Roadmap towards full exploitation of the GNSS Polarimetric Radio Occultations

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Scope of this document

The aim of this document is to identify the required steps towards full exploitation of the GNSS polarimetric radio occultation data and technique, and to share it with potential interested agencies and related scientific communities.

Executive Summary

1. GNSS Polarimetric Radio Occultation (PRO) is a **new technique** to sense **vertical atmospheric profiles of both thermodynamic variables (temperature, pressure, moisture) and hydrometeors**, especially in intense precipitation and convection events. The **proof-of-concept demonstrator** is orbiting aboard the PAZ satellite and acquiring **data since 2018**. Since then, 4 other commercial satellites have orbited GNSS PRO payloads (Spire Global and PlanetiQ Low Earth Orbiters).

2. Despite the **uniqueness of this technique**, its data are **not fully exploited** yet.

3. In part, this is due to the **novelty and non-conventional aspects** of the technique.

4. Five potential applications have been identified thus far: **Diagnosis Tool for NWP and their Microphysics parameterizations; Data Assimilation in NWP Models; Applications for Climate Models; Characterization of Frozen Hydrometeors; and Applications to Other Datasets**.

5. The document briefly analyzes what we know and what we do not know about GNSS PRO, and what **we need to learn** (studies), **develop** (software, tools) or **acquire** (data) to foster the **exploitation of the GNSS PRO** signals.

6. The top identified **priorities** are:
    a. STUDIES: to understand the best way to model (simulate) GNSS PRO observations, which **level of detail is required** (e.g., knowledge of the exact habit, size distribution and orientation vs bulk properties of the given hydrometeor species). This has an impact on most of the envisaged applications.
    b. DATA: to secure **3 months of at least 2000 daily GNSS PRO profiles globally distributed** during the Northern Hemisphere **Winter** season[1]. This would be required for data assimilation impact studies.
    c. TOOLS: Forward Operator, Tangent Linear and Adjoint Operators, all the **tools** required for **Case studies, sensitivity studies, data assimilation and OSE/OSSEs**.

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[1] During June-July-August 2023 (Northern Hemisphere Summer season), Spire Global and PAZ GNSS PRO reached a total of ~2000 daily profiles globally distributed (see Figure 3.1).

1. Background

1.1 GNSS Polarimetric RO in a nutshell

Global Navigation Satellite Systems (GNSS) signals such as the Global Positioning System (GPS) are transmitted in a circularly polarized state. GNSS Radio Occultation (RO) payloads assembled in low Earth orbit (LEO) use circularly polarized antennas to acquire GNSS signals when the GNSS source satellite is setting or rising above the Earth's horizon. The thermodynamic structure of the atmosphere acts as a lens, refracting the signals and bending its trajectory. The GNSS RO technique can precisely measure the bending suffered by the signals and extract the vertical structure of the pressure, temperature and humidity of the atmosphere around the 'tangent point' (point closest to the Earth surface along the signal trajectory) *[e.g., Anthes et al., 2011]*.

GNSS Polarimetric Radio Occultation (PRO) was suggested in 2009 (published in *Cardellach et al., 2015*), and it expands the standard RO technique by receiving the GNSS signals in two orthogonal linear (horizontal and vertical, or H/V) polarizations, instead of circular polarization. The presence of aspherical hydrometeors along the trajectory of the signal induces larger delays in the horizontal component than the vertical one, given that aspherical hydrometeors tend to get oriented with their largest dimension along the local horizontal direction. This is a tiny effect, but it accumulates along the ray trajectory up to a fraction of the electromagnetic carrier wavelength. This observable, called the polarimetric phase shift ($\Delta\phi$) can be measured by dedicated GNSS PRO receivers and represents the integrated specific differential phase shift (K_{dp}) along the ray path. It is possible to assign a $\Delta\phi$ measured value to each ray, identified by the height of its tangent point, h_t: $\Delta\phi(h_t)$, revealing the vertical structure of the hydrometeors. In the GNSS RO community, phase delays are typically given in units of length rather than degree or radians. GNSS PRO is usually given in mm, with a dynamic range of zero (no hydrometeors) to several tens of mm (large intense cell).

Uniquely, this technique also provides the collocated thermodynamic profiles as in traditional RO, simultaneously to the $\Delta\phi$ profiles, as depicted in Figure 1.

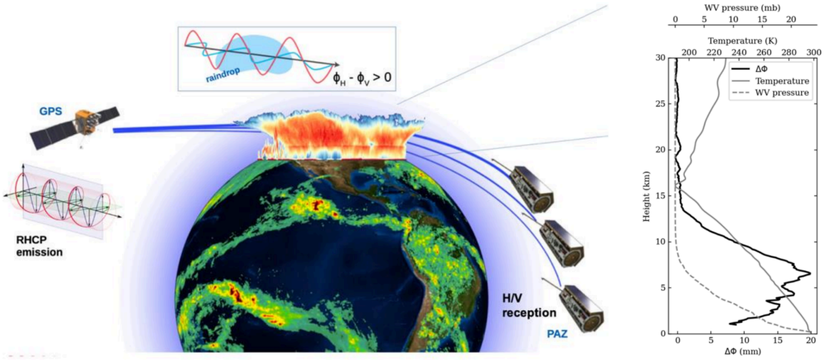

Figure 1.1: *Sketch of the GNSS PRO technique, where RO payload modified to acquire signals at two orthogonal polarizations (H/V) collect signal in limb sounding geometry. Vertical profiles of standard RO products (T, p, q) are obtained simultaneously with collocated polarimetric phase shift profiles ($\Delta\phi$), that relate to the presence of aspherical hydrometeors along the ray trajectories. Figure from Turk et al., 2024.*

Equation 1 below describes the $\Delta\phi$ measurement, in units of mm:

$$\Delta\phi(h_t) = \phi_H(h_t) - \phi_V(h_t) = \int_{R(h_t)} K_{dp}(l)dl \quad \text{[Eq.1]}$$

where ϕ_H and ϕ_V are the carrier phase or excess phase measurements at H and V polarizations, $R(h_t)$ is the trajectory of the ray with its tangent point at height h_t and K_{dp} is the specific differential phase shift described Equation 2 (in units of mm per km across the rain cell):

$$K_{dp} = \frac{\lambda^2}{2\pi} \int Real\{f_H(D) - f_V(D)\}N(D)dD \quad \text{[Eq. 2]}$$

With λ being the electromagnetic wavelength of the GNSS signals (~190 mm for GPS L1), f_H and f_V are the forward scattering amplitudes corresponding to the scattering of H- and V-polarized signals off a single hydrometeor particle of diameter D, and $N(D)$ represents the particle size distribution *[Cardellach et al., 2015]*.

The ‘standard’ RO profiles (bending angle, refractivity, temperature, pressure, water vapor) can be obtained from the excess phase at each of the individual polarizations, ϕ_H and ϕ_V, or by combining them both, as UCAR has demonstrated in their near-real time processing of the PAZ mission *[Douglas et al., 2019, Padullés et al., 2024]* and Spire/EUMETSAT shown through the operational processing of Spire PRO data. PlanetiQ has also demonstrated an SNR-weighted enhancement of this technique in their near-real time processing of the GNOMES-5 P-RO antenna *[Kursinski et al., 2024]*.

