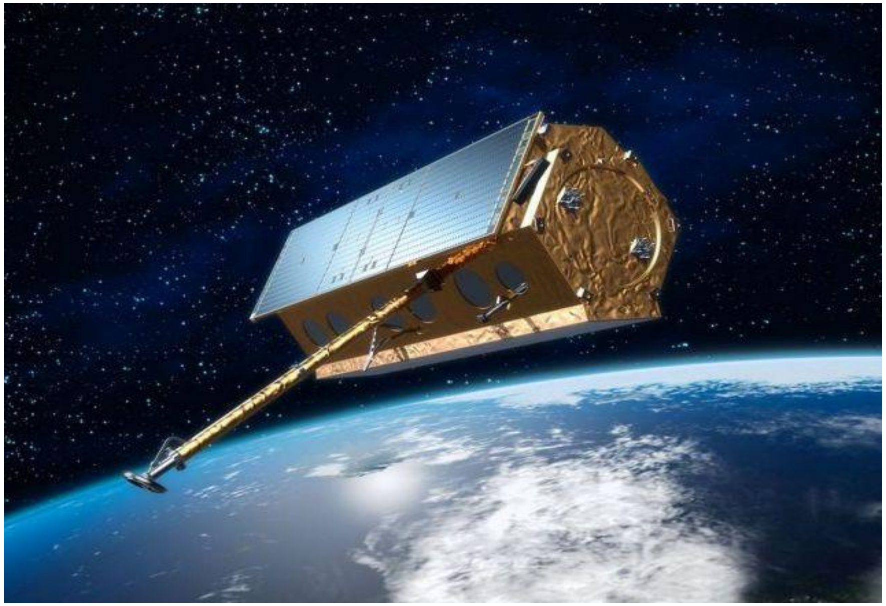
Polarimetric RO processing at UCAR



Doug Hunt, Sergey Sokolovskiy, Hailing Zhang, Hsiao-Chun Lin, Teresa Vanhove, Jan Weiss
University Corporation for Atmospheric Research (UCAR, Boulder CO, USA)
Estel Cardellach, Ramon Padulles
Institute of Space Sciences (ICE, CSIC)
Institute for Space Studies of Catalonia (IEEC) Barcelona, Spain

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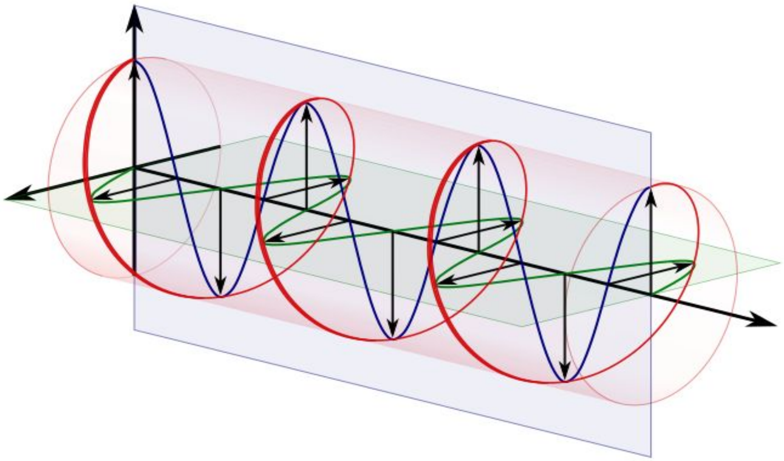
Contents

Polarimetric Radio Occultation (PRO)

GNSS signals are Right Hand Circularly Polarized. A typical receiver antenna is designed to receive such signals and deliver phase and amplitude (SNR) values.

The PAZ satellite (and now 3 Spire satellites) instead collect GPS data from two separate antennas: One designed to capture horizontal polarization (H) and another to capture vertical polarization (V) as shown in the arrows in the figure to the right:



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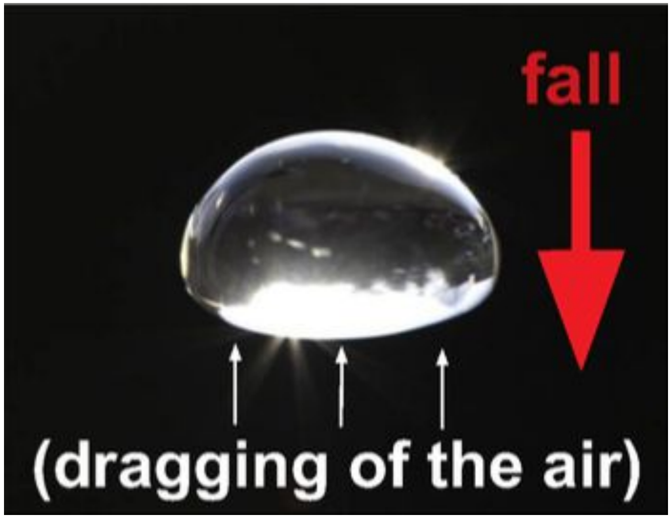


Heavy rain slows H and V polarized signals differently. The difference in H and V ($\Delta\phi$) should be sensitive to heavy rain fall.

