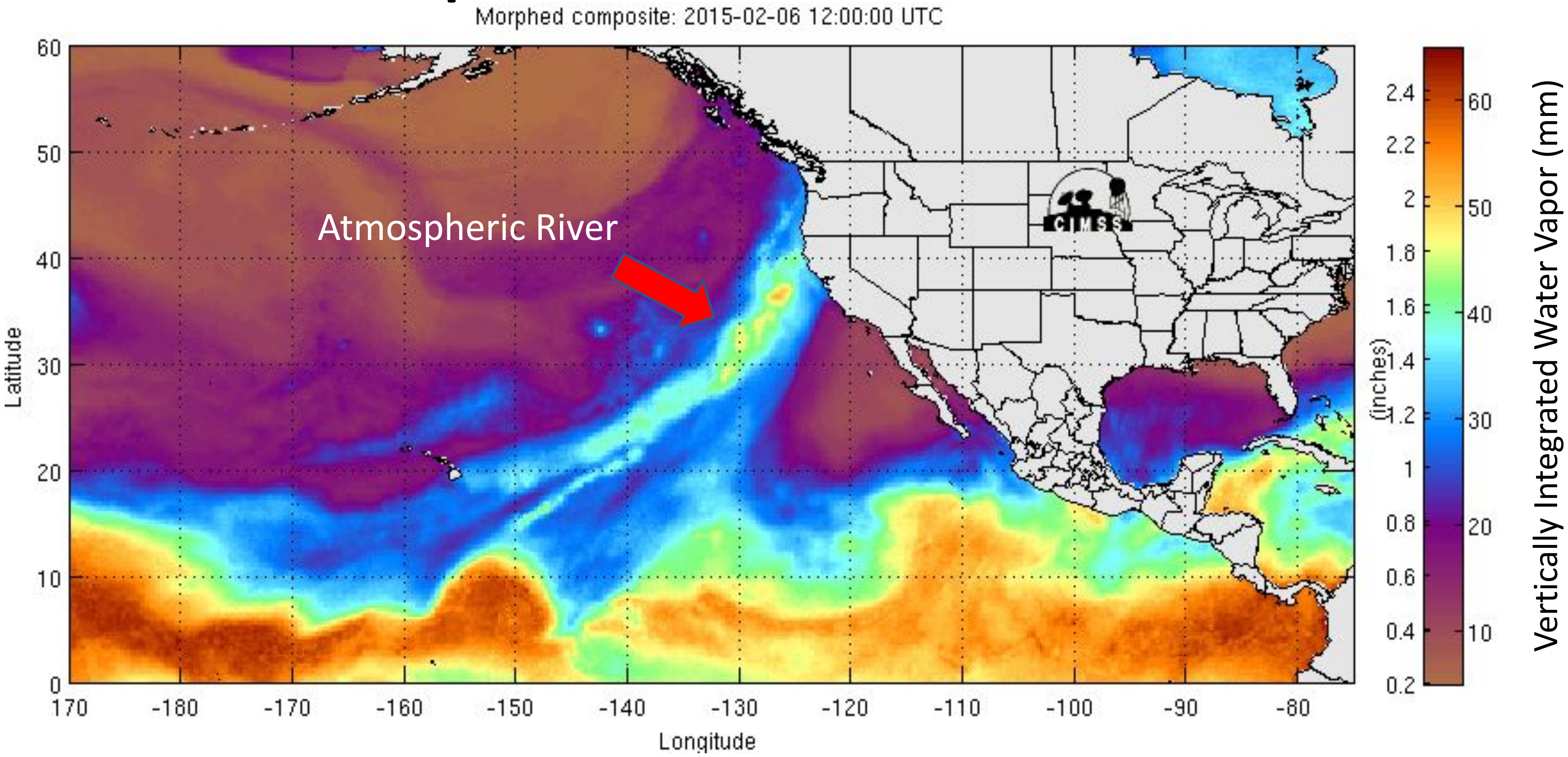
Evaluation of GNSS Radio Occultation observations in Atmospheric Rivers



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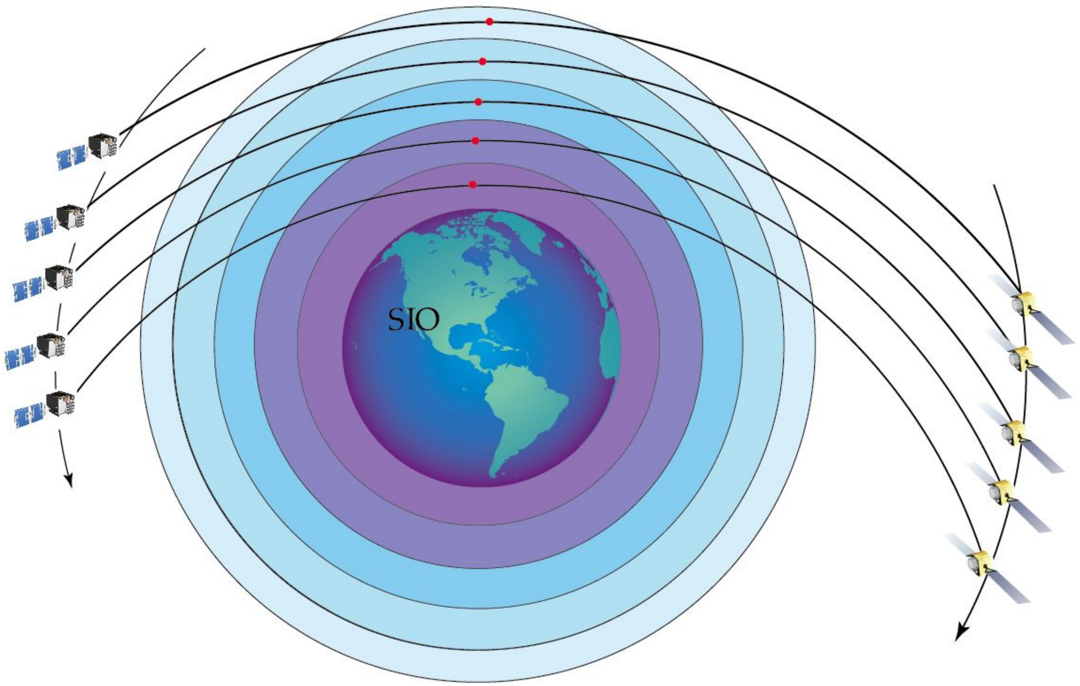
Motivation:
Could GNSS RO observations provide useful details about the structure of Atmospheric Rivers?

- GNSS Radio Occultation (RO) provides high vertical resolution observations of water vapor which could be useful in determining the depth of a moist layer and its vertical structure, e.g. in Atmospheric Rivers (ARs).
- The AR Reconnaissance (AR Recon) campaigns have extensively sampled ARs over the northeastern Pacific with dropsondes in multiple intensive observation periods (IOPs) over several winter seasons.
- Several new GNSS RO datasets have become available over the past several years and their ability to sample ARs and their surrounding environment is of great interest for high resolution cases

The GNSS RO Observation Technique



Specific Questions to be Addressed

1. What is the quality of GNSS RO and Dropsonde observations in the northeastern Pacific during atmospheric river events based on comparisons with reanalysis?

2. How do the different GNSS RO constellations compare in quality?

3. Are GNSS RO observations able to penetrate the core of ARs?

4. What can we learn about the quality of GNSS RO observations through comparisons with AR Recon dropsondes that are close in time and also space?

Data Sources

AR Recon Dropsondes Observations

- 2018/2019/2020 winter seasons over the northeast Pacific
- A total of 29 Intensive Observing Periods (IOPs)

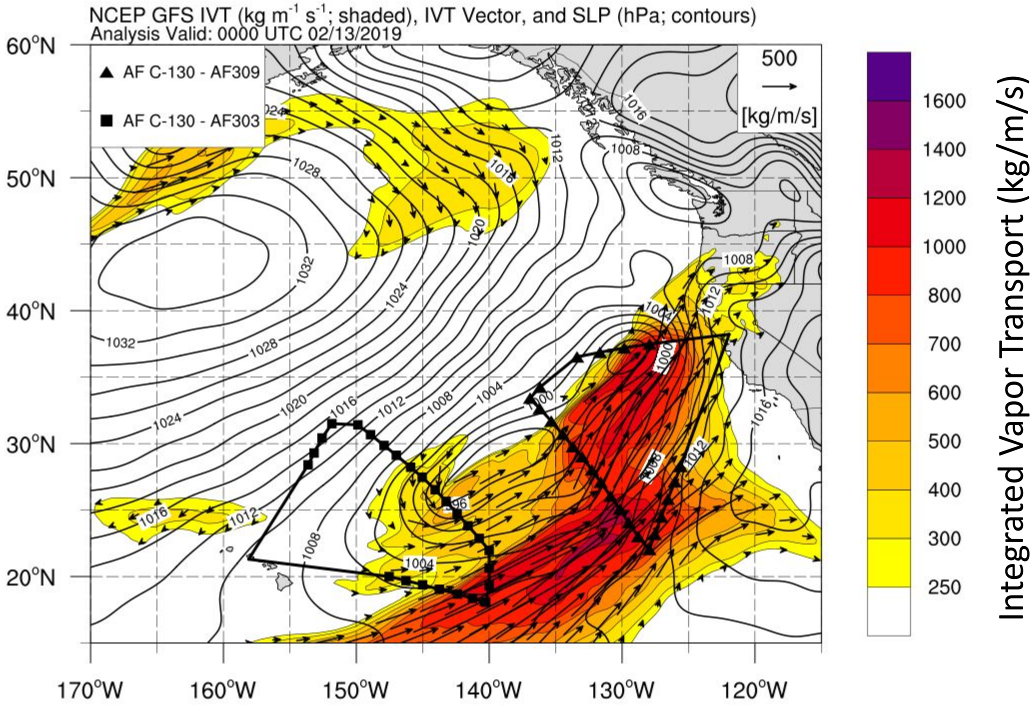
GNSS Radio Occultation Datasets

1. Operational Spaceborne RO (2018/2019/2020):
   Tried and true constellations
   e.g. COSMIC1, METOP, KOMPSAT, PAZ
2. COSMIC2, the next generation RO constellation (only 2020):
   Higher SNR -> deeper profiles
3. Commercial Smallsat RO (only Spire for 2019):
   Higher density, more profiles

European Reanalysis 5 (ERA5) product

- 0.25° horizontal resolution on 37 pressure levels
- 1 hourly temporal resolution

Example IOP:
The intense Valentine's Day AR Event
Sampled just before landfall in 2019



