Validation of the Polarimetric Radio Occultation and Heavy Precipitation (ROHP) Data and Potential Applications to Weather Modeling

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J. David Neelin, Yi-Hung Kuo (UCLA)

Ramon Padullés, Estel Cardellach, Antonio Rius (Instituto de Ciencias del Espacio (ICE-CSIC/IEEC), Barcelona, Spain)

Sergio Tomás (now at Spire, Inc.)

Topics for This Presentation

1) Background on radio occultation measurements

2) Polarimetric RO (PRO) data from PAZ/ROHP (launched Feb 2018)

3) PRO data analysis and science

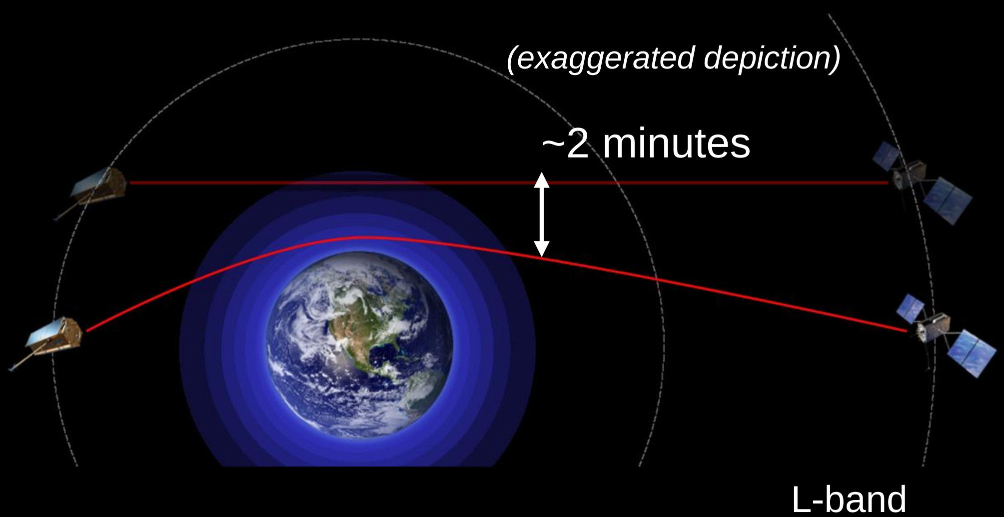
4) Ideas for uses within weather modeling

5) Constellation concept

Global Navigation Satellite System (GNSS) Radio Occultations (RO)

Dedicated L-band (near 1.4 GHz) GNSS receivers track the GNSS (GPS, Galileo, GLONASS etc.) phase delay as they occult (rise or set) behind the Earth

- The signal is bent due to the index of refraction gradients in the atmosphere
- RO receivers precisely track the time derivative of the phase between consecutive measurements (Doppler shift)
- After removing geometric effects due to relative motion of the two involved satellites, the atmospheric bending angle can be inferred



High vertical resolution (~200m), global distribution, all weather capability; coarse along-ray resolution (~100 km)

Excess phase

↓

Bending angle α

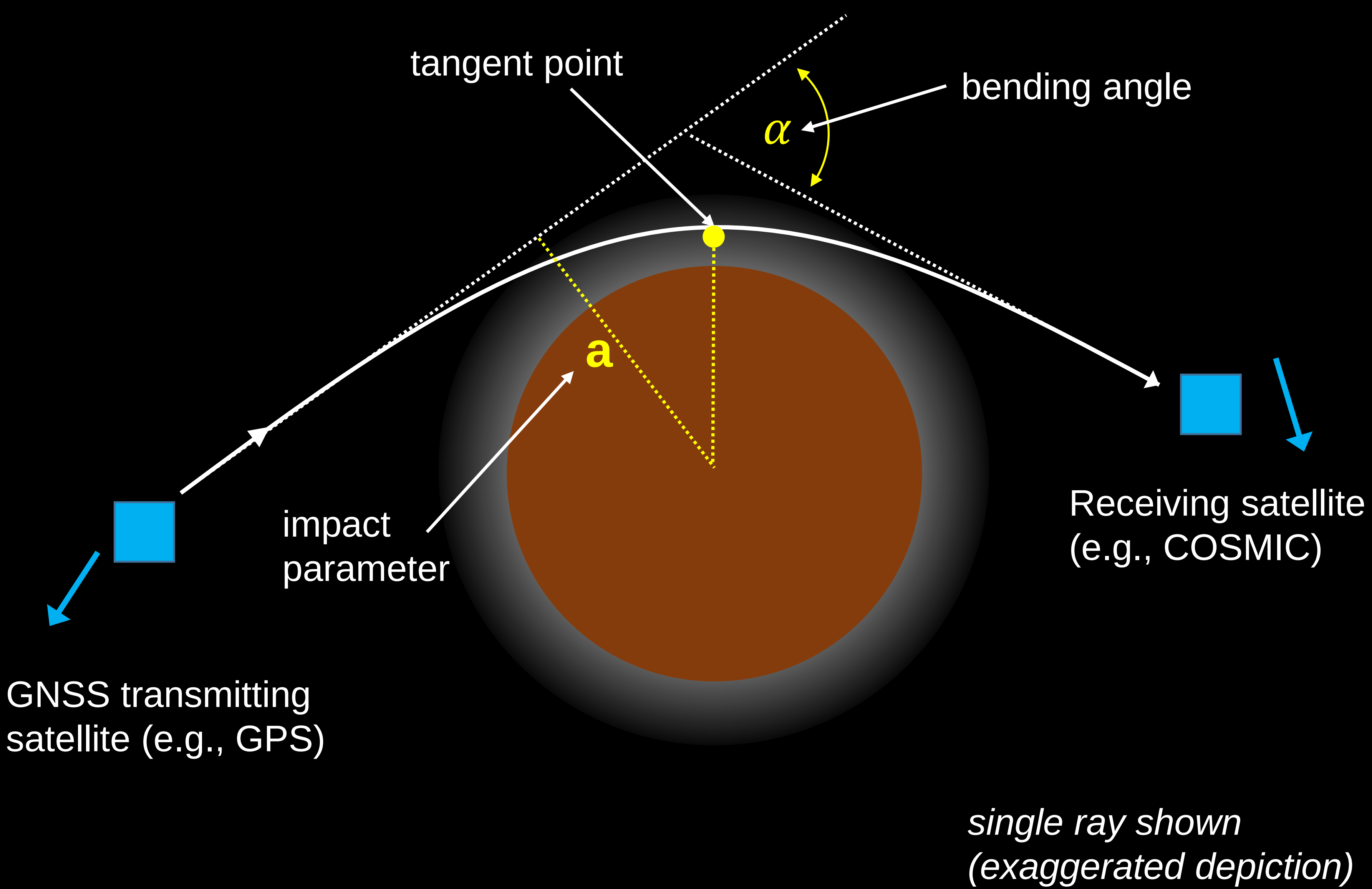
Spherically symmetric atmosphere ↓ Inverse Abel transform

Index of refraction *n(z)*

Variational analysis ↓ T from models to infer q

T(z), q(z)

RO Geometry and Terms



RO Capabilities

- RO provides the thermodynamic profiles essential for understanding weather events, which may be degraded or difficult to retrieve from other sensors (e.g., GPM radar, IR, passive MW):
  - Temperature/water vapor under all-weather, all-sky conditions (*e.g., extreme weather, tropical convection*)
  - High vertical resolution (100–200 m) (*e.g., PBL profiling, gravity waves*)

- An ever-expanding set of RO observations (COSMIC-2, GRACE-FO, Sentinel-6, commercial, etc.) provides improved sampling and accuracy, and extended record for studying interannual, intraseasonal, and diurnal variabilities.

- Polarimetric RO (secondary payload on the Spanish PAZ s/c) provides additional information on precipitation and convective environment. **Subject of the remainder of this presentation**.

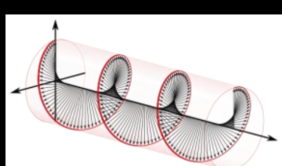
Polarimetric Radio Occultations (PRO) Concept

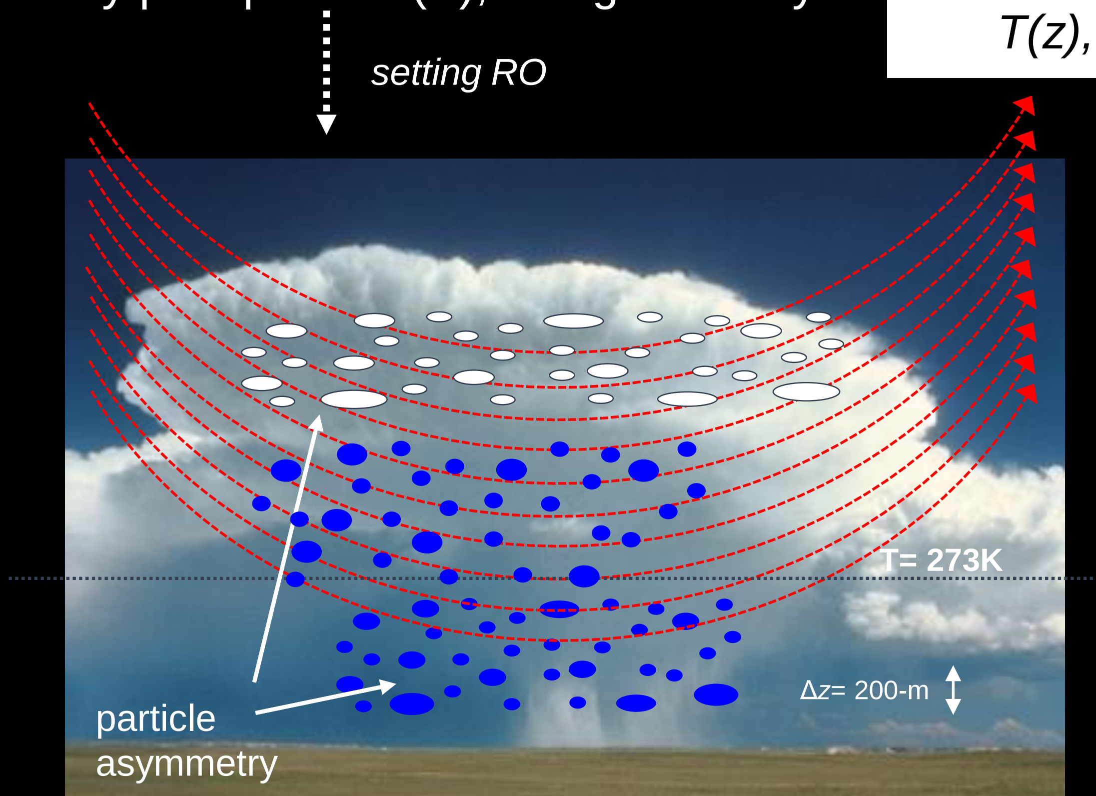
GNSS (L-band) propagation through precipitation induces a cross-polarized component, measureable as a differential phase delay between H and V polarizations: $\boldsymbol{\Delta\phi}$

Potential to extend the capabilities of normal RO, with ***simultaneous*** measurements of the profile of water vapor (q), temperature (T) and an *indication* of heavy precipitation (P), along each ray

T(z), q(z) + P(z)

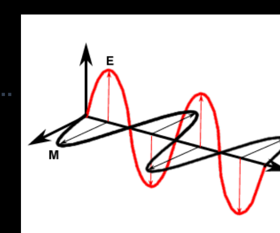
GNSS
RHC transmit





Simultaneous
H/V receive

q(z), T(z), P(z)



(exaggerated depiction)

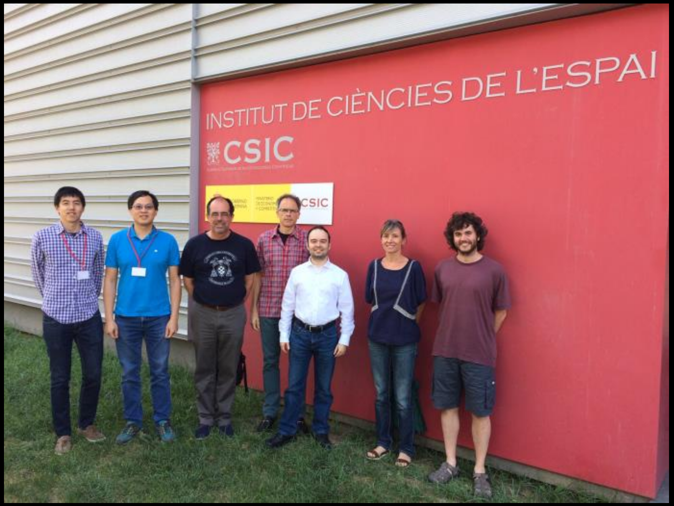
ROHP-PAZ (Radio Occultation Heavy Precipitation with PAZ)

rohp-PAZ

PI: Dr. Estel Cardellach (ICE – IEEC/CSIC, Barcelona)

JPL Participation through the NASA ESUSPI program

- Proof of concept mission for precipitation detection using Polarimetric RO on the Spanish PAZ satellite
- Main payload of PAZ is an X-band SAR, operated by Hisdesat for the Spanish government
- Equipped with dual-pol RO antenna in the aft-direction.
- Launched Feb 22, 2018 from VAFB
- Sun-synchronous dusk/dawn polar orbit, 514-km
- Polarimetric experiment activated on May 10, 2018
- **Expected lifetime: 7-10 years** (*Note TerraSAR-X is at 13 yrs and still operational*)