So, the idea is that PRO gives one all the benefits of normal radio occultation with added information on precipitation.

Source: Cardellach: Tutorial on GNSS Polarimetric Radio Occultations (GNSS PRO)

Single Polarization Processing

It is possible to do normal RO processing not only with data from an RHCP antenna (the usual case), but with either linear polarization (H or V) as well.

1. Start with high rate opnGns occultation data
2. Remove orbital motion (LEO and GNSS POD data), GNSS clocks (e.g. IGS products), and LEO clocks (via differencing with a high elevation (reference) satellite)
3. Compute an atmospheric Doppler model from climatology
4. Integrate this model to get a phase model, then difference it with the observed (excess) phase computed above
5. This phase angle $\Delta\theta$ is now rotating slowly enough to generate meaningful I and Q components: $I = SNR * \cos(\Delta\theta), Q = SNR * \sin(\Delta\theta)$
6. Apply navigation bits to the open-loop portion of I and Q
7. Stitch open- and closed-loop I's and Q's together (not needed for Spire)
8. Compute phase via $atan2(Q, I)$
9. Fix full cycle slips by adding or subtracting 2π to minimize the difference between samples
10. Add the phase model back in to get connected excess phase
11. These connected L1 and L2 phases are then submitted to the *inversion process* to compute bending angle, refractivity, and finally temperature and pressure profiles. This same inversion process is used by all other missions.

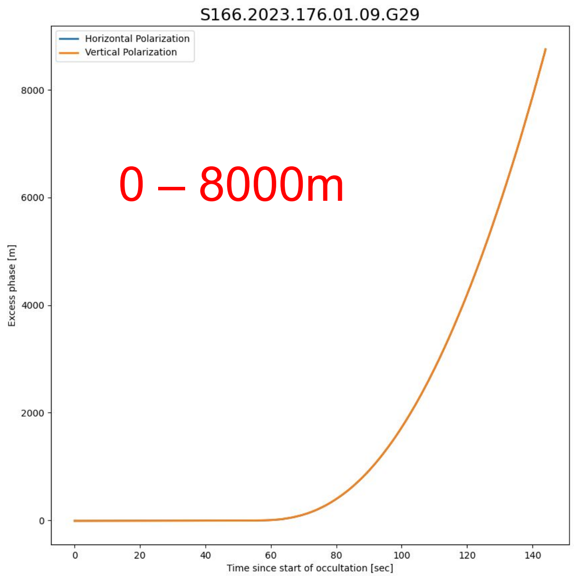
PRO ($\Delta\phi$) Processing

- The process outlined in the PAZ PRO literature from the ICE group were followed, with much experimentation.
- The results shown on the next slides include the following steps:
  1. Start with H or V excess phases as computed on the previous slide.
  2. $\Delta\phi$ = H – V. Now we have an uncalibrated profile that descends into noise at the bottom. Both H and V excess phases reach several kilometers in magnitude, whereas $\Delta\phi$ tops out at 20-30 millimeters for an extreme rain case. Care is necessary!
  3. Compute I and Q from this difference, then phase-connect again: This fixes full cycle slips in $\Delta\phi$. Next do a two stage correction for ½ cycle slips for the closed loop Paz data.
  4. Compute the Mean Sea Level altitudes for each profile using standard inversion code and a climatological model. This is a rough Abel inversion.
  5. Subtract a linear fit from 20 to 70km MSL altitude.
  6. Truncate $\Delta\phi$ based on several criteria. This gets rid of wildness at the bottom as the signals pass into noise.
  7. Apply a 6^{th} order Butterworth low-pass filter with a cutoff frequency of 1 Hz. This cleans the signal up, getting rid of high frequency clutter.

