Polarimetric GNSS RO aboard the PAZ satellite: status of the ROHP-PAZ experiment

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https://paz.ice.csic.es
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• Polarimetric RO (PRO) is a NEW MEASUREMENT CONCEPT

• It combines radio occultation links of the GNSS with the polarimetric properties of the forward scattering off big rain droplets (and other hydrometeors): GNSS polarimetric radio occultations (GNSS-PRO)

• HYPOTHESIS: polarimetric information sensitive to heavy precipitation

• If successful, GNSS-PRO would represent the only sensor that can infer both

  VERTICAL PROFILES OF ATMOSPHERIC THERMODYNAMICS
  +

  VERTICAL PROFILES OF HEAVY RAIN
Why are coincident thermodynamic and precipitation vertical profiles required?

- They might help understanding the thermodynamic conditions underlying intense precipitation.

- This is relevant because extreme events remain poorly predicted with the current climate and weather model parametrization.

- A better understanding is necessary towards improving climate models and quantifying the impact of climate variability on precipitation.
Why are coincident thermodynamic and precipitation vertical profiles required?

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...to address open science questions: POTENTIAL TO CONTRIBUTE ANSWERING SCIENTIFIC QUESTIONS OF RELEVANT SOCIETAL IMPACT!
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‘TYPICAL’ GNSS RO PRODUCTS: VERTICAL PROFILES OF THERMODYNAMIC VARIABLES at the tangent point (typically temperature, pressure, humidity)
‘NEW’ GNSS-PRO PRODUCTS:
VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure, water vapor)
+ VERTICAL PROFILES OF INTENSE RAIN
‘NEW’ GNSS-PRO PRODUCTS:
VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure, water vapor)
+ VERTICAL PROFILES OF INTENSE RAIN
To understand this concept it is important to keep in mind that the big falling rain drops ARE NOT like this
To understand this concept it is important to keep in mind that the big falling rain drops ARE NOT like this

but rather LIKE

The bigger the drop, the larger the asymmetry effect

More large drops in heavier rain
precipitation cell
precipitation cell

Local horizontal direction: maximize polarimetric phase shift

**L-band:** penetrates all weather systems

**RHCP:** 50% H-pol 50% V-pol
Robust to Faraday rotations
precipitation cell

\[ \Delta \phi^{atm} = \int_{L} K_{dp}(l) \, dl \]

Observable: horizontally integrated polarimetric phase shift (or polarimetric phase delay):

\[ \Delta \phi = \phi_H - \phi_V \]
Vertical scanning
This new measurement concept is being proved aboard the Spanish PAZ LEO

→ the Radio Occultation and Heavy Precipitation aboard PAZ experiment (ROHP-PAZ)

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Spanish PAZ satellite:

- Main payload, X-band SAR
- Polar orbit (97.4 deg) at ~514 km altitude, sun-synchronous dusk/dawn
- GPS receiver
- One 2-pol (H/V) RO antenna
The ROHP-PAZ experiment is led by ICE-CSIC IEEC: concept, experiment design, technological requirements, funding responsibilities…

But it has only been possible because of the committed support, collaboration and agreements with:

- **Hisdesat**: company owner of PAZ
- **NASA/Jet Propulsion Laboratory**: scientific interest in products and post-processing algorithms, NASA grants for their participation
- **NOAA**: near-real time ground-segment operations, NRT data dissemination of the ‘standard’ products to weather services worldwide
- **UCAR**: generation of the NRT ‘standard’ products for NOAA
Successful launch on **February 22, 2018**, by SpaceX (Falcon9). GNSS RO experiment **activated on May 10, 2018**.
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The IGOR receiver provides amplitudes and phases of each polarization channel.

UCAR and JPL process at level-1: SNR, excess phase $\phi$, at each polarization: $\phi_H$, $\phi_V$ → suitable to play with polarimetry.

Ideally, the only difference between $\phi_H$ and $\phi_V$ would be the larger delay induced by hydrometeors at H-pol than V-pol (and a constant $90^0$ shift).