Credit: Hisdesat

PAZ artistic view

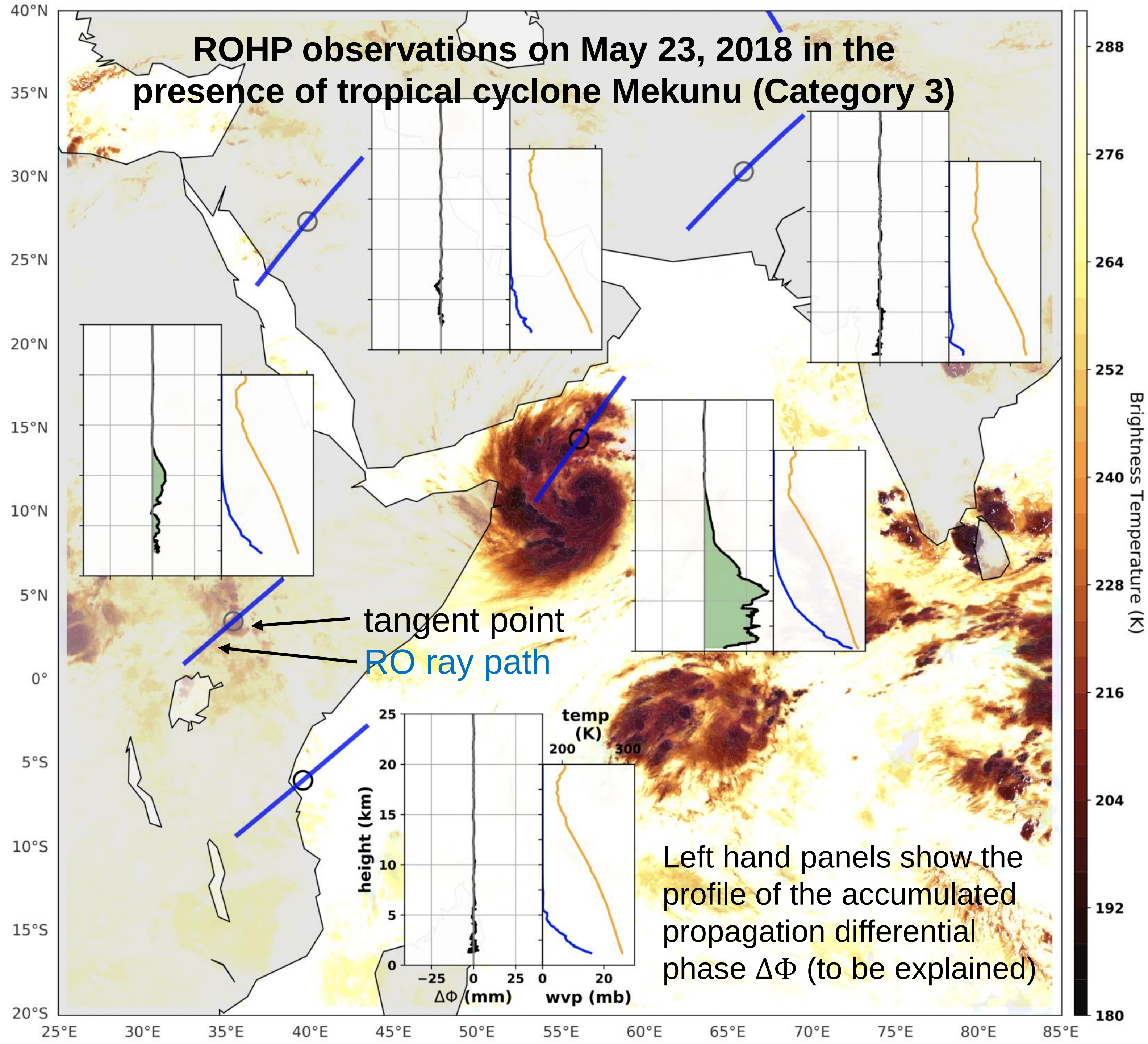
Credit: Hisdesat

PAZ Dual Polarization antenna

Credit: Hisdesat

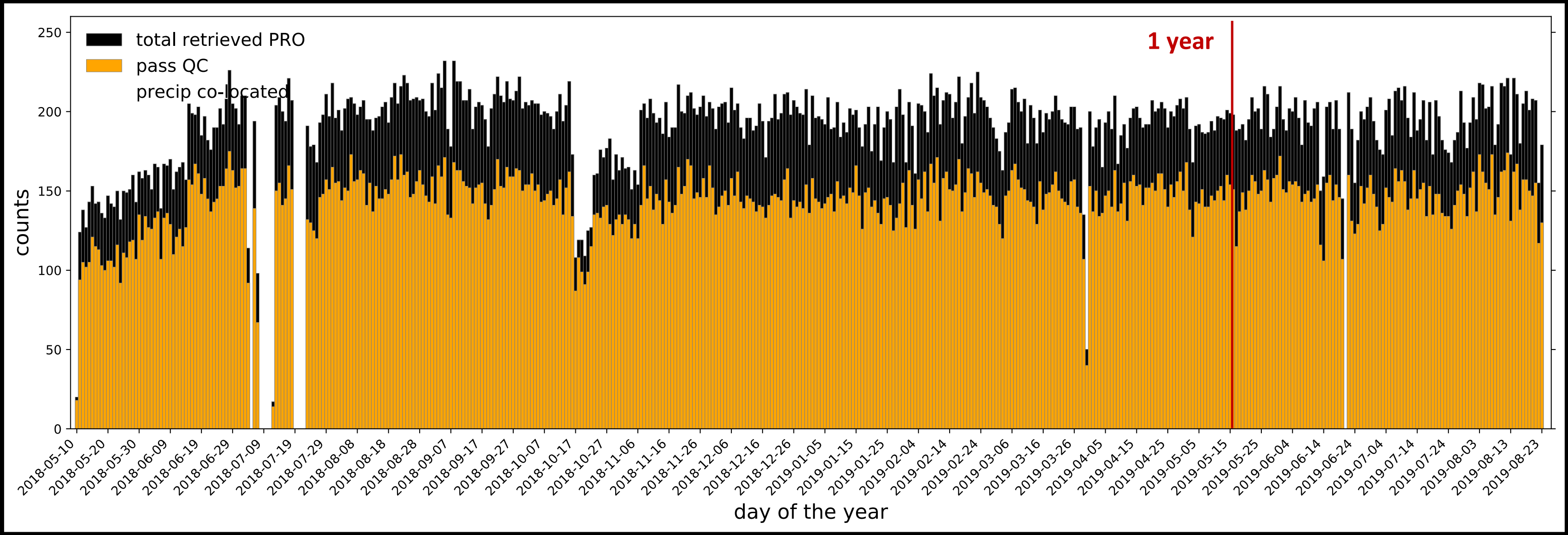
PAZ satellite deployment

Credit: SpaceX


ROHP observations on May 23, 2018 in the presence of tropical cyclone Mekunu (Category 3)
tangent point
RO ray path
Left hand panels show the profile of the accumulated propagation differential phase ΔΦ (to be explained)
height (km)
25
20
15
10
5
0
−25
0
25
ΔΦ (mm)
temp (K)
200
300
0
20
wvp (mb)
40°N
35°N
30°N
25°N
20°N
15°N
10°N
5°N
0°
5°S
10°S
15°S
20°S
25°E
30°E
35°E
40°E
45°E
50°E
55°E
60°E
65°E
70°E
75°E
80°E
85°E
Brightness Temperature (K)
288
276
264
252
240
228
216
204
192
180

Status of PAZ processing at JPL

Total number of processed Polarimetric ROs [up to 2019 – 08 – 23]



Total number of processed profiles:
87,938

Total gone through QC:
68,557

Precipitation information (surface):
47,228

Near real time **standard RO products** are processed by UCAR and distributed via the GTS (since Dec 2019) for NWP data assimilation.

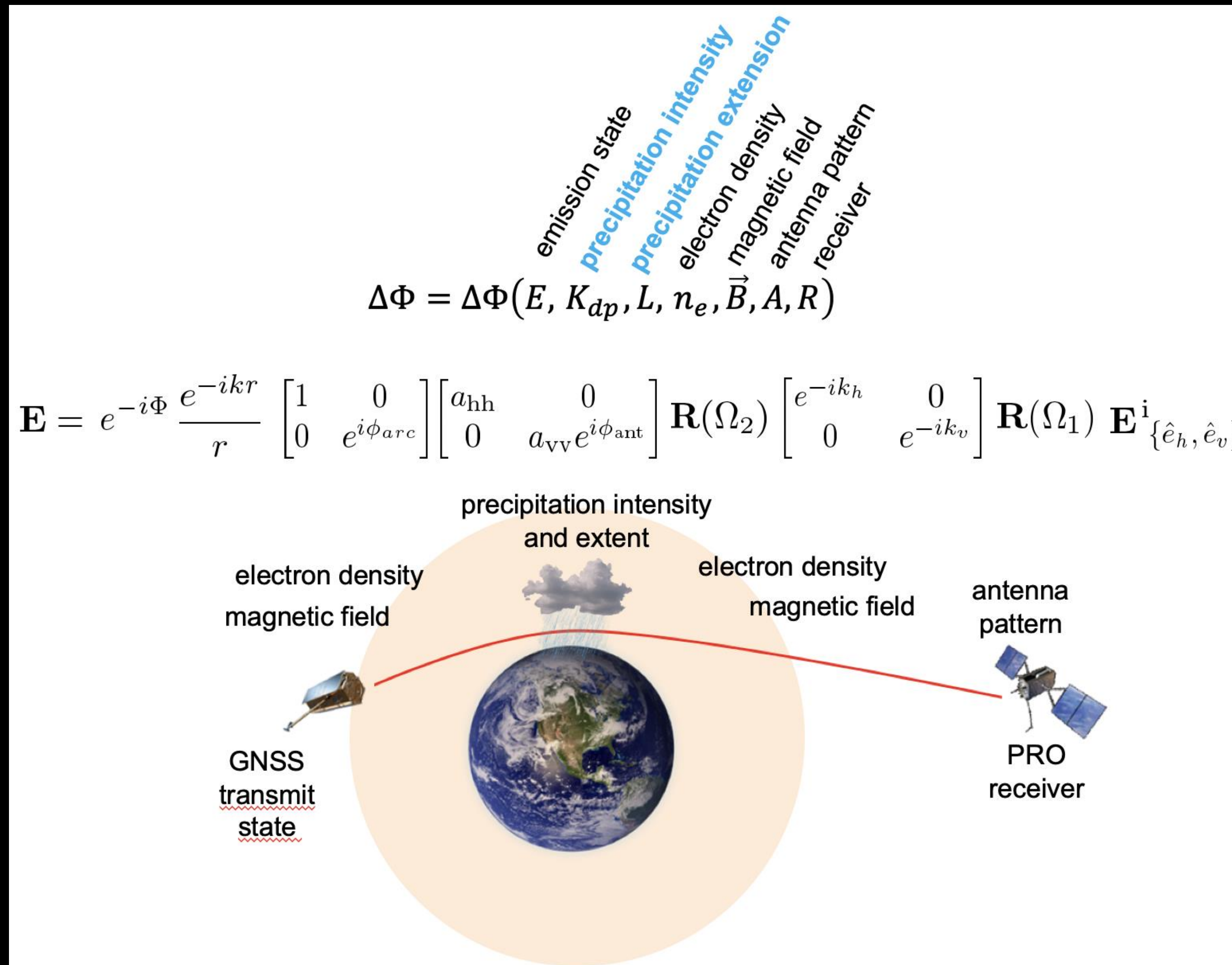
Polarimetric RO products are available from official PAZ-ROHP website at ICE-CSIC/IEEC (https://paz.ice-csic.es).

Contributions to the Polarimetric Phase

The polarimetric phase difference (H – V) observable $\Delta\phi$ depends on factors besides precipitation (e.g., antenna & ionosphere).

Tomas et al., IEEE TGRS, 2018

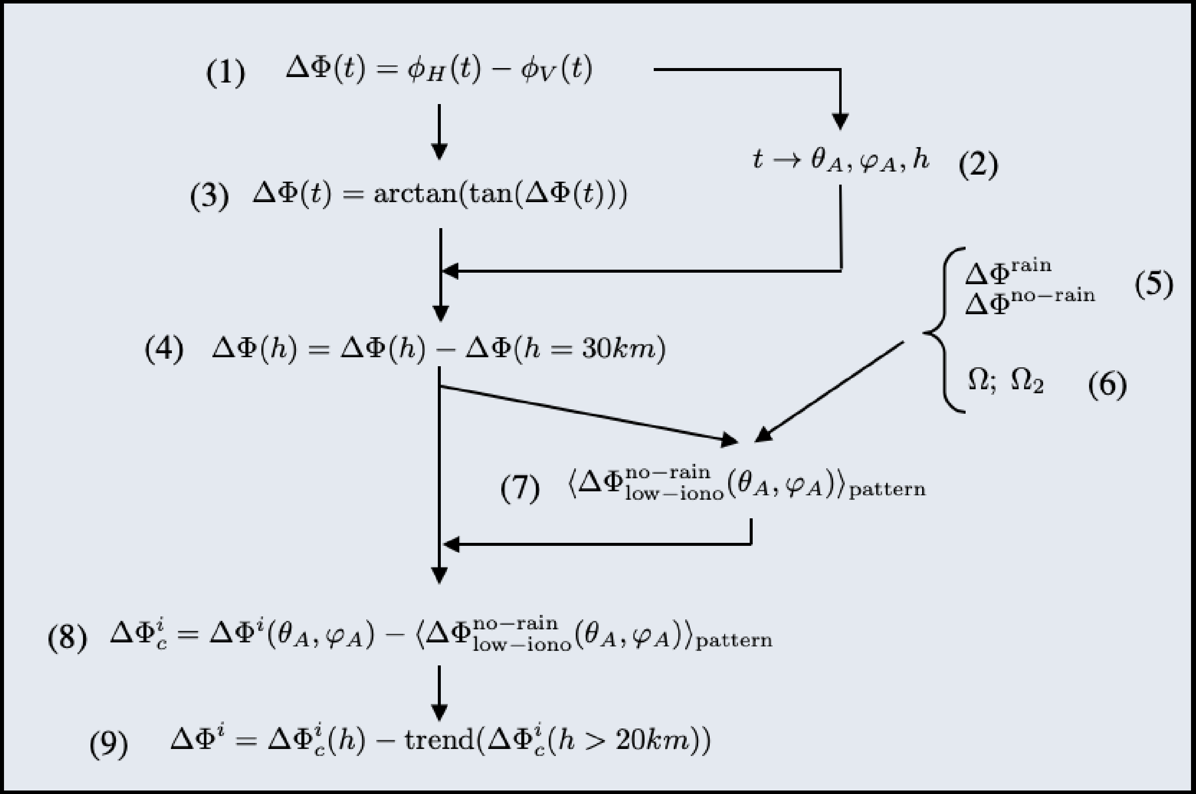
Careful calibration is needed to remove non-hydrometeor effects.



