Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

IEEC

Roadmap towards full exploitation of the polarimetric radio occultations

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Mandate

The **2nd PAZ-Polarimetric Radio Occultation User Workshop** took place the 28th and 29th November, 2023, at the Keck Institute in Caltech, Pasadena CA, USA *[Turk et al., BAMS 2024]*.

80 people registered for this hybrid event, with 28 participants in-person. Participants from 14 countries, 3 continents and over 40 different affiliations, including government agencies, research centers, universities and private companies in the space sector discussed the current status of this new technique and applications being developed.

As a result of the workshop, a working group is discussing **the steps towards fully exploitation of the GNSS Polarimetric Radio Occultation (PRO) data**, its use for and in numerical weather prediction, climate and other atmospheric sciences.

This talk

"As a novel technique, GNSS PRO has not been fully exploited yet, despite the unique capability to sense both thermodynamics and cloud microphysical aspects.

A community effort is being made to analyze the current gaps of knowledge and modelling tools in GNSS PRO, as well as the next steps required to fully exploit these signals, considering the enhanced density of GNSS PRO currently available.

We want to present the preliminary outcome of the analysis, in the form of

(1) current status and gap analysis,
(2) identified milestones and
(3) draft roadmap to achieve them"

Target

Once the document is mature, we plan to distribute across

- space (NASA, ESA, TASA, ...)
- science (NSF, ERC, ...)
- operational (NOAA, EUMETSAT, ECMWF, CMA, CGMS...)

Agencies.
It will also be available to the scientific community.

Potential uses identified

- Diagnosis Tool for NWP and Microphysics models
- Data Assimilation in NWP
- Climate models and applications
- Characterization of Frozen Particles
- Validation of other data sets

Contents

- GNSS PRO in a nutshell
- Current Status:
  - Data availability
  - What we know
  - What we do not know
- Steps forward:
  - Towards Model Diagnosis Tool (NWP, Microphysics)
  - Towards DA in NWP
  - Towards use in Climate applications
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  - Towards use for Validation of other data sets
- Funding Opportunities
- Timeline

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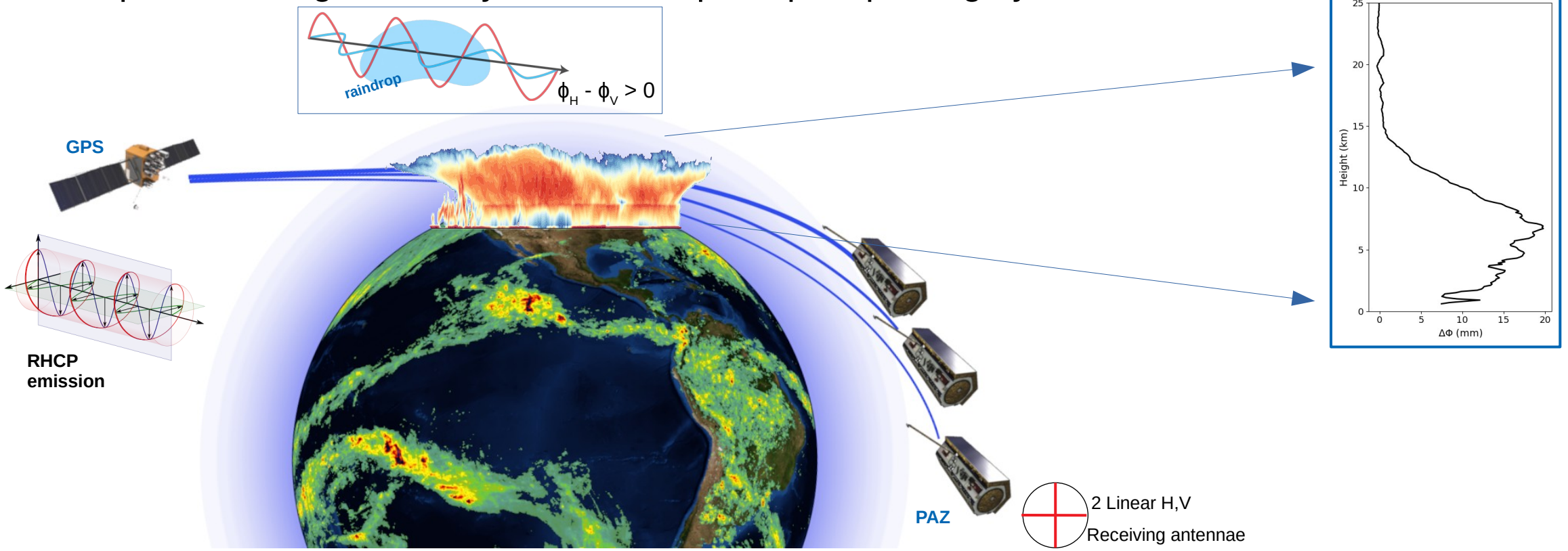
Polarimetric Radio Occultations (PRO)