1.2 GNSS PRO demonstration mission

The Radio Occultation and Heavy Precipitation experiment aboard PAZ (ROHP-PAZ) was proposed by the Institute of Space Sciences (ICE-CSIC)/Institute of Space Studies of Catalonia (IEEC) to the Spanish Space Research Plan in 2009, with support from JPL, UCAR and NOAA. It uses a modified IGOR Precise Orbit Determination (POD) and Radio Occultation receiver (same as in COSMIC/Formosat-3 constellation) to collect polarimetric radio occultations. It was launched in February 2018 and the GNSS PRO experiment was activated in May 2018. Since then, it has been collecting (and still collects) on the order of ~200 profiles per day (except for a period of time where power saturation issues dropped the number to ~100 daily profiles), globally distributed.

A few months after launch, it was demonstrated that GNSS PRO signals are sensitive to vertical structures of hydrometeors, with strong sensitivity to hydrometeors above the freezing layer (frozen particles), as shown in Figure 2 *[Cardellach et al., 2019]*. These data sets are being used to better understand the technique itself and envisage new scientific and operational applications (see Section 2.2, respectively).

Furthermore, the signals are processed by UCAR under a NOAA contract to produce and disseminate the traditional thermodynamic RO products to worldwide weather services, in near-real time (NRT) where they are assimilated into some of the global weather forecast systems. Currently, different types of ROHP-PAZ data are available at three different servers, at ICE-CSIC/IEEC, UCAR and JPL.

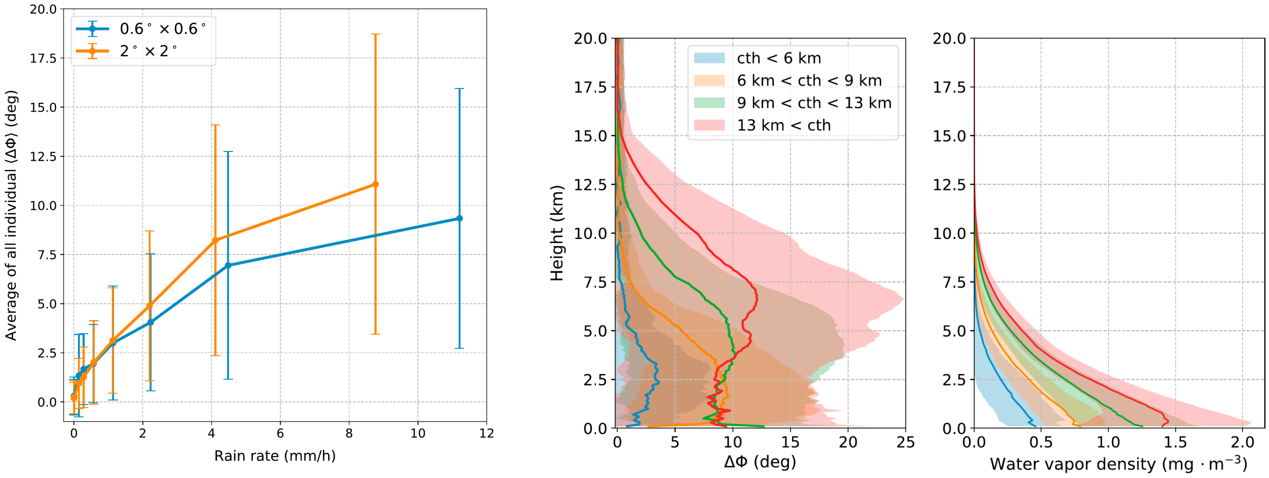

Figure 1.2: *Early results of the ROHP-PAZ experiment, after 5 months of operations. On the left, distribution of the polarimetric shift of individual profiles, averaged between 0 and 10 km, as a function of the IMERG surface rain rate averaged across two different resolutions below the PRO profile; Center: Mean (solid line) and dispersion (shade) of four subsets of data, all correspond to cases with precipitation. They are grouped according to the estimated cloud top heights (CTHs) as shown in the legend. Right: Mean (solid line) and dispersion (shade) of the observed Global Navigation Satellite System radio occultation water vapor density as function of the altitude, for the same subsets as the central figure. Figures from Cardellach et al., 2019.*

1.3 Mandate of the 2nd PAZ-Polarimetric Radio Occultations User Workshop

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., 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 met during the 10th International Radio Occultation Working Group[2] workshop (IROWG-10) and it has further discussed a roadmap towards full exploitation of the GNSS Polarimetric Radio Occultation (PRO) data, its use for and in numerical weather prediction, climate and other atmospheric sciences.

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[2] https://irowg.org/

2. What we know and we do not know about GNSS PRO

2.1 Facts

Resolution

In the case of standard RO, the contribution is maximized around the tangent point, with an effective horizontal resolution of ~100/150 km in the direction along the rays *[e.g., Anthes, 2011]*. For PRO, the contribution does not maximize anywhere along the ray-paths, and therefore contribution from all areas crossed by the rays must be equally taken into account. This means that horizontal and vertical resolution might mix. Nevertheless, and given that the polarimetric phase shift profile also informs about the maximum altitude at which hydrometeors are sensed, this constrains the horizontal extent of the potential contributions while the vertical resolution is well localized. This is shown in Figure 2.1.