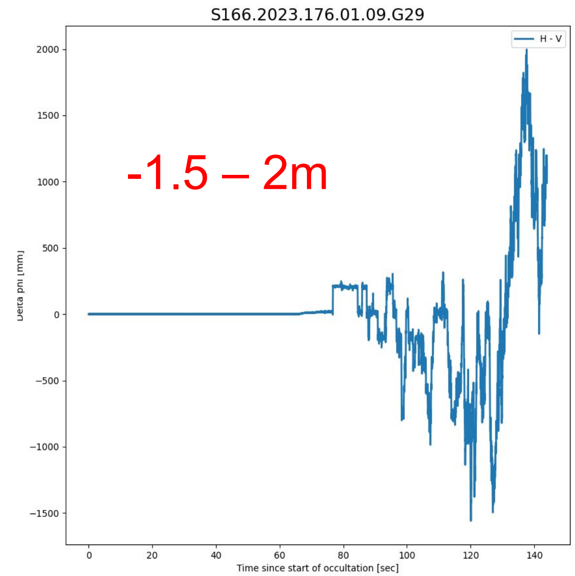
Thanks to Estel Cardellac, Ramon Padulles and the ICE group for documenting their $\Delta\phi$ process thoroughly (see references). The UCAR processing of Spire and Paz data benefitted greatly from their methods!

Δϕ Processing (cont.)

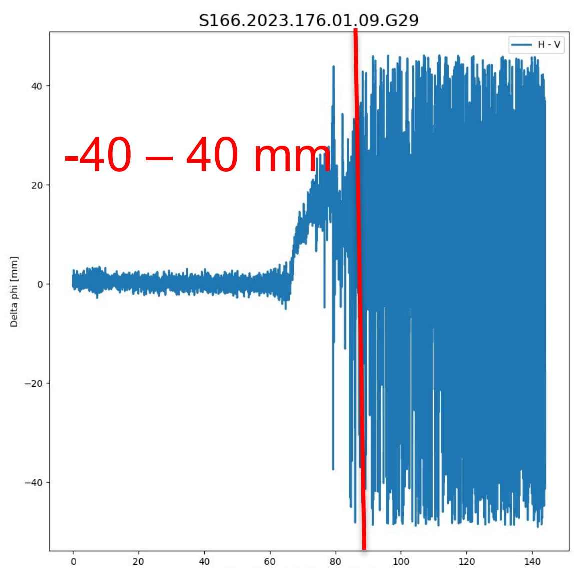
1) Original H and V excess phases



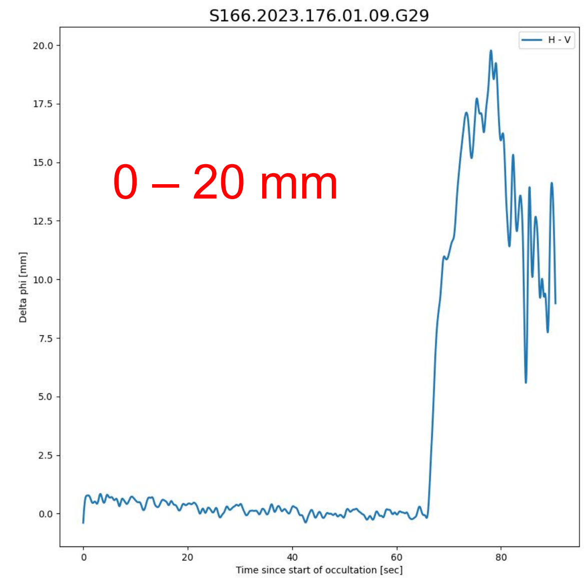
2) Raw H – V. Note cycle slips and noise at the end



3) Cycle slip correction, removal of offset and linear trend



4) Noise truncation, low-pass filtering



Differences Between Spire and PAZ PRO Processing

- PAZ is GPS-only. Spire tracks GPS, GLONASS, Galileo, and Beidou.
  - Only GPS, GLONASS, and Galileo results are shown here.
- PAZ only tracks setting occultations. Spire tracks rising and setting.
- PAZ tracks closed loop, then open loop data. Spire tracks all open loop data.
  - PAZ data requires ½ cycle slip fixing before and after H/V combination, Spire does not.
- PAZ uses separate receiver channels with separate time stamps for H and V tracking. Spire tracks H and V with a shared time stamp.
  - No interpolation of time stamps is needed for Spire. No phase alignment is required between H and V channels for Spire.

