Atmospheric Structures Observed in the Lower Troposphere with PlanetiQ RO Data and Implications

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September 17, 2024

Outline

- Importance of lower troposphere (LT) & PBL
- RO's unique ability to characterize it
- Key challenges in the LTBL
- Overview of our new retrievals
- Examples including sondes
- Ability to observe convection and need for 3D retrievals
- Preliminary conclusions
- Next steps

Improving RO Impact in the Lower Troposphere

TOWARD A GLOBAL PLANETARY BOUNDARY LAYER OBSERVING SYSTEM

THE NASA PBL INCUBATION STUDY TEAM REPORT

The National Academy of Sciences (NAS) 2017 Decadal Survey stated that observing the Planetary Boundary Layer (PBL) is a top priority because of

1. its critical importance for understanding and predicting weather & climate
2. our present ability to measure the PBL is quite poor over most of the globe.

Challenge: Observing PBL globally requires satellites but profiling the PBL from orbit is very difficult because of its short vertical extent, closeness to the surface and frequent cloudiness.

- GNSS RO's unique combination of features are well suited to profiling the PBL globally
  - Very high vertical resolution: 20m - 200 m
  - High precision and accuracy
  - All weather: Long wavelengths penetrate clouds and precipitation
  - Over all surfaces: Insensitive to underlying surface conditions
- GNSS RO is the only present system capable of profiling the PBL from space under any and all conditions

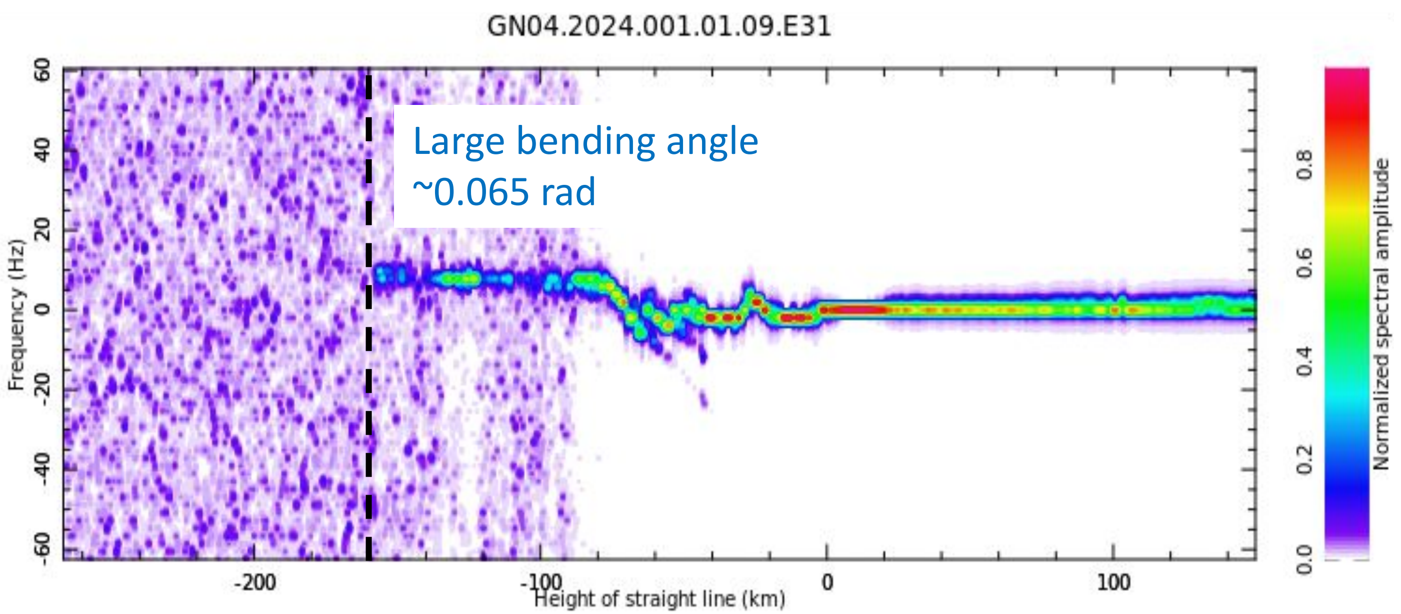
⇒ GNSS RO was one of key techniques identified by NAS/NASA for measuring the PBL

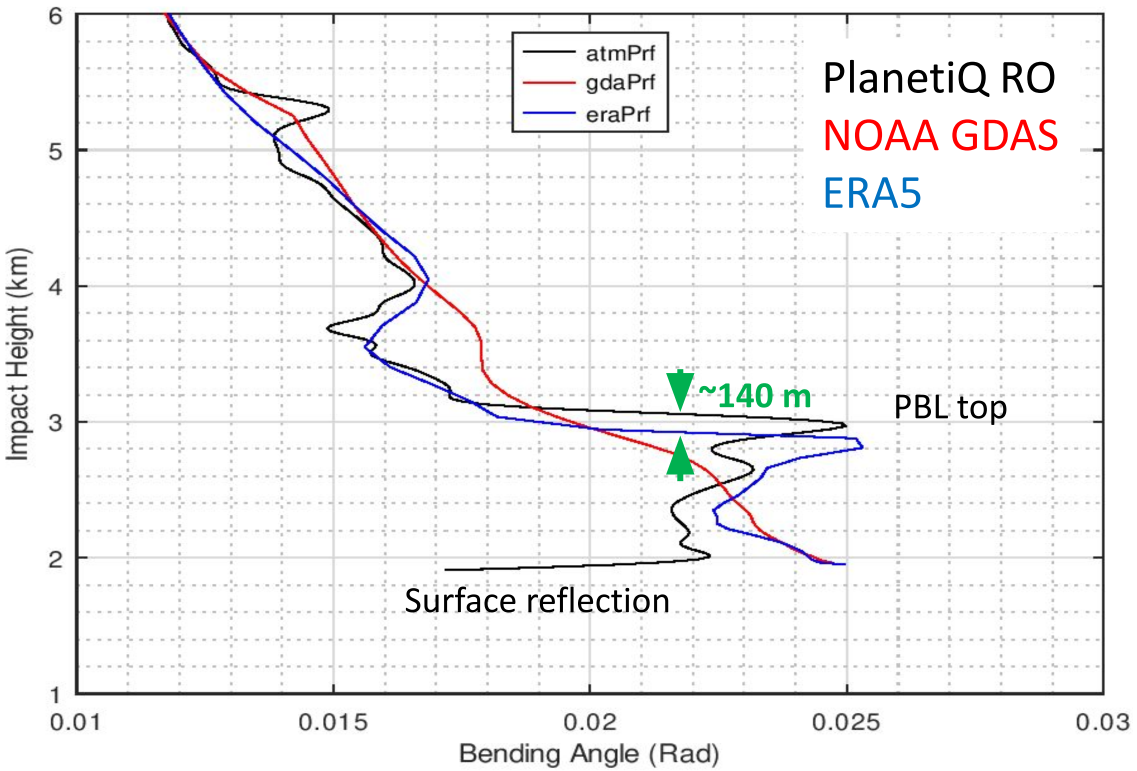
Key Challenges

1. NWP DA is avoiding RO in LTBL: Stable forward operator NLPEP
2. RO underestimating large BAs in LTBL: Retrieve large BAs correctly using high SNR RO,
3. Noisy LTBL BA limits impact on NWP: Work to minimize BA noise in LTBL
4. BA uncertainty estimates: Characterize and estimate BA noise and uncertainty
5. Desire better vertical res. in LTBL: Determine achievable vertical resolution (and achieve it)

Profile in South Atlantic

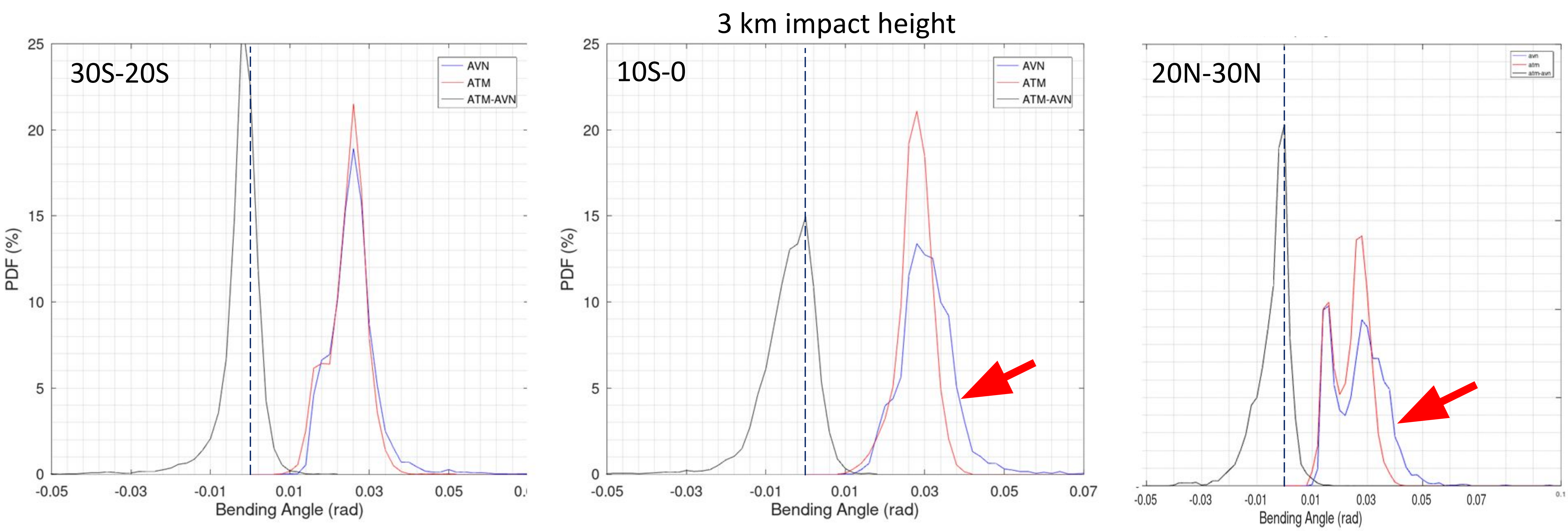
- Good looking RO profile, pretty well matched to ERA5
- Sharp PBL top observed by RO and ERA5 but not by GDAS
- ERA5 PBL top is ~140m below the RO observed PBL top
- Max retrieved BA ~0.025 rad = 1.4 deg
- SLTA -160 km corresponds to BA ~0.065 rad = 3.7 deg





Systematically Underestimated BAs & Saturation in LTBL

- Comparing bending angles derived from avnPrf, GDAS and ERA5, indicates PlanetiQ atmPrf bending angles saturate with RO BAs, seldom exceeding 0.04 rad = 2.3 deg.
- The fact that we observe deep signals and our RO 2D SNR (BA, IH) spectra does capture signatures of large BA's **BUT** those large BA's are not getting retrieved in atmPrf, indicates a systematic (UCAR/AER) **retrieval limitation**.



Detecting large BAs & ducting in PlanetIQ occultations

Sliding spectra | Bending angle profiles | Sliding spectra | Bending angle profiles

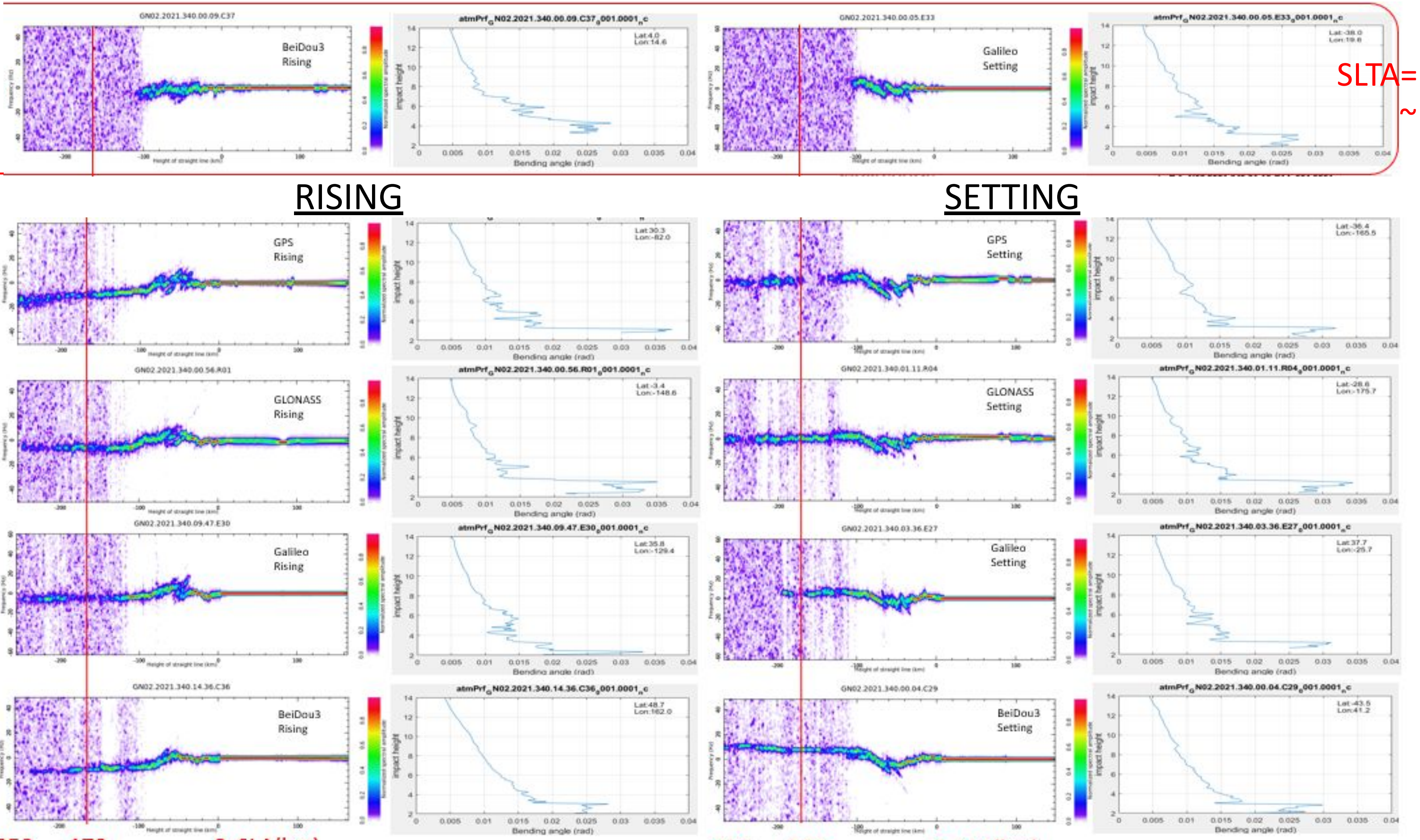
Cases with No ducting

SLTA= -100 km ~ 0.04 rad

RISING | SETTING

Cases with ducting

SLTA= -170 km ~ 0.07 rad

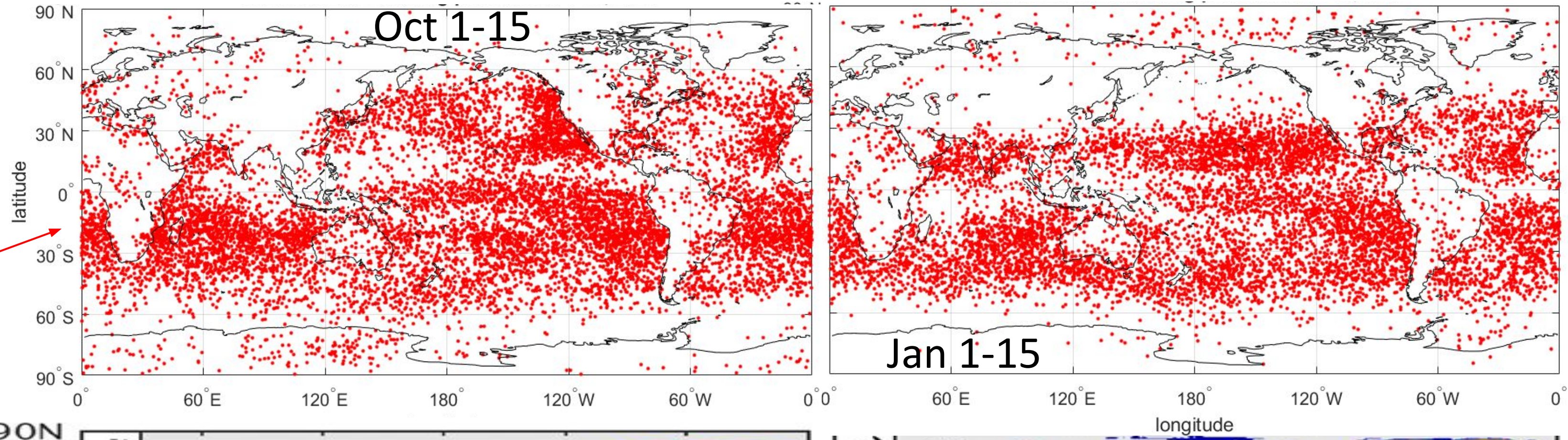


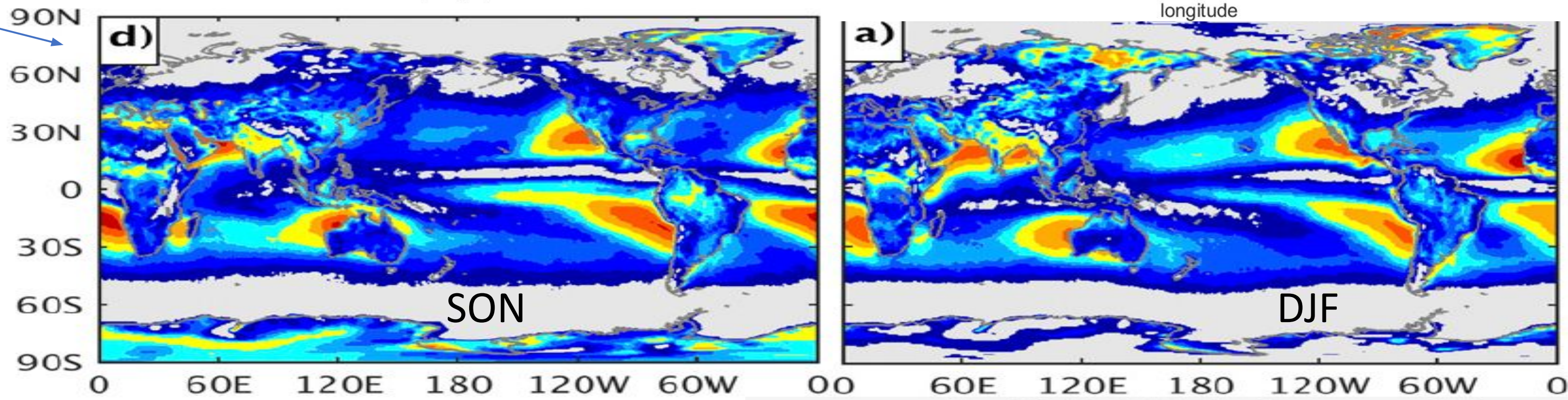
-250 -170 0 SLA(km) | -250 -170 0 SLA(km)

Based on Sokolovskiy et al. 2014

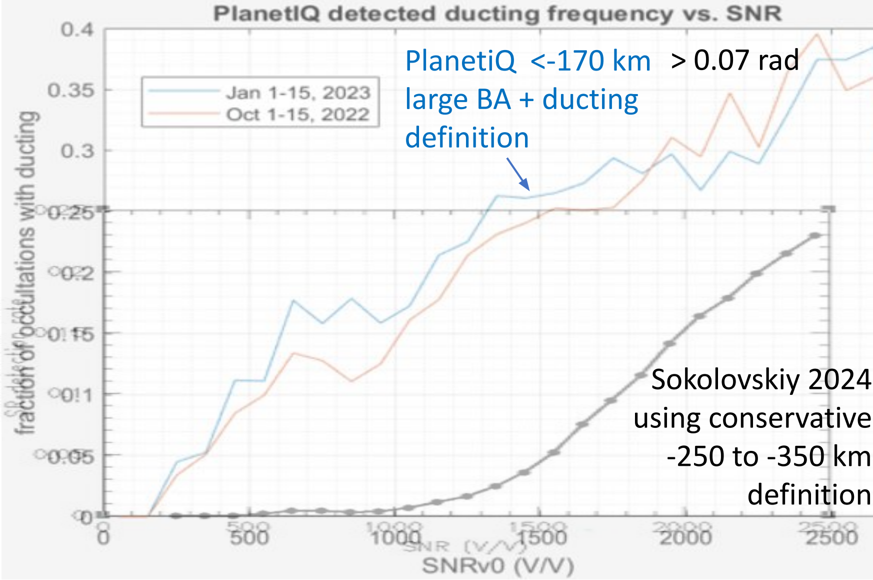
Frequency of large bending angles & ducting

- Occultations with bending angles **>0.07 rad** & ducting detected in our data
- Ducting prediction by Feng et al. 2020 based on ERA Interim
- Frequency in ERAI is likely underestimated due to limited vertical resolution
- Mostly over oceans and associated with vertical moisture gradients
- Occurs most often in subtropical marine cloud regions critical for climate
- Ducting important for TC forecasting
- Ducting over Antarctica is due to [illegible]e thermal inversions dT/dz > +140K/km(!)