- Concept introduced in 2009
- RO rays are collected using a 2-linearly **polarized** antenna (H,V)

- If these rays happen to cross precipitation, a **positive differential phase** shift is expected owing to the asymmetric shape of precipitating hydrometeors



Polarimetric Radio Occultations (PRO)

- This 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).
- The hypothesis is that this polarimetric information is sensitive to heavy precipitation.
- If successful, it would represent the only sensor that can infer both

VERTICAL PROFILES OF ATMOSPHERIC THERMODYNAMICS (T, p, q)

+

VERTICAL PROFILES OF HYDROMETEORS

GNSS PRO aboard PAZ

- A **proof-of-concept experiment** aboard the Spanish **PAZ satellite: Radio Occultation and Heavy Precipitation with PAZ (ROHP-PAZ)**
- Modified IGOR receiver
- Agreements with **NOAA** and **UCAR** for dissemination in **NRT of 'traditional' RO** profiles
- Close collaboration with **NASA/JPL** for **scientific investigations**

- PAZ launched in 02/2018
- ROHP-PAZ activated in 05/2018
- Continuous data acquisitions since then...

Visit **https://paz.ice.csic.es**

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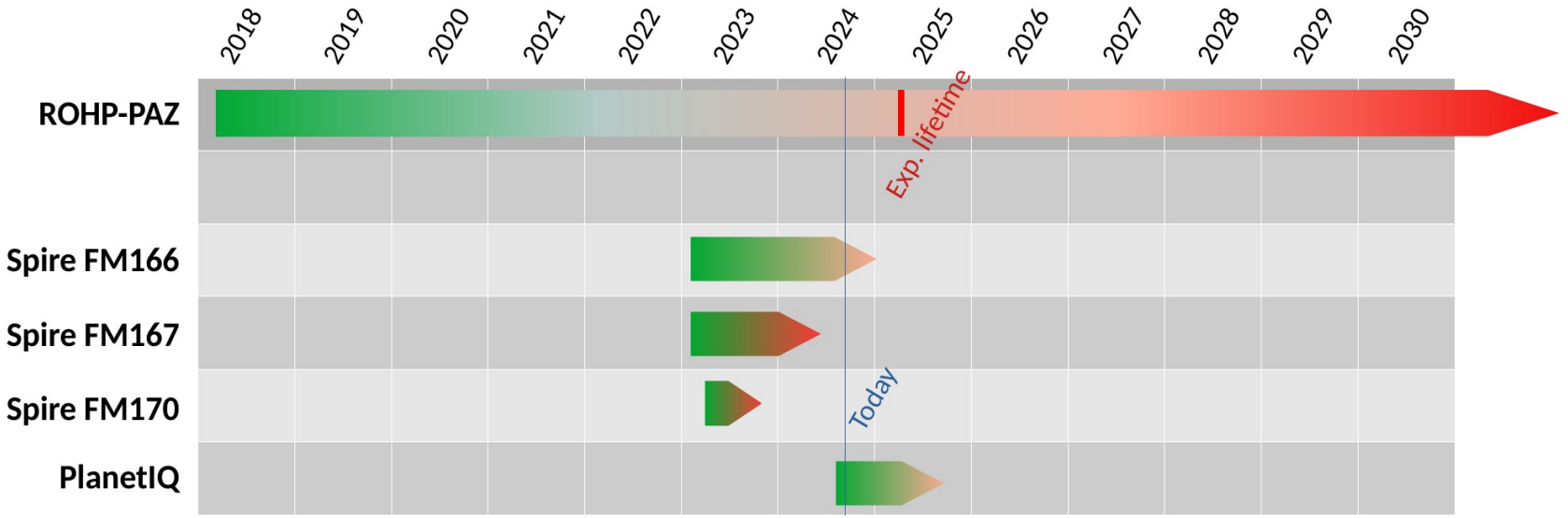
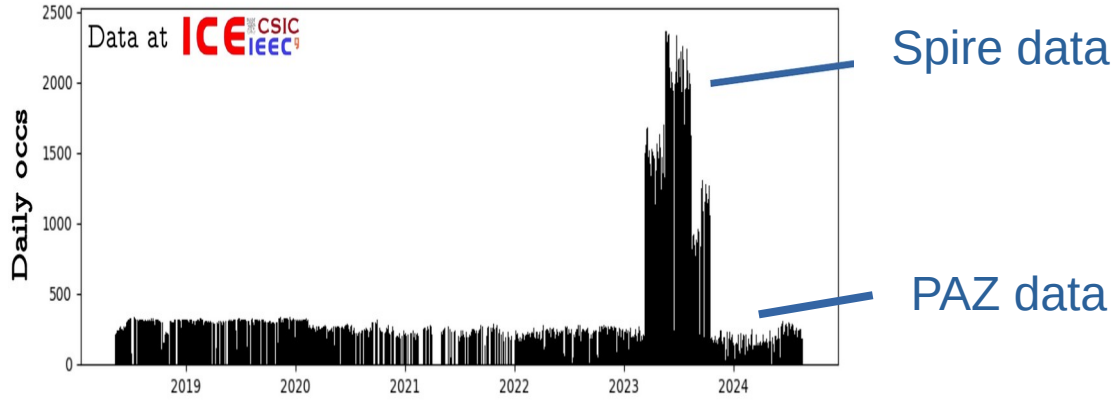
Data availability

- **UCAR** provides 'traditional' thermodynamic profiles
- **IEEC** adds polarimetric phase shift + other information
- **JPL** provides both, independent processing





What we know

- When there is no precipitation, the vertical profile of the polarimetric phase shift stays within the noise level [10.1029/2018GL080412, 10.5194/amt-13-1299-2020]
