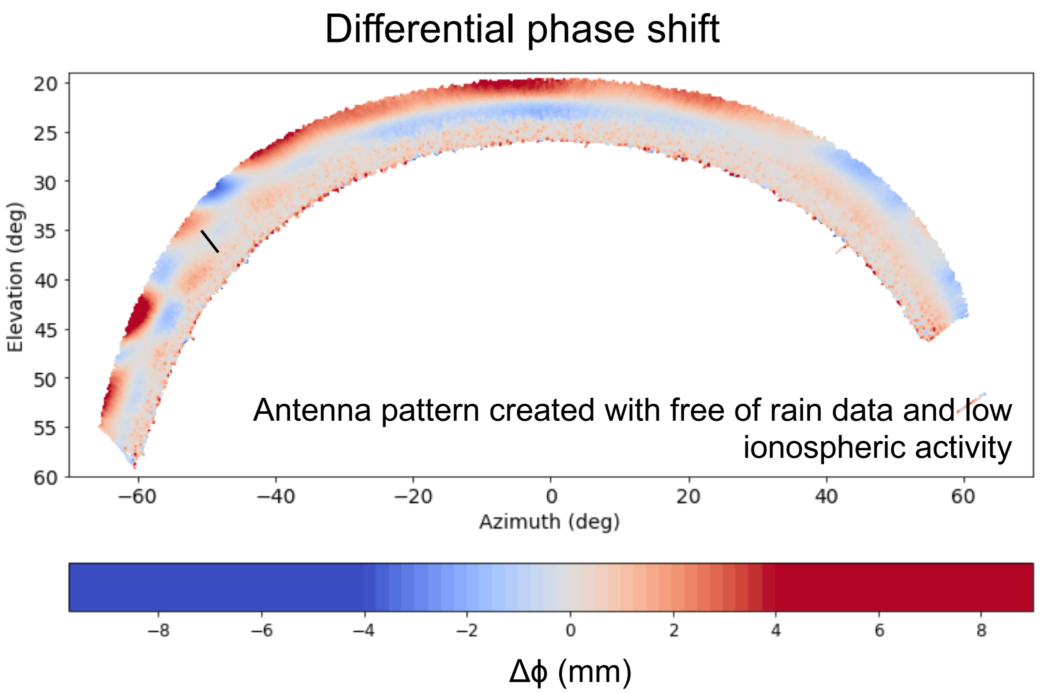


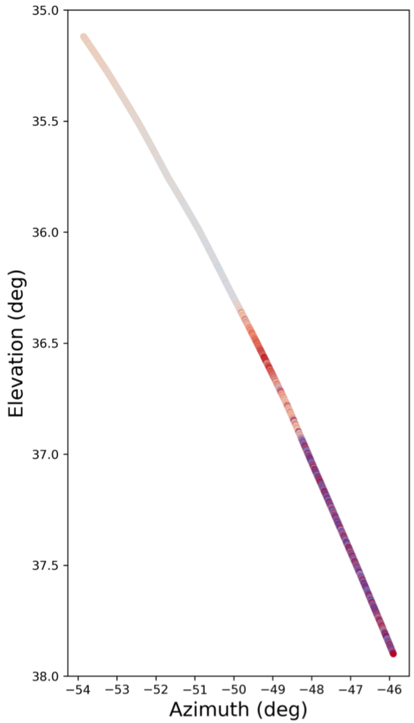
Δϕ (mm)