- Determined ducting % vs SNR
  - Very high SNR required to detect ducting
  - Large bending angles **>0.07 rad** and ducting likely occurs in ~1/3 of occultations



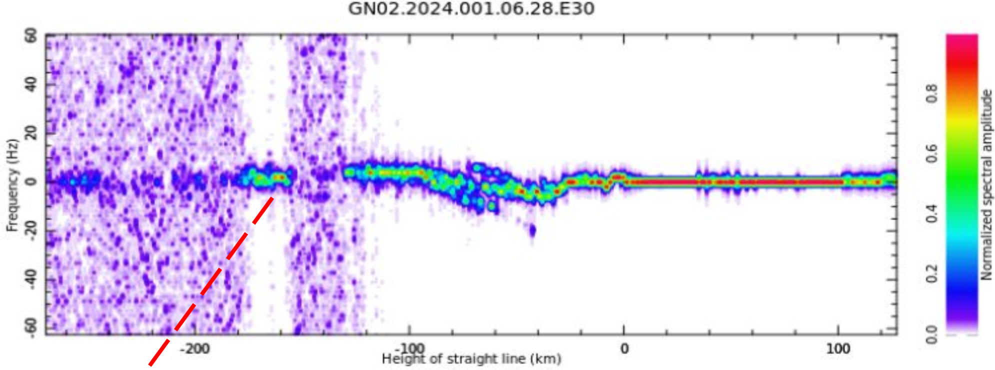
Retrieval Work

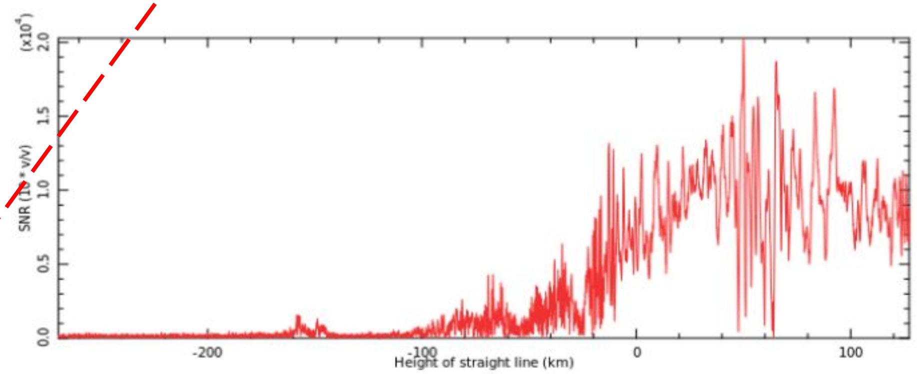
- Goal: Capture the large bending angles in our retrievals, with reduced noise and uncertainty, with better than 100 m vertical resolution

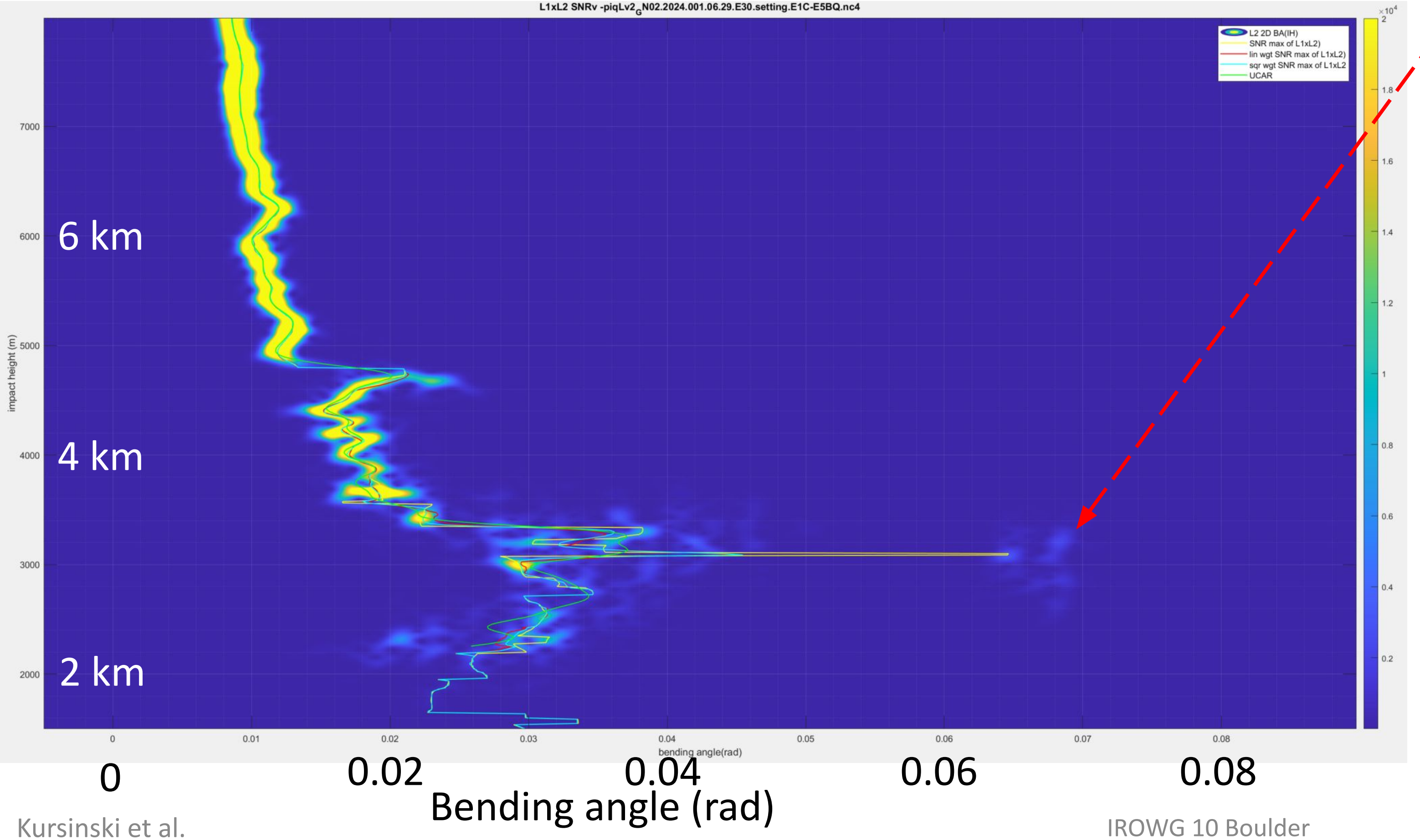
- We have developed a phase matching (PM) retrieval capability
- We generate 2D SNR(BA,IH) spectra via sliding window phase matching (SWPM) at **both L1 and L2**
- To derive 1D BA(IH) profiles, at each IH we take the average of the BAs at which there is a relative maximum (peak) SNR at **both L1 and L2** and weight those BAs by the square of their voltage SNRs in forming their average.

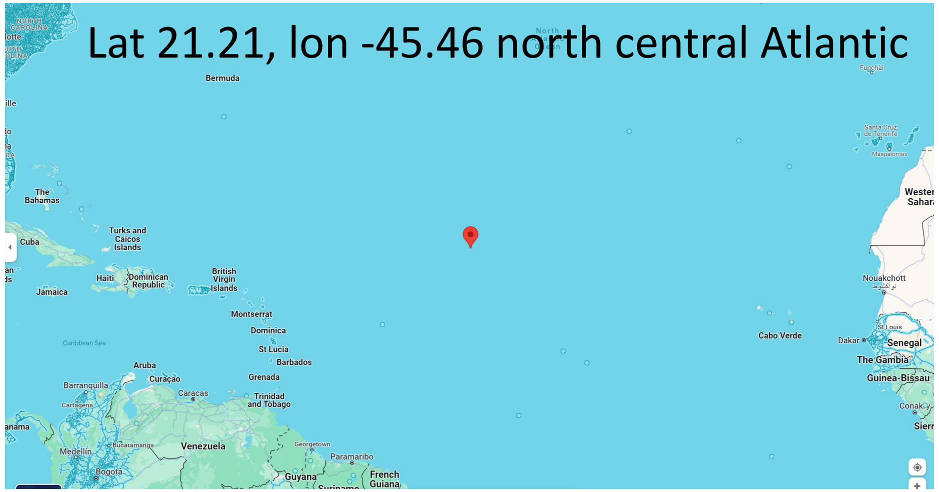
Deep occultation example

- Jan 6, GNOMES-2 occ with GNSS E30
- Ducting, ionosphere noise, surface reflection









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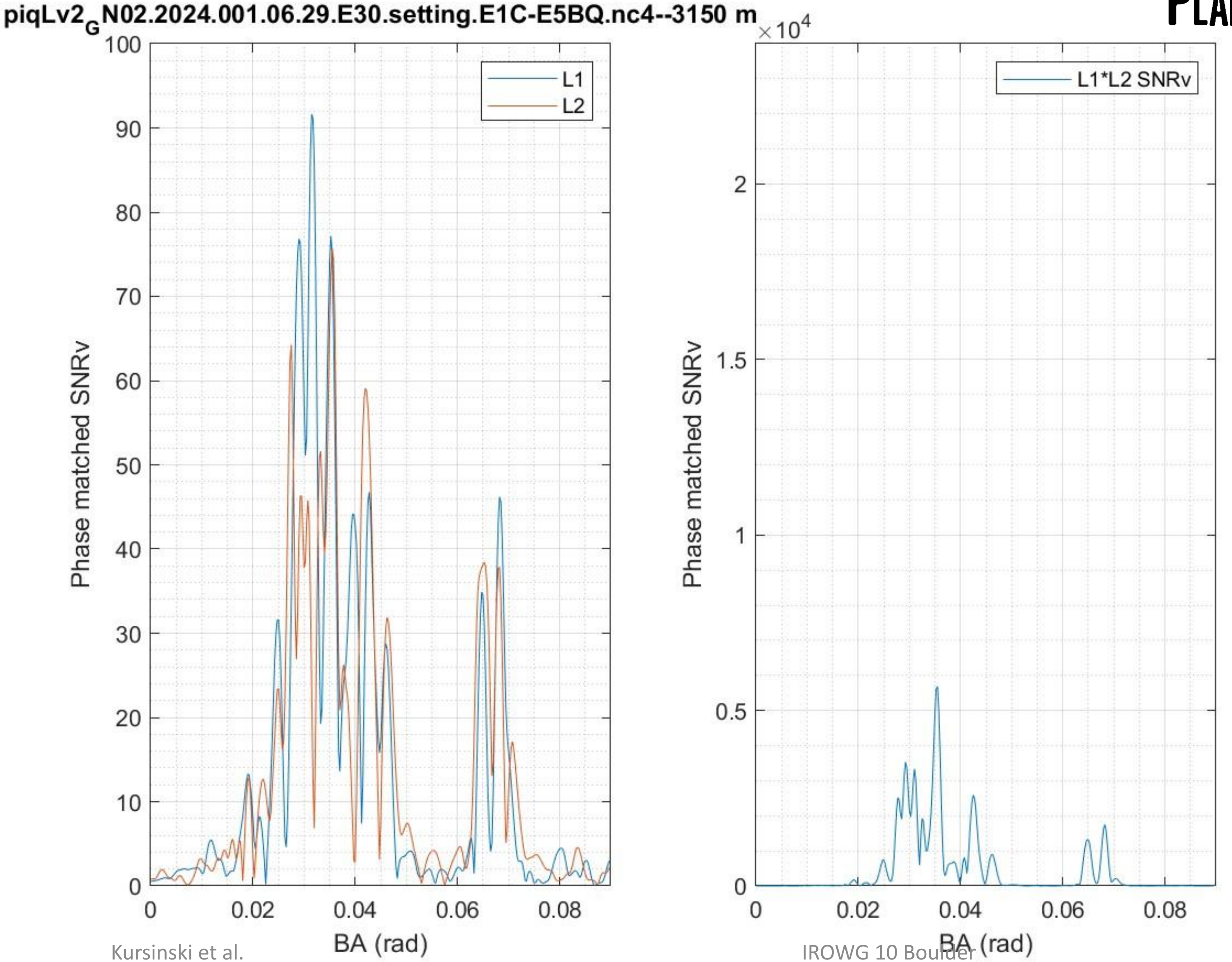
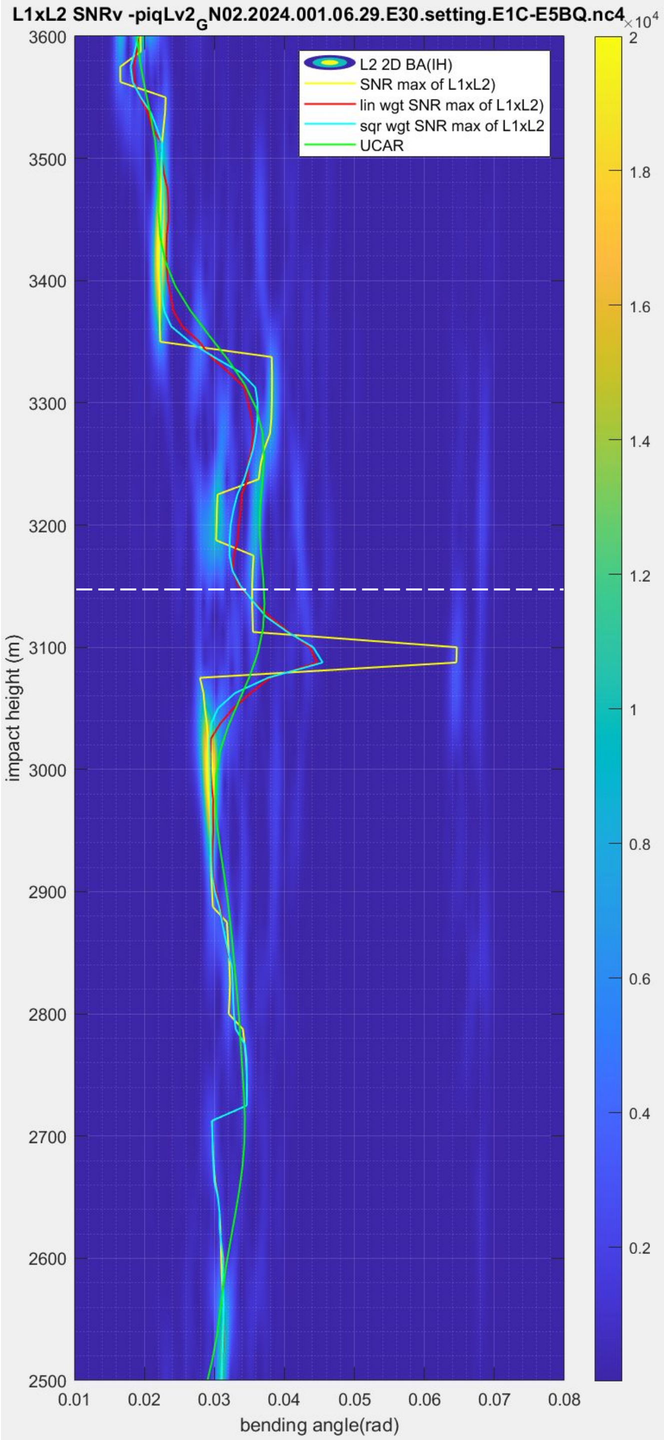
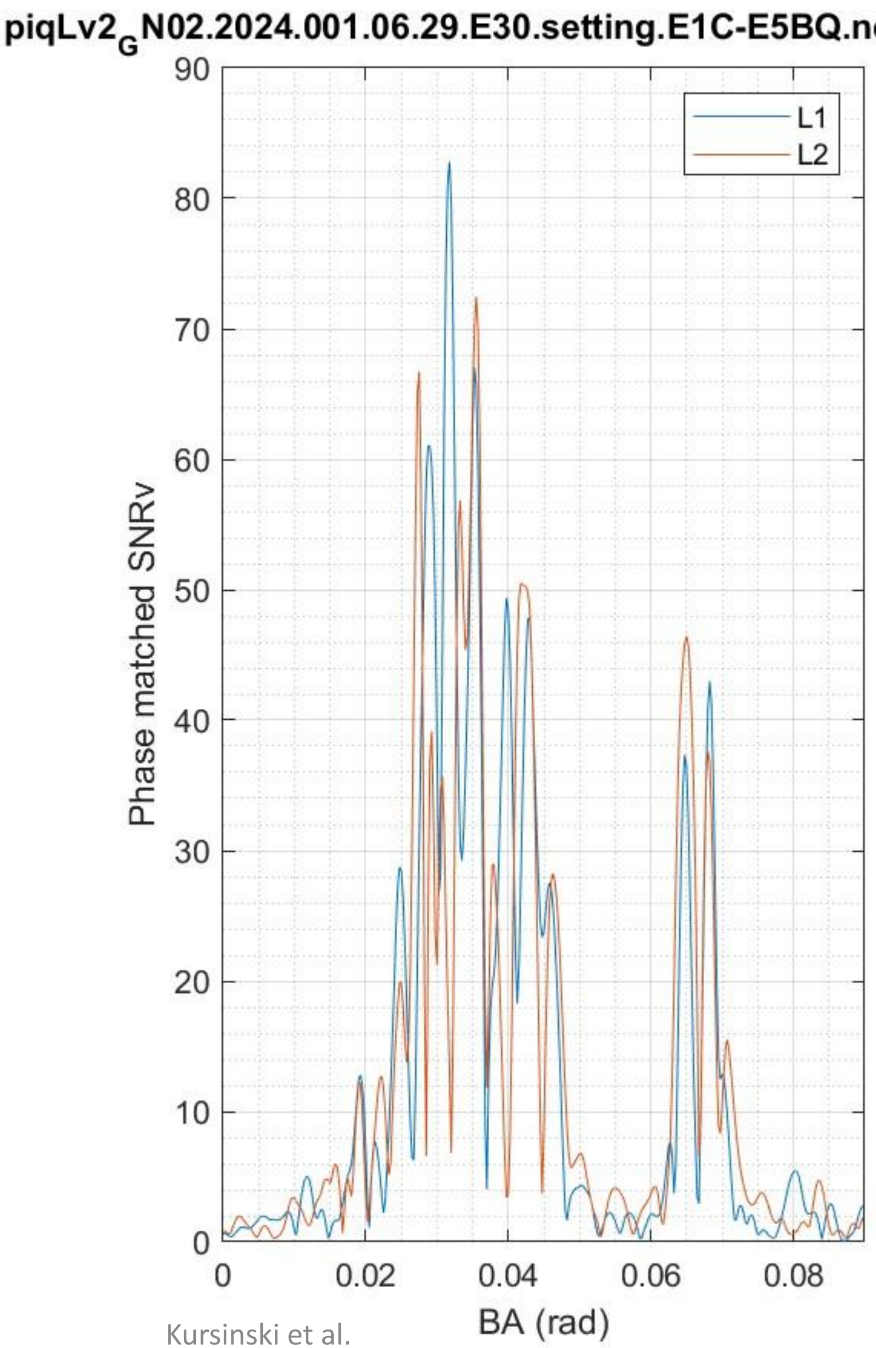

piqLv2_GN02.2024.001.06.29.E30.setting.E1C-E5BQ.nc4--3150 m
L1
L2
Phase matched SNRv
BA (rad)
×10^4
L1*L2 SNRv
Phase matched SNRv
BA (rad)


