PLANETIQ

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NASA CSDA Webinar

Agenda

- About PlanetiQ
- Fundamentals of GNSS-RO
- Data provided through NASA CSDA
- Case study examples
- Additional PlanetiQ products
- Future outlook
- Q&A

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About PlanetiQ

- PlanetiQ is a small company of scientists and engineers with many decades of experience in radio occultation measurements, instrumentation, information extraction and applications dating back to Voyager.
- We work closely with NASA, NOAA, USAF, USSF, EUMETSAT, ESA and NWP/research centers including JCSDA, NOAA EMC & STAR, NASA GMAO, ECMWF, UKMO and ECCC.
- Located in Golden, CO
- In 2025 won the largest satellite weather data award ever from NOAA/NESDIS ($24.3M)
- Our goal is to make dense measurements of the highest quality, at low cost, to enable better understanding, modeling and forecasting of weather, space weather, and climate

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Classes of data types

- Neutral atmosphere RO
- Ionosphere RO
- Grazing surface reflections

- We want to know what the customers/PI's want in order to decide how best to focus our resources to satisfy our customers' needs

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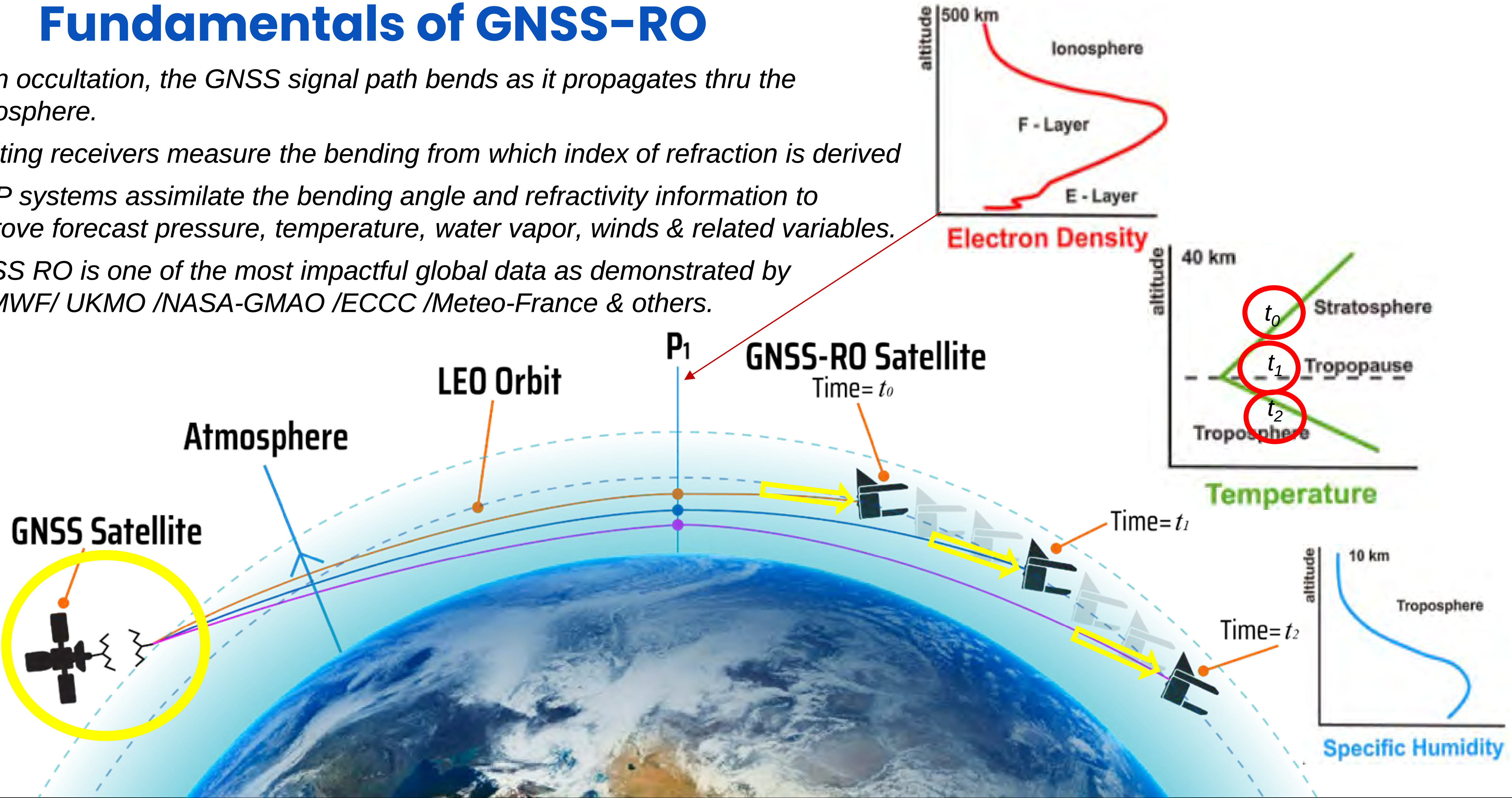
Fundamentals of GNSS-RO

- *In an occultation, the GNSS signal path bends as it propagates thru the atmosphere.*
- *Orbiting receivers measure the bending from which index of refraction is derived*
- *NWP systems assimilate the bending angle and refractivity information to improve forecast pressure, temperature, water vapor, winds & related variables.*
- *GNSS RO is one of the most impactful global data as demonstrated by ECMWF/ UKMO /NASA-GMAO /ECCC /Meteo-France & others.*



Key RO features

GNSS-RO is a powerful remote sensing technique due to its unique combination of features including

- Balloon-like, very high vertical resolution (~100m) from orbit
- Profiling through all types of weather
- High precision for weather and constraining process to improve models
- High accuracy for bias correction and climate monitoring
- Profiling to, or close to, the surface over any type of surface, yielding complete and unbiased global coverage

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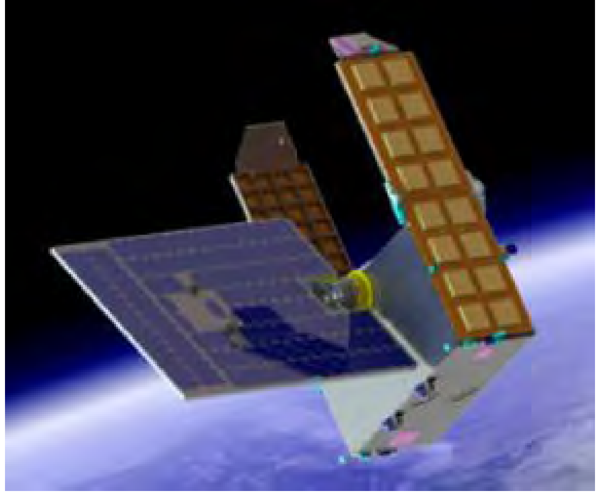
Summary of PlanetiQ capabilities

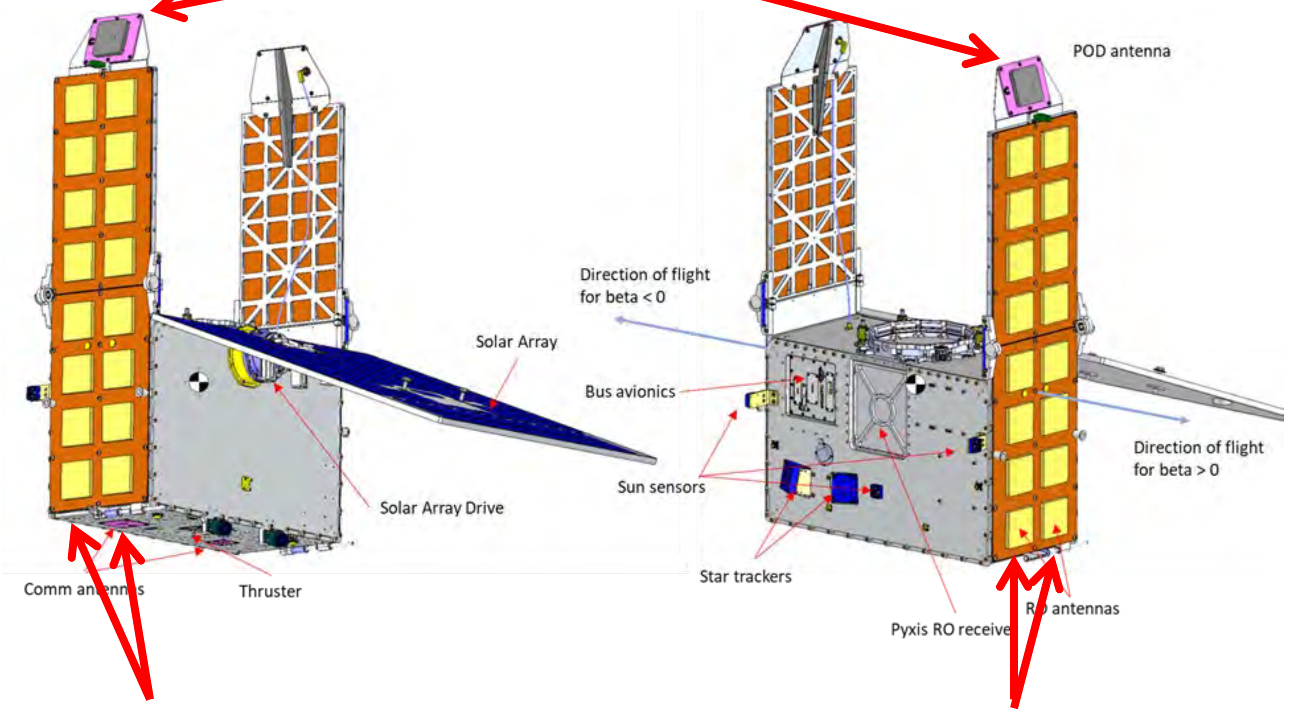


- Receivers track 4 GNSS constellations:
  - GPS (w/L2c) , GLONASS, Galileo, BeiDou3
- NOAA RODB2 DO-5 contract delivery began 9/18/25
  - Delivering 7000 neutral atmosphere RO/day
  - Includes 500 enhanced high signal-to-noise ratio (SNR) profiles
  - Also includes 2,500 low-latency Total Electron Content (TEC) tracks for space weather
- Satellites 4-6 carry thrusters to adjust orbits to extend lifetime & better coverage
- Full pole-to-pole coverage
- PlanetiQ RO validated by multiple entities (ECMWF, UK Met, NOAA, ECCC, …)
- Flexible and adaptable: modifiable software and firmware on orbit
- Available with dual polarization (i.e. Polarized RO=PRO)
- Data archive available back to 2021

PlanetiQ Pyxis GNSS RO instrument overview

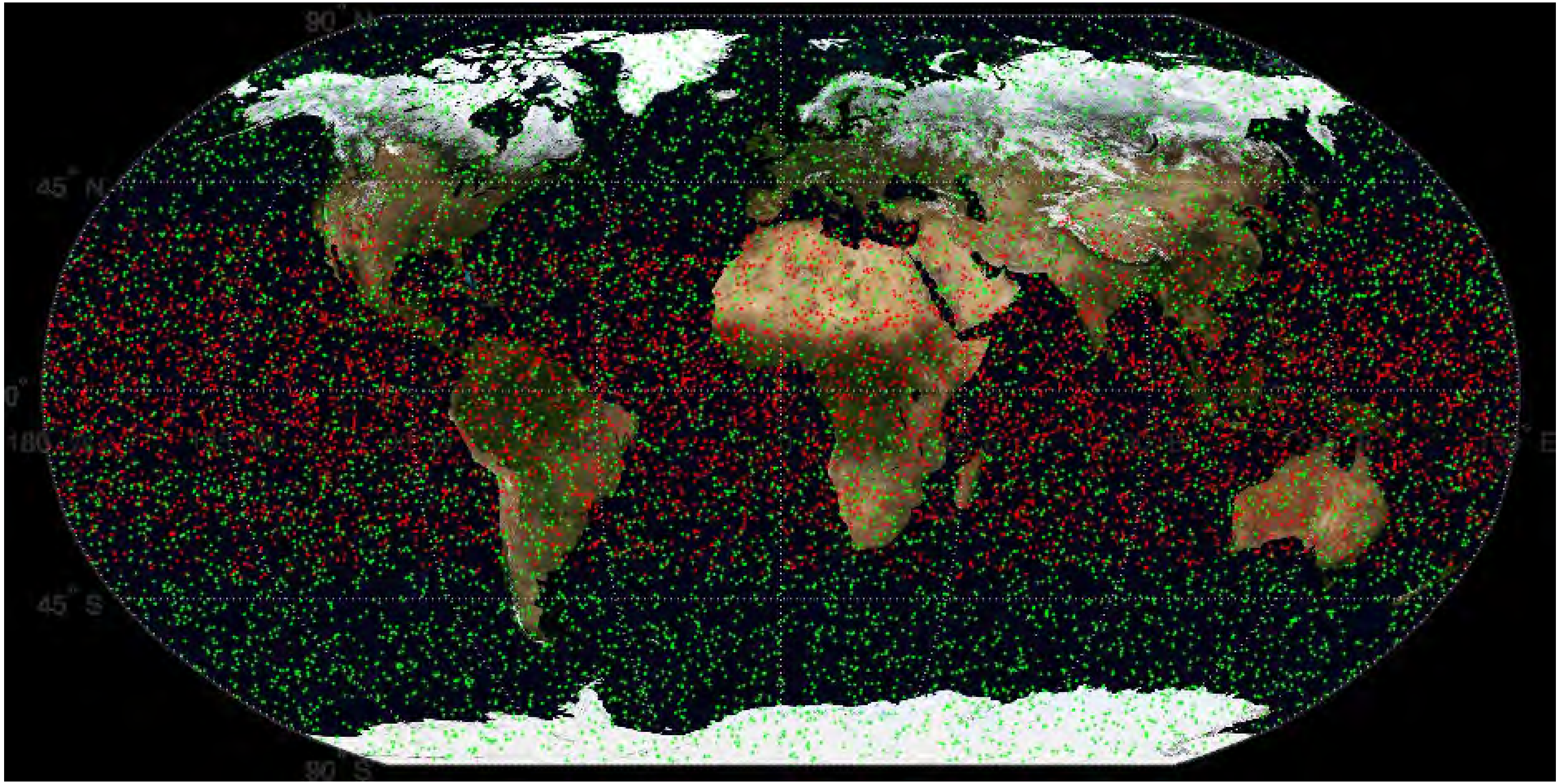
- Tracking: All four worldwide GNSS constellations on open-access frequencies: ~100 GNSS sats
- > 2500 NRT-usable neutral atmosphere RO/receiver-day
  - Meet all of NOAA’s NRT specs for SNR & & latency
- Pyxis software and FPGAs are fully reprogrammable on orbit.
- Have been generating neutral atmosphere & space weather RO since October 2021
- GNOMES-4 & -5 + YAM-8 on-orbit
  - with more to come

Two hemispheric RCP antennas to acquire POD and ionosphere data



Two forward facing and two aft facing high gain RCP antenna columns electrically oriented creating a fan shaped beam at the limb to acquire very high SNR RO

Current GNSS-RO coverage, high SNR



Red = COSMIC-2 GNSS-RO vertical profiles   Green = PlanetiQ GNSS-RO vertical profiles

File types and contents summary (part 1)

Green: Onramp 1
Orange: Onramp 2

4 File types	Neutral atmosphere "excess phase"	Bending angle refractivity files	Calibrated TEC	Ionosphere calibrated phase	New Onramp 2 capabilities piqLv2
Processing level	1B	2	1B	1B	2
Similar CDAAC file type	conPhs	atmPrf	podTc2	scnPhs	conPhs + atmPrf + …
Key data types	High rate dual frequency carrier phase and amplitude Transmitter & receiver positions	Profiles of bending angle vs impact height Refractivity vs geometric height, latitudes and longitudes	TEC calibrated for transmitter & receiver DCBs and local multipath Scintillation indices S4 and σ_{ϕ}	High rate carrier phase & amplitude Transmitter & receiver positions	High rate dual freq carrier phase & amplitude Transmitter & receiver positions Profiles of bending angle vs impact height Refractivity vs geometric height, latitudes & longitudes Dual linear polarization phase & amplitude Isolated grazing reflection phase & amplitude
Data rates	100 Hz GPS, BDS3 & GLONASS 125 Hz Galileo	Vertical separation between points is ~ 20 m.	TEC at 1Hz Scintillation indices every 10 seconds	50 Hz for GPS, Galileo and BDS3	100 Hz GPS, BDS3 & GLONASS 125 Hz Galileo Vertical separation between points is ~ 11 m.
Key features	High rate, High SNR				High rate, High SNR
NSS antenna type	High gain RO	High gain RO	Low gain POD	Low gain POD	High gain RO
Altitude range	Straight line altitude approximately -250 to +150 km	Bending angle: near surface to 80 km Refractivity: near surface to 60 km	90 km to above satellite altitude	90 to 500 km when S4 > 0.2 for altitudes between 120 & 500 km	Straight line altitude approximately -250 to +150 km Bending angle: near surface to 80 km Refractivity: near surface to 60 km Grazing reflections: surface

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File types and contents summary (part 2)

Green: Onramp 1
Orange: Onramp 2

4 File types	Neutral atmosphere “excess phase”	Bending angle refractivity files	Calibrated TEC	Ionosphere calibrated phase	New Onramp 2 capabilities piqLv2
Geophysical variable					
Neutral atmosphere	X	X			X
Ionospheric TEC			X		
Ionosphere scintillations	Below 150 km		S4 and σ_ϕ indices		Below 150 km
Es layers	X			X	X
Grazing reflections	X				X

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Retrieval system overview & explanation