ROHP – PAZ experiment

Antenna pattern – correction of the data

2018-10-24-14:03paz_gps68

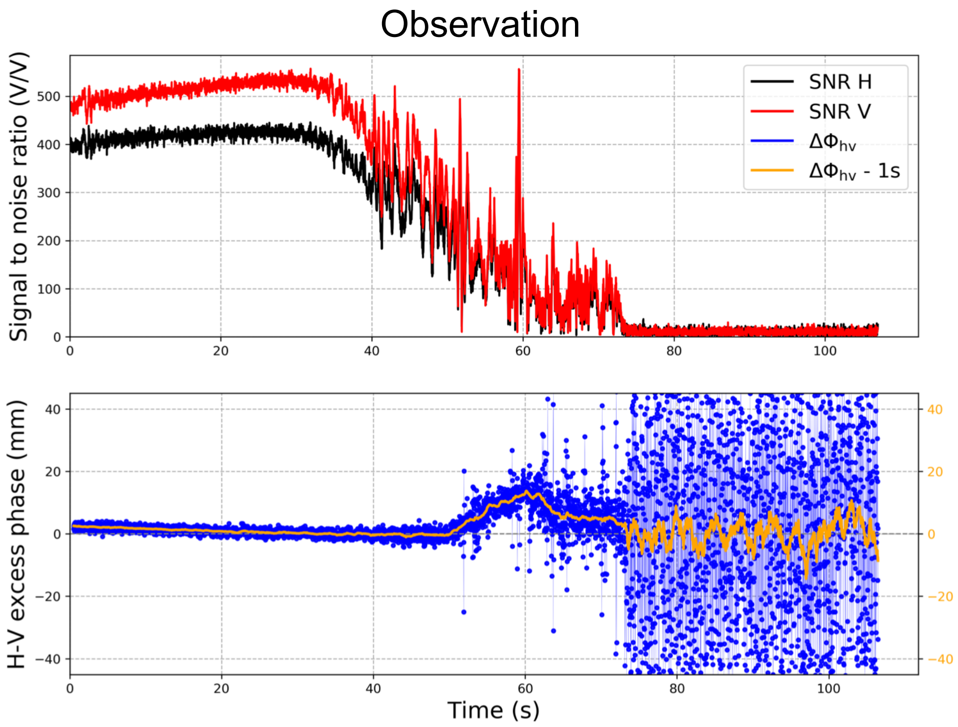


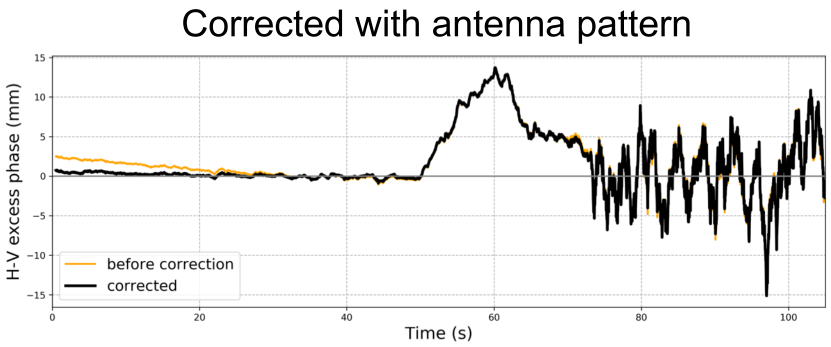


ROHP – PAZ experiment

Calibration and Validation

2018-10-24-14:03paz_gps68





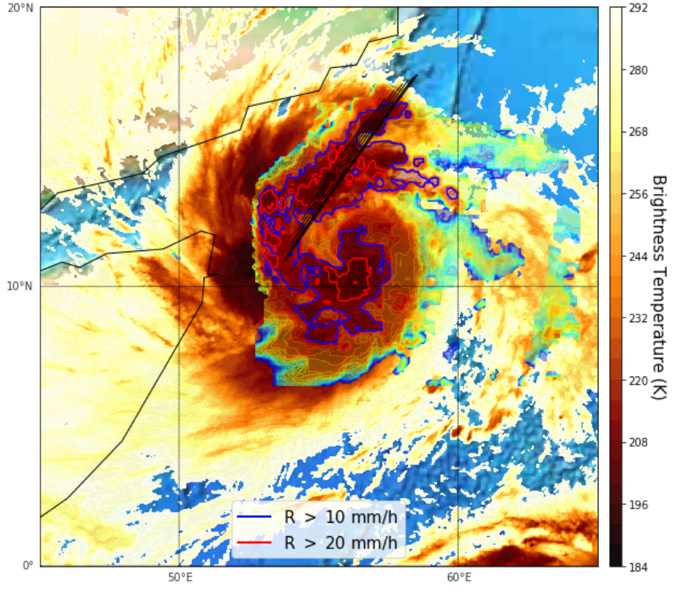
Smoothing procedure:

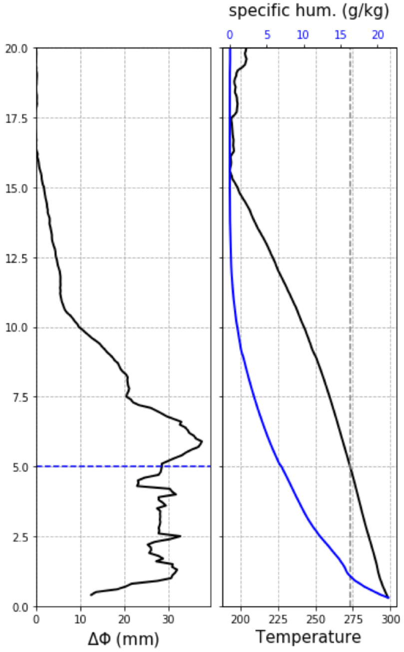
- 1-s weighted average with SNR

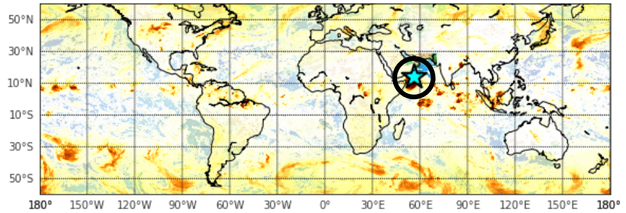
Calibration and Validation: Example

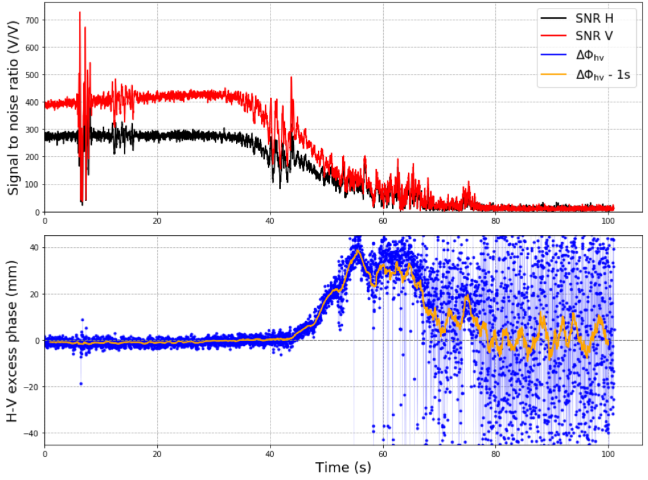
Tropical Cyclone (Cat 3) Mekunu

2018-05-23-03:04paz_gps56



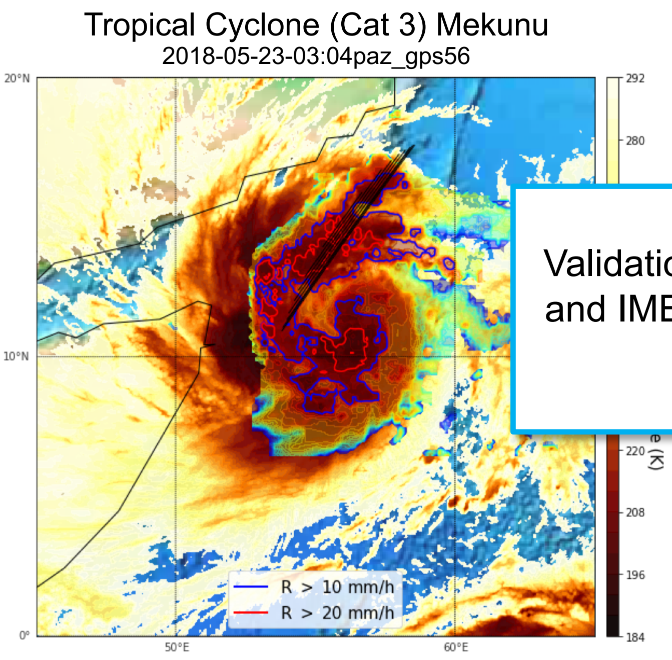


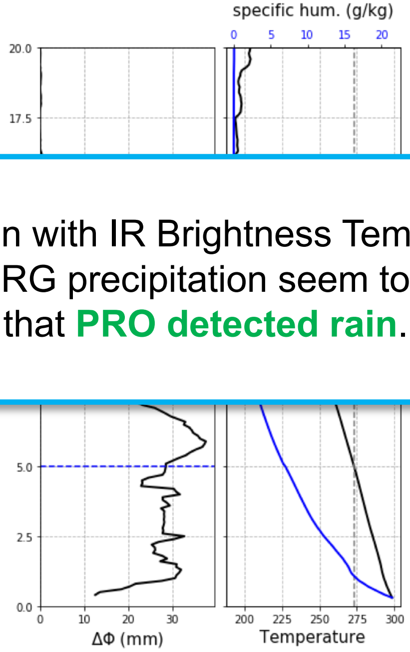


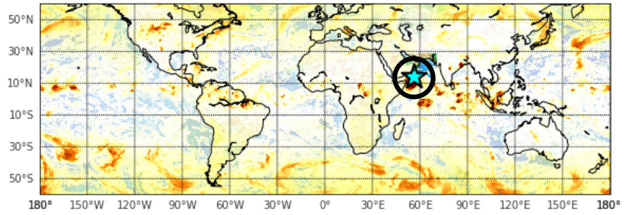


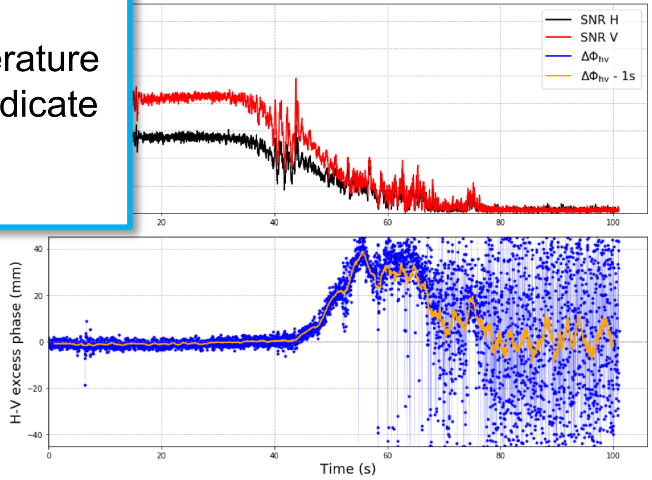
ROHP – PAZ experiment

Calibration and Validation: Example





