PlanetiQ Level-2 RO Data Processing System

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Outline

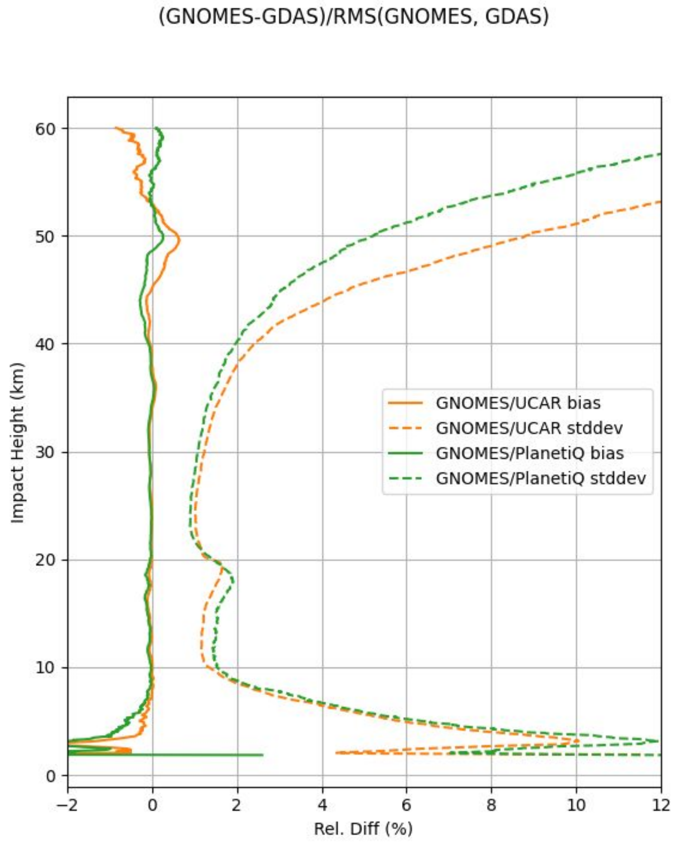
- Performance Highlights

Life of a single profile

- Data Preparation
- Geometric Optics Processing
- Wave Optics Processing with Sliding-Window Phase Matching
- Application of Wave Optics to Polarimetric-RO

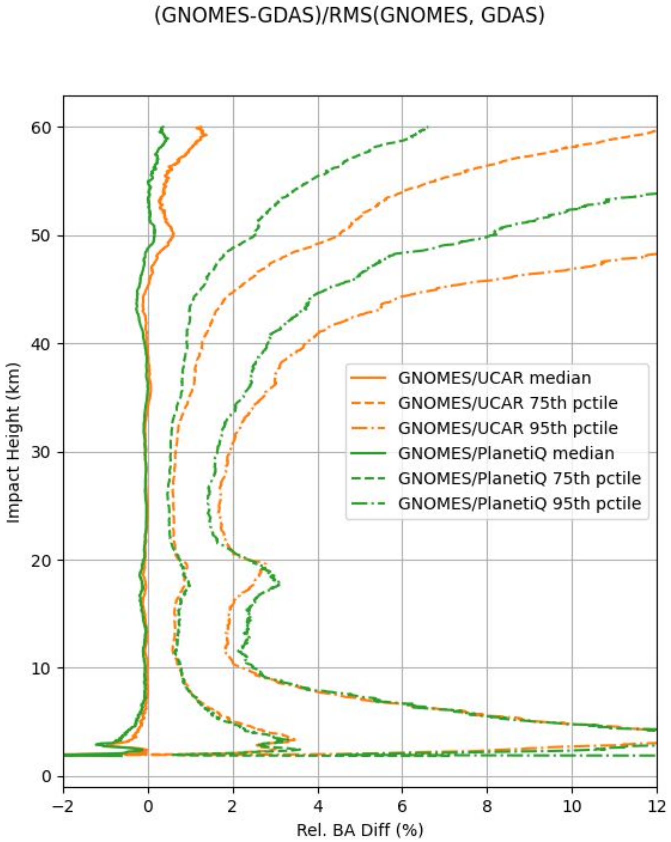
Geometric Optics: Performance Highlights

- Tighter bias and ~½ stddev in upper stratosphere
  - PlanetiQ using slightly *finer* vertical resolution > 40km
  - Using broadcast orbits & clocks for Tx
  - Using onboard nav solution for Rx
  - Without any climatological model at all
- Slightly higher BA variation in WO region due to finer vertical resolution
  - PiQ: 100m > 8km; 50m < 8km
  - UCAR: 500m - 250m - 100m
- Small mean bias < 8 km under investigation



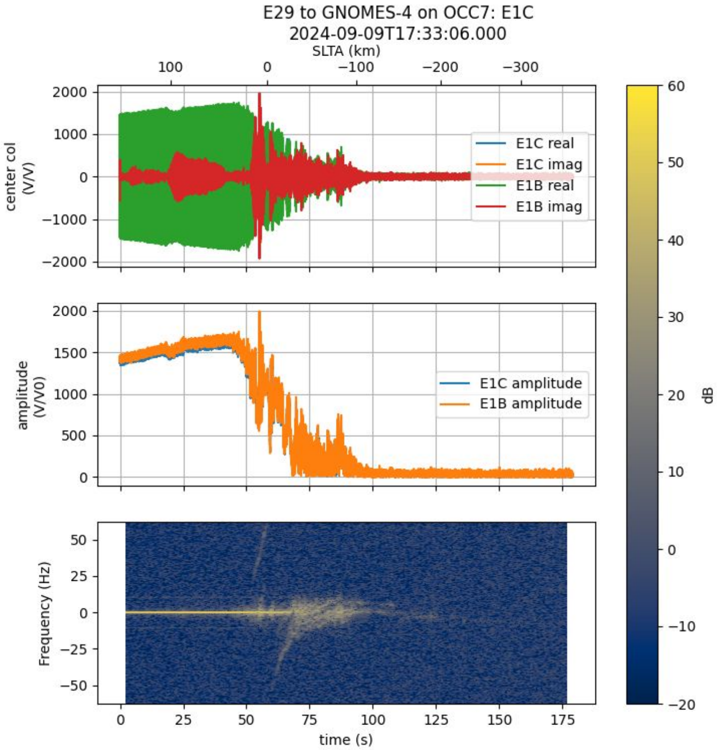
Geometric Optics: Performance Highlights

- Non-Gaussian statistics show similar picture
- Tighter median and ~½ noise in upper stratosphere
- Trading places in WO region for 95th percentile
- 25th percentile and 95th percentile very similar < 10 km



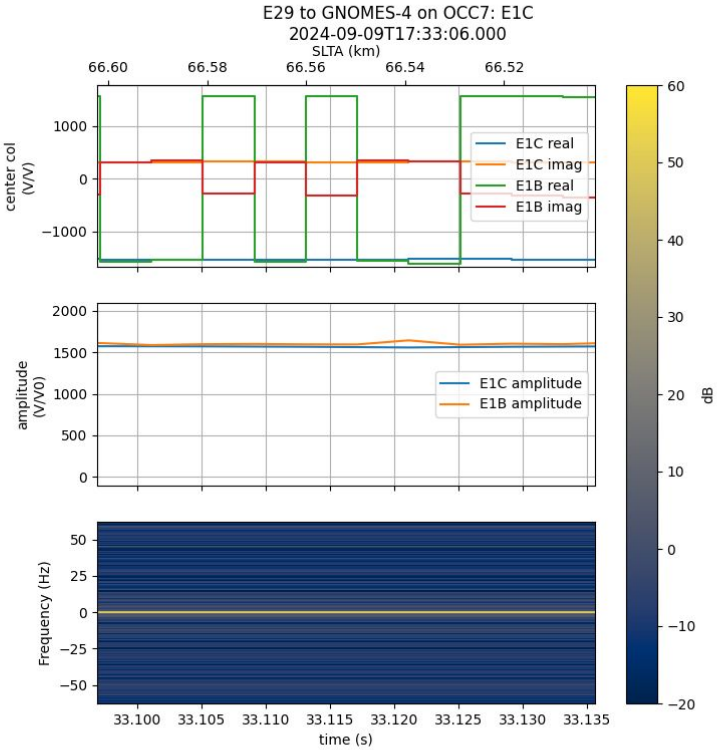
Geometric Optics: Initial Conditions

- I&Q Complex, 125 Hz Pilot Chn
- I&Q Complex 250 Hz
  Nav-modulated subchannel where applicable
- Time-matched carrier phase model for each
- Represent signal as unevaluated sum of phase-continuous reference frame and complex wave field in that frame
- Peak SNR ~1600 V/V (each) in this case



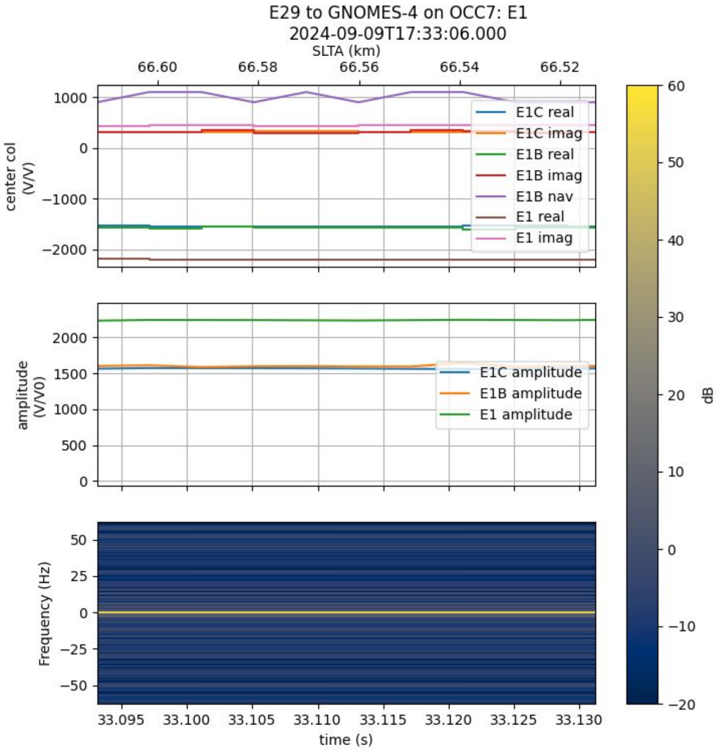
Geometric Optics: SNR Optimization

- Zoom on previous to highlight nav modulation & timestamp relationships
- Timestamps & carrier phase model correspond to leading edge of each correlation interval
- Trivializes pilot+data combination in receiver’s reference frame