R. Padullés, Ph.D. dissertation, Univ. of Barcelona, 2017

Calibration Procedure

Padullés et al. *Atmos. Meas. Tech.*, https://doi.org/10.5194/amt-13-1299-2020

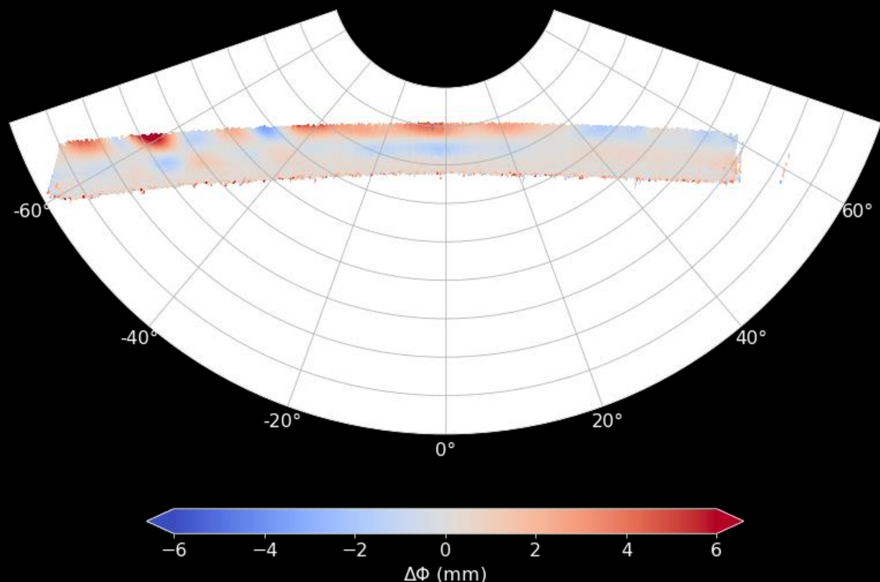


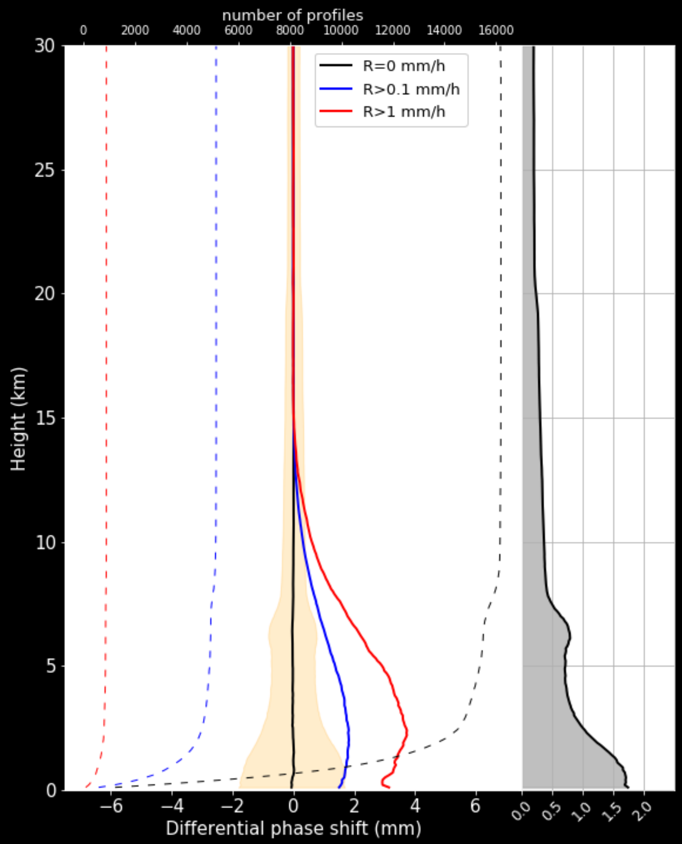
1) "Raw" observable
2) Mapping time -> height, elevation, azimuth, etc…
3) Correction of remaining cycle slips
4) **Set a zero-reference at the top of the observation (well above clouds)**
5) **Colocations with Precipitation (*)**
6) **Colocations with n_e & B (*)**
7) Antenna pattern (free of rain data and low ionospheric activity)
8) Correction of antenna pattern
9) Remove remaining trends

(*) *Requires external data or model*

On-Orbit Calibration of Antenna Pattern (largest impact)

Residual phase pattern from **no-rain, low-iono** PAZ occultations





1st Polarimetric RO User Workshop (23 April 2020, online)

Participation from 50 attendees including major weather agencies (NOAA, ECMWF, MetOffice, JMA), NASA, universities

rohp-PAZ

1st PAZ Polarimetric Radio Occultations User Workshop
ICE-CSIC/IEEC, Barcelona, April 23, 2020

Institute of Space Sciences (ICE-CSIC) and Institute for Space Studies of Catalonia (IEEC)

Polarimetric Radio Occultation is a new atmospheric sounding technique that has been validated with data from the Radio Occultations Through Heavy Precipitation (ROHP) instrument aboard the PAZ low Earth orbiting satellite.

In addition to the 'standard' GNSS radio occultation (RO) products (vertical profiles of T, p, q), this experiment exploits the polarimetric phase shift, $\Delta\phi$, between the horizontal and vertical polarization for detecting and quantifying hydrometeors (heavy precipitation events, convective rain, frozen particles and mixed phase).

The vertical structure of the hydrometeors, at a few hundreds of meter vertical resolution, emerges as the near-horizontal integral of the specific phase shift along the radio occultation link:

Status of the mission:

- Satellite launched Feb'2018.
- The **R**adio **O**ccultation and **H**eavy **P**recipitaton experiment (ROHP-PAZ https://paz.ice.csic.es), was activated in May'2018.
- Data continuously acquired since then.
- Sensitivity of $\Delta\phi$ to hydrometeors.

Objectives of the workshop:

- Provide potential users with an understanding of the data, their geophysical content, possibilities and limitations.
- Enable data providers better understanding on the needs of scientific users, and link the two communities to develop new products and applications.

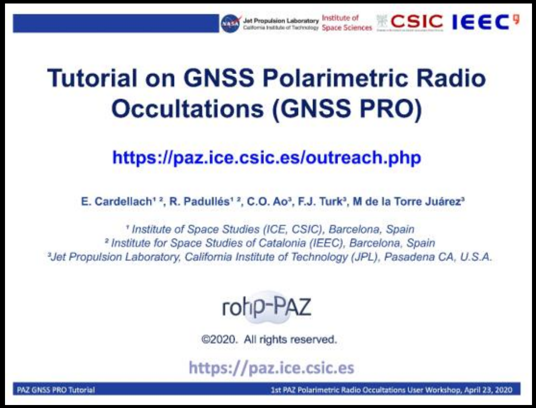
Target audience:

Scientists working on observational or modelling aspects of

- precipitation,
- convection,
- extreme events,
- microphysics schemes,
- model evaluation (climate, NWP),
- RO data assimilation

that might benefit from this expanded RO capability.

Interested? POC: Estel Cardellach
paz@ice.csic.es



Tutorial on GNSS Polarimetric Radio Occultations (GNSS PRO)

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

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[1] Institute of Space Studies (ICE, CSIC), Barcelona, Spain
[2] Institute for Space Studies of Catalonia (IEEC), Barcelona, Spain
[3] Jet Propulsion Laboratory, California Institute of Technology (JPL), Pasadena CA, U.S.A.

rohp-PAZ

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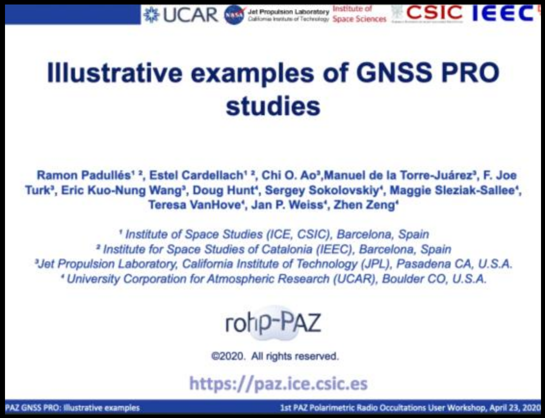
https://paz.ice.csic.es

PAZ GNSS PRO Tutorial — 1st PAZ Polarimetric Radio Occultations User Workshop, April 23, 2020



Illustrative examples of GNSS PRO studies

Ramon Padullés[1,2], Estel Cardellach[1,2], Chi O. Ao[3], Manuel de la Torre-Juárez[3], F. Joe Turk[3], Eric Kuo-Nung Wang[3], Doug Hunt[4], Sergey Sokolovskiy[4], Maggie Sleziak-Sallee[4], Teresa VanHove[4], Jan P. Weiss[4], Zhen Zeng[4]

[1] Institute of Space Studies (ICE, CSIC), Barcelona, Spain
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[3] Jet Propulsion Laboratory, California Institute of Technology (JPL), Pasadena CA, U.S.A.
[4] University Corporation for Atmospheric Research (UCAR), Boulder CO, U.S.A.

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https://paz.ice.csic.es

PAZ GNSS PRO: Illustrative examples — 1st PAZ Polarimetric Radio Occultations User Workshop, April 23, 2020

Links to the presentations:

https://paz.ice.csic.es/documents/outreach/GNSS-PRO_PAZ_Part-1_Tutorial_1st_PAZ_Workshop_April23_2020.pdf
https://paz.ice.csic.es/documents/outreach/GNSS-PRO_PAZ_Part-2_IllustrativeExamples_1st_PAZ_Workshop_April23_2020.pdf

Links to the videos of the first two parts of the workshop:

https://paz.ice.csic.es/documents/outreach/GNSS-PRO_PAZ_Part-1_Tutorial_1st_PAZ_Workshop_April23_2020_video.mp4
https://paz.ice.csic.es/documents/outreach/GNSS-PRO_PAZ_Part-2_IllustrativeExamples_1st_PAZ_Workshop_April23_2020_video.mp4

Current PAZ Status

- PAZ has been in orbit for over two years. The ROHP instrument has provided more than 80,000 polarimetric RO (as of late 2019).
- On-orbit calibration has been proven useful to remove non-hydrometeor effects (dominated by antenna cross-pol).
- The PAZ-ROHP data demonstrated, for the first time, that polarimetric RO can be used to detect heavy precipitation as well as upper-level ice (more on that later).
- Together with standard RO products that provide the moist thermodynamical environment, polarimetric RO technique can lead to **potential new applications**.

PAZ polarimetric products currently available from ICE-CSIC/IEEC (https://paz.ice-csic.es) and will be available from JPL in July 2020 (https://genesis.jpl.nasa.gov).

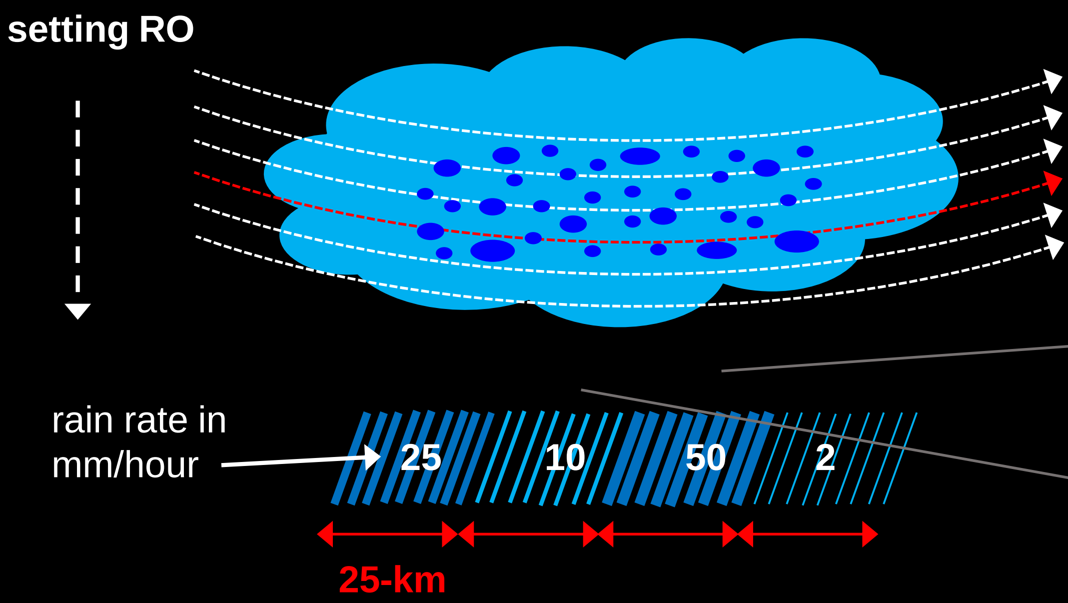
Up Next:

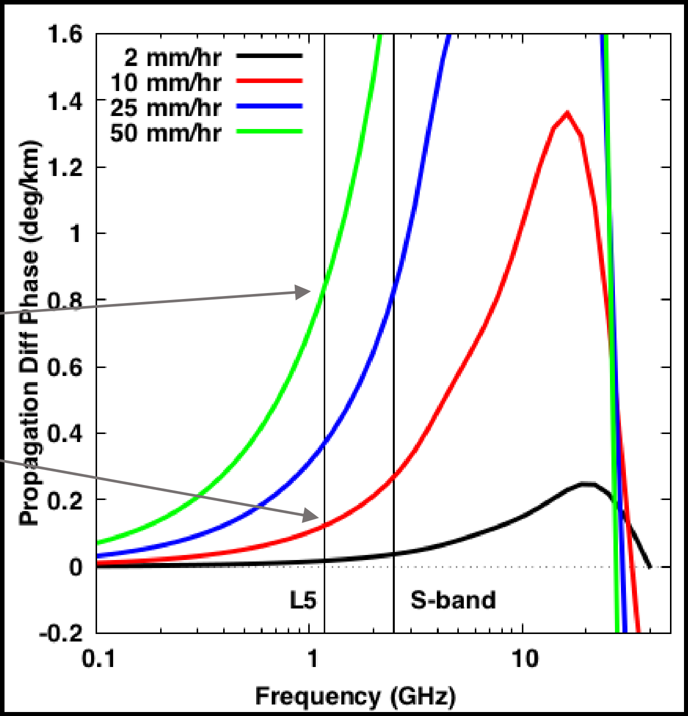
PRO data analysis and science

Some ideas for uses within weather modeling

Constellation concept

Relating Polarimetric Phase Difference to Precipitation





Polarimetric differential phase shift (ϕ_{DP}) due to rain is a path-weighted sum =

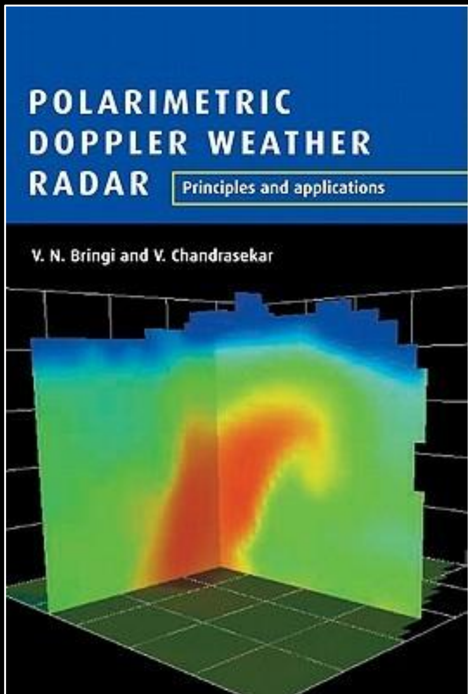
0.35(25) + 0.1(25) + 0.8(25) + 0.05(25)= 14.5 deg= 5 mm

Prelaunch Assumption:
Assuming -3dB performance with respect to COSMIC-1 equipment, PAZ will detect precipitation events inducing $\Delta\phi$ > 1.5 mm.