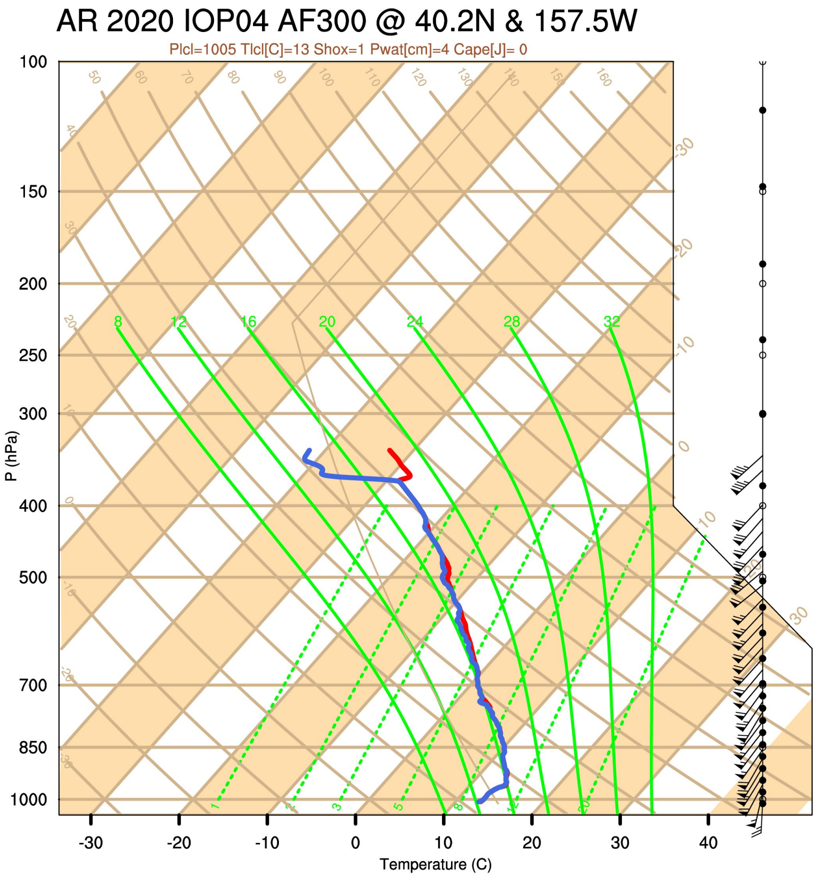
Methods

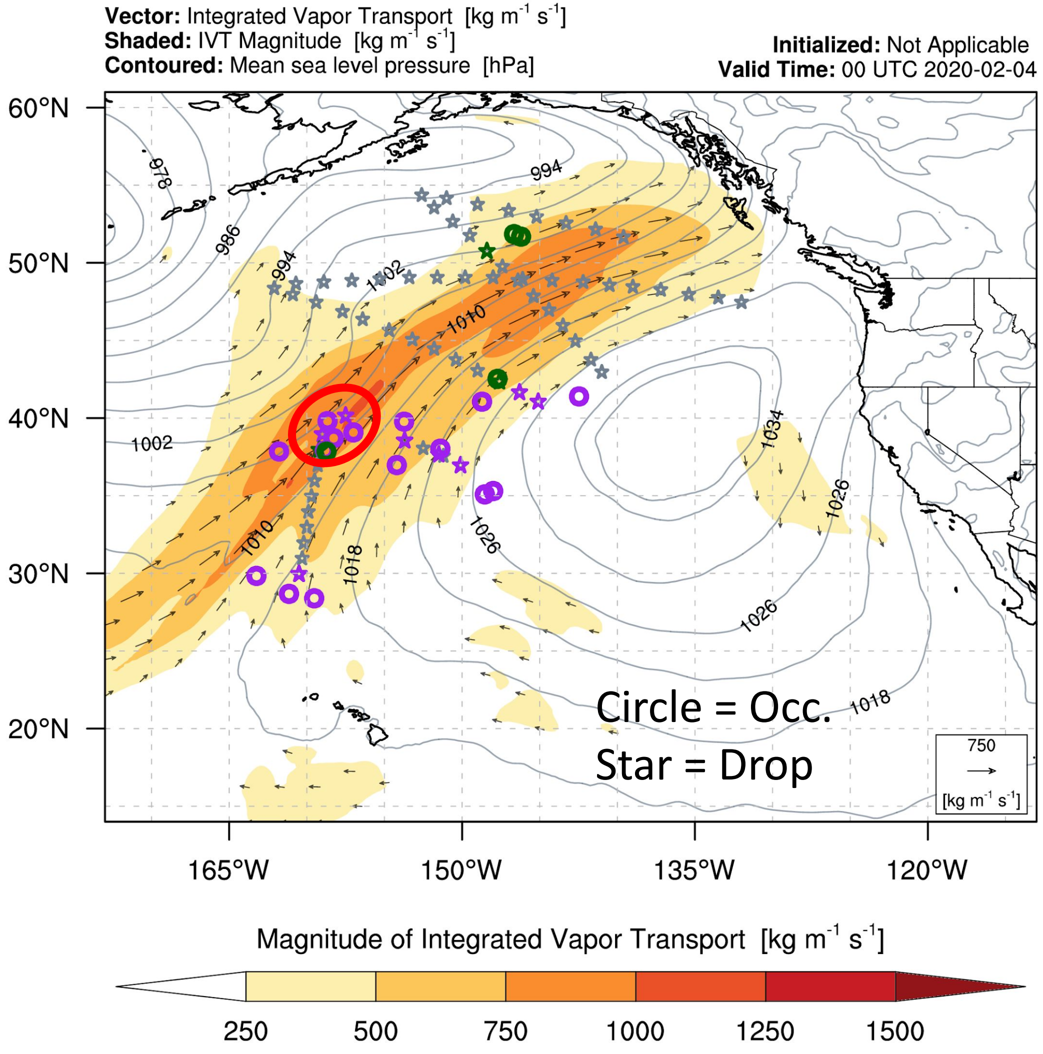
- Identify occultations +/- 12 hours from center time of each IOP (0000 UTC) over the northeastern Pacific region (10 - 60 N & 170 - 100 W)
- Extract refractivity profiles from ERA5 Reanalysis along the drifting tangent points of each RO and dropsonde profile.
- Divide observations into those inside (threshold of IVT > 250 kg/m/s) and outside of the AR
- Identify pairs of nearby AR Recon dropsondes & Radio Occultation (RO) profiles (within 2 h & 300 km)

Direct Comparison between RO & Dropsondes

Representative examples from each constellation

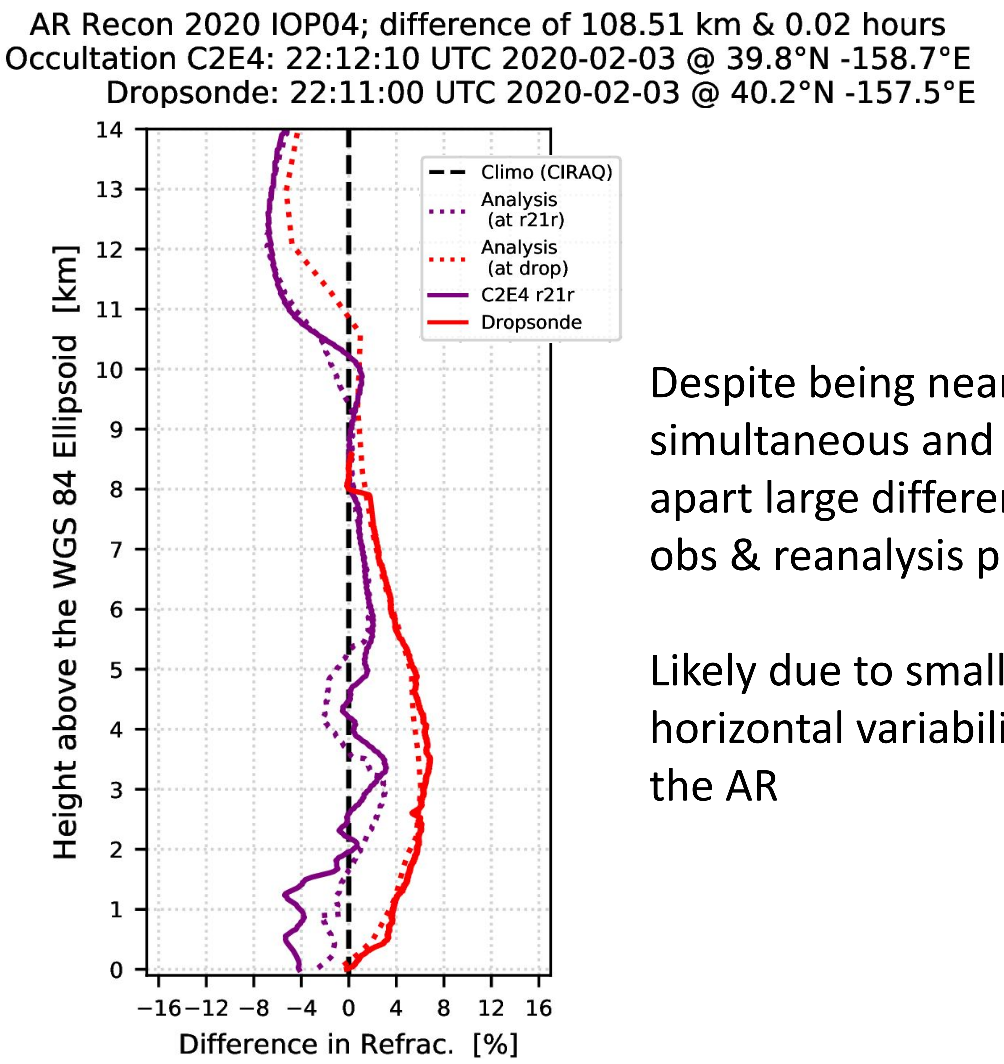
Occultation/Dropsonde Pair #1 – COSMIC2 observation Inside AR





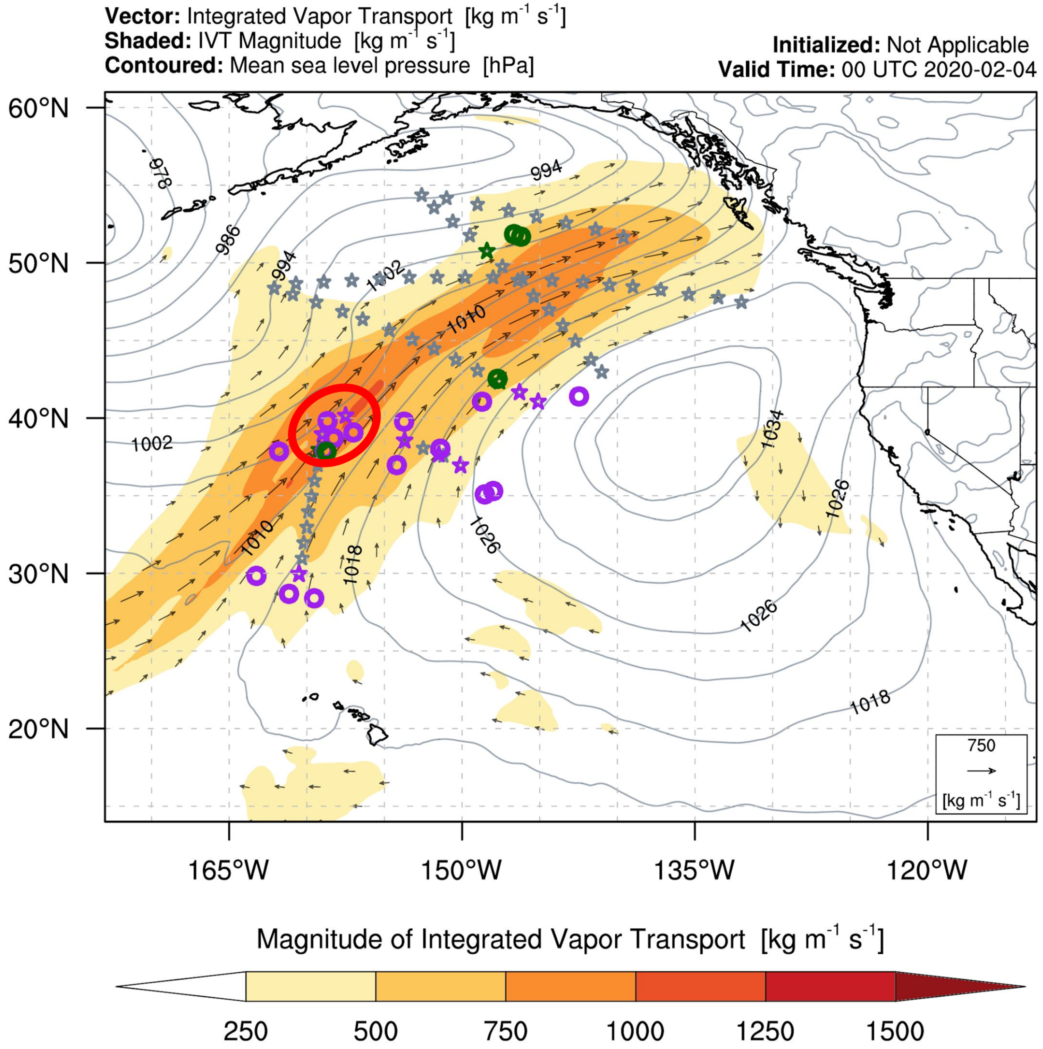
Fully saturated dropsonde profile from inside the core of a strong AR.

The COSMIC2 occultation samples down to the surface within the core of the AR.

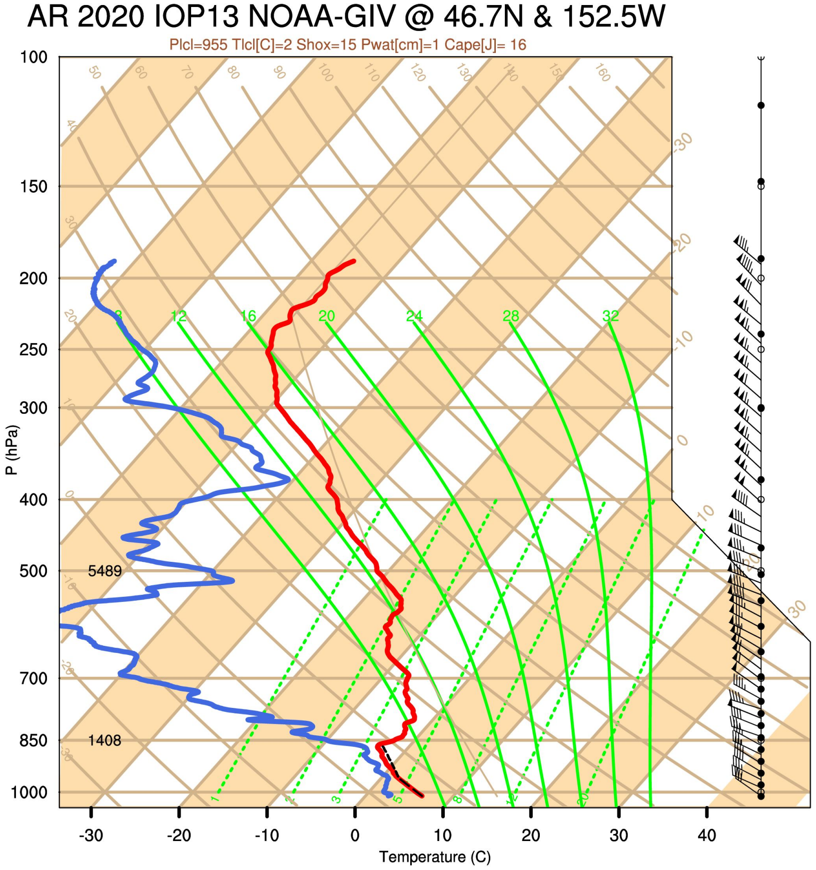


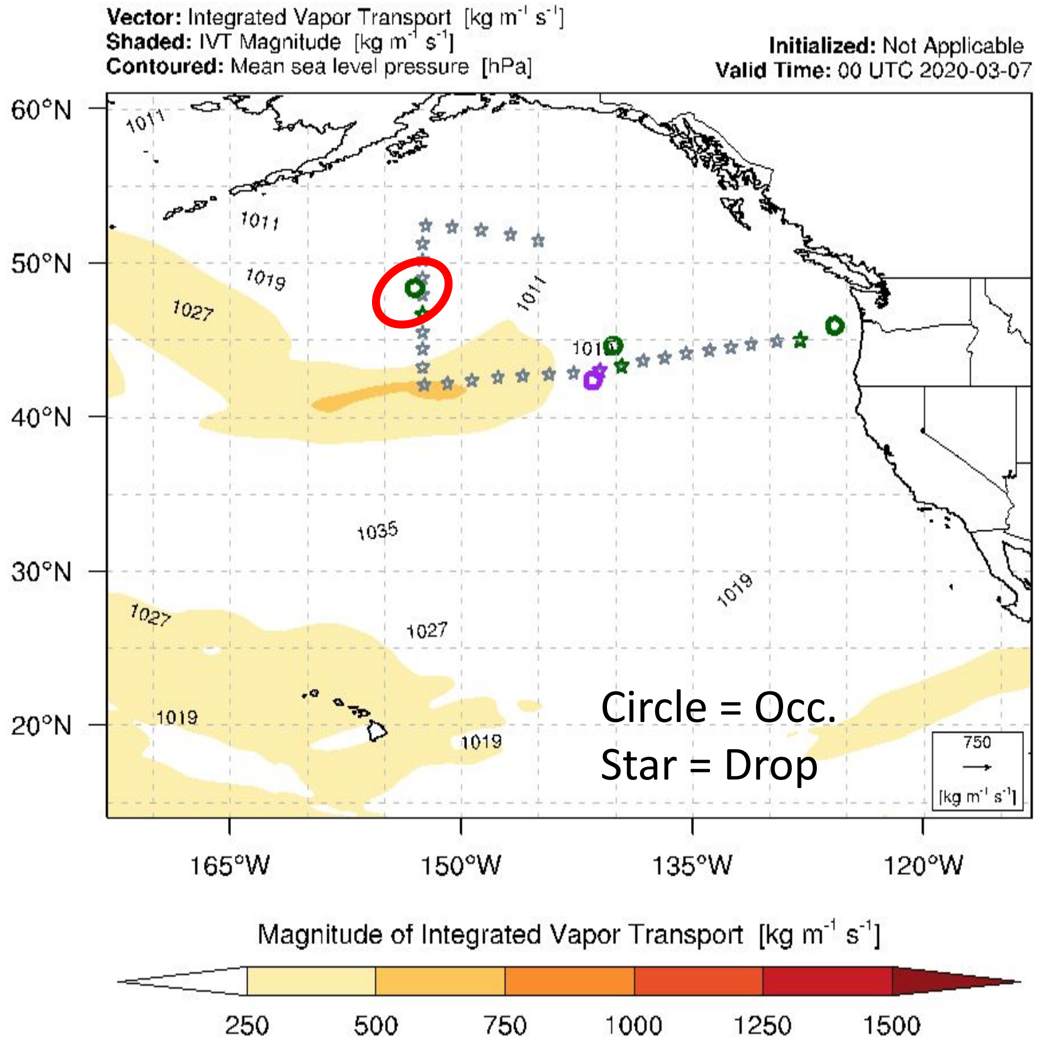
Despite being nearly simultaneous and 100 km apart large differences in both obs & reanalysis profiles.