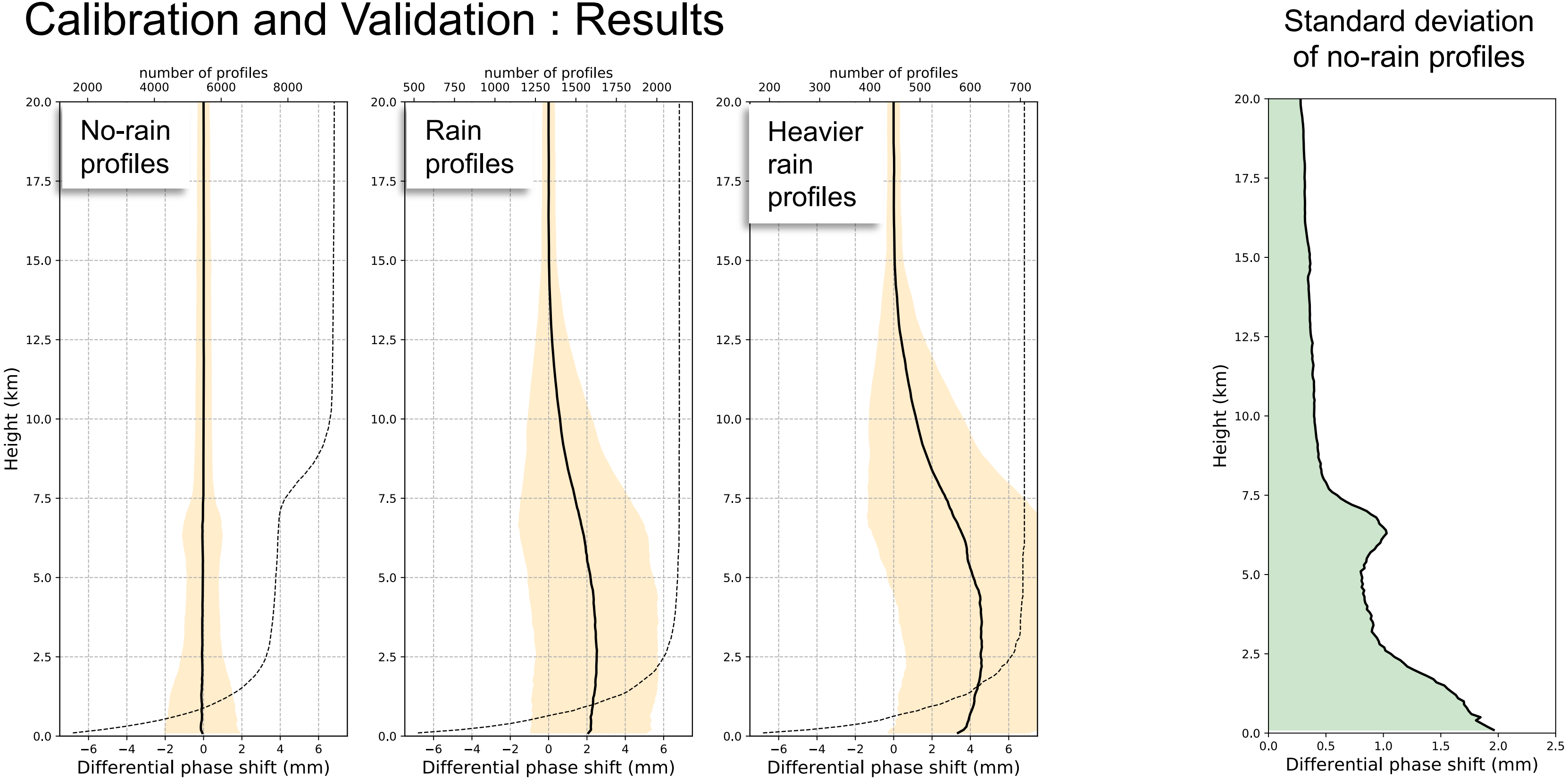




Validation with IR Brightness Temperature and IMERG precipitation seem to indicate that **PRO detected rain**.

ROHP – PAZ experiment

Calibration and Validation : Results



Calibration and Validation : Results

Almost no false positives

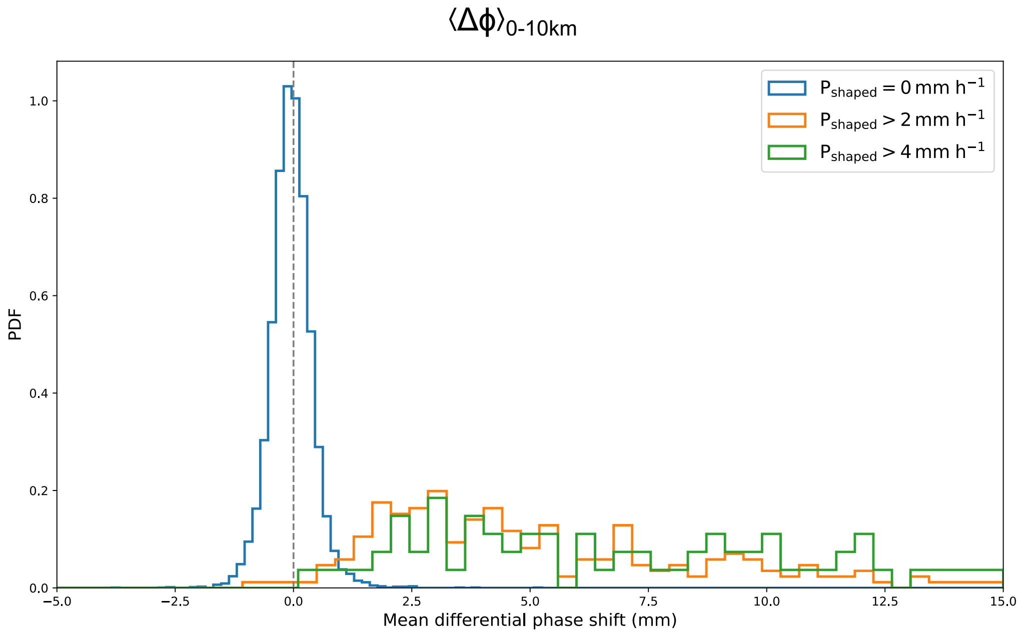
No rain profiles with $\langle\Delta\phi\rangle_{0\text{-}10km} > 1$ mm: **0.3 %**

No rain profiles with $\langle\Delta\phi\rangle_{0\text{-}10km} > 2$ mm: **0.02 %**