This value would clearly indicate the presence of heavy precipitation somewhere along the ray path.

But different path lengths and rain intensities could yield a similar phase difference.

Long Heritage in Polarimetric Doppler Radar Community



Specific differential phase shift

$$K_{DP} = \frac{180}{\lambda} \int Re(f_H - f_V)\, N(D)\, dD$$

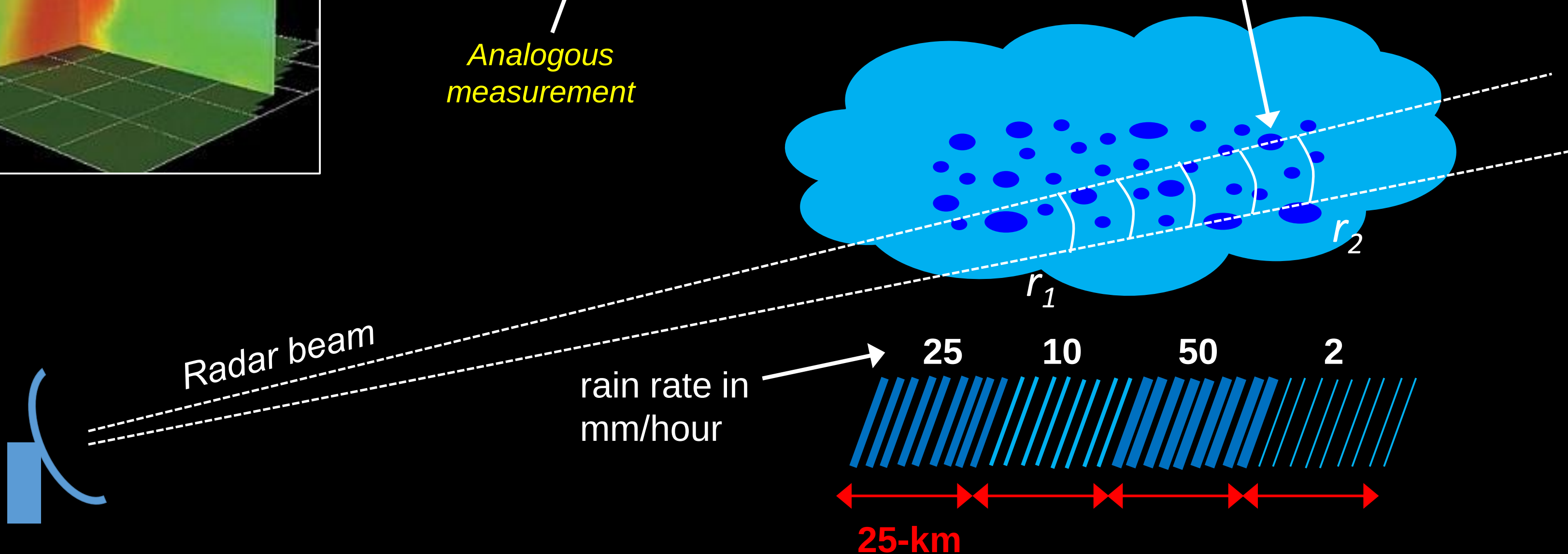
forward scattering amplitudes

Propagation differential phase shift

$$\phi_{DP} = 2 \int_{r_1}^{r_2} K_{DP}(r)\, dr$$

Analogous measurement

N(D)= hydrometeor size distribution within each radar pulse volume

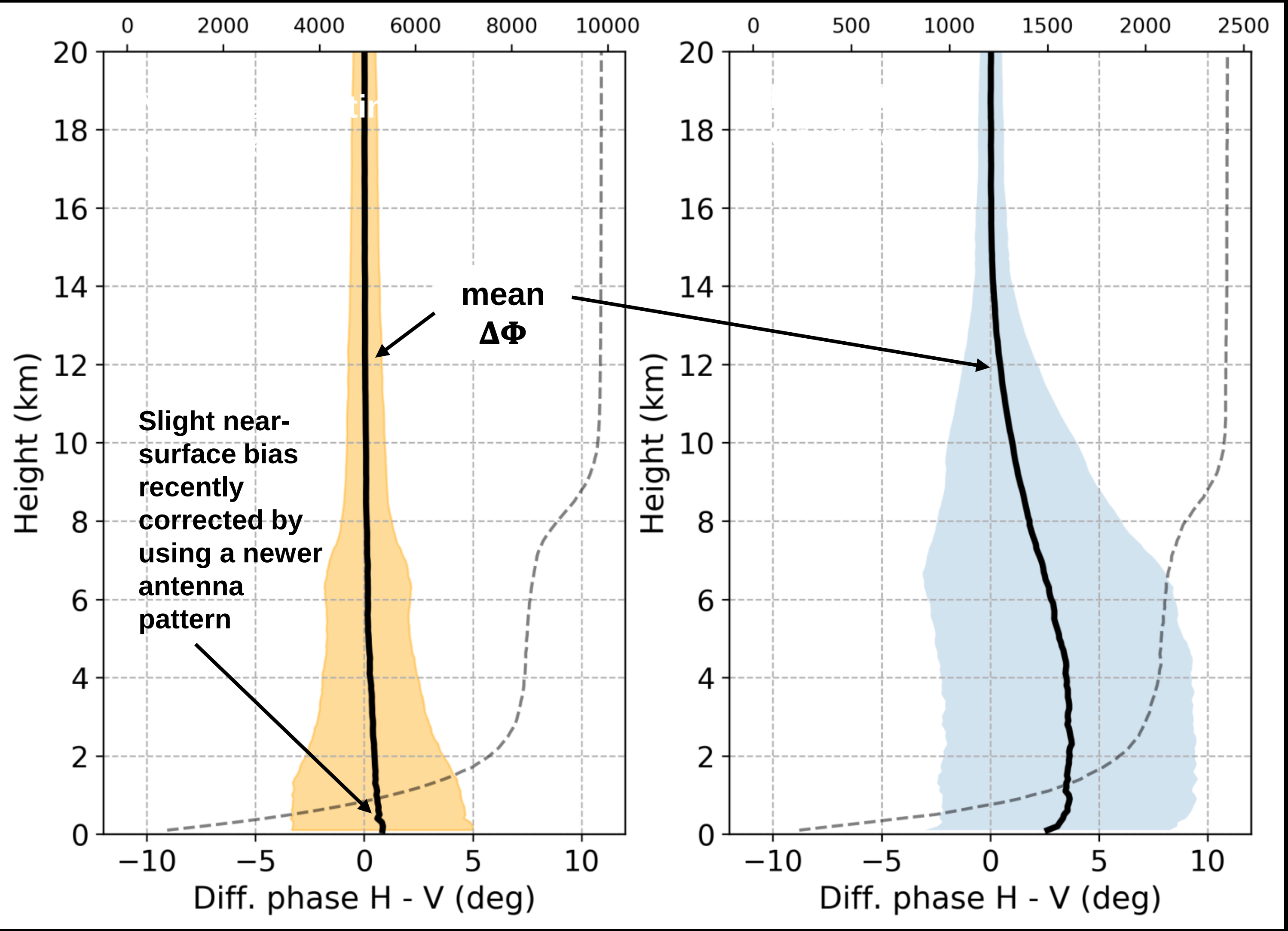


NEXRAD ground-based radars

(exaggerated depiction)

ROHP data through mid-2019

Nearest 30-min IMERG used to separate rain/no-rain events

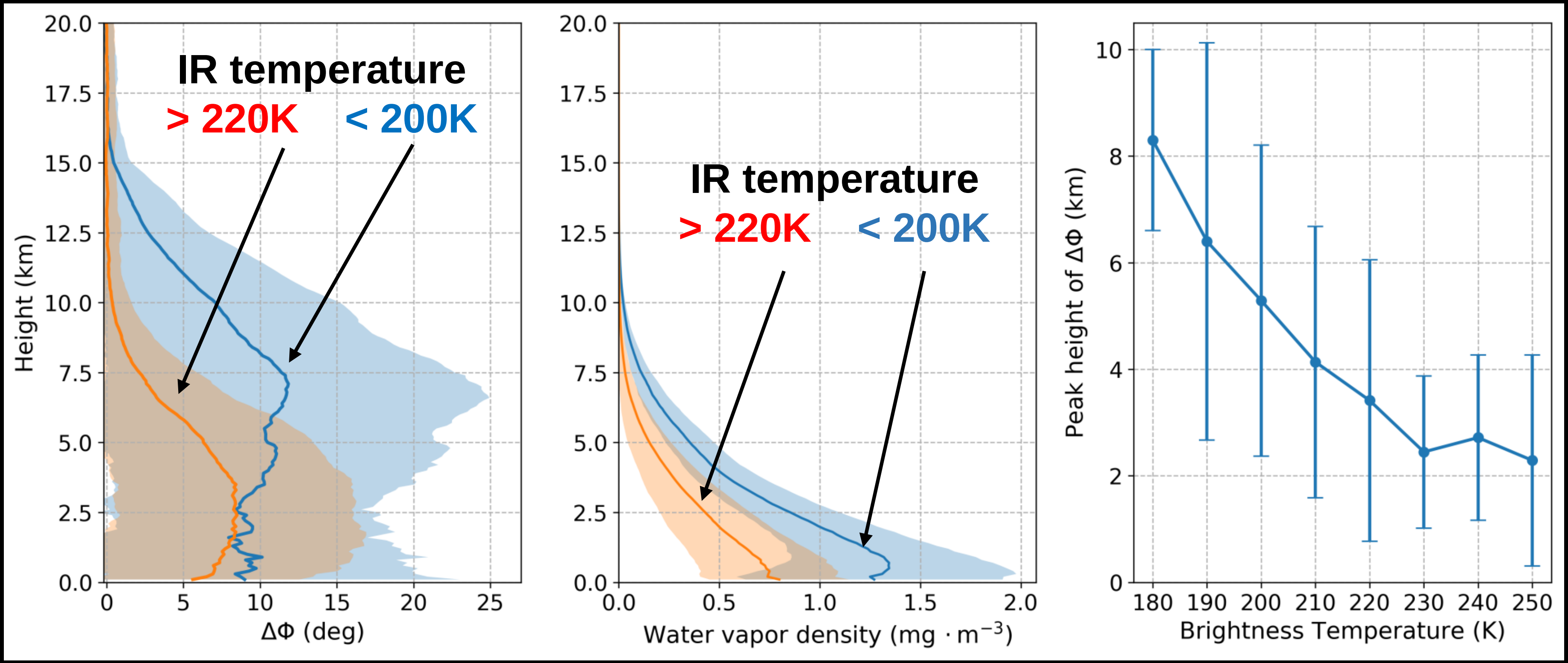


Padullés, R., C.O. Ao, F.J. Turk, and M. de la Torre-Juárez, B.A. Iijima, K.N. Wang, E. Cardellach, 2019. Calibration and Validation of the Polarimetric Radio Occultation and Heavy Precipitation experiment Aboard the PAZ Satellite. *Atmos. Meas. Techniques*, https://doi.org/10.5194/amt-2019-237