L1xL2 SNRv -piqLv2_GN02.2024.001.06.29.E30.setting.E1C-E5BQ.nc4
L2 2D BA(IH)
SNR max of L1xL2)
lin wgt SNR max of L1xL2)
sqr wgt SNR max of L1xL2
UCAR
impact height (m)
bending angle(rad)
×10^4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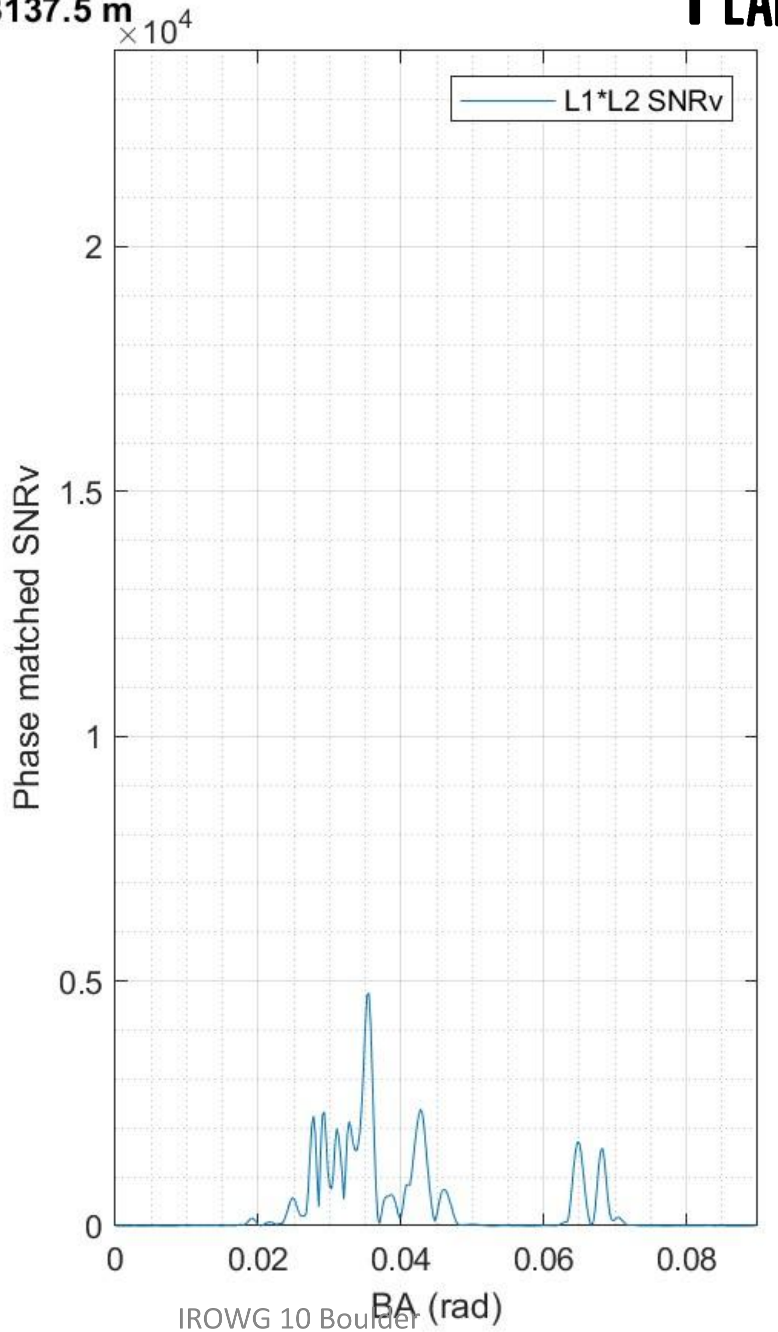
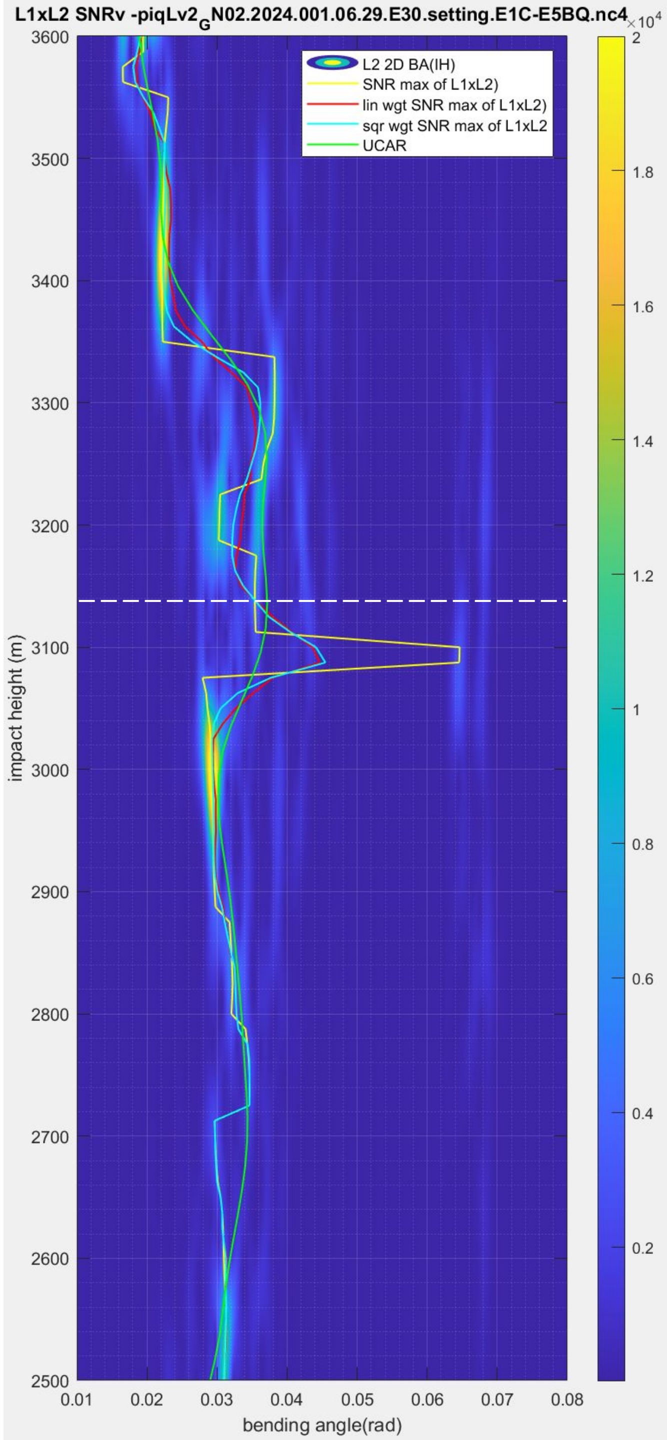
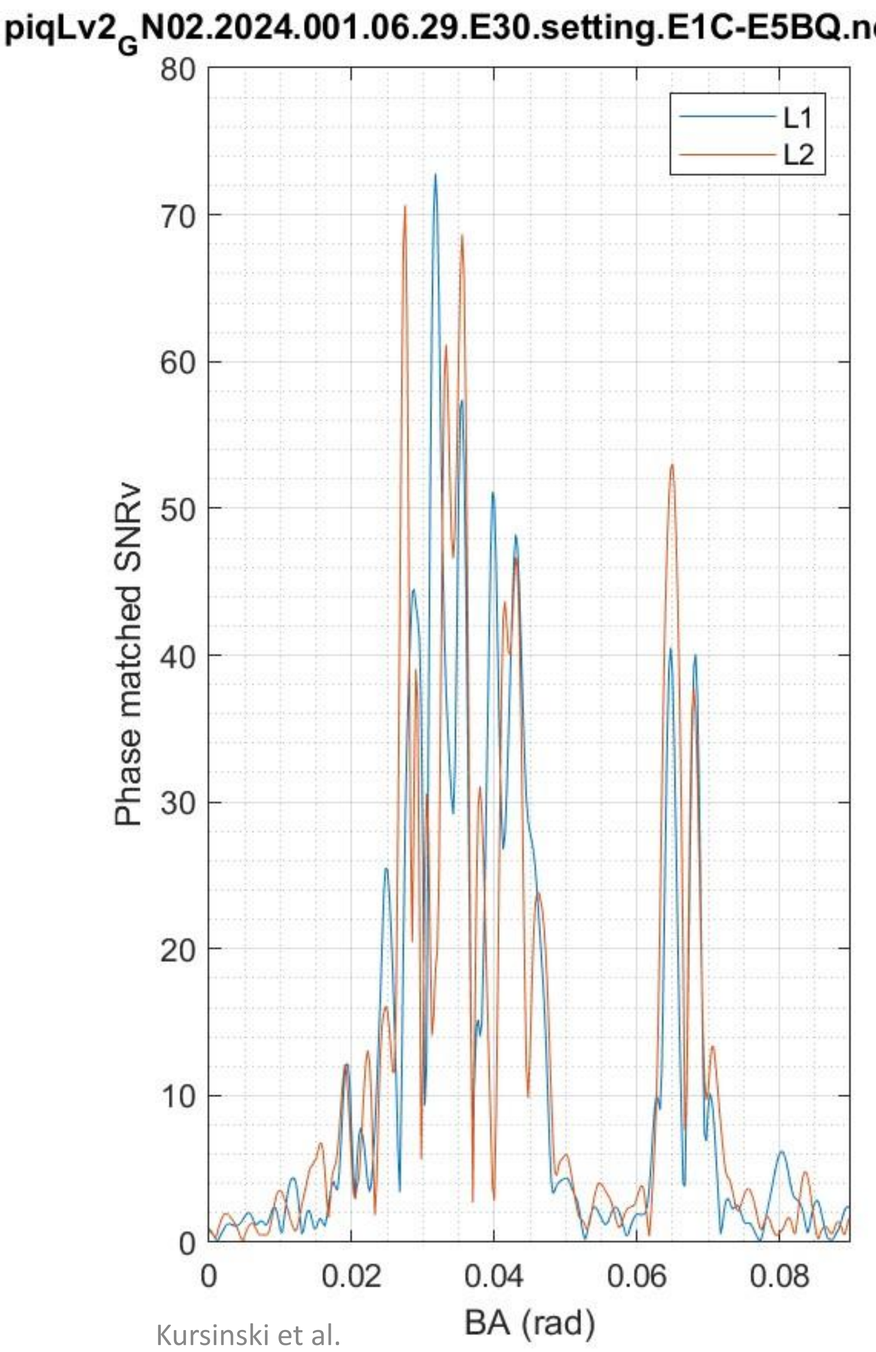
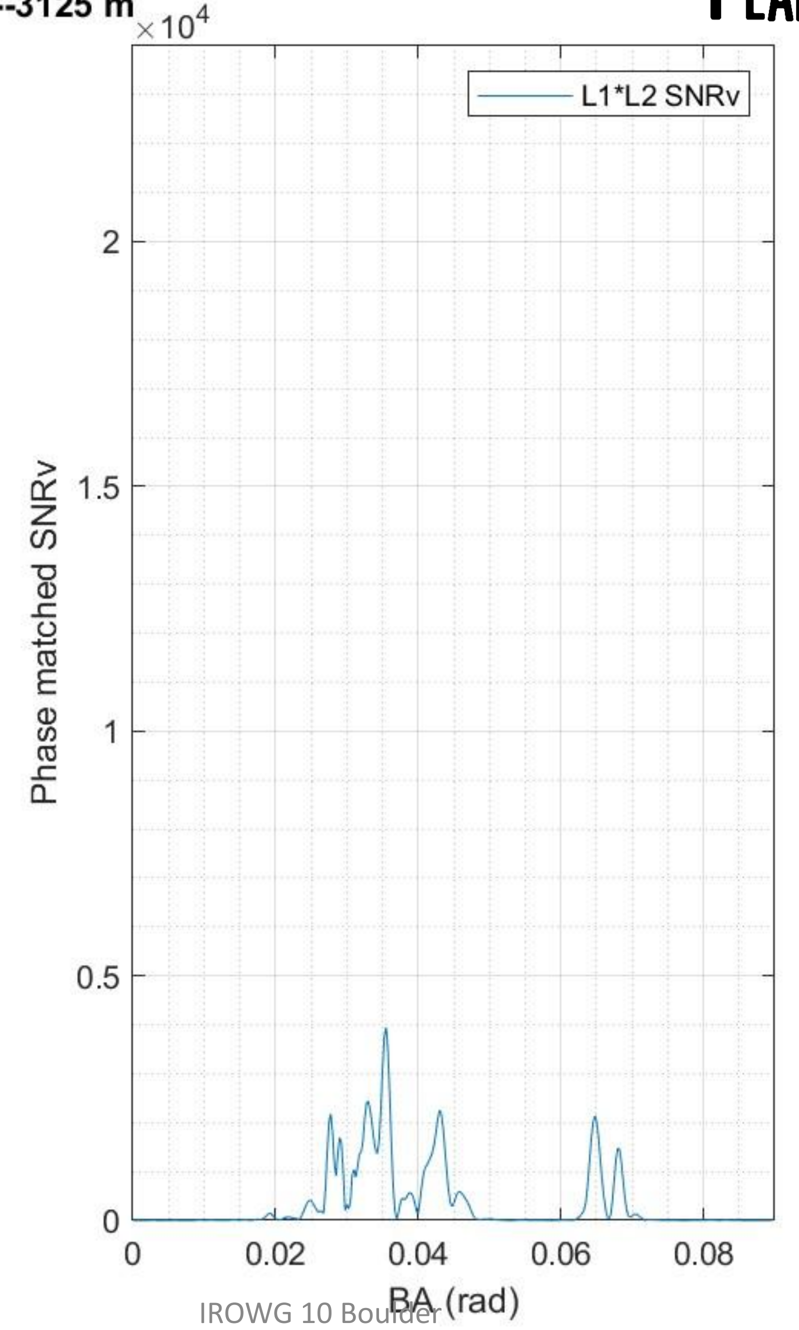
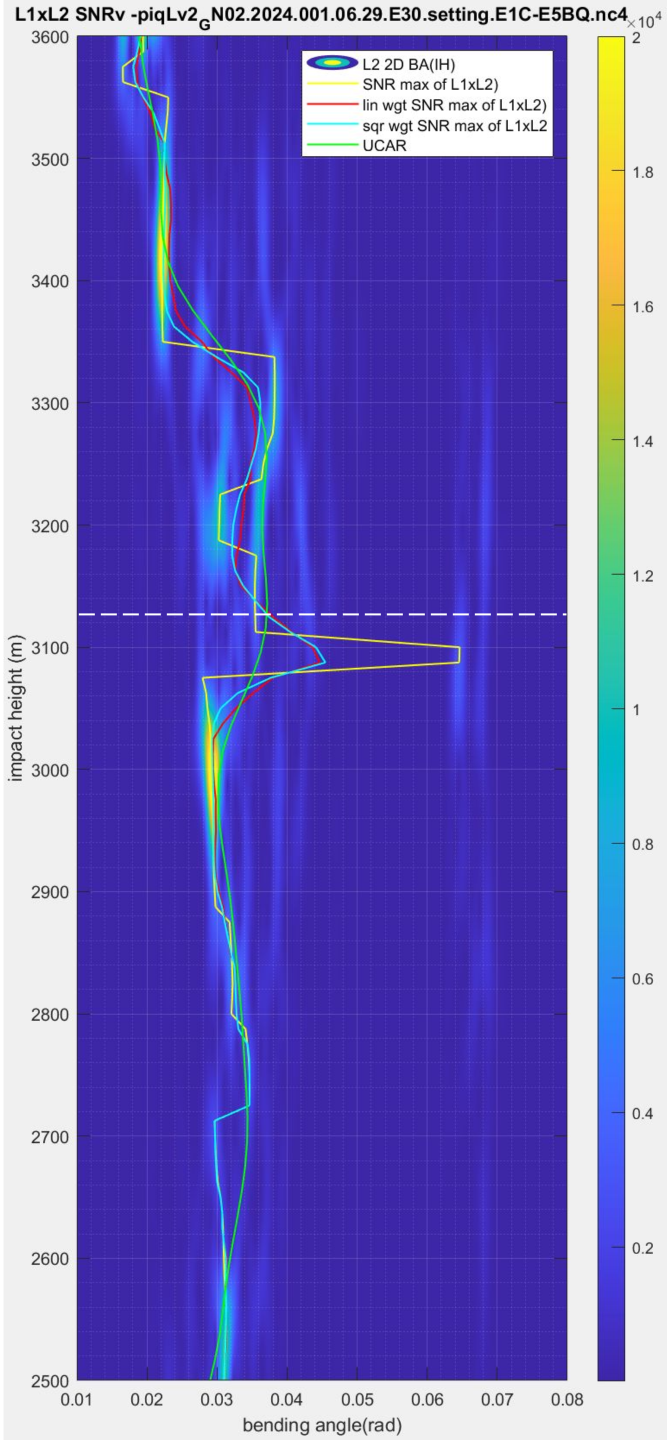
L1
L2
Phase matched SNRv
BA (rad)


×10^4
L1*L2 SNRv
Phase matched SNRv
BA (rad)

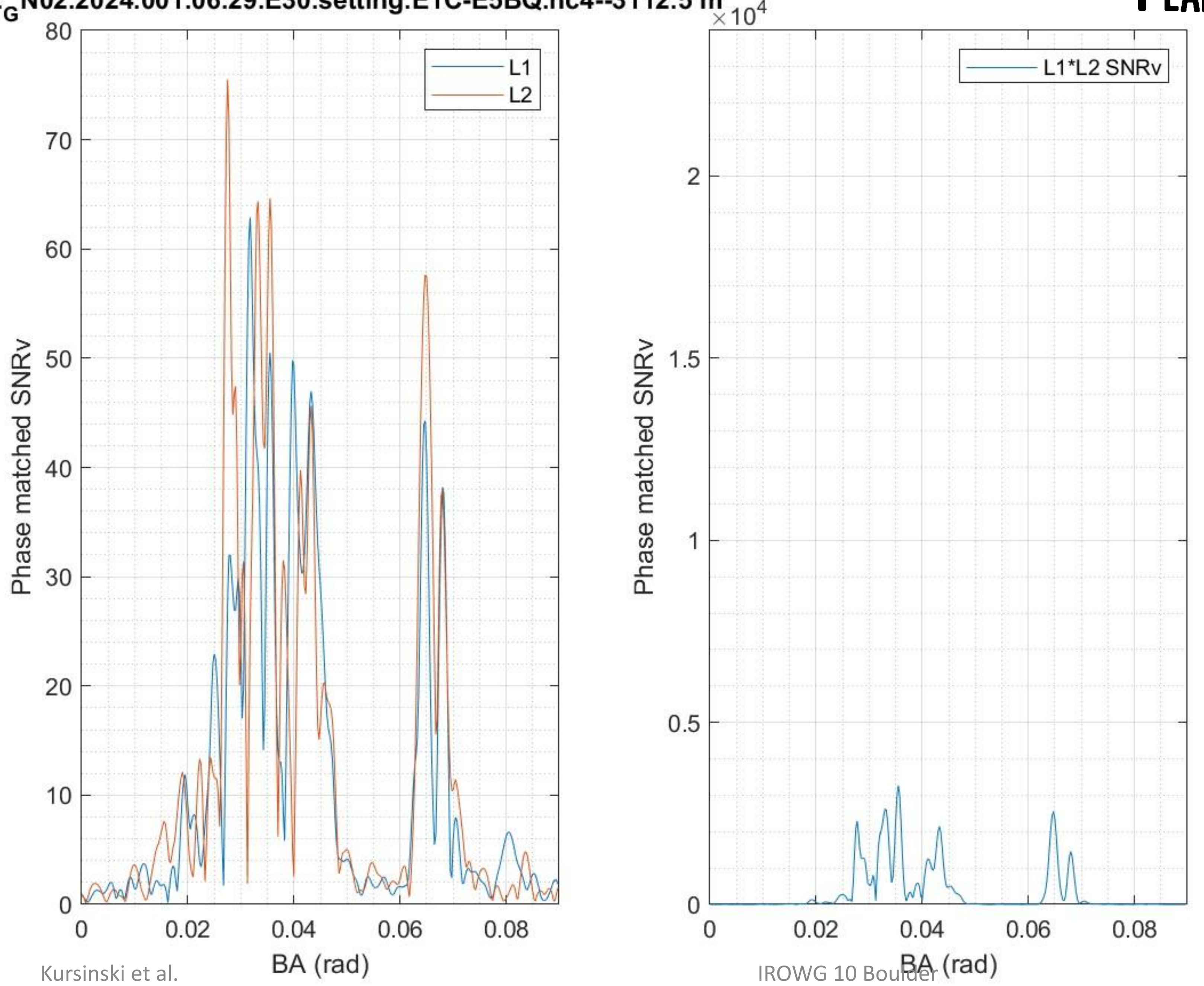

L1xL2 SNRv -piqLv2GN02.2024.001.06.29.E30.setting.E1C-E5BQ.nc4
L2 2D BA(IH)
SNR max of L1xL2)
lin wgt SNR max of L1xL2)
sqr wgt SNR max of L1xL2
UCAR
impact height (m)
bending angle(rad)

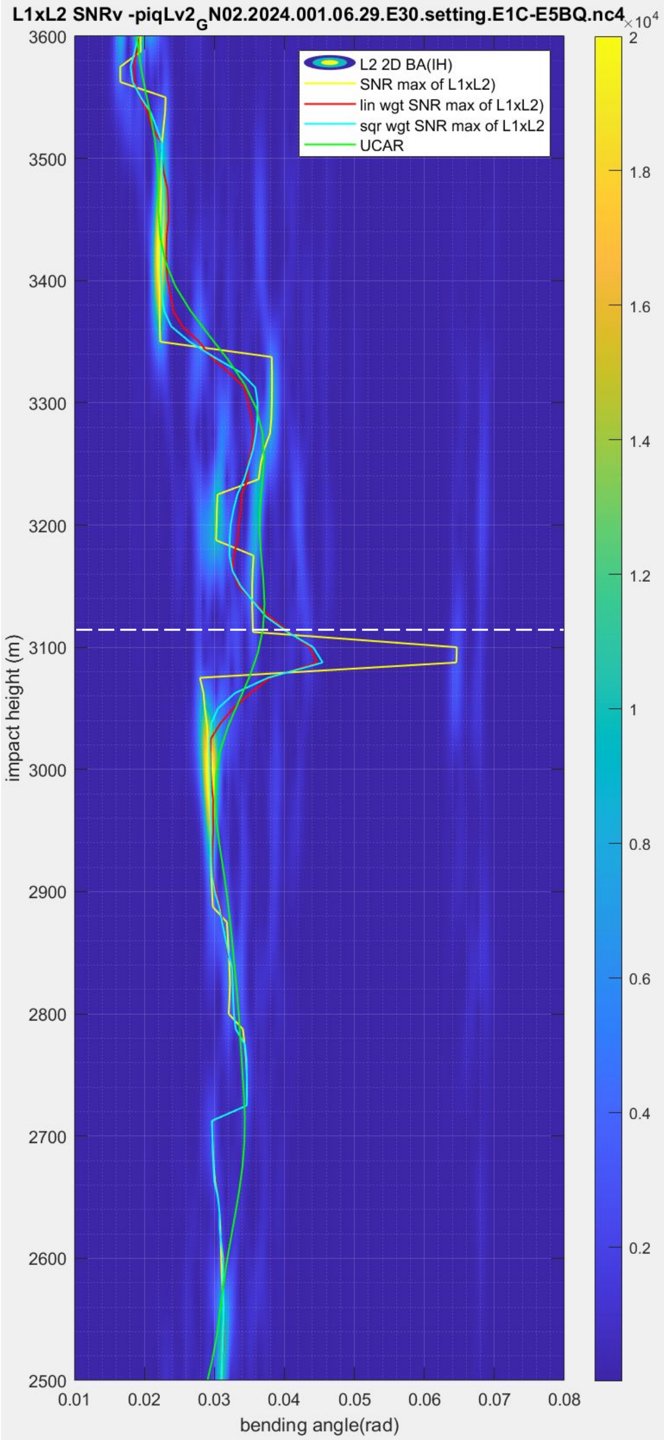

piqLv2GN02.2024.001.06.29.E30.setting.E1C-E5BQ.nc4--3125 m
L1
L2
Phase matched SNRv
BA (rad)
0
10
20
30
40
50
60
70
80
0
0.02
0.04
0.06
0.08


×10^4
L1*L2 SNRv
Phase matched SNRv
BA (rad)
0
0.5
1
1.5
2
0
0.02
0.04
0.06
0.08


L1xL2 SNRv -piqLv2GN02.2024.001.06.29.E30.setting.E1C-E5BQ.nc4
L2 2D BA(IH)
SNR max of L1xL2)
lin wgt SNR max of L1xL2)
sqr wgt SNR max of L1xL2
UCAR
impact height (m)
bending angle(rad)
×10^4
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