Very few false negatives

Rain profiles with $\langle\Delta\phi\rangle_{0\text{-}10km} < 1$ mm: **2 %**

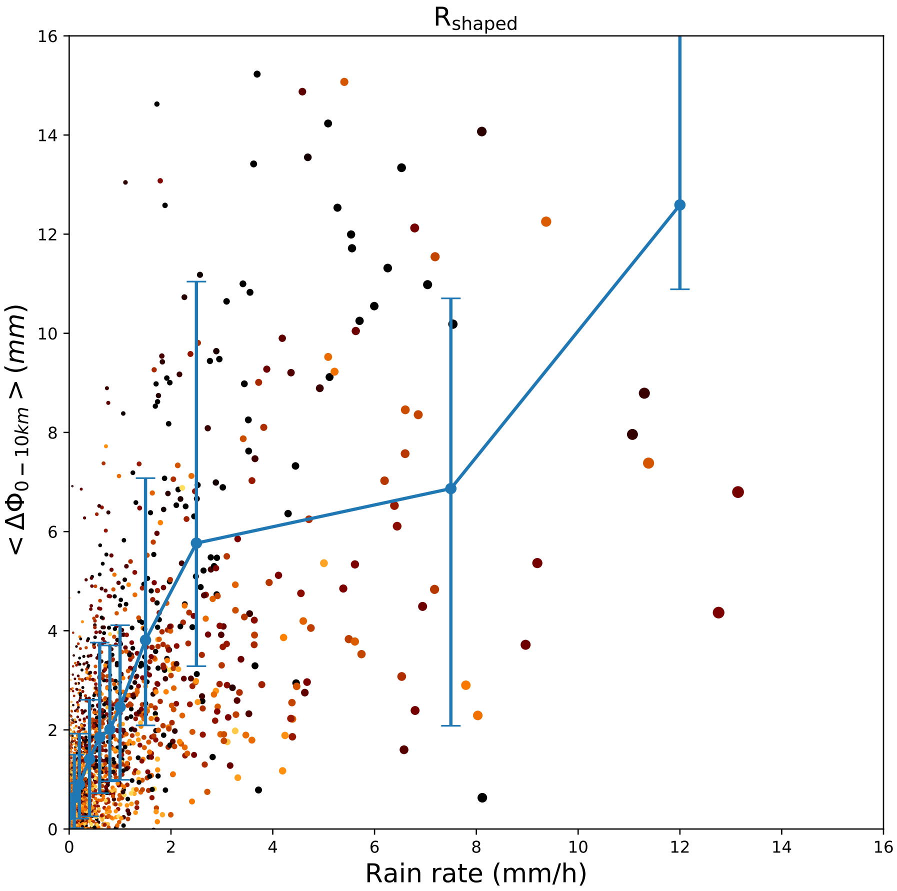
Rain profiles with $\langle\Delta\phi\rangle_{0\text{-}10km} > 2$ mm: **8 %**



ROHP – PAZ experiment

Calibration and Validation : Results

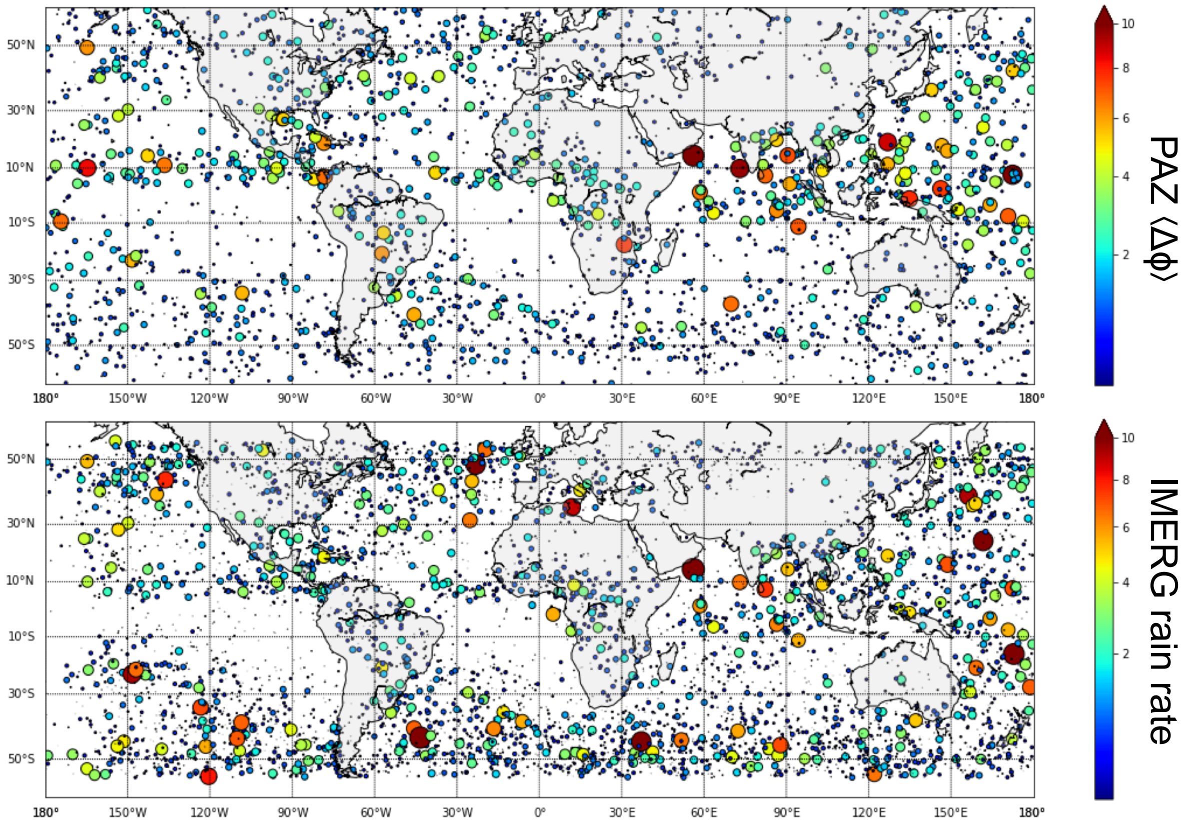
- Each PRO has:
    - ⟨Δϕ⟩$_{0\text{-}10km}$, R, location, etc…
- ⟨Δϕ⟩ increases as rain rate increases
- Not only "detection", but sensitivity to intensity



ROHP – PAZ experiment

Sensitivity to precipitation

- Precipitation patterns can be easily recognized using PAZ data
- Overall, good agreement between ⟨Δϕ⟩ and R
- Disagreement in the magnitude
  [still working on ⟨Δϕ⟩ --> R]