Likely due to small scale horizontal variability within the AR



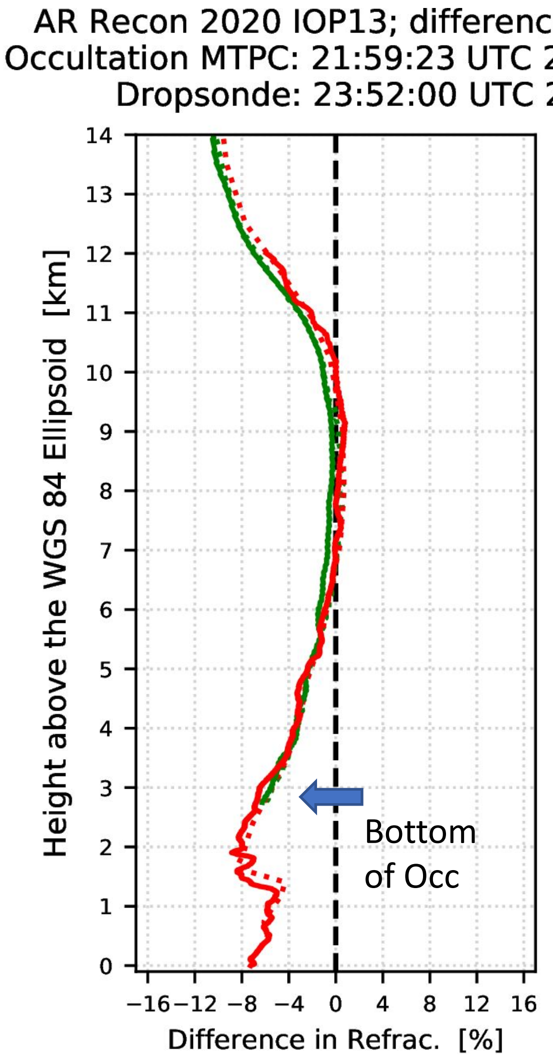
Occultation/Dropsonde Pair #2 – Operational observation poleward of AR





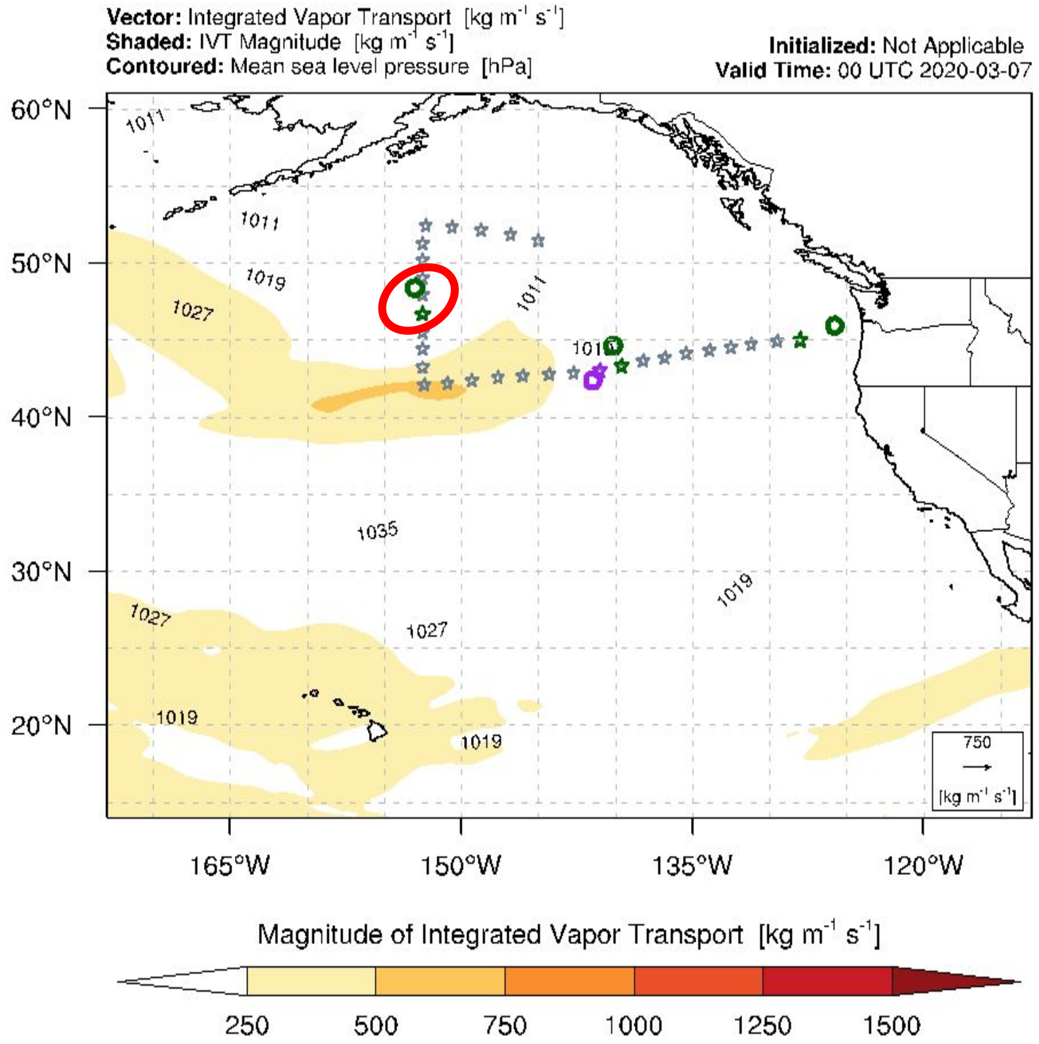
Very dry dropsonde profile with a strong low-level temperature inversion on the cold side of a weak AR.

The Operational occultation cannot sample below the top of the boundary layer outside the AR.

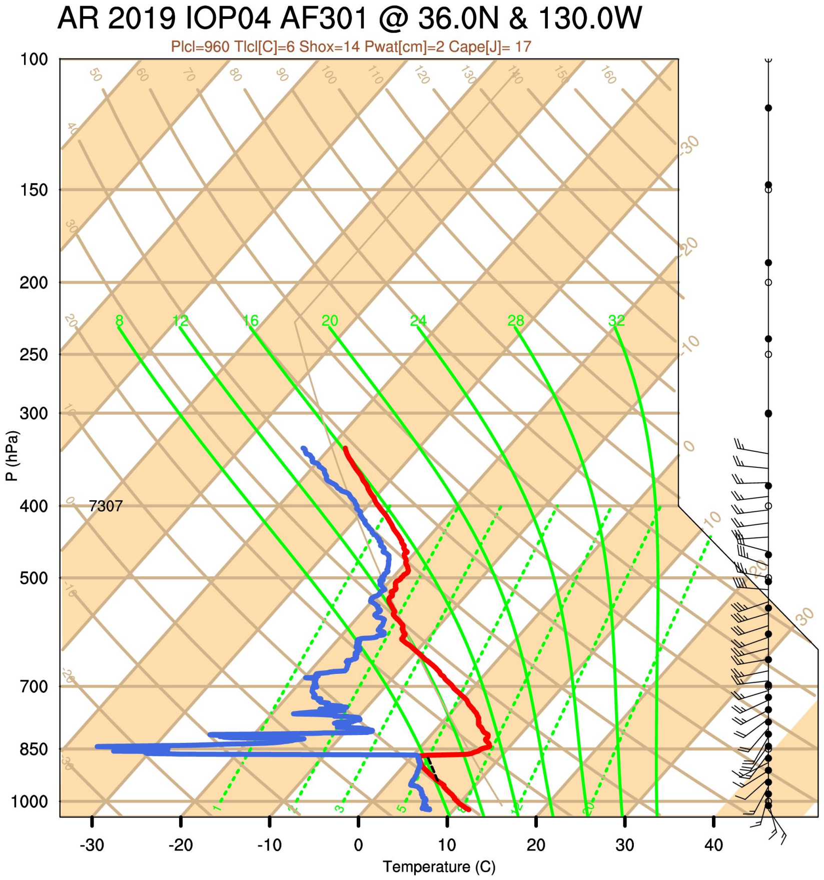


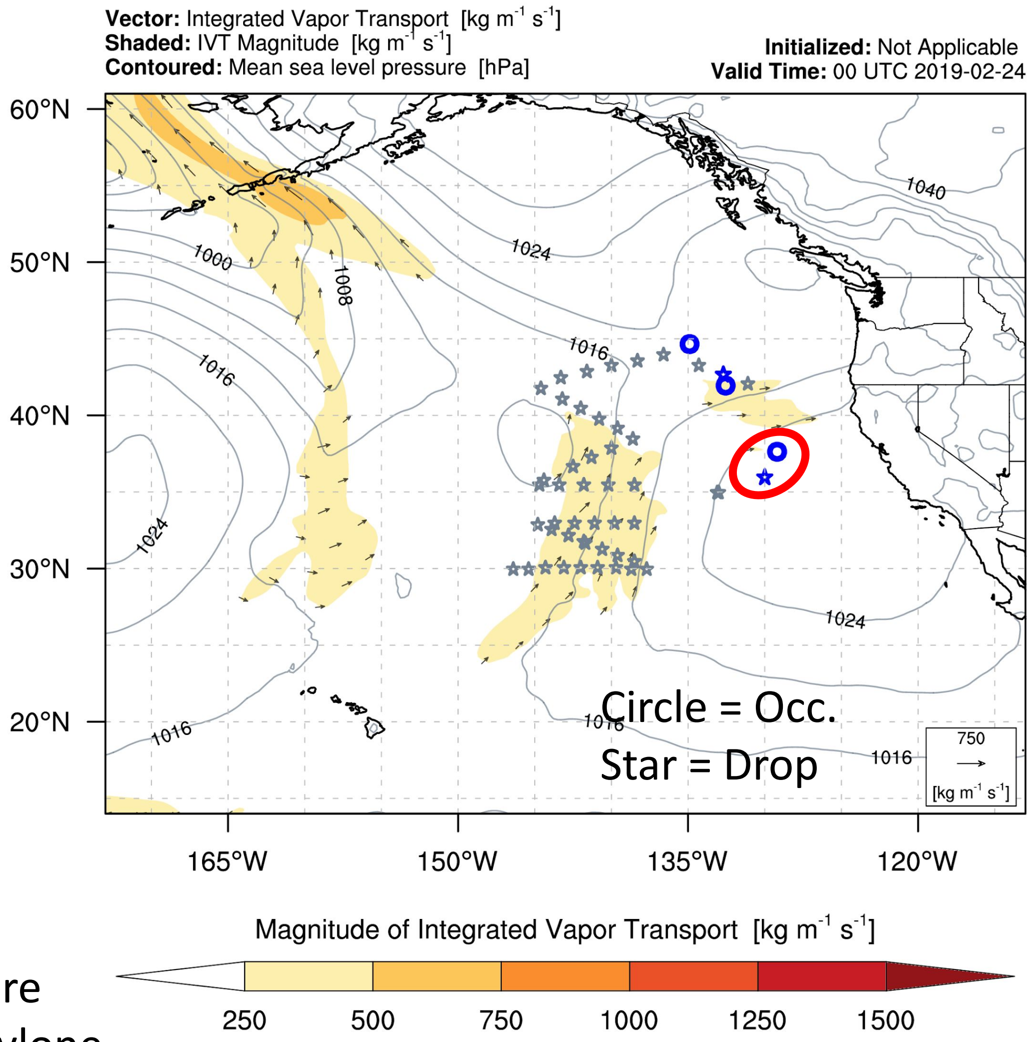
Pair is relatively far apart in space & time but both observations and reanalysis agree well (likely due to homogeneous atmosphere).

Occultation is truncated at ~ 3 km by strong inversion layer.



