Comparing Methods to Retrieve Atmospheric Parameters from Airborne Radio Occultation

Kate Lord[1], Jennifer Haase[1], Bing Cao[1], Noah Barton[1], and Pawel Hordyniec[2]

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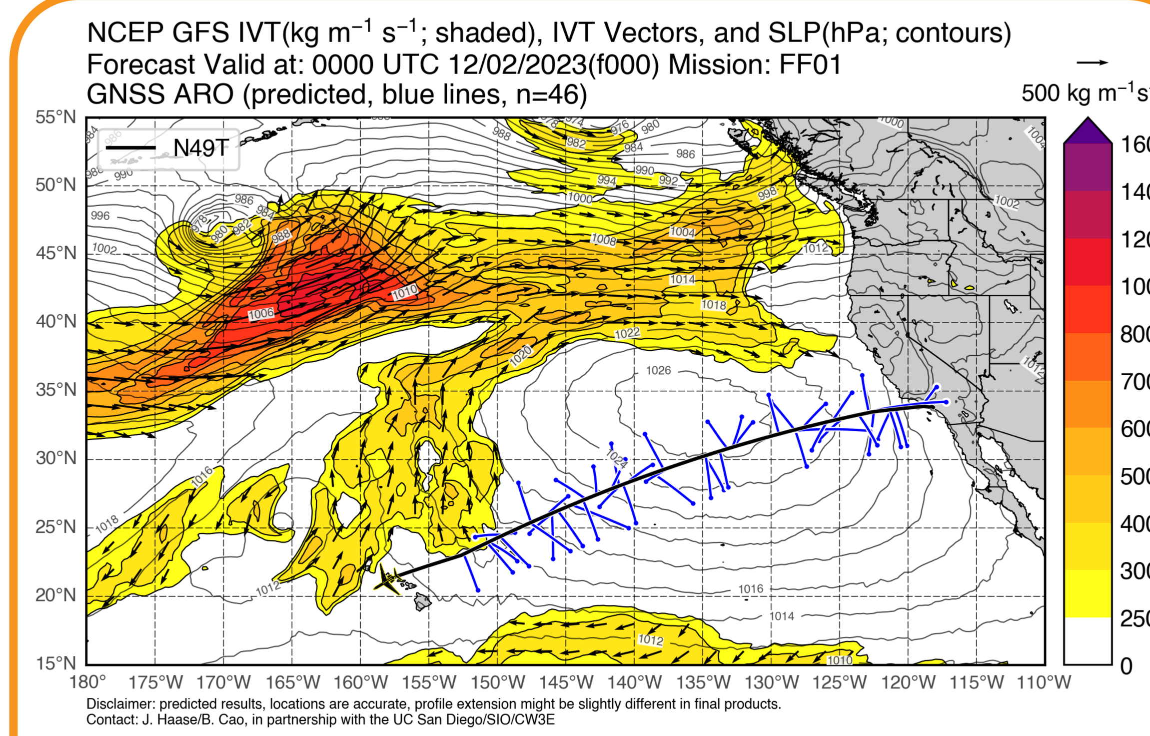
Objectives

- Study atmospheric rivers (ARs) using airborne radio occultation (ARO)
- Analyze two methods that calculate bending angle of the raypath from excess phase: Geometric Optics (GO) and Phase Matching (PM)
- Use a test case to compare GO and PM
- Long term: develop algorithm to determine which regions of the AR would benefit from PM (Wang 2017)

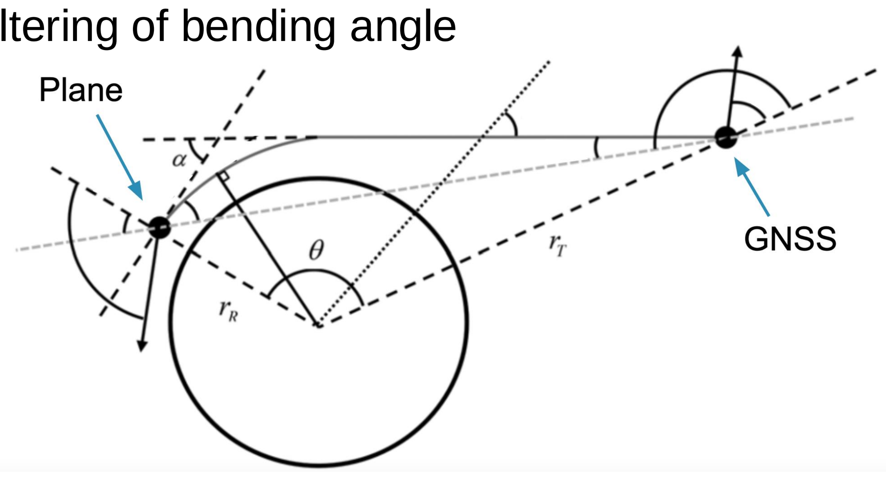


The test case, FF01, was recorded on Dec. 1, 2023.

Methods of Deriving Bending Angle

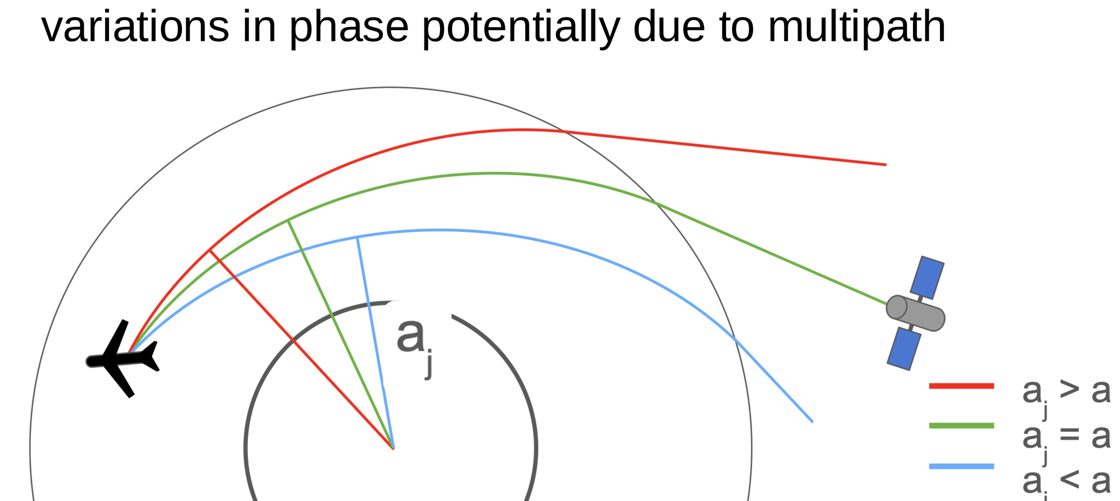
Geometric Optics

- Relationship between excess Doppler and the geometry of the raypath
- Solve for bending angle and impact parameter
- Only one value of excess Doppler for each time point
- Only one bending angle and one impact parameter at each time point
- Cannot be used when there is atmospheric multipath
- Algorithm was optimized to use heavy smoothing of the excess phase to reduce noise, and Savitzky-Golay filtering of bending angle