Occultation geometry

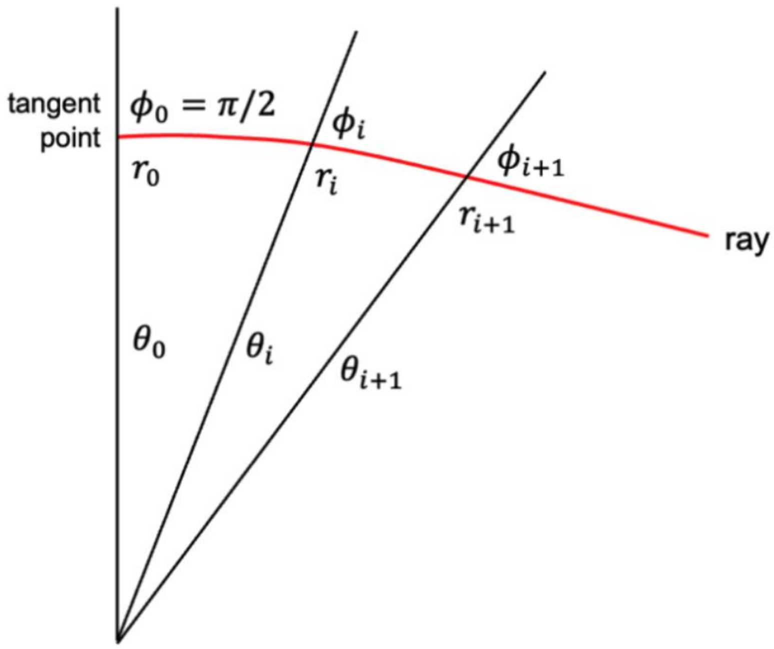
An algorithm due to Sergey Sokolovskiy (UCAR) was implemented to determine the ray path taken by any PRO occultation to allow precise comparison with ancillary data, such as the IMERG rain rate dataset.

Given (from an atmPrf file):

1. The vectors to the points of ray path perigee (Lat, Lon, MSL_alt)
2. A vertical profile of refractivity (Ref)

Compute the 2D path of the ray trajectory (r_i, θ_i) using a finite difference version of this equation:

$$\Delta\alpha = -a \int_{x_i}^{x_{i+1}} \frac{dn/dx}{n(x)\sqrt{x^2 - a^2}} dx$$

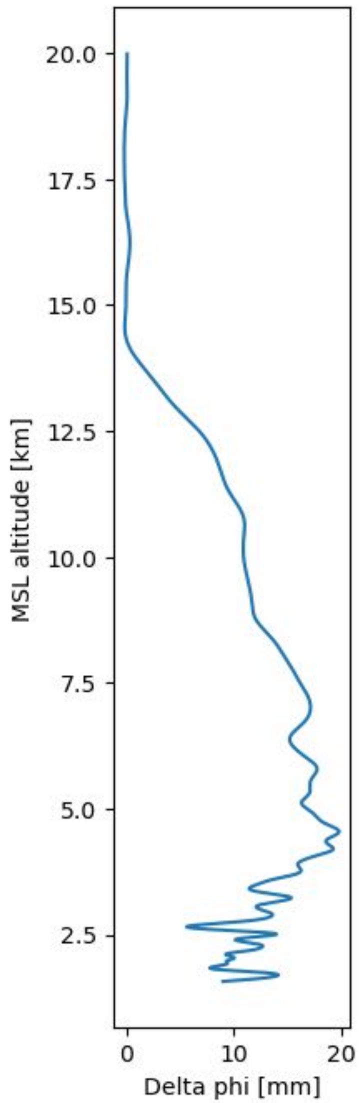


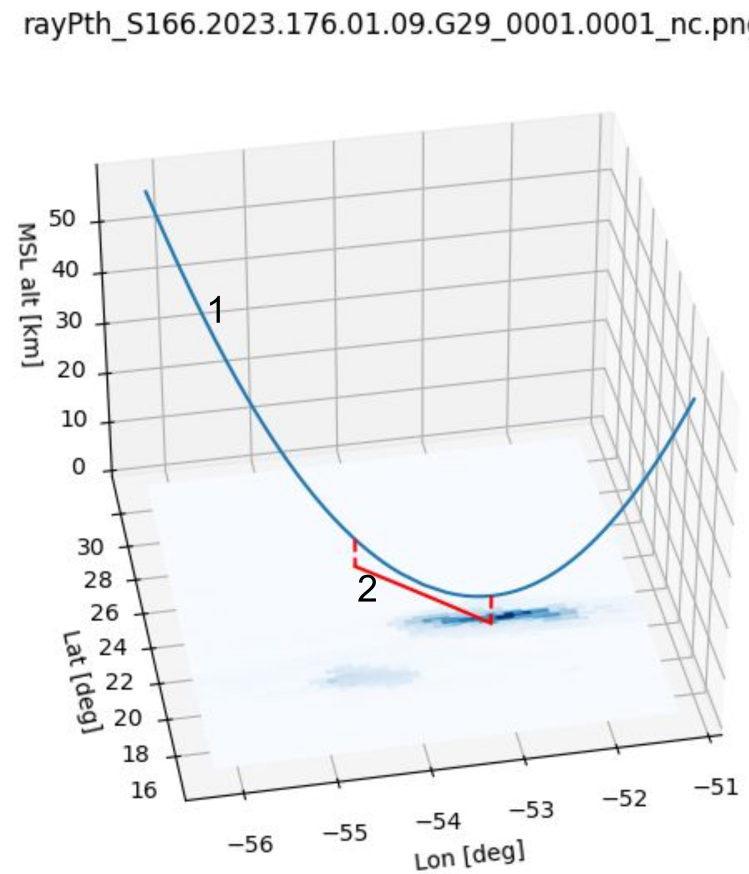
Then orient this 2D path in 3-space using the azimuth angle (Azim in the atmPrf file) at chosen points along the ray path.