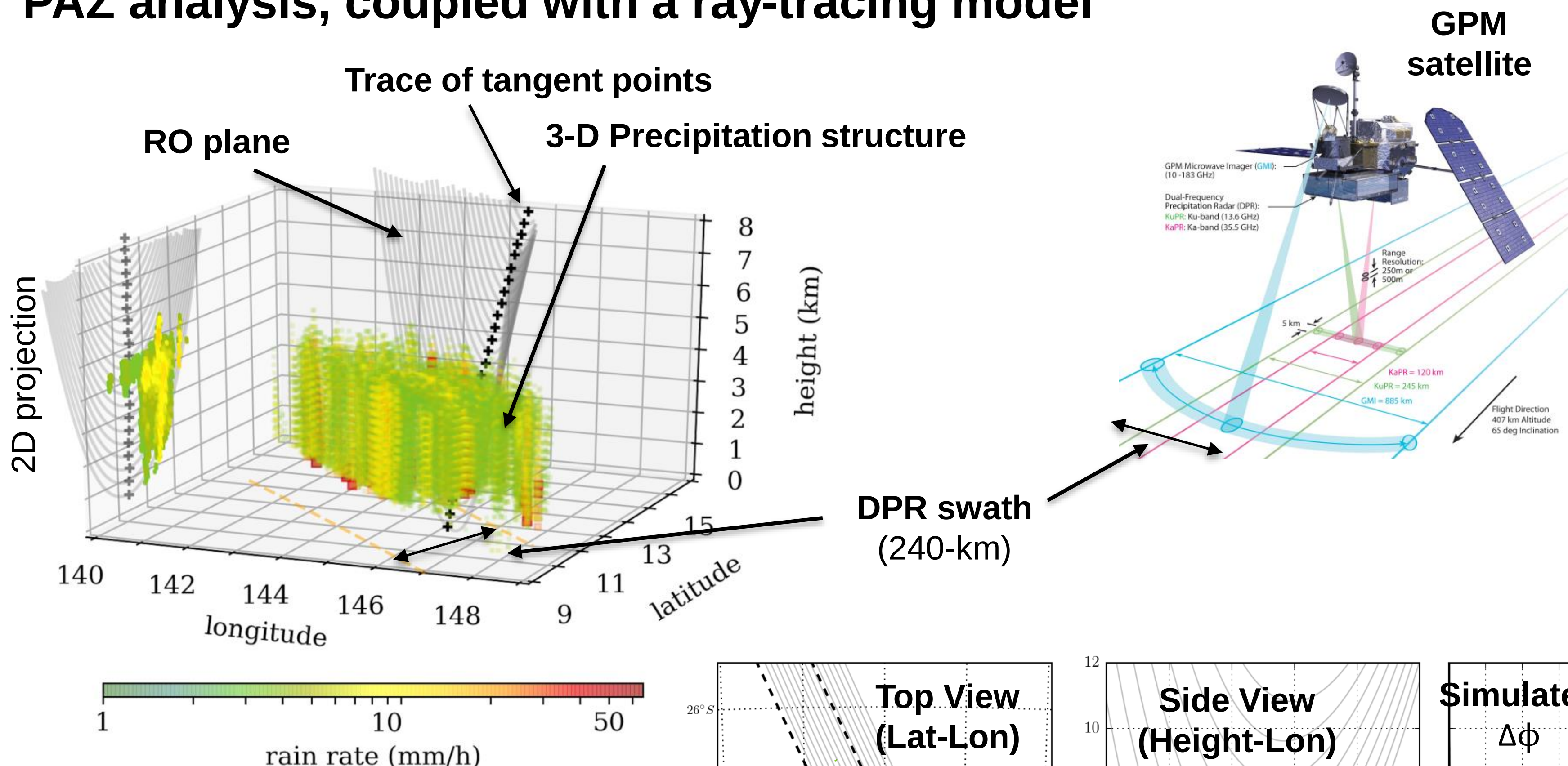
ROHP data through mid-2019

Nearest 30-min IMERG used to separate rain/no-rain events
Global IR composite (used by IMERG) for IR cloud top temp

Mixed phase and upper level ice detection?



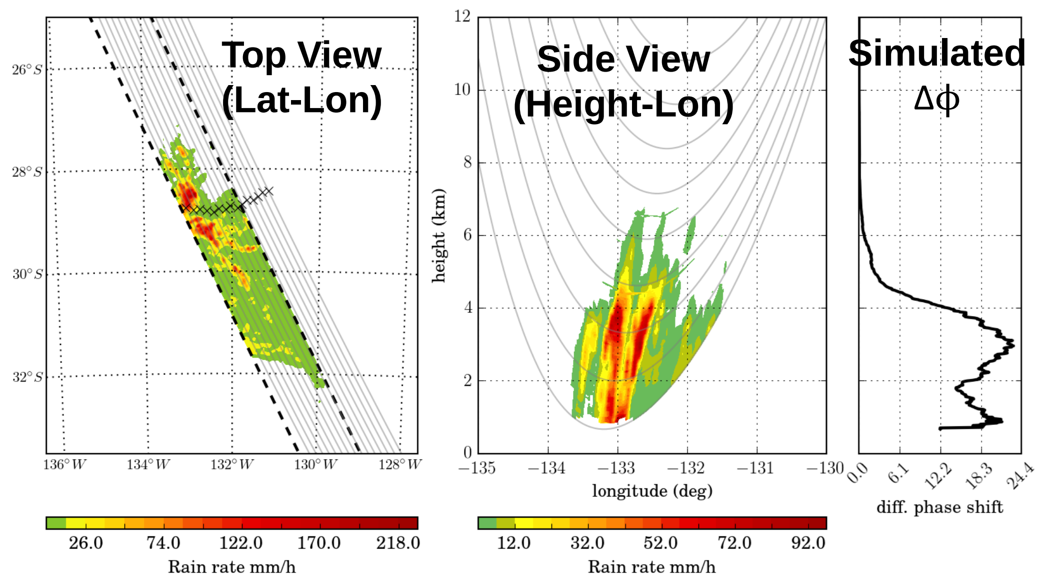
Use of GPM radar precipitation data for pre- and post-launch ROHP – PAZ analysis, coupled with a ray-tracing model



GPM 2B.GPM.DPRGMI (combined product) derives particle size distribution (PSD) parameters at each vertical (250-m) bin

Enables Δϕ to be simulated along simulated ray path

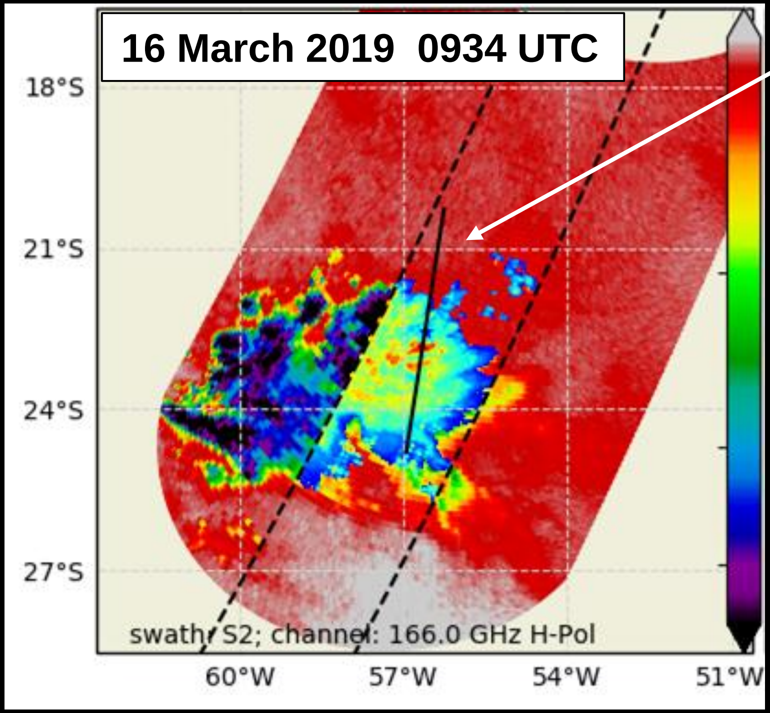
Compare with actual ROHP profiles



Precipitation Microphysics

What is being sensing above the freezing level?

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



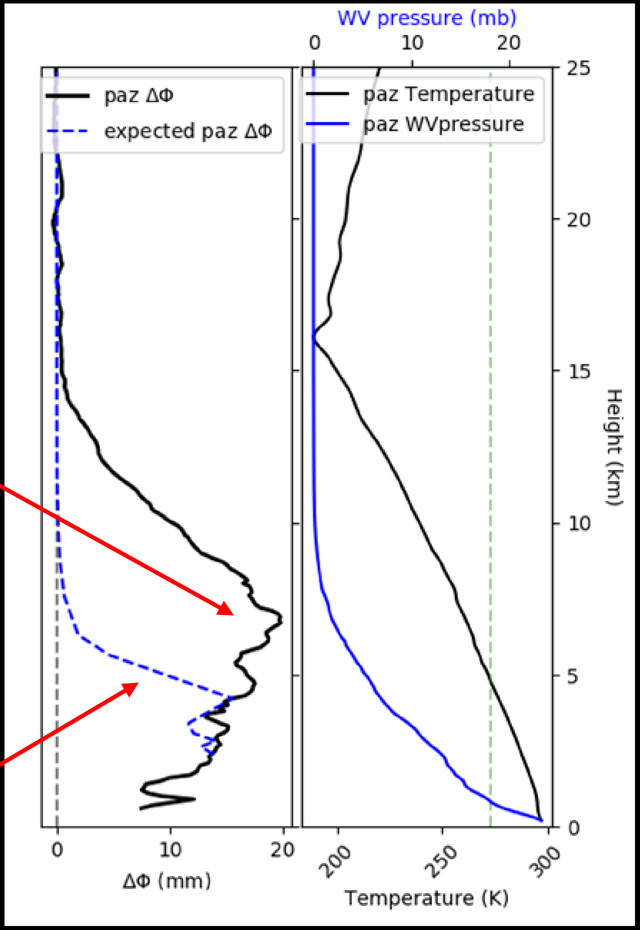
GPM-GMI 166H

ROHP mid-level ray path

Large ROHP Δϕ extending well above 10-km height

But simulations using DPR particle size distribution (PSD) parameters can't replicate this magnitude

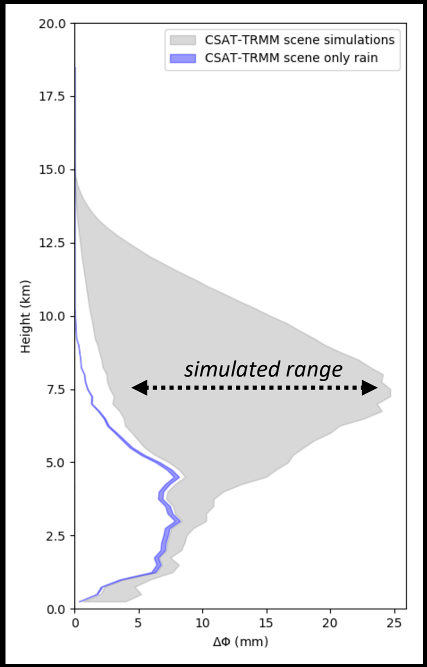
Vertically-Resolved Precipitation Structure



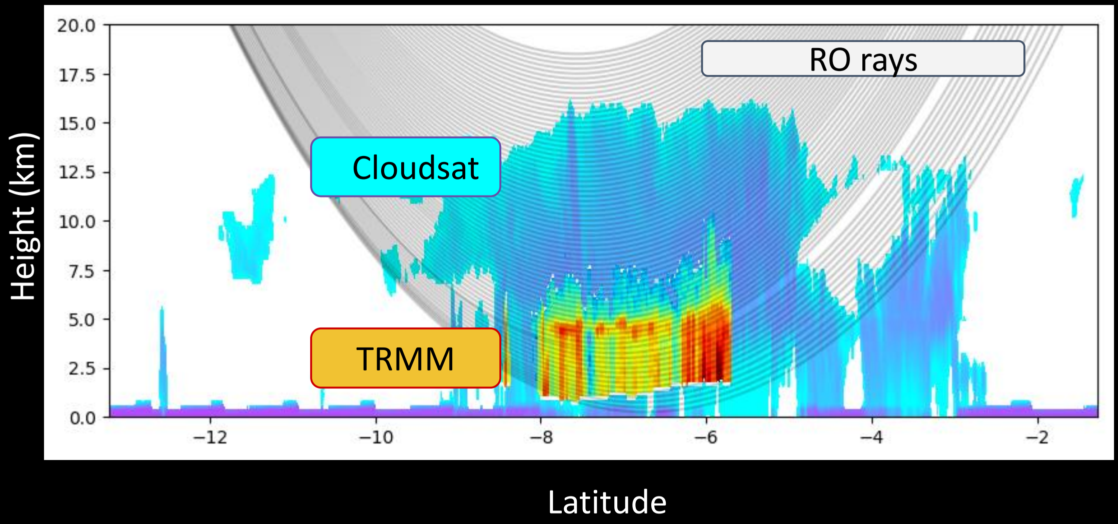
Precipitation Microphysics

Sensing of Upper-Level Ice

- Exploit 2BCSAT-TRMM and 2BCSAT-GPM coincidence database
  - > 20000 observations 2006-2019
- GPM DPR (13/35 GHz), TRMM PR (13 GHz): Sensitive to rain, large ice
- Cloudsat: W-band radar (94 GHz): Sensitive to smaller particles



Δϕ simulations using TRMM-PR PSD augmented by CloudSat ice PSD (where PR is insensitive) cover the observed range, showing evidence of sensitivity to upper level ice

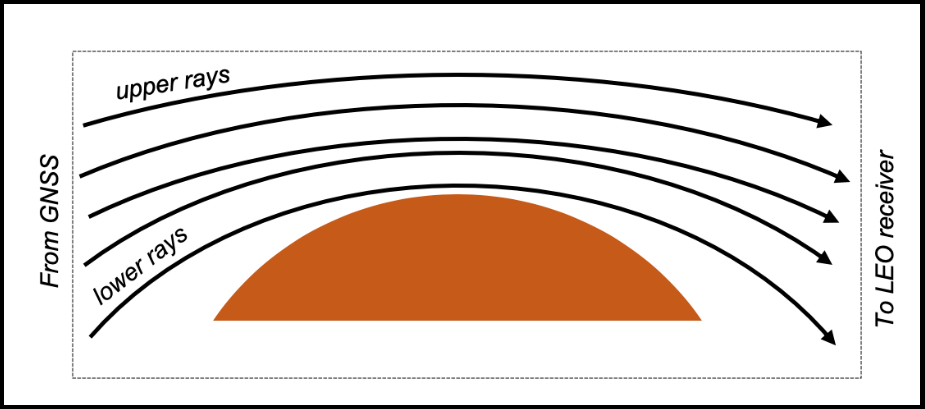


Particles randomly oriented +
a variable % of fully horizontally oriented

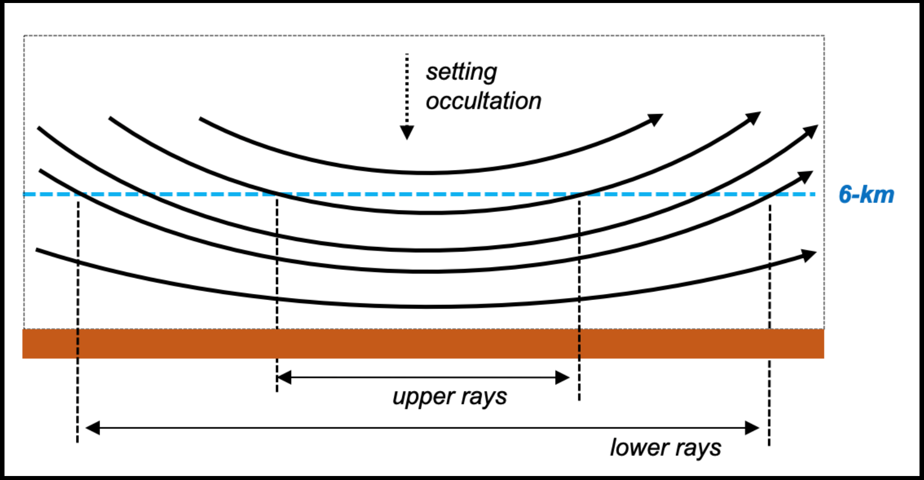
- The % of horizontally oriented increases linearly with height from 1% at the top to:
  - 10 % at the freezing Level (left gray)
  - 75 % at the freezing Level (right gray)