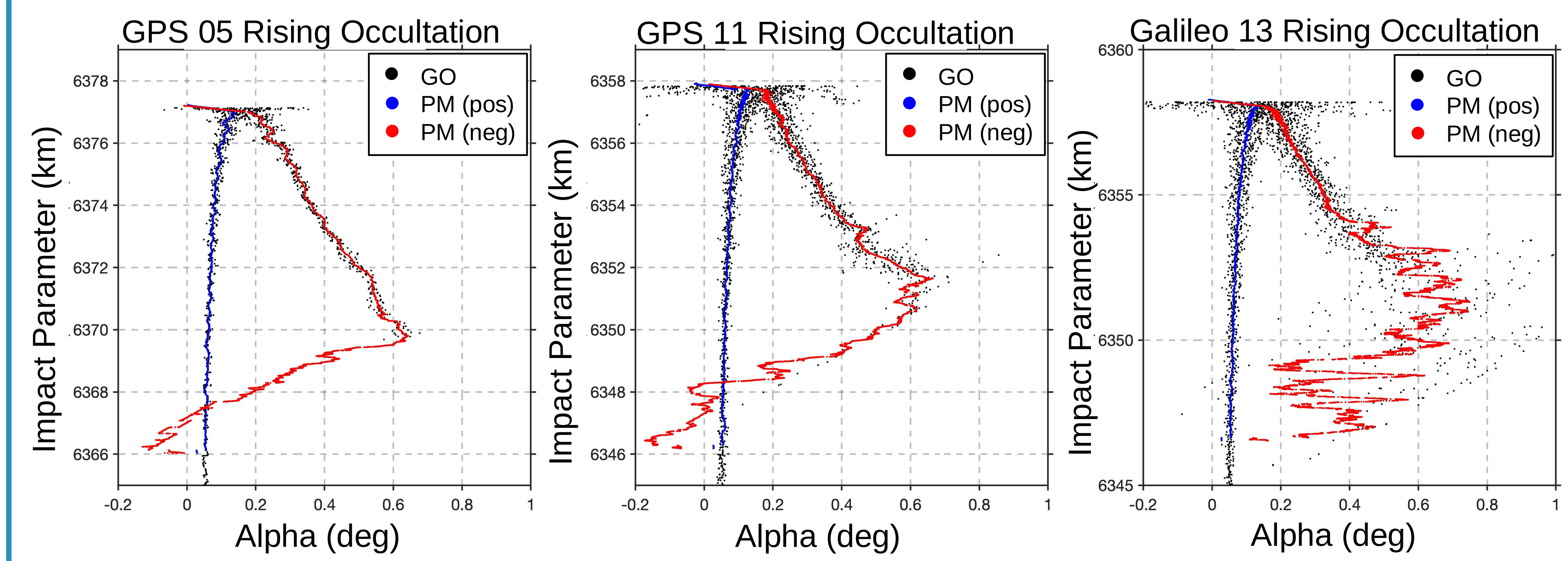
Phase Matching

- Replica signals are generated based on variety of potential impact parameters
- Replicas are compared to incoming signal
- Closest match is found via method of stationary phase
- Can handle multipathing because multiple impact parameters, $\mathbf{a}_j$, will return valid results
- Filtering is applied at the end to allow for large variations in phase potentially due to multipath



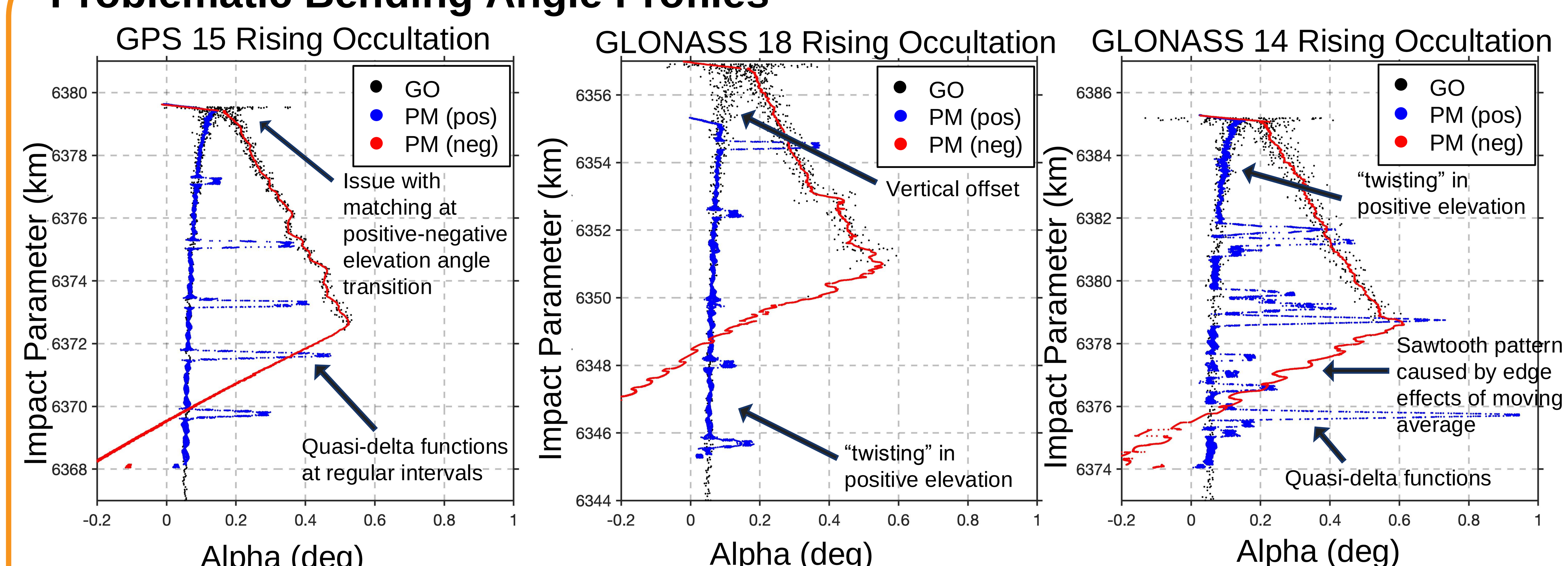
Investigation of Filtering and Artifacts

Bending Angle Profile Examples from GO and PM



Bending angle profiles from GO (black), PM positive elevation angle (blue), and PM negative elevation angle (red). Excess phase used in GO is unfiltered, and PM bending angle is filtered using a 4 second moving average. PM successfully retrieves monotonically varying impact parameter. Profiles show evidence of variation seen for increasing moisture in the profiles (Xie et al., 2018) and increasing penetration in well-mixed moisture profile (Murphy and Haase, 2022). Further investigation of the potential effect of the synoptic environment on the profile characteristics is ongoing.

Problematic Bending Angle Profiles



There are several types of artifacts present in many of the profiles generated from prototype code. They are currently under investigation. The moving average filter in PM likely exacerbates these artifacts.