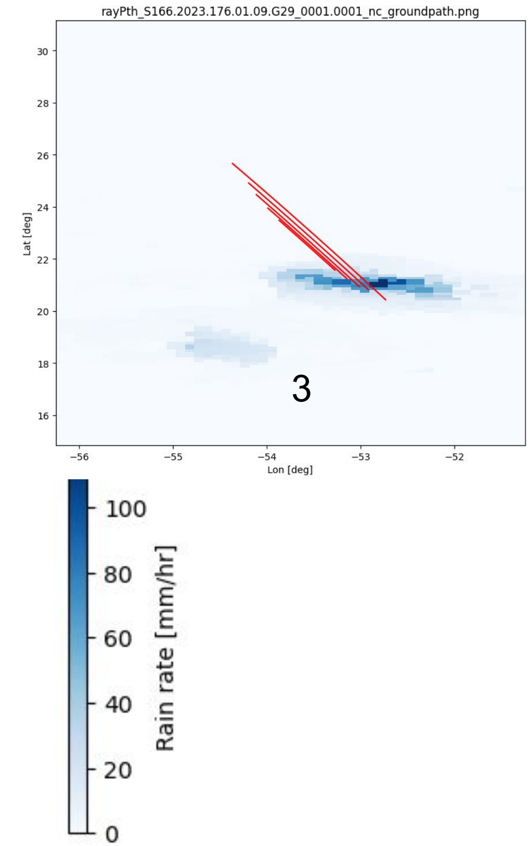
Convert these to lat/lon/alt triples and write to a new file type rayPth which is modelled on the iceCol file from the ICE group.

Occultation geometry (cont.)

Here is the ray path of the $\Delta\phi$ profile from a few slides ago.