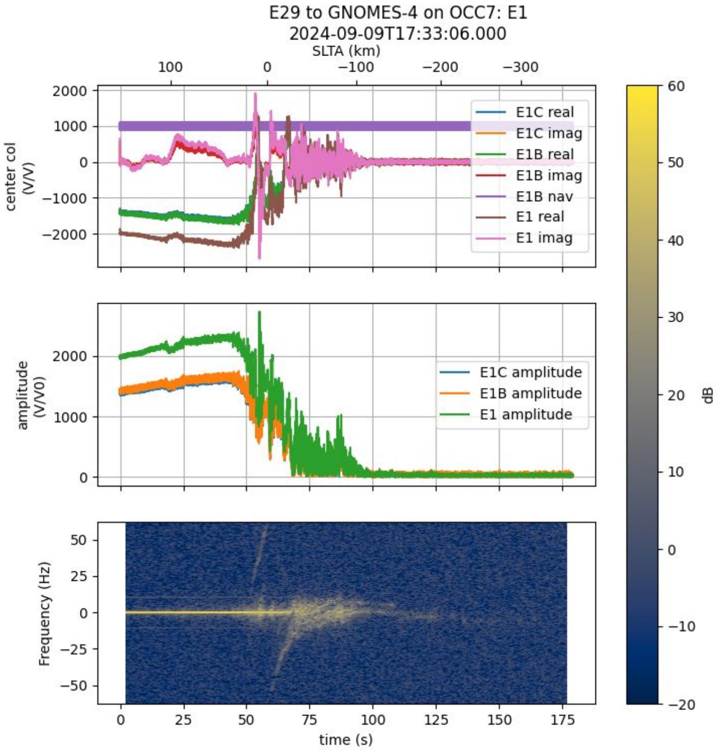
Geometric Optics: SNR Optimization

- Zoom on previous to highlight nav modulation & timestamp relationships
- Timestamps & carrier phase model correspond to leading edge of each correlation interval
- Trivializes pilot+data combination in receiver’s reference frame
- Boost’s signal strength by sqrt(2) / ~41%



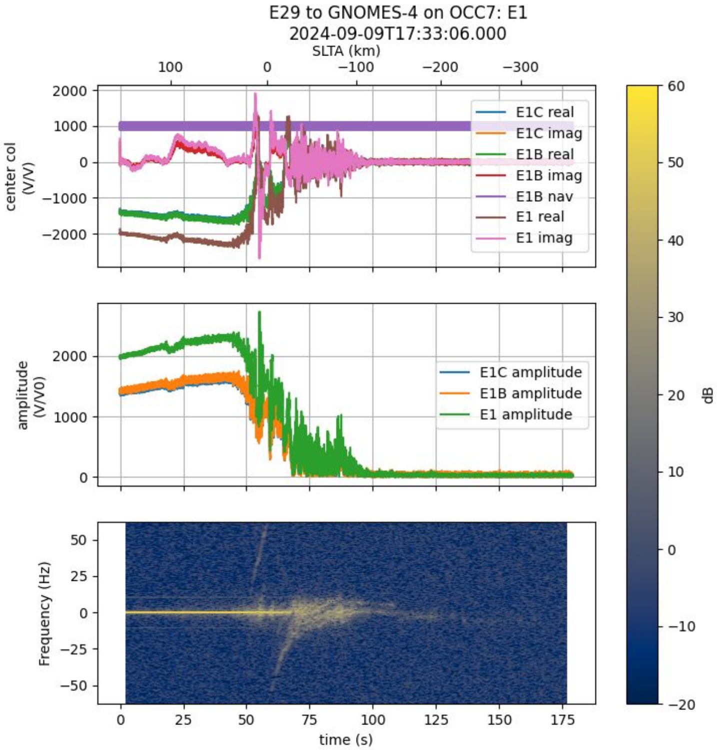
Geometric Optics: SNR Optimization

- Zoom on previous to highlight nav modulation & timestamp relationships
- Timestamps & carrier phase model correspond to leading edge of each correlation interval
- Trivializes pilot+data combination in receiver's reference frame
- Boost's signal strength by up to sqrt(2) / 41%
    - ~2300 V/V-sqrt(Hz) in this case!



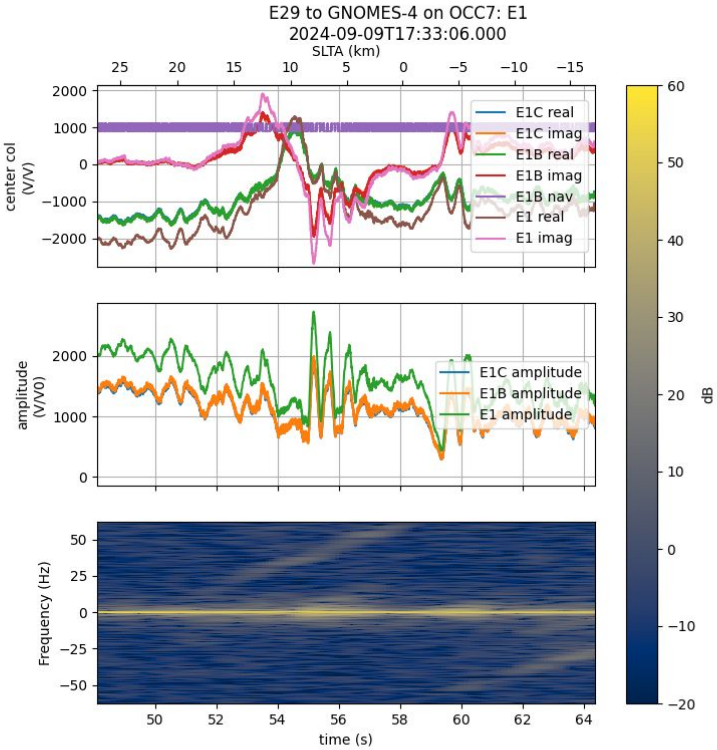
Geometric Optics: Phase Estimation

- Rx model is good but not perfect
  - <<< 1 turn of error from +150km to +15 km



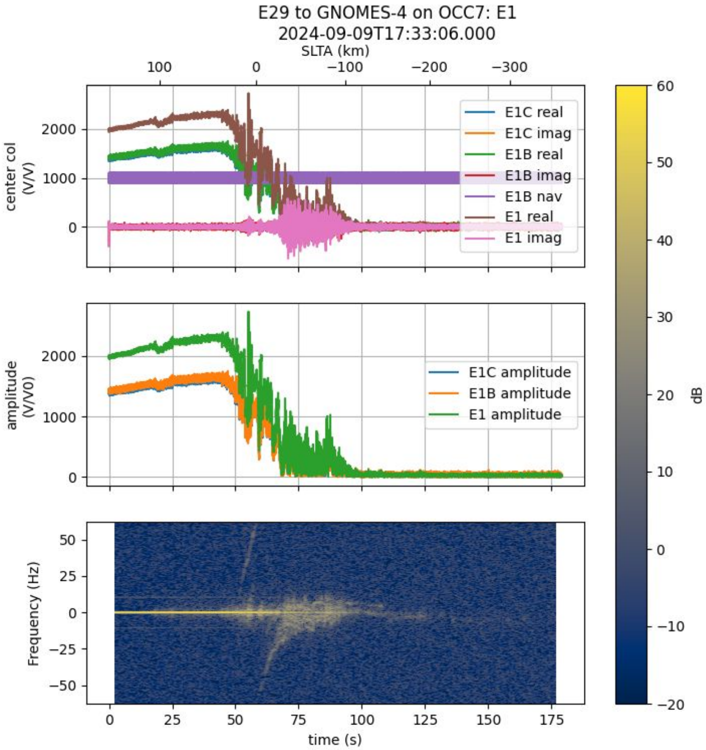
Geometric Optics: Phase Estimation

- Rx model is good but not perfect
  - <<< 1 turn of error from +150km to +15 km
- Example: un-modeled disturbance near tropopause



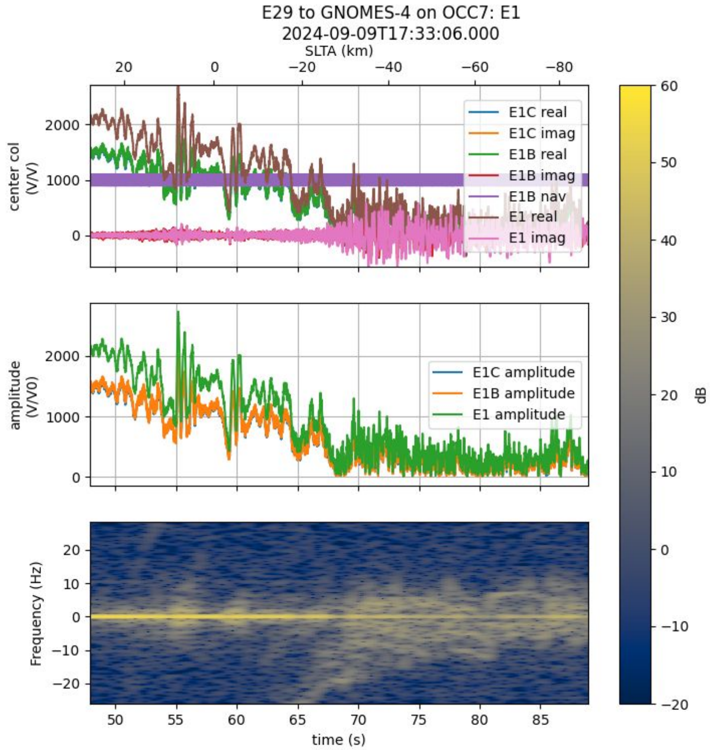
Geometric Optics: Phase Estimation

- Answer: Closed-Loop Tracking!
- Type-II PLL implemented with Rauch-Tung-Striebel algorithm
- Extended Kalman Filter forward pass, followed by a fix-up "smoothing" filter reverse-time pass
- Carries information backwards across fade periods