Likely causes of artifacts:

- Edge effects from finite time series
- Cycle slips
- Mis-match in sampling/ interpolation issues

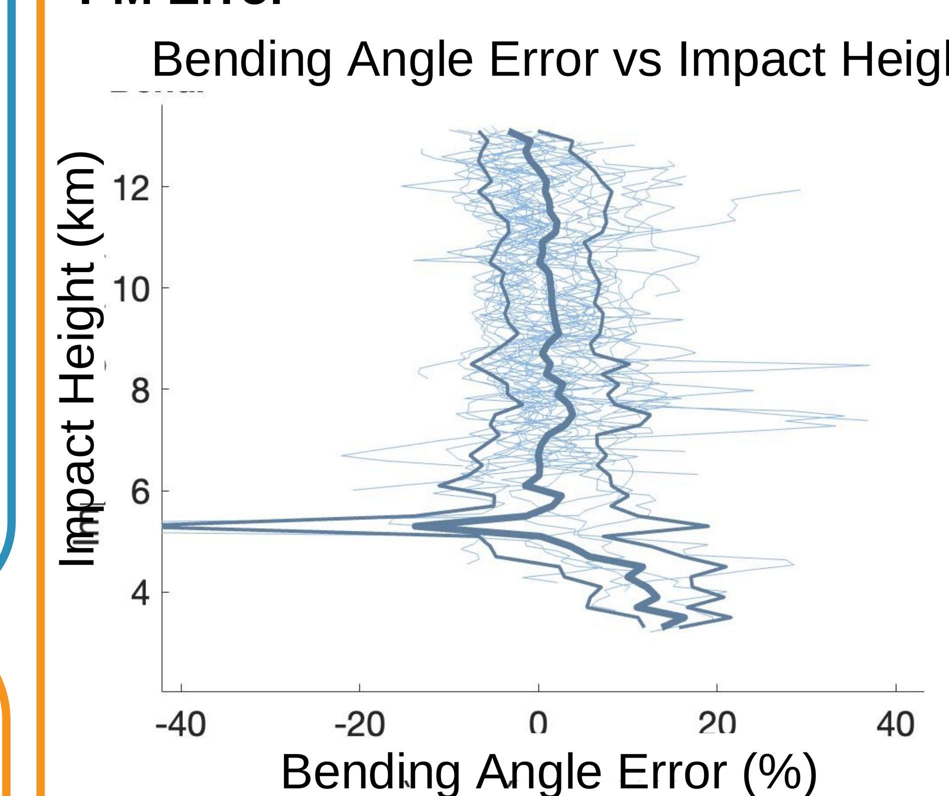
Statistical Comparison of PM and ERA5 simulations

Simulated bending angle

- Meteorological fields: ECMWF ERA5 reanalysis, 137 levels
- Raytracing: ROPP forward model is 2D, uses tangent point drifting

The ROPP forward model calculates the accumulated bending angle using a 2D slice of the ERA5 meteorological data along the raypath through the atmosphere.

PM Error



Preliminary comparison of PM retrievals with forward modeled bending angle. Standard deviation of observed minus simulated bending angle is less than 13% above 6 km. As measurements approach the surface, increasingly few penetrate the atmosphere. Limitations of closed loop tracking lead to the large standard deviation and potential bias around 6 km.

Inadequate sampling of subsignals by closed loop tracking likely contributes to large negative biases at lower limit of profile (Sokolovskiy 2010) and will be improved by OL Tracking. For now, measurements below the maximum bending angle have been ignored.

Conclusions

- Initial results comparing phase matching retrievals and simulated excess phase observations were consistent in bending angle with standard deviation <13% above 6 km.
- The phase matching method shows promise in providing a superior profiles from unfiltered excess phase observations.
- Further advantages are expected from postprocessed GNSS recordings using open loop tracking, which is able to continue recording in adverse multipathing conditions.
- A detailed investigation of the artifacts shows where the signal processing can potentially be improved. This may include designing a filter specifically for PM. Future recordings will also be higher sample rate, decreasing the need to interpolate excess phase before calculations.

Acknowledgements

AR Recon data collection and analysis supported by the **Atmospheric River Research Program** of the California Department of Water Resources. Additional support provided by NASA Award 80NSSC23K1307. We thank the CW3E AR Reconnaissance program for the flight opportunities and the NOAA Aircraft Operation Center and the Air Force for the operation of ARO equipment and the use of their aircraft. ROPP software is provided by the Radio Occultation Meteorology Satellite Application Facility (ROMSAF). ECMWF reanalysis-5 (ERA-5) products provided by the European Center for Medium-range Weather Forecasting.

References:

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Sokolovskiy, S., C. Rocken, W. Schreiner, and D. Hunt (2010), On the uncertainty of radio occultation inversions in the lower troposphere, *J. Geophys. Res.*, 115, D22111, doi:10.1029/2010JD014058.

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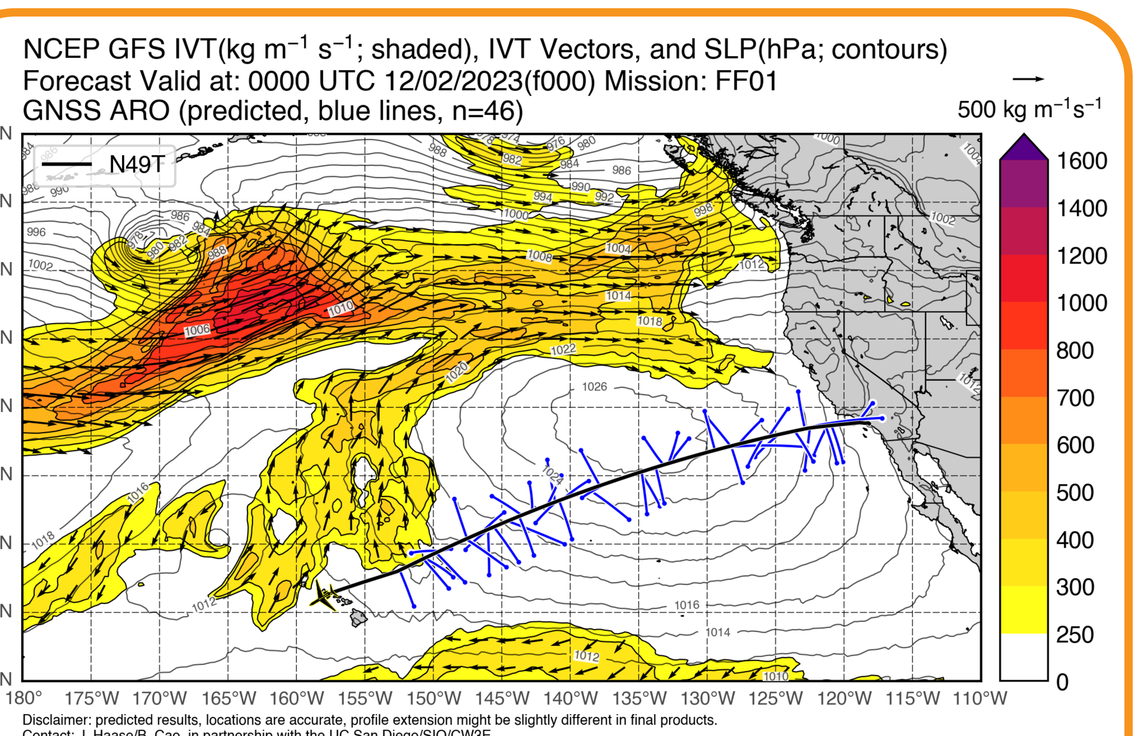

The test case, FF01, was recorded on Dec. 1, 2023.