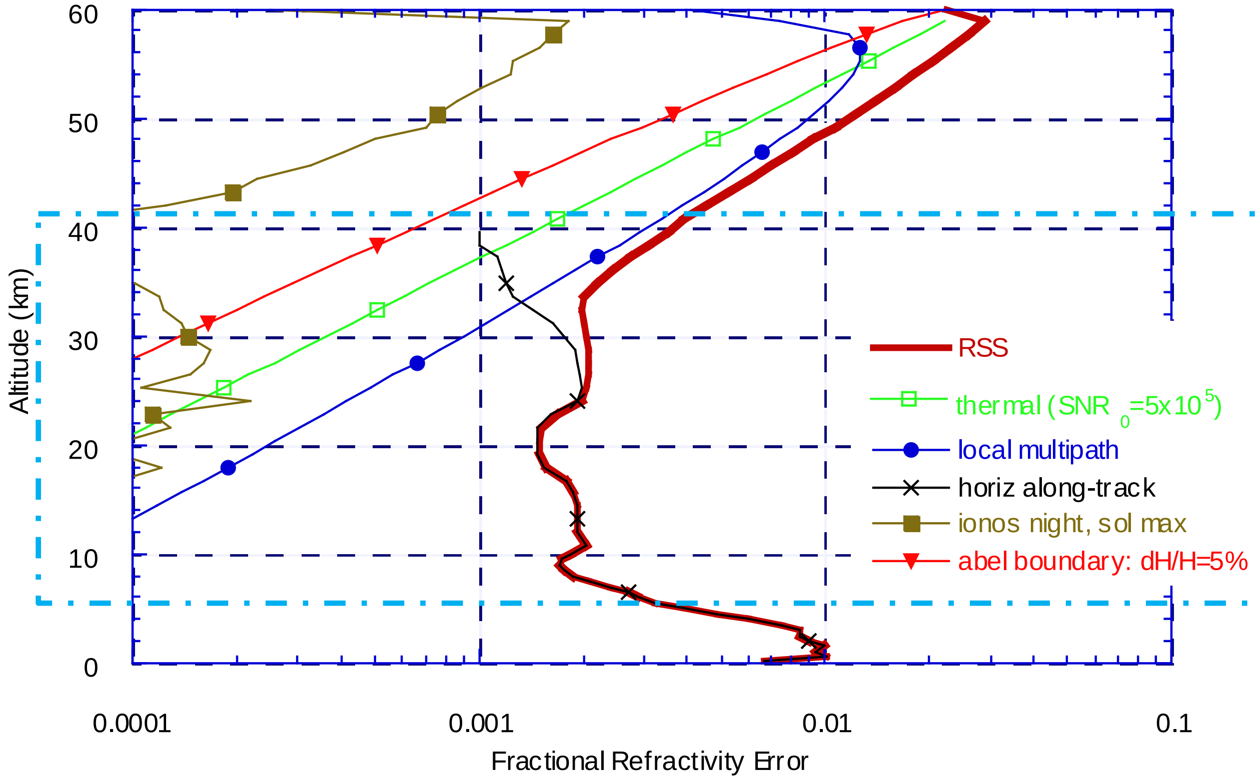
Bending Angle	• Bending angle vs refractive radius
Refractivity	• Refractivity vs height (=z) $N = a\,\rho_{dry} + b\,\rho_{wet}/T$
Density	• Density(z) via refractivity equation
Pressure	• Pressure(z) via hydrostatic balance
Temperature	• Temperature(z) via eqn. of state (~ideal gas law)
Winds	• Winds indirectly from horizontal pressure gradients between multiple RO
Humidity	• Accurate high vertical resolution water vapor in lower to upper troposphere

- Altitude range: 0 to ~60 km
- Resolution vs altitude

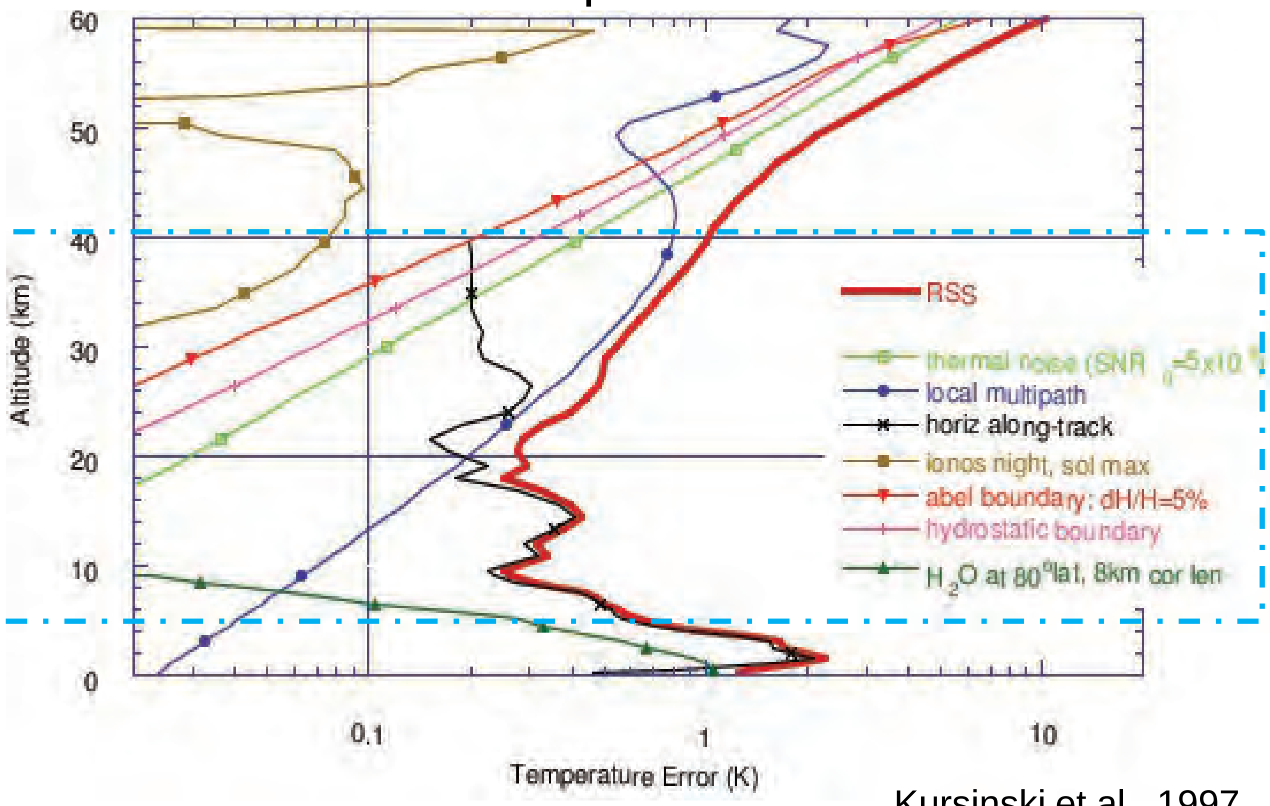
NOTE: Kursinski et al. 1997 as a starting point if you are not familiar with GNSS RO

Accuracy

Refractivity $= c\,P/T + d\,P_w/T^2$



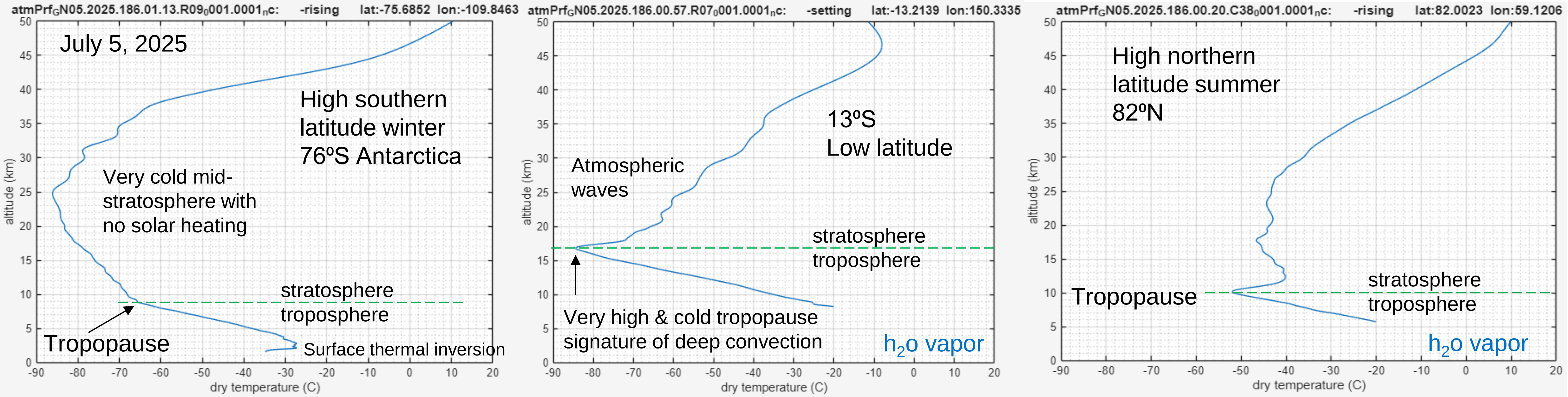
Temperature



Kursinski et al., 1997

- RO temperatures are likely the most accurate that exist in the Upper Troposphere Lower Stratosphere (UTLS)

RO temperature profiling examples

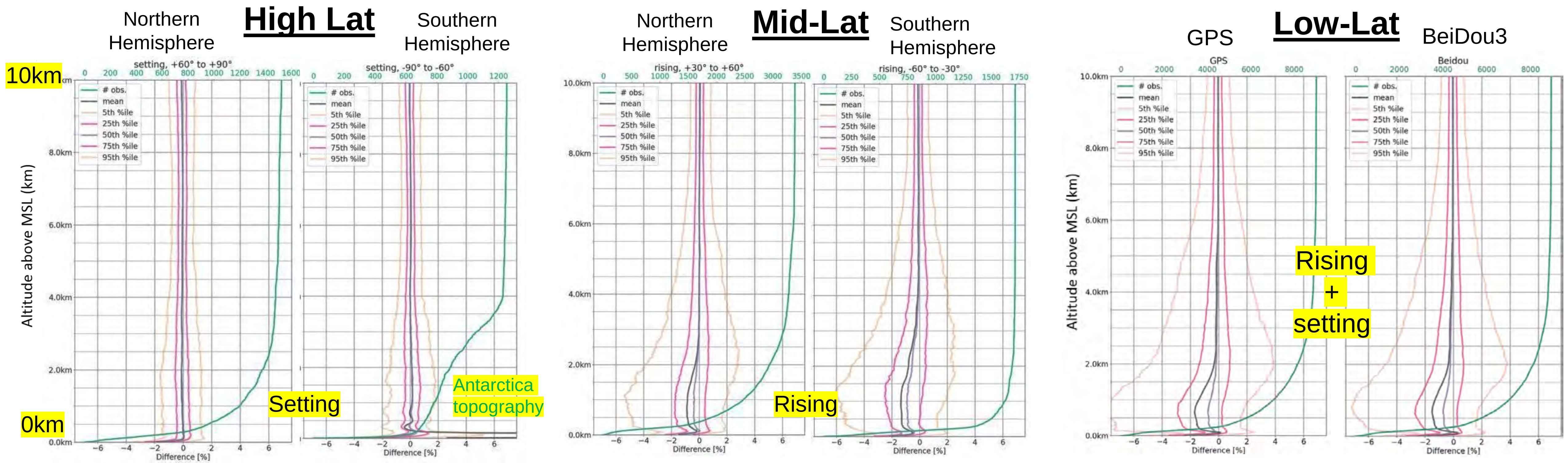


- Balloon-like sounding from orbit
- Likely the most accurate thermometer that exists in the UTLS
- Lapse rates from precise high vertical resolution temperature profiles

Refractivity: RO vs NOAA forecast

- Performance in percentiles: 5, 25, 50, 75, 95 and mean
- Little difference across GNSS constellations and between rising and setting occultations
- **Typical of high quality GNSS RO**

➢ Some negative bias and skew apparent at lowest altitudes caused by horizontal structure and ducting



Humidity

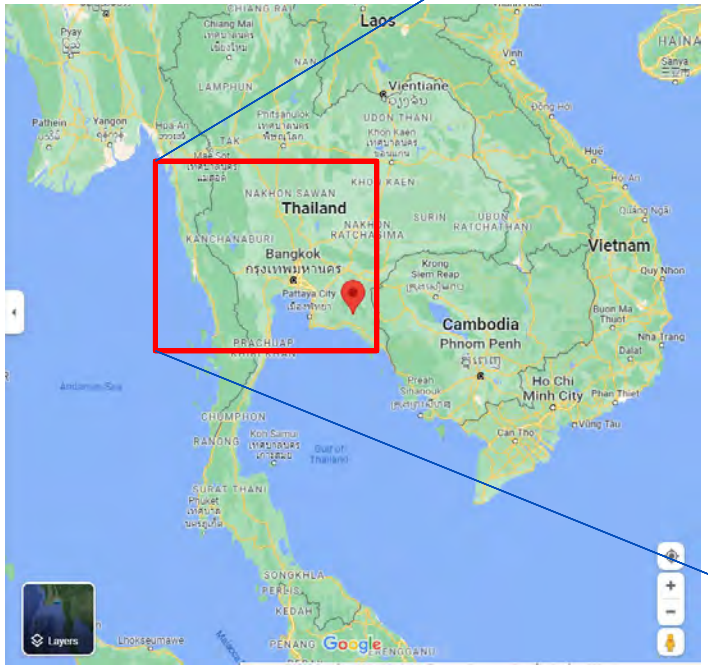
- $\rho_{h2o} = [N - a\ \rho_{dry}] *T/b$
- Derive high vertical resolution water vapor in lower to upper troposphere
- Humidity is derived in two ways, Direct method and 1DVar
- Direct method accuracy at low latitudes shown in table to the right
- Examples follow

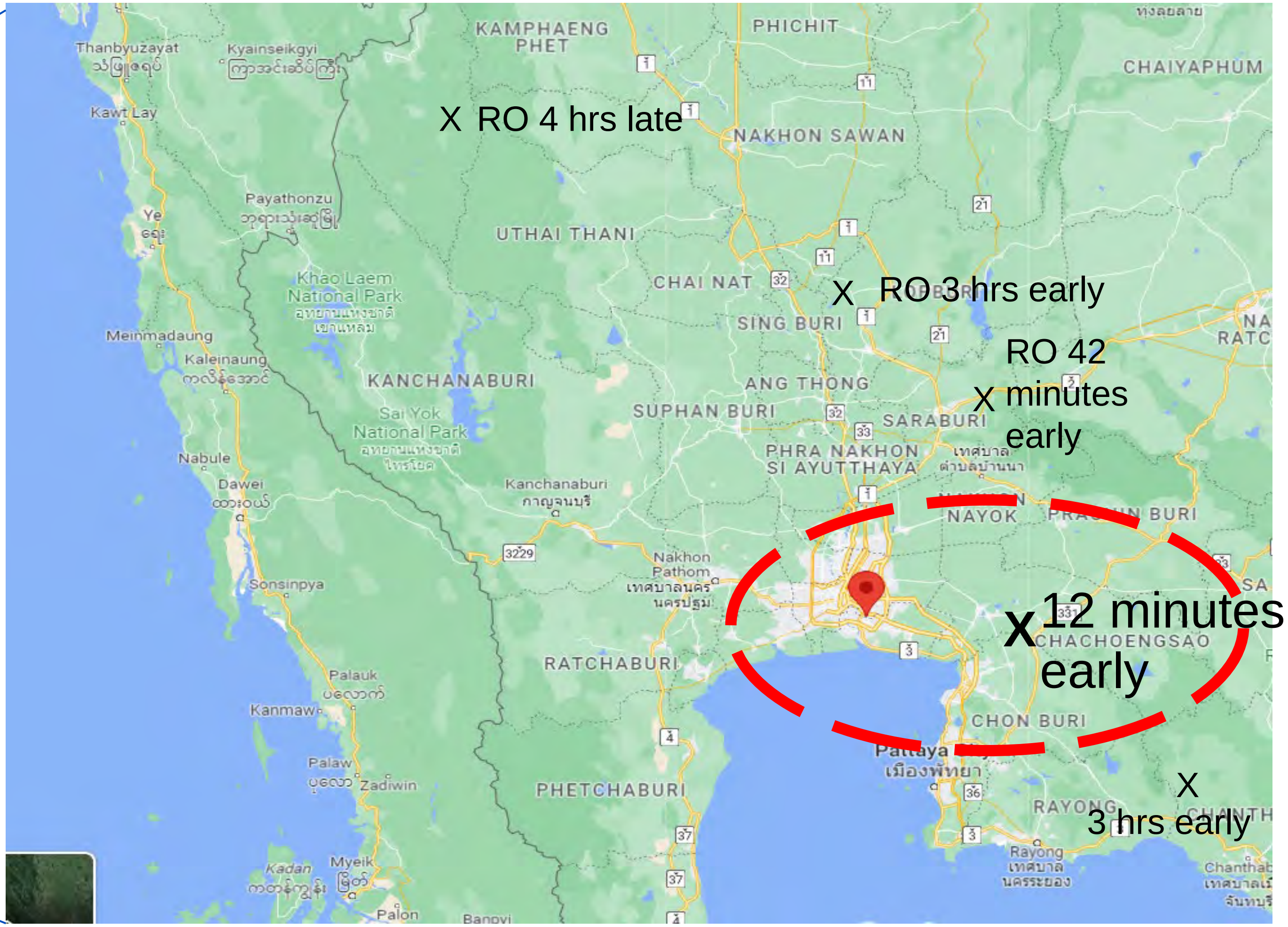
Pressure (hPa)	Altitude (km)	Specific humidity stdev (g/kg)
346	8	0.14
547	5	0.25
725	2.7	0.39

Estimated direct method accuracies from *Kursinski and Gebhardt, 2014*

Very sharp vertical humidity structure captured by RO & sonde

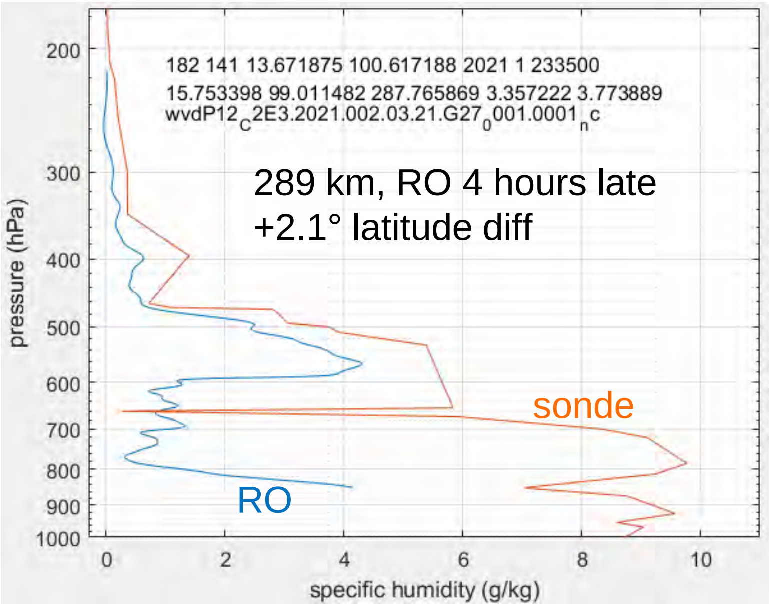
- Close collocation: Bangkok
- 5 RO near sonde
- 1 extremely close collocation