piqLv2GN02.2024.001.06.29.E30.setting.E1C-E5BQ.nc4--3112.5 m





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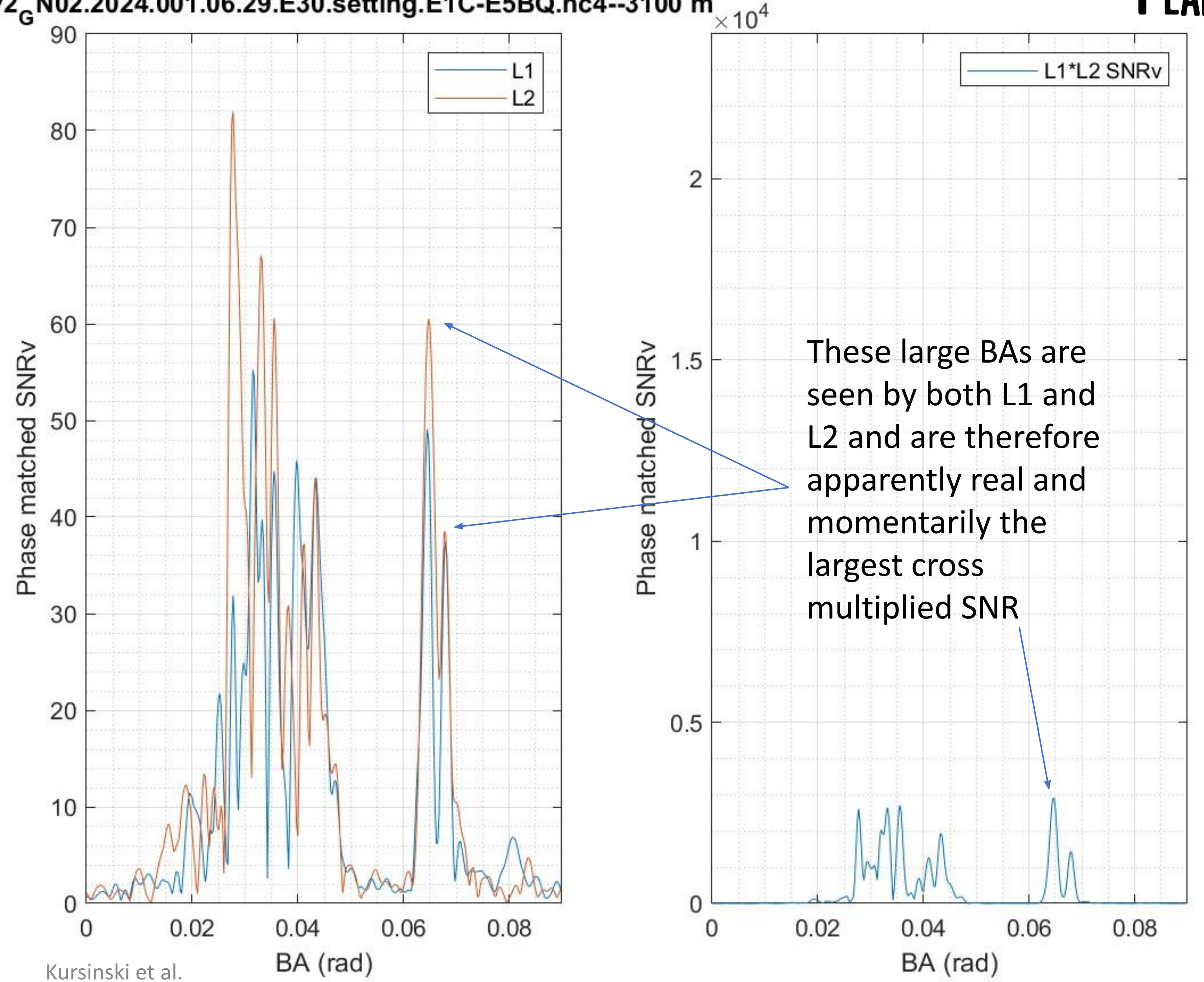
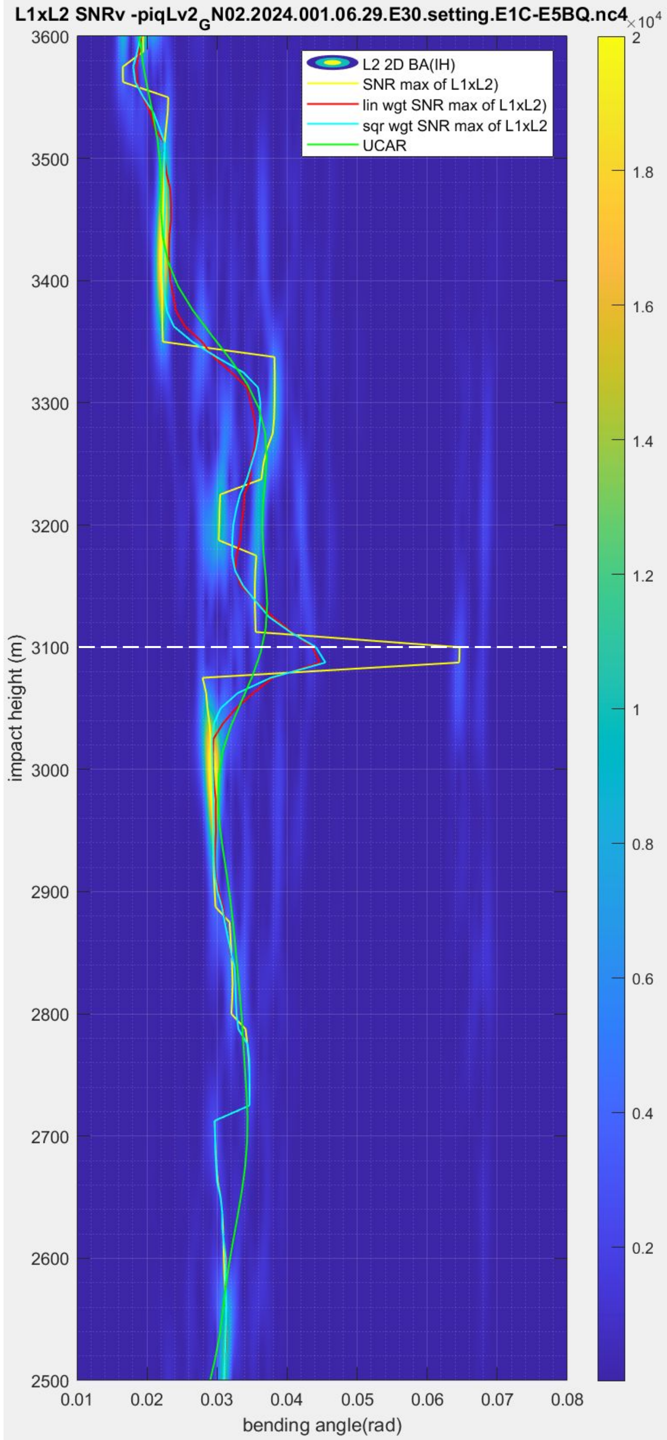
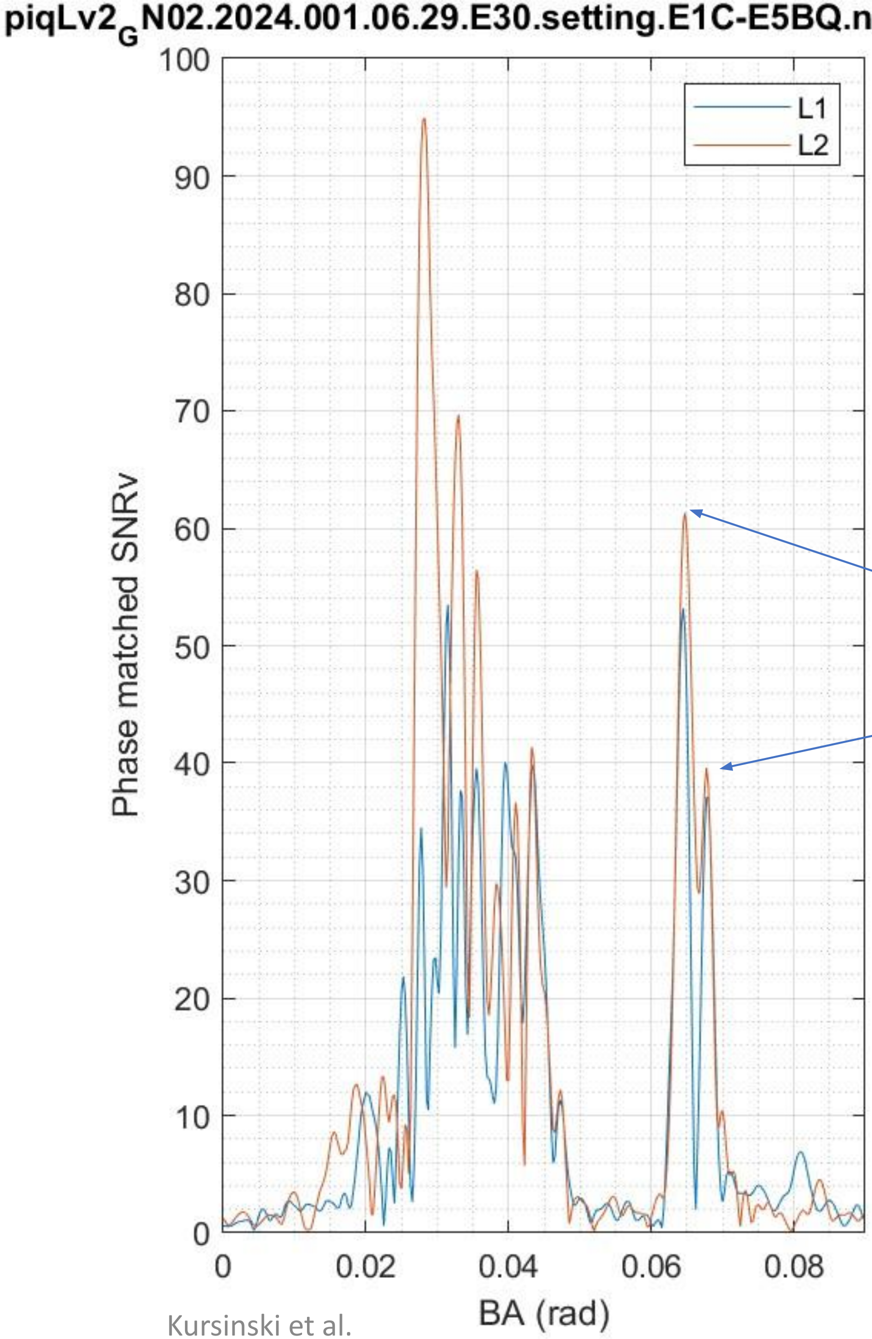
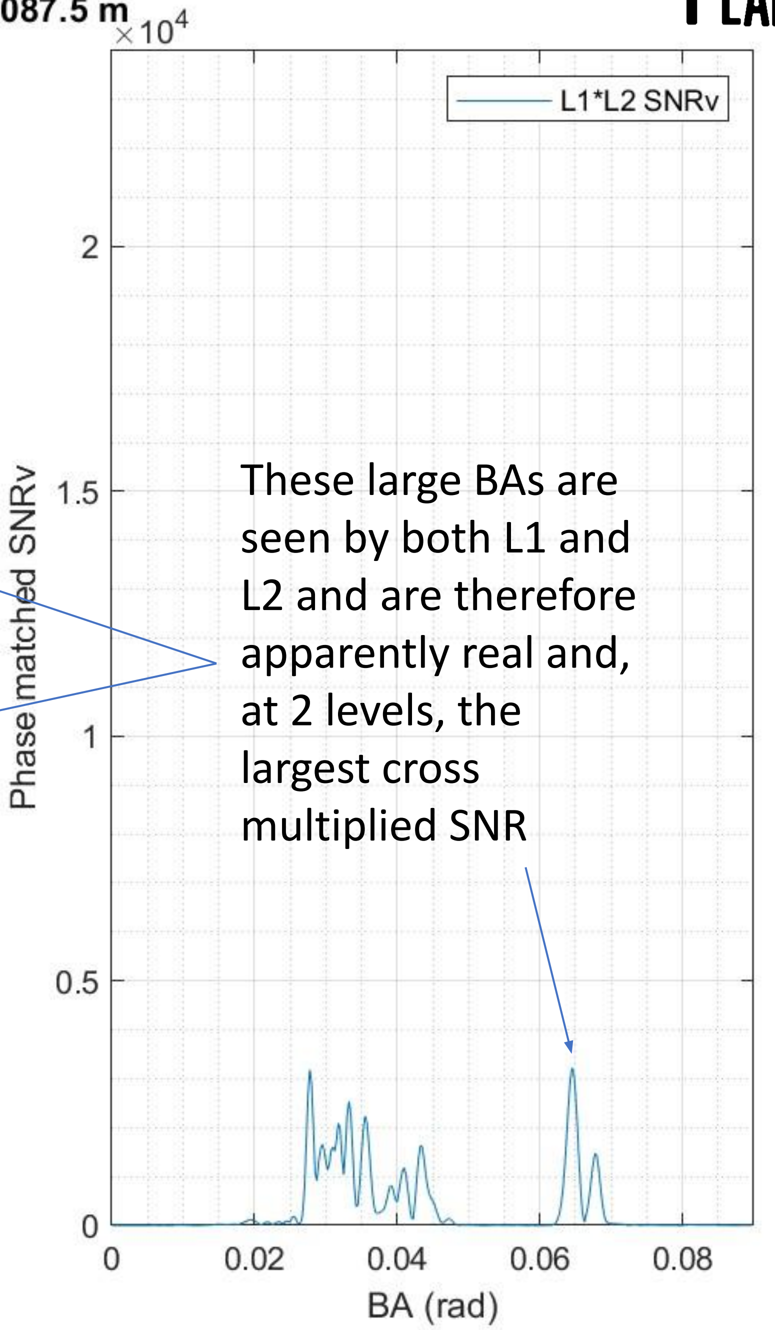
piqLv2$_G$N02.2024.001.06.29.E30.setting.E1C-E5BQ.nc4--3100 m





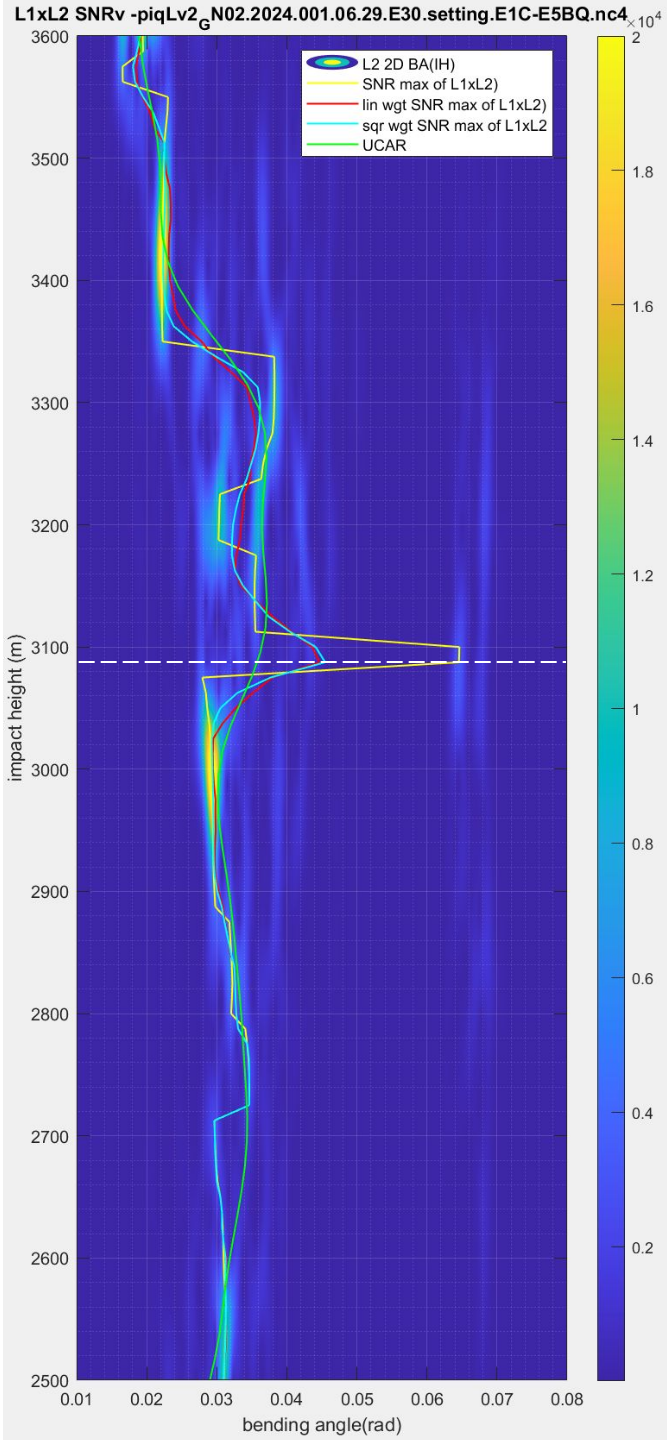
Kursinski et al.



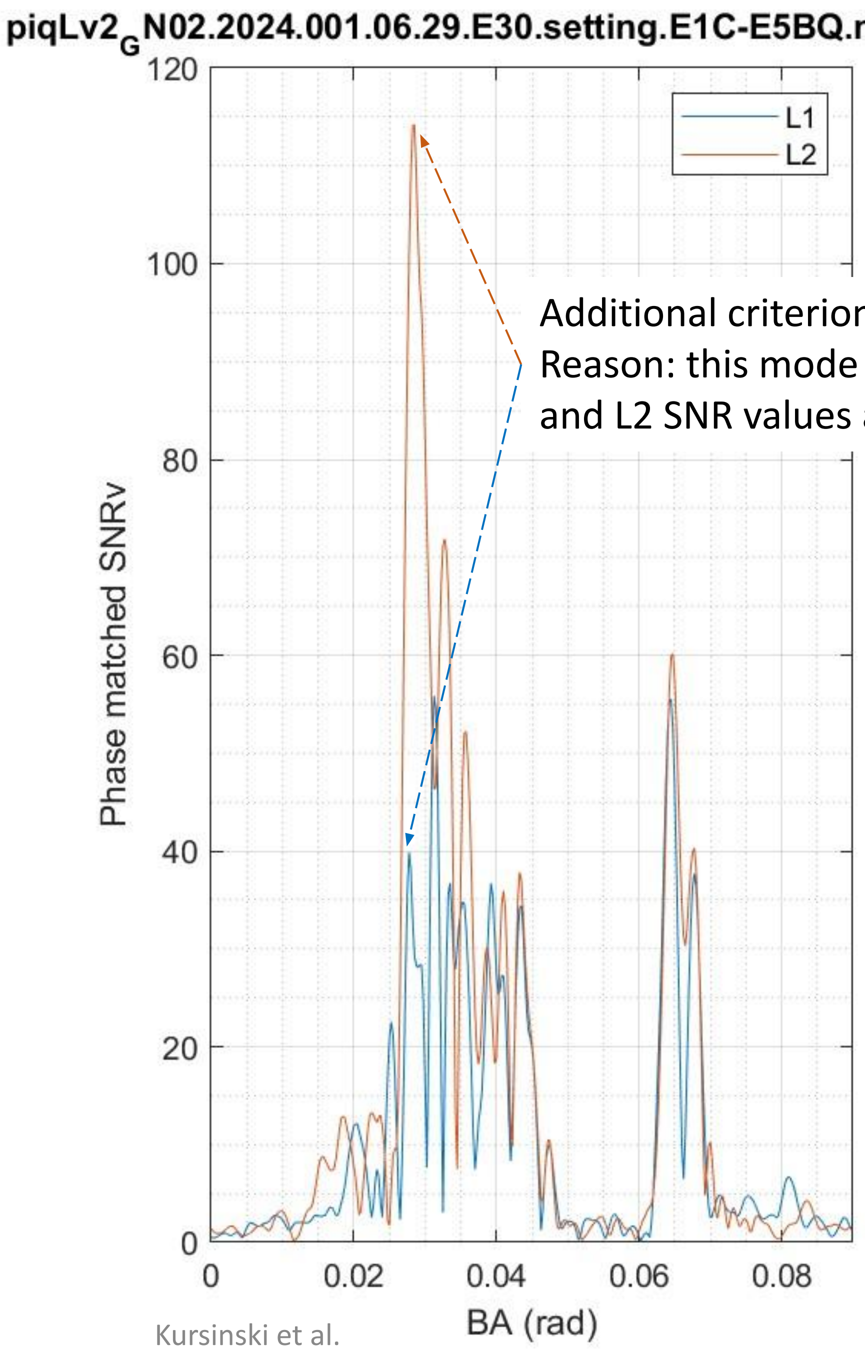


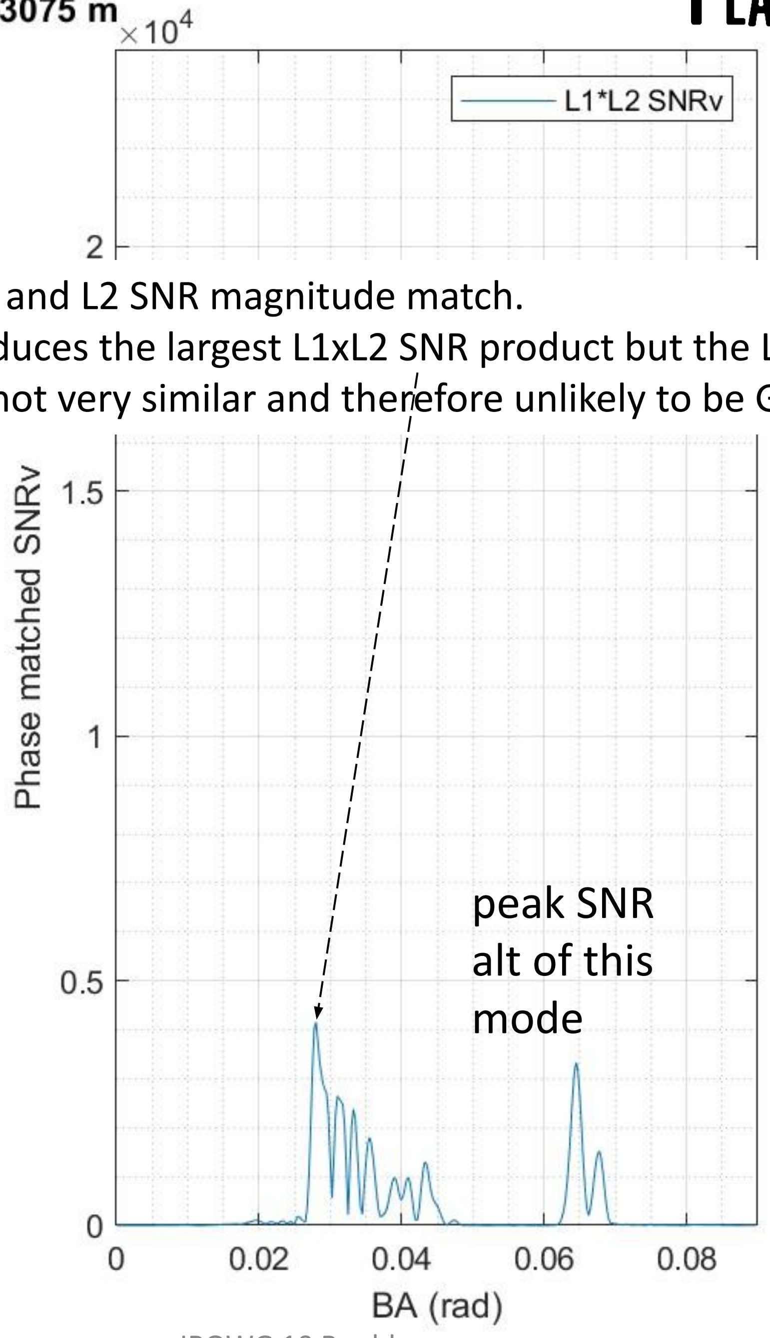
These large BAs are seen by both L1 and L2 and are therefore apparently real and, at 2 levels, the largest cross multiplied SNR

PLANETiQ



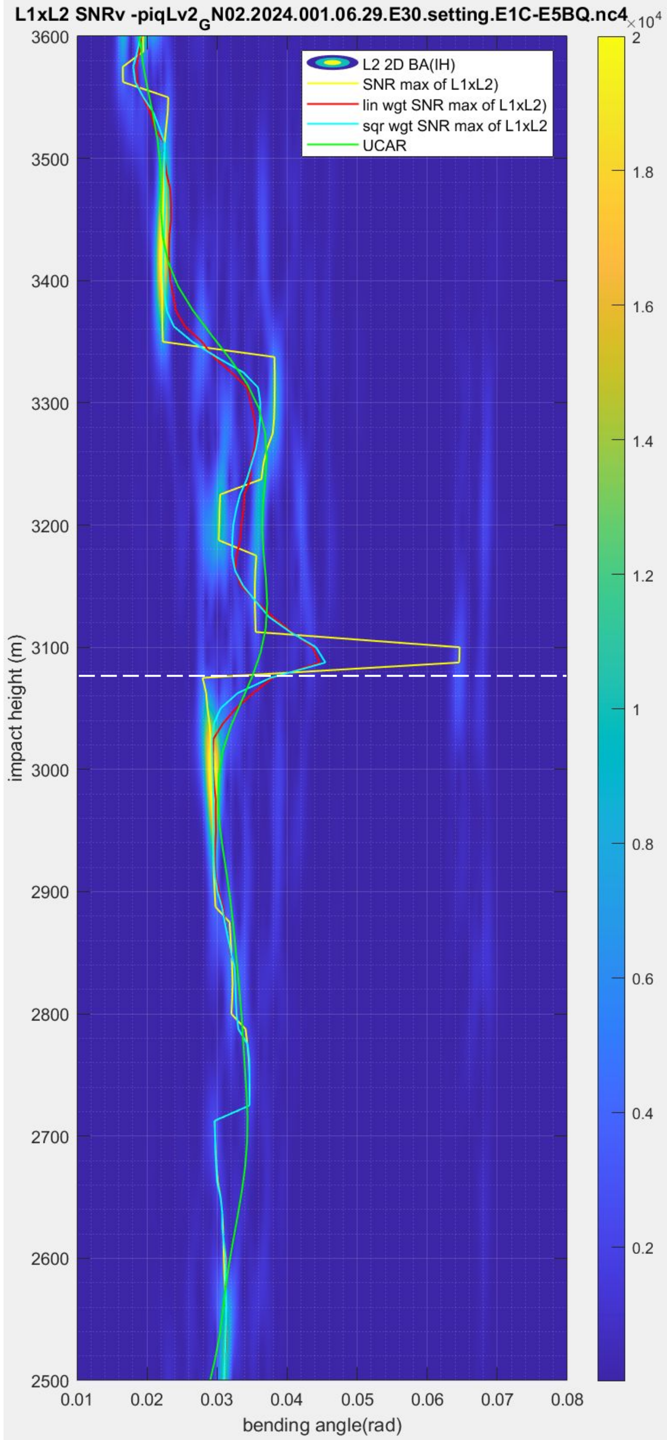
Kursinski et al.