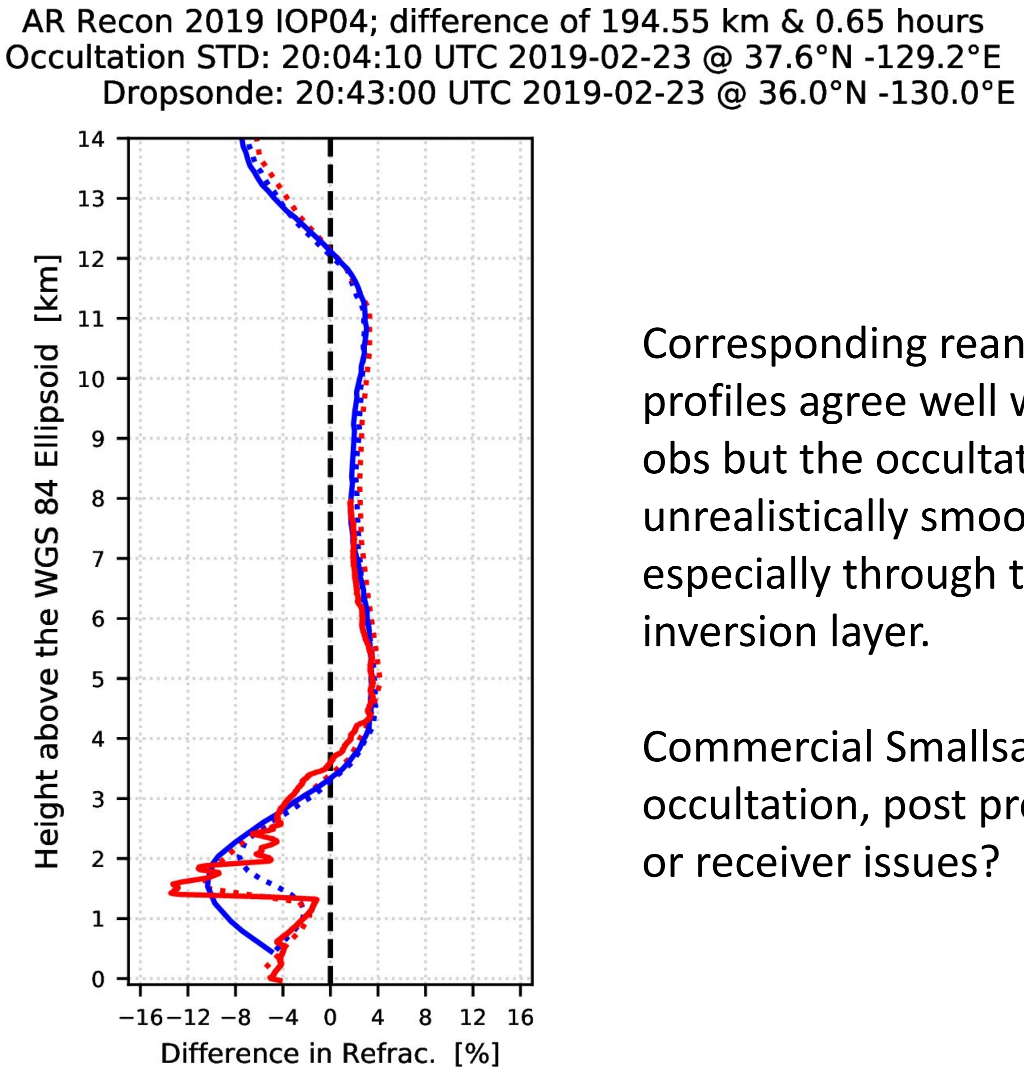
Occultation/Dropsonde Pair #3 – SmallSat (Spire) observation in an Anticyclone





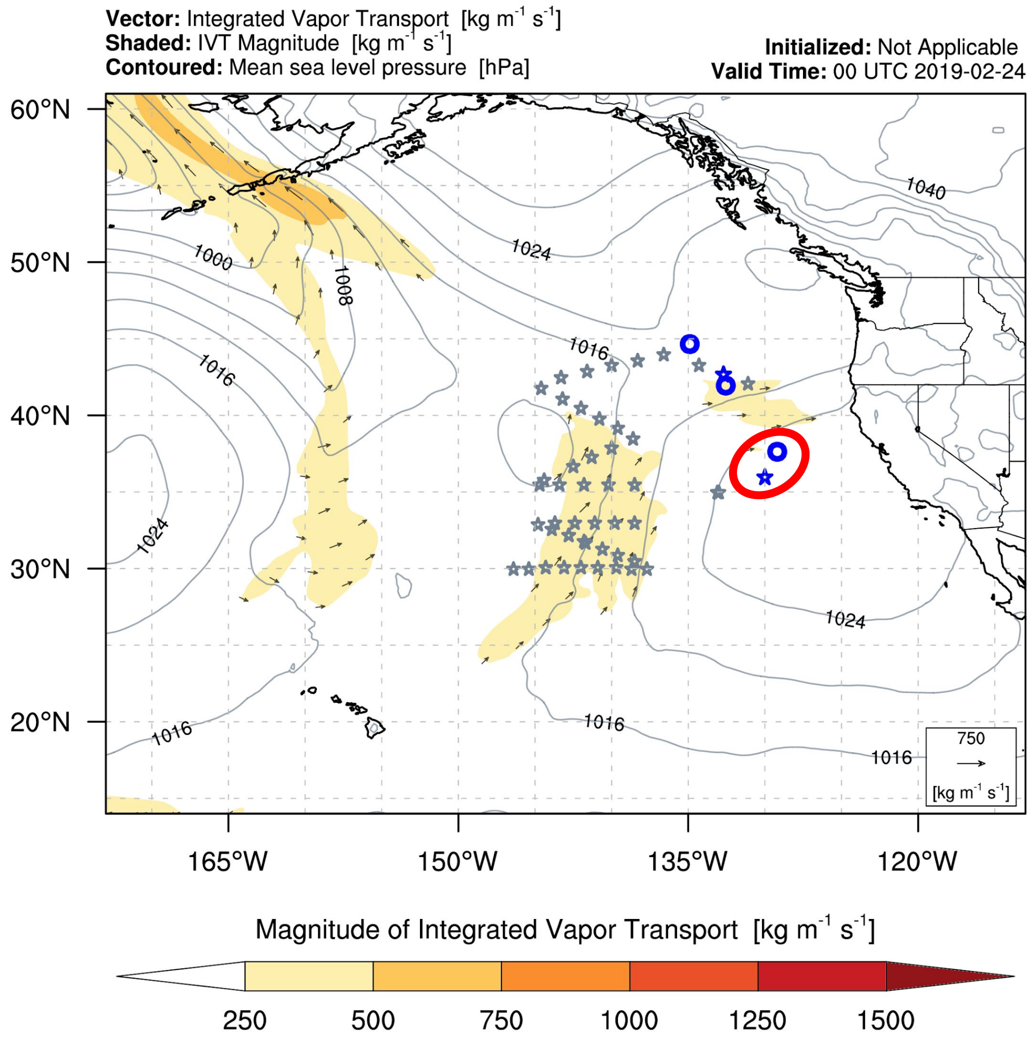
Relatively dry dropsonde profile with a strong low-level temperature inversion on the warm side of a weak AR under a subtropical anticyclone.

The SmallSat Spire occultation samples below the boundary layer but is unrealistically smooth.



Corresponding reanalysis profiles agree well with the obs but the occultation is unrealistically smooth especially through the inversion layer.

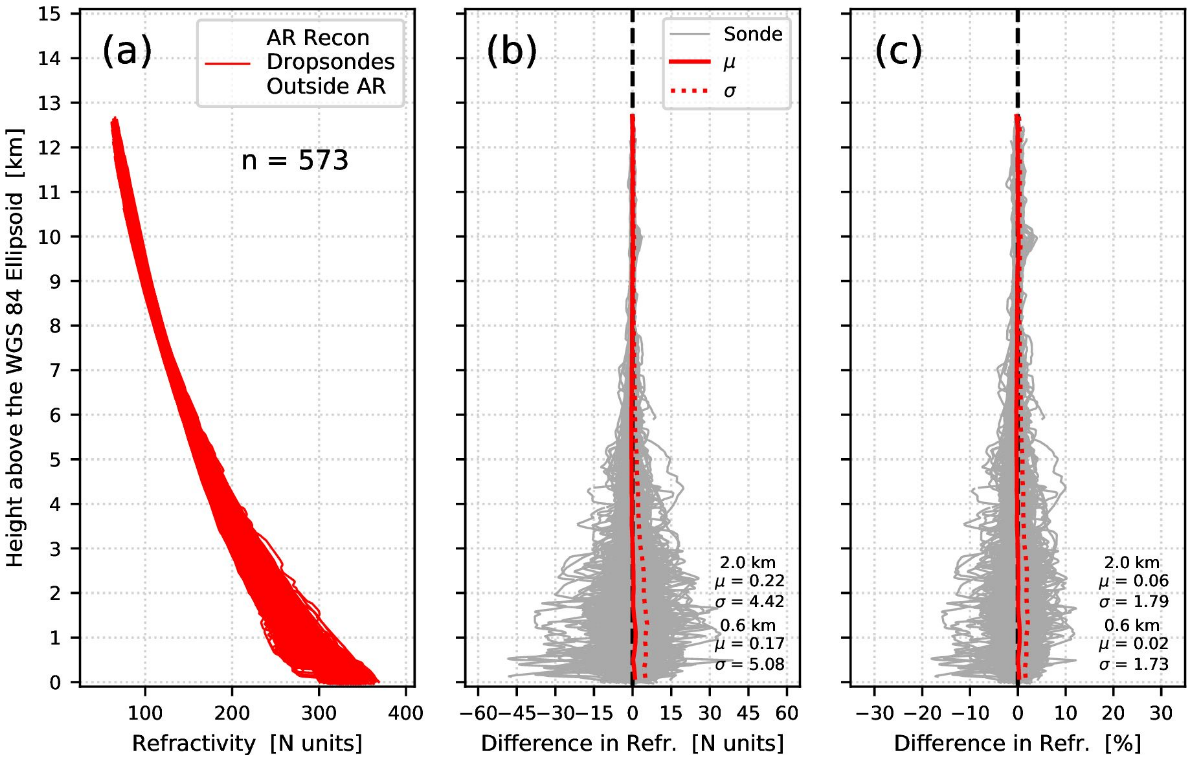
Commercial Smallsat occultation, post processing or receiver issues?



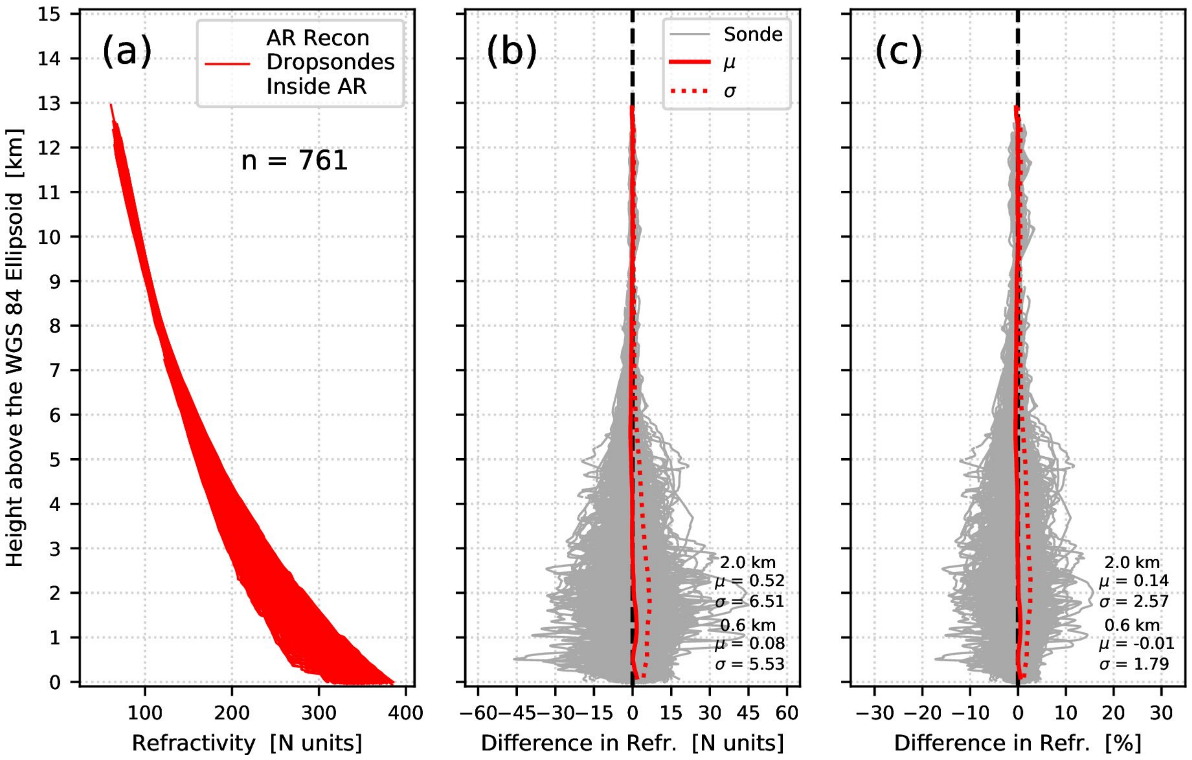
Comparison between Observations & Reanalysis