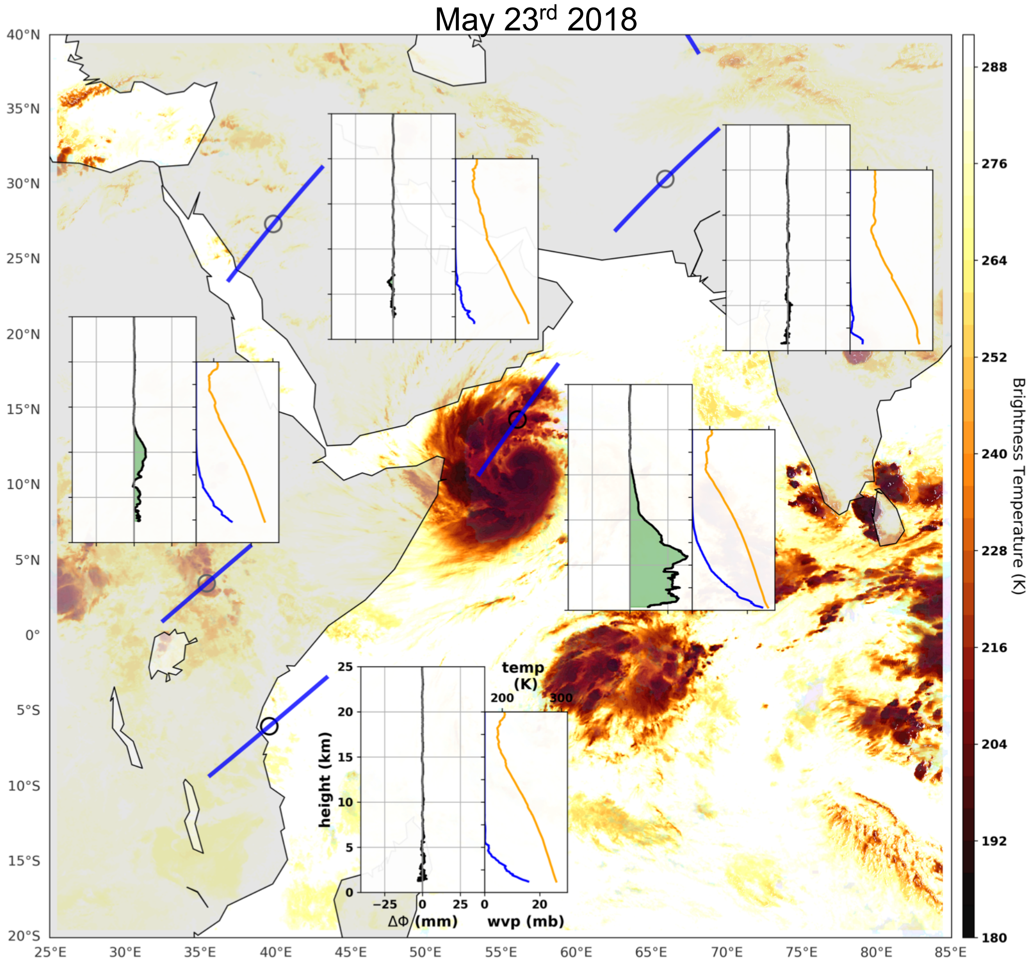


ROHP – PAZ experiment

Sensitivity to precipitation

- Coincident precipitation and thermodynamic profiles

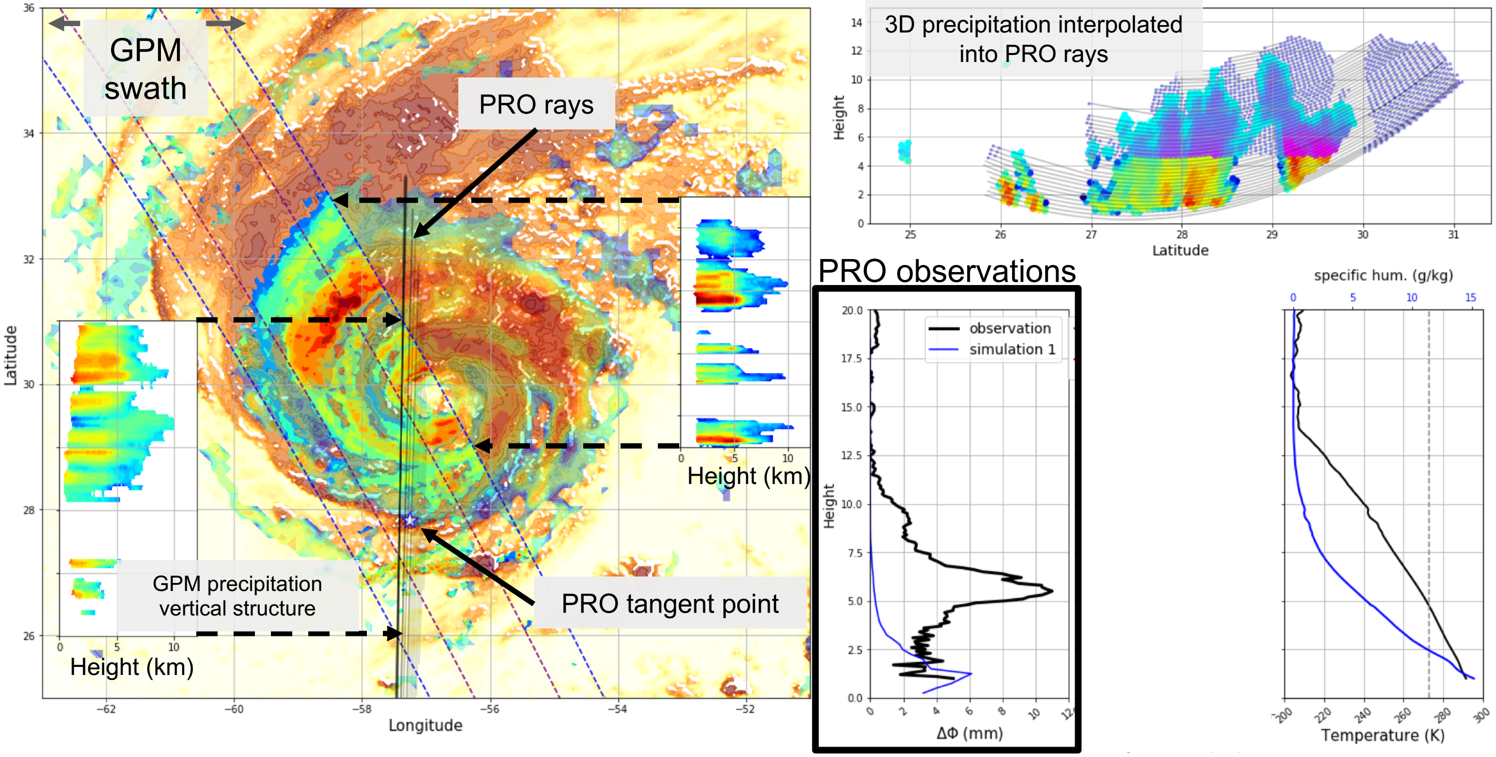
- With the ability to detect precipitation, we can distinguish the thermodynamic profiles that have been obtained under different precipitation conditions