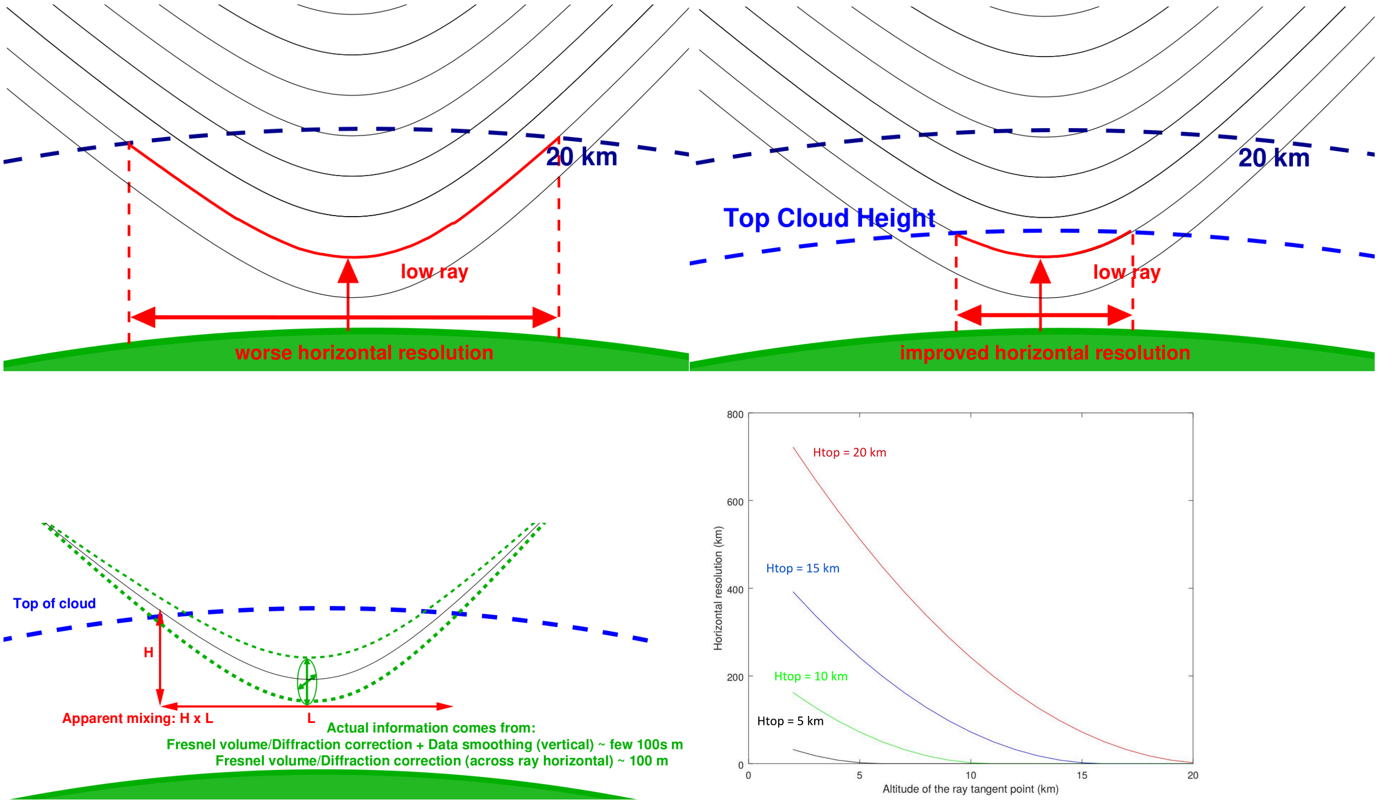

Figure 2.1: *Sketches to explain the GNSS PRO resolution. The heuristic knowledge that hydrometeors are confined to the lowest 20 km of the atmosphere imposes a minimum to the horizontal resolution , The extent of the ray below this altitude depends on the altitude of its tangent point (top-left). Further, polarimetric signals identify the top of the cloud, generally lower than 20 km, leading to a stronger constraint to the minimum horizontal resolution. (top-right). Furthermore, the location along the ray is well characterized, so we can talk of localized resolution (bottom-left). It is possible to estimate the horizontal extent as a function of the altitude of the tangent point and the maximum altitude at which GNSS PRO obtains signal, as shown on the bottom-right. Figures from GNSS PRO Tutorial, Cardellach et al., 2020.*

Response from the media

- When there is no precipitation, the vertical profile of the polarimetric phase shift stays within the noise level [*Cardellach et al., 2019, Padullés et al., 2020*].
- When there is precipitation above 1 mm/h threshold (average rain rate across 0.6°x0.6° surface), the polarimetric phase shift exceeds the noise level [*Cardellach et al., 2019, Padullés et al., 2020*].
- Strong signals are detected above the freezing layer [*Cardellach et al., 2019, Padullés et al., 2020*].
- The strong signals above the freezing layer correlate with the presence of frozen particles [Turk et al., 2021, Padullés et al., 2022, Padullés et al., 2023].
- The vertical structures sensed with the PRO $\Delta\phi$ are consistent with the 3D polarimetric measurements of co-located ground-based NEXRAD radars [*Paz et al., 2024*].
- At the moment, the only Level-2 geophysical variable produced is a proxy of the top of the cloud, through determination of the highest altitude where the polarimetric observable is larger than the noise level *[Padullés et al., 2024]*. Nevertheless, Level-2 variables along the rays are difficult to retrieve, jeopardized by the geometry (long integration along the ray-path, combination of altitudes, etc), which induces ambiguities: different combinations of the location and amount/type of particles along the ray-path can induce the same observable (integrated polarimetric phase shift). Suggestions for LUT-based retrievals were described and validated with synthetic data in [*Cardellach et al., 2018*], but tests with actual data prove it difficult [*de la Torre-Juárez, 2022*].
- The difference between the bending angle induced by hydrometeors at H and V polarizations also shows sensitivity to the presence of hydrometeors [*Wang et al., 2022*].
- Polarimetric RO does not degrade traditional (non-polarimetric) thermodynamics measurements [*Nguyen et al., 2023, Padullés et al., 2024; Talpe et al., 2024*].

2.2 Envisaged Applications

Table 2.2a: Envisaged applications: PRO as diagnosis tool for microphysics schemes in NWP models.

Diagnosis Tool for NWP and Microphysics models	
Rationale:	Cloud microphysics models describe the formation, growth and sedimentation of water particles (hydrometeors). The parameterization of cloud microphysics is used in NWP models to govern the transport, local change, and thermodynamic effects of hydrometeor particles in clouds. Multiple microphysical parameterization schemes exist, each producing different results in NWP. Given that PRO signals are sensitive to both thermodynamics and presence of hydrometeors, comparing actual PRO profiles against simulated PRO profiles given by different schemes might help identify the most appropriate method to represent the clouds and precipitation particles sampled. Given enough representative sampling, PRO could enable the microphysical parameterization to be optimized globally.
Potential relevance:	Cloud and precipitation processes are one of the main sources of uncertainties in numerical weather prediction *[e.g., Bauer et al., 2015]*. Many of the uncertainties might relate to the lack of observations suitable to challenge the representation of cloud and precipitation processes in atmospheric models *[e.g., Trömel et al., 2021]*.
What has been proven/done so far:	Murphy et al., 2019, showed that airborne PRO profiles $\Delta\phi(h_t)$ simulated using different microphysics schemes presented differences among them larger than the expected noise of the PRO observables, thus detectable and characterizable via this technique.

Table 2.2b: Envisaged applications: assimilation of PRO observables in NWP models

Data assimilation (DA) in NWP	
Rationale:	Because the PRO observable comes from a geographical area covering a long “horizontal” path and the precipitation structures tend to present much smaller scales, it becomes difficult to directly ‘retrieve’ meaningful geophysical variables (not averaged along these large geographical regions). An alternative way to benefit from the information embedded in these observables would be to directly assimilate them into NWP, where the background NWP model already has 3D hydrometeor information (water content) needed to simulate PRO observations, and the DA system might be able to fully exploit the information content from these observations.
Potential relevance:	This approach has potential for extracting the geophysical information from the PRO observables to inform NWP models.
What has been proven/done so far:	A simple forward operator has been described *[Padullés et al., 2022]* and tested *[Hotta et al., 2024]* on a few tropical cyclones and atmospheric river events. Despite being a very simple forward model, a good match was found

	between data and model simulations for the atmospheric river cases, while tropical cyclones presented mixed results.