Quantitative Comparison between Dropsondes & Reanalysis

Outside of an AR



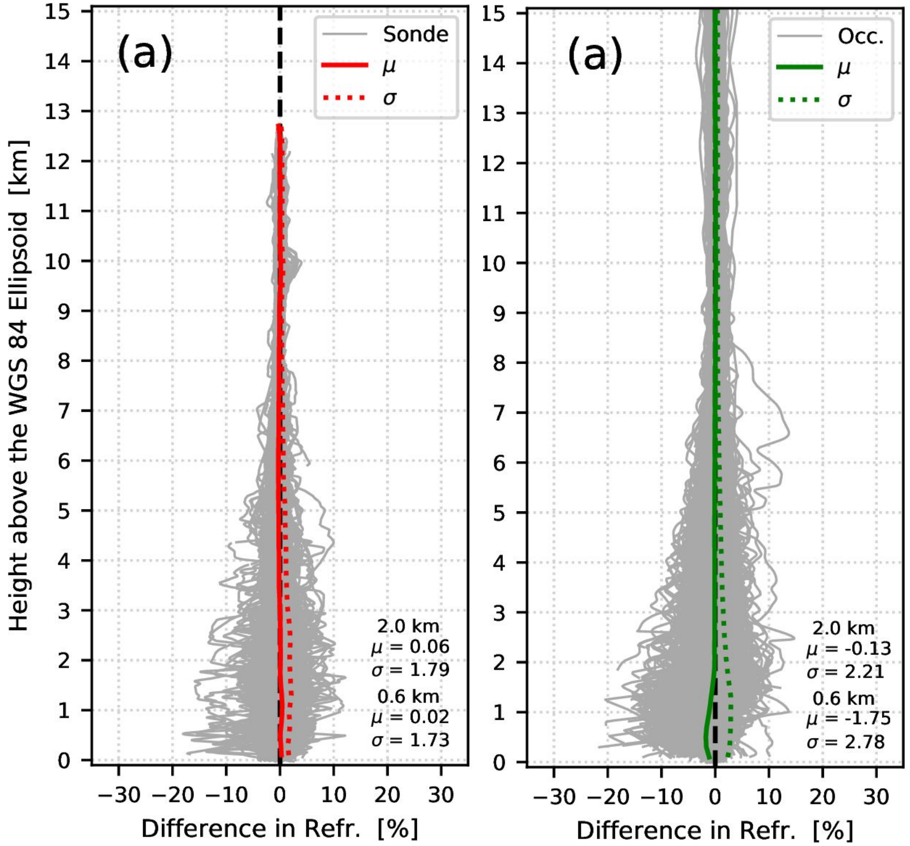
Within an AR



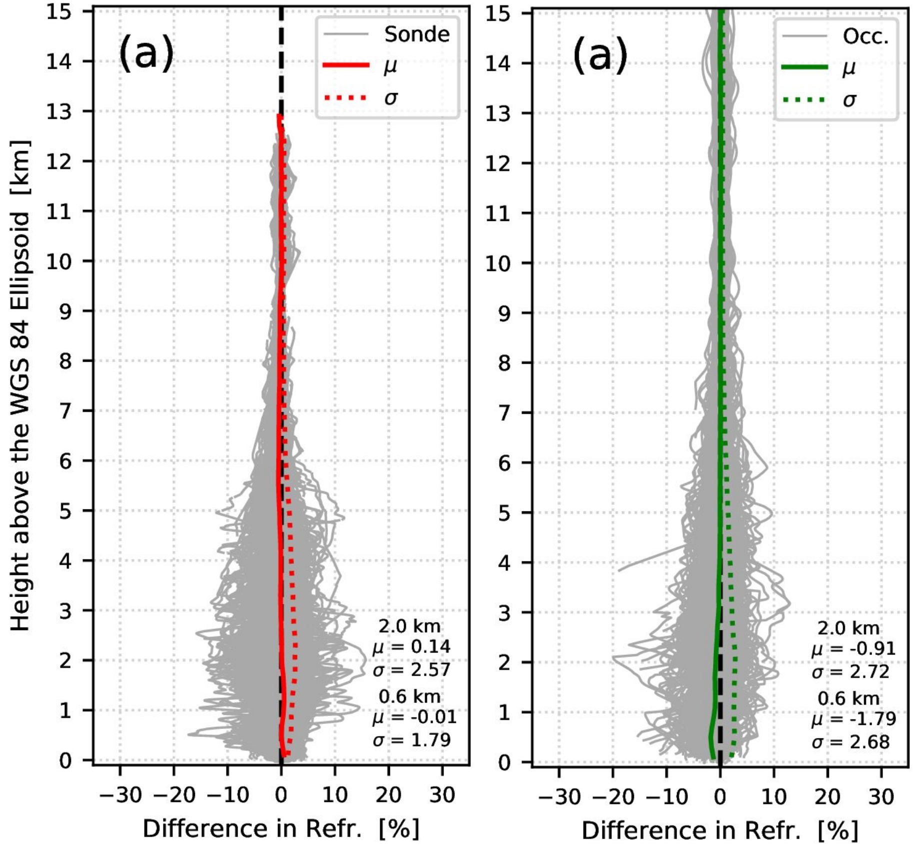
Small positive μ bias. Larger σ between 1 to 7 km inside AR .

Quantitative Comparison between RO & Reanalysis – Operational Occultations

Outside of an AR



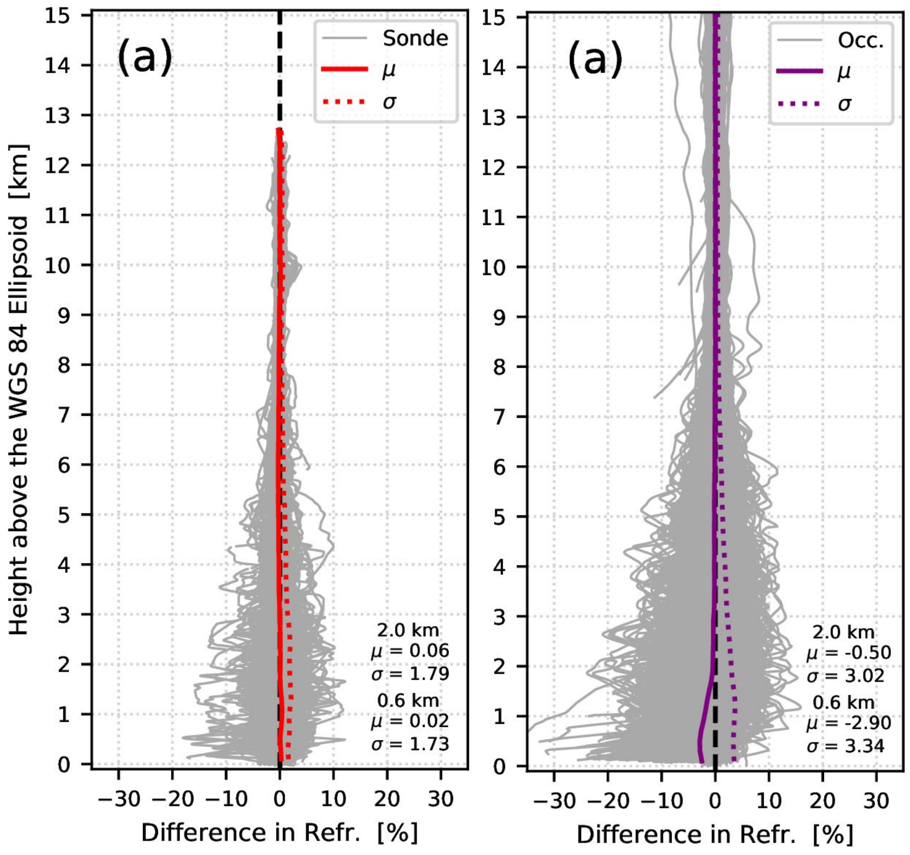
Within an AR



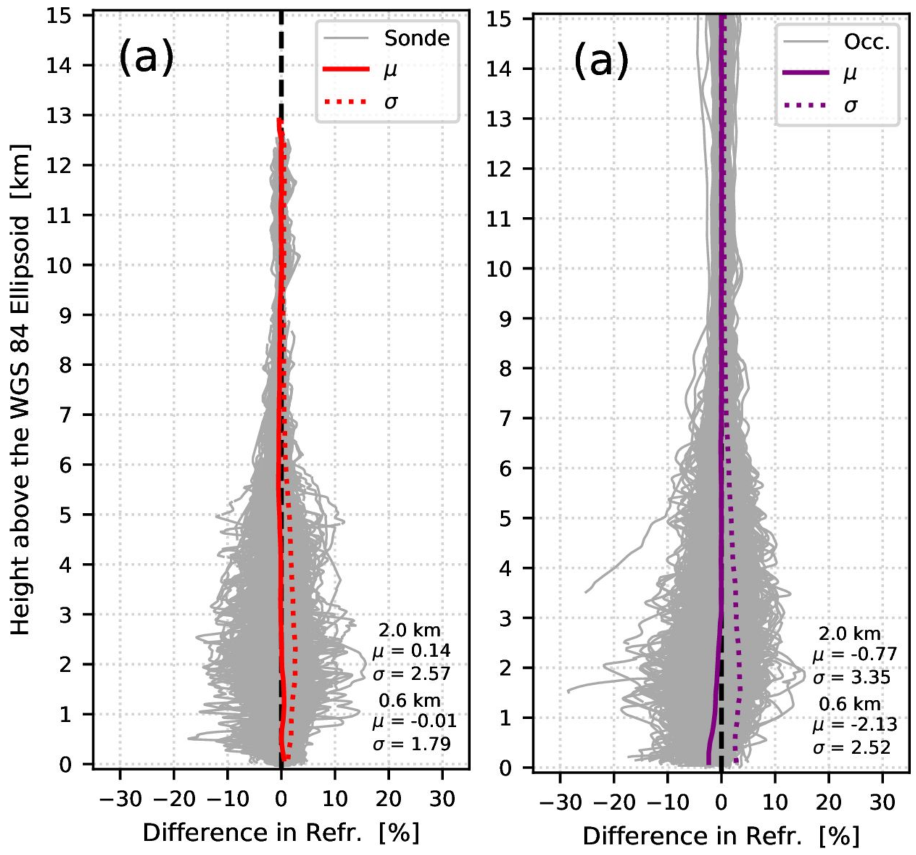
Negative μ bias, larger between 1-3 km inside AR. Larger σ below 1.5 km outside AR

Quantitative Comparison between RO & Reanalysis – COSMIC2 Occultations

Outside of an AR



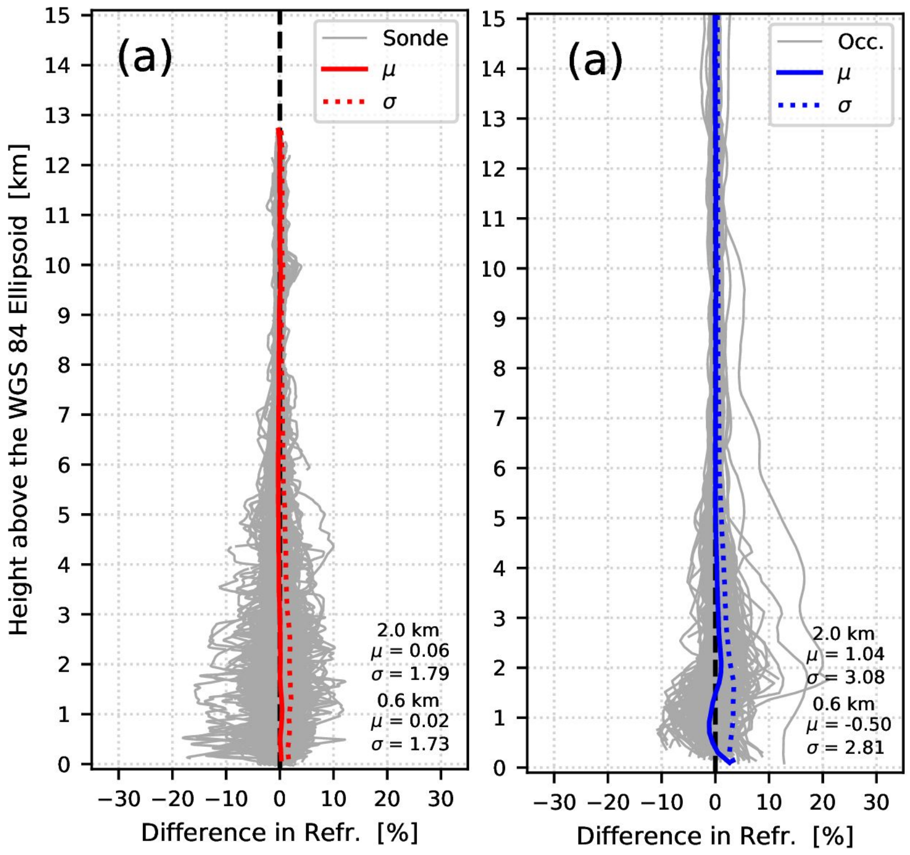
Within an AR



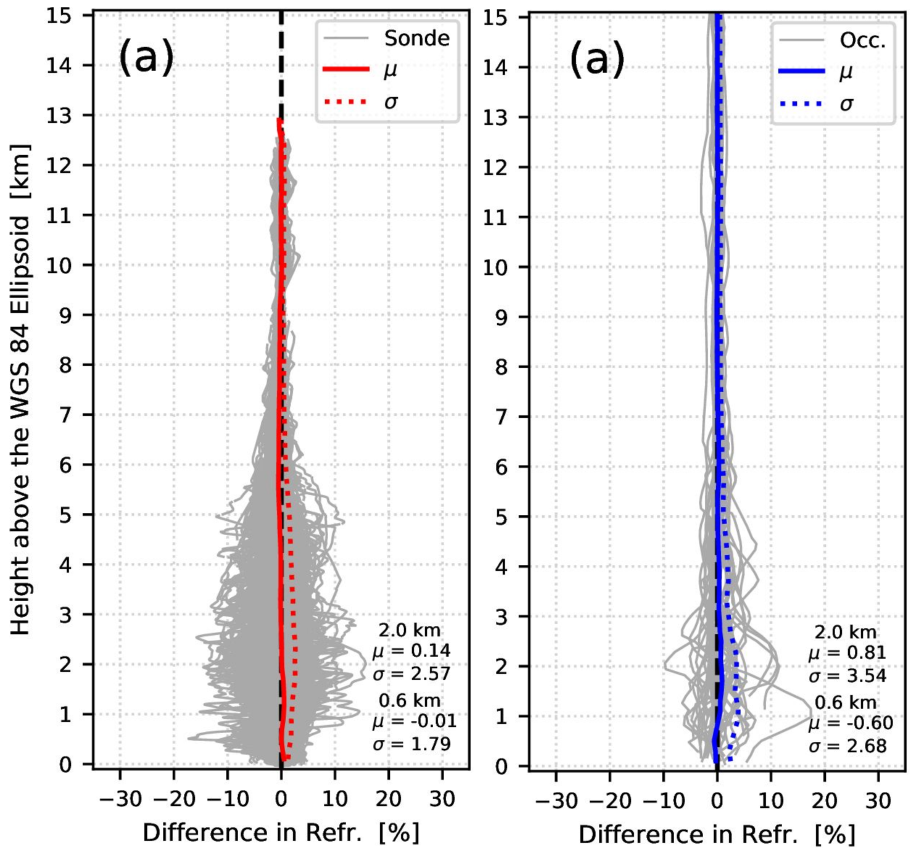
Negative μ bias, larger between 1-3 km inside AR. Larger σ below 1.5 km outside AR