Methods of Deriving Bending Angle

Geometric Optics

- Relationship between excess Doppler and the geometry of the raypath
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- Only one bending angle and one impact parameter at each time point
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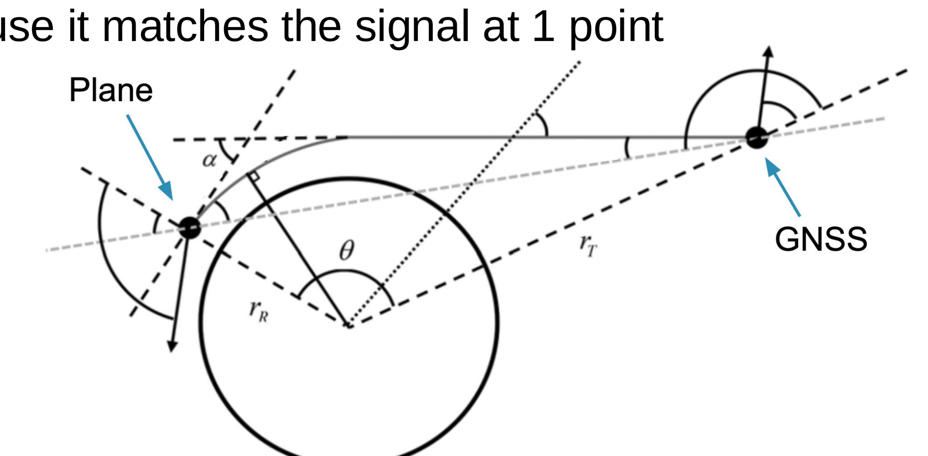
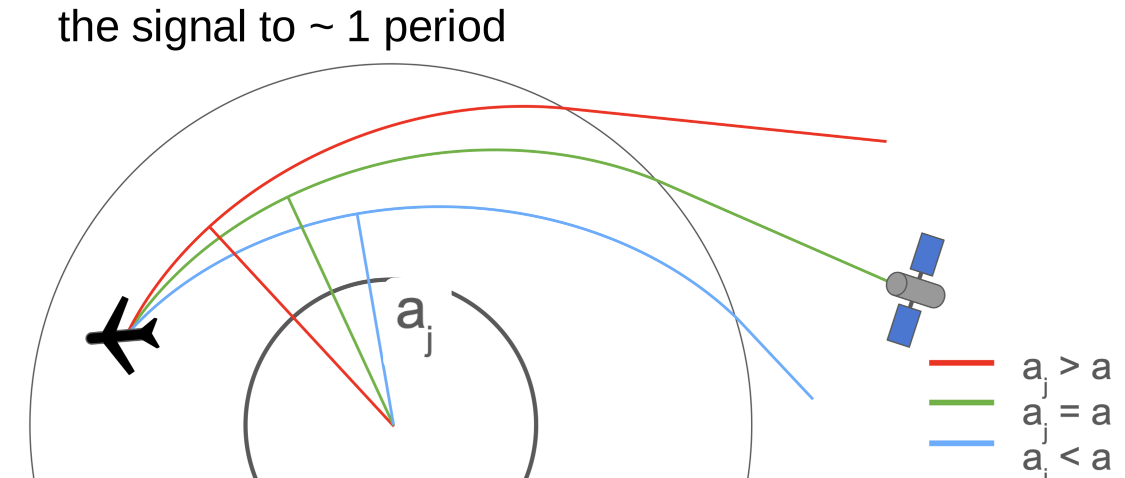
- Algorithm requires heavy smoothing of the phase because it matches the signal at 1 point



Phase Matching

- Replica signals are generated based on variety of potential impact parameters
- Replicas are compared to incoming signal
- Closest match is found via method of stationary phase
- Can handle multipathing because multiple impact parameters will return valid results
- Algorithm requires less filtering because it matches the signal to ~ 1 period



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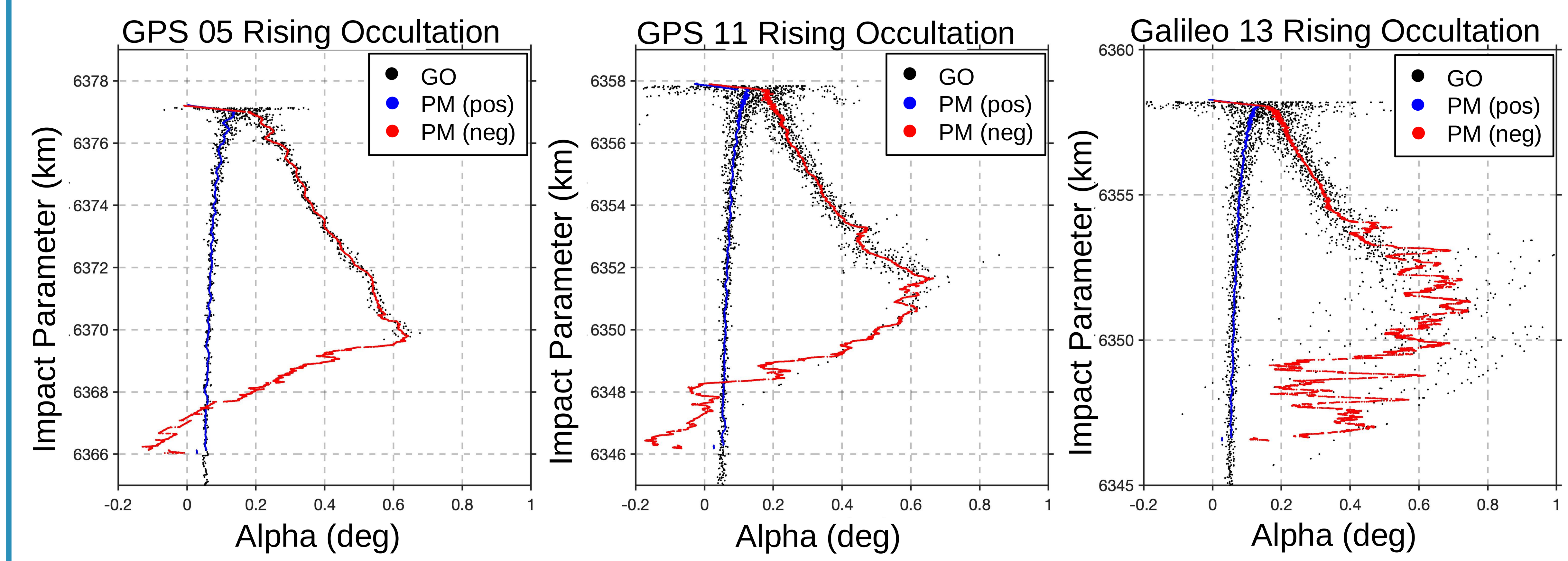
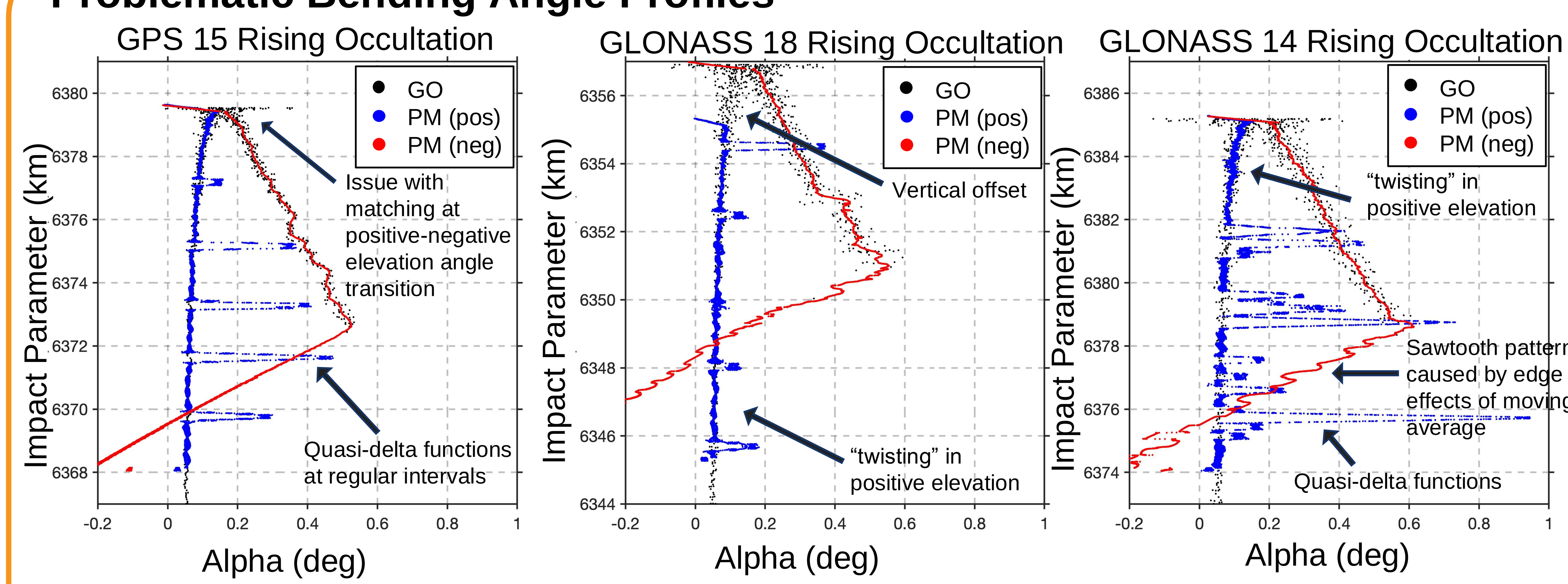


