Polarimetric GNSS RO: status of the PAZ mission and polarimetric retrieval algorithms

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INTRODUCTION:
- Summary of polarimetric RO (PRO)
- Summary of PRO in PAZ Low Earth Orbiter (ROHP-PAZ)
- PRO observable: polarimetric phase-shift

SEPARATIVITY ALGORITHM

STATISTICAL INVERSION ALGORITHM
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SEPARTIVITY ALGORITHM

STATISTICAL INVERSION ALGORITHM
PRODUCTS: VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure from refractivity)
PRODUCTS: VERTICAL PROFILES OF THERMODYNAMIC VARIABLES (typically temperature, pressure from refractivity) + VERTICAL PROFILES OF [INTENSE] RAIN
- New concept, to be proven aboard the PAZ Spanish LEO
- Similar to polarimetric radars, but FORWARD SCATTERING (propagation) rather than BACK-SCATTERING
- **GNSS**: Signals at L-band: ~1.5 GHz
  (this is ~1/2 of NEXRAD polarimetric radars, at 3 GHz)
- [Padullés et al. 2016] shown in a mountain-based experiment that heavy rain induced polarimetric effects in GNSS at slant geometry:
Spanish PAZ satellite

- Main payload, X-band SAR
- Polar orbit (97.4 deg) at ~514 km altitude
- IGOR+ GNSS receiver
- A 2-pol (H/V) RO antenna
- Launch: Q4 2017
Rain drop: flattered by air dragging

Tangential propagation: asymmetric drops induce different propagation parameters in the vertical and horizontal polarization components.

But at **L-band**: small signal!

→ Different attenuation (amplitude): calibration issues

→ Different phase delay: **GNSS very GOOD at measuring phase-delay!**
On the conservative side, we then expect that PAZ will be able to measure **polarimetric phase-shift better than 1.5 mm delay (2.8 degrees pol. Phase-shift) at 1 Hz**.

Heavy rain events induce polarimetric phase shifts larger than this threshold (78,000 COSMIC profiles co-located with TRMM):
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\[ \chi_{\text{ion2}}(t) \approx \frac{\pi}{2} + \cos 2\Omega_2(t) \Phi_{\text{dp}}(t) - 2m \sin \theta(t) \]
\[ \approx \frac{\pi}{2} + [1 - 2\Omega_2^2(t)] \Phi_{\text{dp}}(t) - 2m \sin \theta(t) \]

Seperability of systematic effects in polarimetric GNSS radio-occultations for precipitation sensing

Sergio Tomás, Ramon Padullés and Estel Cardellach Member, IEEE

\[ E = E_h \hat{h} + E_v \hat{v} = E_R \hat{u}_R + E_L \hat{u}_L \]
\[ E_t = e^{j\phi_{\text{atm}}} e^{-j\kappa_0 r} \mathbf{A} \mathbf{T}_{\text{ion2}} \mathbf{T}_{\text{tr}} \mathbf{T}_{\text{ion1}} \mathbf{E}_\text{in}, \]
\[ \mathbf{U}_{\text{LC}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & -j \\ 1 & j \end{bmatrix}, \quad \chi = \frac{E_v}{E_h}, \]
\[ \mathbf{U}_{\text{CL}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ j & -j \end{bmatrix}, \quad \chi^c = \frac{E_L}{E_R}. \]
\[ \mathbf{T}_{\text{tr}} \approx \begin{bmatrix} e^{-j\Phi_h} & 0 \\ 0 & e^{-j\Phi_v} \end{bmatrix}. \]
\[ \mathbf{T}_{\text{tr}} \approx \begin{bmatrix} T_{hh} + T_{vv} & T_{hh} - T_{vv} \\ 0 & 0 \end{bmatrix}. \]
\[ \mathbf{T}_{\text{tr}}^c = \frac{1}{2} \begin{bmatrix} T_{hh} + T_{vv} & T_{hh} - T_{vv} \\ T_{hh} - T_{vv} & T_{hh} + T_{vv} \end{bmatrix}. \]
\[ \chi^c = \frac{1 + j\chi}{1 - j\chi}, \quad \delta^c = \delta_L - \delta_R = 2\varphi. \]
\[ -j\chi = \frac{1 - \chi^c}{1 + \chi^c}. \]
\[ \epsilon(\text{dB}) \equiv 20 \log \frac{\max |\mathcal{E}|}{\min |\mathcal{E}|} = 20 \log \frac{E_{0,R} + E_{0,L}}{E_{0,R} - E_{0,L}}, \]
\[ \Phi_{\text{dp}} = \int_{L_{\text{tr}}} K_{\text{dp}}(l) dl, \]
\[ \Omega(r) = -\frac{2.36 \cdot 10^4}{f^2} \int N_0(r) B_L(r) dr, \]
\[ \tan \gamma = \frac{1 - \tan \frac{\Phi_{\text{dp}}}{2}}{1 + \tan \frac{\Phi_{\text{dp}}}{2}} = \frac{\tan \frac{\pi}{4} - \tan \frac{\Phi_{\text{dp}}}{2}}{1 + \tan \frac{\pi}{4} \tan \frac{\Phi_{\text{dp}}}{2}}. \]

\[ \chi_{\text{out}}(\Omega) = e^{j2\Omega} \chi_{\text{in}}. \]

\[ \Omega_2(f_1, t) = \pm \left[ \frac{1}{2} \frac{\phi_{\text{hydro}}(f_1, t) - \nu \phi_{\text{hydro}}(f_2, t)}{\nu^4 \phi_{\text{hydro}}(f_1, t) - \nu \phi_{\text{hydro}}(f_2, t)} \right]^{1/2}. \]
H-pol and V-pol components captured at the receiver are affected by rain, but also by other effects:

Common H/V propagation effects

Calibrable Rcv systems

Hydrometeors effect

Emitted field

\[ E = e^{-i\omega t} e^{-ikr} \begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi_{arc}} \end{bmatrix} \begin{bmatrix} a_{hh} & 0 \\ 0 & a_{vv} e^{i\phi_{ant}} \end{bmatrix} \mathbf{R}(\Omega_2) \begin{bmatrix} e^{-ik_h} & 0 \\ 0 & e^{-ik_v} \end{bmatrix} \mathbf{R}(\Omega_1) E^i \{\hat{e}_h, \hat{e}_v\} \]

Only affect polarimetric differential phase if input field is not circular
H-pol and V-pol components captured at the receiver are affected by rain, but also by other effects:

- Common H/V propagation effects
- Calibrable Rcv systems
- Hydrometeors effect
- If emitted field is RCHP

\[ E = e^{-i\Phi} e^{-ikr} \begin{bmatrix} 1 & 0 \\ 0 & e^{i\Phi_{arc}} \end{bmatrix} \begin{bmatrix} a_{hh} & 0 \\ 0 & a_{vv} e^{i\Phi_{arc}} \end{bmatrix} R(\Omega_2) \begin{bmatrix} e^{-ik_h} & 0 \\ 0 & e^{-ik_v} \end{bmatrix} R(\Omega_1) E^i \{\hat{e}_h, \hat{e}_v\} \]

Ionosphere-2 and hydrometeors can be separated if either:
- both polarimetric differential amplitude and phase can be measured
- or only differential phase is measured but Faraday rotation in ionosphere-2 is within +/-15 deg.
How often the Faraday rotation at iono-2 will be $< |15\ \text{deg}|$?

95% of the cases among $>220,000$ RO COSMIC rays below 20 km along GPM swath simulated.
Is it correct to assume circular transmission? **NO, GNSS do not emit pure RHCP**

Then, the ionosphere before hydrometeors DO affect, too → the differential polarimetric field has all components tangled!!!!

Suggested approach:
- extrapolation of the polarimetric differential phase measured above the rain (e.g. 20 km) down to the surface, assuming it will contain the effects due to: transmitter + iono1 + iono2 + receiver initial phase
- subtraction of this extrapolated profile
Simulations based on 30,000 'fake' RO rays artificially co-located with GPM rain events

ABSOLUTE ERROR in the estimated hydrometeor induced polarimetric phase shift (5% worst cases removed)

GNSS transmission assumed 1.8dB ellipticity

5 different orientations of the ellipse

L1, L2, combined
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STATISTICAL INVERSION ALGORITHM
Probability of intense precipitation from polarimetric GNSS radio occultation observations


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DOI: 10.1002/qj.3161  View/save citation
The separability algorithm isolates the hydrometeor component from other effects. Now this hydrometeor-induced polarimetric phase-shift must be inverted to rain information.

STATISTICAL INVERSION APPROACH:
Which are the chances that a RO ray with a given altitude of its tangent point has cross a rain cell of certain characteristics?

To answer this questions we have artificially co-located 'RO rays' along the GPM mission swath (>200,000 profiles) and obtained $\Delta \Phi(h_t)$ to produce Lookup Tables (LUT), our the inversion tools.

We have generated LUT for most probable mean rain rate along the ray $<R>^*$, most probable maximum rain rate along the ray path $R_{\text{max}}^*$, and several percentiles of $<R>$ and $R_{\text{max}}$. 
How to build the LUT?

- Up to ~200,000 profiles

**25th percentile:**
- 75% is larger than this value

**Most probable**
- $\langle R \rangle$

**Distribution of $\langle R \rangle$ where** $1.5 \text{ mm} < \Delta \Phi < 2.0 \text{ mm}$ and $1.5 \text{ km} < h_{tp} < 1.75 \text{ km}$
Examples of a few LUT
How to use the LUT for data inversion?
Final polarimetric RO product:

Standard RO
Thermodynamic products

Hydrometeor products
PAZ will orbit a polarimetric RO payload, to prove the concept.

- Planned launch: Q4 2017

- Selected polarimetric observable: phase-delay difference between H and V linear polarizations

- Expected instrumental pol-shift precision, conservative case: better than 1.5 mm (1 Hz) at surface level, improving with altitude

- An algorithm to isolate the hydrometeor component of the polarimetric phase-shift has been developed and validated through synthetic data (errors below noise level)

- A statistical inversion approach has been suggested, which provides the probability of rain (different percentiles and most probable) as a function of altitude → polarimetric product
Thank you for your attention!

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