However, other systematic effects do not cancel out. Largely the antenna phase pattern.
\( \phi H - \phi V \) without further processing looks wrong (h_exL1 - v_exL1):

Remaining cycle slips

\( \Delta \phi \) ranges meters!!!
PRO PROCESSING:

φH-φV without further processing looks wrong:

1) correct residual cycle-sips!!
ϕH-ϕV without further processing looks wrong:

2) function of altitude and smooth (1-sec filter)
PRO PROCESSING:

- $\phi_H - \phi_V$ without further processing looks wrong:

but still some residual trends above 20 km...

2) function of altitude and smooth (1-sec filter)
PRO PROCESSING:

$\phi_H - \phi_V$ now calibrated!

3) linear fit above 20km, then subtracted to the whole profile
• After simple calibration:

RAIN FREE:
- average → 0
- bias ~ 1° (bottom)
- dispersion:
  <2° @ h>4.5km
  <4° @ surface

RAIN EVENTS:
- clear positive mean (<~10km)
- mean > rain-free
- dispersion (except bottom)
- dispersion larger:
  diversity of rain rate
  inaccuracy co-location
Improved calibration strategy, accounting for antenna pattern:

Calibration and Validation of the Polarimetric Radio Occultation and Heavy Precipitation experiment Aboard the PAZ Satellite

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Under review at Atmospheric Measurement Techniques

(Padullés et al., IROWG-ROM SAF 2019, next talk)
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5) Reflectometry

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Geophysical Research Letters

RESEARCH LETTER

Sensing Heavy Precipitation With GNSS Polarimetric Radio Occultations

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Jan 2019
• Results using **first 5 months** of data: May 10 to October 10 2018

• Co-located with IMERG 2D rain products + successful QC: **14,297** with **4,338 rainy cases**

• **IMERG provides 2D rain rate** combined from different sources, in 30 minute interval, but ~14% detection failures

• Co-location by **averaging wide areas of IMERG** rain around the GNSS-PRO central point

IMERG co-location not perfect, invalid set of data for one-to-one validation, but valid approach to **statistically check the response of GNSS-PRO to hydrometeors**
for each individual profile → histograms:

\[ \langle \Delta \phi \rangle \text{ for } 0\text{km-20km} \]

RAIN-FREE events:
- 98.4% with \( \langle \Delta \phi \rangle < 2^\circ \)
- 99.97% with \( \langle \Delta \phi \rangle < 4^\circ \)

‘false intense rain positives’: for \( \langle \Delta \phi \rangle > 4^\circ \) → 0.96%

NOTE: not a detection algorithm, yet Exercise to check meaning of the signals, to understand the observables, link to hydrometeors...
\[ \langle \Delta \phi \rangle_{0\text{km-20km}} \] for each individual profile → link to rain rate:

GRL 2019
Validation of the vertical structure of $\Delta \phi(h)$:

All cases with $R_{20} > 1\text{mm/h}$
Validation of the vertical structure of $\Delta \Phi(h)$:

High sensitivity to mixed phase + Cloud ice

All cases with $R_2 \geq 1 \text{mm/h}$
• **STRONG SIGNAL DUE TO FROZEN PARTICLES** (cloud ice, mixed phase…)

• **OPPORTUNITY**: unique new way of sensing frozen particles. Can it be used to improve micro- physic aspects? Role of these particles in extreme events?

• **CHALLENGE**: polarimetric shift mixes rain and other hydrometeors. The Look-Up Tables (LUT) prepared for the rain retrievals did not include contribution from frozen hydrometeors, so new LUTs need to be developed.
• Extraction of large scale precipitation information from intermediate observables?
Convective precipitation from ERA-5:

- $H_{\text{top}} > 10 \text{ km}$
- $5 \text{ km} < H_{\text{top}} < 10 \text{ km}$
- $2 \text{ km} < H_{\text{top}} < 5 \text{ km}$
- $H_{\text{top}} < 2 \text{ km}$

4.5 months of PAZ data
STUDIES: Other observables

H top (color) $\langle\Delta\Phi\rangle$ _freezing^20km (size)

May 10 – Sep 30, 2018
Contents:

1) Sensing hydrometeors
2) Other observables
3) Thermodynamics of heavy precipitation
4) Polarimetric bending-impact space
5) Reflectometry
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**

We need more globally distributed and vertically resolved observations
Vertical structure of precipitation from RO

Using RO thermodynamic retrievals and GPM IMERG precipitation:

Solid lines: Specific humidity (top) and relative humidity (bottom) averaged on different precipitation ranges as a function of height.