Precipitation Climatology

Spherical geometry



Projected onto a flat Earth



The $\Delta\phi$ profile provides an indication of "cloud top", in the sense of the level where sufficiently large aspherical hydrometeors are present

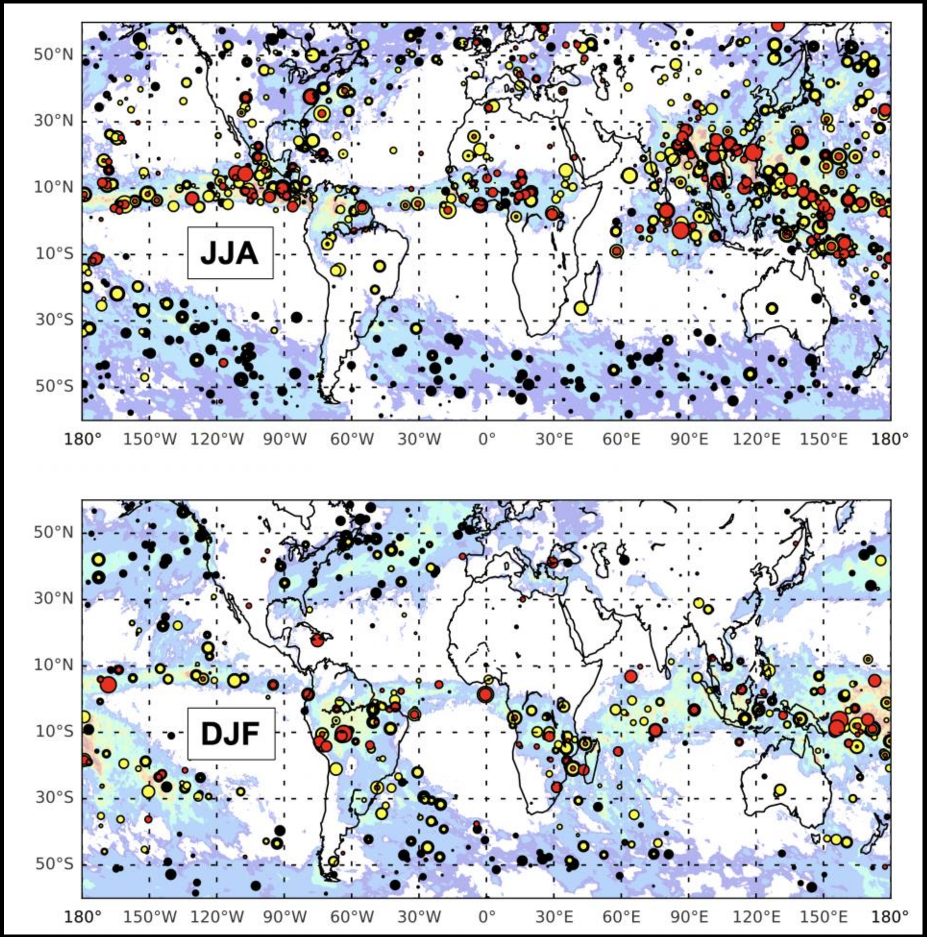
In the example shown, $\Delta\phi$ exceeded a threshold value beginning at 6-km

Find the level of the $\Delta\phi$ maximum

How does this compare to known precipitation patterns?

Padullés, R., Cardellach, E. & Rius, A., 2016. Untangling rain structure from polarimetric GNSS Radio Occultation observables: A 2D tomographic approach. *European Journal of Remote Sensing* 571–585. doi:10.5721/eujrs20164930.

Precipitation Climatology



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

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

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

The color contour background is IMERG over the same 3-month period

Good agreement with known global precipitation patterns

ROHP adds an additional indication of vertical precipitation structure

Some Ideas for Use in Weather Modeling

1) Since the RO propagates through heavy precipitation, the $\Delta\phi$ signal may directly reveal details on sensitivity to the water vapor structure, or model bias under heavy precipitation conditions.

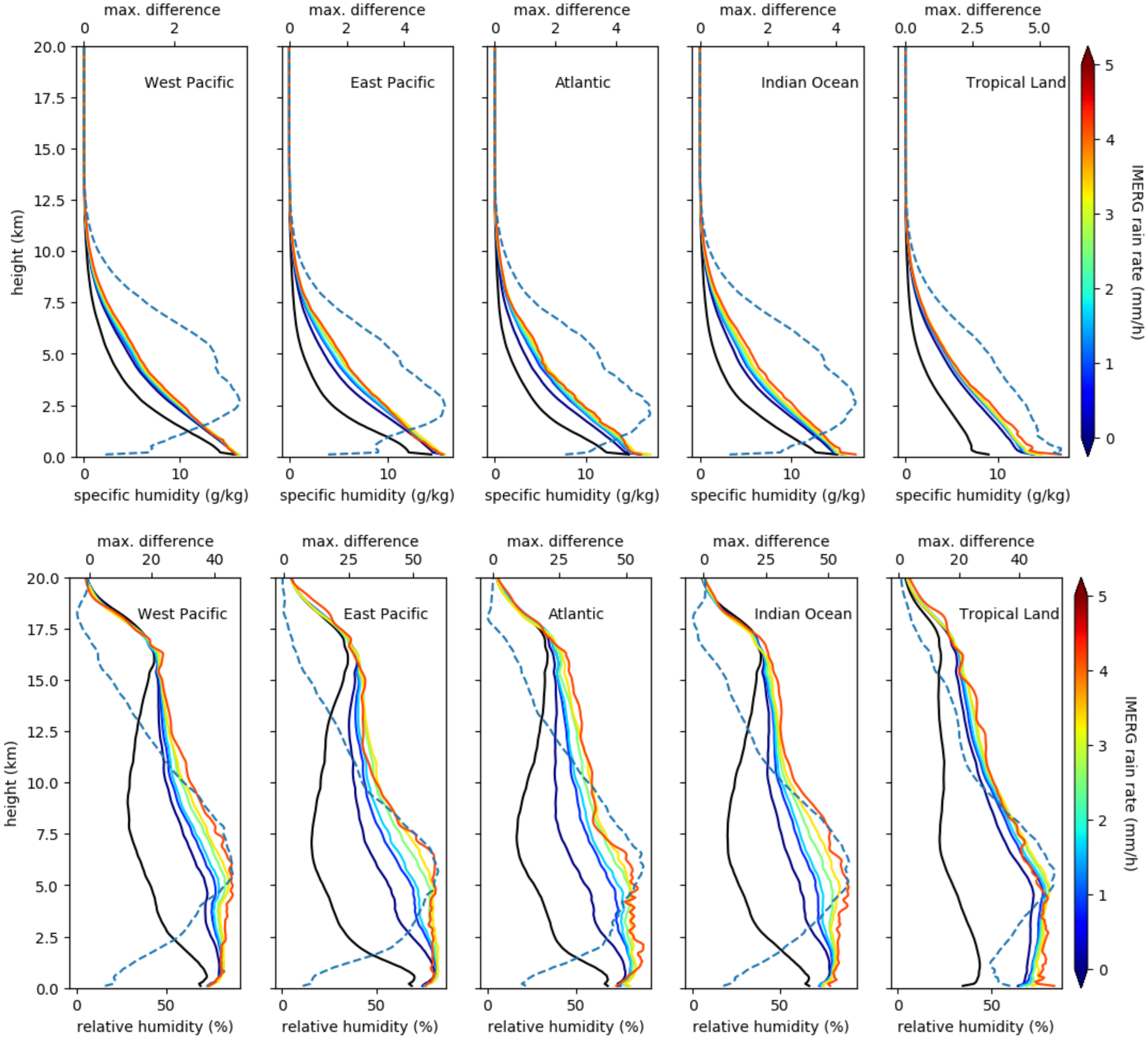
2) Knowledge of the moist thermodynamic profile within precipitation may be useful to evaluate the convective parameterization schemes used in climate and NWP forecast models. Even if RO's are assimilated, $\Delta\phi$ is a coincident, independent observation.

3) Traditional RO's are already routinely assimilated in NWP models and have demonstrated positive impact. Advance RO forward observation operators and the assimilation of rain-affected data.

4) As the number of RO observations continues to increase, assess the value of RO's in close space/time proximity (versus the more homogeneous spread e.g. COSMIC-2), to capture close-by observations near low-level moisture gradients (indicative of the presence or development of heavy precipitation).

5) Improved depiction of 3-D water vapor structure from increasingly dense constellations of RO and ATMS-like passive MW sounders.

Vertical Water Vapor Structure Conditioned on Precipitation



Co-located PAZ and IMERG data

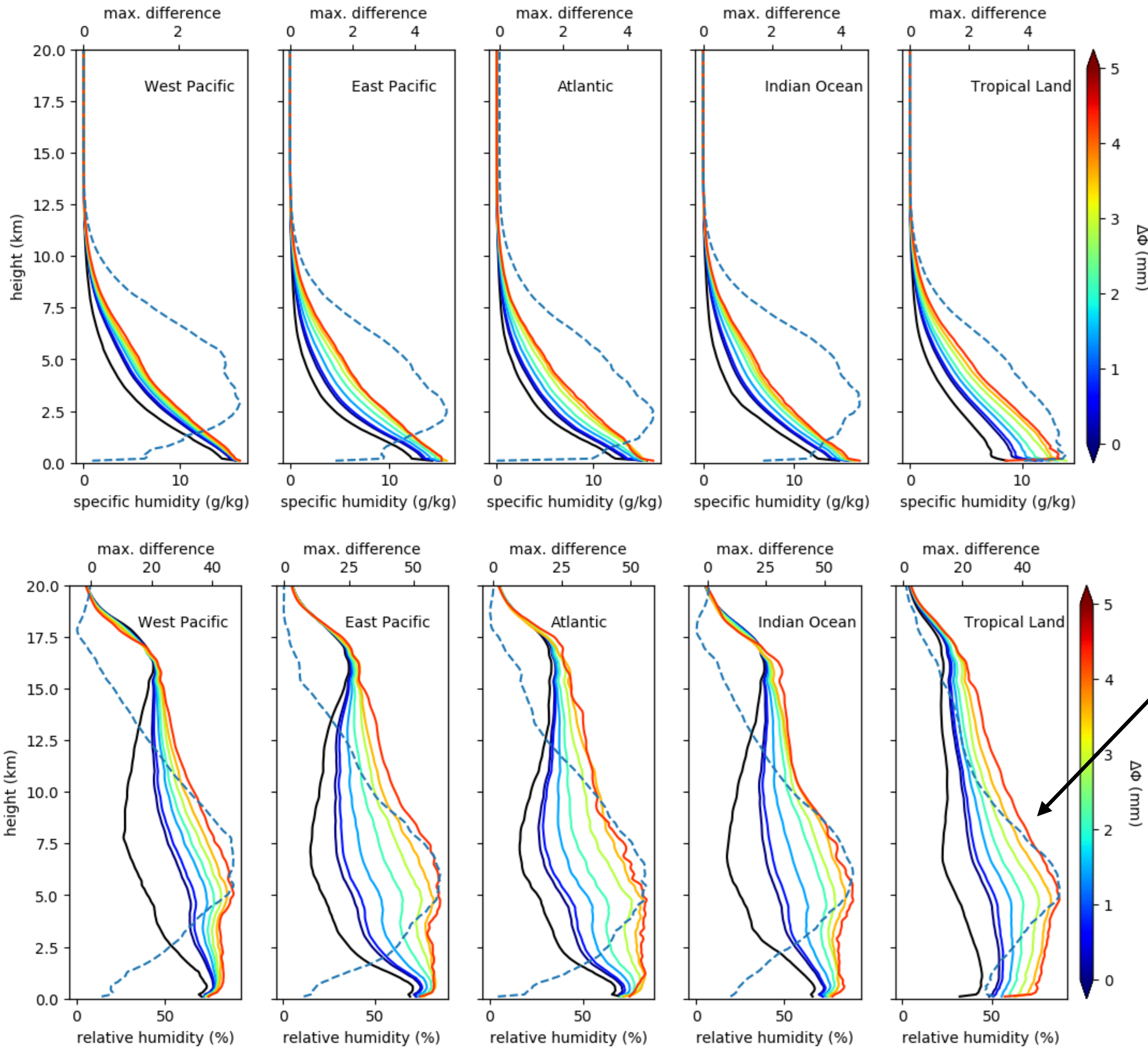
Specific humidity (top)
Relative humidity (bottom)

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

Data are 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 Water Vapor Structure Conditioned on Precipitation



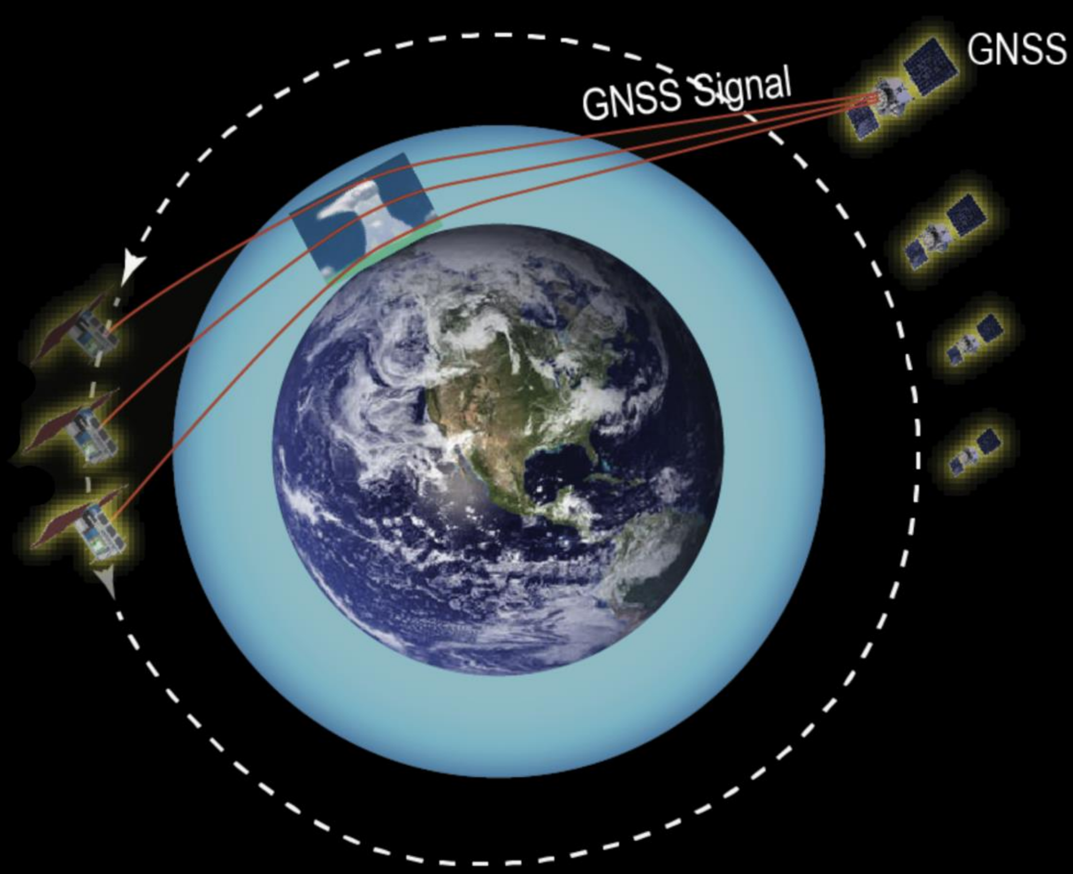
Same data as shown in previous slide, the difference being:

Data are averaged on different ROHP **Δϕ ranges** (*solid colored lines, according to color scale*)

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

Schiro, K. A. & J.D. Neelin, 2019. Deep Convective Organization, Moisture Vertical Structure, and Convective Transition Using Deep-Inflow Mixing. *J. Atmos. Sci.* **76**, 965–987.