Quantitative Comparison between RO & Reanalysis – Spire Occultations

Outside of an AR



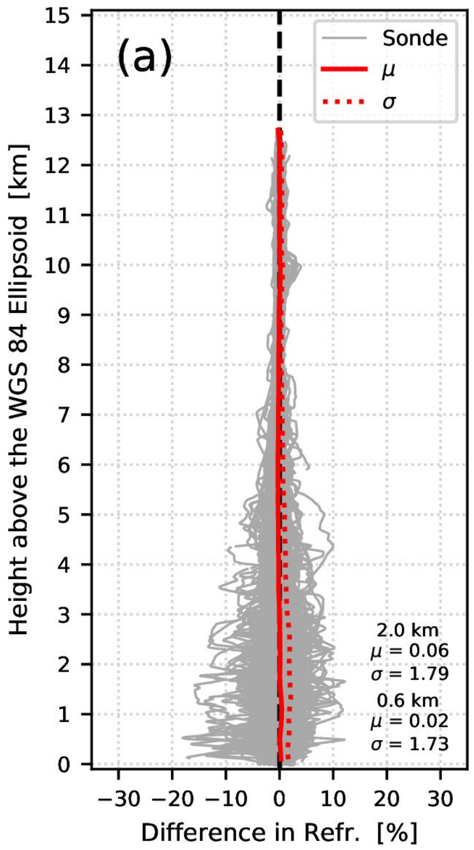
Within an AR

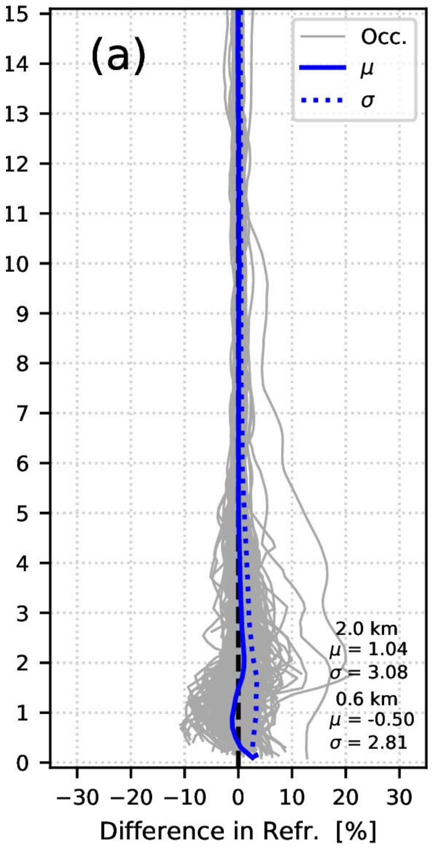


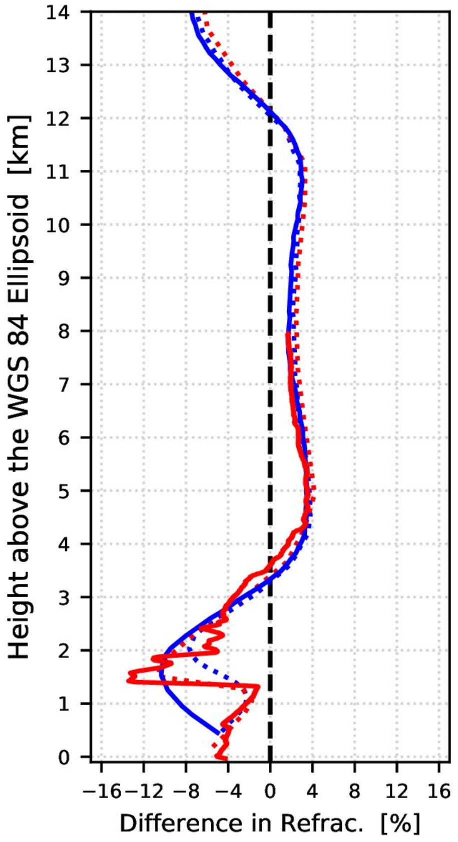
Negative μ bias, larger between 1-3 km inside AR. Larger σ below 1.5 km outside AR

Quantitative Comparison between RO & Reanalysis – Spire Occultations

Outside of an AR







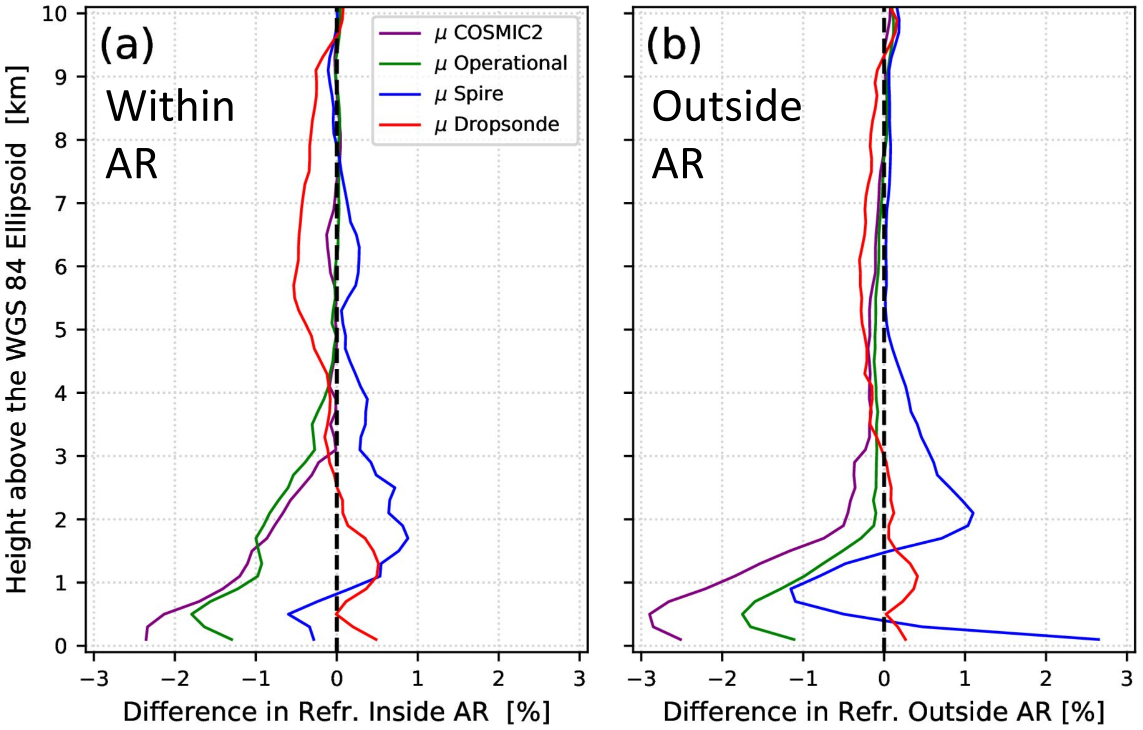
Systematic error expected due to unrealistic smoothing of observed profile in lower troposphere.

Not only a problem below, also systematically biased above where other dataset do not have bias

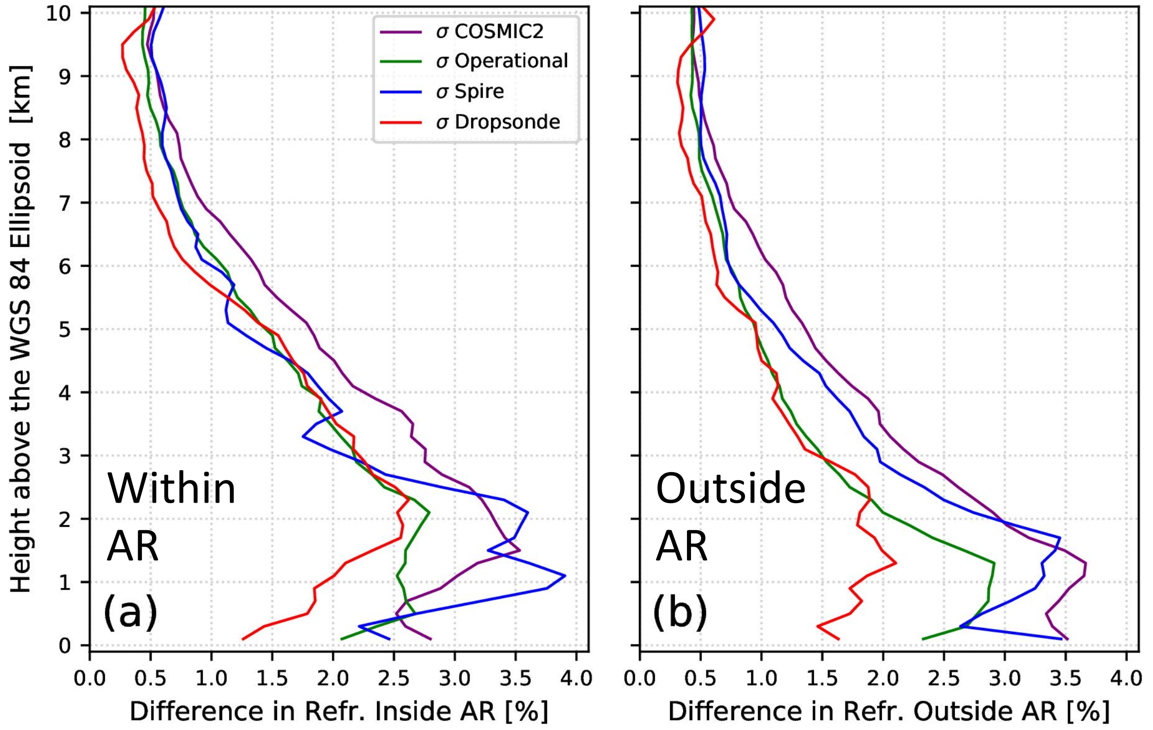
Summary and Interpretation

Intercomparison between Observed Datasets

Mean



Standard deviation



Max negative bias for occultations at 0.5 – 1 km
Spire has positive bias through much
of the troposphere

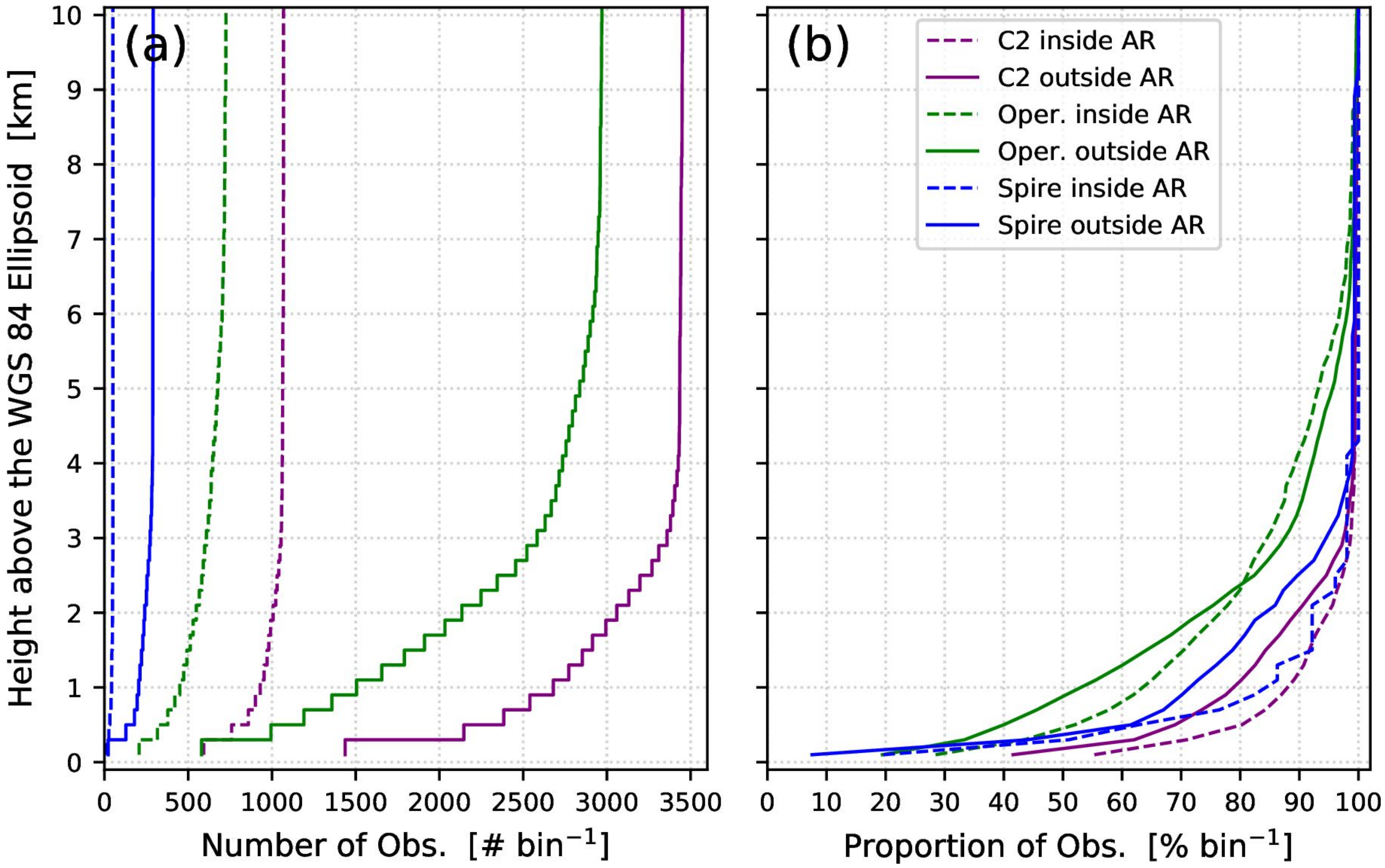
Dropsondes match Operational occ above 2 km
COSMIC2 has much larger σ than Operational
Spire is between Oper & COSMIC2 until 2 km

RO profiles penetrate deeper within an AR than in the surrounding environment.

COSMIC2 & Spire penetrate deeper than Operational Occultations

Inside the AR deeper penetration
a more saturated environment throughout the lower troposphere with a lack of strong vertical gradients in moisture and temperature

Outside the AR
more likely to be vertical gradients of moisture and temperature in the lower levels (e.g. sharp boundary layers related to subsidence associated with the subtropical anticyclone).