- When there is precipitation across the PRO rays >1 mm/h, the polarimetric phase shift exceed the noise level [10.5194/amt-13-1299-2020]
- Strong signals are detected above the freezing layer [10.1029/2018GL080412, 10.5194/acp-2022-300]
- The strong signals above the freezing layer correlate with the presence of frozen particles [10.5194/acp-2022-300, 10.1109/TGRS.2021.3065119]
- PRO Δφ products have long horizontal resolution, but verticaly constrained
- Standard RO products from PRO antennae are of equivalent quality as from RO antennae.

What we do not know

SOME KEY OPEN QUESTIONS:

1) Which level of detail is required to properly model the GNSS PRO observables?

2) Are all required details available in NWP models?

3) Would the modelling of the GNSS PRO observable vary depending on the type of meteorologic event? (e.g., tropical mesoscale convective systems, Mei-Yu convection, atmospheric river, tropical cyclones, and extratropical cyclones – including polar lows and Kona lows?). Or can the forward modelling be independent of the phenomena? (e.g., same empirical/semi empirical coefficients for any type of event).

4) In case of proper forward modelling from NWP fields and parameters, could the DA system 'correct' the background model with the GNSS PRO observables?

5) How many GNSS PRO profiles would be needed to have some impact on NWP?

6) How relevant is to process the signals in wave optics rather than geometric optics (current approach)?