Table 2.2c*: Envisaged applications: PRO to improve Climate model parameterizations.*

Climate models and applications	
Rationale:	Being that GNSS PRO is the only technique with the capacity to sense vertical profiles of both thermodynamic variables and hydrometeors linked to intense precipitation events, these data sets could be used to better understand the thermodynamic conditions underlying intense precipitation. This could enable the large scale parameterization of these extreme events, especially in climate models.
Potential relevance:	Understanding the thermodynamic conditions underlying intense precipitation is relevant because these events remain poorly predicted with the current climate model parameterization. A better understanding of the thermodynamics of heavy precipitation events is necessary for improving climate models and quantifying the impact of climate variability on precipitation *[e.g., Wentz et al., 2007, Allan and Soden, 2008]*.
What has been proven/done so far:	*Padullés et al. 2022b* showed that there is potential to use this technique as a diagnosis tool for climate models' free water vapor - precipitation relationships, which have large dispersion among them *[e.g., Turk et al., 2022, Fig. 3]*. This was done using standard RO collocated with IMERG.

Table 2.2d*: Envisaged applications: PRO to characterize frozen particles.*

Characterization of Frozen Particles	
Rationale:	GNSS PRO is very sensitive to hydrometeors above the freezing layer. In particular, only non-spherically symmetric scatterers can induce polarimetric phase shift. This effect is maximum at the PRO geometries (propagation along the local horizontal direction).
Potential relevance:	Providing implication on the orientation of the particles can be relevant for ice water content retrievals *[e.g. Kaur et al. 2022]*; and also relevant to passive microwave radiative transfer simulations *[e.g. Kim et al. 2024]*.
What has been proven/done so far:	Good sensitivity to frozen hydrometeors has been shown *[e.g., Padullés et al., 2022, 2023]*.

Table 2.2e*: Envisaged applications: PRO for other data sets, (2.2e1) to evaluate and augment current global precipitation datasets, and (2.2e2) to guide assimilation of rain-impacted MW radiances.*

1) Application to other data sets: Evaluation and augmentation	
Rationale:	GNSS PRO informs about precipitation globally, under all weather conditions, day and night with deep penetration, so it could be used to help

	validate other global satellite precipitation datasets (e.g., IMERG, GSMaP, etc), as well as contribute to multi-mission precipitation datasets and products.
Potential relevance:	Over global oceans, there are few sources for independent validation of global precipitation datasets such as IMERG and GSMaP., especially sources with capacity to inform about the vertical structures. Currently, these global products do not provide vertical structure content or direct information on the type of storm (e.g., shallow, deep convection) that produced the precipitation that is reported. The GPM DPR radar provides direct precipitation profiling capability, only within its limited (240-km) swath. While PRO does not provide a “point” type observation such as IMERG, it could be used to examine when, where and how particular precipitation type characteristics are associated with the reported near-surface precipitation intensity.
What has been proven/done so far:	ROHP-PAZ data have been matched up at the “swath level”, i.e., Level-2, with several radiometers in the GPM constellation and with the GPM (Ku/Ka-band) and CloudSat (W-band cloud) radars *[Padullés et al., 2022, Turk et al., 2021]*. A few publications have shown qualitatively comparisons of “gridded level”, i.e, Level-3 data, which are the most commonly used format for global precipitation data users, such as side by side comparisons of IMERG climatology with PRO delta-phi profile structure, see the recent summary paper *Turk et al., 2024*.
2) Application to other data sets: Guide assimilation of MW radiances	
Rationale:	PRO could also be used to assist the assimilation of passive MW radiances measured by MW radiometers (e.g., ATMS, GMI, future MetOp-SG MWI, MWS) for global precipitation forecasts. By nature of its long (19 cm) wavelength and limb (side-viewing) geometry, PRO profiles are influenced by only a few descriptive terms, mainly overall particle axis ratio. With this feature, nearby PRO observations can be used to refine (or eliminate from consideration) the choice of microphysics used in the passive MW radiative transfer model within the model ensemble forward operator (e.g., RTTOV-SCATT, etc).
Potential relevance:	One of the largest sources of uncertainty is the selection of the complex ice particle microphysics, which is described by many factors, and largely controls the magnitude of the passive MW radiances over precipitating regions. PRO observations can potentially be used to refine (or eliminate from consideration) certain choices of microphysics used in the assimilation of rain-impacted passive MW radiances in NWP forecast model ensembles. For example, previous results have shown that profiles simulations using low-density spheroids with a relatively wide range of axis ratio agree with the PRO observations when using aggregates, while high-density

	(approaching pure ice) and low axis ratio spheroids agree better with thin, pristine ice crystals.
What has been proven/done so far:	Some comparisons of the explicit scattering properties (i.e., derived from Discrete Dipole Approximation – DDA – of unique crystal shapes), and their spheroidal counterparts have been published. See Appendix B of *Turk et al., 2021*. These early findings suggest that PRO can guide and/or refine the appropriate use of ice particle shape, sizes and composition employed in the assimilation of passive MW high frequency radiances.

2.3 Uncertain aspects

There is the hypothesis that, GNSS working at a relatively long electromagnetic wavelength (L-band, ~20 cm wavelength), the forward scattering process along the PRO ray trajectory does not depend on the fine details of the particles (exact shape, ratio and orientation), but on ‘bulk’ characteristics.

If this hypothesis could be confirmed, the forward modeling of the GNSS PRO observable would not depend on the fine details of the particles, so it would be possible to link the observable to simpler parameters (e.g., water content) and perhaps a few empirical or semi empirical factors. These should not depend on strong assumptions about the particles, so it would become easiest for NWP models to simulate, based on fields, variables and parameters of the model.

Given that it has been proven hard to retrieve level-2 geophysical variables, an alternative approach to exploit satellite data is their assimilation into NWP. For this, one must be able to forward model the observable (see comments above). Even in the case that the forward modeling were feasible and sufficiently good, and even if it carried information about the inaccuracies of the background model, it is uncertain whether the DA system would be able to ‘correct’ the model (e.g., location of a tropical cyclone, increase or decrease in water content and precipitation, etc).

Beyond NWP applications, several studies have suggested using GNSS PRO data to help investigate assumptions and convective parameterization schemes in climate and forecast models [*Emmenegger et. al., 2024]*. In the current suites of climate models, the observed “pickup” of precipitation as a function of layer-averaged water vapor and temperature is captured with varying accuracy (see Figure 2.3). These convective transition statistics serve as diagnostics for the parameterization of convection in climate and weather forecast models by characterizing the dependence of precipitation on the moisture-temperature environment. Previous investigations [*Padulles et al*, 2022b] used COSMIC RO data to demonstrate the different precipitation pickup relationships that arise when conditioning these same data on different pressure level layers in the Lower Free Troposphere (LFT), thereby functioning as a test for vertical sensitivity to moisture. With the expanding density of PRO, there are occasions when multiple receiving satellites will occult the same GNSS transmitter, within a time offset relevant to the convective time scale (e.g., 10 mins or less) *[Padullés et al., 2024b]*. Near precipitation, these observations would provide sampling of the moisture structure inside of the precipitation alongside its surrounding environment [*Turk et al., 2022*]. However with current PRO sampling density, these ideas have not been thoroughly investigated for climate and NWP model uses.