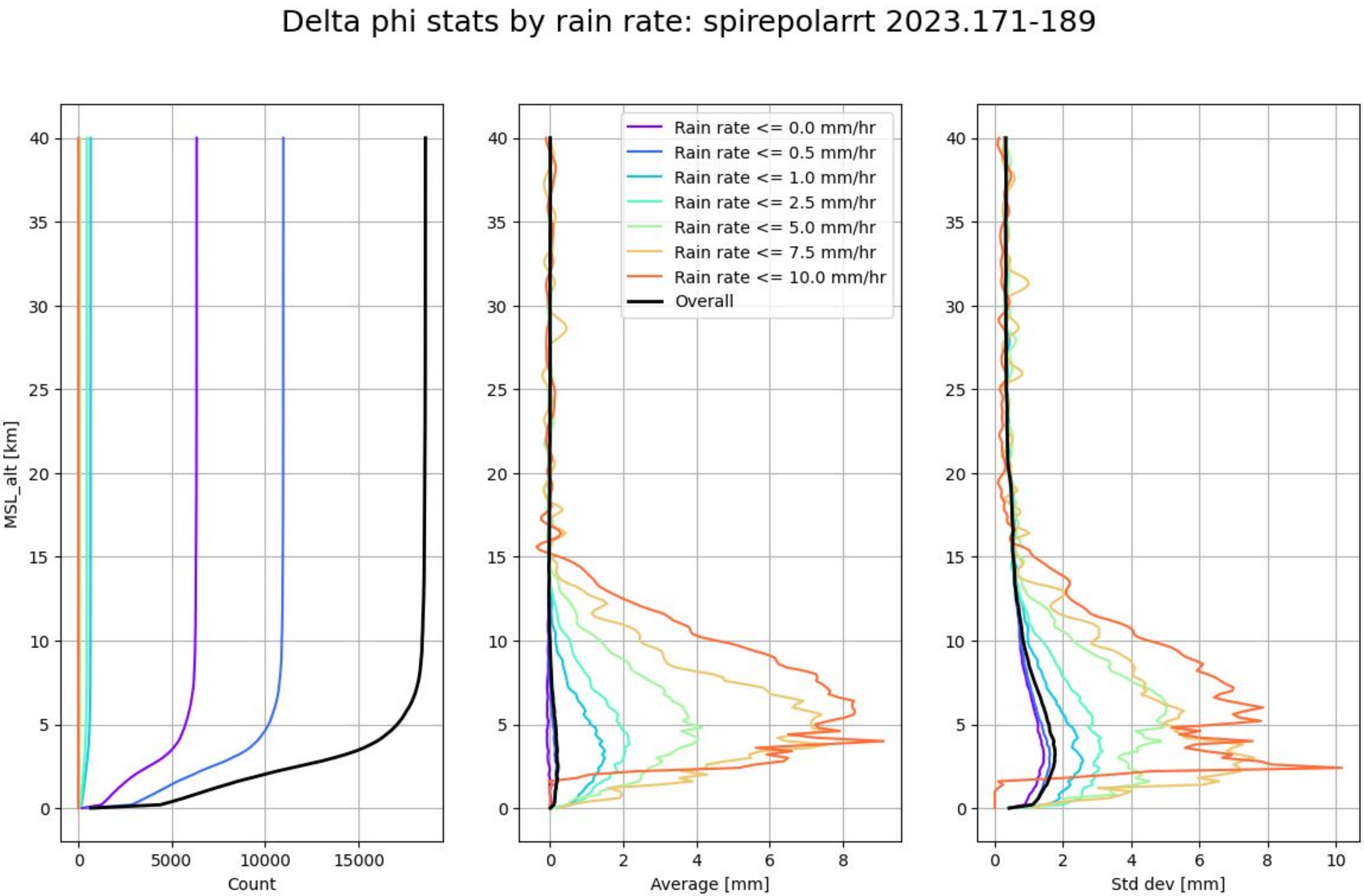




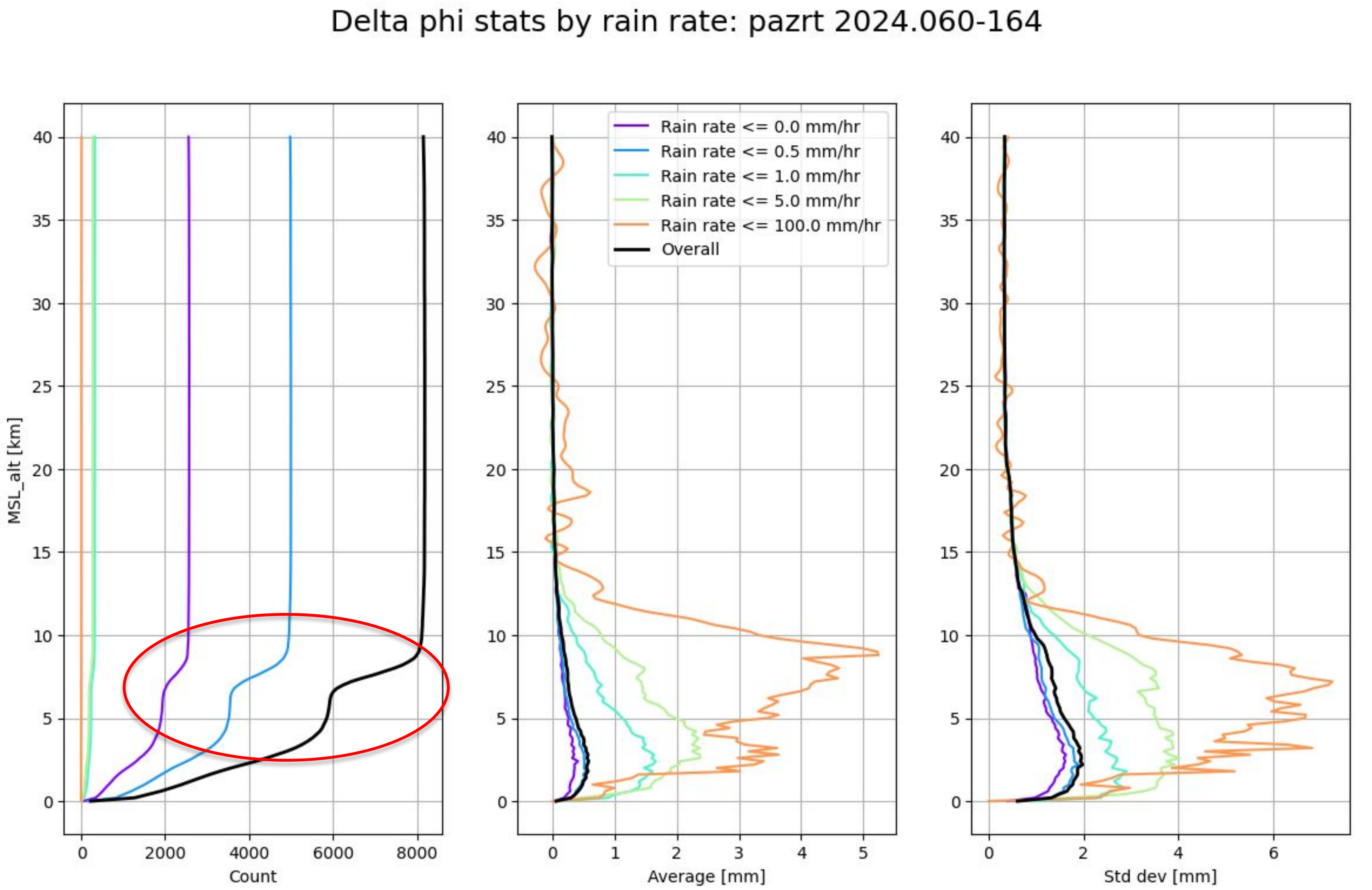
1. Bottom-most ray
2. Projection of bottom ray to surface (height <= 6km)
3. Surface plot of selected rays from bottom to top, all below 6km