Bending angle profiles from GO (black), PM positive elevation angle (blue), and PM negative elevation angle (red). GO is unfiltered and PM is filtered using a 4 second moving average. PM successfully retrieves monotonically varying impact parameter. Profiles show evidence of variation seen for increasing moisture in the profiles (Xie et al., 2018) and increasing penetration in well-mixed moisture profile (Murphy and Haase, 2022). Further investigation of the potential effect of the synoptic environment on the profile characteristics is ongoing.

Problematic Bending Angle Profiles



There are several types of artifacts present in many of the profiles generated from prototype code. They are currently under investigation. Removing the moving average filter from PM will likely affect these artifacts.

Likely causes of artifacts:
- Edge effects from finite time series
- Cycle slips
- Mis-match in sampling/ interpolation issues

Conclusions

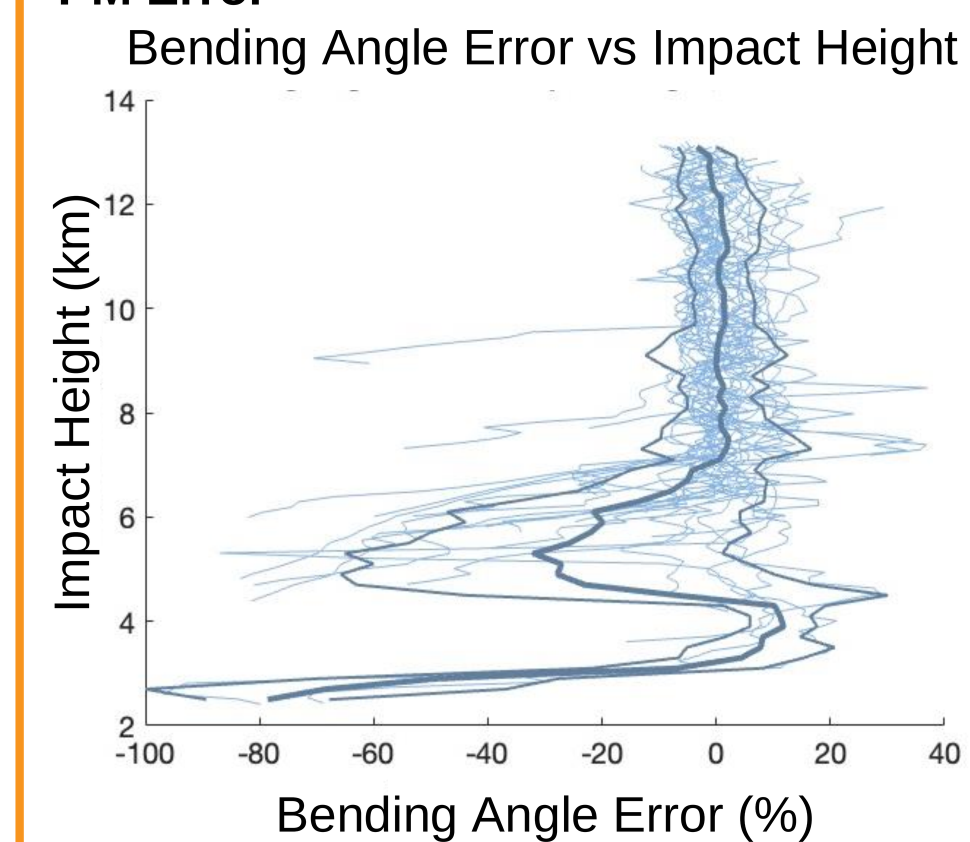
- Initial results comparing phase matching retrievals and simulated excess phase observations were consistent in bending angle with standard deviation of 16% above 7 km.
- The phase matching method shows great promise in providing a superior profiles from unfiltered excess phase observations.
- Further advantages are expected from postprocessed GNSS recordings using open loop tracking, which is able to continue recording in adverse multipathing conditions.
- A detailed investigation of the artifacts shows where the signal processing can potentially be improved.

Statistical Comparison of PM and ERA5 simulations

Simulated bending angle
- Background: ECMWF ERA5 reanalysis, 137 levels
- Model: ROPP forward model is 2D, uses tangent point drifting

The model simulates the bending angle by using the background meteorological data to project the raypath as it progresses through the atmosphere.

PM Error



Preliminary comparison of PM retrievals with forward modeled bending angle. Deviations from model simulations are less than 16% above 7 km. As measurements approach the surface, increasingly few penetrate the atmosphere. This leads to the large standard deviation and potential bias around 6 km.

Next Steps

The next step is to ameliorate the artifacts as much as possible. This may include designing a filter specifically for PM. Future recordings will also be higher frequency, decreasing the need to interpolate excess phase before calculations.

Acknowledgements

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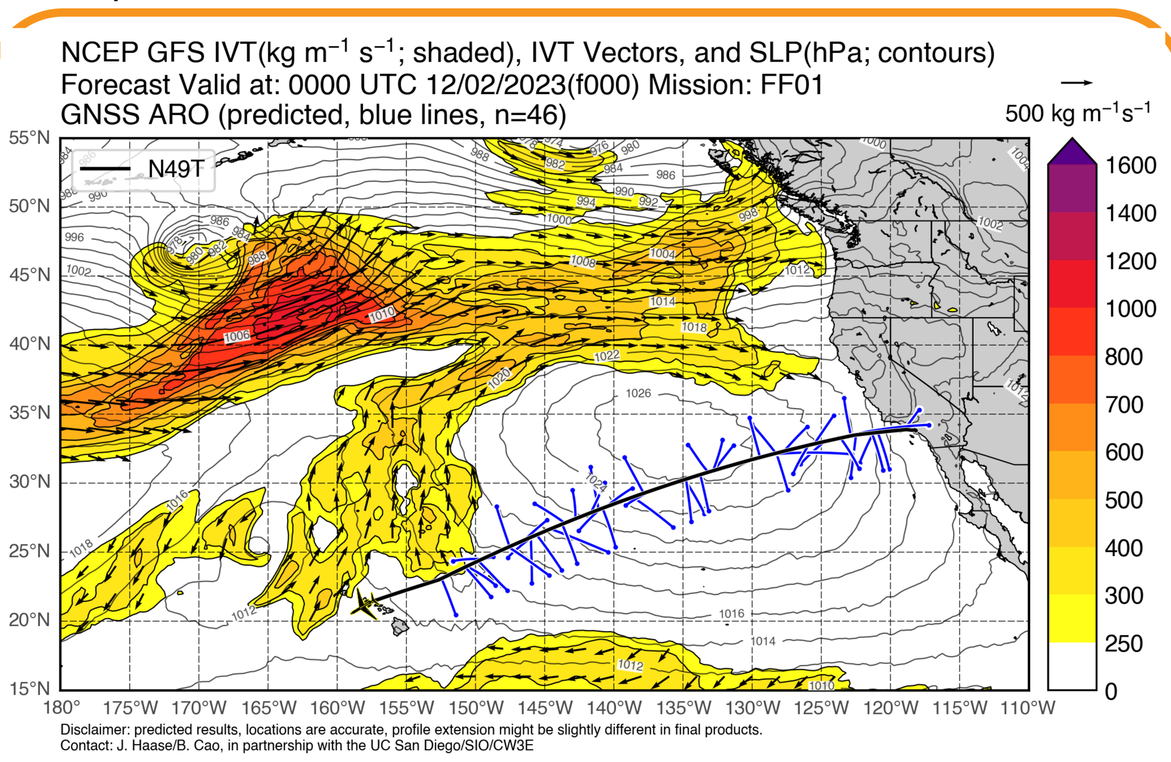
Atmospheric Rivers