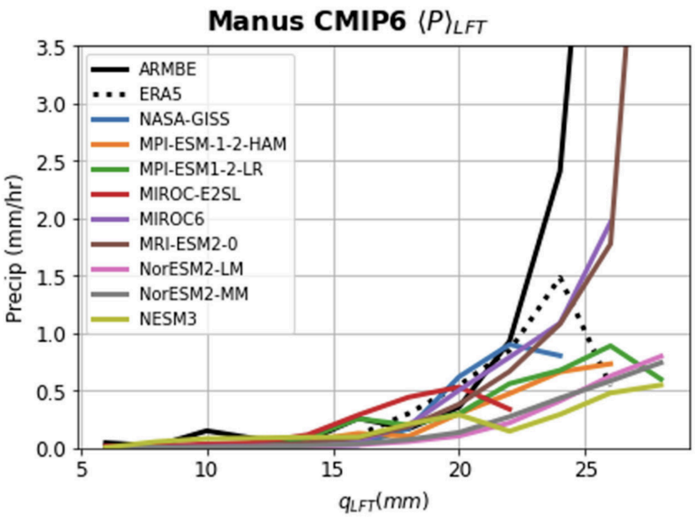

***Figure 2.3**: Precipitation rate (mm h^{-1}) conditionally averaged as a function of lower free-tropospheric water vapor q_{LFT} (units of mm) from ten models participating in the 6th phase of the Coupled Model Intercomparison Project – CMIP6 (colored lines), relative to the Atmospheric Radiation Measurement Best-Estimate (ARMBE) observations (solid black line). Plot from Turk et al., 2022.*

Another non-NWP use for PRO would be to add to or improve upon the validation of global satellite precipitation datasets, such as the IMERG, GSMaP and others, that are currently produced as part of the NASA/JAXA Global Precipitation Measurement (GPM) program. Over global oceans and remote land areas, there are few sources for independent validation of GPM Level-3 precipitation products such as IMERG. Currently, IMERG does not provide vertical structure content or direct information on the type of storm (e.g., shallow, deep convection) that produced the precipitation that is reported. The GPM dual-frequency (DPR) radar provides direct precipitation profiling capability, only within its limited (240-km) swath. Details of the associated environmental structure within and surrounding the precipitation is inferred separately, usually interpolated from coarse synoptic global forecast models. These models may or may not have placed the precipitation in the same location and at the same time as the observations. While PRO does not provide a “point” type observation such as IMERG, it also serves to provide an additional means to evaluate global precipitation datasets especially over open ocean, where traditional validation sources such as ground radars and rain gauges are limited or non-existent. Nevertheless, with PRO being an along-track integrated observation without a clear precipitation level-2 product, the optimal way to use GNSS PRO for validation of other data sets needs to be investigated.

Open Questions

Several open questions need to be addressed:

1. What level of detail is required to properly model the GNSS PRO observables?
2. Is it better to extract the information from the polarimetric phase shift $\Delta\phi$ or the polarimetric bending difference $\Delta\alpha = \alpha_H - \alpha_V$?

3. Are all required details available in NWP models?
4. Would the modeling 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 modeling be independent of the phenomena? (e.g., same empirical/semi empirical coefficients for any type of event).
5. In case of proper forward modeling from NWP fields and parameters, could the DA system 'correct' the background model with the GNSS PRO observables?
6. How many GNSS PRO profiles would be needed to have some impact on NWP?
7. How relevant is it to process the signals in wave optics rather than geometric optics (current approach)?
8. Can GNSS PRO be used to evaluate microphysics schemes? In which way can this be implemented? Which is the effect of the different uncertainties (forward model uncertainties, other assumptions made by the NWP/Climate model, model initialization…) in determining the optimal microphysics?
9. Can GNSS PRO be used to evaluate large scale parametrization of convective precipitation? Is the lack of a level-2 product a drawback for this application?

3. Steps forward

In order to find answers to the questions posed in Section 2.3 and foster the use of the GNSS PRO data across the envisaged applications, we analyze them by ‘key elements’, that is, data, tools or knowledge/studies required to be able to develop the applications described in Section 2.2. A block diagram in Figure 3 shows the major key elements identified and their interaction.

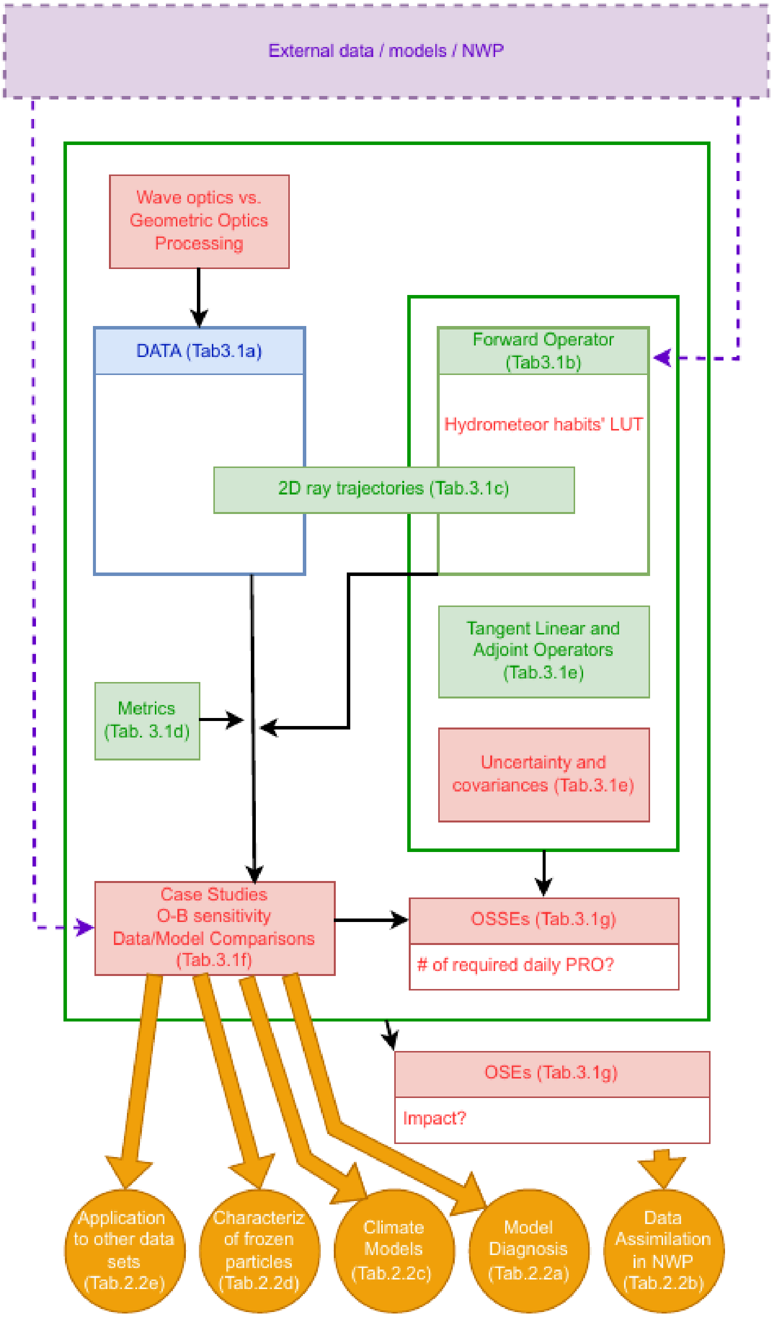

***Figure 3**: Diagram of the major key elements identified in this study, and the way they feed each of the GNSS PRO applications. Blue for data elements, red for knowledge/study elements, green for tool/software elements. External elements in magenta, GNSS PRO applications in orange.*