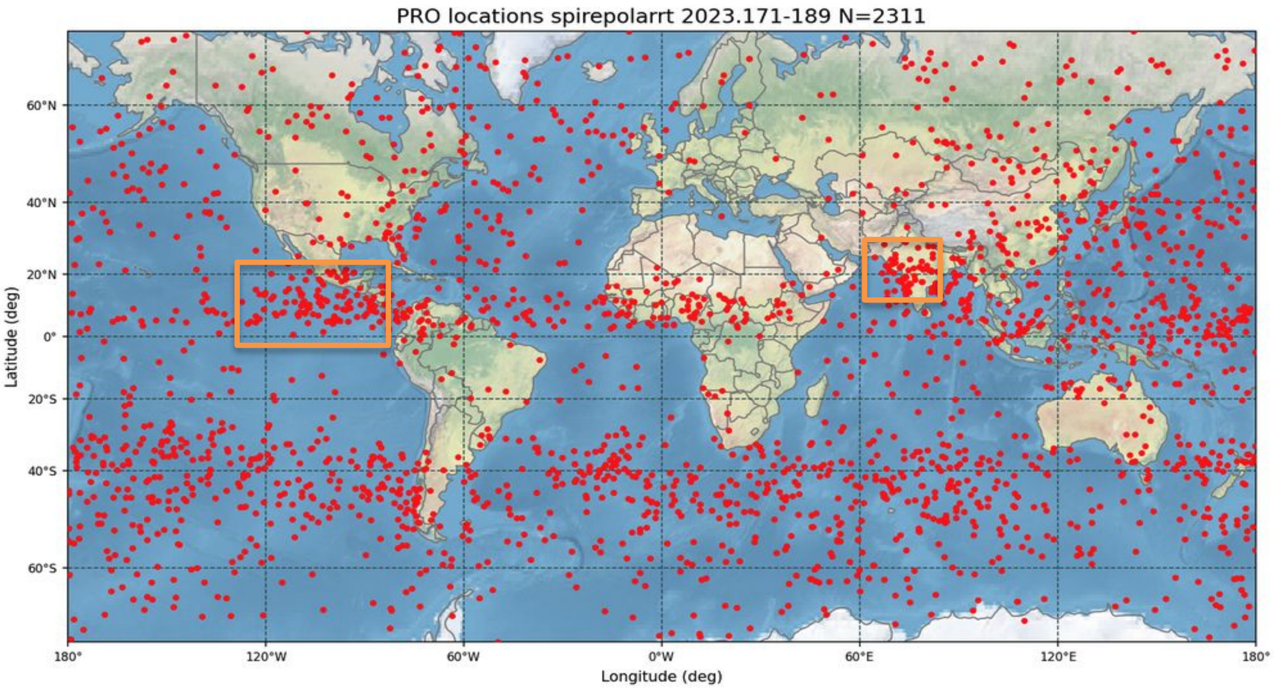
The ray path of the bottom level of an occultation, plotted on top of the IMERG rainfall dataset (1). In this case the ray path ground track (2) intersects an area of heavy rainfall. The average rain rate over all occultation ground tracks (the solid red lines in plot 3.) is used for comparison.