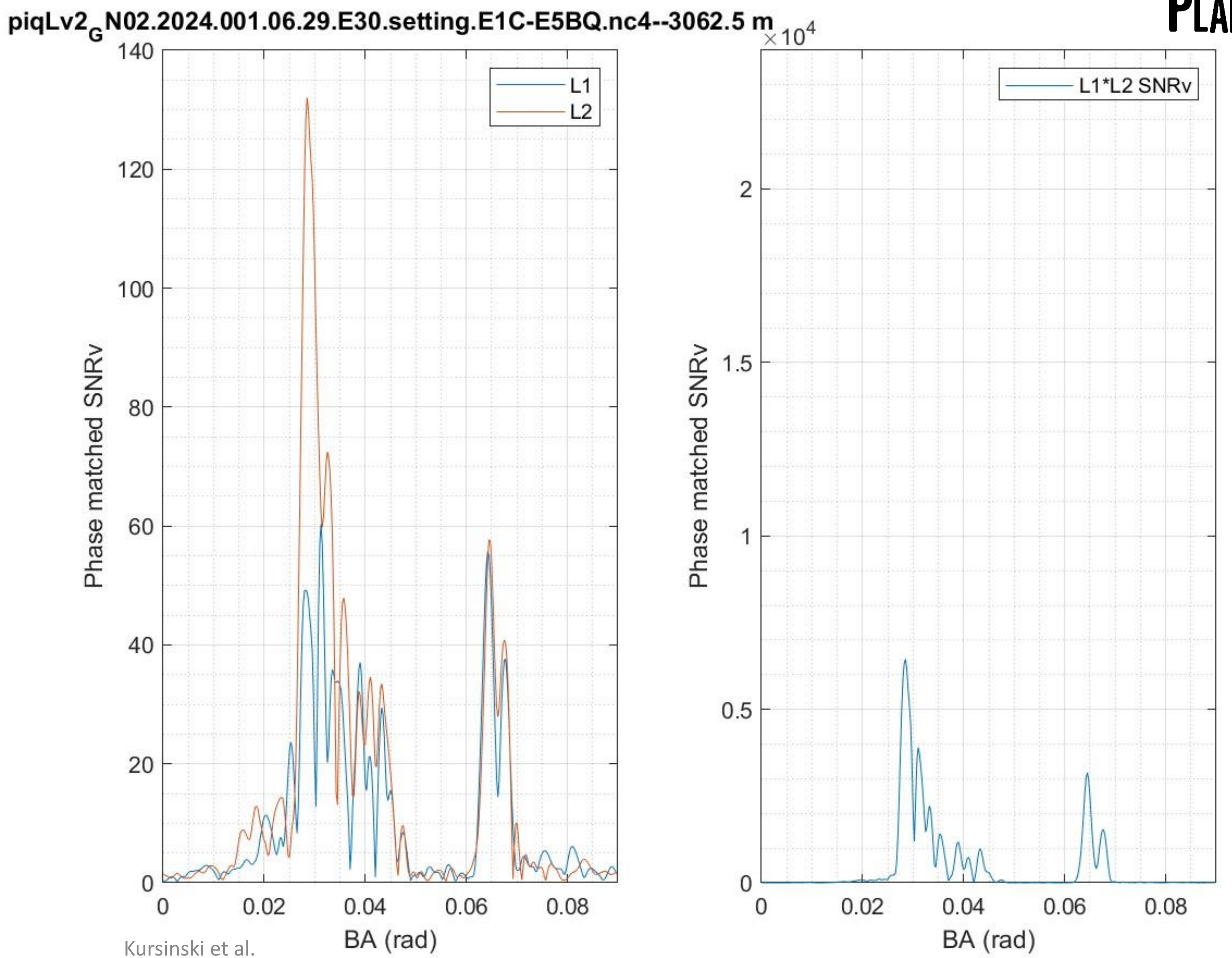


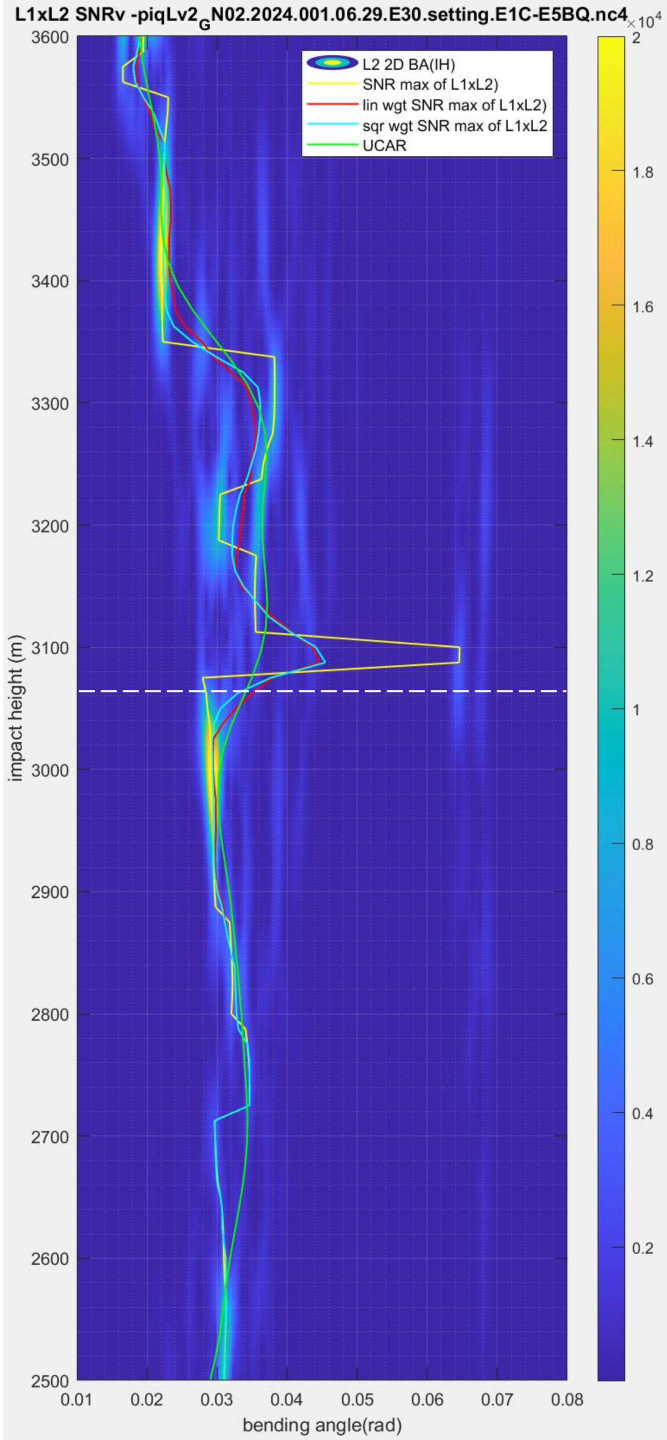


Additional criterion: L1 and L2 SNR magnitude match.
Reason: this mode produces the largest L1xL2 SNR product but the L1 and L2 SNR values are not very similar and therefore unlikely to be GO.

peak SNR alt of this mode




piqLv2GN02.2024.001.06.29.E30.setting.E1C-E5BQ.nc4--3062.5 m
L1
L2
Phase matched SNRv
BA (rad)
L1*L2 SNRv
×10^4
Phase matched SNRv
BA (rad)


L1xL2 SNRv -piqLv2GN02.2024.001.06.29.E30.setting.E1C-E5BQ.nc4
L2 2D BA(IH)
SNR max of L1xL2)
lin wgt SNR max of L1xL2)
sqr wgt SNR max of L1xL2
UCAR
impact height (m)
bending angle(rad)
×10^4

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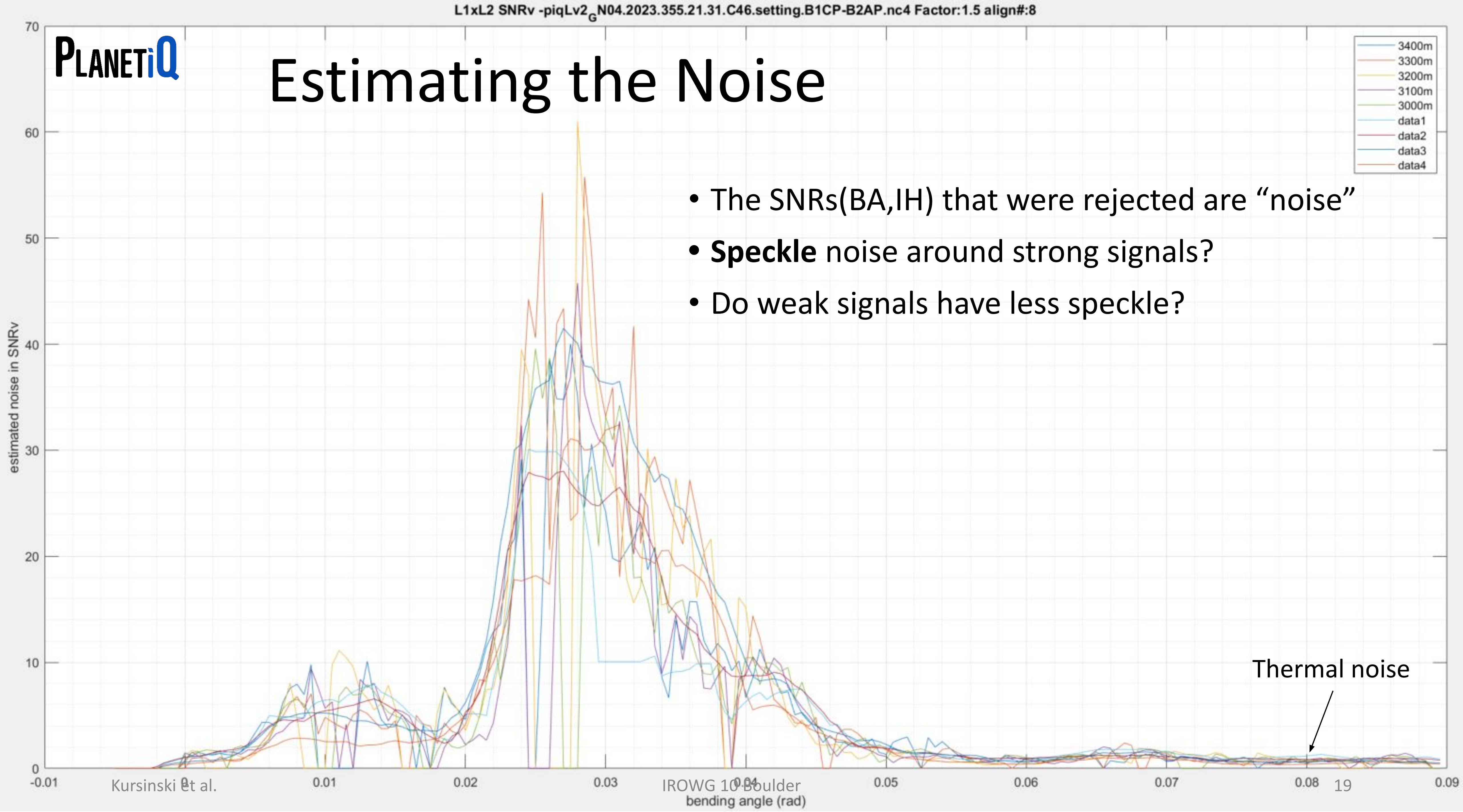
Estimating the Noise

- The SNRs(BA,IH) that were rejected are "noise"
- **Speckle** noise around strong signals?
- Do weak signals have less speckle?



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Close Sonde Collocation Examples

- Using high resolution radiosonde profiles with ~ 10 m vertical sampling
- Collocation criteria: within ±3 hours and 60 km in the lower part of the profile
- Found 28 collocations out of >30,000 RO = 1 in 1,000

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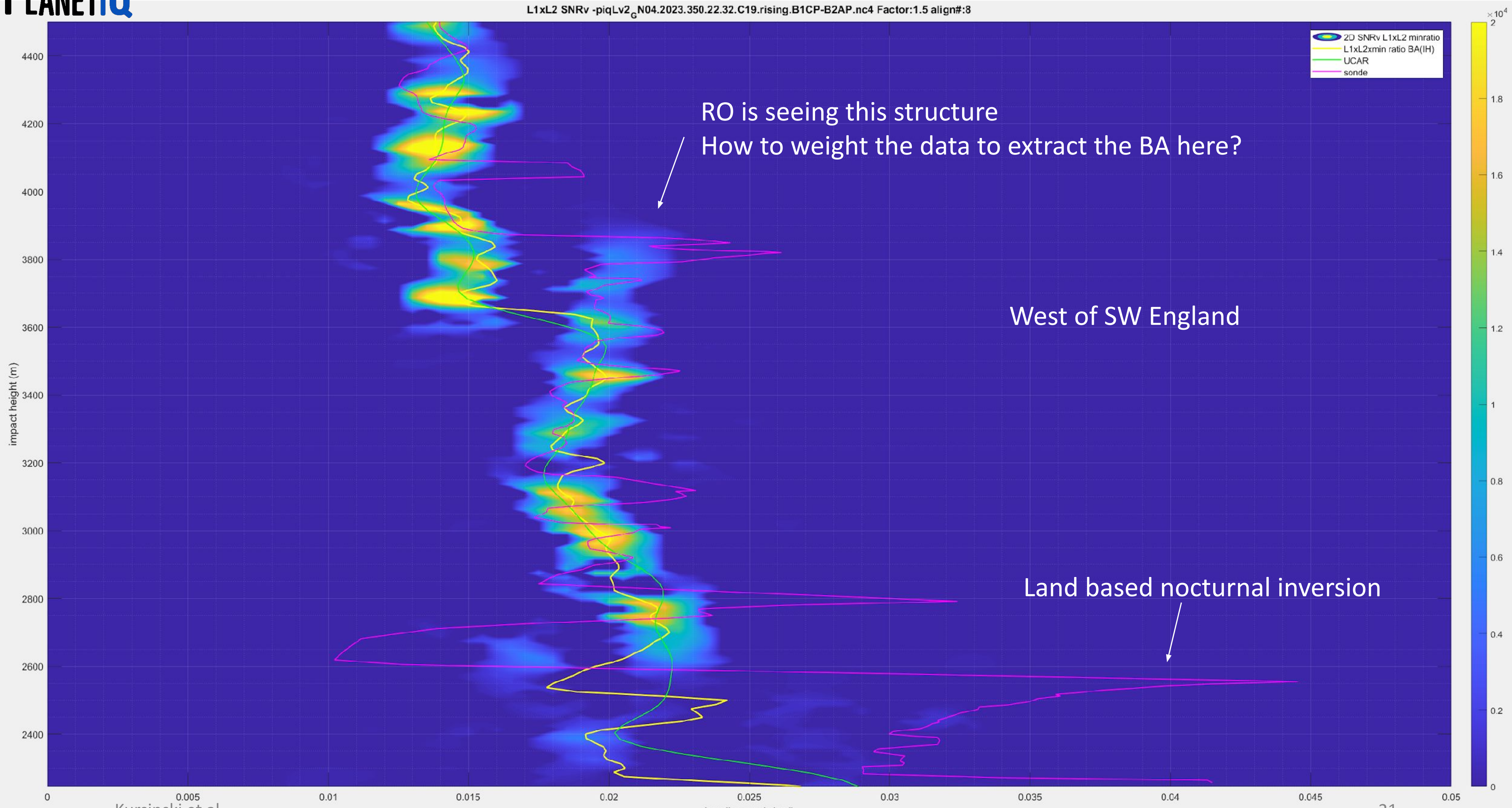
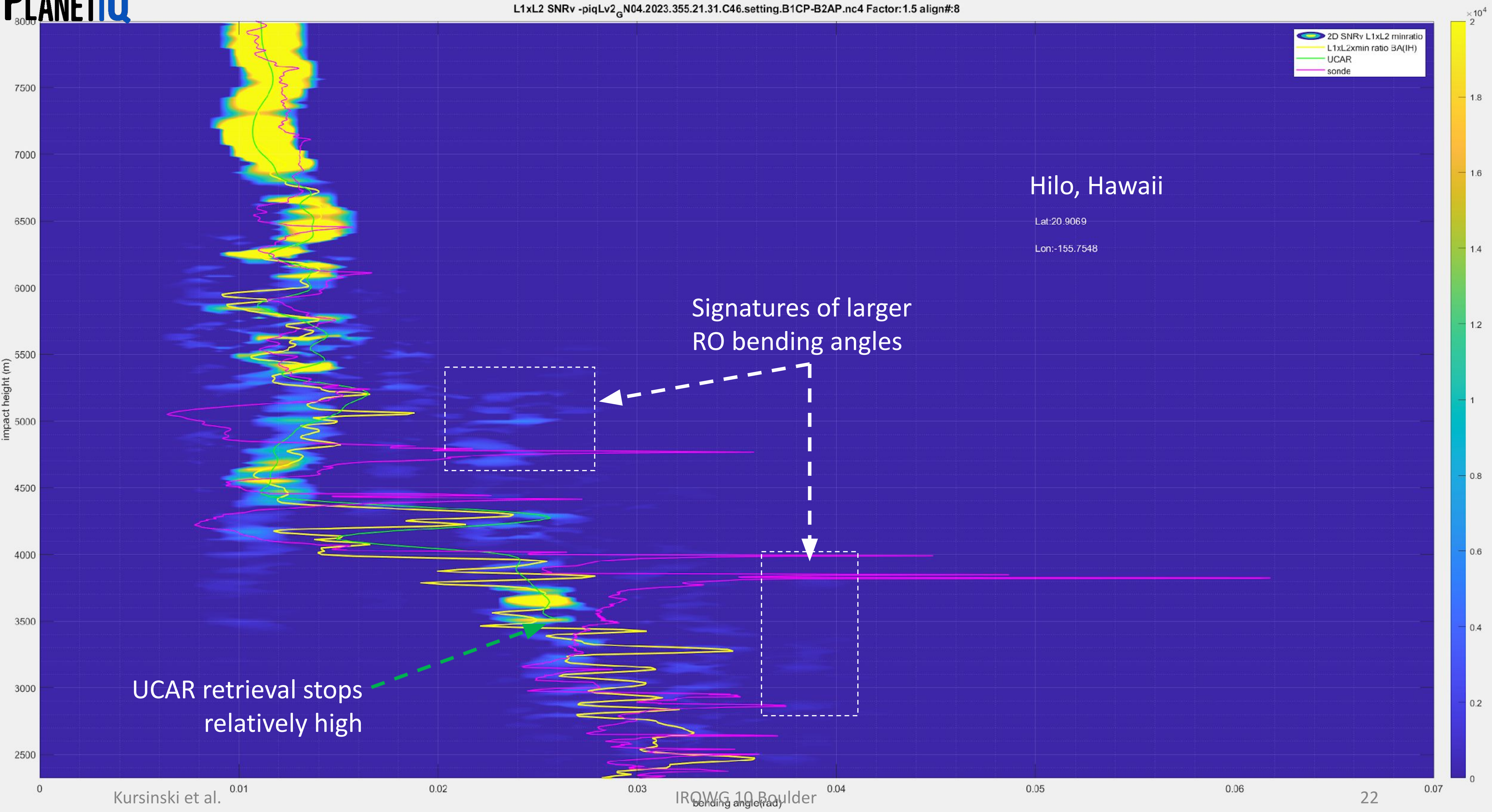

L1xL2 SNRv -piqLv2_GN04.2023.350.22.32.C19.rising.B1CP-B2AP.nc4 Factor:1.5 align#:8
2D SNRv L1xL2 minratio
L1xL2xmin ratio BA(IH)
UCAR
sonde
impact height (m)
bending angle(rad)
×10^4
RO is seeing this structure
How to weight the data to extract the BA here?
West of SW England
Land based nocturnal inversion