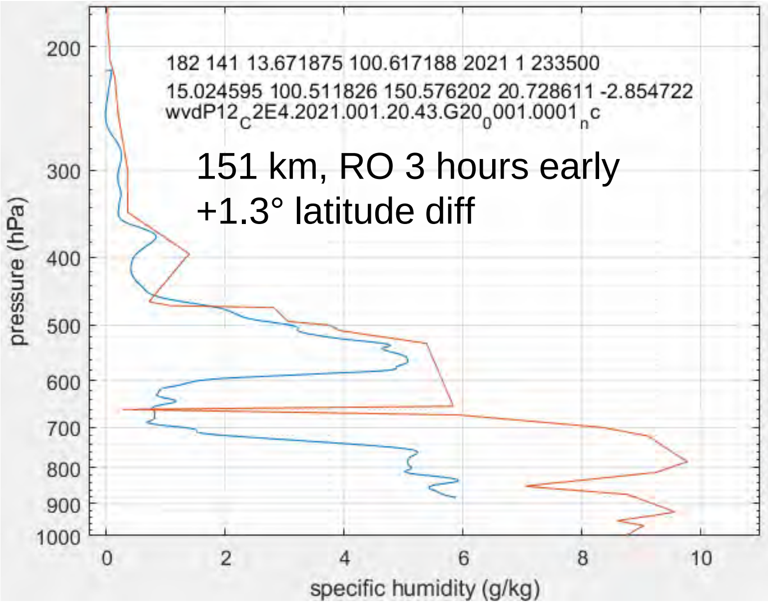


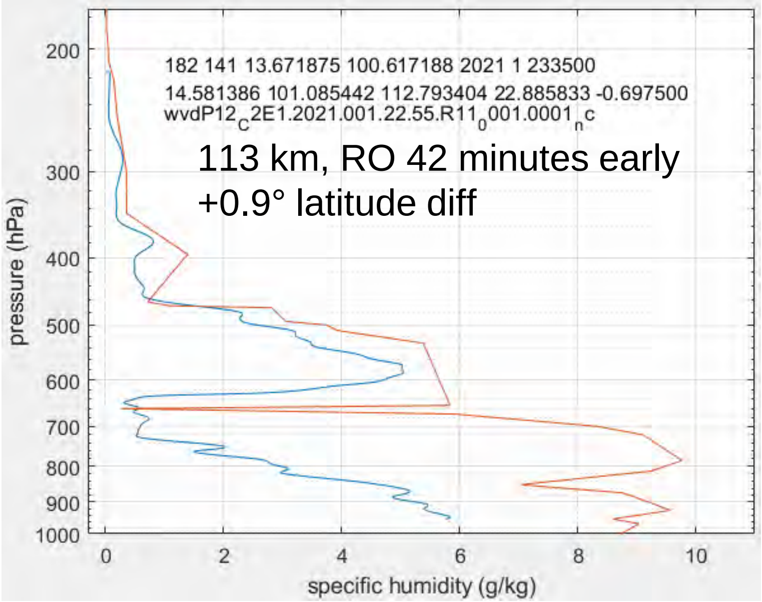


Very sharp vertical structure captured by RO & sonde 1/2/21

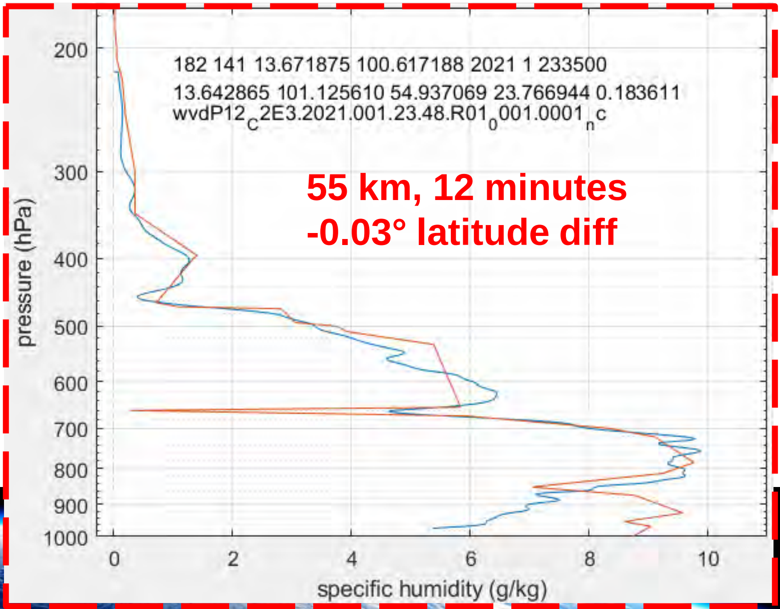
RED=sonde
BLUE=RO

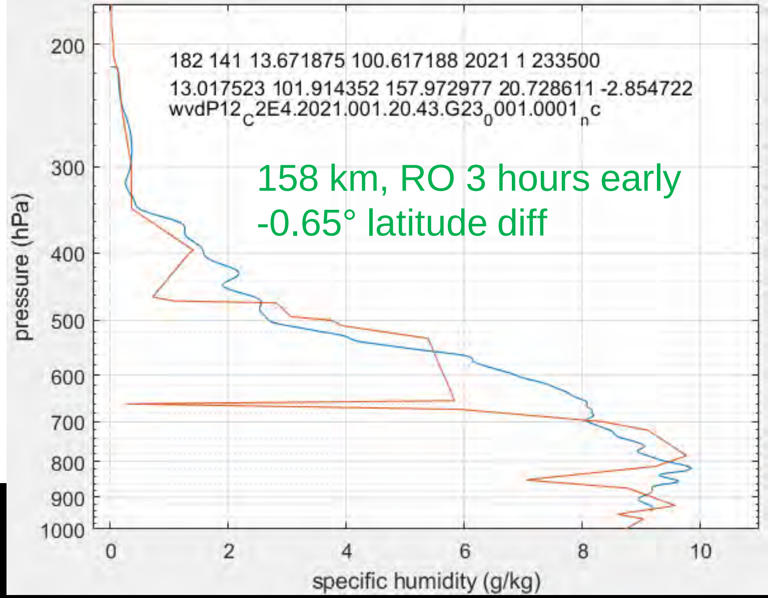






- Very close RO profile matches sonde very closely down to 875 hPa including very thin, dry layer
- There is a strong latitudinal gradient
- RO profile 80 km south and 3 hours earlier is similar to the sonde profile
- RO profiles north of the sonde are more inland and see much drier air in LT
- RO-sonde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





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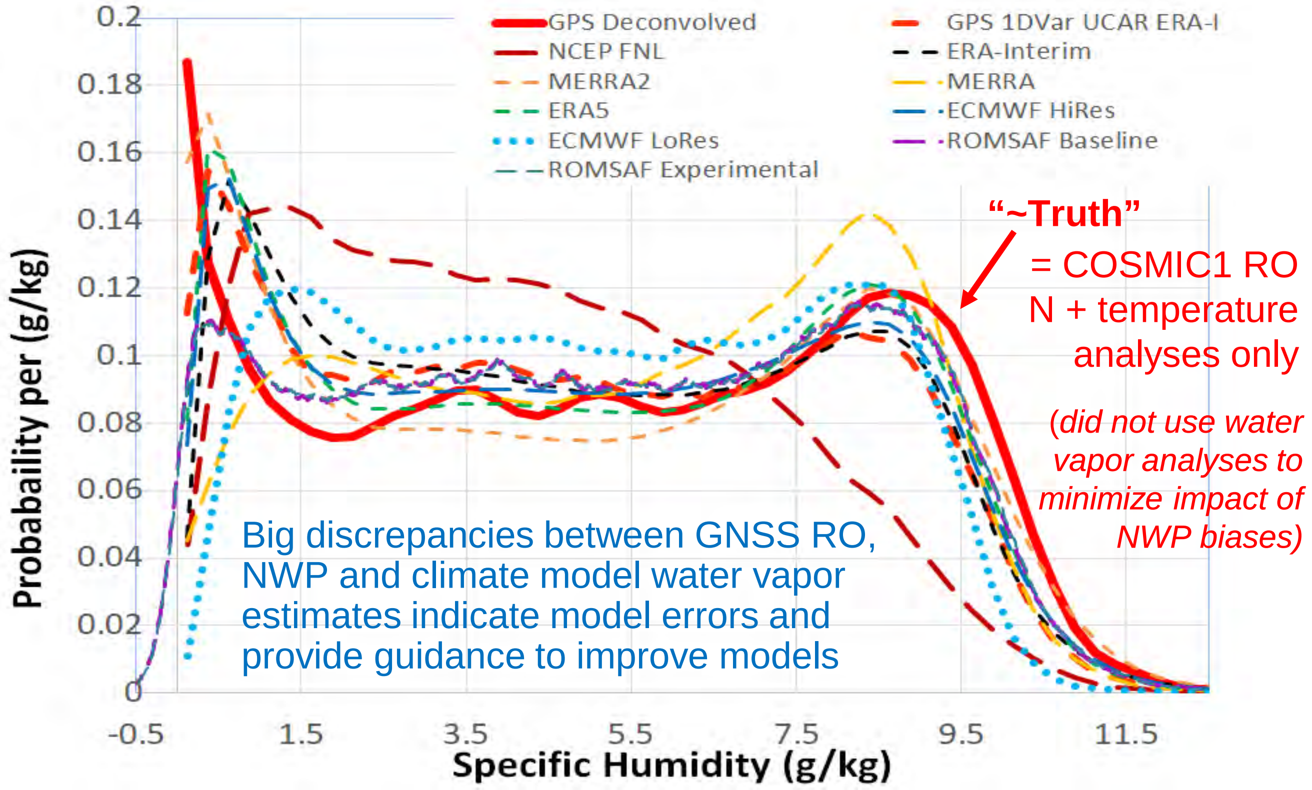
Humidity histograms and model evaluation

- Water vapor can be derived from RO measurements of refractivity
- Histograms of specific humidity derived via Direct method and RO's unbiased coverage
- For evaluating NWP models, reanalyses and climate models
- Working to achieve unbiased water vapor **inside** the PBL at low latitudes

Comparison of low latitude water vapor histograms at 725 hPa

30°S-30°N
Full annual cycle,
Just above PBL



NWP impact

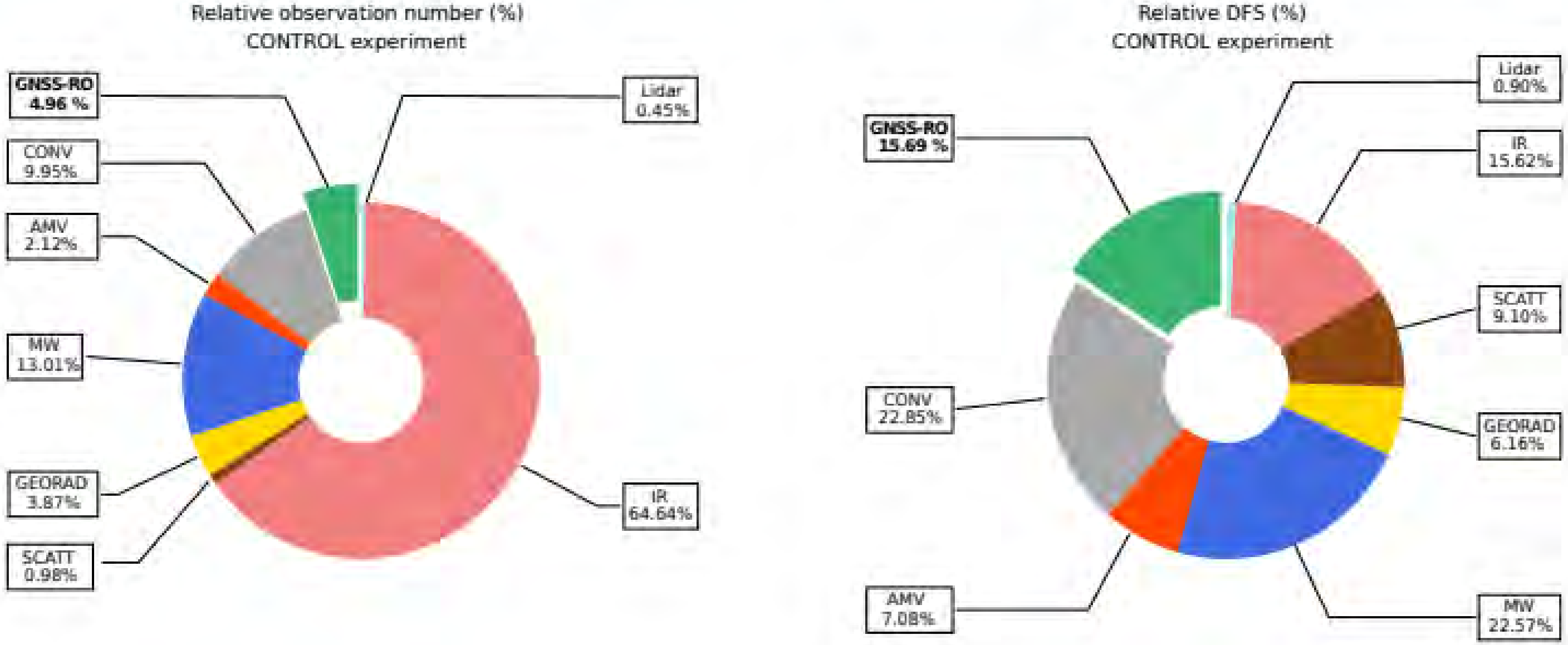
Meteo-France

Present RO:

- 4.96% of the input observations
- ⇒ 15.69% of the impact

DFS diagnosis for the CONTROL experiment

- Relative observation number (left) and relative DFS (right) for CONTROL (2022/09/01)

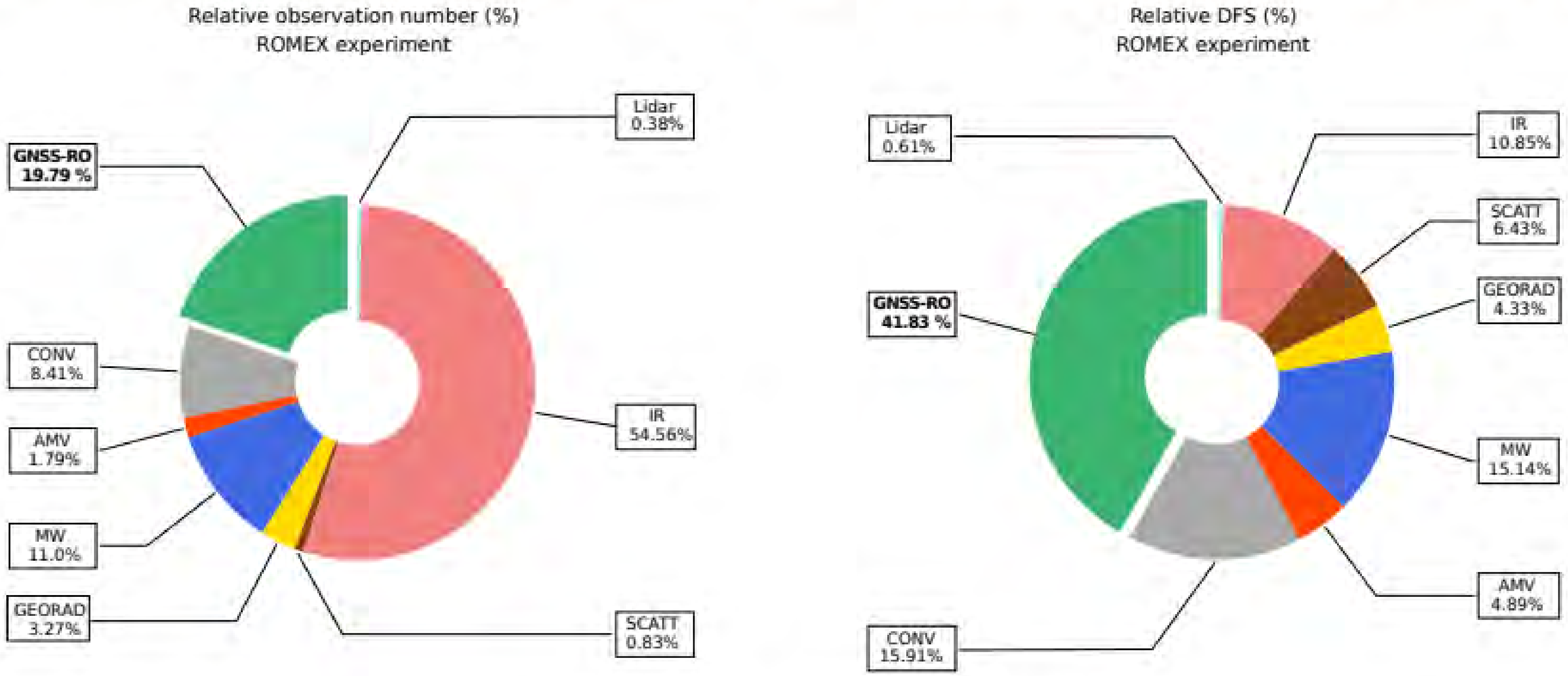


with courtesy H. Benichou (DirOP/COMPAS/COM)

NWP impact

DFS diagnosis for ROMEX experiment

- Rel. observation number (left) and relative DFS (right) for ROMEX experiment (2022/09/01)



with courtesy H. Benichou (DirOP/COMPAS/COM)

- Strong increase of the DFS for GNSS-RO ⇒ 1st rank with more than 41% of the total DFS !

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Meteo-France

ROMEX (35k RO/day):

- 19.79% of the input observations

⇒ 41.83% of the impact

Profiling the lower troposphere & boundary layer (LTBL)

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 quite difficult because of its short vertical extent, closeness to the surface and frequent cloudiness.