Statistics by IMERG rain rate, Spire

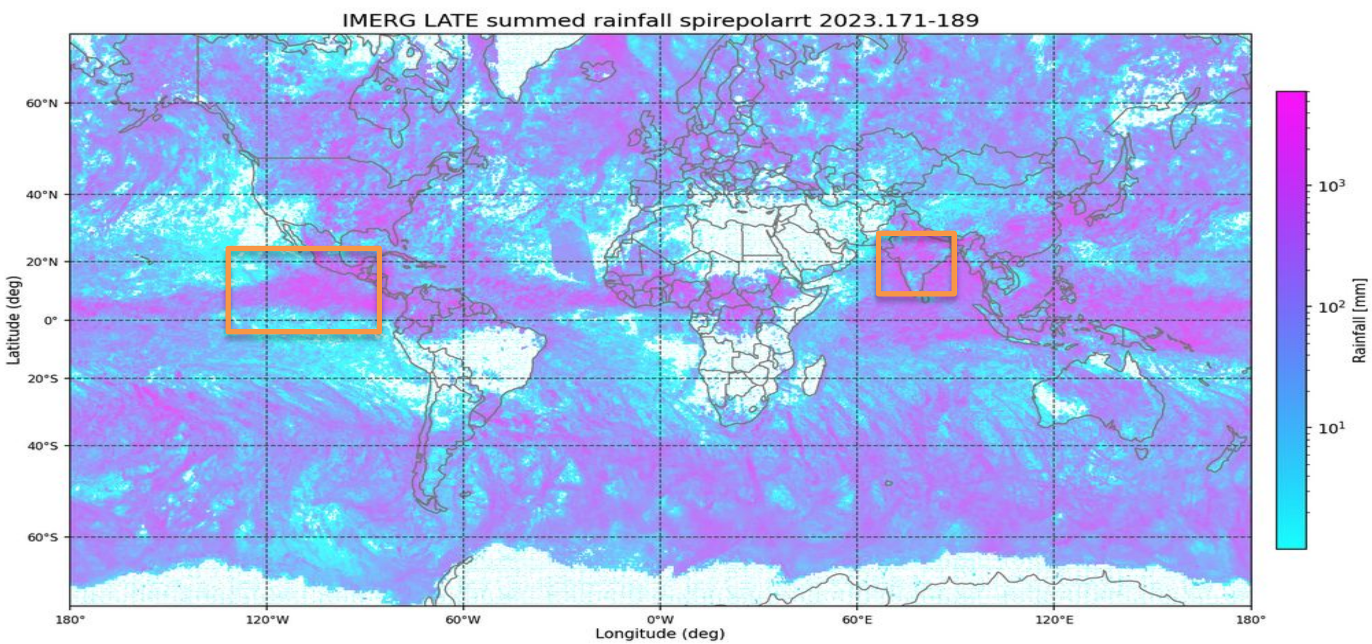


Statistics by IMERG rain rate, Paz





All Spire polarimetric occultations from two weeks in June/July 2023 which have a maximum delta phi > 4 mm which occur under 12 km MSL altitude and which have the sum of delta phi (< 12 km) greater then 700mm.



Spire FMs 166, 167, 170. All in sun synchronous polar orbits.

Note similarities with a total IMERG rainfall map for the same dates.

https://gpm1.gesdisc.eosdis.nasa.gov/data/GPM_L3/GPM_3IMERGHHL.06

Conclusion

- PAZ data processed at UCAR since May 2018
- Spire and Paz $\Delta\phi$ processing under construction starting in Nov. 2023. Much tuning and QC work done.
- Spire test PRO data set (2023.171-189) processed.
- Large Spire PRO data set (2023.067-2024.158) is being processed.
- An algorithm for computing the Mean Sea Level Height of a delta phi profile before the formal inversion takes place has been developed.
- Tools for computing RO ray path based on a spherically symmetric refractivity profile have been developed.
- Tools for comparing delta phi with IMERG rain rate data set based on RO ray path have been developed.
- UCAR plans studies using 2023-2024 Spire PRO data with ray paths to investigate:
  - Atmospheric rivers
  - Tropical cyclones
  - Weather model micro-physics

References

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