Atmospheric Rivers (ARs) are composed of different regions in terms of water content, temperature, and other parameters. Sharp vertical gradients make some areas hard to penetrate using Airborne Radio Occultation (ARO). We use two methods to calculate the bending angle of the raypath from excess phase: Geometric Optics (GO) and Phase Matching (PM). With the eventual goal of developing an algorithm to determine which regions of the AR would benefit from PM, here we use a test case to compare the two methods.

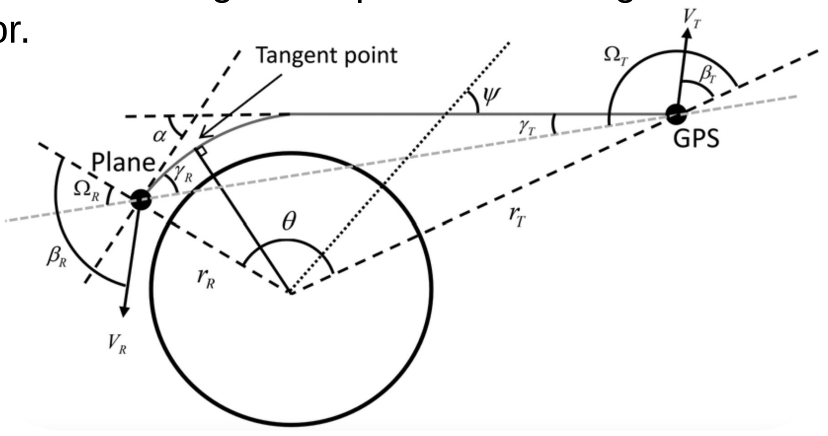


The test case, FF01, was recorded on Dec. 1, 2023. It made landfall Jan. 17, 2024 over Northern California and Oregon, and was rated a weak AR.

Methods

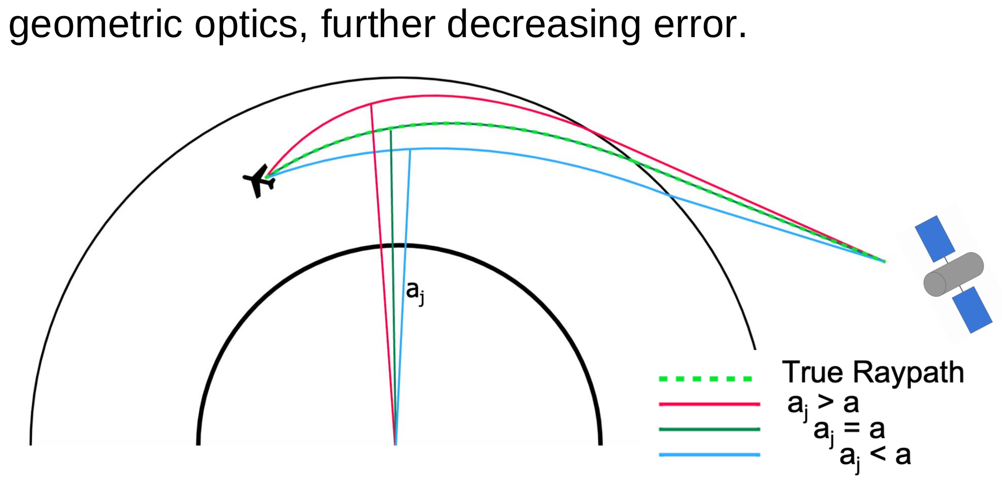
Geometric Optics

Excess Doppler can be calculated from excess phase. This can be substituted into an equation that relates the excess Doppler to parameters of the geometry of the raypath, including refractive bending angle.
We can then use these relationships to solve for bending angle and impact parameter. Under GO, there is only one value of excess Doppler for each time point, and there is only one bending angle and one impact parameter at each time point. Thus, GO cannot be used when there is atmospheric multipath. Also, the GO algorithm requires heavy upstream smoothing of the phase, resulting in additional error.



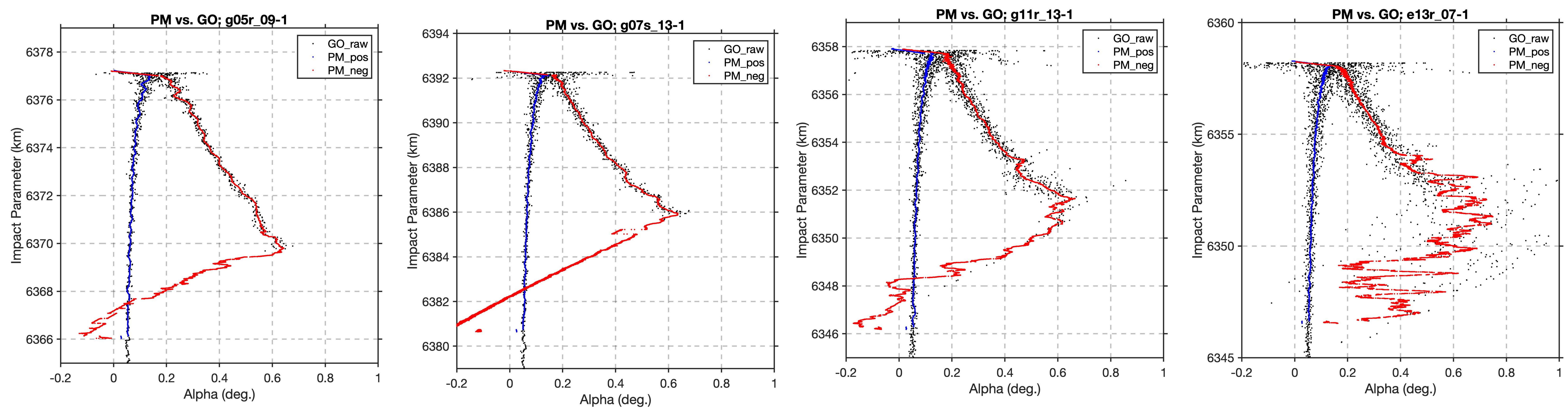
Phase Matching

The receiver measures the incoming signal. Different possible replica signals are generated from a variety of impact parameters. These are compared against the incoming signal, and the closest match is selected. In the case of multipath, multiple impact parameters will return valid results, so we can still derive refractivity and other variables from this data. The phase matching algorithm requires far less filtering than geometric optics, further decreasing error.