- GNSS RO's unique combination of very high vertical resolution, high precision & accuracy, and profiling in any weather conditions, and over any & all surfaces is well suited to profiling the PBL globally
- GNSS RO is the only present system capable of profiling the PBL from space under any and all conditions

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

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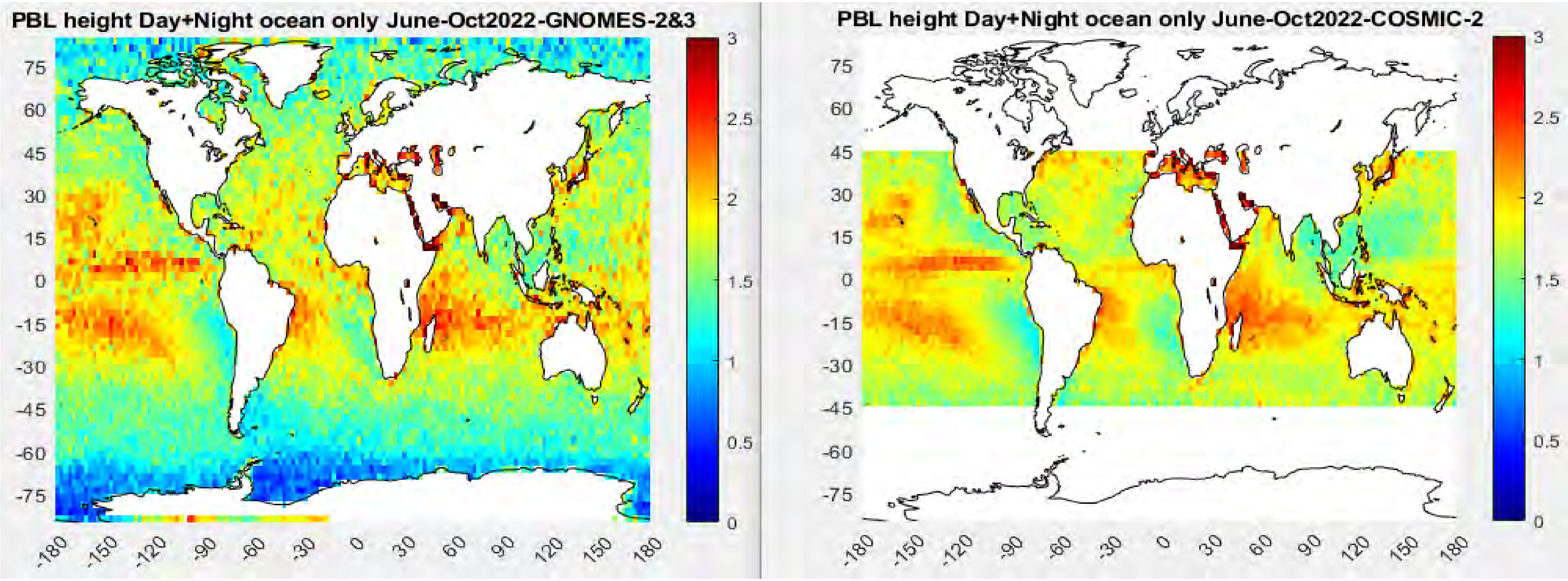
Average PBL height PlanetIQ vs COSMIC-2

- Similar heights in overlap region



This is great but we also want to profile ***inside*** the PBL, down to the surface

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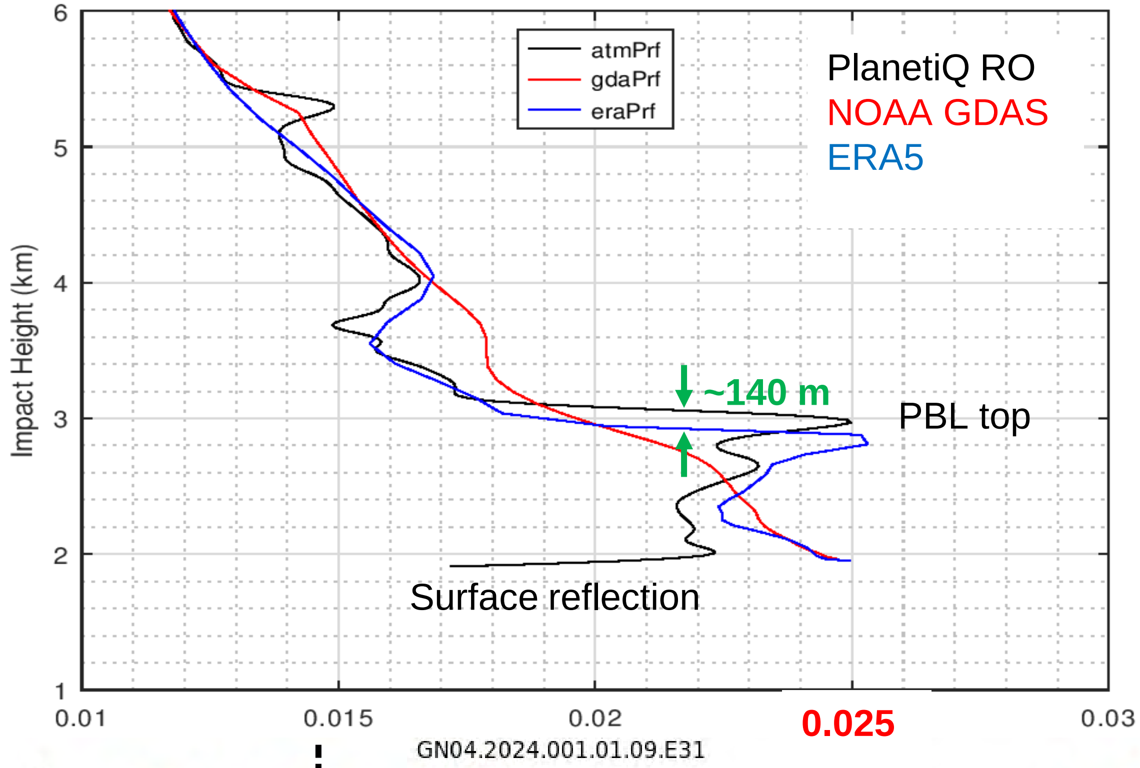
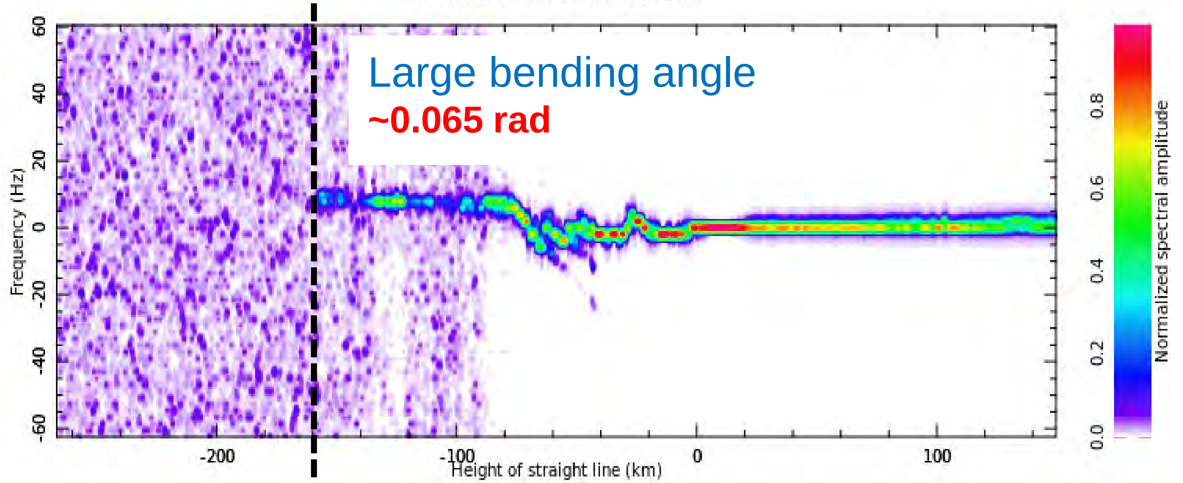
Profile in South Atlantic

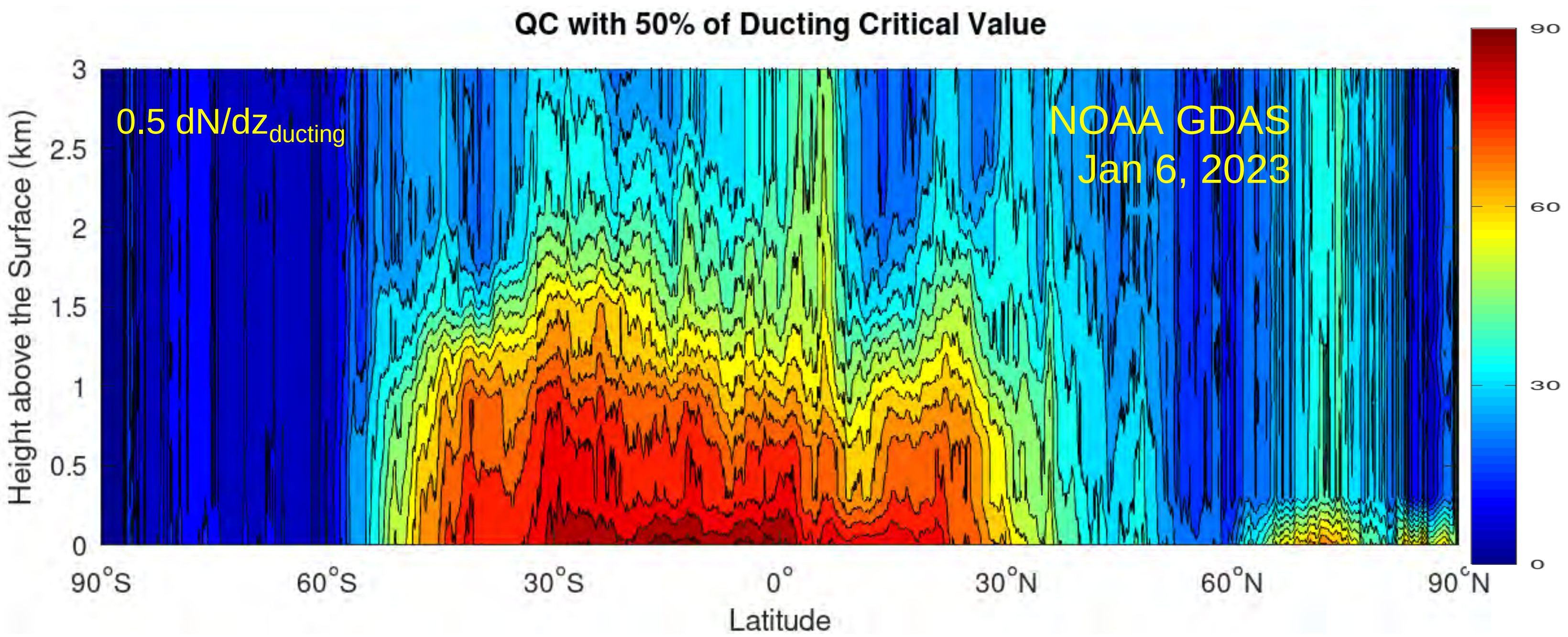
- Good looking RO profile of LTBL.
- Sharp PBL top observed by RO and ERA5 but not by GDAS
- ERA5 PBL top is ~140m below the RO observed PBL top
- Max retrieved BA ~**0.025** rad = 1.4 deg
- However, SLTA -160 km corresponds to BA ~**0.065** rad = 3.7 deg





NWP rejection of RO data in lower troposphere

- NWP systems presently reject RO data when forecast dN/dz approaches ducting conditions ($|dN/dz| > 1/R_{earth}$)
- Figure shows % of RO rejected when NOAA forecast dN/dz exceeds 50% ducting threshold.
- From 50S to 30N, ~2/3 of the globe, below ~1.5 km, most of the RO observations will be rejected by the 50% SR criterion
- This check & rejection avoids an instability in DA systems



% Rejection when $|dN/dz_{GFS}| > 0.5\ |dN/dz_{ducting}|$

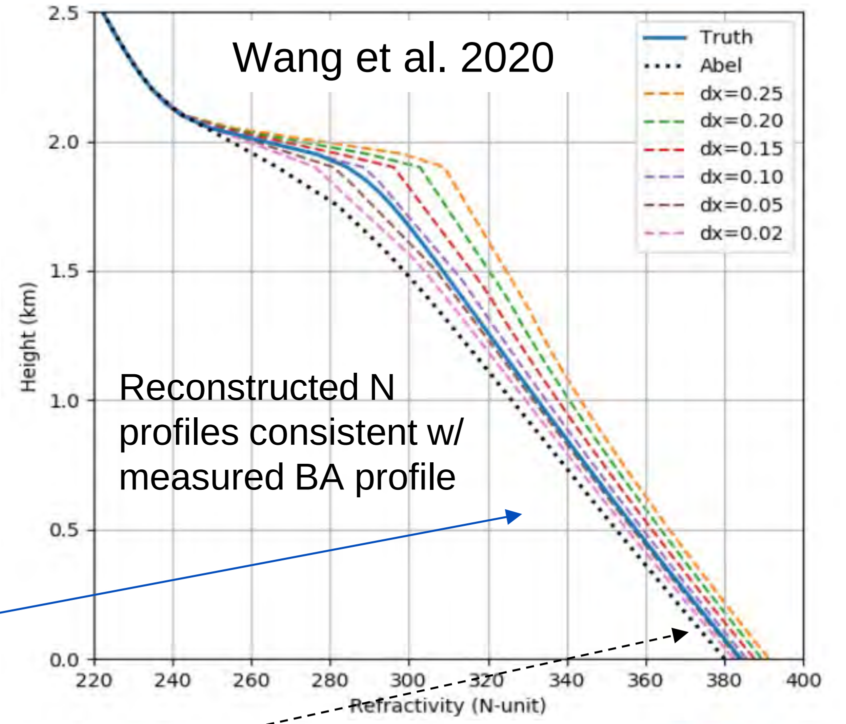
Ducting: BA ⇔ N ambiguity

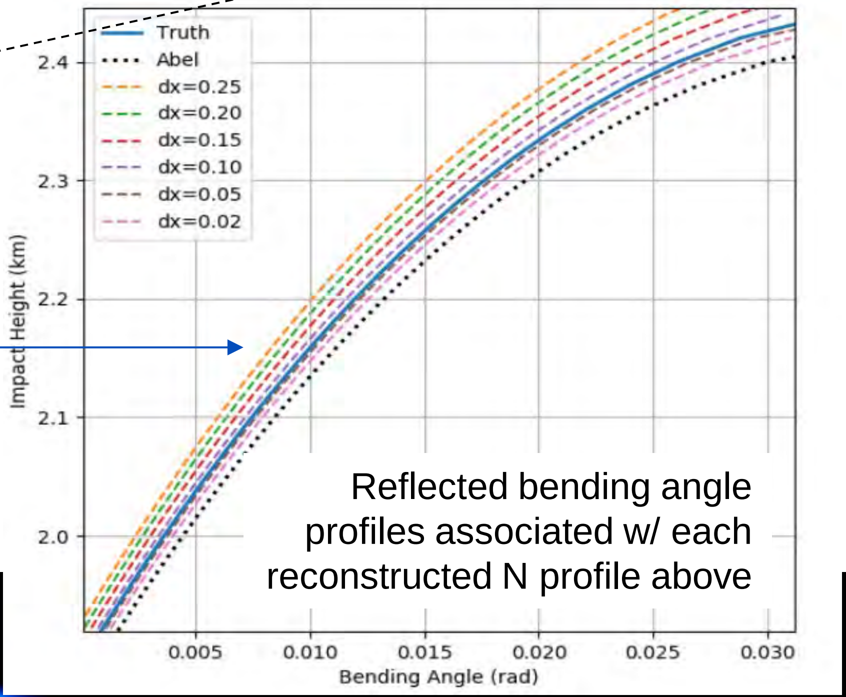
- At sharp humidity transition between drier free troposphere above & moist boundary layer below, $|dN/dz| > 1/R_{Earth}$, causing the ray path radius of curvature to be smaller than Earth's radius.

⇒ Creates a non-unique relation where the observed bending angle profile is consistent with a continuum of refractivity profiles

⇒ Tends to cause a systematic underestimate of refractivity which NWP wants to avoid.

⇒ The ambiguity can be solved by measuring the bending angle profile of the signal reflected off Earth's surface





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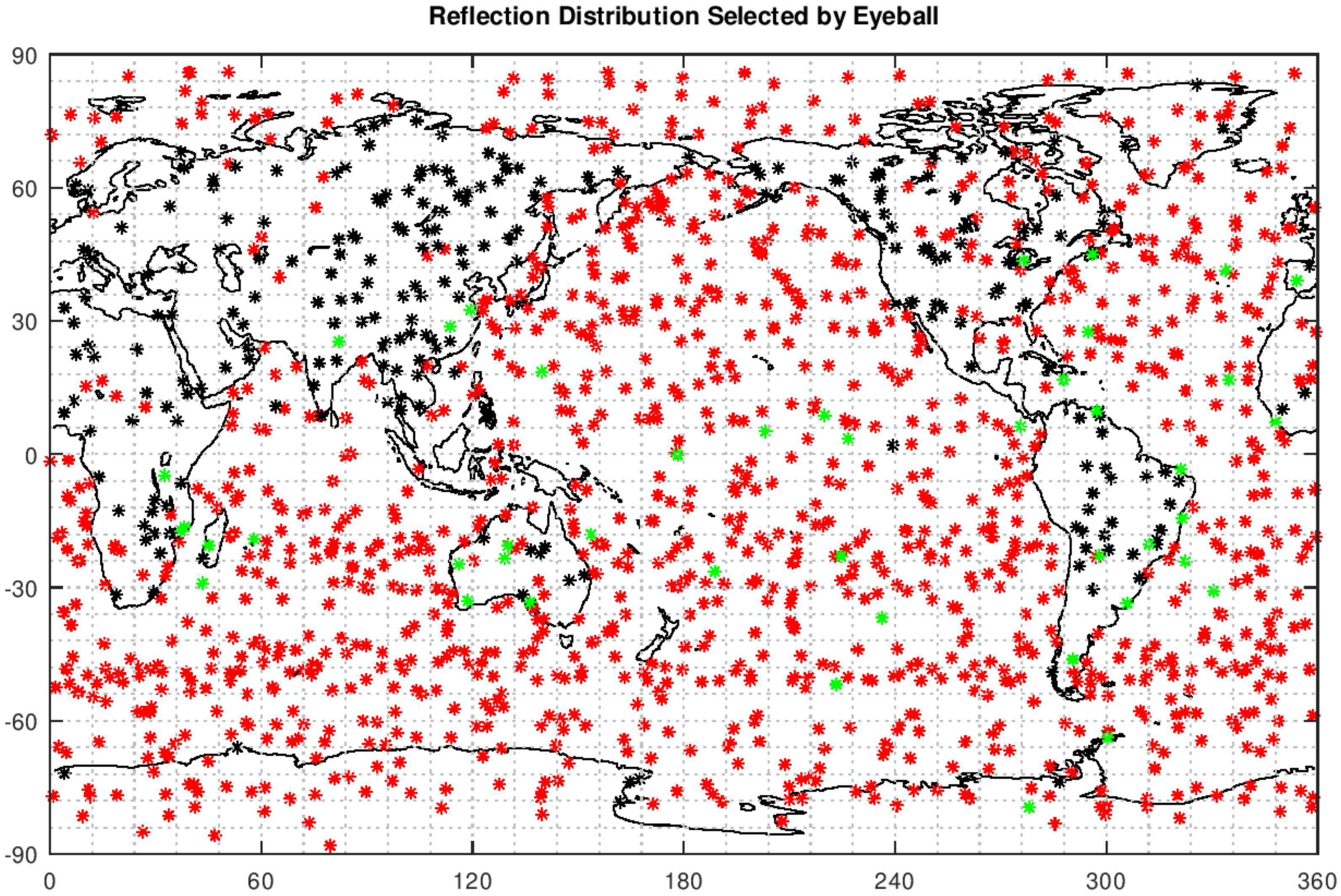
Grazing reflections