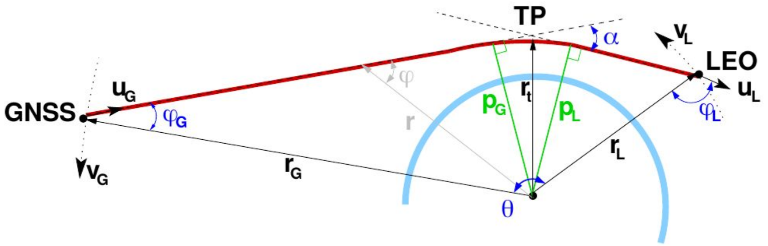


Geometric Optics: Phase Estimation

- Answer: Type-II PLL implemented with Rouch-Tung-Striebel algorithm
- Extended Kalman Filter forward pass, followed by a fix-up “smoothing” filter reverse-time pass
- Carries information bidirectionally across fade periods
- Implemented by adding to both carrier phase model and complex residue
  - -> Still unevaluated sum of ref frame + complex residual



Geometric Optics: Fundamental Equations



Similar to ROPP's choices, except in treatment of doppler and time

Exactly correct when solving within a common coordinate time (GPS system time) and inertial coordinate system (ECIF at occultation's epoch)

$$
\begin{aligned}
d &= \mathbf{v}_{Tx}^T \mathbf{u}_{Tx} - \mathbf{v}_{Rx}^T \mathbf{u}_{Rx} \\
1 &= \mathbf{u}_{Tx}^T \mathbf{u}_{Tx} \\
1 &= \mathbf{u}_{Rx}^T \mathbf{u}_{Rx} \\
0 &= \mathbf{r}_{Rx} \times \mathbf{u}_{Rx} - \mathbf{r}_{Tx} \times \mathbf{u}_{Tx} \\
\phi_{Rx} &= \measuredangle(\mathbf{u}_{Rx}, \mathbf{r}_{Rx}) \\
\phi_{Tx} &= \measuredangle(\mathbf{u}_{Tx}, \mathbf{r}_{Tx}) \\
\alpha &= \phi_{Rx} + \phi_{Tx} + \theta - \pi \\
a &= \|\mathbf{r}_{Tx}\| \, sin\, \phi_{Tx} = \|\mathbf{r}_{Rx}\| \, sin\, \phi_{Rx}
\end{aligned}
$$

Geometric Optics: Ionosphere Correction

Other researchers:

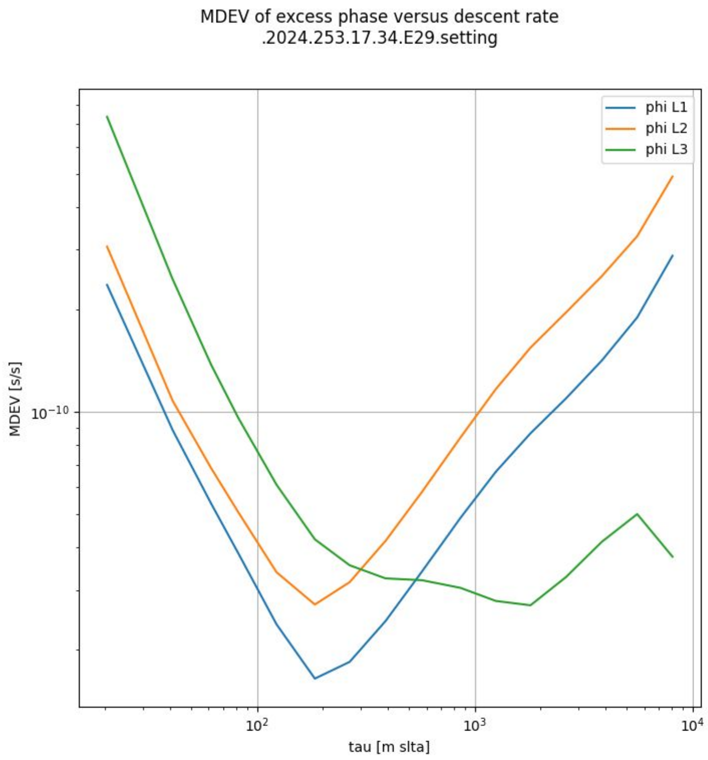
- L3 = L1 + k*filter(L1 - L2)

Reasonable choice… when L2 is noisy

Time domain view shows for high-SNR L2 signals (like GNOMES!) ionosphere-free phase strictly better than either L1 or L2 even for much finer resolution than Fresnel scale

Recall: limiting resolution ~first fresnel zone (~1.3 km)

-> no filtering required

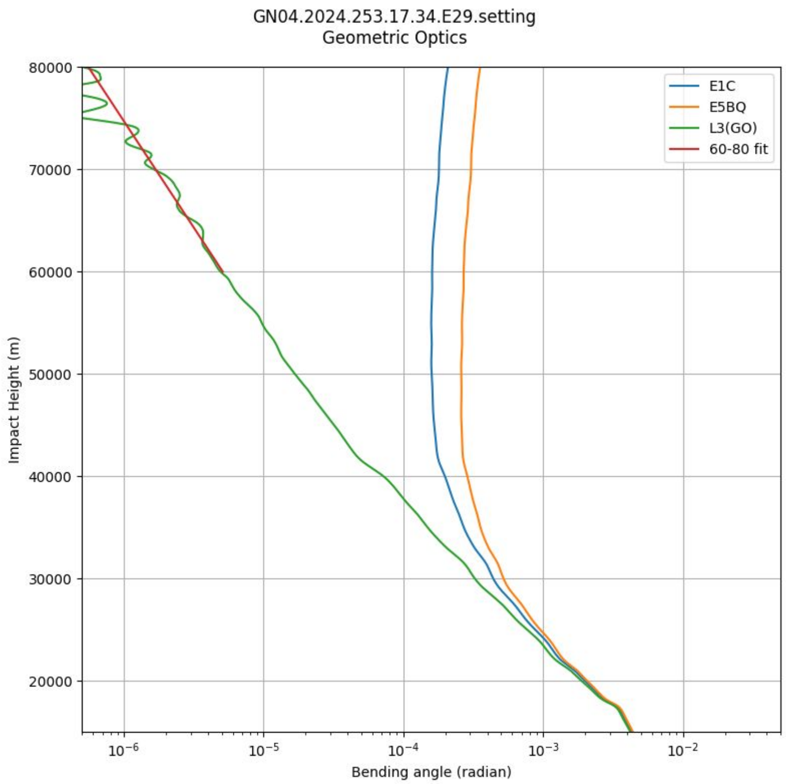


Geometric Optics: Ionosphere Correction

Result: Extremely clear profiles, even well above 60km

stdv_60_80 metric is evaluated with respect to an exponential fit

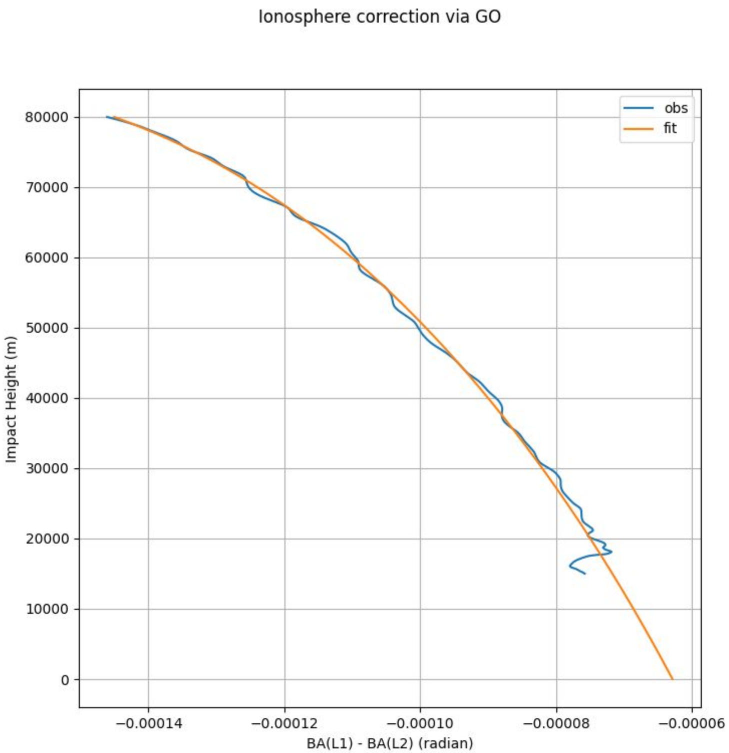
2e-7 radians!