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



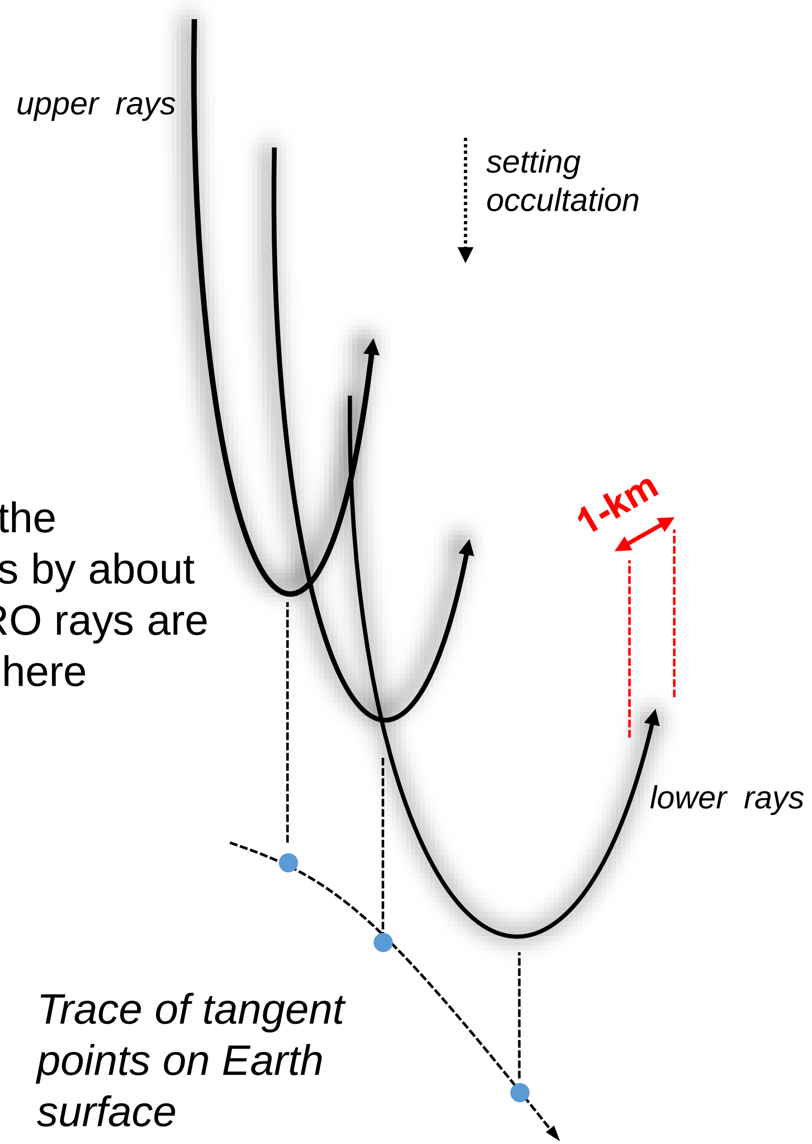
Turk et. al., Remote Sens. **2019**, *11*(20), 2399
https://doi.org/10.3390/rs11202399

A polarimetric RO ray path from a ROHP observation may traverse and detect a region of heavy precipitation, but there is no direct way contrast the T/q profile with the surrounding environment

Most RO constellation orbits emphasize maximizing sampling density

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

RO Horizontal Resolution: “Along-ray” View



During each RO, the tangent point drifts by about 50-km while the RO rays are within the troposphere

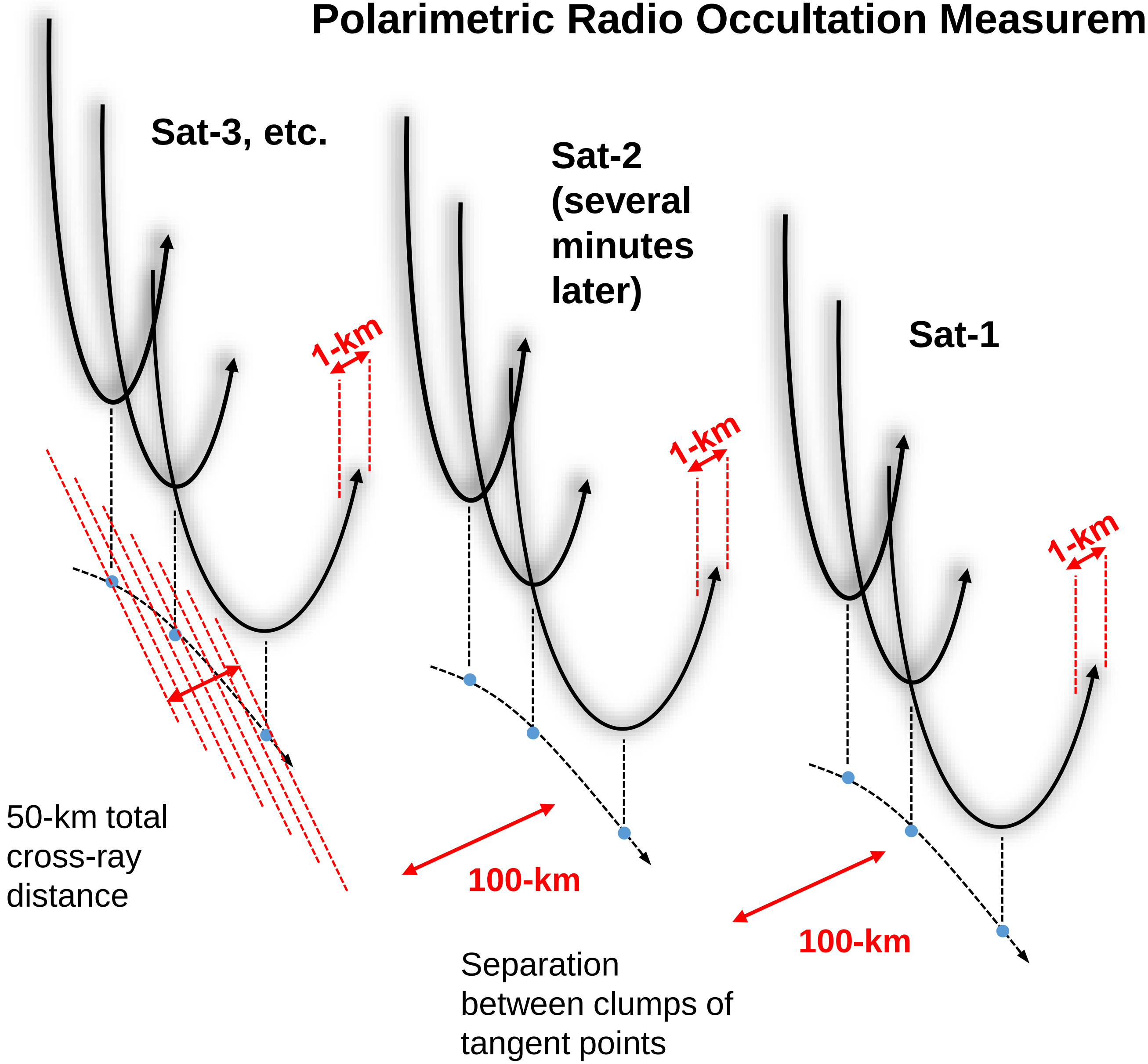
The resolution in the “along-ray” dimension is fairly coarse, ~150-km

Th resolution in the “across-ray” dimension is very high (1-km), finer than any current passive MW radiometer horizontal resolution

Essentially limited by the Fresnel volume of the propagation path

(conceptual only, not to scale)

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



(conceptual only, not to scale)

After an RO completes, there is an ~10-15-min time window when trailing receiving satellites (same orbital plane) see the same transmitting GNSS satellite

Each RO takes about 2-mins

Transmitting GNSS sat has moved by the time the next sat begins its RO

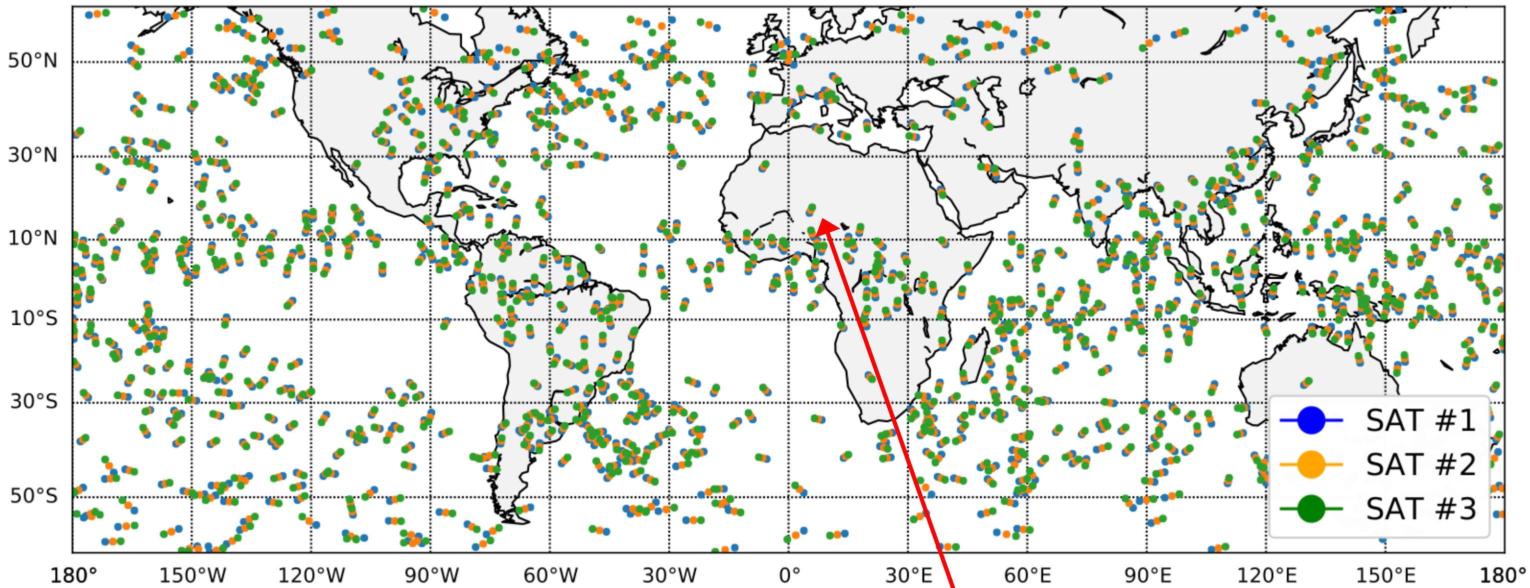
RO's are separated, but "clump" together

Rays paths are essentially "parallel" to each other (don't cross)

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

- 3 satellites, 45-deg inclination, each with PRO capability
- Tracking GPS and GLONASS, nominal 2-min separation between adjacent satellites
- Precession of -3 deg/day is included to obtain realistic sampling
- Provides approx. 400,000 events/year (an "event" is all three RO's together)

One-Day Events Intersecting Extreme (IMERG) Precipitation ($\Delta\phi$ > 6 mm)