- Grazing reflections determined by eye = “Truth”
- Red = reflection
- Black = no reflection
- Green = unsure
- 95% of the occultations over the ocean have reflections
- We are in the process of implementing a detection method + the Xie method to solve the ducting ambiguity



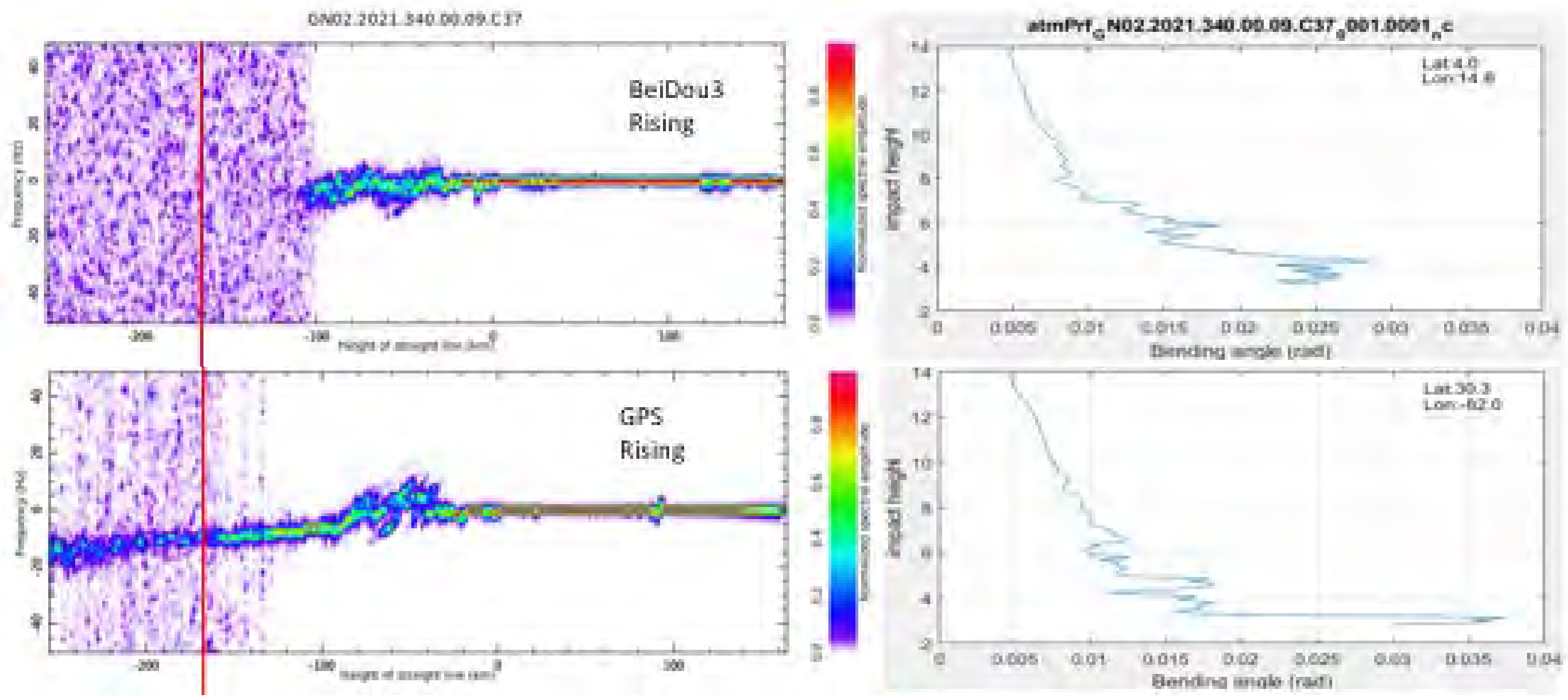
Detecting ducting in PlanetiQ occultations

Sliding spectra

Bending angle profiles

no ducting

ducting

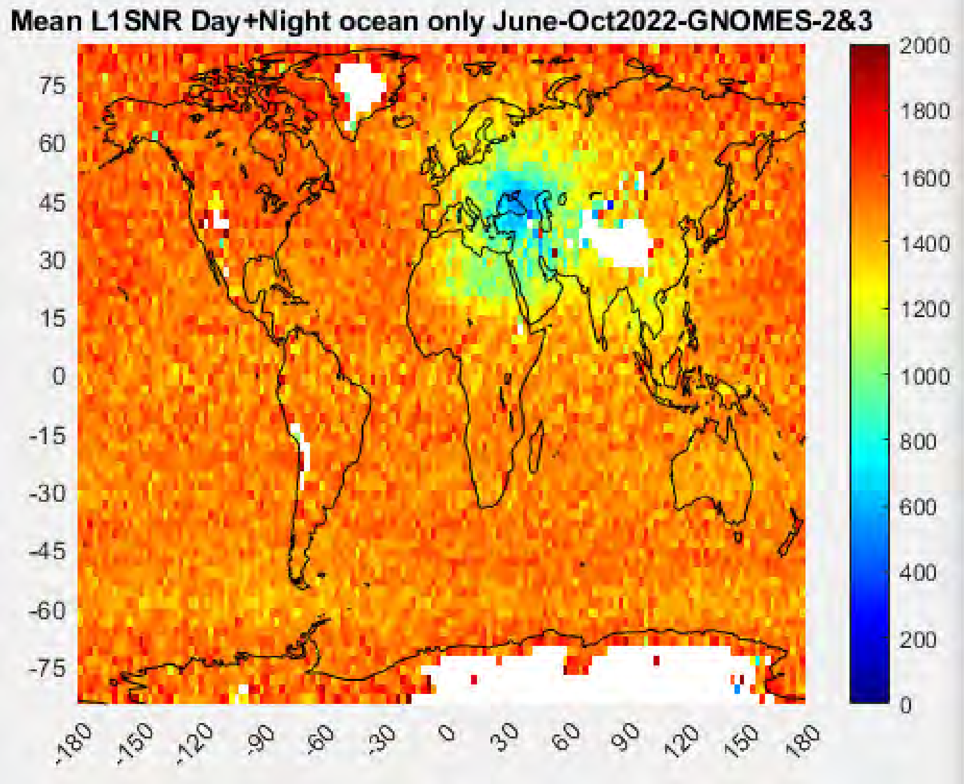


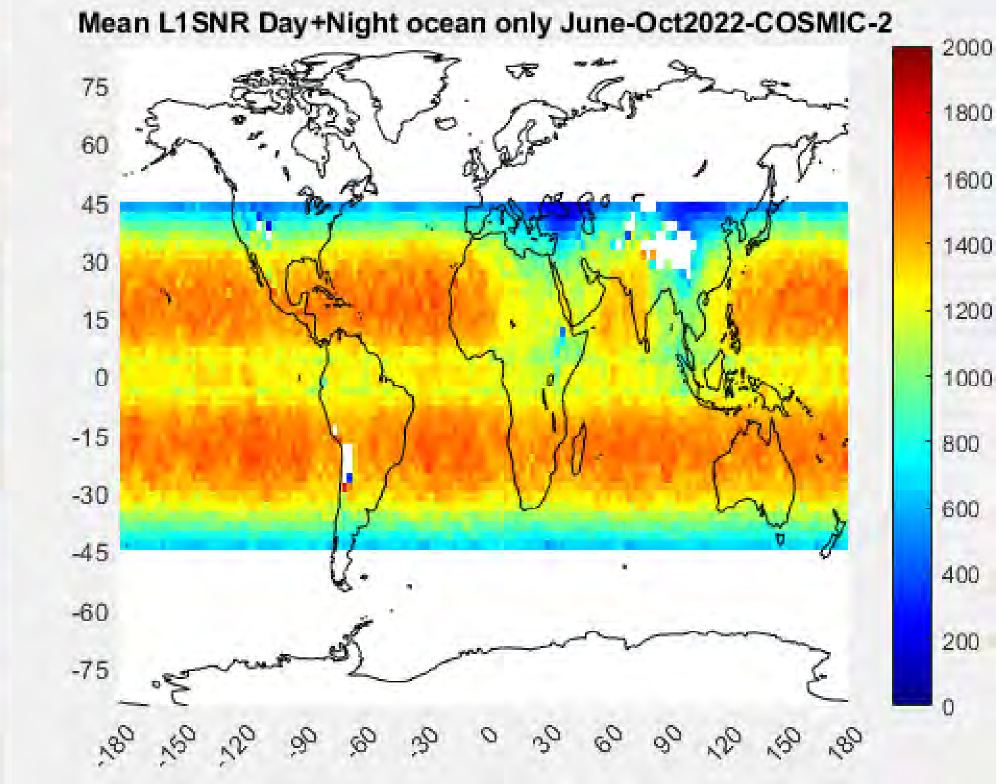
Based on Sokolovskiy et al., 2014

- Ducting is detected via the presence of signals deep in the occultation that would otherwise not be there.
- Detecting such weak signals requires very high SNR
- COSMIC-2 and PlanetiQ provide information to NWP about ducting for decision making

GNSS RO with high SNR, global coverage

PlanetiQ SNRs > COSMIC-2 SNRs and uniform except around jamming areas



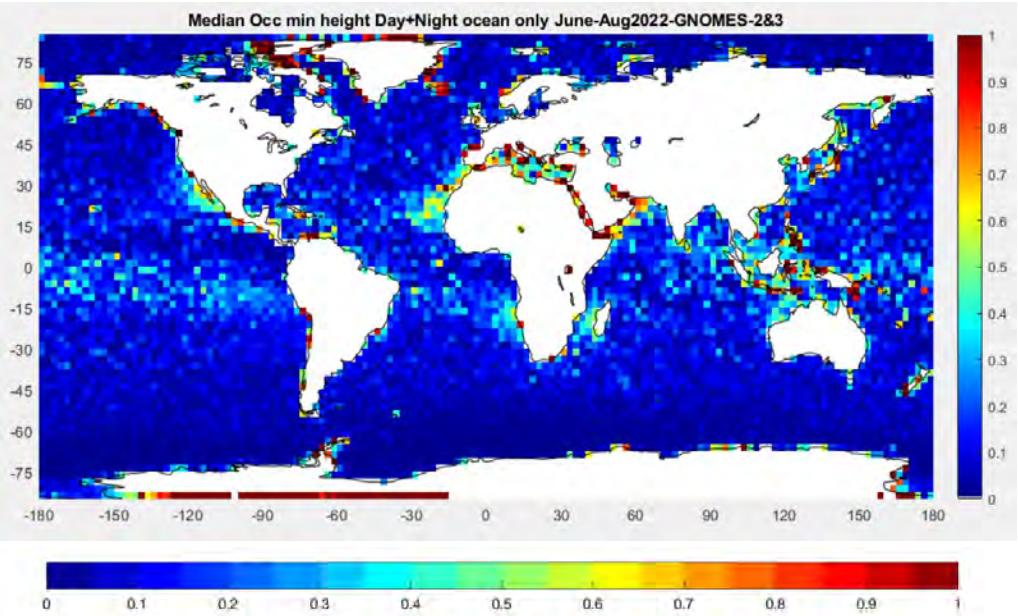


Penetration depth comparison

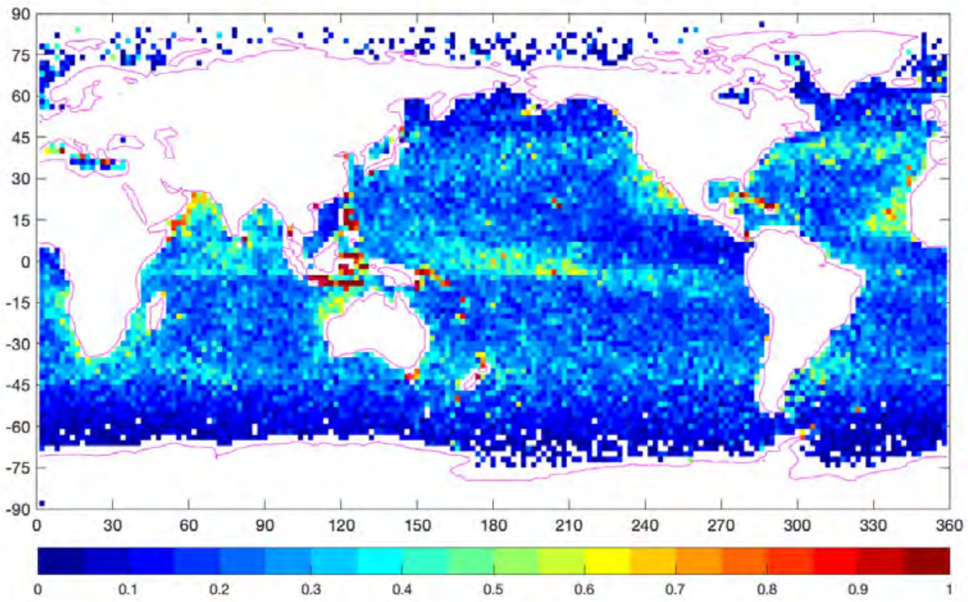
COSMIC-2 & Sentinel 6 vs PlanetiQ

PlanetiQ's higher SNR occultations profile even closer to the surface than COSMIC-2, providing more complete profiling of the entire PBL

Median minimum profile height (in km) from 5 months of PlanetiQ

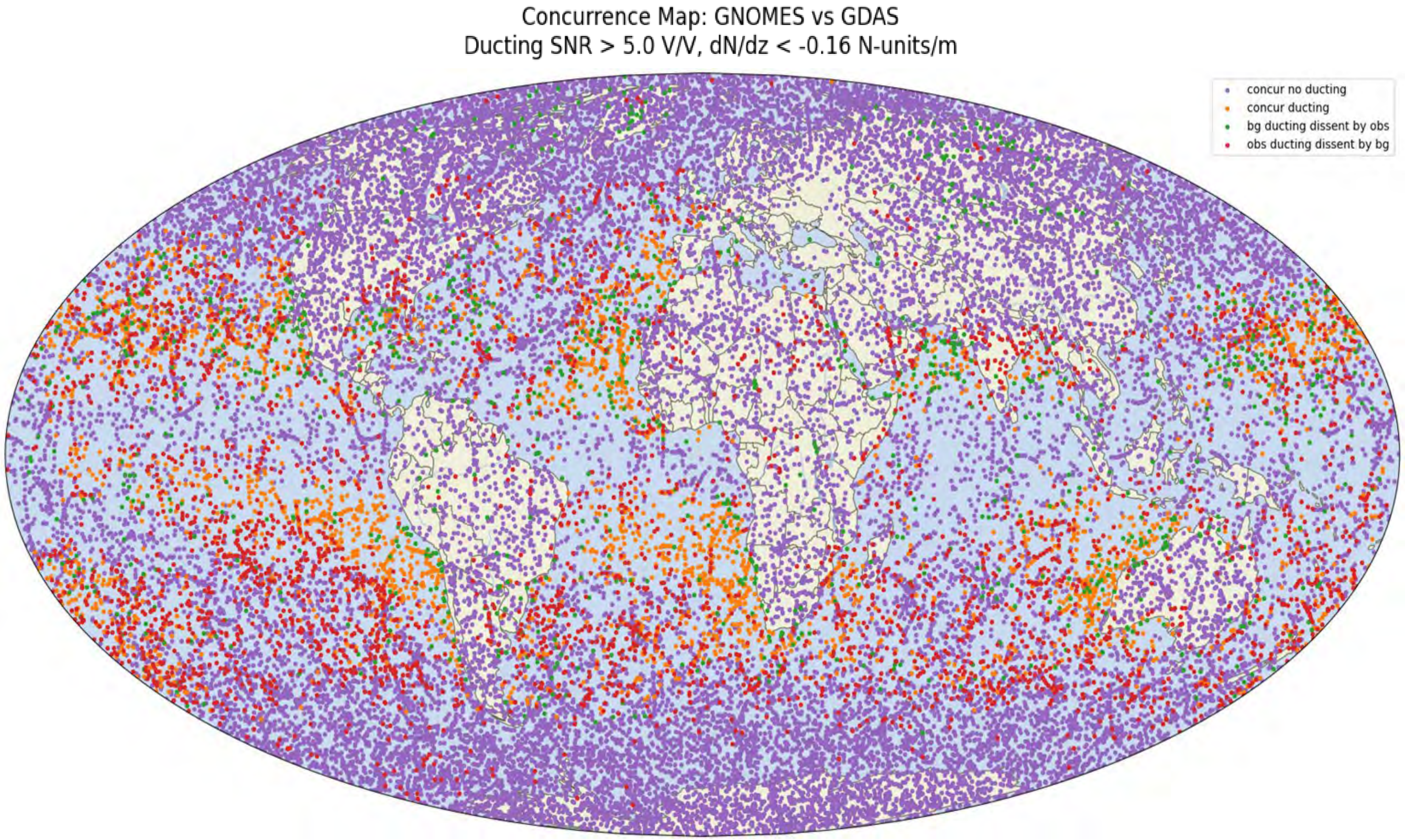


Median minimum profile height (in km) from 1 year of COSMIC-2 and Sentinel-6 (Ao et al., IROWG 2022)