Geometric Optics: Ionosphere Extrapolation

For us, entire GO exercise exists primarily to provide an extrapolation for wave optics processing

Extrapolation method similar to 2016 Z. Zeng @ UCAR



Wave Optics: Fundamental Equations

Similar to Sievert's Sliding-Window Phase Matching

Differences:

- Use full phase-matching chirp signal model Φ_{PM} instead of BA-local approximation
- Maintain signal model u as phase-continuous reference frame Φ_R and complex wave field ũ in that frame
- Use PM chirp-like model to transform wave field instead of the geometric-optics global excess phase estimate

Low-pass filter the transformed complex wave field to identify bending at each impact height

$$u(t) = exp\left(i\phi_R(t)\right)\tilde{u}(t)$$

$$\alpha(t, a_x) = \theta(t) + sin^{-1}\left(\frac{a_x}{r_{Rx}(t)}\right) + sin^{-1}\left(\frac{a_x}{r_{Tx}(t)}\right)$$

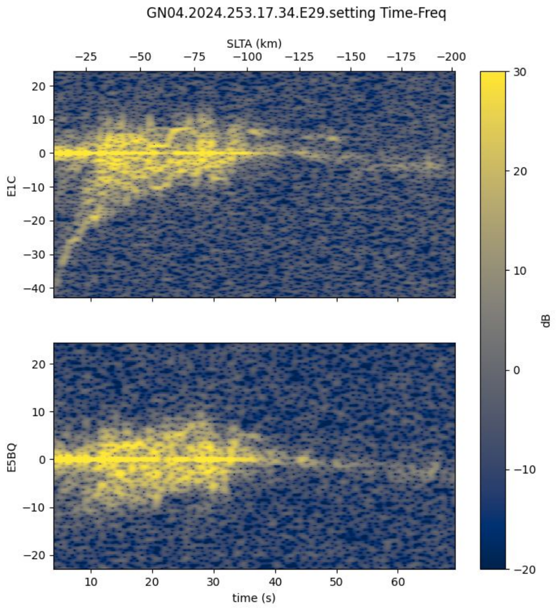
$$\phi_{PM}(t, a_x) = k\left(\sqrt{\|\mathbf{r}_{Rx}\|^2 - a_x^2} + \sqrt{\|\mathbf{r}_{Tx}\|^2 - a_x^2} + \alpha(t, a_x)a_x\right)$$

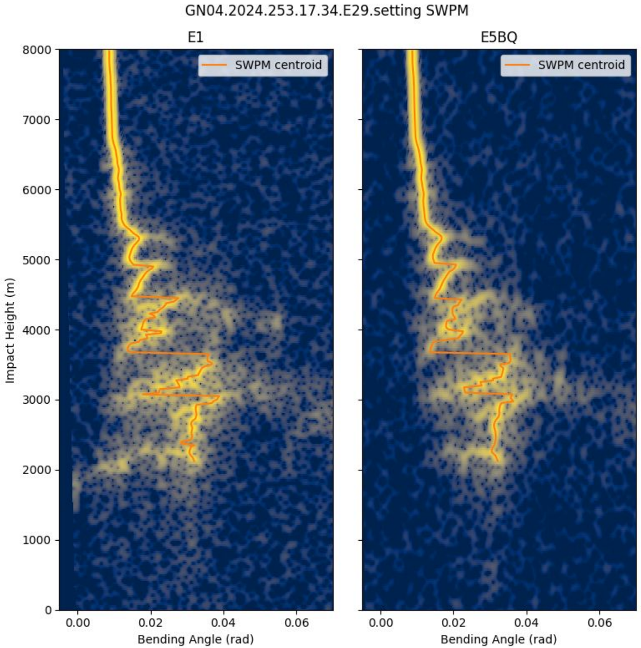
$$u_{PM}(t) = exp\left(i(\phi_R(t) - \phi_{PM}(t, a_x))\right)\tilde{u}(t)$$

$$u, \tilde{u}, u_{PM} \in \mathbb{C}$$

Wave Optics: Atmospheric Multipath

Atmospheric multipath-munged mud → Clear Picture





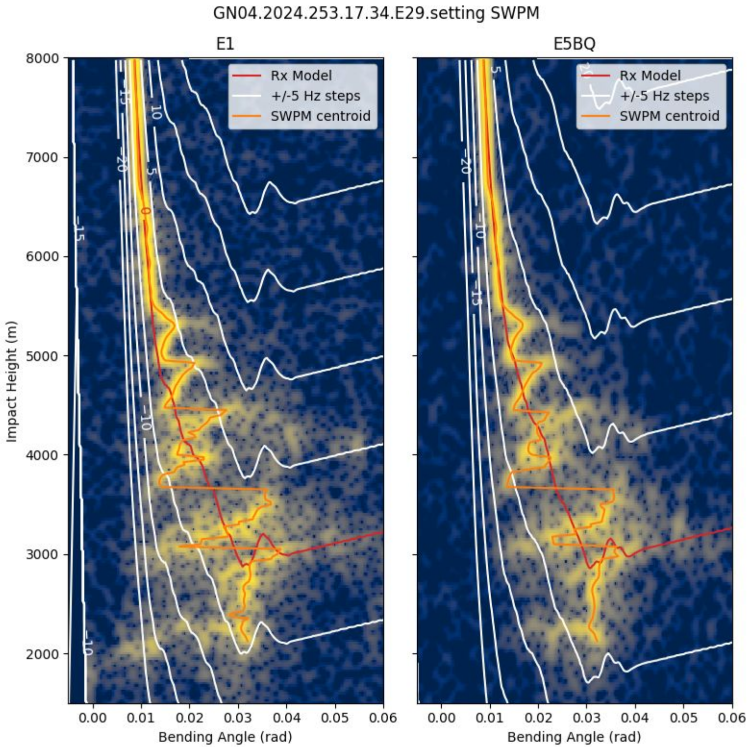
SWPM: New Capabilities

Insensitive to choice of receiver's reference frame

Researchers have previously reported inability to reliably recover sharp BA(IH) due to open-loop model tracking errors.

SWPM: can recover sharp BA(IH) transients without dependency on phase model.

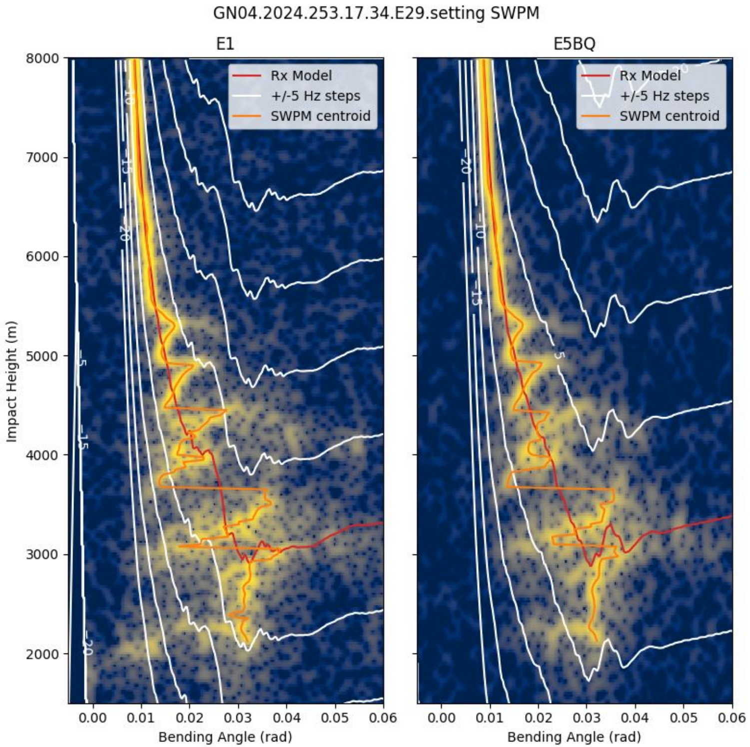
Contours show frequency shift W.R.T. receiver's model



SWPM: New Capabilities

Insensitive to choice of receiver's reference frame

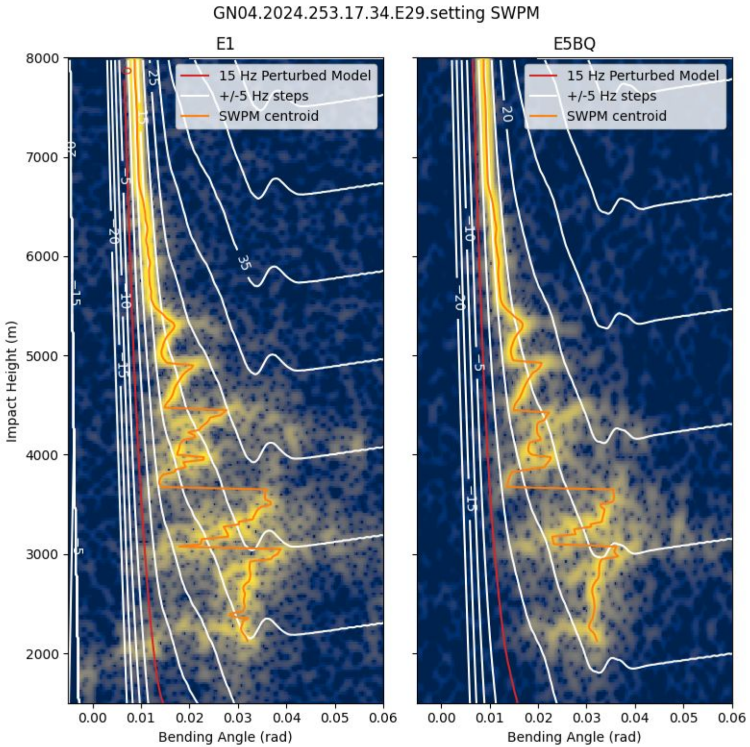
Contours show frequency shift W.R.T. Geometric Optics RTS PLL model
-> Exact same result



SWPM: New Capabilities

Insensitive to choice of receiver's reference frame

Contours show frequency shift W.R.T. a smoothed and 15 Hz perturbed model
-> Exact same result