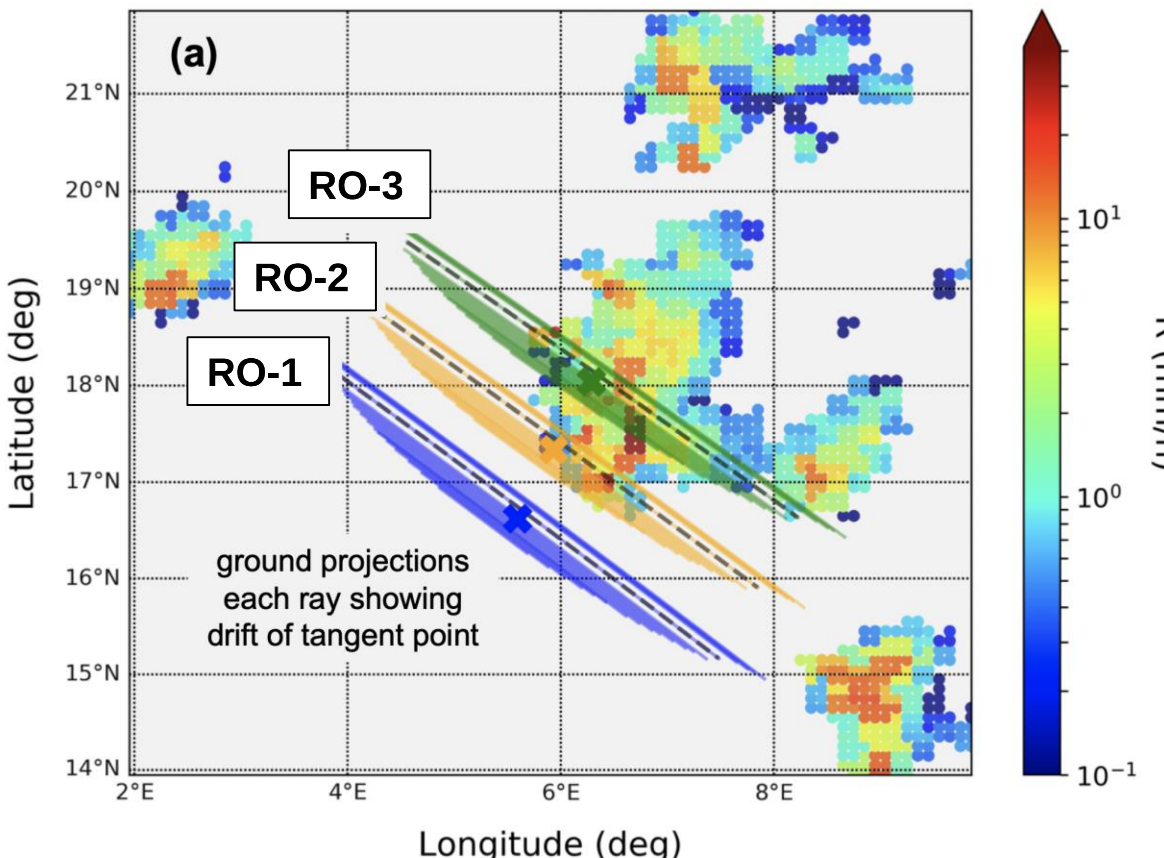
Colors indicate RO tangent point from Sat-1, Sat-2 and Sat-3

Zoom into some specific cases (next slide)

Note that the PRO tangent point locations tend to clump in triplicates

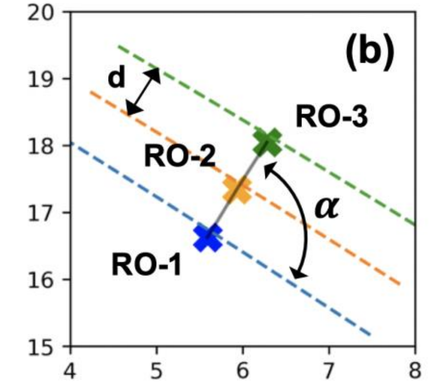
Benefits of a Closely-Spaced Satellite Constellation of Atmospheric Polarimetric Radio Occultation Measurements

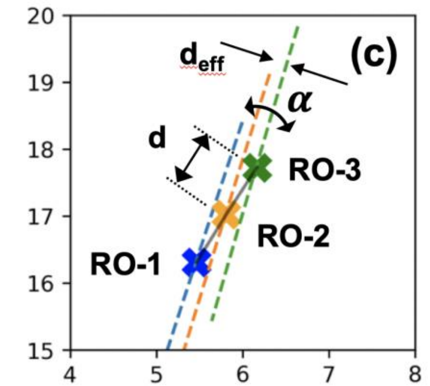
One Simulated Event near (18N, 6E)
Nearest 30-min GPM IMERG precip rate (color scale)



Only rays below 6-km shown
Ray path (high rays) < ray path (lower rays)

Ray paths from this set of RO's are well-separated

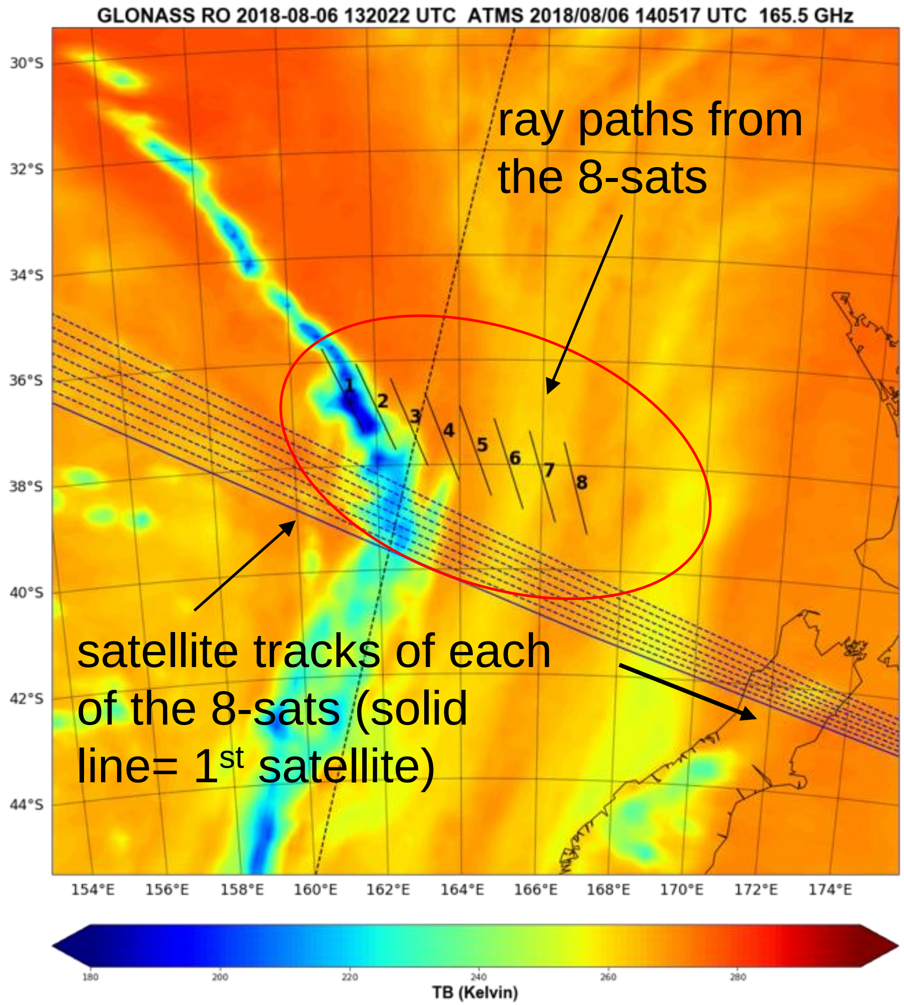




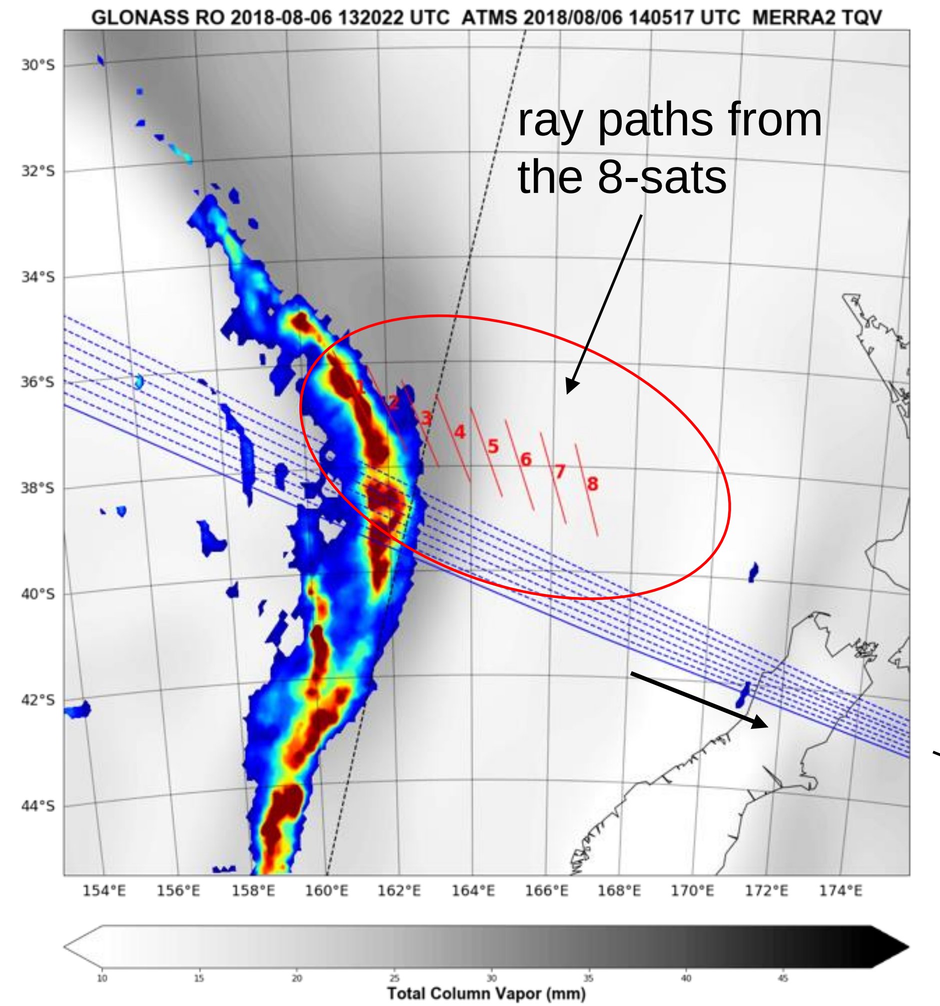
Depending upon the relative azimuth of the RO, others are less well-separated

Combining PRO and ATMS-like Passive MW Observations

- Same simulation configuration as before, but 8 satellites instead of three
- High-frequency passive MW provides an additional constraint on cloud structure



NPP 2018/08/06
ATMS 165.5 GHz TB (Kelvin)



Nearest 30-min GPM IMERG precip (colors)
Interpolated MERRA2 total vapor (grayscale)

Recent Publications

Cardellach, E., S. Oliveras, A. Rius, S. Tomás, C.O. Ao., G.W. Franklin, B.A. Iijima, D. Kuang, T. Meehan, R. Padullés, F.J. Turk, et al., 2019. Sensing Heavy Precipitation with GNSS Polarimetric Radio Occultations. *Geophysical Research Letters*, *46*, 1024–1031. https://doi.org/10.1029/2018GL080412

Padullés, R., C.O. Ao, F.J. Turk, and M. de la Torre-Juárez, B.A. Iijima, K.N. Wang, E. Cardellach, 2019. Calibration and Validation of the Polarimetric Radio Occultation and Heavy Precipitation experiment Aboard the PAZ Satellite. *Atmos. Meas. Techniques*, https://doi.org/10.5194/amt-2019-237

Turk, F.J.; Padullés, R.; Ao, C.O.; Juárez, M.T.; Wang, K.-N.; Franklin, G.W.; Lowe, S.T.; Hristova-Veleva, S.M.; Fetzer, E.J.; Cardellach, E.; Kuo, Y.-H.; Neelin, J.D., 2019. Benefits of a Closely-Spaced Satellite Constellation of Atmospheric Polarimetric Radio Occultation Measurements. *Remote Sens.*, *11*, 2399. https://doi.org/10.3390/rs11202399

Padullés, R., Cardellach, E., Wang, K. N., Ao, C. O., Turk, F. J., and de la Torre-Juárez, M., 2018. Assessment of GNSS radio occultation refractivity under heavy precipitation, *Atmospheric Chemistry and Physics,* https://doi.org/10.5194/acp-2018-66.

Juárez, M. de la T., R. Padullés, F.J. Turk, and E. Cardellach, 2018: Signatures of Heavy Precipitation on the Thermodynamics of Clouds Seen From Satellite: Changes Observed in Temperature Lapse Rates and Missed by Weather Analyses. *J. Geophys. Res: Atmospheres*, *123*, 13033-13045. https://doi.org/10.1029/2017JD028170

Tomás, S., Padullés, R. & Cardellach, E., 2018. Separability of Systematic Effects in Polarimetric GNSS Radio Occultations for Precipitation Sensing. *IEEE Transactions on Geoscience and Remote Sensing* **56**, 4633–4649. https://doi.org/10.1109/TGRS.2018.2831600

Cardellach, E., Padullés, R., Tomás, S, Turk, F. J., Ao, C. O., and de la Torre-Juárez, M., 2017. Probability of intense precipitation from polarimetric GNSS radio occultation observations, *Q. J. Royal Meteorological Soc*iety, 12. https://doi.org/10.1002/qj.3161

Padullés, R. Cardellach, E. de la Torre Juárez, M., Tomas, S., Turk, F. J., Oliveras, S., Ao, C. O. and Rius, A., 2016. Atmospheric polarimetric effects on GNSS Radio Occultations: the ROHP-PAZ field campaign, *Atmospheric Chemistry and Physics*, 16, 635-649, https://doi.org/10.5194/acp-16-635-2016.

Cardellach, E., Tomás, S., Oliveras, S., Padullés, R., Rius, A., De la Torre-Juárez, M., Turk, F.J., Ao, C.O., Kursinski, E.R., Schreiner, B., Ector, D. and Cucurull, L., 2014. Sensitivity of PAZ LEO Polarimetric GNSS Radio-Occultation Experiment to Precipitation Events, *IEEE Trans. Geoscience and Remote Sens.*, 53,190-206, http://doi.org/10.1109/TGRS.2014.2320309

Summary

ROHP-PAZ has been successfully been collecting polarimetric RO for (as of May 2020) over two years, ROHP instrument fully functional

Data have been successfully calibrated and validated for $\Delta\phi$ sensitivity to precipitation using coincidences with NASA Global Precipitation Measurement (GPM) data products (IMERG, DPR+GMI combined algorithm), and geostationary satellite imagery

Evidence of sensitivity to upper-level ice noted, by comparing ROHP data to simulations derived from 3-frequency (DPR Ku/Ka + CloudSat W-band) radar observations, and 166 GHz GMI polarization differences

Currently further analyzing for RO sensitivity to solid phase, including cold-season precipitation

Potential for use in weather modeling: Model diagnostics, independent validation data source, potential for DA

https://paz.ice.csic.es