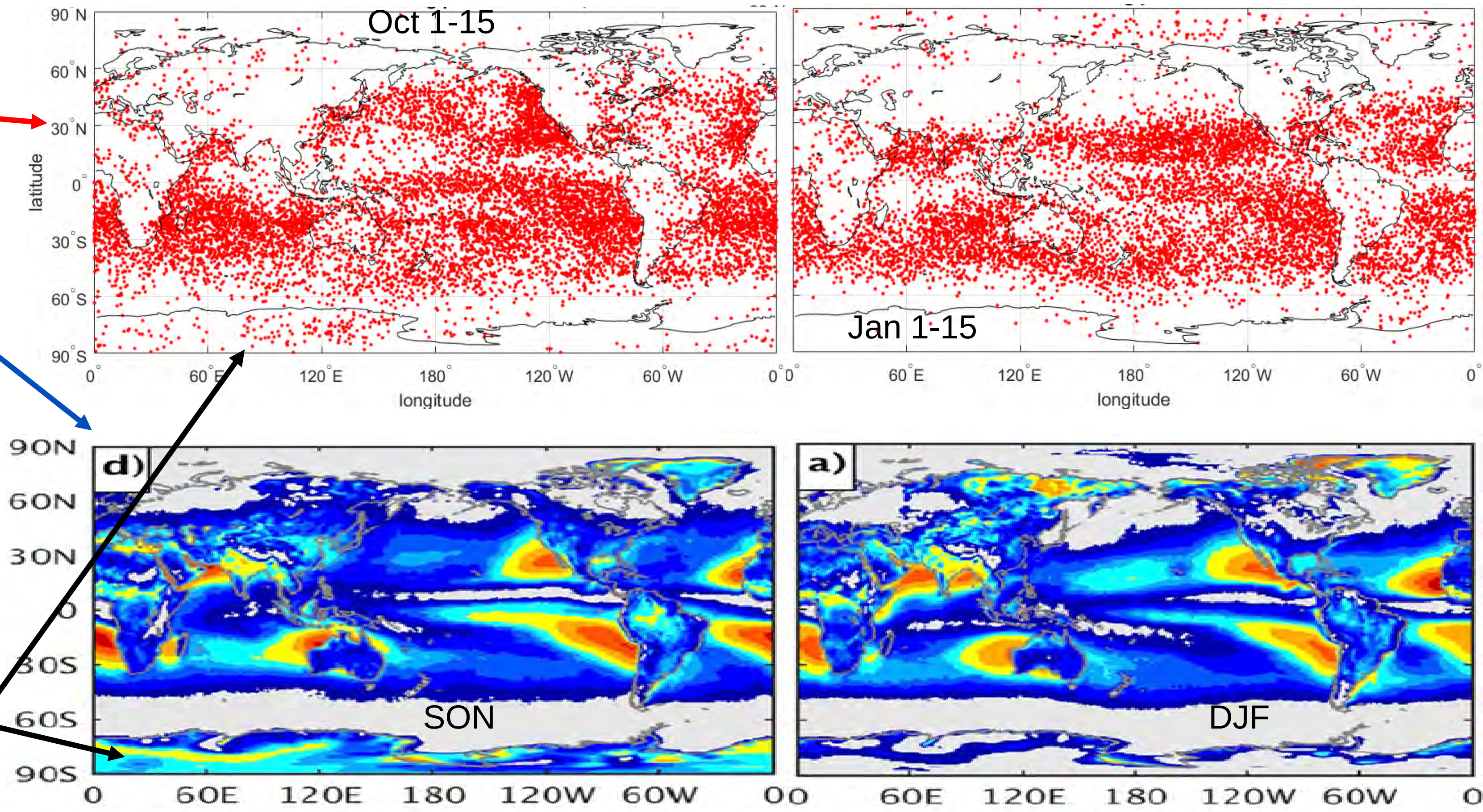
Ducting locations and concurrence with GDAS

- Implemented new ducting detection method based on deep signals in our 2D SWPM SNR(BA,IH) results
  - Superior to UCAR ducting detection method
- Performed initial evaluation of ducting consistency between RO and NOAA GDAS (127 lev.) and ERA-5 (137 lev.)
  - Purple & orange indicate agreement.
  - Red & green show disagreement



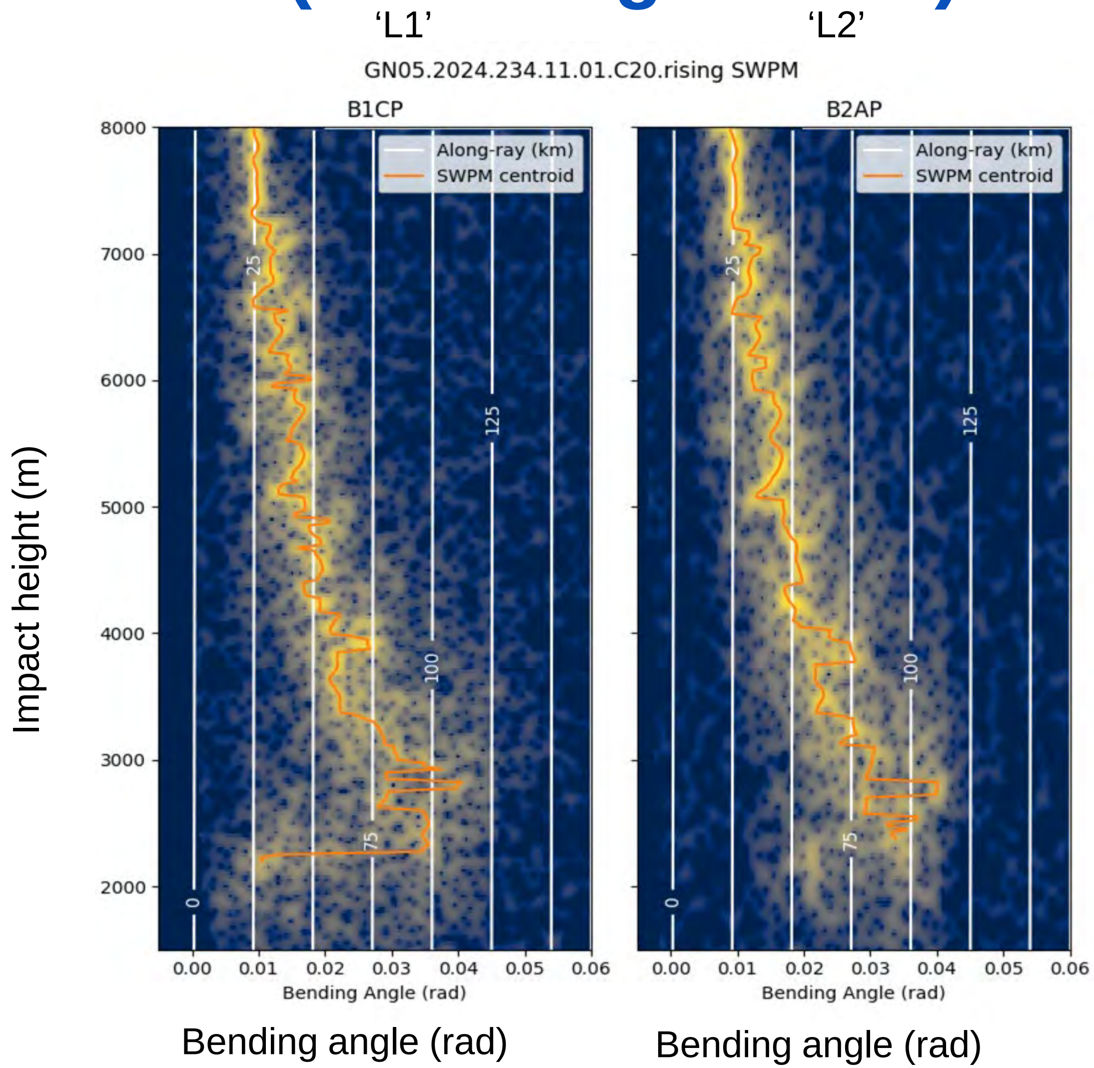
Frequency of large bending angles & ducting

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



NASA On-ramp 2: Sliding-Window Phase (Matching SWPM)

- Extension of work by Sievert et al. into a complete retrieval system
- Implemented by PlanetiQ to study ducting and tangent point drift
    - Solves bottom-of-track truncation tradeoff
    - Eliminates dependency on open-loop model frequency error
    - Eliminates cycle slip ambiguities
    - New foundations for ducting detection and reflection signal processing



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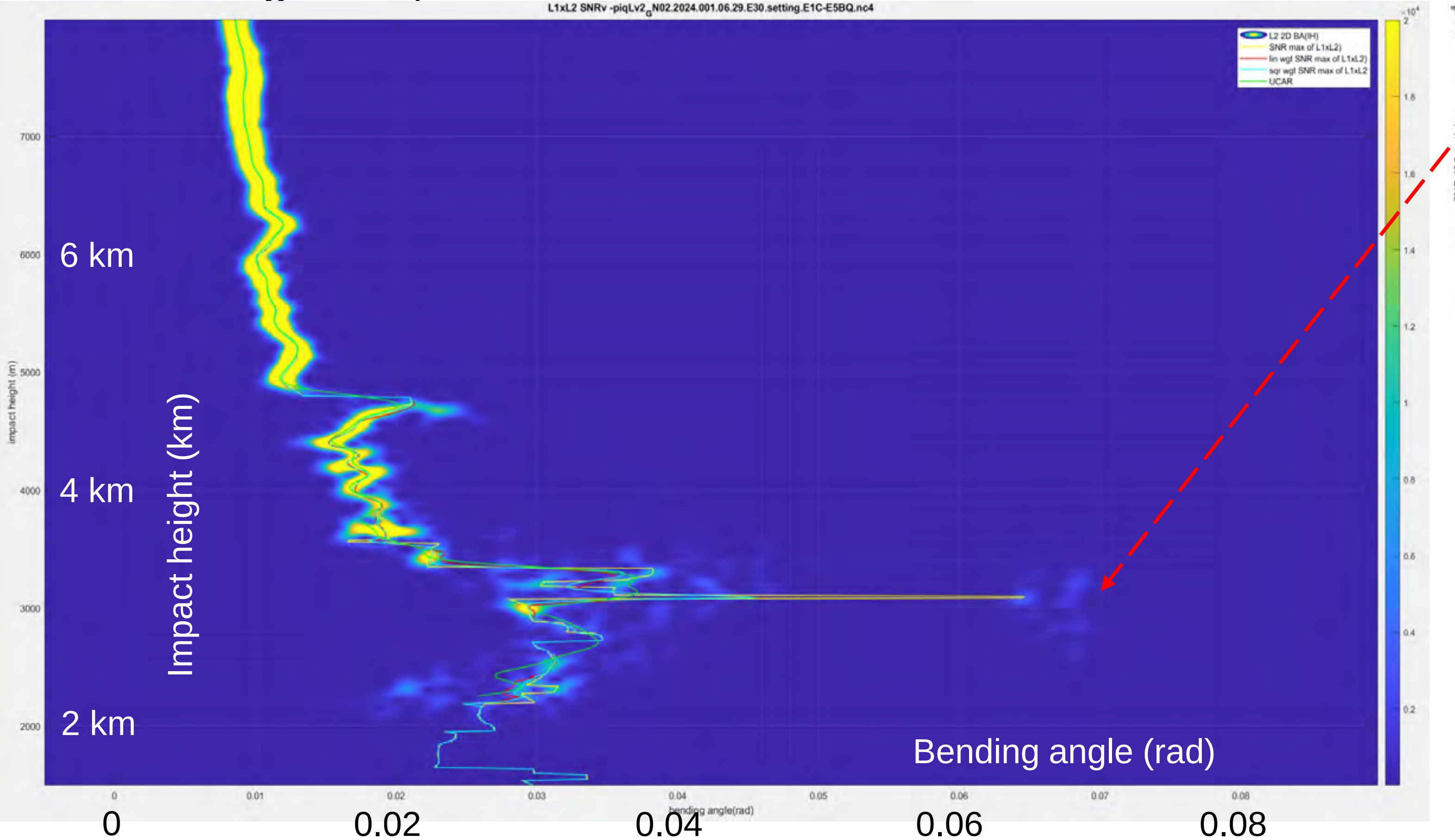
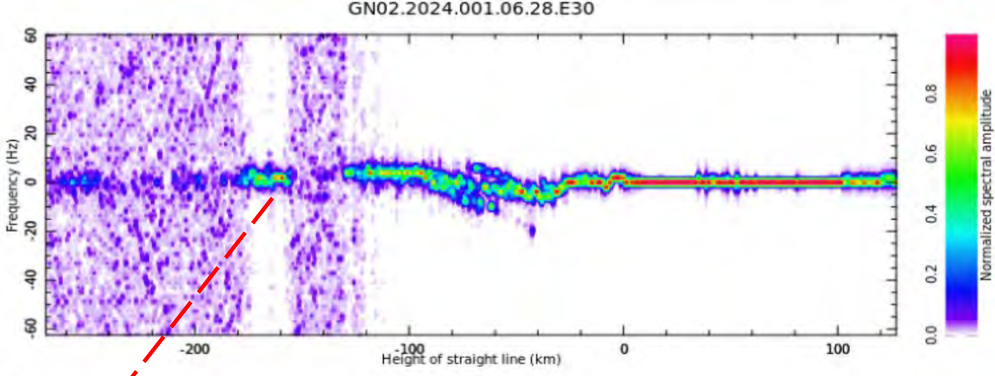
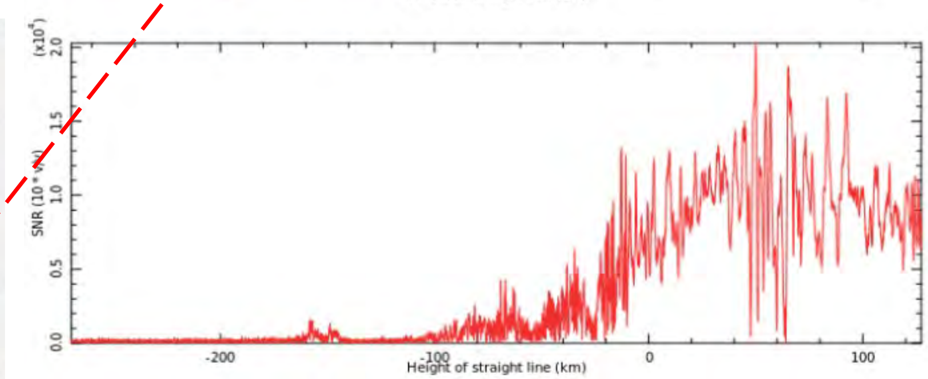
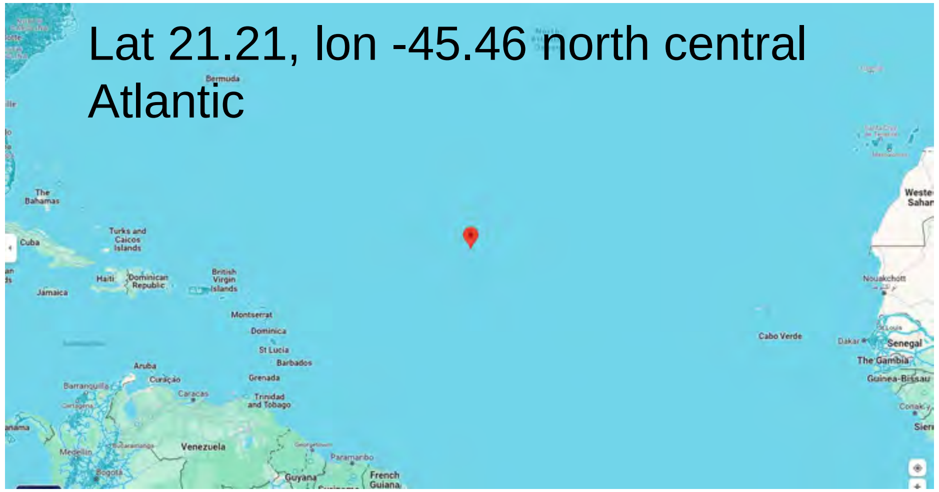
Deep occultation example