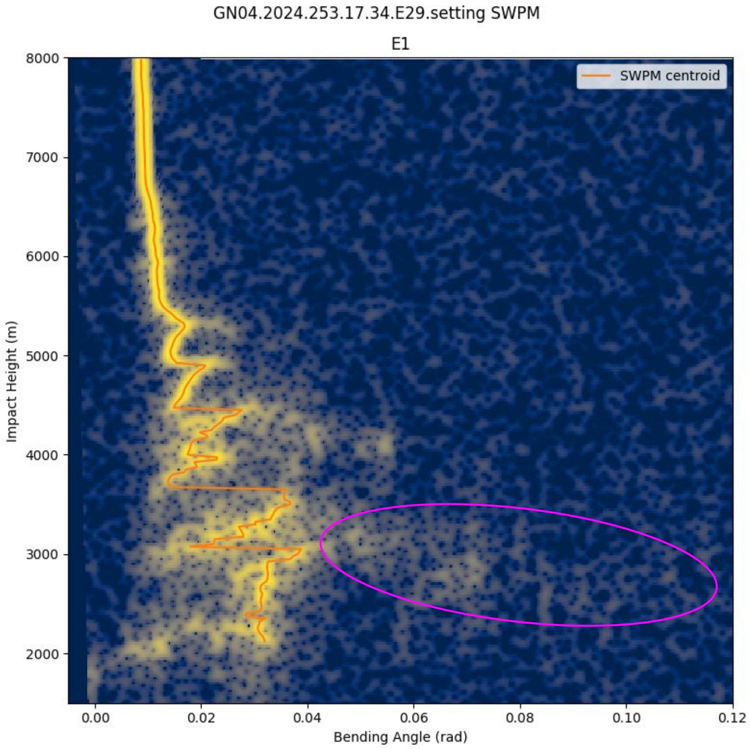
SWPM: New Capabilities

Insensitive to cycle slips

Never makes noise-dependent connected-phase decisions
-> Never has “cycle slips”

-> Usable for ducting height estimation, where applicable

Sometimes, not trivial to associate ducting signals with specific BA(IH) step

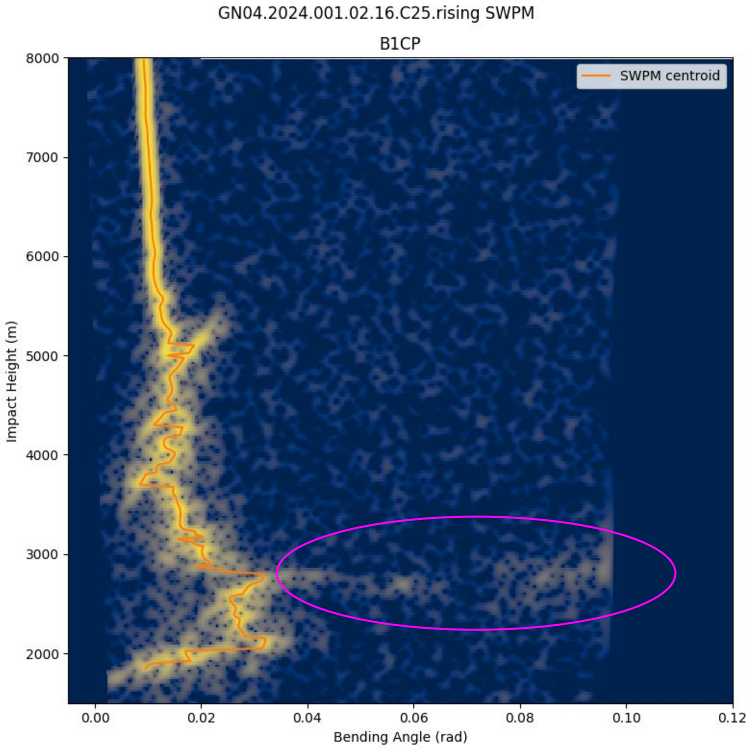


SWPM: New Capabilities

Insensitive to cycle slips

-> Usable for ducting height estimation, where applicable

Other times, quite clear



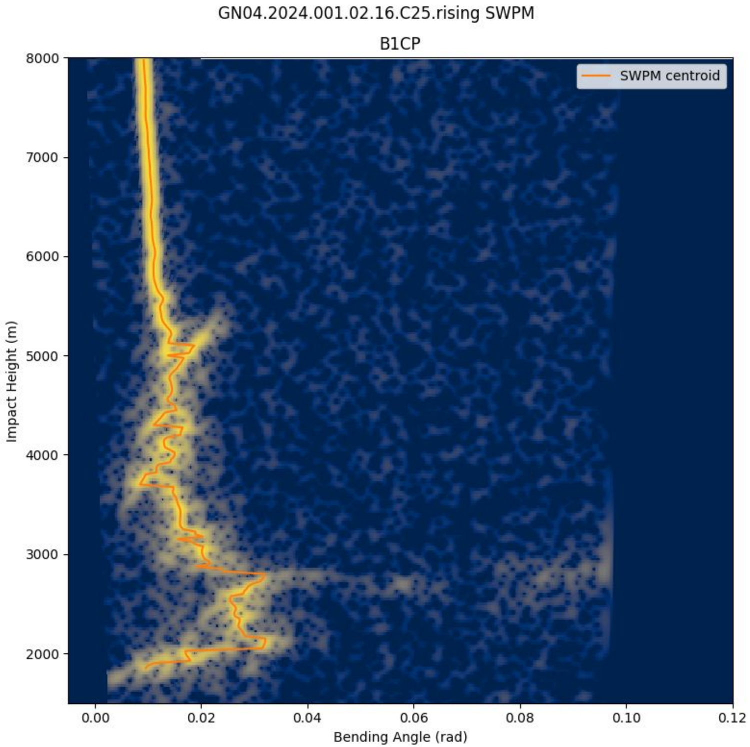
SWPM: New Capabilities

Insensitive to track depth truncation

Researchers have previously reported positive BA biases due to noise entering WO from deeper SLTA regions

Due to use of local windows: Get exact same BA retrieval independent of truncation

-> Can process extremely deep profiles without worrying about introducing BA biases

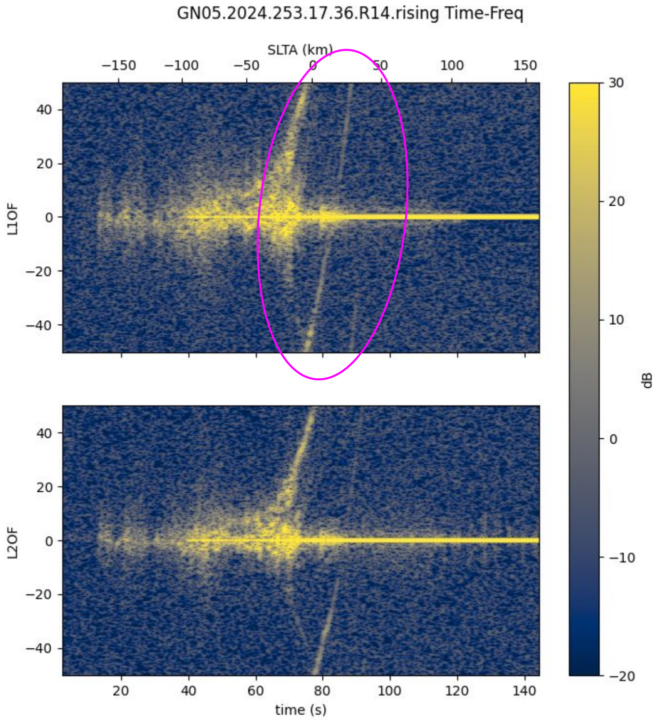


SWPM: Reflection Signal Processing

Reflection signals are routinely collected as side-effect of RO signal tracking

Researchers have proposed methods to learn about atmospheric refraction using reflections

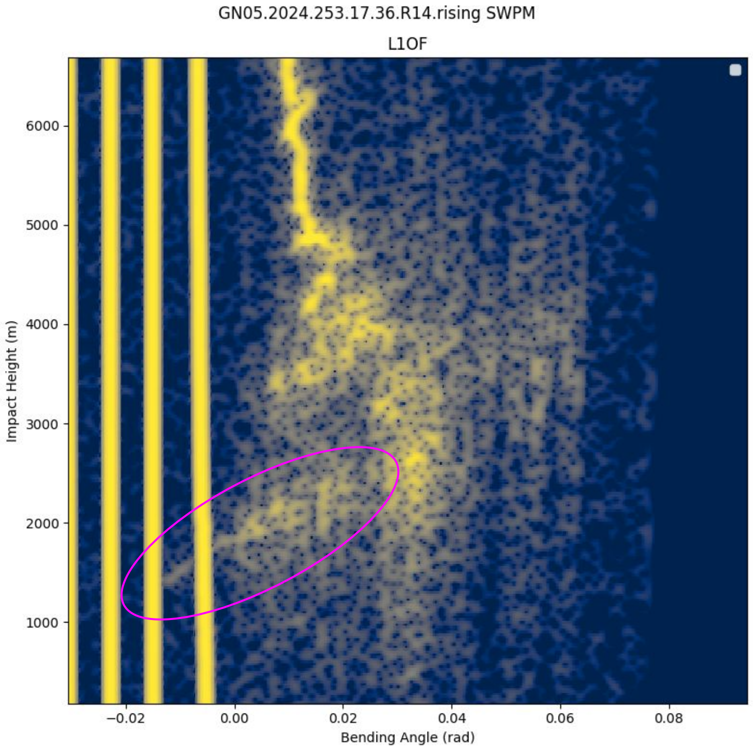
Some reflection signals wrap around Nyquist aliasing frequencies