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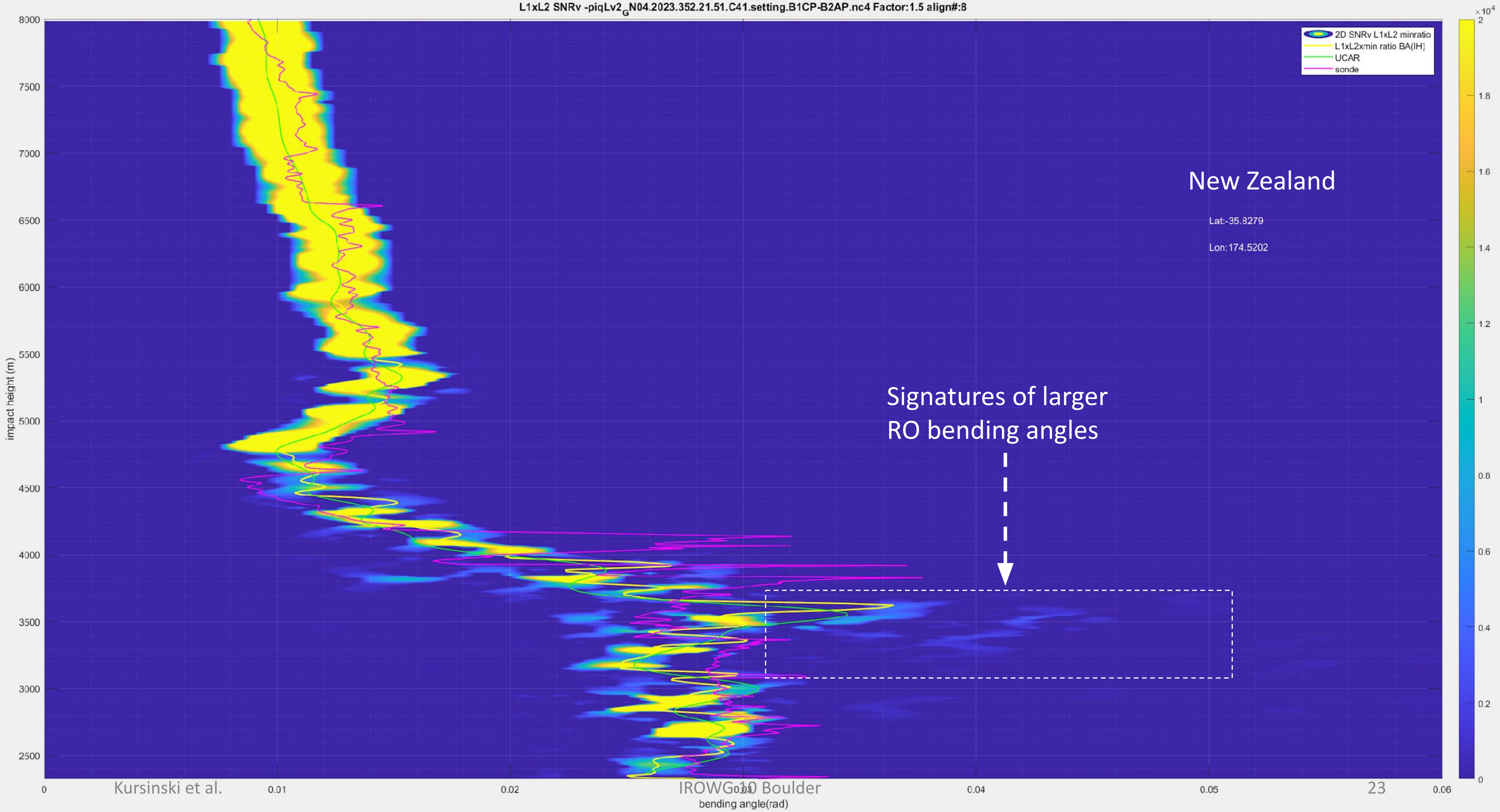
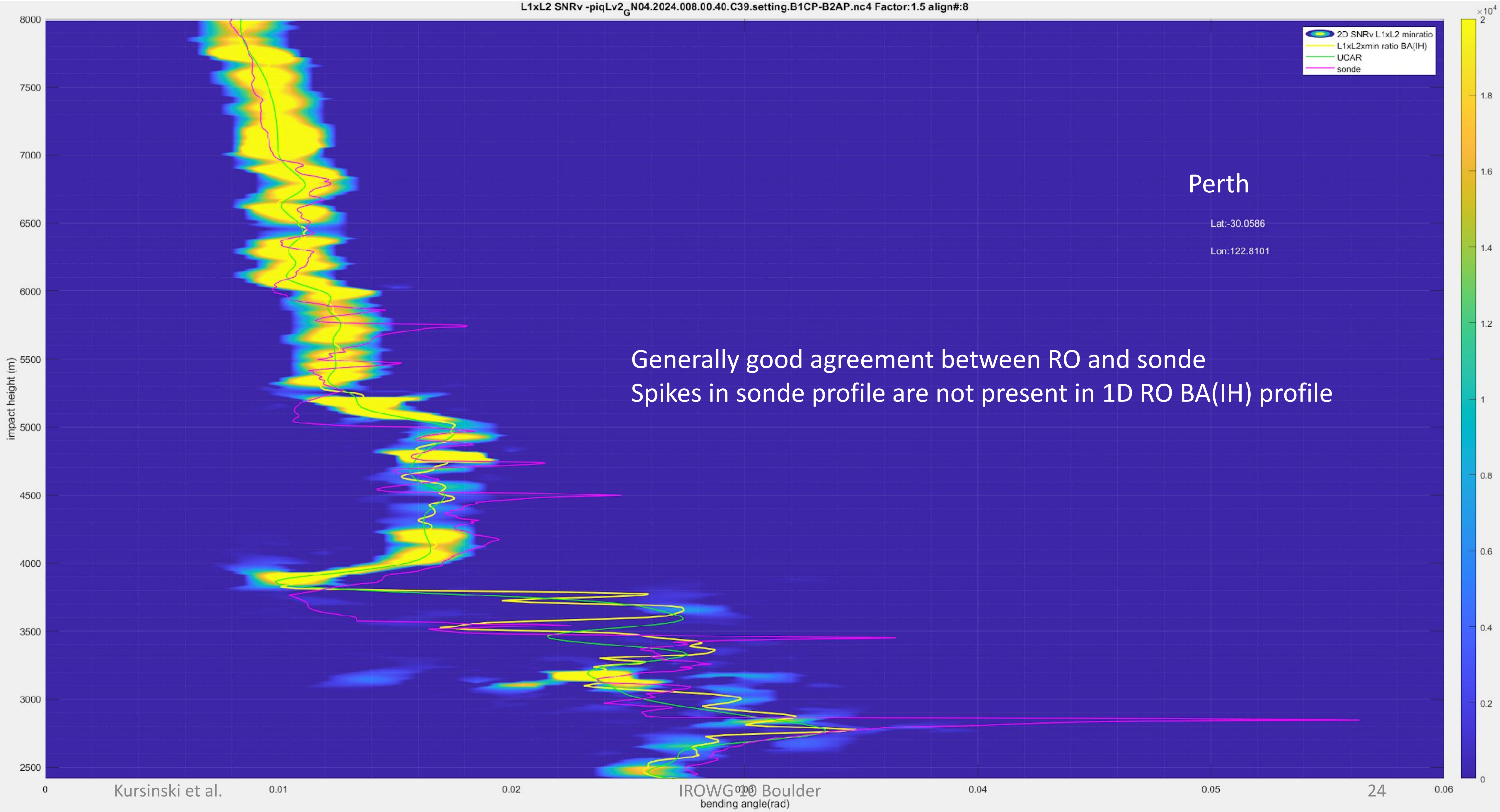
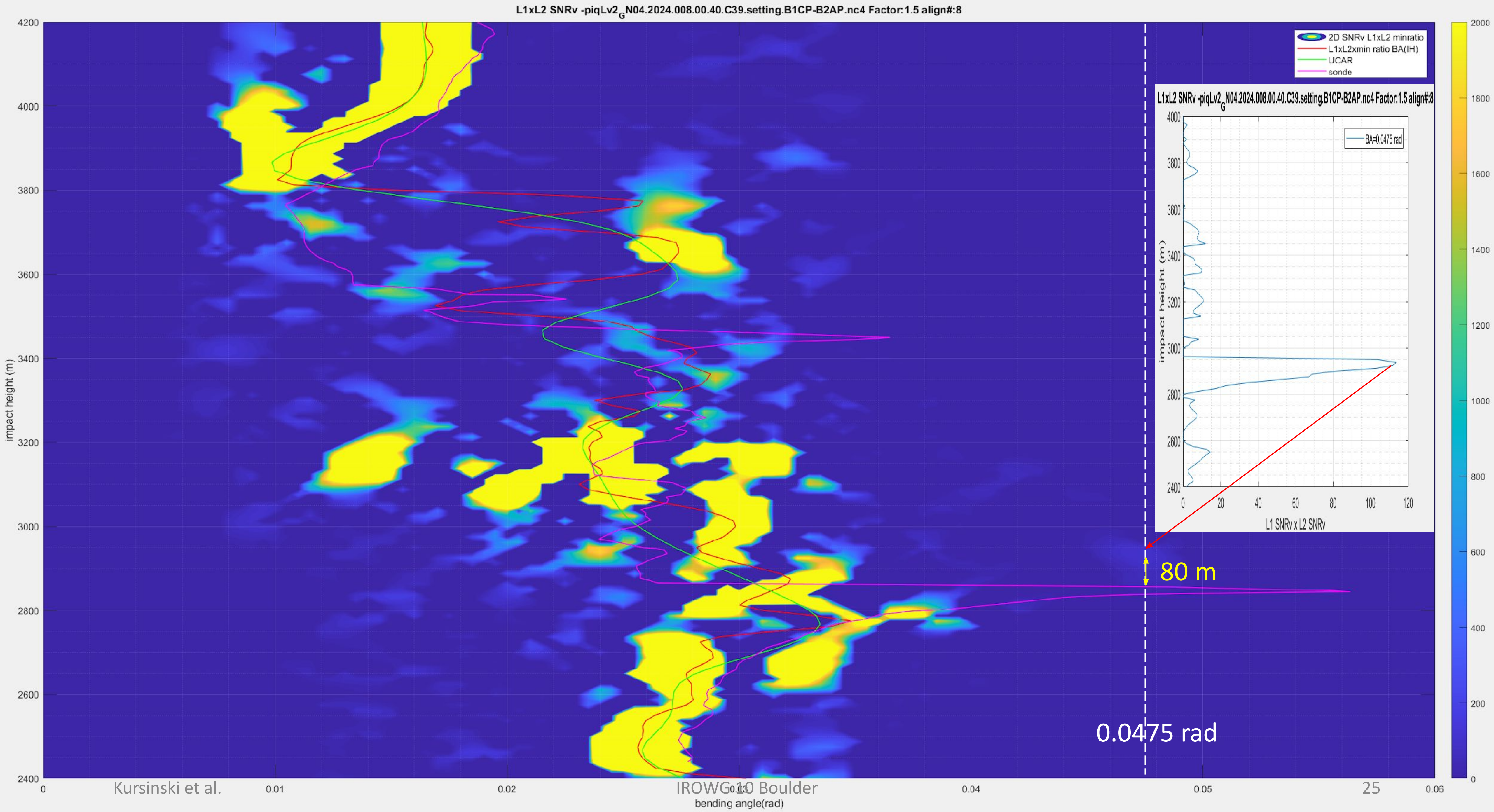
L1xL2 SNRv -piqLv2_G N04.2023.355.21.31.C46.setting.B1CP-B2AP.nc4 Factor:1.5 align#:8
2D SNRv L1xL2 minratio
L1xL2xmin ratio BA(IH)
UCAR
sonde
Hilo, Hawaii
Lat:20.9069
Lon:-155.7548
Signatures of larger RO bending angles
UCAR retrieval stops relatively high
impact height (m)
bending angle(rad)



L1xL2 SNRv -piqLv2_GN04.2023.352.21.51.C41.setting.B1CP-B2AP.nc4 Factor:1.5 align#:8
2D SNRv L1xL2 minratio
L1xL2xmin ratio BA(IH)
UCAR
sonde
New Zealand
Lat:-35.8279
Lon:174.5202
Signatures of larger RO bending angles
impact height (m)
bending angle(rad)



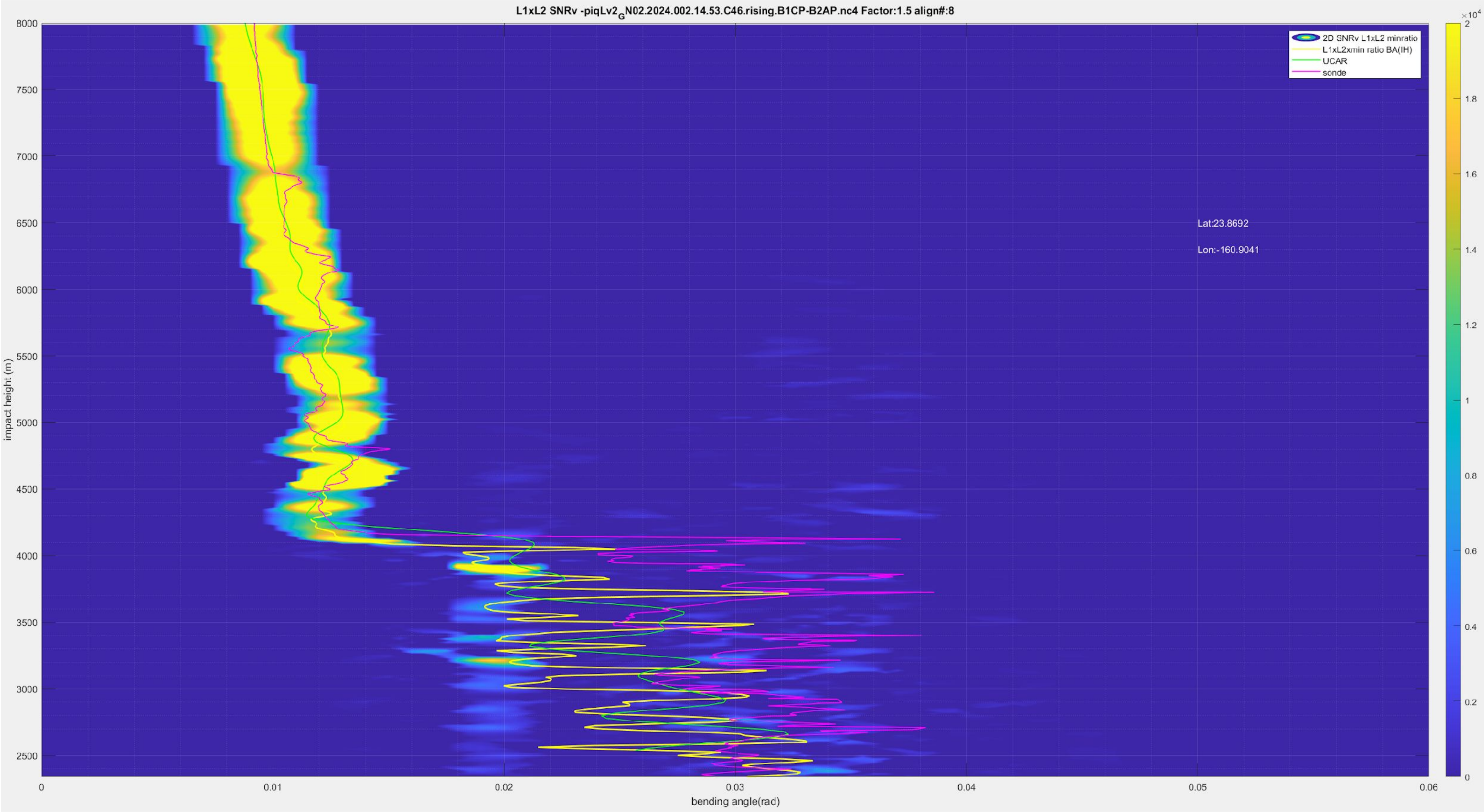
L1xL2 SNRv -piqLv2_GN04.2024.008.00.40.C39.setting.B1CP-B2AP.nc4 Factor:1.5 align#:8
2D SNRv L1xL2 minratio
L1xL2xmin ratio BA(IH)
UCAR
sonde
Perth
Lat:-30.0586
Lon:122.8101
Generally good agreement between RO and sonde
Spikes in sonde profile are not present in 1D RO BA(IH) profile
impact height (m)
bending angle(rad)
×10^4



L1xL2 SNRv -piqLv2_G N04.2024.008.00.40.C39.setting.B1CP-B2AP.nc4 Factor:1.5 align#:8
impact height (m)
bending angle(rad)
2D SNRv L1xL2 minratio
L1xL2xmin ratio BA(IH)
UCAR
sonde
L1xL2 SNRv -piqLv2_G N04.2024.008.00.40.C39.setting.B1CP-B2AP.nc4 Factor:1.5 align#:8
BA=0.0475 rad
L1 SNRv x L2 SNRv
80 m
0.0475 rad

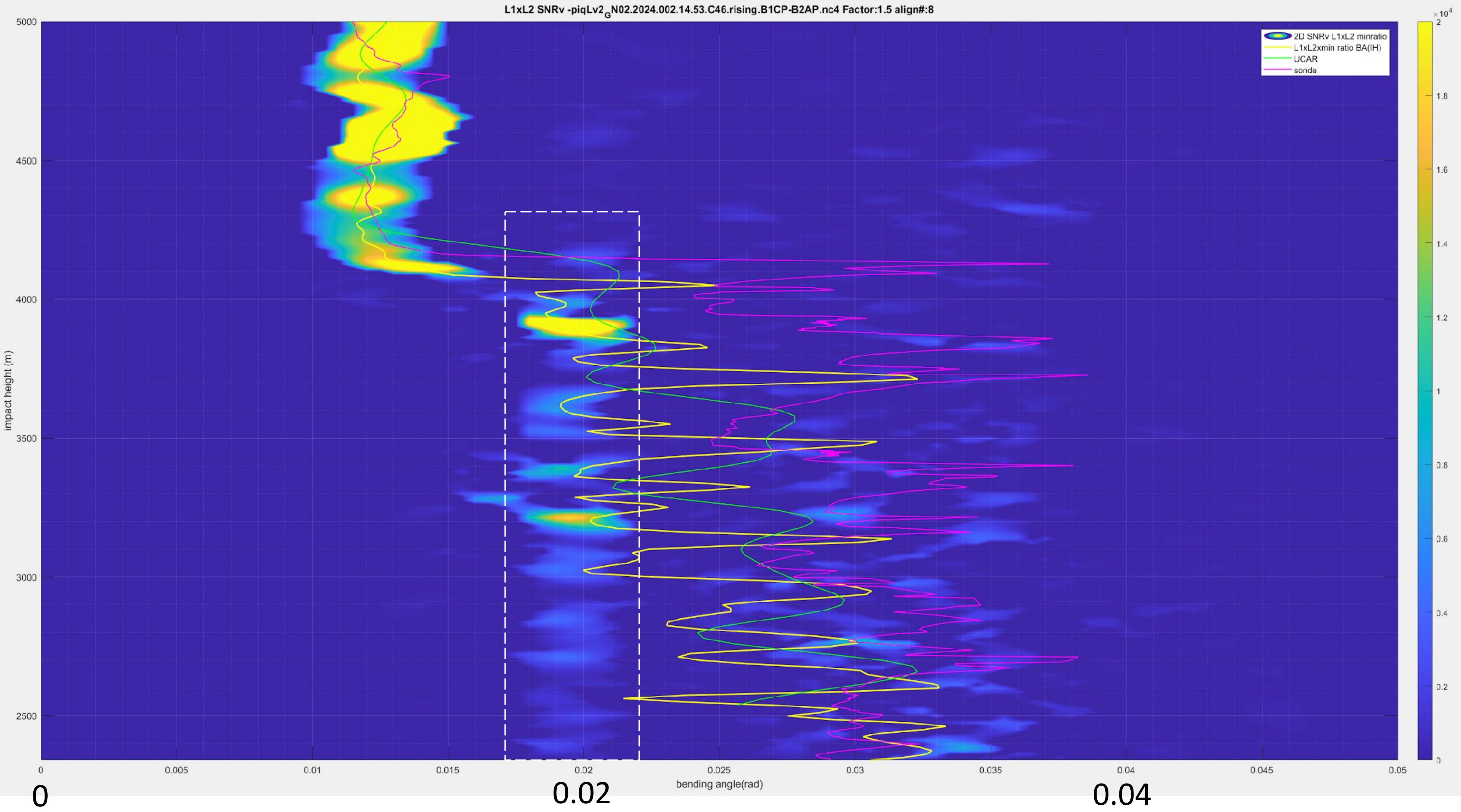
Lihue, Hawaii

- Sharply topped PBL around 4100 m
- RO picks up the height of the PBL top pretty well
- However, the RO BAs in the PBL are largely underestimated relative to the sonde



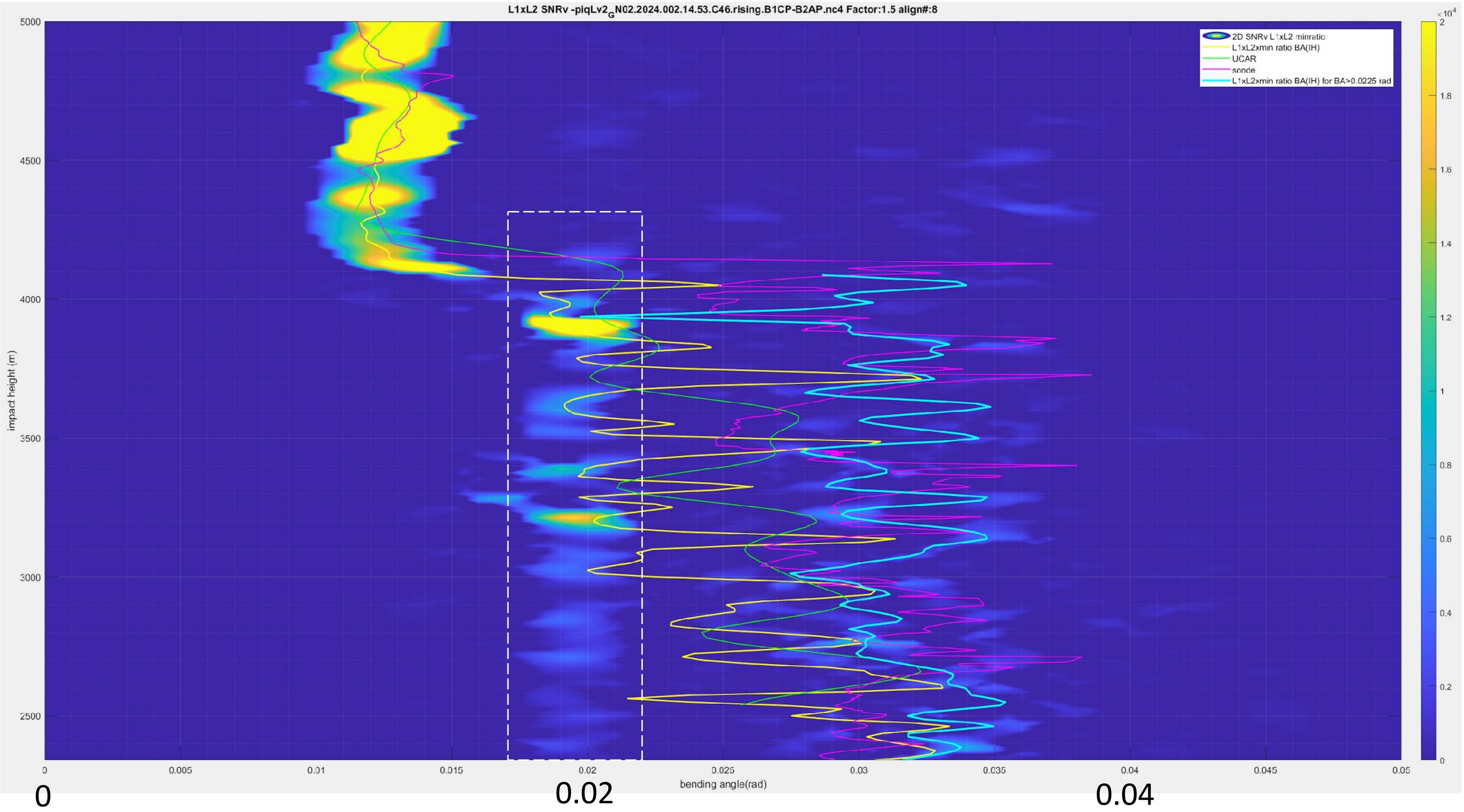
Lihue, Hawaii (zoomed in)

- The column of relatively high SNRs at BA=0.02 rad looks odd and possibly erroneous.
- It looks like it was vertically smeared somehow
- Note that it does not extend above the top of the BL implying it is a real atmospheric effect
- Perhaps it is due to a convection within the BL?