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

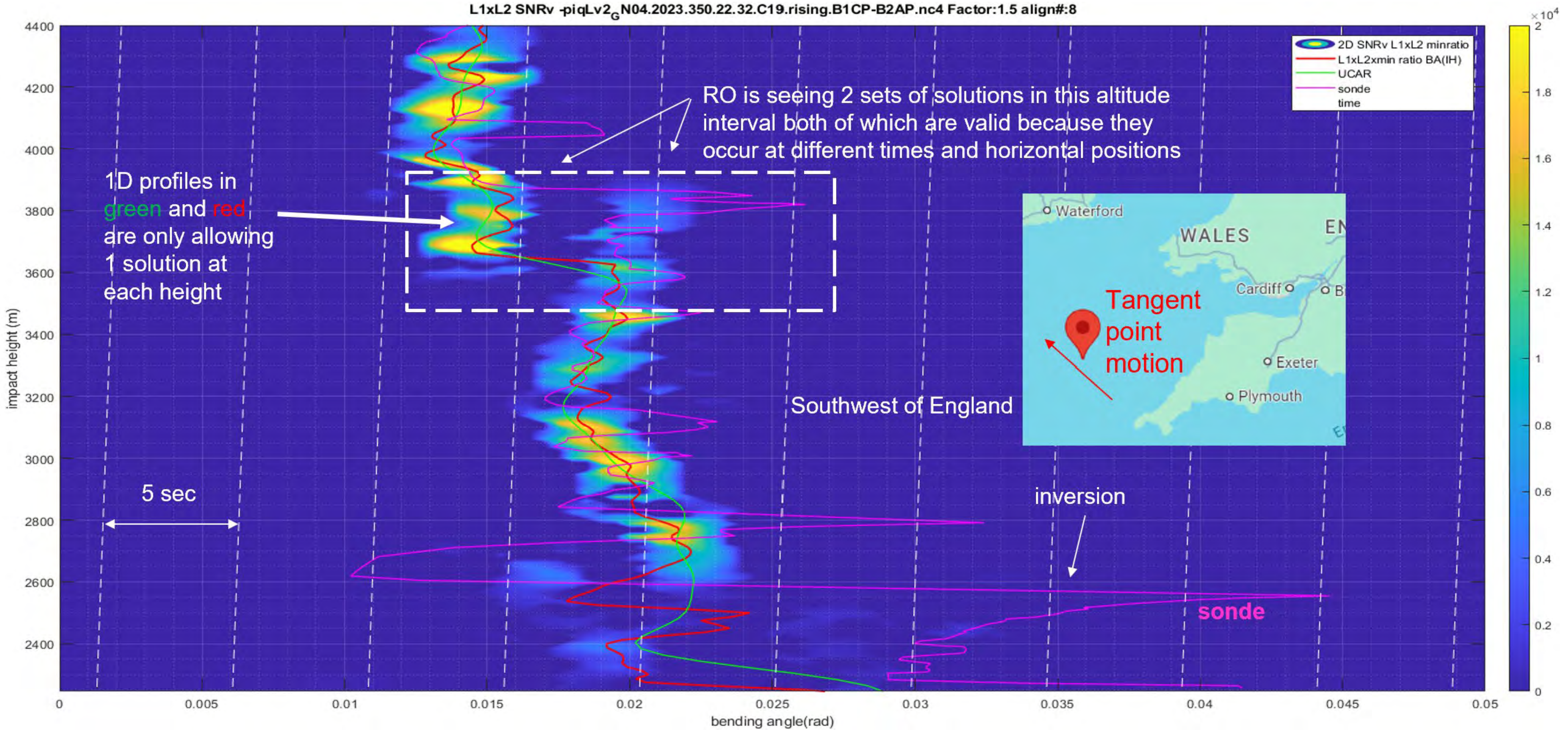




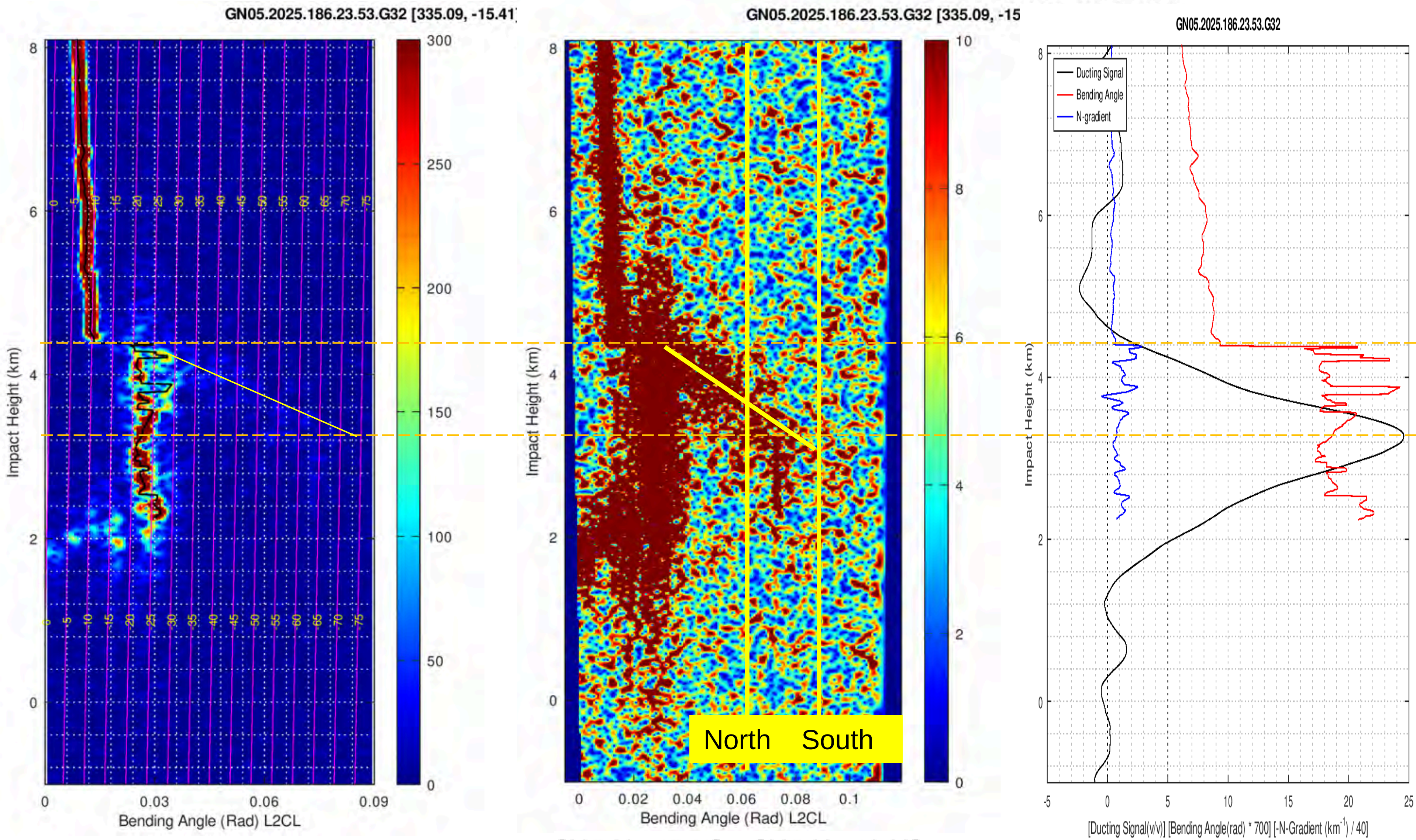




Horizontal information from SWPM RO



Horizontal scan of PBL top

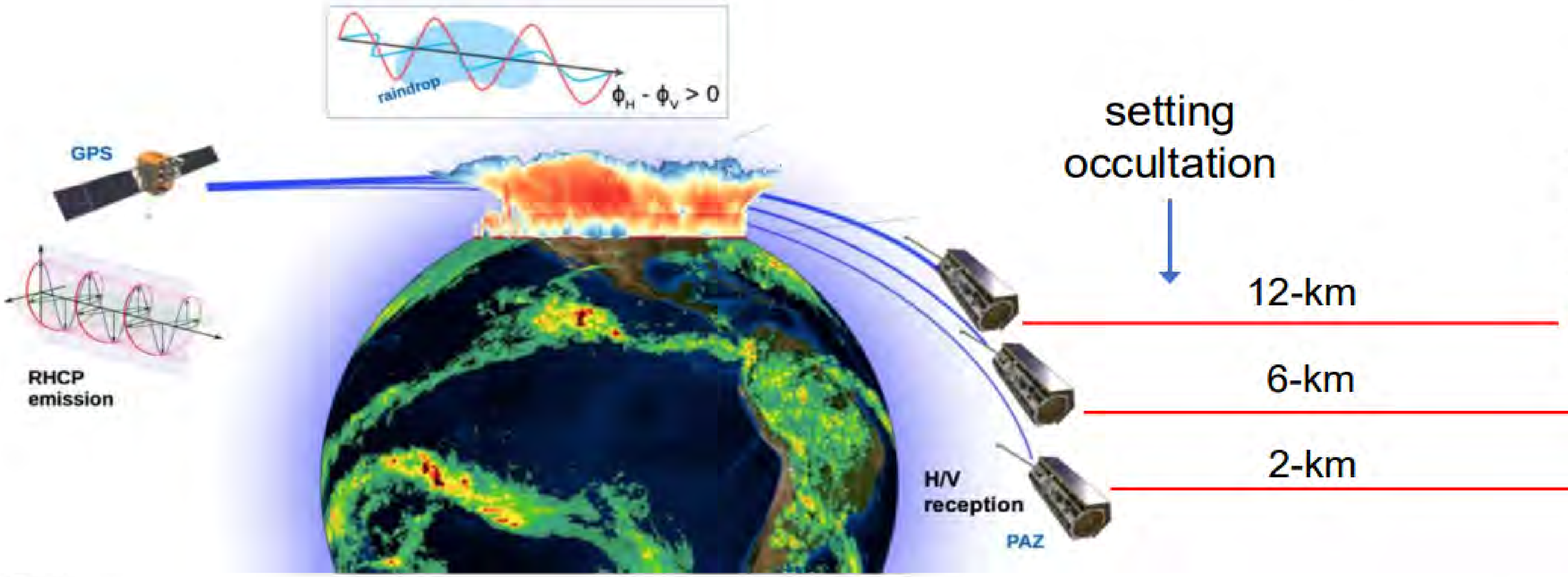


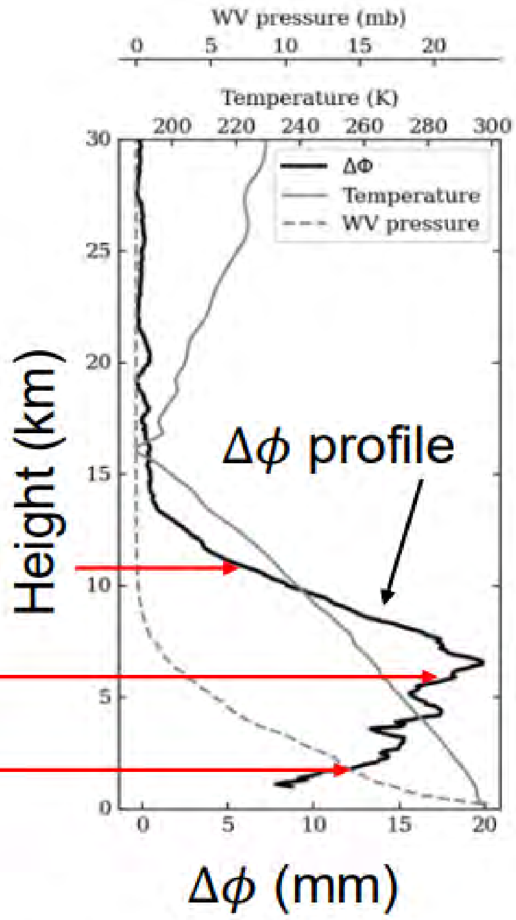
[335.09, -15.41] to [335.83, -13.93]

- Occ shows that PBL top tilts upward from south to north.
- Ducting detection from 0.065 to 0.09 rad finds lower altitude because the larger bending angles are to the south

Borrowed from Turk et al 13A.5
Thursday 9:30 am

Polarimetric RO Concept





Polarimetric RO (PRO) relies upon hydrometeor shape asymmetry, such that a **differential phase time delay ($\Delta\phi$)** is induced between the H- and V-polarized GNSS signals propagating through precipitation media

The (T, p, q) profile and the $\Delta\phi$ profile sample the identical air mass

The $\Delta\phi$ profile provides an indication of precipitation along each ray path

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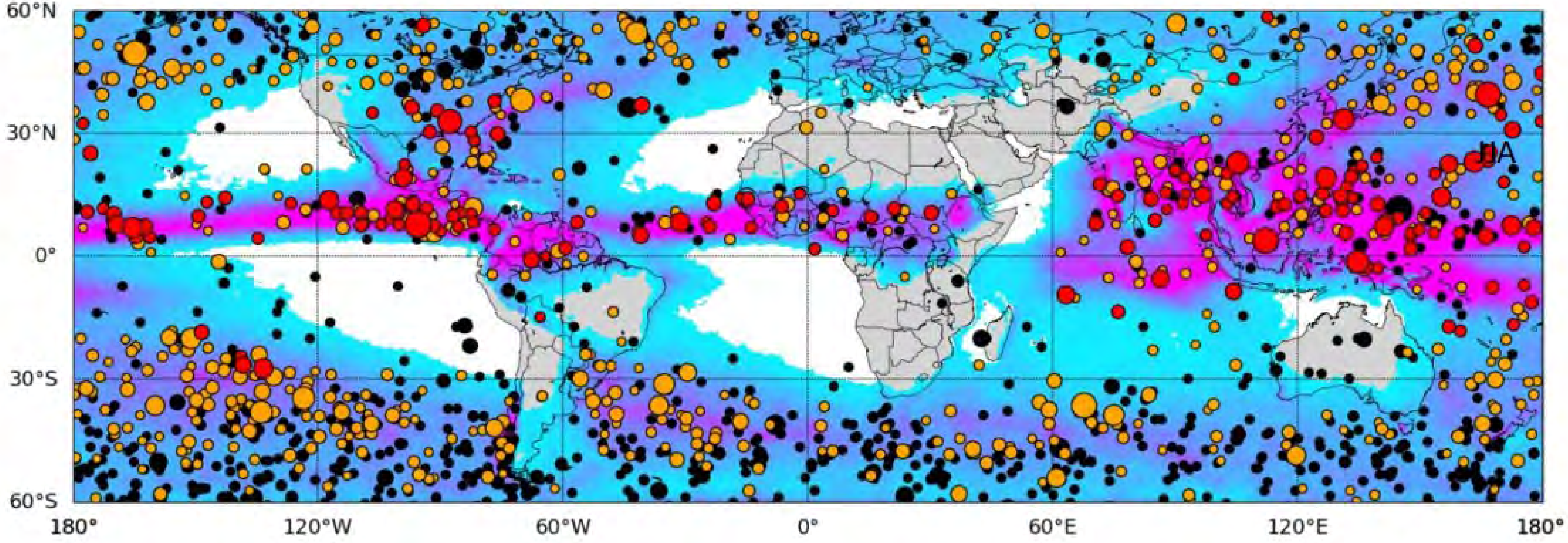
Locations of the upper percentile (top 20%) of the top-most height of the measured ROHP polarimetric phase shift ($\Delta\phi$)

2018-2023 JJA



For each PRO, the usual standard RO Level 1, 2 products are available

Top-Most Height
10-15 km
5-10 km
Below 5 km

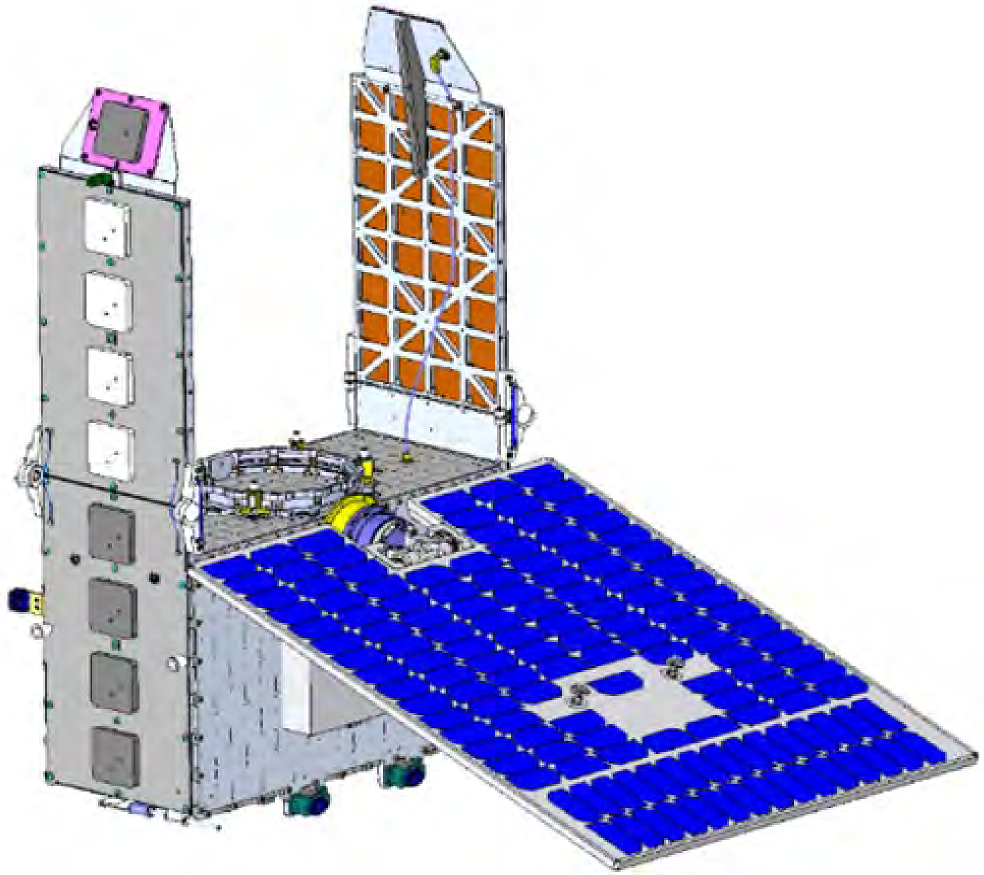
NASA IMERG: Integrated Multi-satellite Retrievals for GPM (Global Precipitation Measurement)

Turk et al., 2024. Advances in the Use of Global Navigation Satellite System Polarimetric Radio Occultation Measurements for NWP and Weather Applications. *Bull. American Meteorol. Soc.* https://doi.org/10.1175/BAMS-D-24-0050.1

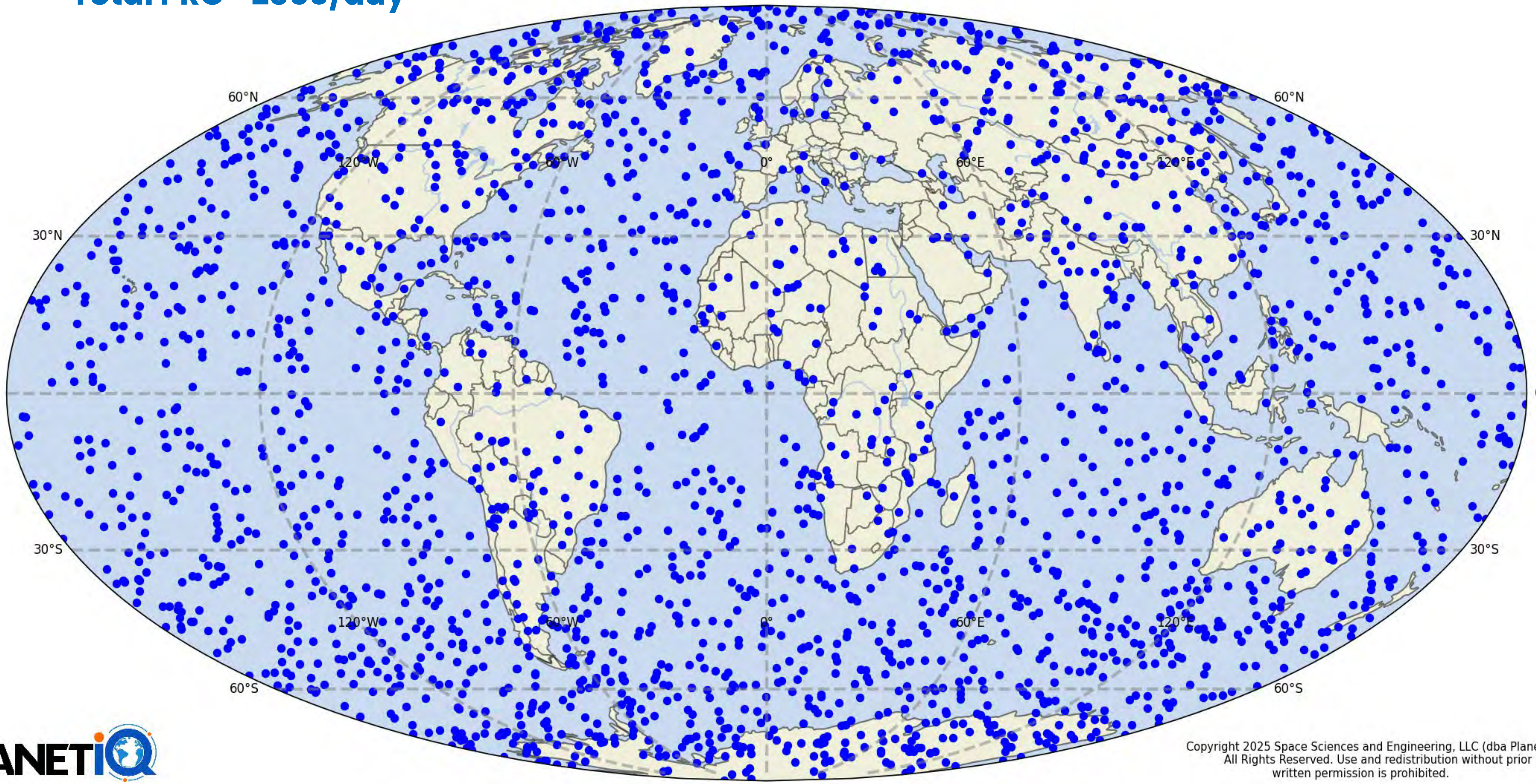
Polarimetric RO instrument: GNOMES-5

Dual linear polarization on GNOMES-5 + YAM-8

- 4 antennas the same as SC 1-4
  - Dual Hemispherical POD antennas
  - Dual-column high gain RCP antennas for RO
- One RCP RO pair replaced with dual linear pol. pair
  - GNOMES-5: PRO antenna faces rising direction
  - ~2 dB penalty in SNR relative to dual column RCP
- OL track H and V polarizations separately
- H & V are combined to increase SNR for normal RO. Currently in-service for delivery to NOAA
- Calculate differential H-V phase to measure heavy precipitation & certain clouds
- PlanetiQ is producing thousands of PRO profiles per day