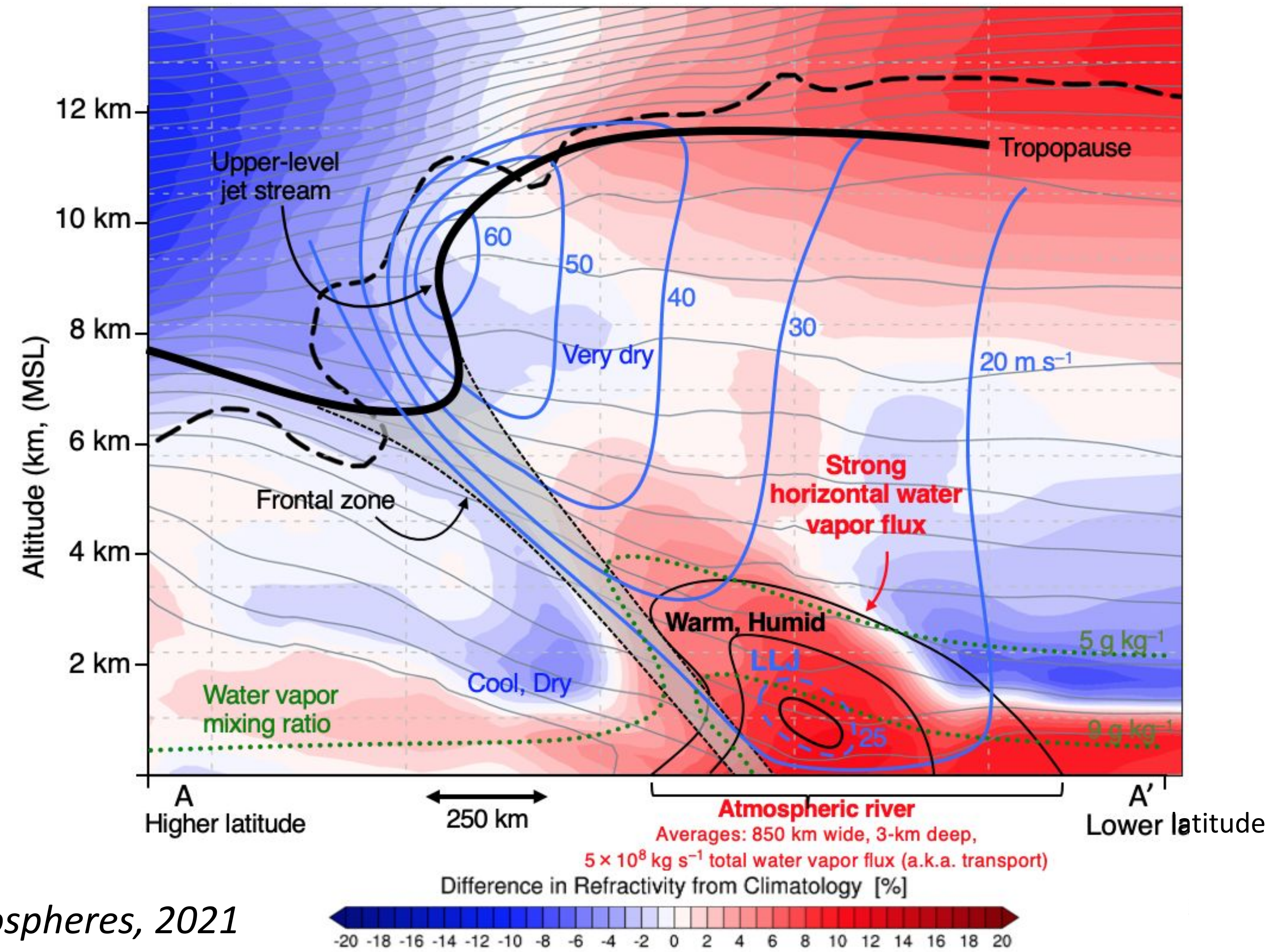


The deeper penetration of RO within an AR is likely related the lack of sharp refractivity gradients in the vertical within the core of an AR.

Vertical transect through an AR from a mesoscale weather model

Anomaly (difference) in refractivity from a climatological profile near the center of the transect.

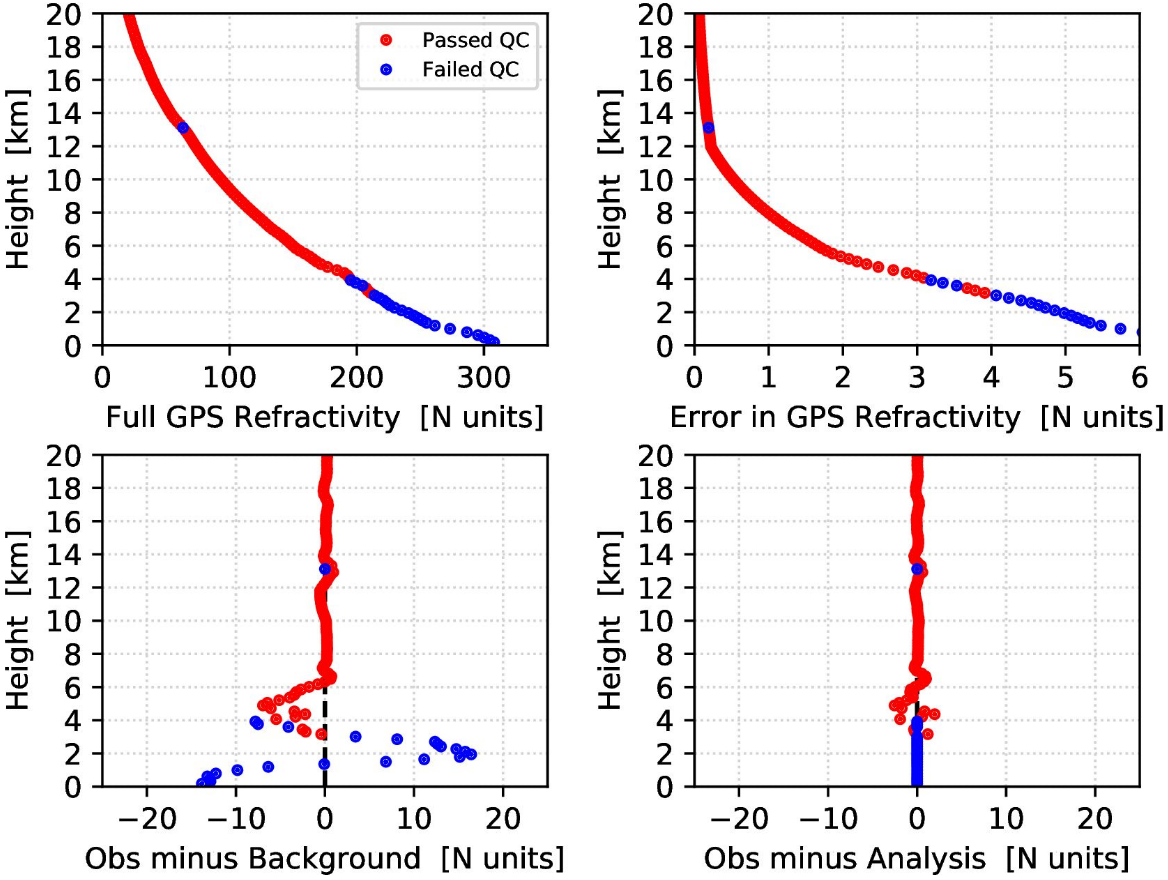
Overlain is a schematic diagram of an AR adapted from Ralph et al. 2017



Haase et al., JGR-Atmospheres, 2021

Data Assimilation (DA) algorithms treat the Spire Occultations similarly to Operational Occultations in the lower troposphere, *despite Spire having major artifacts down there.*

Example Operational Occultation



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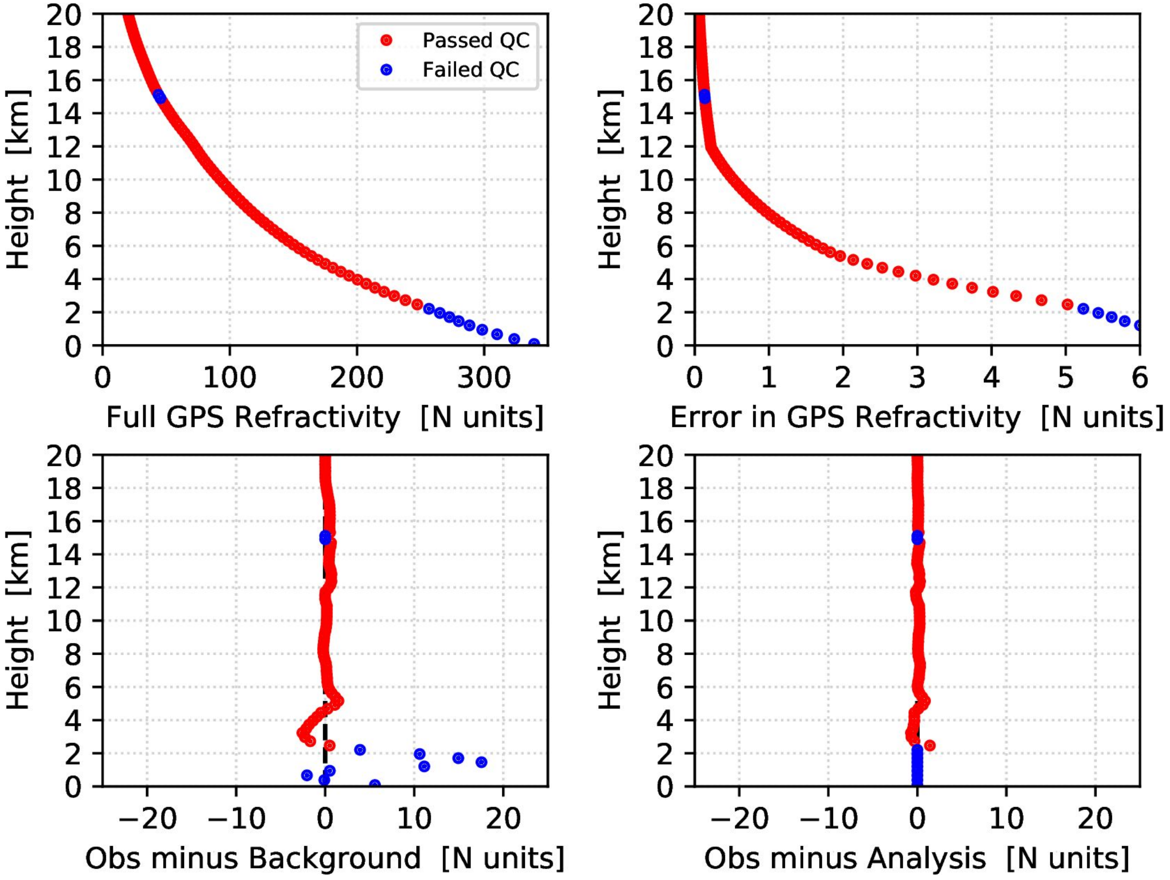

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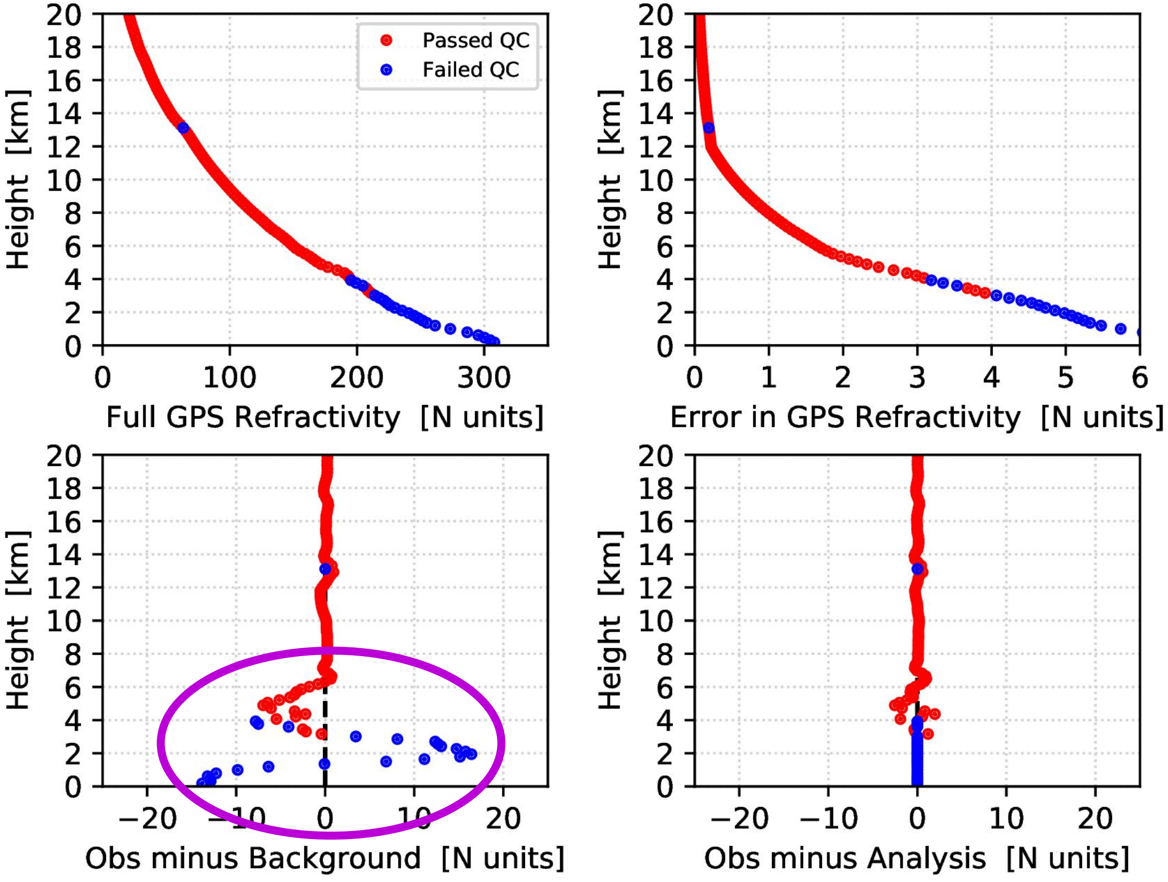
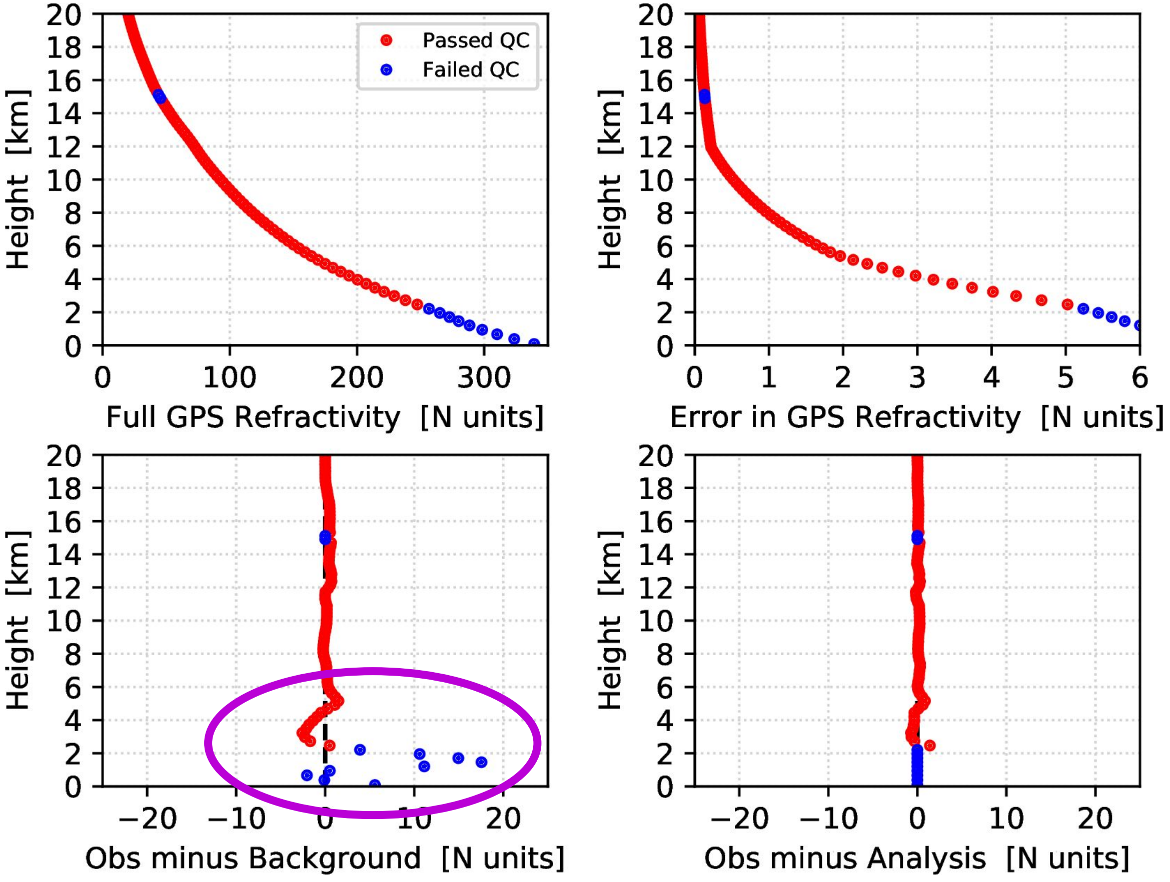