Dashed: Difference between max and min precipitation bin averaged variable {i.e. red – blue lines}

Co-location COSMIC – IMERG precipitation
Vertical structure of precipitation using PRO

Using PRO thermodynamic retrievals and $\langle \phi_H - \phi_V \rangle$ as a proxy for precipitation:

- West Pacific
- East Pacific
- Atlantic
- Indian
- Tropical Land

Preliminary results

$\langle \phi_H - \phi_V \rangle$ as a proxy for precipitation

PAZ data (no co-location)
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Is the differential polarimetric bending angle, $\alpha_H - \alpha_V$, sensitive to hydrometeors?

Wang et al., IROWG-ROMSAF 2019, poster P07
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• As other RO missions, PAZ accidentally captures signals reflected off the Earth surface, too.

• Gorbunov et al., 2018 developed a ‘reflection index’ related to the intensity of the reflected signal.

• It is then possible to check the ratio between both polarizations of the reflected signal.

Is the ratio between the H-pol and V-pol components of the reflected signal providing information on the Earth surface?
• Polarimetric ratio (in dB) of reflections off different surface types:

**LAND** (mostly polar)

**YOUNG ICE**

**OCEAN**

**MULTIYEAR ICE**
STUDIES: Reflectometry

- Sea ice thickness:
  - Sea ice thickness < 1 m
  - Sea ice thickness: 1-2 m
  - Sea ice thickness > 2 m
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- UCAR has released PAZ data at CDAAC (including excess phase and SNR at both polarizations) → $\Delta\phi$ needs to be calibrated!
- IEEC plans to released calibrated $\Delta\phi$ and other derived products soon.
- JPL plans to begin releasing the PAZ data ~ November, including calibrated polarimetric $\Delta\phi$ products (Level 1b).

‘USUAL’ RO SETS:

- UCAR has released PAZ data at CDAAC (including NRT). See Doug’s presentation later.
- NOAA ground segment and UCAR processing chain are operating in NRT. See François’ presentation on Tuesday.
- NOAA working for a second ground station (Finland).
- PAZ data disseminated in NRT through USA PDA system.
- NRL assimilates PAZ data into NAVGEM operationally. See Ben’s presentation tomorrow.
- GTS dissemination only requires a ‘quick checkout’ by NOAA (any time now?).
• PAZ carries a polarimetric RO payload, to prove the **GNSS-PRO** concept.
• New measurement concept: thermodynamics + heavy rain.
• Launched: **Feb 22, 2018**. RO activated on **May 10, 2018**.
• **Polarimetric phase shift linked to precipitation**, larger signals for more intense rain.
• **Vertical features** in polarimetric phase shift **consistent with storms at reaching different altitudes**.
• Strong signals induced by **mixed phase/cloud ice**.
• Use of other derived-observables (top height, signal above freezing level, …) → **potential for convection products**.
• Use of PAZ $\Delta \phi$ and PAZ RO moisture profiles → Direct use of PAZ data for **better understanding of deep convection system**?
• **Polarimetric bending space** also sensitive to precipitation.
• **Polarimetric reflected** signals (??)
• **DATA ALREADY PUBLICLY AVAILABLE, AND SOON DISSEMINATED IN NRT.**
PAZ carries a polarimetric RO payload, to prove the GNSS-PRO concept.

New measurement concept: thermodynamics + heavy rain.

Launched: **Feb 22, 2018**. RO activated on **May 10, 2018**.

Polarimetric phase shift linked to precipitation, larger signals for more intense rain.

Vertical features in polarimetric phase shift consistent with storms at reaching different altitudes.

Strong signals induced by mixed phase/cloud ice.

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Use of PAZ $\Delta \Phi$ and PAZ RO moisture profiles → Direct use of PAZ data for better understanding of deep convection system?

Polarimetric bending space also sensitive to precipitation.

Polarimetric reflected signals (?)

**DATA ALREADY PUBLICLY AVAILABLE, AND SOON DISSEMINATED IN NRT.**

Conclusions:

- Retrieval algorithm not ready yet.
- A lot of potential studies to conduct.
- Possibilities also at high altitudes (ionospheric information?)
- A lot of data and ideas, but a little team to work on it.
- The more scientists look at the data, the quicker and better outcome.
rohp-PAZ

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