3.1 Key elements of the Roadmap

Each of the identified elements in Figure 3 are further analyzed in Tables 3.1a to 3.1h.

Table 3.1a: *GNSS PRO data as key element.*

<table>
<tr><th>Key element:</th><th colspan="3">GNSS PRO data</th></tr>
<tr><td>Description:</td><td colspan="3">Spaceborne GNSS PRO data. Airborne GNSS PRO data.</td></tr>
<tr><td>Current status (Q4 2024):</td><td colspan="3">GNSS PRO acquired from PAZ (ROHP-PAZ experiment) has been collecting between 100 and 200 daily profiles since May 2018, with global distribution. Approximately 10% of them contain strong PRO signatures. ROHP-PAZ continues to operate.

Spire Global launched 3 CubeSats with GNSS PRO payloads in early 2023. Spire satellites have been collecting between 200 and 2000 daily profiles (~950 daily average) in total throughout most of the period since February 2023 with large variability due to payload operational duty cycle changes [<i>Talpe et al., 2024</i>]. The profiles were independently validated by ICE-CSIC, IEEC, showing similar quality to PAZ GNSS PRO profiles [<i>Padullés et al., 2024b</i>]. During ~3 months of the Northern Hemisphere (NH) Summer 2023, Spire satellites along with PAZ acquired a total of about ~2000 daily profiles globally distributed. Current Spire GNSS PRO payloads will cease production by November 2024 due to de-orbiting.

In Q3 2024, PlanetiQ launched a satellite with a GNSS PRO payload, currently acquiring approximately 1000 profiles/day of data [<i>Kursinski et al., 2024</i>]. The next PlanetiQ satellite carrying a similar payload is scheduled to launch in March 2025 which will double the PRO profiles/day to approximately 2000.

Figure 3.1 displays the daily PRO profiles acquired with these missions since May 2018.</td></tr>
<tr><td colspan="4">Requirements:</td></tr>
<tr><td>Application:</td><td>Requirements:</td><td>Current fulfillment:</td><td>Further needs:</td></tr>
<tr><td>Diagnosis Tool</td><td>Sufficient GNSS PRO profiles to identify a large number of interesting different types of case studies, possibly with collocated information from other spaceborne sensors. It would be desirable to explore a range of weather circumstances, with a spectrum of different expected contents of horizontal structure according to the NWP system,</td><td>~200 PAZ GNSS PRO profiles have been identified across Tropical Cyclones, ~2000 across Atmospheric Rivers, ~50 fully within NEXRAD weather radar footprints with precipitation cells

Spire Global PRO</td><td></td></tr>
</table>

	from very stratiform and uniform over several hundred km, to highly developed and presenting structures of few km across.	satellites present similar numbers as PAZ.	
DA into NWP	It is not clear how many profiles would be needed to prove impact in global and regional NWP. Initial studies would require at least a few thousand daily profiles during 3 months in NH-Summer and 3 months in NH-Winter.	~2000 daily profiles currently acquired during 3 months in Summer	Higher daily numbers might be required. Global data during 3 NH-Winter months would be required.
	If assessed feasible and of impact, NRT operational data in sufficient numbers would be required.	Not sufficient numbers.	Pending, conditional.
	BUFR format that includes all relevant PRO information.	Modifications in BUFR format are being discussed. The new description includes a few fields for GNSS PRO (e.g., polarimetric phase shift)	Identify relevant information that would need to be included in the BUFR file, and modify it accordingly. Other fields might be required and not accounted in the current discussion (e.g., polarimetric differential bending, impact height linked to time)
Climate Models:	Statistically significant number of profiles in each geographic region for each precipitation regime, over land and ocean, to be able to relate the thermodynamic information with the precipitation information at different regimes, ideally in all local times and seasons.	Light to moderate precipitation regimes are well represented with PAZ GNSS PRO data acquired for more than 6 years over land and ocean, but in a single local time slot. Spire CubeSats helped populate other local time zones, but for NH-Summer only.	Poor population of Extreme events. Very poor population in diversity of local times.
	Understanding whether satellite particularities might	Indirect comparison between Spire LEOs	

	introduce biases in the thermodynamic-precipitation relationship as measured with GNSS PRO	and PAZ GNSS PRO profiles showed similar but not identical results. However, they were neither collocated nor in the same local time, so sensing different scenarios.	
Characterization of Frozen Particles:	Spaceborne and airborne GNSS PRO measurements across case studies together with relevant other sensors or information about hydrometeor types, habits and particle size distributions.	N/A	Pending.
Application to other data sets	Sufficient PRO profiles collocated with other precipitation and cloud related missions and instruments.	resPrf PAZ PRO files provided by IEEC contain information about collocations with GPM and radiometers. No statistics conducted.	Extended catalog of both PAZ, Spire and PlanetiQ PRO profiles collocated with other precipitation and cloud related missions with precipitation events active.