Comparing Geometric Optics and Phase Matching Methodologies

Bending Angle Profile Examples

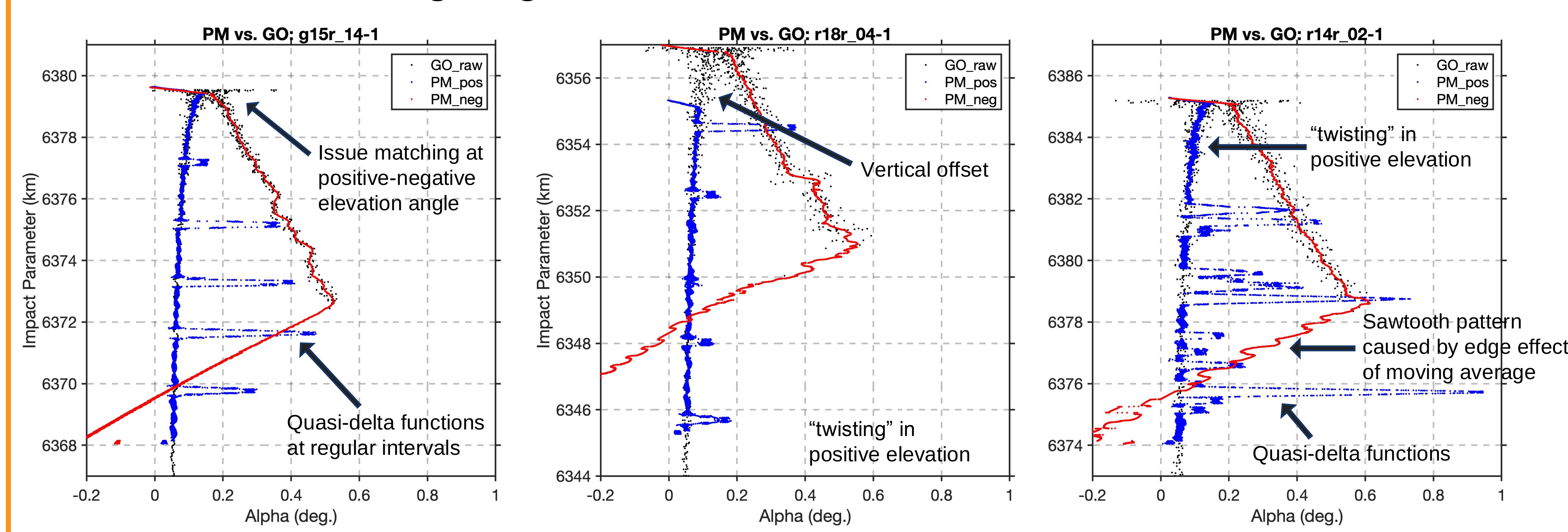


→ Increasing variability in individual GO observations →
→ Increasing penetration depth→

Much noisier retrievals from GO.

- PM successfully retrieves monotonically varying impact parameter.
- Profiles show evidence of variation seen for increasing moisture in the profiles (Xie et al., 2018) and increasing penetration in well-mixed moisture profile (Murphy and Haase, 2022)
- Further investigation of the potential effect of the synoptic environment on the profile characteristics is ongoing.

Problematic Bending Angle Profiles



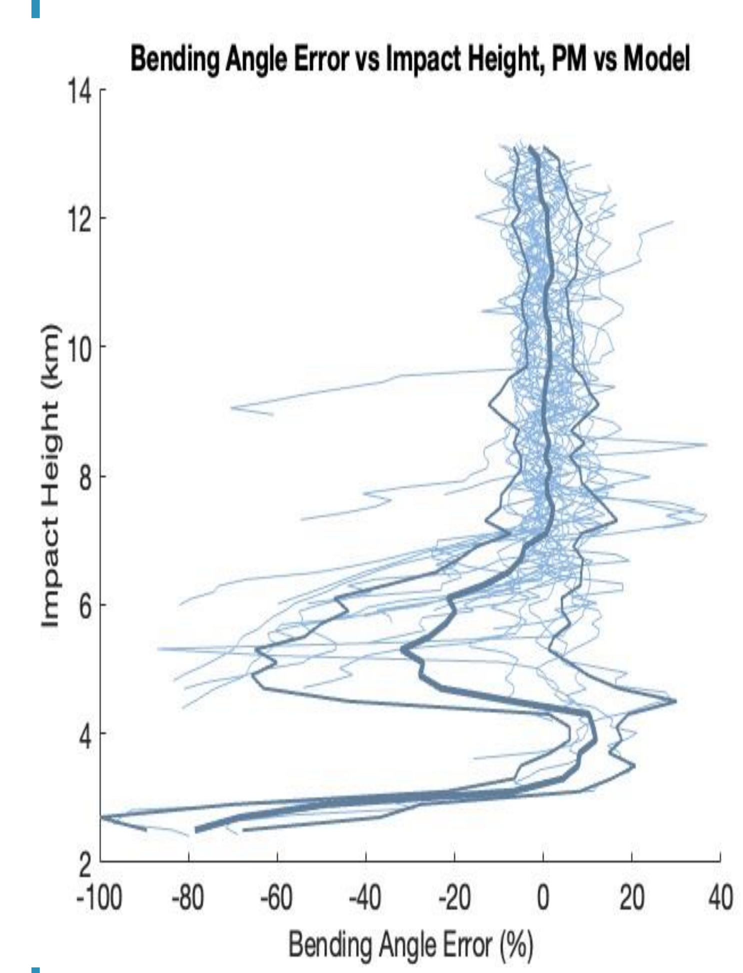
Many types of artifacts are present in some profiles when using the prototype code, most likely linked to edge effects from the finite time series, cycle slips or mis-match in sampling. These are currently under investigation.

Conclusions

- Initial results comparing phase matching and geometric optics retrievals on filtered excess phase observations showed the methods were consistent in bending angle with standard deviation of 16%.
- The phase matching method shows great promise in providing a superior profiles from unfiltered excess phase observations.
- Improvements are evident in the observations from the conventional geodetic receivers. Even further advantages are expected from postprocessed GNSS recordings using open loop tracking.
- A detailed investigation of the artifacts shows where the signal processing can potentially be improved.