SWPM: Reflection Signal Processing

Lifting anti-aliasing safeguards may allow processing more of these ancillary reflection signals in BA(IH) space

Natural outcome from using complex transformed wave field and local analysis instead of globally-connected phase



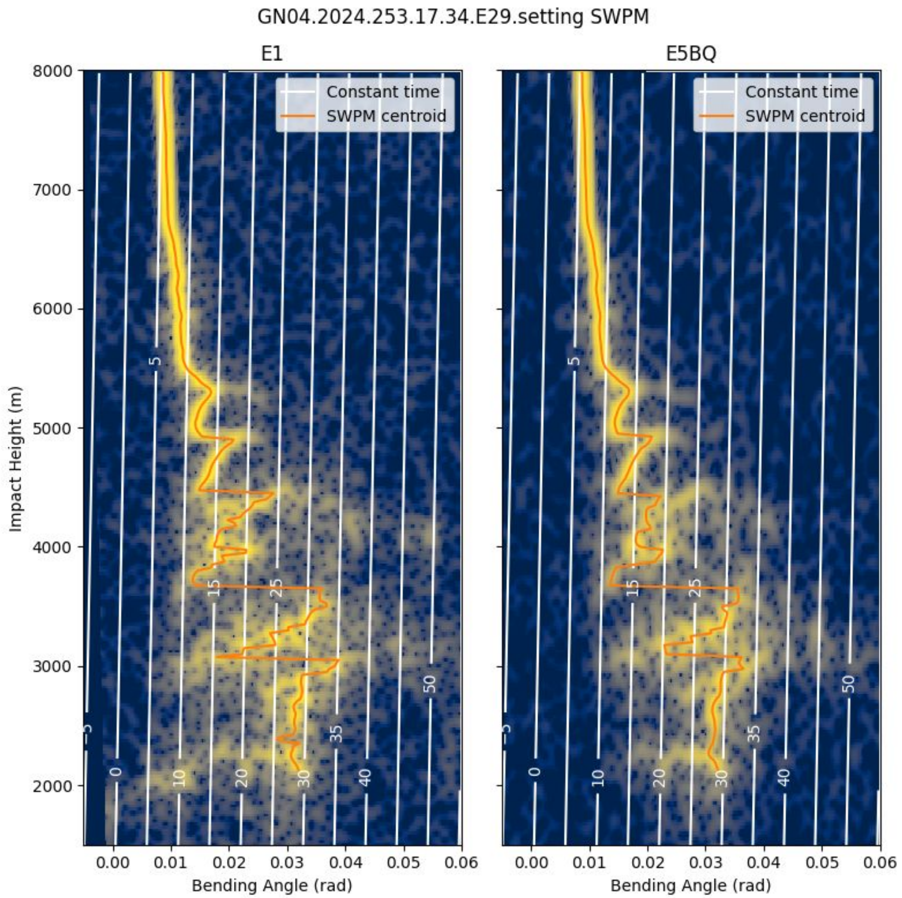
SWPM: 4DVar Aids

Data format includes Time(BA, IH) in addition to geometry as an aide to 2D BAFO users

Shown: 5-second contours

Epoch chosen to be 0 km SLTA intercept. Provides multidimensional origin:

- 0 time
- 0 km SLTA
- 0 bending (ie, atmo-free)
- 0 impact height

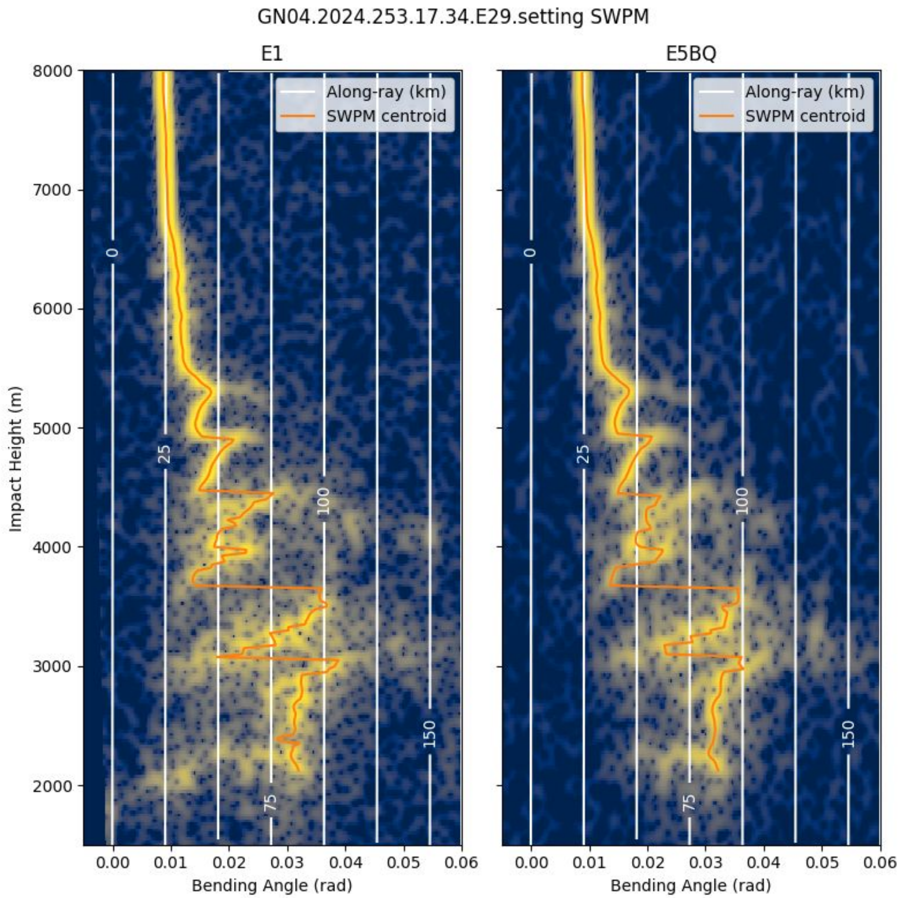


SWPM: 4DVar Aids

Can use geometry info and Geometric Optics to calculate ray's tangent point

Shown: tangent point displacement in along-ray axis

- Positive: From Tx towards Rx
- More bending -> displaces bending towards lower-altitude member (Rx)
- Contours: 25 km/ea

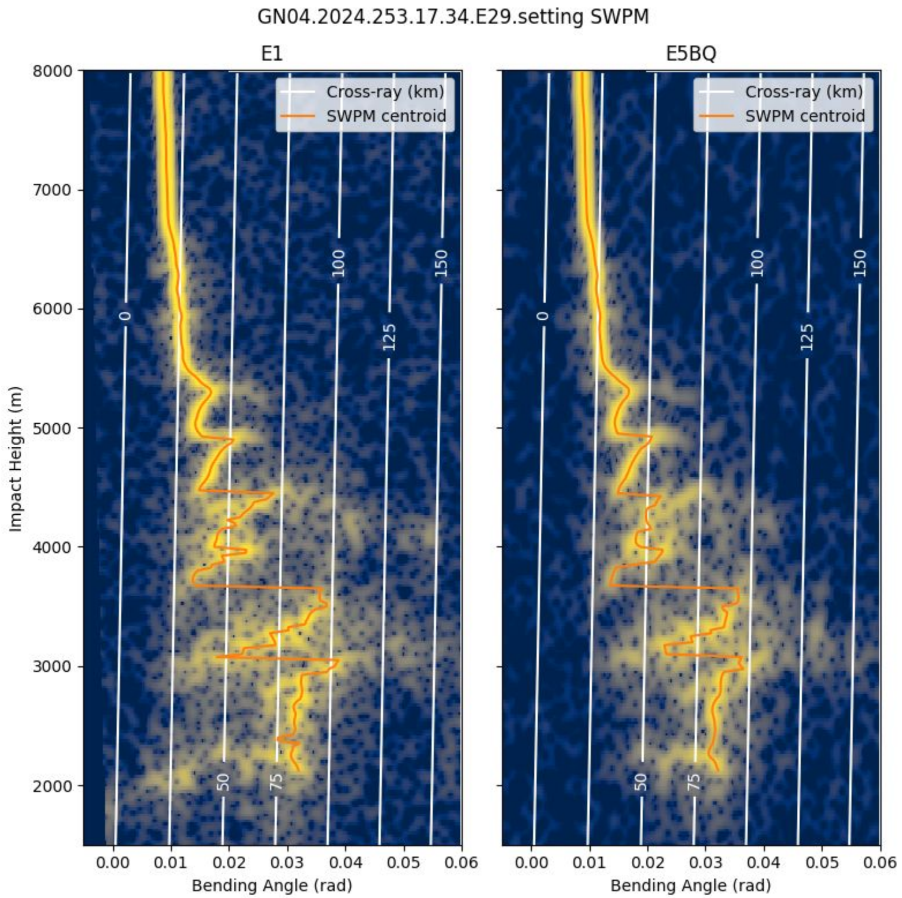


SWPM: 4DVar Aids

Can use geometry info and Geometric Optics to calculate ray's tangent point

Shown: tangent point displacement in cross-ray horizontal axis

- Positive: to ray's left along surface
- More displacement -> more sliding motion along surface
- Contours: 25 km/ea



SWPM: Polarimetric RO Processing

GNOMES-5 equipped with one P-RO antenna

- Launched 2024-08-16
- Sci. operations < 1 day later
- Tracking all four worldwide GNSS
- Tracking dual-frequency for each (6x GNSS bands total)

H-V phase shift determination easy: “Just” angle(conjugate($u_{PM,V}$)*$u_{PM,H}$)

Never need to fix-up “cycle slips” since we don’t count cycles, just measure wave fields
(calibration challenges remain unaffected…)