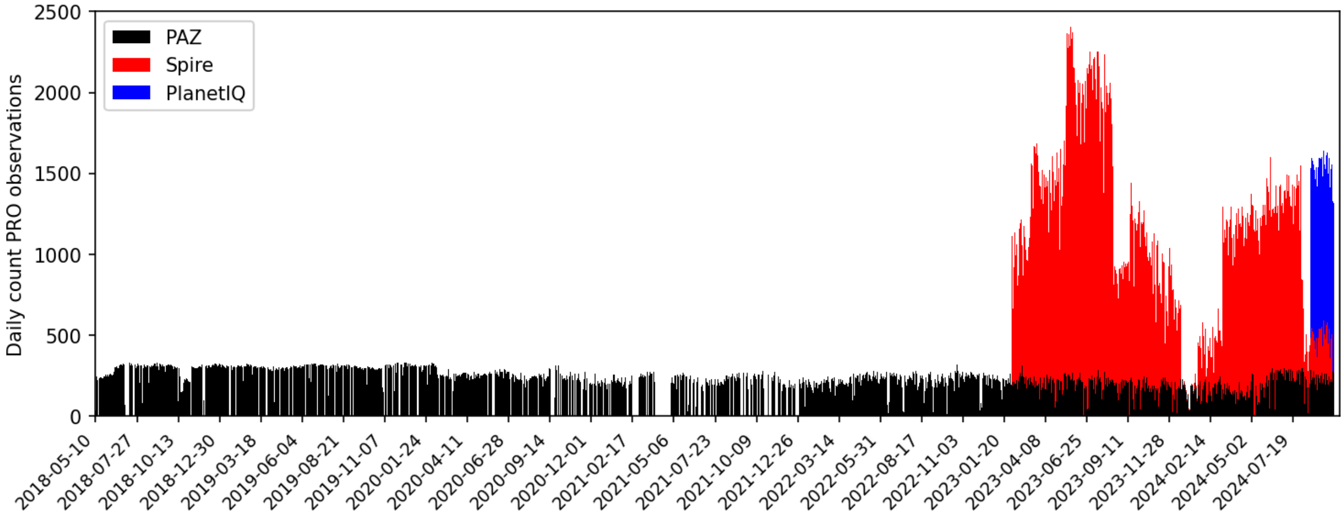

Figure 3.1 *Time series of the total number of daily PRO profiles collected from PAZ, Spire Global and PlanetiQ. The Y-axis shows the total number (adding different missions, when available).*

Table 3.1b: *PRO Forward Operator as a key element.*

Key element:	**Forward Operator**

Description:	A model to estimate the expected vertical profile of polarimetric phase shift that a GNSS PRO sensor would measure across a given ‘scene’, scene is here understood as the atmospheric hydrometeor fields along the PRO rays. Software implementation of the model.
Current status (Q4 2024):	At the moment we distinguish between: - ‘simple’ operator, in which the specific polarimetric phase shift Kdp relates to the hydrometeor water content WC as a function of the axis ratio *a,* and an effective density ϱ of the hydrometeors, assuming fixed values for both *a* and ϱ: $$K_{dp} = \frac{1}{2} C \rho WC(1-a)$$ [Eq. 3] - ‘exact’ operator, for which the forward scattering of L-band signals are resolved off particular shapes of hydrometeors (habits), e.g., as shapes collected in ARTS, and weighted as a function of a particular particle size distribution N: $$K_{dp} = \frac{\lambda^2}{2\pi} \int Real\{f_H(D) - f_V(D)\} N(D) dD$$ [Eq. 2] - ‘bulk’ operator, for which the forward scattering of L-band signals are resolved off particular shapes of the hydrometeors (habits), e.g., as shapes collected in ARTS, weighted as a function of an ensemble of particle size distributions: $$K_{dp} = X \cdot WC$$ [Eq. 4] $$X =< \frac{\frac{\lambda^2}{2\pi} \int Real\{f_H(D) - f_V(D)\} N(D) dD}{\int N(D) D^3 dD} >_N$$ [Eq. 5] The ‘simple’ approach has been implemented and tested *[Padullés et al., 2022, Hotta et al., 2023]*. The forward scattering off all ARTS habits has been conducted, and the scattering elements stored. This enables both the ‘exact’ and the ‘bulk’ implementations, but the work has not been published, yet.

Requirements:

Application:	**Requirements:**	**Current fulfillment:**	**Further needs:**
Diagnosis Tool	For the ‘simple’ operator: to understand the best values to be assumed for a and ϱ, to understand if they depend on hydrometeor type (rain, snow, ice, …).	Prototype FOs implemented with fixed a and ϱ values [*Padullés et al., 2022, Hotta et al., 2023*]	Investigate optimal a and ϱ values, their dependency on hydrometeor species and type of precipitation event, if any.
	For ‘exact’ operator: a look-up table with the forward scattering matrix elements required to model the specific polarimetric phase shift Kdp, and at least one reasonable	Done for L1 frequency band and all shapes in ARTS (habits).	To make it publicly available. To repeat for the L2 frequency band.

	particle size distribution.		
	For the ‘bulk’ operator: a look-up table with the specific polarimetric phase shift Kdp as a function of the water content of each hydrometeor habit.	Some exercises done.	Complete the exercises, complete the look-up table and make it publicly available.
	Metrics to evaluate the performance of the different models.	Now RMSD between forward modeled and measured is used.	Analyze different possible metrics to select the most suitable. See Key element ‘Metrics’, Table 3.1d
DA into NWP	To select one of the approaches discussed above for implementation into the DA software.	N/A	Pending.
	If the ‘bulk’ or ‘exact’ approaches are selected, to implement it consistently with other potential radiative transfer modules of the NWP (e.g., RTOVS or CRTM).	N/A	Pending.
	To select if the observables to be assimilated are polarimetric phase shift $\Delta\phi$ or bending difference $\Delta\alpha$.	N/A	Pending.
Characterization of Frozen Particles:	‘Bulk’ or ‘exact’ required.	Same as for the Diagnosis Tool application, above.	Same as for the Diagnosis Tool application, above.
Application to other data sets	Understanding how to link the polarimetric phase shift measured by PRO with other missions’ and instruments’ precipitation and cloud observables.	Same as for the Diagnosis Tool application, above.	With the tools developed for Diagnosis Tool and existing hydrometeor catalogs (e.g., ART-SCATT) link the PRO observables (horizontal propagation at L-band) with the observables of other missions/instruments.

Table 3.1c: *2D ray trajectories as a key element.*

Key element:	**2D ray trajectories**		
Description:	Geolocalization of the ray trajectory points, required to properly model the GNSS PRO observables. This can be provided by the data providers or estimated as part of the forward operator.		
Current status (Q4 2024):	Ray tracers for GNSS RO radio-links exist for geometrical optics		
Requirements:			
Application:	**Requirements:**	**Current fulfillment:**	**Further needs:**
Diagnosis Tool DA into NWP Characterization of Frozen Particles: Application to other data sets	Geometrical optics 2D ray tracers.	Several implemented, e.g., ROM SAF open source ROPP. Coordinates of the ray trajectories at 5km along-ray resolution and 100 m ray spacing are given in ROHP-PAZ resPrf files at ICE-CSIC.	
	Equivalent ray tracer for wave optics approach.	PlanetiQ has a strategy to link the impact height obtained through the wave optics approach with ray trajectories.	To be implemented and tested.

Table 3.1d: *Metrics Performance as a key element.*

Key element:	**Metrics for model performance evaluation**		
Description:	A quantitative way to analyze the goodness of a model when compared to actual data.		
Current status (Q4 2024):	Each weather service has its own performance evaluation method.		
Requirements:			
Application:	**Requirements:**	**Current fulfillment:**	**Further needs:**
Diagnosis Tool, DA into NWP, Characterization of Frozen	A metrics to properly distinguish good matches between data and models along the full length of the	Not analyzed.	Not analyzed.

Particles, Application to other data sets	profile, considering biases, dispersion, correlation (despite altitude shifts), etc.		