7) Can GNSS PRO be used to evaluate microphysics schemes?

8) Can GNSS PRO be used to evaluate large scale parametrization of precipitation?

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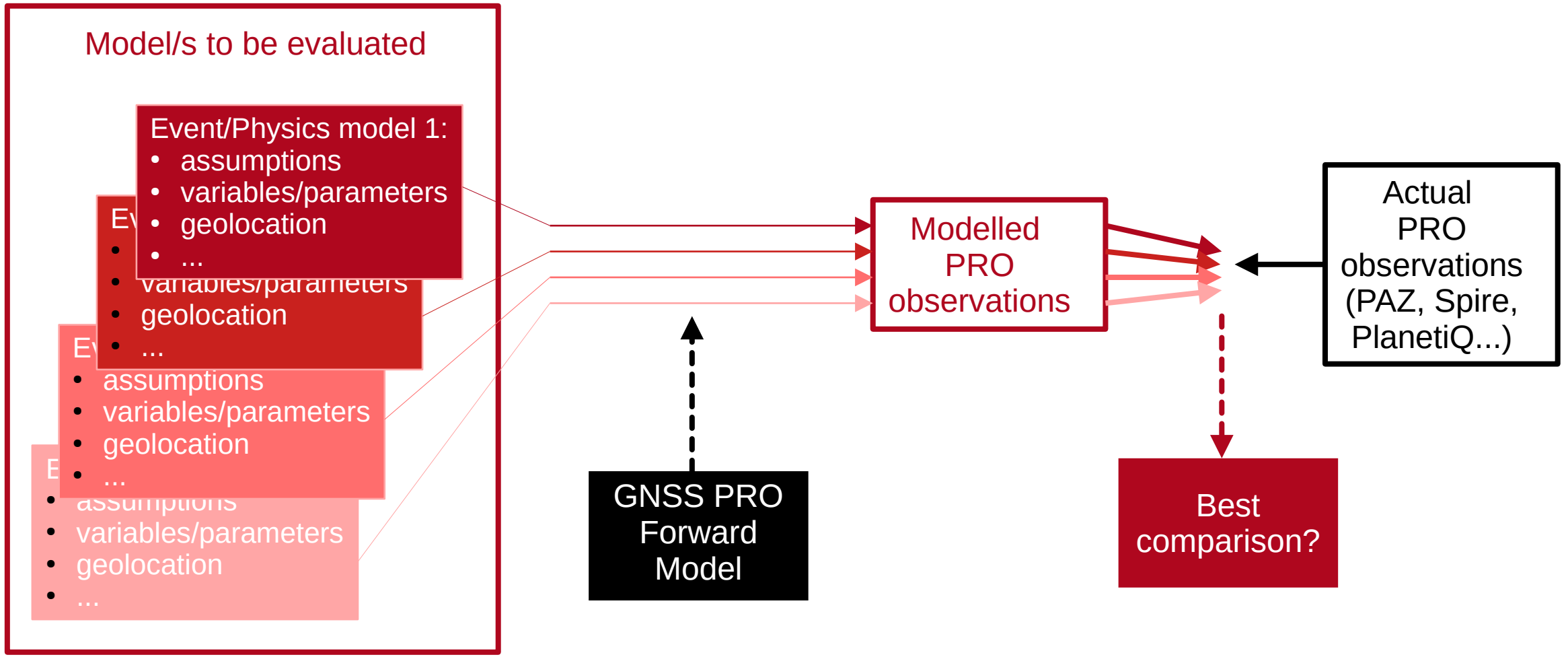
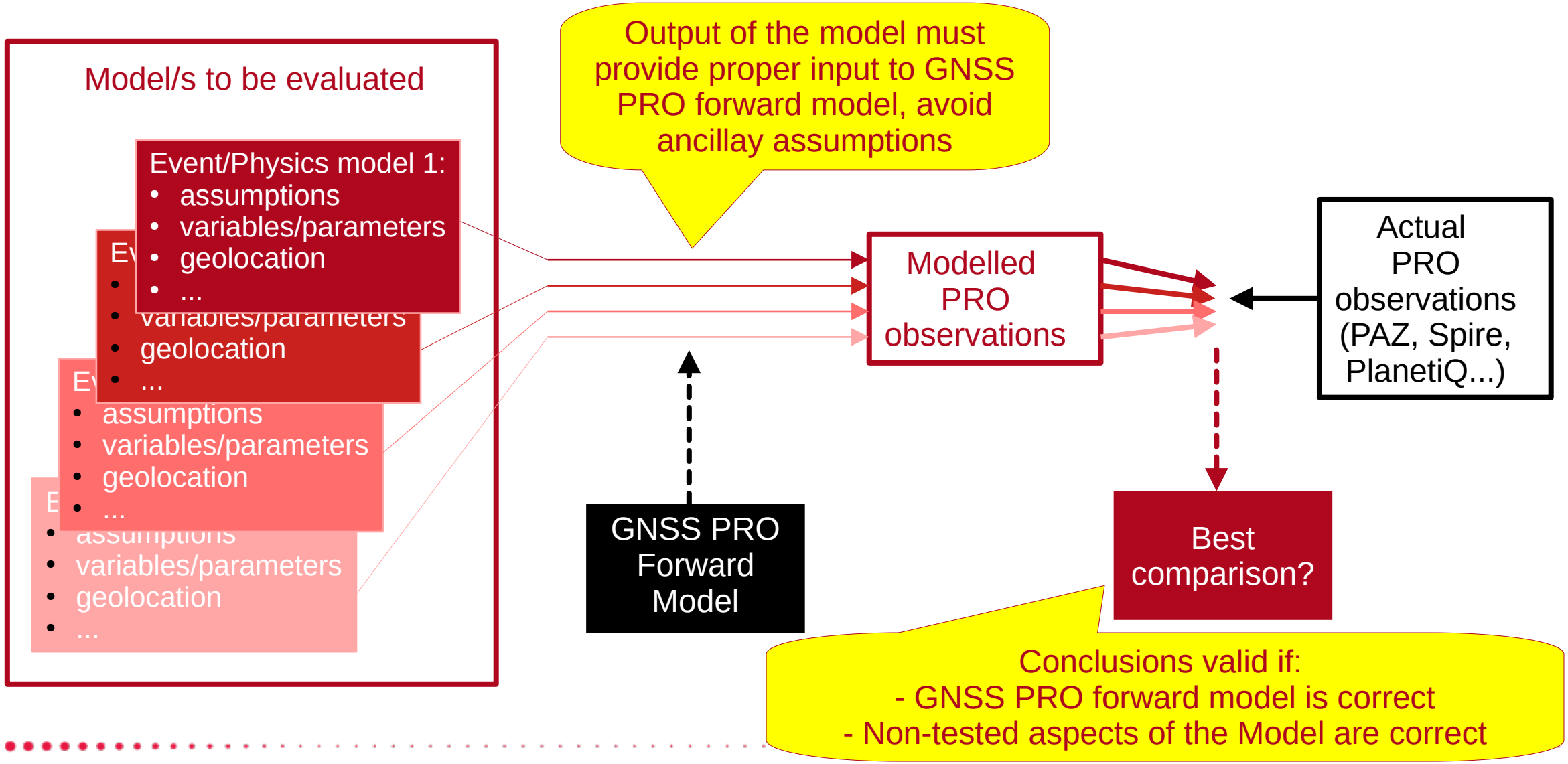
Diagnosis Tool