ROHP – PAZ experiment

Sensitivity to precipitation: vertical structure

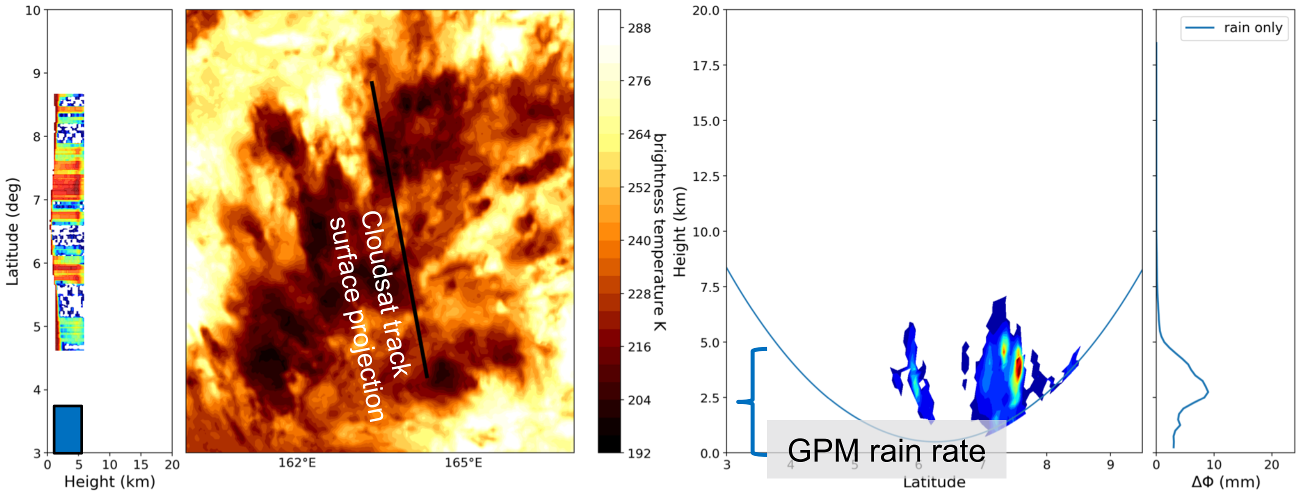
Hurricane Leslie + Coincidence with GPM core satellite overpass



ROHP – PAZ experiment

Sensitivity to precipitation – But also something else?

Simulations of Δϕ based on coincident GPM and Cloudsat observations



GPM and Cloudsat reflectivity
GPM : below Freezing Level
Cloudsat: above Freezing Level

Simulations of PRO observations using rain only (GPM provided), Ice only (cloudsat provided), and the sum of both

ROHP – PAZ experiment

Sensitivity to precipitation – But also something else?

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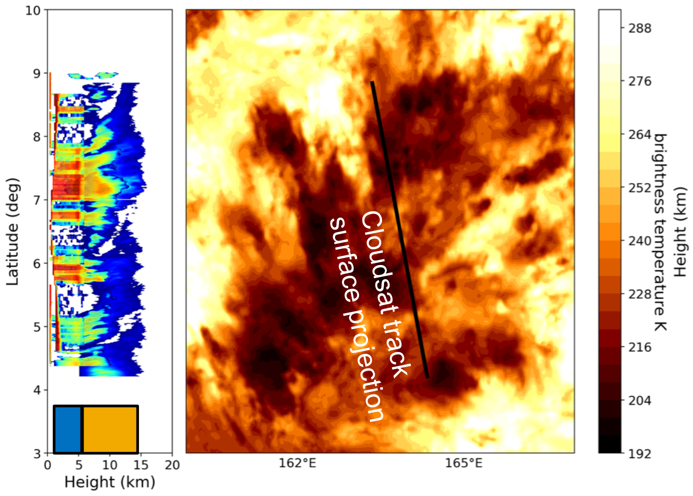