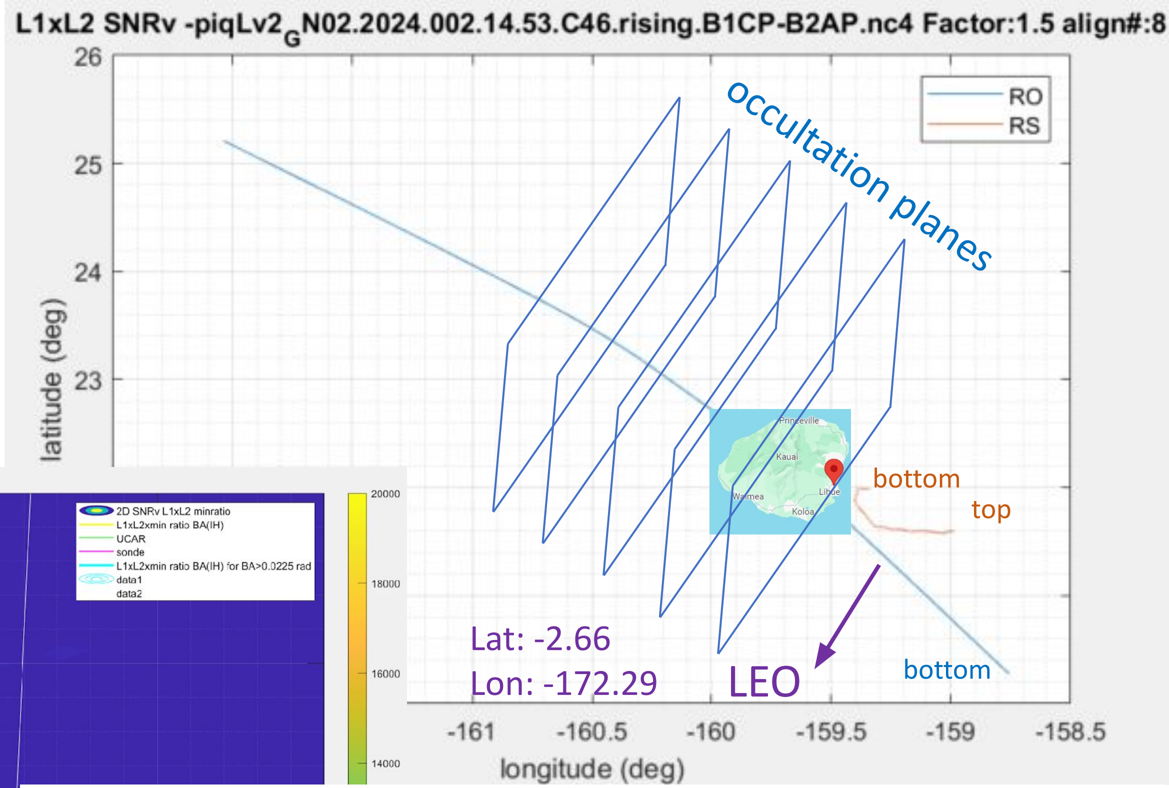
Lihue, Hawaii (zoomed in)

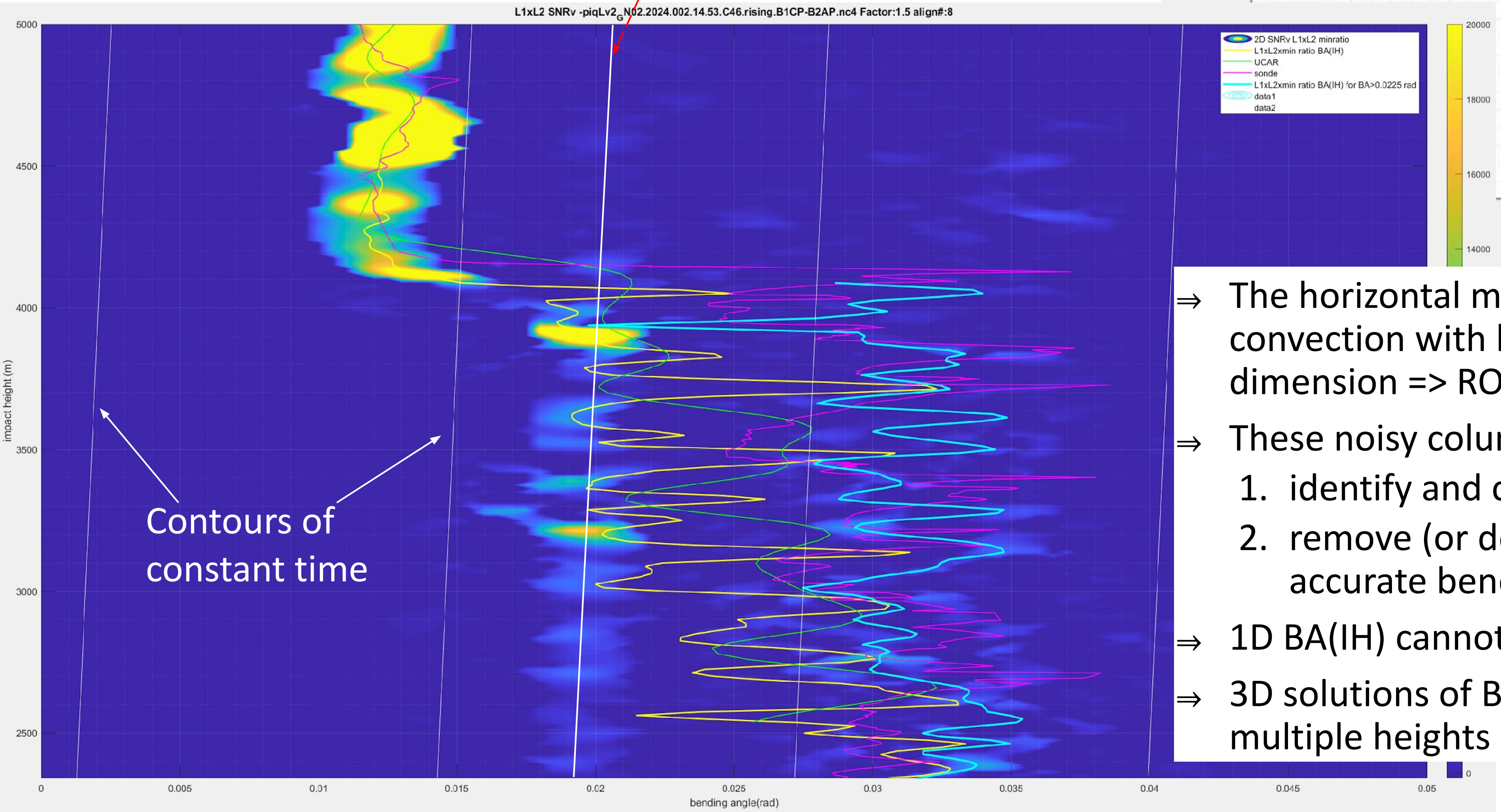
- There is almost no signal SNR at BAs slightly larger than 0.0225 rad.
- Try another bending angle retrieval avoiding that column…
- The cyan line shows the RO BAs derived up to IH=4100 m **using only SNRs for BA>0.0225 rad**
- Overall, the cyan line matches the sonde BA profile much better than the yellow RO profile
- What is going on here?!!



PlanetiQ Some Implications

- The noisy column occurs essentially at one time implying an occultation plane which is "noisy".
- Hypothesis: Noisy BA(IH) column is due to convection over Kauai whereas the surrounding air over the ocean is less convective (because this is January 2 = winter)



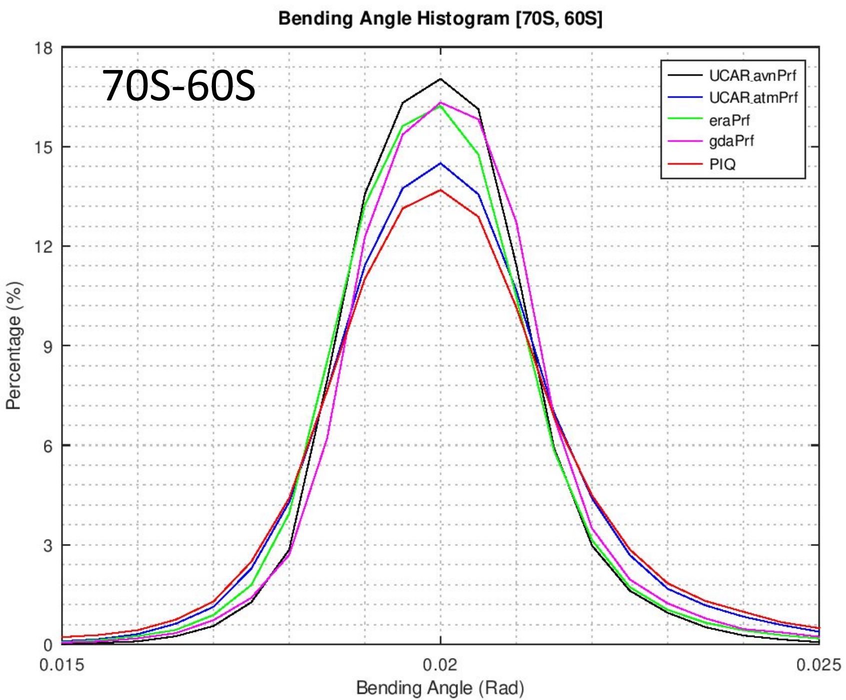


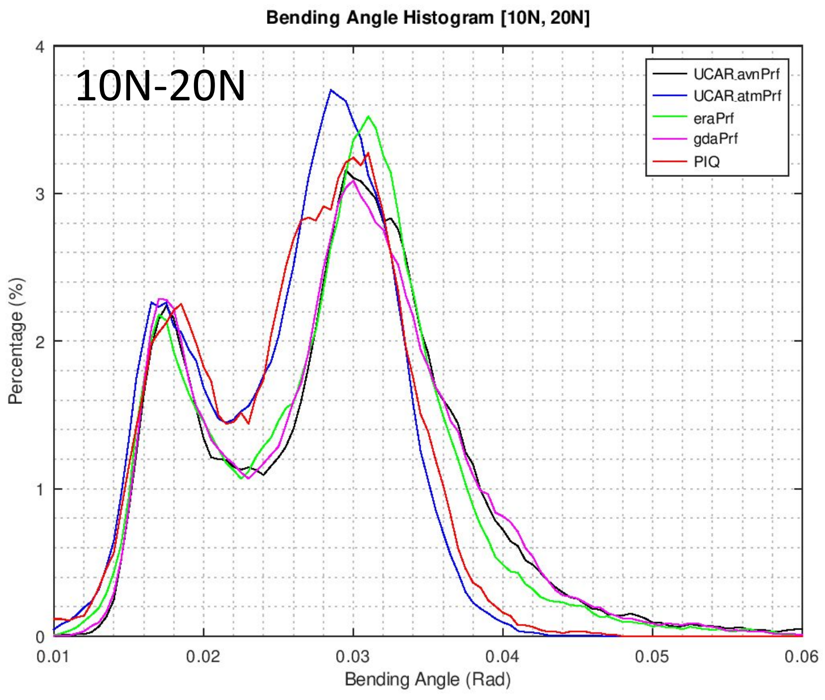
- ⇒ The horizontal motion of RO ray paths senses convection with horiz. resolution in the cross track dimension => RO is providing 3D information
- ⇒ These noisy columns/planes must be isolated to
  1. identify and characterize convection and
  2. remove (or de-weight) them to derive more accurate bending angles
- ⇒ 1D BA(IH) cannot represent what RO is sensing.
- ⇒ 3D solutions of BA(IH, lat, lon, time) are required with multiple heights allowed in each occultation plane

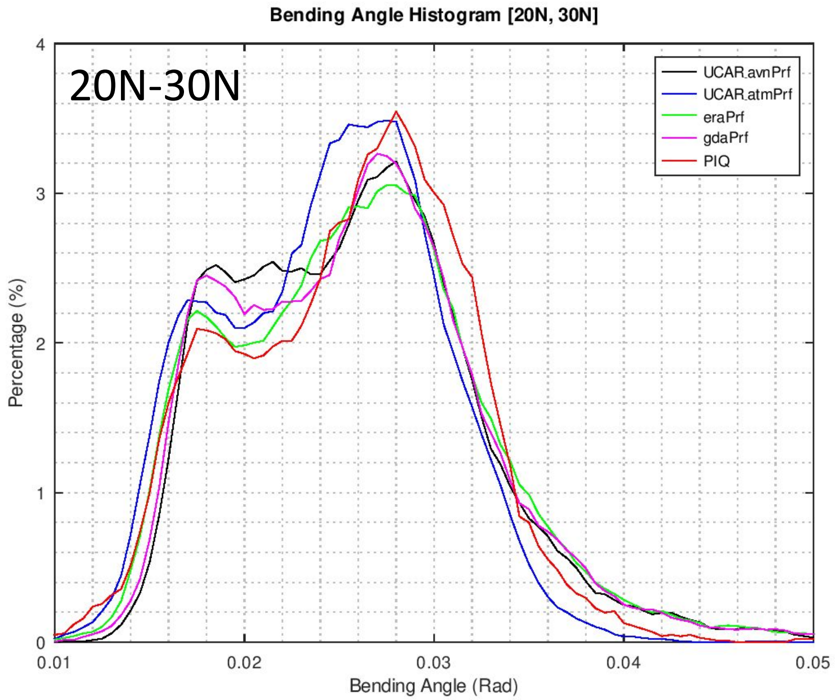
Bending angle histogram comparisons of our new retrievals by latitude at 3km impact height

- avnPrf (lower res NOAA 12 hr forecast)
- GDAS (high res)
- ERA5
- UCAR atmPrf
- PlanetiQ retrieval

At low latitudes, RO is not capturing the large bending angles but our preliminary retrievals are capturing a bit more of the large bending angles than the UCAR retrievals. More work is needed







Preliminary Conclusions

- This is a work in progress on examining bending angles in the LTBL
- Wide variety of behavior observed in LTBL dependent on latitude, season and weather
- Achieving 50-100m(?) vertical resolution to resolve PBL top for Xie et al. ducting method
  - Bangkok case demonstrates the very fine vertical resolution is real and tight collocation can be critical
- Value of higher SNR:
  - Detecting ducting AND frequency of detected ducting increases with higher SNR
  - Acquiring grazing reflections to use in solving the ducting BA vs N ambiguity,
  - Capturing signatures of large BAs and reducing negative bias in large bending angles
  - High SNR at L1 & L2 critical to isolating geometric optics solutions among diffraction (speckle) noise
- Our preliminary new retrievals
  - Use L1 and L2 to determine the optical “modes” common to both, to derive less noisy and more robust solutions as well as the speckle noise level
  - Generally agree with UCAR, particularly above 5 to 6 km where bending angles are relatively simple
  - Finer vertical resolution than UCAR retrievals
    - which also mean more variability, which NWP systems may not like
  - Profile deeper than UCAR profiles (no statistics yet on penetration depth)
  - Large bending angle improvement evaluated in part via Histograms
  - Lots more to be done

Preliminary Conclusions (cont'd)

- Noise:
  - Ionosphere scintillations can be a big source of noise,
  - **Speckle noise is present,** due to convection
  - Vertical columns of noise at constant time appear to be signatures of convection
  - Use understanding of noise in estimating BA uncertainty
- In the LTBL, given RO horizontal motion particularly at low latitudes, we need to think beyond 1D solutions
  - Much better solution is 3D: BA(IH, lat, lon, t)
  - Decompose each occultation into series of ~planes that the beam is sliding through
  - Finer horizontal resolution in cross track direction
    - Diffraction limited cross track horizontal resolution is 1.4 km
  - Properly account for lat-lon horizontal motion
  - Changes needed to BUFR to allow 3D bending angle retrievals (multiple bending angles at the same impact height)

PlanetiQ

Next steps

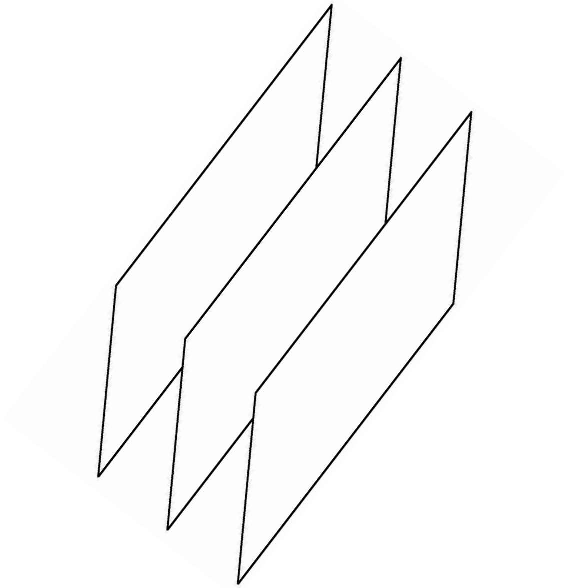
- Understand the signal and noise and SNR when **speckle** is present,
- Improve the weighting to account for defocusing
- Improve the weighting based on comparisons with high resolution sondes
- Comparisons with collocated high resolution sondes to evaluate overall performance and particularly how to interpret the large bending angles
- Move toward deriving 3D BA(IH, lon, lat, time)
- Estimate the BA(IH, lat, lon, time) uncertainty
- Can columns of noise associated with convection be isolated to
  1. identify and characterize convection?
  2. remove that data to better determine BA(IH, lon, lat, time)?

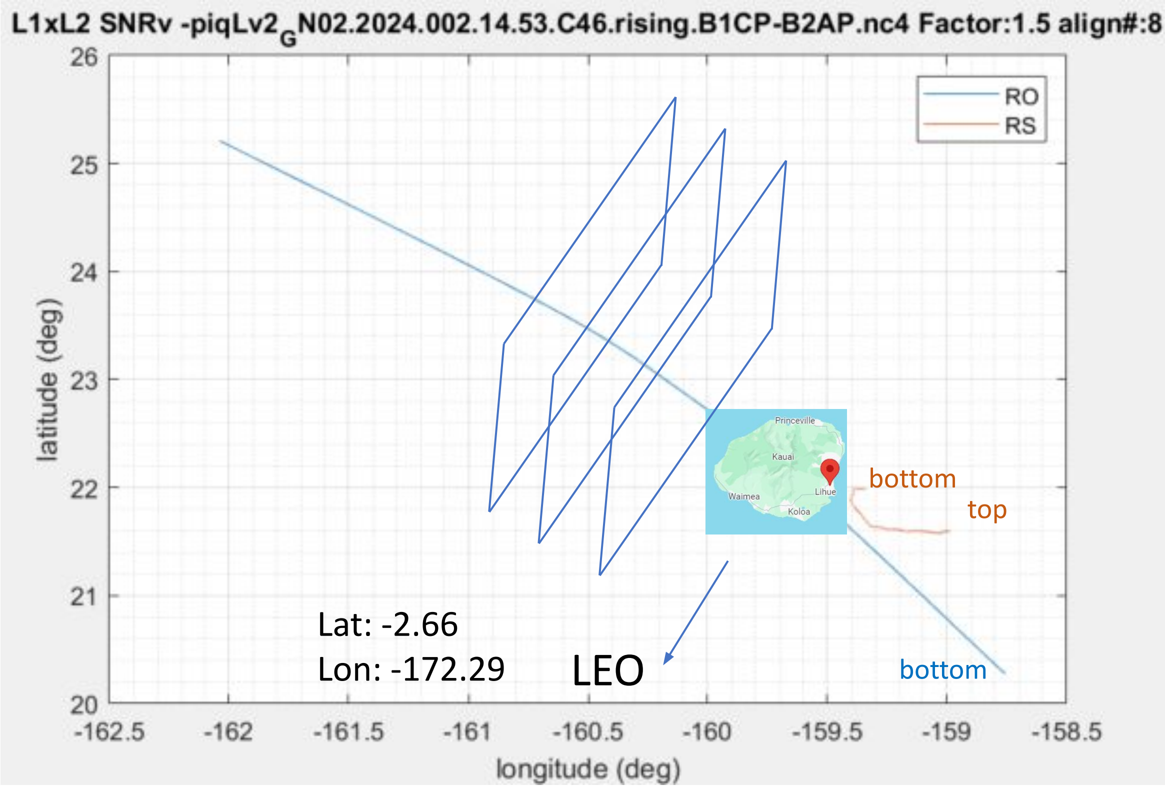
Backup slides

Motivation: NAS/NASA Importance of PBL Observations

- **NWP** and DA (including reanalysis) systems can be significantly improved with more accurate PBL observations and models.
  - Assimilation of space-based global observations of PBL thermodynamic structure would lead to (1) **better initial conditions** for forecast models and (2) **more accurate global reanalyses**.
  - More detailed observations of global PBL structure will lead to (3) improved **PBL parameterizations** for weather prediction and reanalysis.
- **Climate** model projections remain uncertain and it is essential, for decision making, to reduce these uncertainties.
  - Much of the uncertainty regarding these projections is anchored in **PBL-modulated cloud feedbacks**.
  - In order to systematically improve climate model PBL parameterizations, **more detailed observations of the global PBL thermodynamic structure are absolutely crucial**.
  - Space-borne observations provide the only means of obtaining the **global coverage** required over key regions that are remote and vast.
- **Air quality** significantly impacts human health, particularly in and around our growing cities.
  - **PBL height** in particular strongly modulates the impacts of surface pollutant emissions via dilution (lower air quality is associated with a shallower PBL).
  - Improved observations of PBL height and thermodynamic structure will lead to improved air quality characterization and forecasts.
- **Solar and wind power** are critical players in energy production.
  - To optimize energy production using wind and solar power, there is a crucial need for **better PBL observations**, which will lead to **improved wind and solar power planning and more accurate production forecasts**.

- S

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Lon: -172.29
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-160
-159.5
-159
-158.5

PLANETiQ Steps to Retrieval 1D BA(IH) profile

Objective: Derive a 1D BA(IH) profile from a 2D SNR(BA,IH) spectrum generated by sliding window phase matching (SWPM).

At a given IH, we often have the ambiguity that there are SNR peaks at multiple BAs.

To estimate the single BA at each IH, we weight the BAs at that IH based on the SNR for each BA at that IH

After studying a series of complicated 2D SNR(BA,IH, RF) spectra in detail, in order to minimize diffraction noise, we use only the BAs that have maximum SNRs **at the same BAs at L1 and L2**. Geometrics optics solutions should be the same at L1 and L2.