Diagnosis Tool: warnings



Required key elements

- **GNSS PRO Data** across events of interest where to test the NWP/Microphysics models.
- **Forward model / operator** for GNSS PRO signals.
- **2D Ray Trajectories**: as part of FO or given by GNSS PRO data providers
- Relationships between **hydrometeor content and specific differential phase shift (Kdp)**. These can be
  - ‘simple’, scalar relationship between water content and Kdp
  - ‘bulk’ based on the exact scattering off a given particle/habit (e.g., one of the particles as in ART) averaged across different particle size distributions,
  - ‘exact’ when based on the exact scattering off a given particle/habit (e.g., one of the particles as in ART) and a particular particle size distribution.

Data Assimilation

- Given that GNSS PRO observables are integrated along long rays, it is difficult to invert them into level-2 (geophysical) variables.
- An alternative use is the assimilation of the GNSS PRO observables (level-1) into NWP models.

Required key elements

- **GNSS PRO Data** to have potential for some impact in the weather forecast; NRT data for operations.
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- **Tangent linear** and **adjoint operators**, **uncertainty** and **covariance aspects**.
- **O-B sensitivity studies**.
- **OSSE and OSE simulations**, impact assessment., estimation of the optimal number of required GNSS PRO profiles.
- **Research to operations (R2O)** if impact results are convincing and sufficient NRT data are secured.

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Up to 2000+ PRO profiles during ~3 months (Spire + PAZ). New launches (e.g., PlanetiQ)

Not yet

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Simple approach to be implemented into ROPP (ROM SAF)

Required key elements: status

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IEEC ResPrf provide them; ROPP includes 2D operators

- **Tangent linear** and **adjoint operators**, **uncertainty** and **covariance aspects**.
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  - 'bulk' based on the exact scattering off a given particle/habit (e.g., one of the particles as in ART) averaged across different particle size distributions, — In progress under ROM SAF
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In progress with ‘simple’ operators, soon with ‘bulk’ and ‘exact’ models

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Not ready

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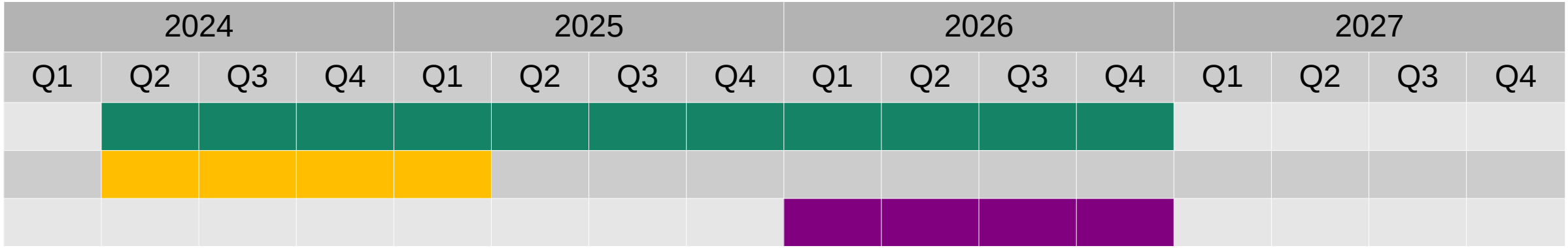
Similar analysis being conducted

Pending

Timeline and Gaps (Diagnosis Tool and DA into NWP)



- **Sufficient data for impact studies**? ~2000 PRO/day Summer'23, may not be sufficient (Winter period? More than 2000 PRO/day?…)
- GNSS PRO Forward Operator into ROPP, including 2D operator, tangent linear and adjoint operators
- Look-Up Tables (LUT) for 'bulk' and 'exact' hydrometero habit to Kdp relationships, based on ARTS shapes
- Potential funding for initial impact studies (NOT SECURED)
- **GAPS: Pending funding / unclear schedule for**:
    - More density of data, future data
    - Detailed analysis of optimal representation
    - Detailed analysis of uncertainty and covariance aspects

Summary

- A '*whitepaper & roadmap*' towards full exploitation of GNSS PRO signals is being discussed
- We identify the key elements required to enable a series of different applications of GNSS PRO signals
- Analysis shown for two applications: 'Model Diagnosis Tool' and for 'Data Assimilation into NWP'
- Similar exercises being discussed for three other applications
- The timeline indicates that most key elements (for Diagnosis and NWP DA) might be ready by end of 2026
- Aspects that require funding opportunities and further work are also identified

Thank you!

Feel free to contact me (estel at ice.csic.es)

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