Table 3.1e: *PRO TL and A Operators, Uncertainty and Covariance as key elements.*

Key element:	**Tangent Linear, Adjoint Operators, Uncertainty and Covariance**		
Description:	Other elements required in DA schemes, in addition to the FO.		
Current status (Q4 2024):	Not implemented		
Requirements:			
Application:	**Requirements:**	**Current fulfillment:**	**Further needs:**
DA into NWP	TL and Adjoint operators.	Not implemented.	To be implemented.
	Uncertainty analysis.	The uncertainty in $\Delta\phi$ as a function is height is assumed as the standard deviation of the $\Delta\phi$ profiles that correspond to scenarios without precipitation, according to external independent sources.	Investigate ways to estimate noise at independent profiles (and altitudes)
	Covariance of the observations.	N/A	To be developed.

Table 3.1f: *Case Studies and Sensitivity Analysis as key elements.*

Key element:	**Case Studies and O-B Sensitivity Analysis**
Description:	Case studies and sensitivity analysis focus on different phenomena and/or different microphysics.
Current status (Q4 2024):	Preliminary work done using - ECMWF IFS model [*Hotta et al., 2023*] over atmospheric river (AR) and tropical cyclones (TC) case studies. - WRF over AR and TC with multiple microphysics (unpublished work, but presented in scientific conferences *[Paz et al., 2024a, 2024b, 2024c; Chen et al., 2024]*. - Case studies using PAZ PRO profiles co-located with NEXRAD polarimetric ground-based radars [*Paz et al., 2024*].
Requirements:	

Application:	**Requirements:**	**Current fulfillment:**	**Further needs:**
Diagnosis Tool DA into NWP	Extensive cases to be studied under different types of events, such as tropical mesoscale convective systems, Mei-Yu convection, atmospheric river, tropical cyclones, and extratropical cyclones – including polar lows and Kona lows, for multiple microphysics schemes and testing 'simple', 'exact' and 'bulk' operators	A few AR and TC cases were tested, and ~50 co-located with NEXRAD.	Extensive number of cases, different types of events beyond TC and AR and for 'simple, 'exact' and 'bulk' approaches.
	O-B analysis for global and regional domains.	N/A	Pending.
Characterization of Frozen Particles:	Selected case studies for which independent information about hydrometeor types, habits and particle size distributions is available.	N/A	Pending.
	Airborne PRO campaign with extensive hydrometeor information from dedicated measurements across the PRO rays zone.	N/A	Pending.
Application to other data sets			

Table 3.1g: *OSEs and OSSEs as key elements.*

Key element:	**OSEs and OSSEs**		
Description:	Simulations to both assess the impact of actual GNSS PRO data with actual observation numbers, and estimate the optimal number (and potentially, the geographical distribution) of GNSS PRO observations (satellites) that are needed to improve NWP analyses and forecasts.		
Current status (Q4 2024):	Not implemented.		
Requirements:			
Application:	**Requirements:**	**Current fulfillment:**	**Further needs:**
DA into NWP	OSEs for different types of models (global, HWRF,	N/A	Pending.

	operational HAFS…)		
	OSSEs for different types of models (global, HWRF, operational HAFS…) and with different number and distribution of PRO observations	N/A	Pending.

Table 3.1h: *R2D as a key element.*

Key element:	**R2D**		
Description:	Tasks required to go from research to operations.		
Current status (Q4 2024):	Not implemented.		
Requirements:			
Application:	**Requirements:**	**Current fulfillment:**	**Further needs:**
DA into NWP	R2D	N/A	Only if impact is proven and NRT PRO data are secured.

3.2 Prioritization of pending elements

Studies

1. Studies to identify the optimal and/or most feasible FO (‘simple’, ‘exact’, ‘bulk’) – indirectly, whether proper modeling of PRO requires fine details of the hydrometeors.
2. Characterization of PRO uncertainty and error covariances to enable OSEs and OSSEs.
3. Studies to identify the optimal metrics for evaluation of model performances.
4. Conduct data assimilation single case evaluation test to finalize a data assimilation configuration.
5. Run OSEs to assess impact of current PRO observations into different types (resolution) of NWP models (global, regional, TCs).
6. Run OSSEs to investigate the threshold and optimal number of PRO profiles (and their distribution) to impact different types (resolution) of NWP models (global, regional, TC).
7. Studies to identify optimal ways to use GNSS PRO for validation of other precipitation data sets and to assist assimilation of MW radiances into NWP models.
8. Studies to understand the convenience or inconvenience of using polarimetric differential bending angle instead of polarimetric phase shift as GNSS PRO observable (for DA and/or other applications) - Potential improvement in NWP impact.

Data

1. Secure satellite PRO data, exceeding 2000 daily profiles globally distributed during at least 3 NH-winter months for proper assessment of the potential impact of PRO in NWP.
2. Secure airborne and satellite PRO during campaigns with dedicated sensors to characterize hydrometeors (type, habit and size distribution) and related information.

Software and Tools

1. Implementation of FO, TL and Adjoint operators for DA.
2. Implementation of wave optics processing approaches in PRO.

4. Timeline

Current funded (**bold**) or with funding being secured (but not secured yet) activities:

2024				2025				2026				2027			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	ROM SAF Simple PRO FO in ROPP (2D FO, TL and AO)														
	ROM SAF habits/LUT														
								ESA DA w Simple FO							
				NOAA NESDIS Initial Studies with PRO											

The EUMETSAT's Radio Occultation Meteorology Satellite Application Facility (ROM SAF) devotes a Work Package of the current Continuous Development and Operations Phase to develop the forward operator for GNSS PRO into the open source packages ROPP (package also linked to JCSDA's JEDI effort). As part of this work package, a 2D forward operator plus the tangent linear and adjoint operators will be implemented (in green above), based on the 'simple' approach (Eq. 3 above, as tested in *Hotta et al., 2024*). Furthermore, the work package also includes initial developments towards a complete Look-Up Table (LUT) with the $(f_H - f_V)$ (Eq. 2) and X values (Eq. 5) for each hydrometeor habit in the ART-SCATT package (in yellow above). By mid 2025, the LUT for 'bulk' and 'exact' analysis should be ready. It is uncertain whether these will be incorporated into the ROM SAF implementation of the FO, 2026 version of the ROPP code, or in later versions of ROPP.

With the current secured funding, most elements should be ready for simple DA simulation experiments (OSSE) or data experiments (OSE) by 2026. OSE might be illustrative only provided that sufficient profiles are collected daily for an extended period (~2000 daily PRO profiles were collected between PAZ and Spire Global CubeSats during NH-Summer 2023).

ESA funding for initial data assimilation studies with the simple ROPP implementation of a GNSS PRO FO are planned, but not secured, yet (in purple above).

NOAA will conduct, in 2025-2026, preliminary studies using GNSS PRO data and tools towards assessing the possibility of a Commercial Weather Data Pilot (CWDP) purchase in the future.

Funding for other research studies (PRO as diagnosis tool, understanding frozen hydrometeors being sensed, PRO for large scale parameterization of extreme precipitation, cross-validation of other hydrometeor/precipitation sensors, etc) are not secured.

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