- We multiply L1xL2 to find the correlated solution.
  - As the L1 x L2 product, we conservatively set it equal to the smaller of SNR(L1)^2 and SNR(L2)^2
- We check that the SNR peaks in L1 and L2 are aligned (within 0.002 rad). If their peaks are not aligned at a given BA, we set that L1 x L2 product to zero.

Weighting to obtain the best single BA estimate at each IH

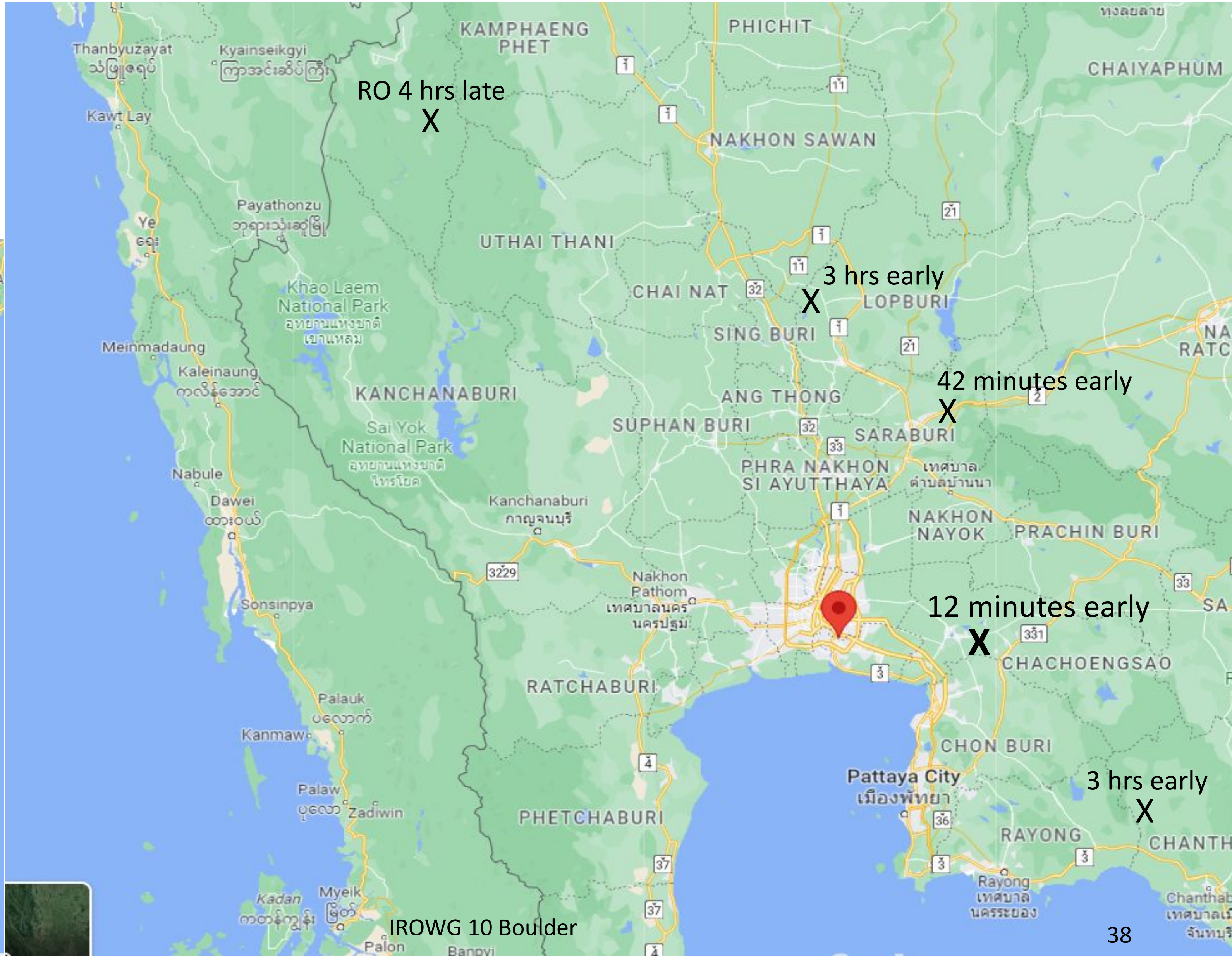
- Form the weighted average:
  - 1/variance ~ $SNRv^2$ weighting generally produces sharp vertical resolution
  - We set a minimum threshold to use with weighted average to avoid noise at other BA entering into the solution

Vertical smoothing

- Vertical sampling is 12.5 meters which is then smoothed via 1:2:1 smoothing to reduce jaggedness

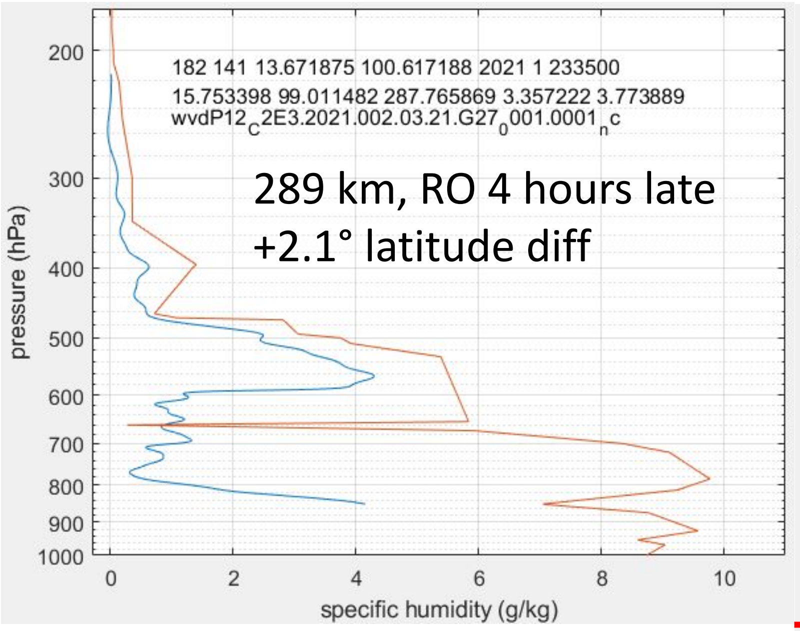
Demonstrating GNSS RO profiling

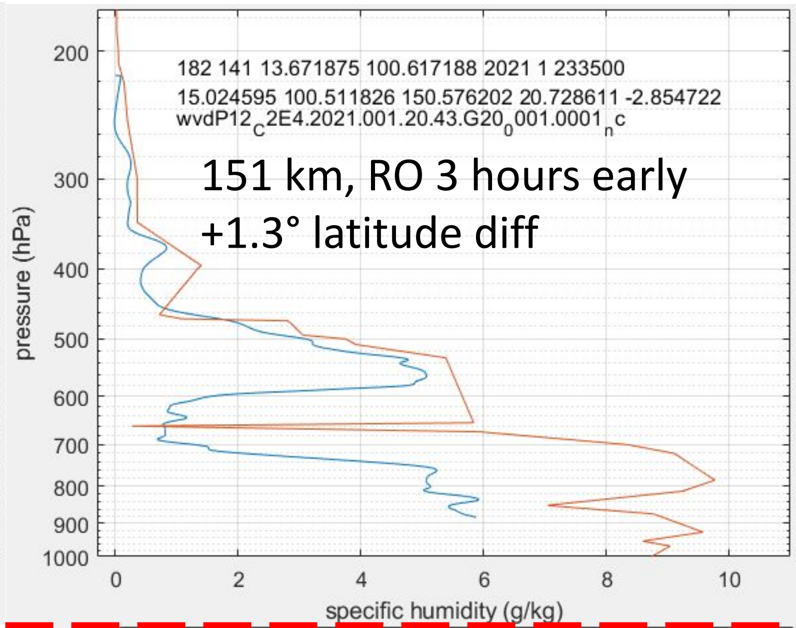
- Close collocation: Bangkok

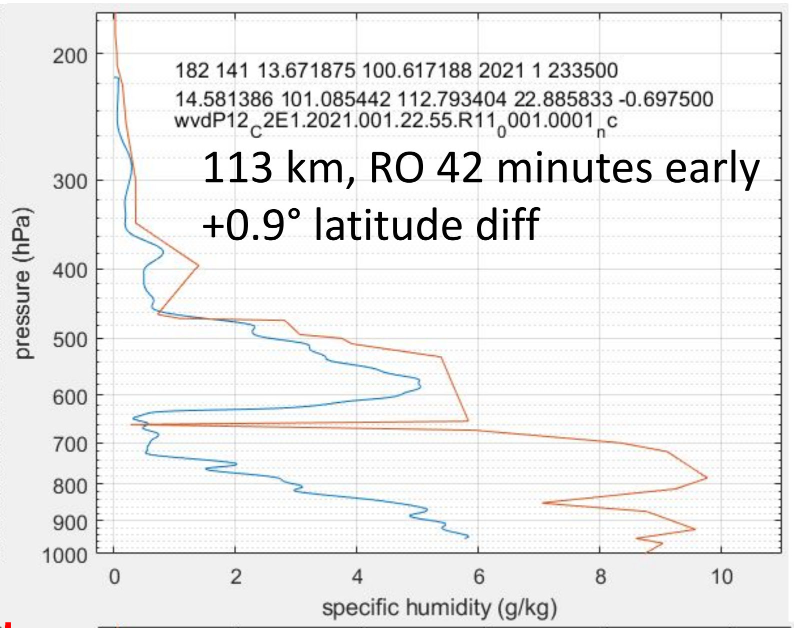


PLANETiQ

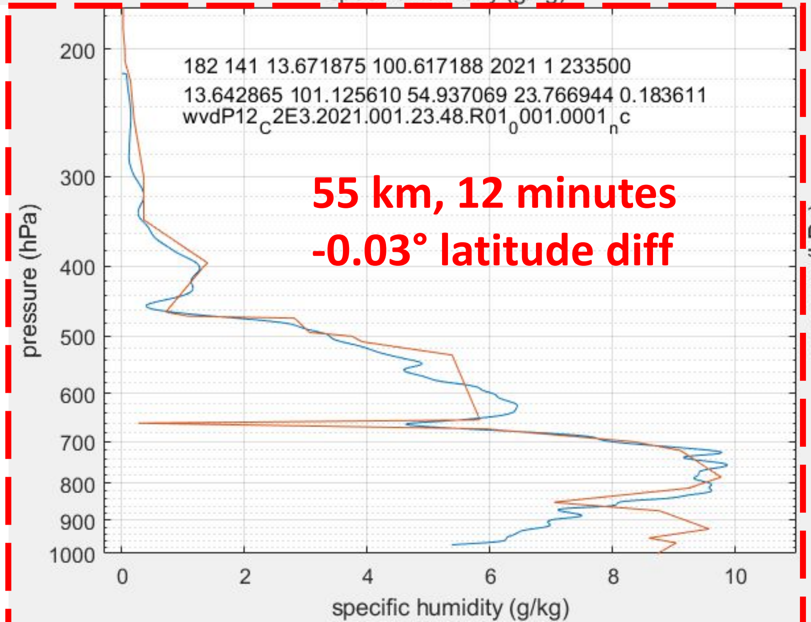
COSMIC-2 example: 5 occultations near Bangkok sonde 1/2/21

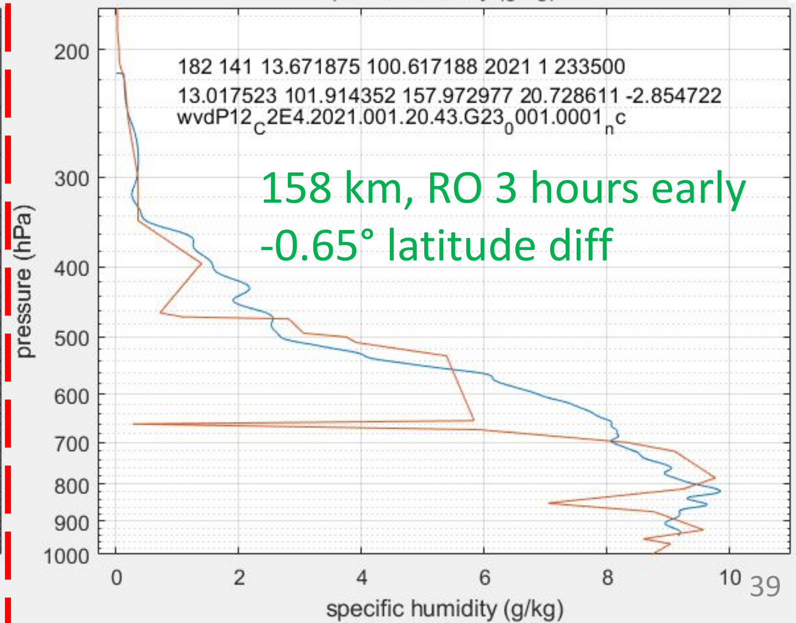






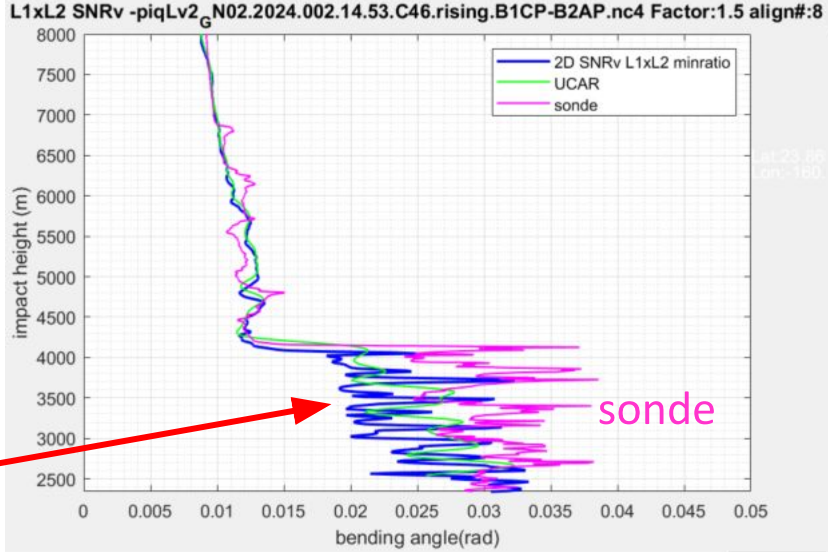
- Very close RO profile matches sonde very closely down to 875 hPa including very thin, dry layer.
- There is a strong latitudinal gradient
- RO profile 80 km south and 3 hours earlier is similar to the sonde profile
- RO profiles north of the sonde are more inland and see much drier air in LT
- RO-sonde difference depends more strongly on latitude separation than total distance or time separation

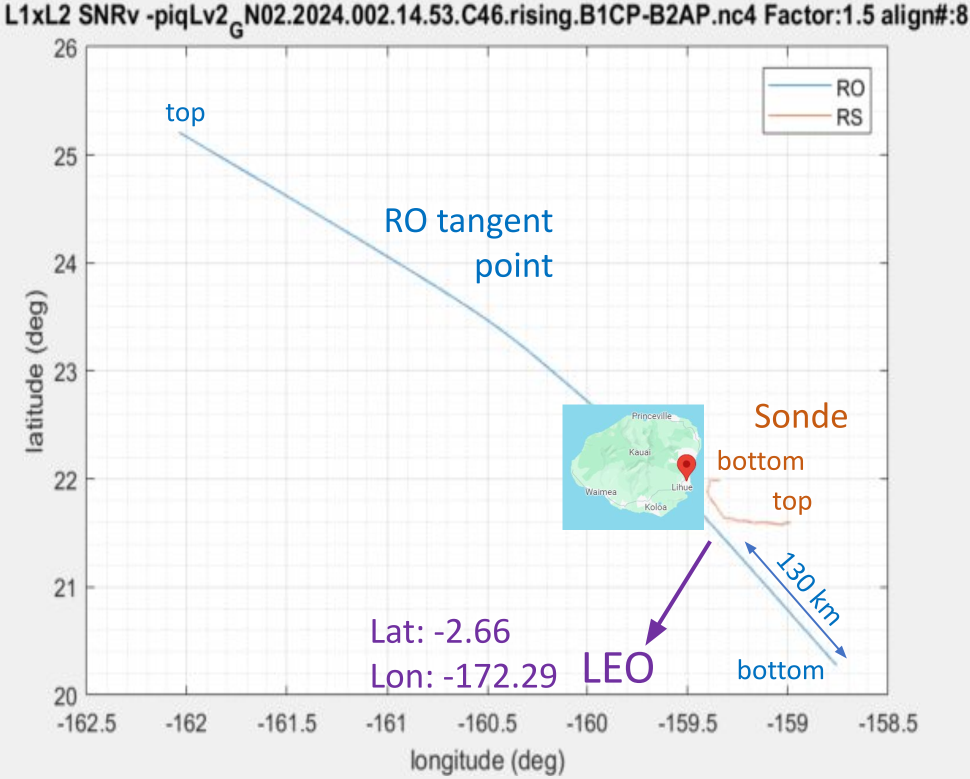


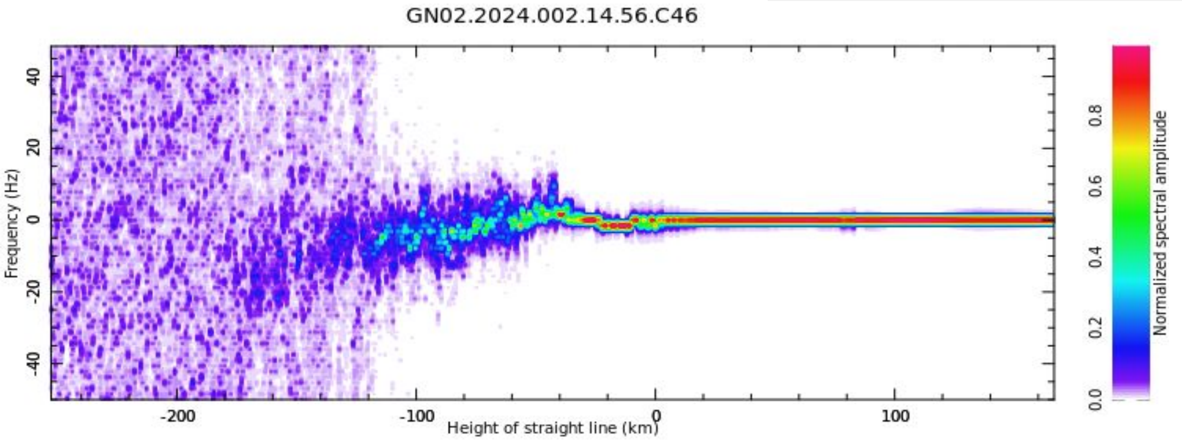


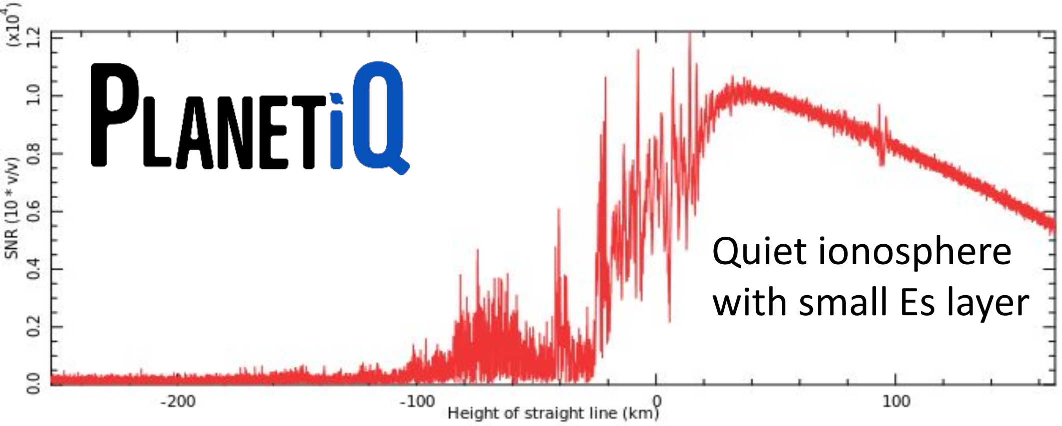
Lihue, Hawaii RO-sonde collocation

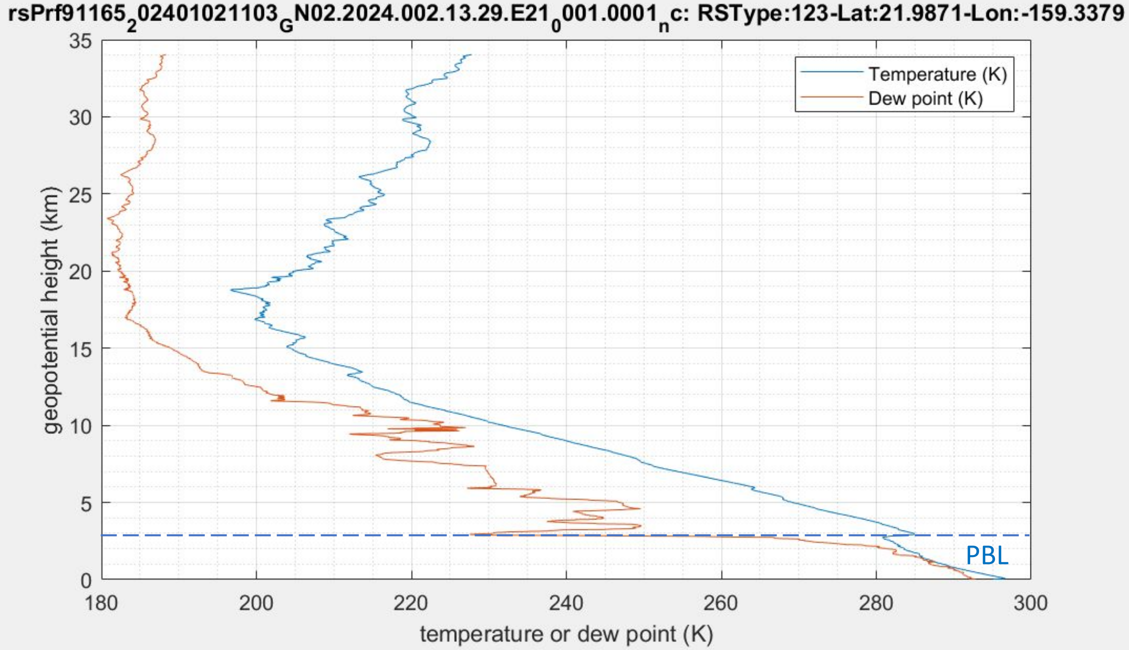
- < 60 km apart
- Sonde is 4 hrs before RO
- Both RO appears to underestimate BA in the BL











Horizontal motion & large bending angles

- For the profile with the large bending angle, the last point observed in the profile is at the BL top where the GNSS & LEO are farthest apart
- For this occultation, the difference between the actual tangent point and the smoothed tangent point reported in the atmPrf file is roughly 30 km in the bottom few km
- For ECMWF’s 9 km resolution global model, that difference spans 3 grid cells