-> P-RO phase shifts in BA(IH) domain

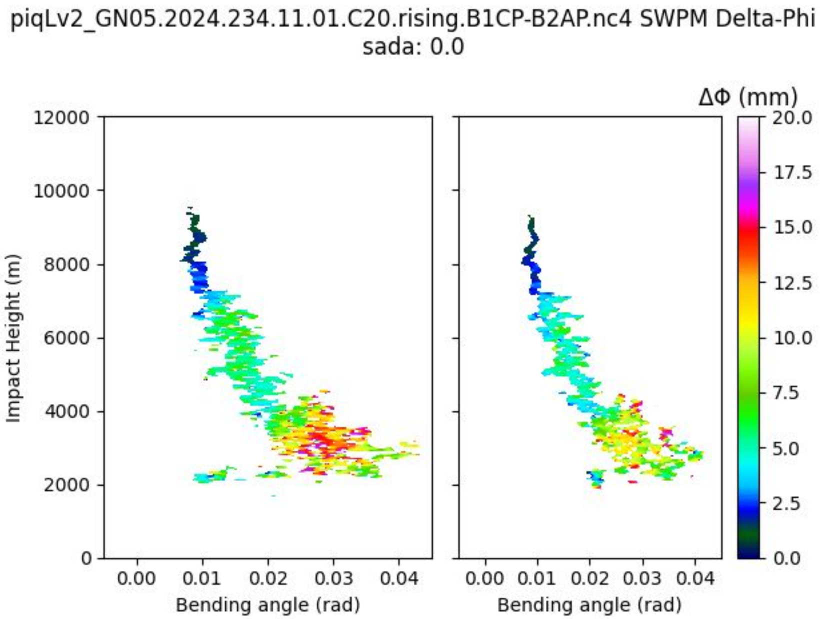
SWPM: Polarimetric RO Processing

GNOMES-5 Can See Rain!
Maybe!

Calibration / Validation still ongoing.

Currently: Hard-zero delta-Phi @ 35 km SLTA

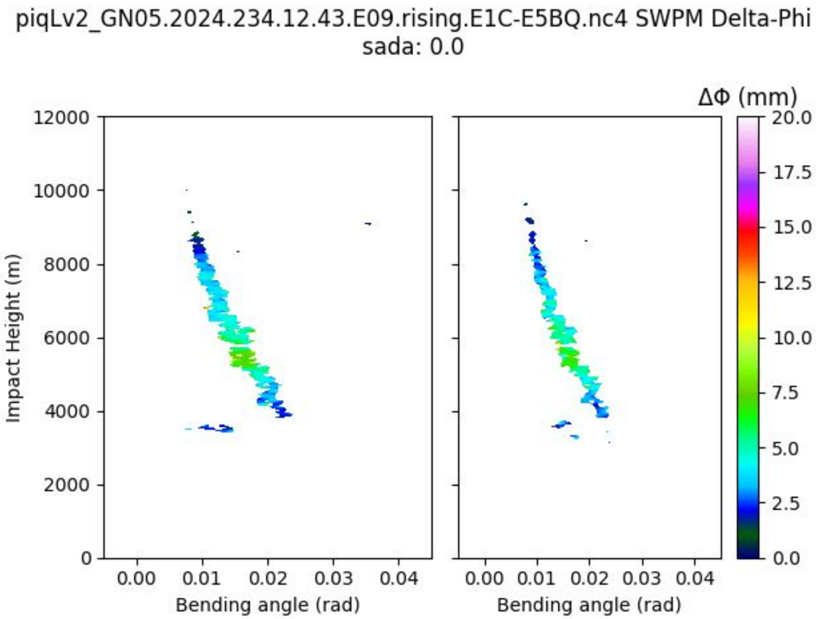
Shown: 4-sigma mask on amplitude of complex difference, colorized by phase of complex conjugate product



SWPM: Polarimetric RO Processing

More Rain! Maybe!

Calibration / Validation still ongoing

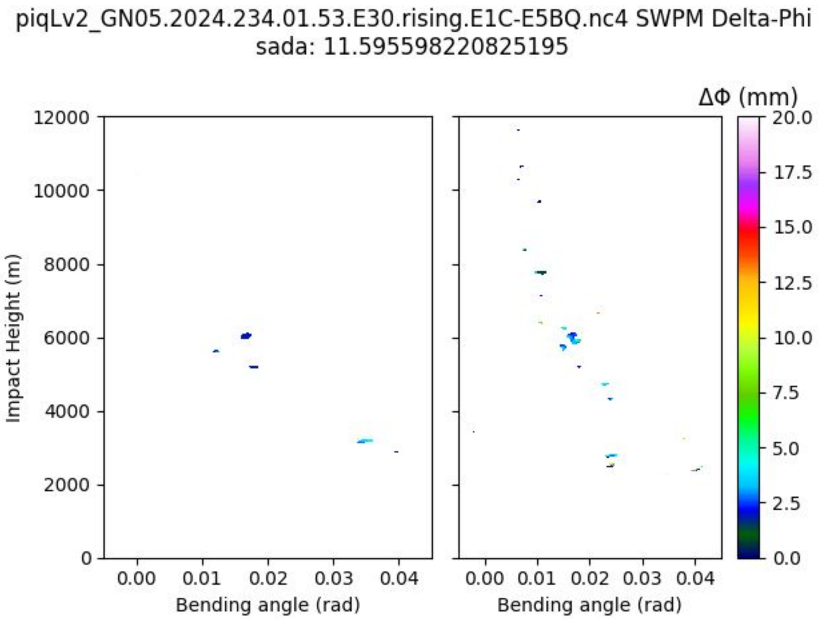


SWPM: Polarimetric RO Processing

Not Raining!

Probably!

Calibration / Validation still ongoing

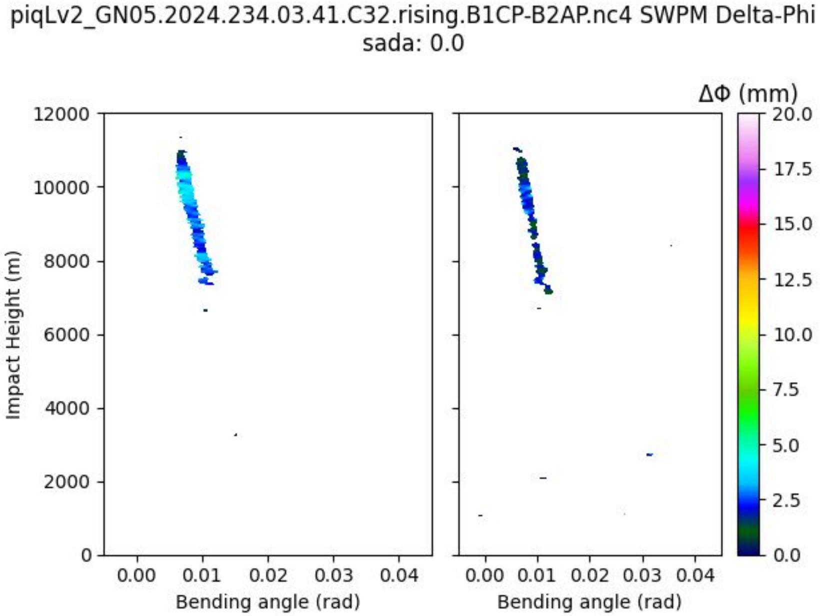


SWPM: Polarimetric RO Processing

Freezing line?

Calibration / Validation still ongoing

Cross-pol sensitivity varies with frequency band and azimuth



Summary and Conclusions

High performance available in the upper stratosphere

- Without ground-based POD, or high-rate clocks, or IGS orbits (on GAL, GPS, BDS anyway…)
- Without any climatological model conditioning at all!
    - 100% observation all the way to the top!

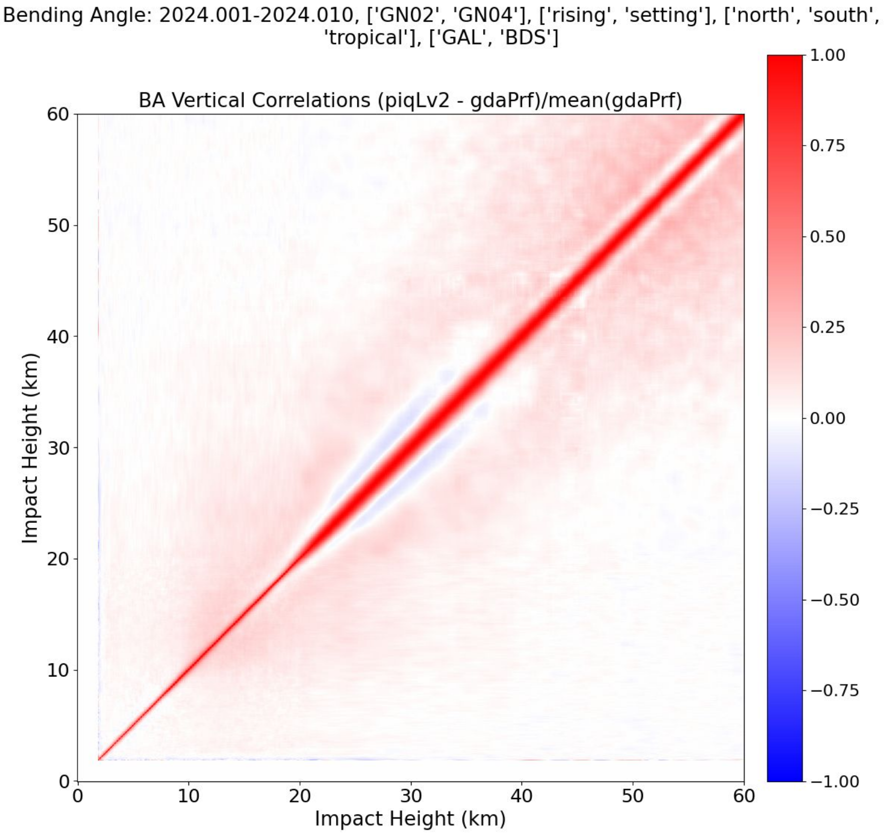
New processing technique derived from SWPM