Example Spire Occultation



Answers to Science Questions

1. What is the quality of GNSS RO observations in the northeastern Pacific during atmospheric river events based on comparisons with ERA5 reanalysis?
    - The agreement of RO with the ERA5 reanalysis is better in the surrounding environment than within the AR
        - More variability in moisture in the observations inside the AR than in the Reanalysis
          E.g., profiles inside the AR have larger mean & stddev between 2-5 km than outside

2. Are GNSS RO observations able to penetrate the core of ARs?
    - A higher proportion of profiles sample below 3 km inside the 250 kg/m/s contour of the AR than in the surrounding environment (unexpected)
    - COSMIC2 & Spire occultations penetrate deeper overall than the Operational occultations

Murphy et al., Evaluation of GNSS RO observations in atmospheric rivers, in prep, MWR

Answers to Science Questions (continued)

3. How do the different GNSS RO constellations compare in quality?
    - In the troposphere, COSMIC2 has larger differences wrt ERA5 compared to the Operational GNSS RO dataset, possibly because COSMIC2 was not yet assimilated into the ERA5 during AR Recon 2020 (though it is assimilated now)
    - The Commercial SmallSat constellation (Spire)is overly smooth through out the troposphere compared to dropsondes
        - *not useful in determining the small-scale vertical structure of the lower troposphere*

4. What can we learn about the quality of GNSS RO observations using comparisons with AR Recon dropsondes?
    - In terms of refractivity (combined T, P, q), RO profiles have small-scale vertical variations similar to dropsondes
    - There are significant differences over small horizontal distances that seem to be physically realistic. Further work should determine how to tune DA algorithms or weight the obs to make better use of these lowest level data.
    - The large negative differences outside the AR in the lowest 3 km could be explained by boundary layer structure -- merits further investigation.

- Small scale variability inside AR necessitates assimilation using a 2D operator
    - Planning future study of statistics using such an operator

Murphy et al., Evaluation of GNSS RO observations in atmospheric rivers, in prep, MWR

The End

How do Spaceborne RO Observations Compare to Dropsondes Qualitatively?

- Airborne Radio Occultation (ARO) is very close in time and space to dropsondes by design (collected from the same aircraft).
- Expand statistics beyond just ARO by finding close pairs of spaceborne RO and dropsondes.
- Identify pairs of nearby AR Recon dropsondes & Radio Occultation profiles (within 2 hours & 300 km)

Airborne Radio Occultation (ARO) has sampled ARs along-side Dropsondes.

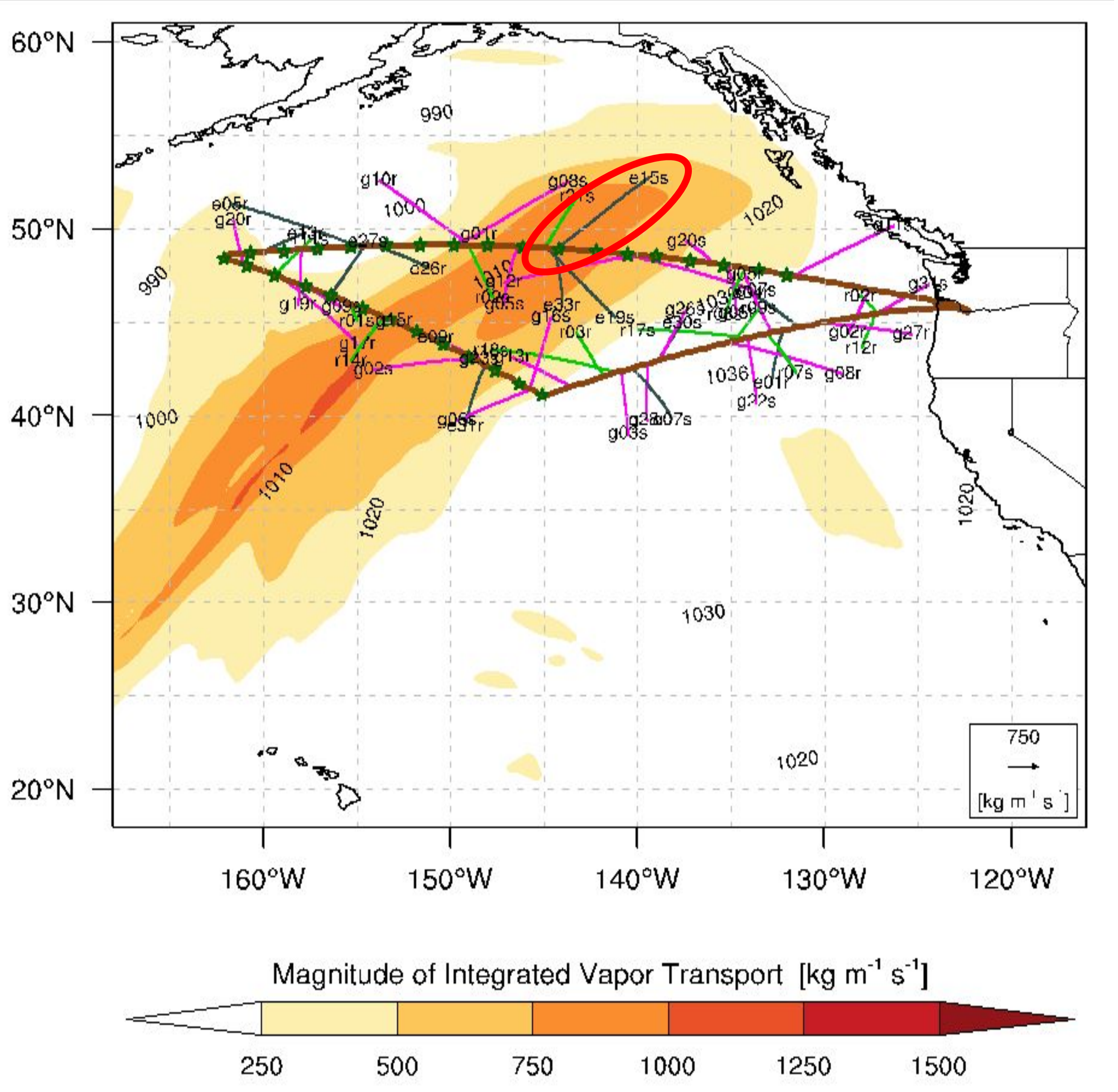
Example from AR Recon 2020 IOP04

Three different GNSS constellations were used:

1. GPS
2. Galileo
3. GLONASS

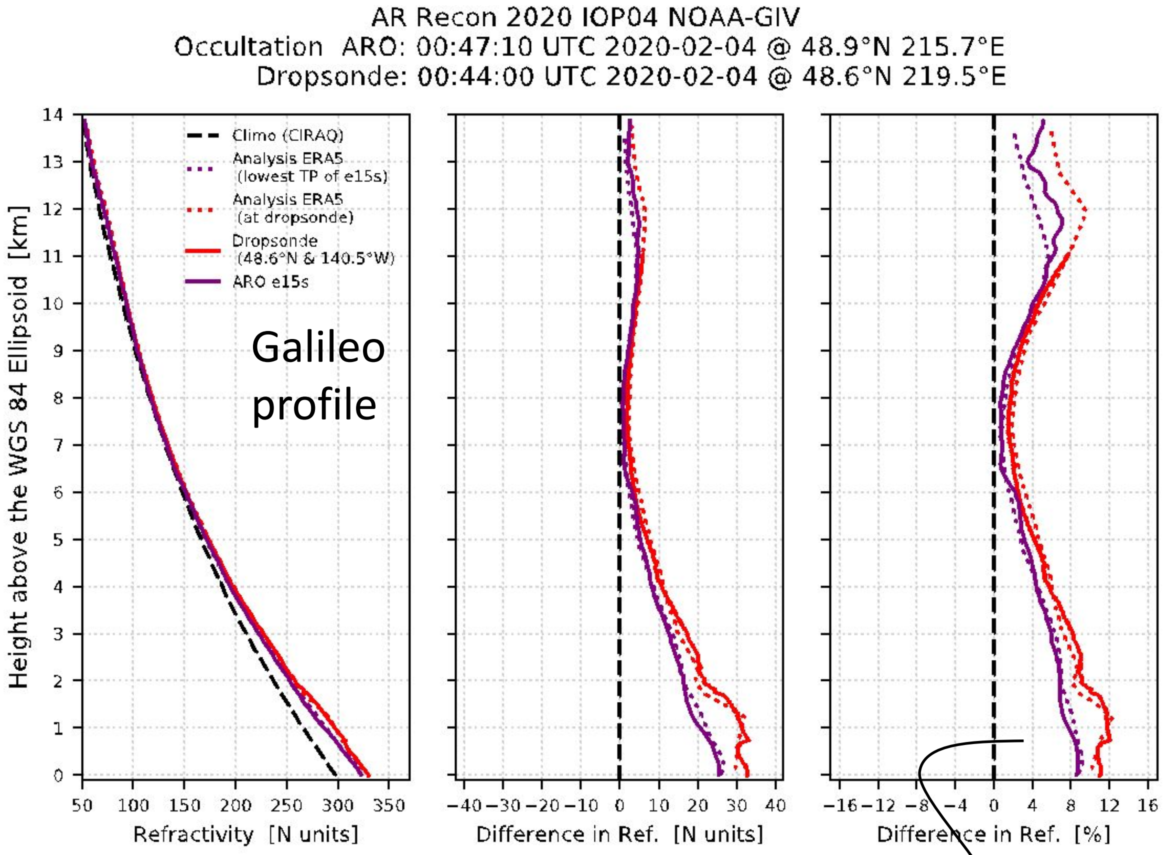
Result is 54 Airborne Radio Occultations (ARO) observed in total over the period from 1900 through 0200 UTC on 03-04 Feb 2020 during the NOAA G-IV flight

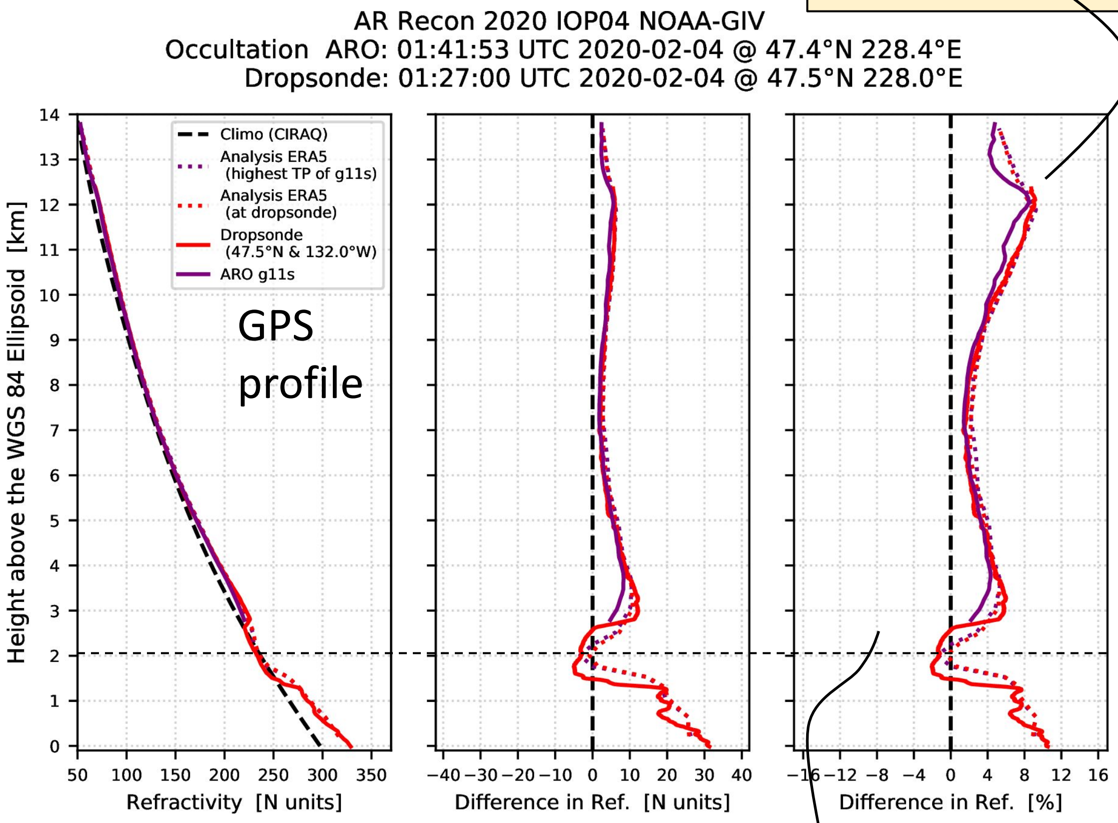
The Galileo occultation circled in red is shown on the next slide



ARO compares well to profiles from nearby dropsondes and Reanalysis.

Provides more detail at the tropopause





Exceptionally good Galileo profile reaches the surface inside the AR core

Typical limit of GPS and Galileo profiles without mini-GISMOS and Open Loop Tracking

Two examples of ARO occultations that were measured near dropsondes in both time and space