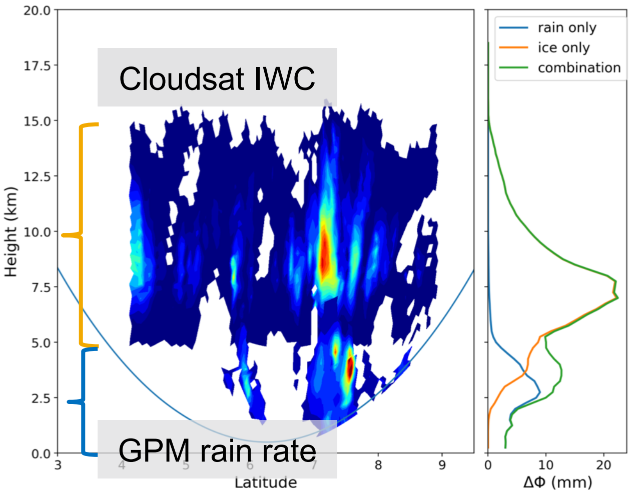

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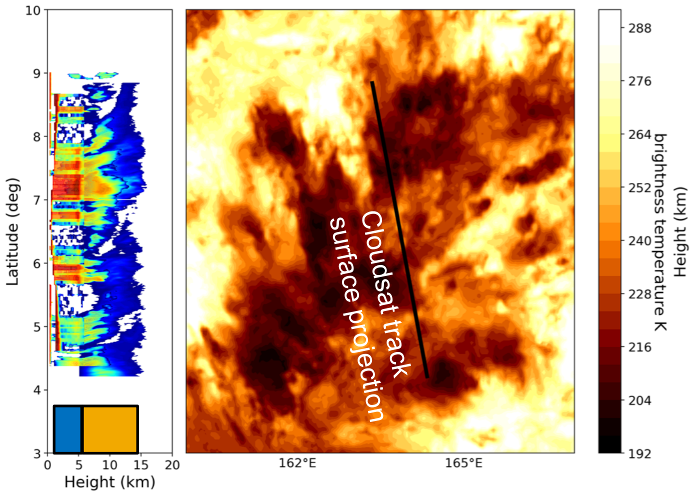
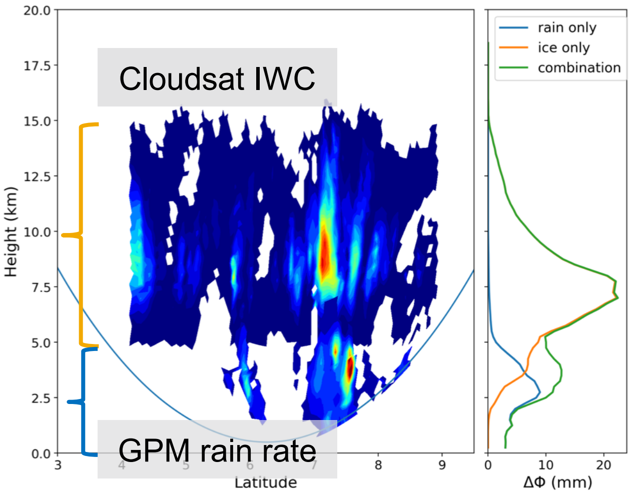
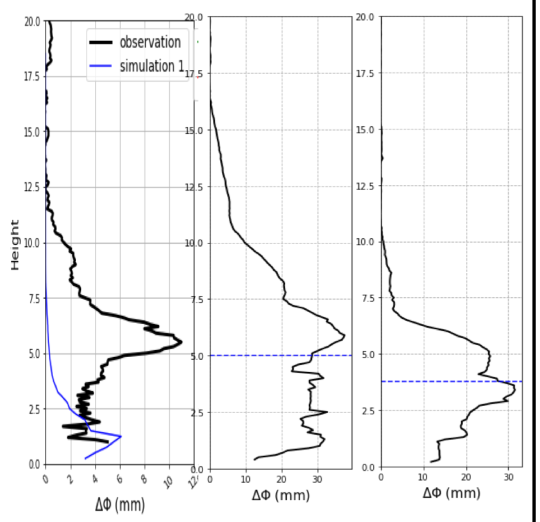




Observed profiles



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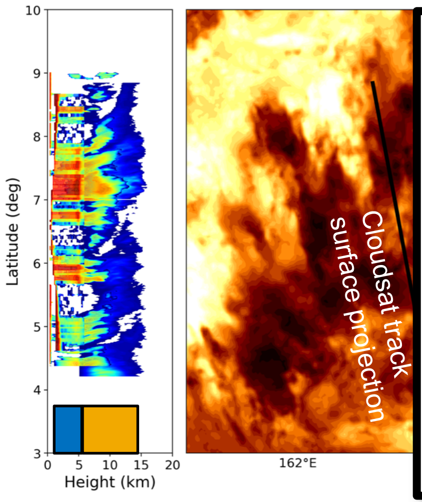

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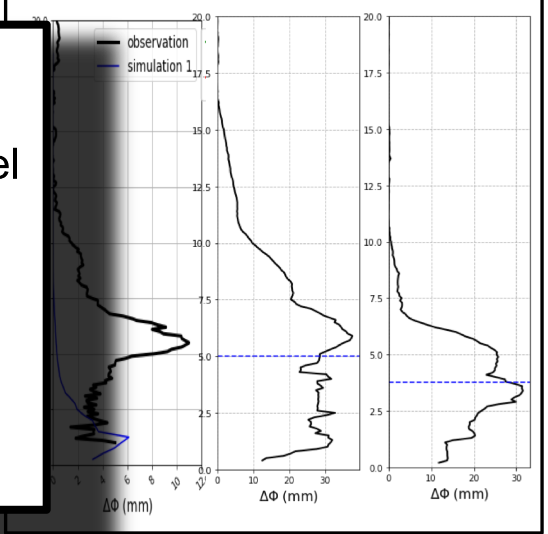

We believe that ice and melting particles can explain the signatures above the freezing level that we see in PRO profiles.

This means that once we understand how these particles induce the Δϕ, we can characterize vertical cloud structures

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Simulations of PRO observations using rain only (GPM provided), Ice only (cloudsat provided), and the sum of both

Summary

- **PAZ** Polarimetric Radio Occultation observations are sensitive to rain

- The standard products (i.e. bending angles, refractivity, and thermodynamics) have nominal quality, comparable to TerraSar-X, Kompsat5.

- We can distinguish whether these profiles were obtained inside heavy precipitation or not

- Potential vertical cloud structure – ice, melting particles, …
- Relationship between $\Delta\phi$ and Rain Rate

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