- Eliminates sensitivity of sharp BA(IH) retrievals to receiver modeling
- Eliminates BA bias sensitivity to truncation
- Supports ducting height estimation
- Extends reach for analyzing ancillary reflection signal collections
- Supports P-RO processing in IH domain

See also E. “Rob” Kursinski’s talk on lower troposphere for more results

Backup: Vertical Correlation of BA Err

(PiQ - GDAS) / GDAS



Backup: Vertical Correlation of BA Err

(PiQ - GDAS) / GDAS

Method shamelessly cribbed from UK-MET, except, using the full-width half-maximum metric instead of stddev of Gaussian fit

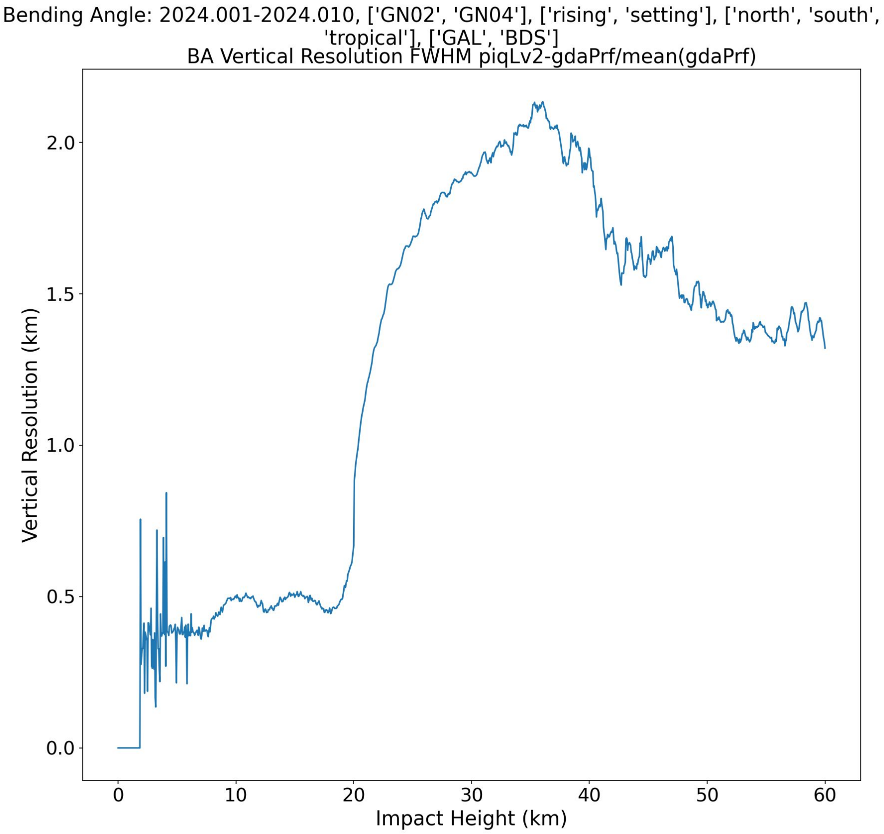
Current filtering configuration:

- 1.25*Fresnel in GO

- 100m 8km - 25km

- 50m < 8 km

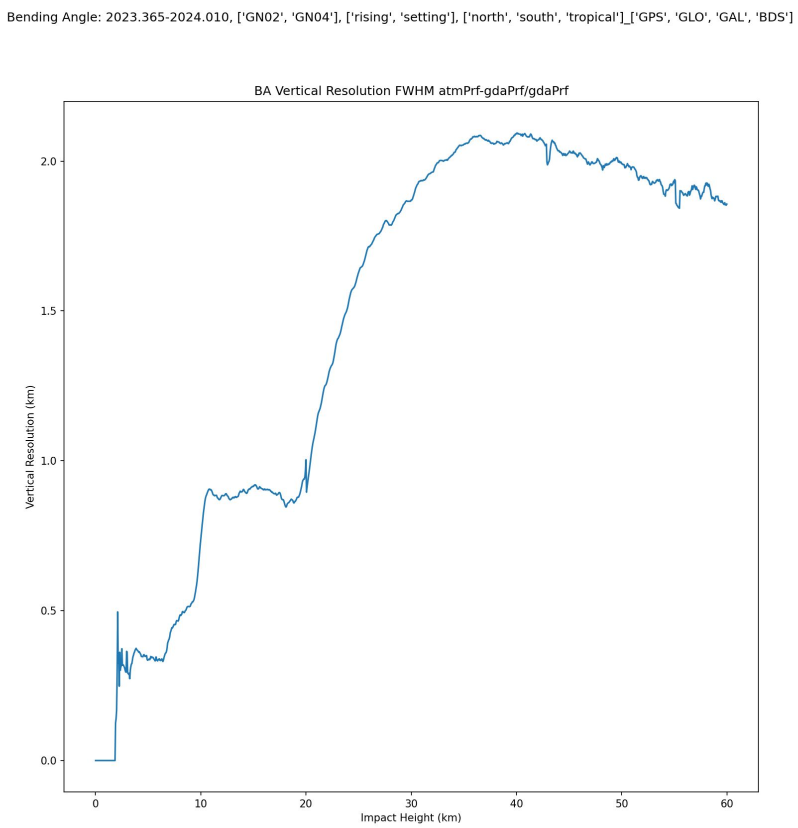
- Transition from GO to WO at 20 km (10km overlap for comparison)



Backup: Vertical Correlation of BA Err

(UCAR - GDAS) / GDAS

For comparison only



Backup: GO versus WO

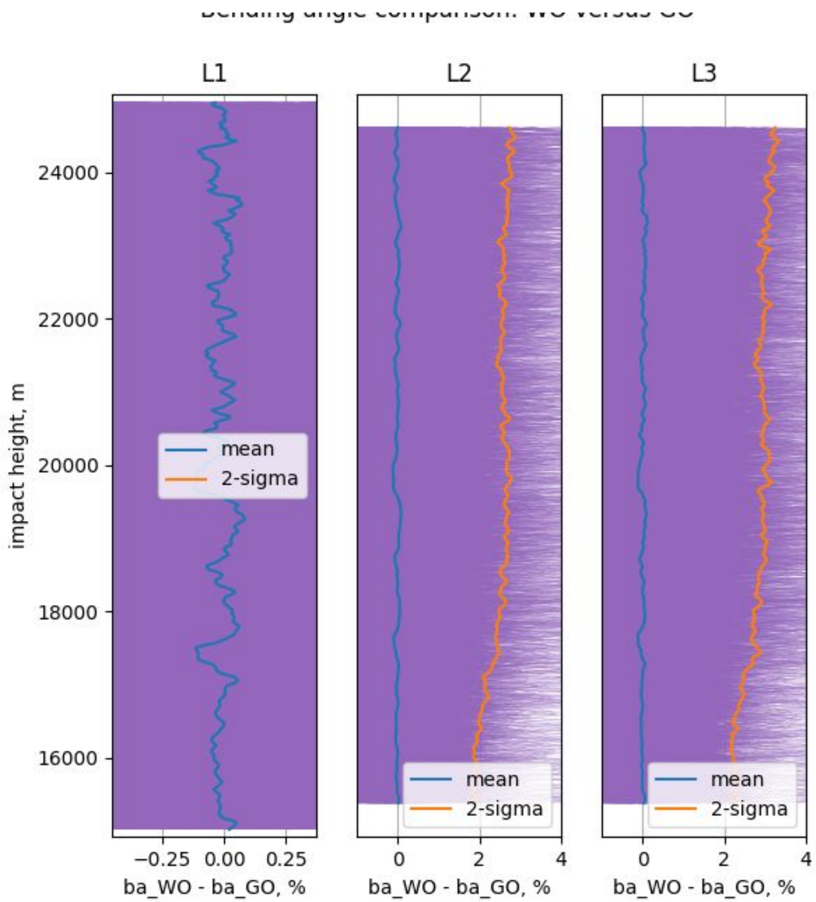
Cross-check between geometric optics and wave optics methods in overlap region between 15km and 25km

L1 zoomed to demonstrate (much) better than 0.1% concurrence in bias

L3(GO) based on iono-free BA weighted diff

L3(WO) based on SNR-weighted sum of iono-corrected WO(L1) and WO(L2)

Method independence serves as strong self-validation in bias: If there is a bias versus background, it is caused by features common to both GO and WO processing methods (bias in background, Fermat's effect, etc)



Favorite References

This system may have been built “from scratch”, but it would not have been possible without learning from numerous prior publications and disclosures. Here follows a subset of the works we found most useful in its development.

1997 Kursinski: Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System

1999 Ashby: NIST Technical Note 1385 GPS Receivers and Relativity

2002 Hajj: A technical description of atmospheric sounding by GPS occultation

2004 Jensen: Geometrical optics phase matching of radio occultation signals

2004 Martin: Complex Signal Processing is Not Complex

2008 Riley: Handbook of Frequency Stability Analysis

2010 Sokolovskiy: On the uncertainty of radio occultation inversions in the lower troposphere

2016 Zeng: Ionospheric correction of GPS radio occultation data in the troposphere

2018 Aparicio: Information content in reflected signals during GPS Radio Occultation observations

2020 Sokolovskiy: (UCAR Technical Note) Standard RO Inversions in the Neutral Atmosphere (Processing Steps and Explanation of Data)

2021 Sievert: Using A Sliding Window Phase Matching Method for Imaging of GNSS Radio Occultation Signals

2021 ROM-SAF: ROPP-11 Preprocessor Module User’s Guide