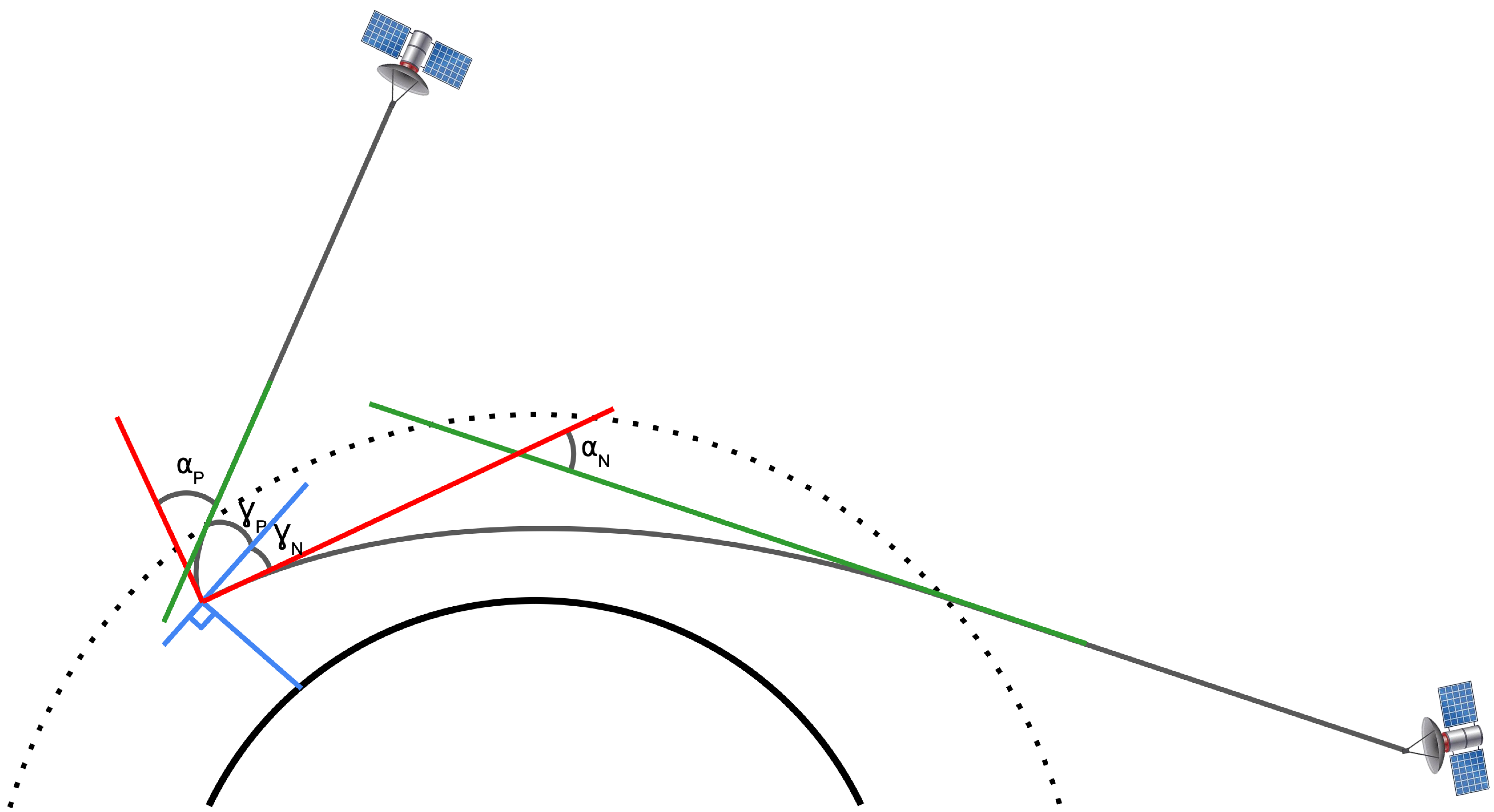
References:
Xie, F., Adhikari, L., Haase, J. S., Murphy, B., Wang, K. N., & Garrison, J. L. (2018). Sensitivity of airborne radio occultation to tropospheric properties over ocean and land. *Atmospheric Measurement Techniques*, *11*(2), 763-780.
Haase and Murphy 2022
Others

Statistical Comparison of PM and ERA5 simulations

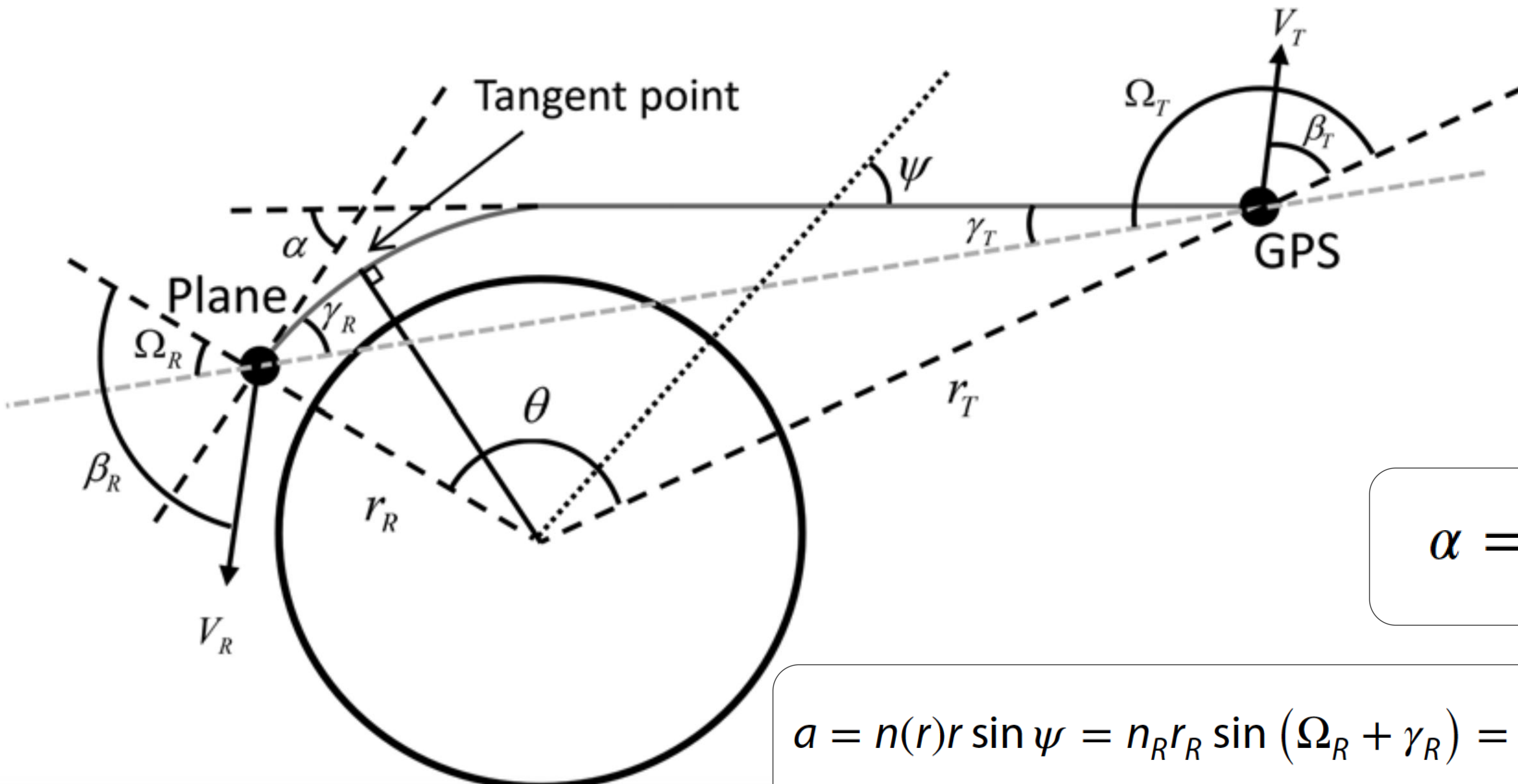


Preliminary statistical comparison of G retrievals where excess phase was filtered with 5 second span Savitzky-Goloy filter and bending angle smoothed with 31 point moving avera (30 sec). Phase matching retrievals used excess phase filtered with 5 second span Savitzky-Goloy filter an moving average filter of XX seconds. (incude the one example from the fer flight here)

Preliminary comparison of PM retrieva with forward modeled bending angle from ROPP operator (also the figure from Ferry) in the ERA5 model.



αP
γP
γN
αN



$$\alpha = \gamma_T + \gamma_R$$

$$a = n(r) r \sin\psi = n_R r_R \sin\left(\Omega_R + \gamma_R\right) = n_T r_T \sin\left(\Omega_T - \gamma_T\right)$$

Bending angle and impact parameter can be calculated from the Excess Doppler equation