Total PRO ~2350/day



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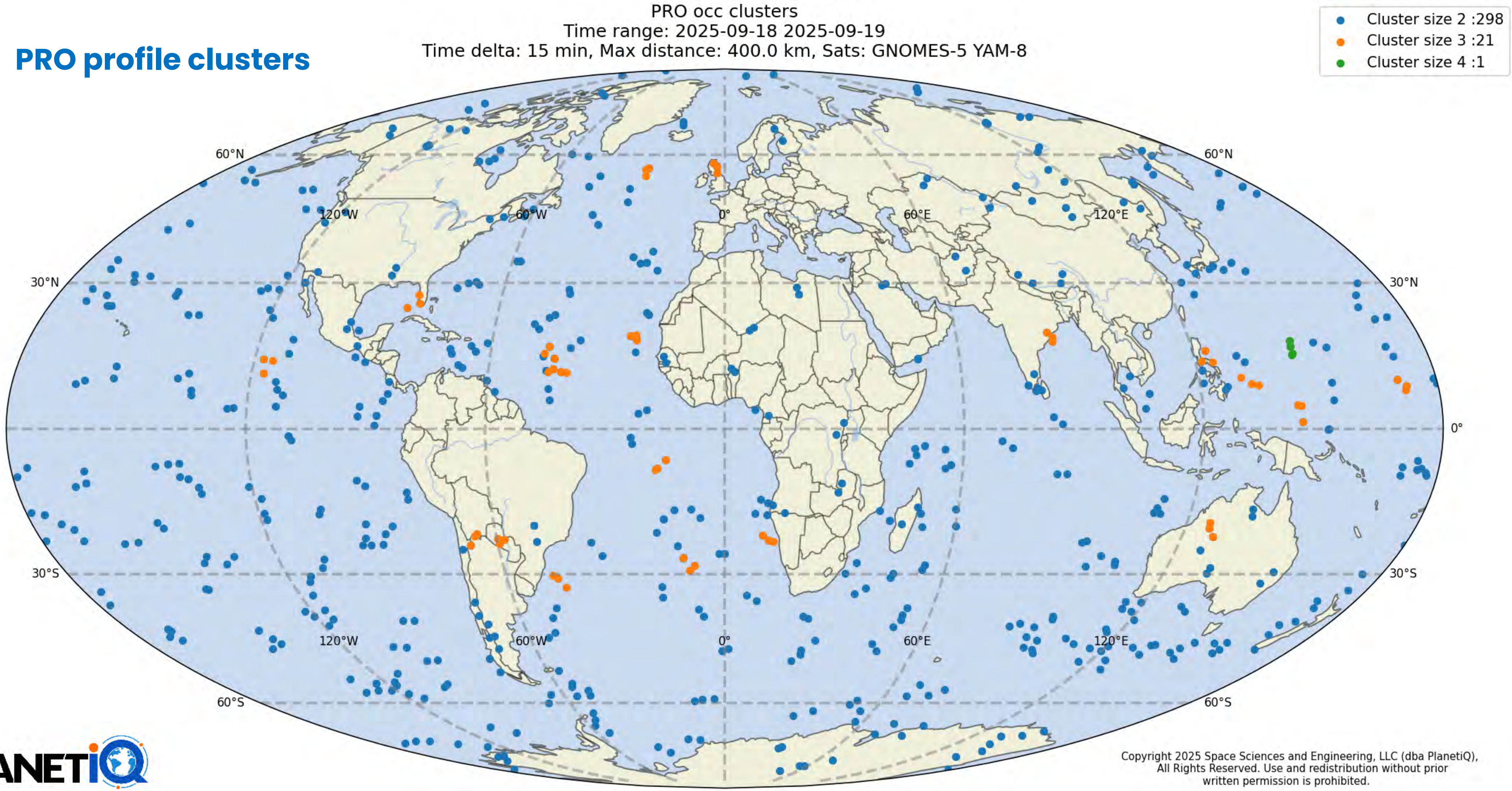
PRO profile clusters



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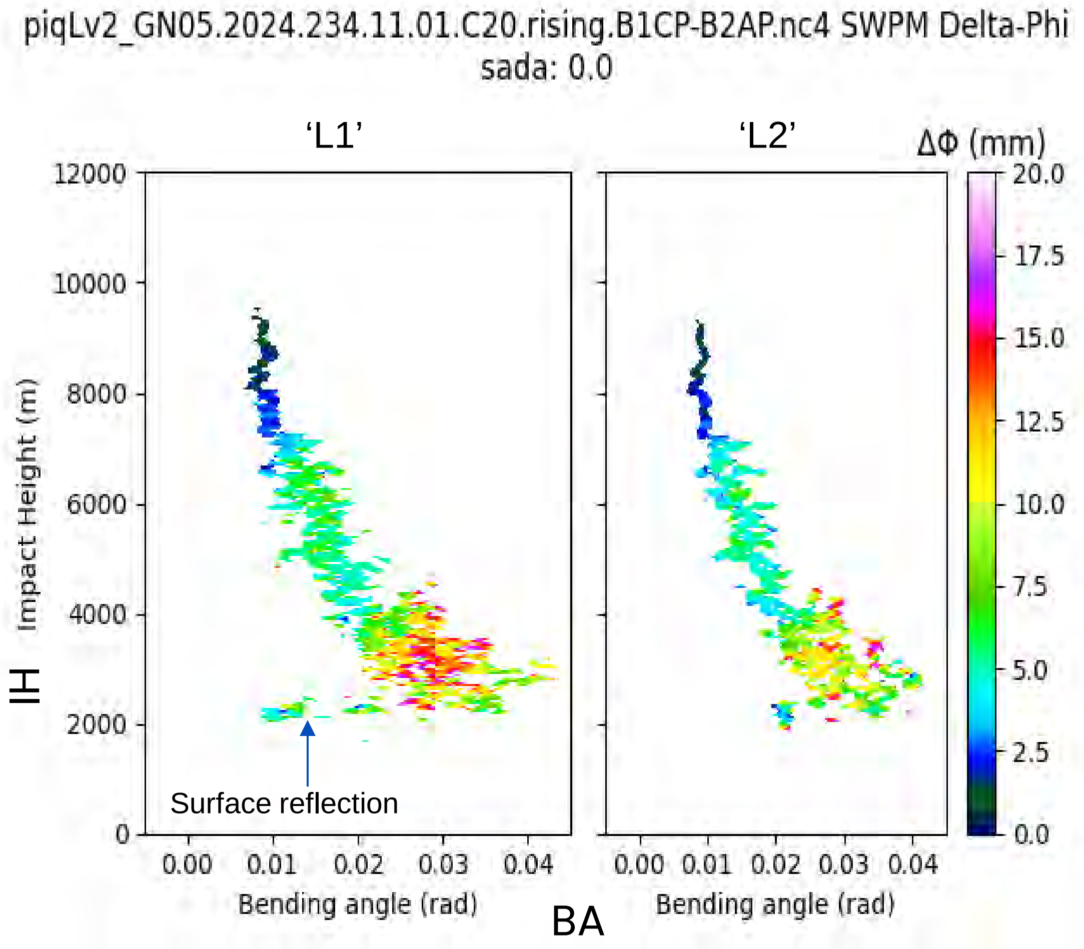
Processing System : Sliding-Window Phase Matching

Shown at right

- Phase shift across entire IH(BA) domain
  - Calculate WO-transformed and filtered phase field in entire domain for H and V separately
  - PRO Calibration: Hard-zero at 35 km SLTA
  - Form phase difference as complex conjugate product of two fields
- Masked by phase shift amplitude > 4-sigma of thermal noise
- **Colors represent magnitude of phase shift, normalized to difference in distance**



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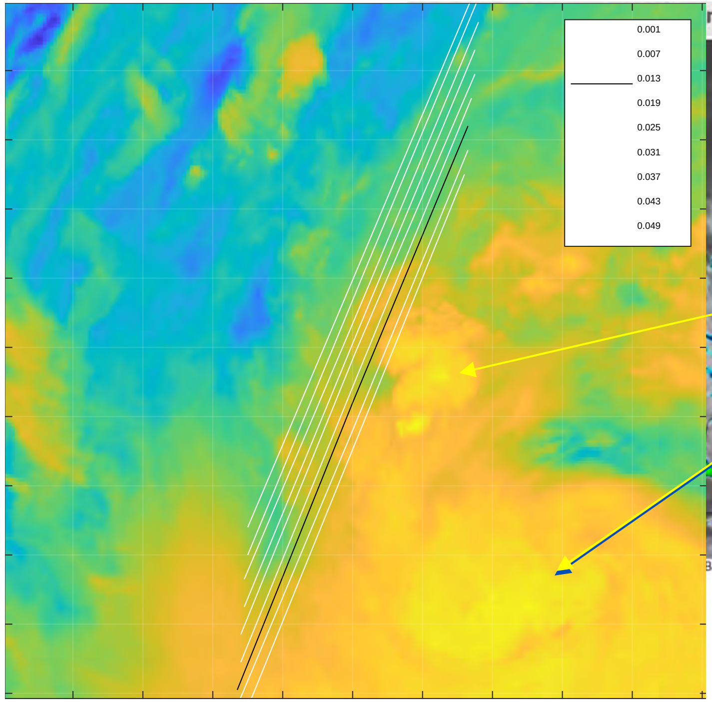
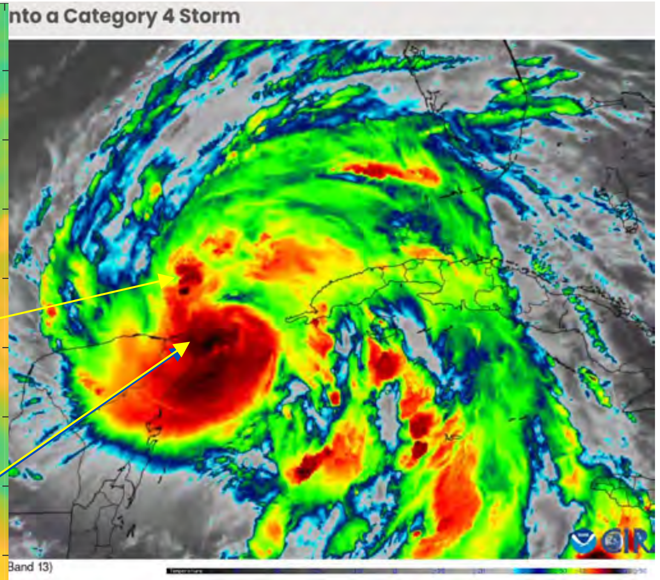
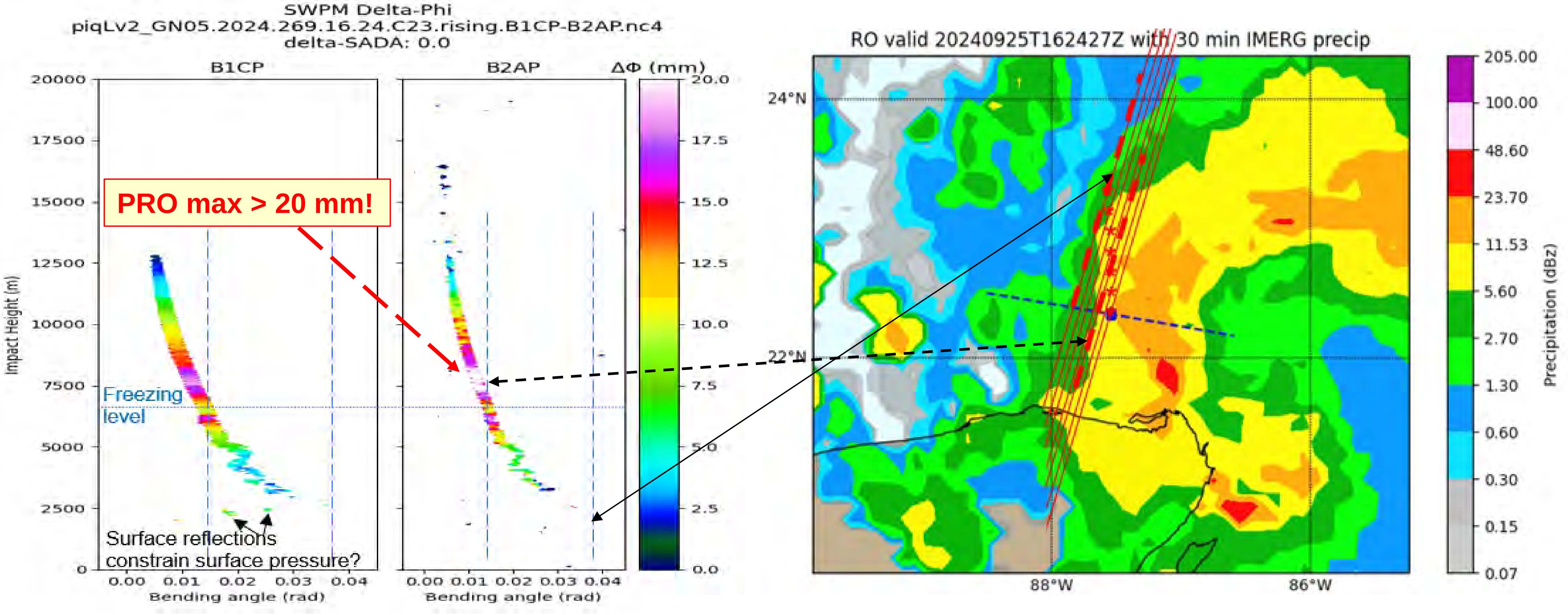
Case Study: Hurricane Helene on Sept 25, 2024

- RO samples western edge of Helene north of Yucatan
- PRO max > 20 mm!
- IMERG strong precipitation but location of RO peak suggests IMERG precip may be underestimated there
- Deep part of occultation is further off the edge of Helene

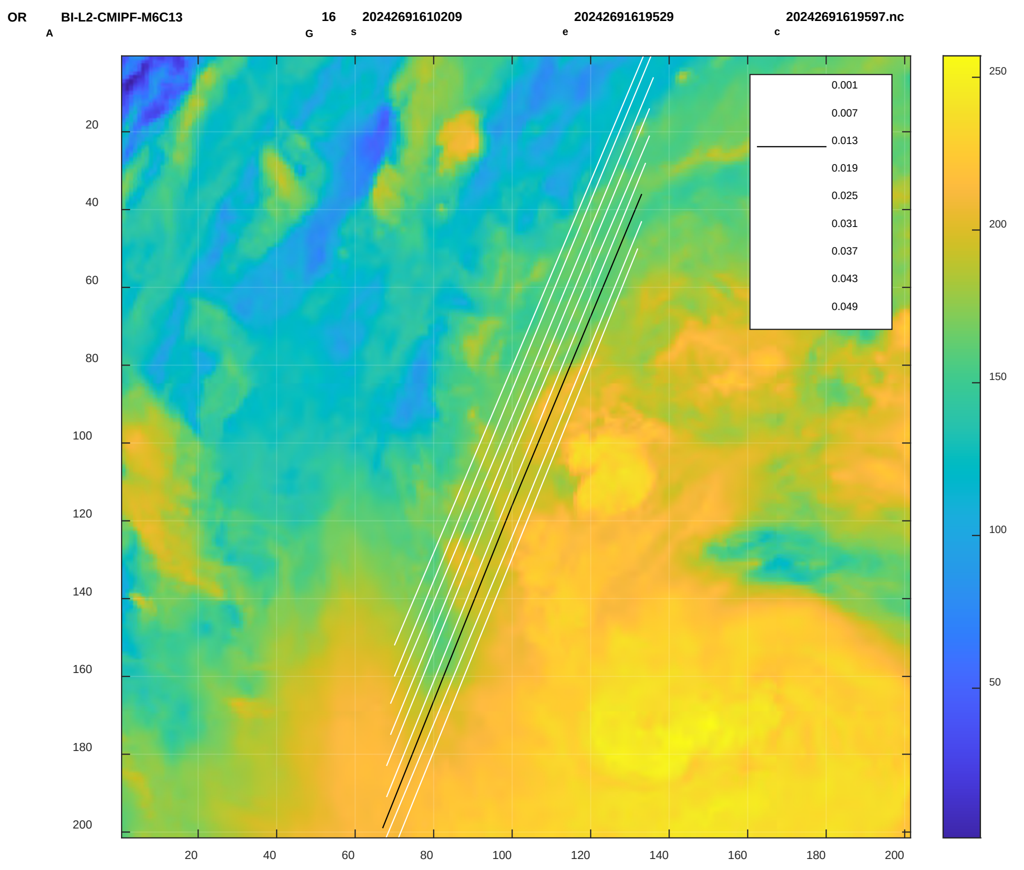




Case Study: Hurricane Helene on Sept 25, 2024

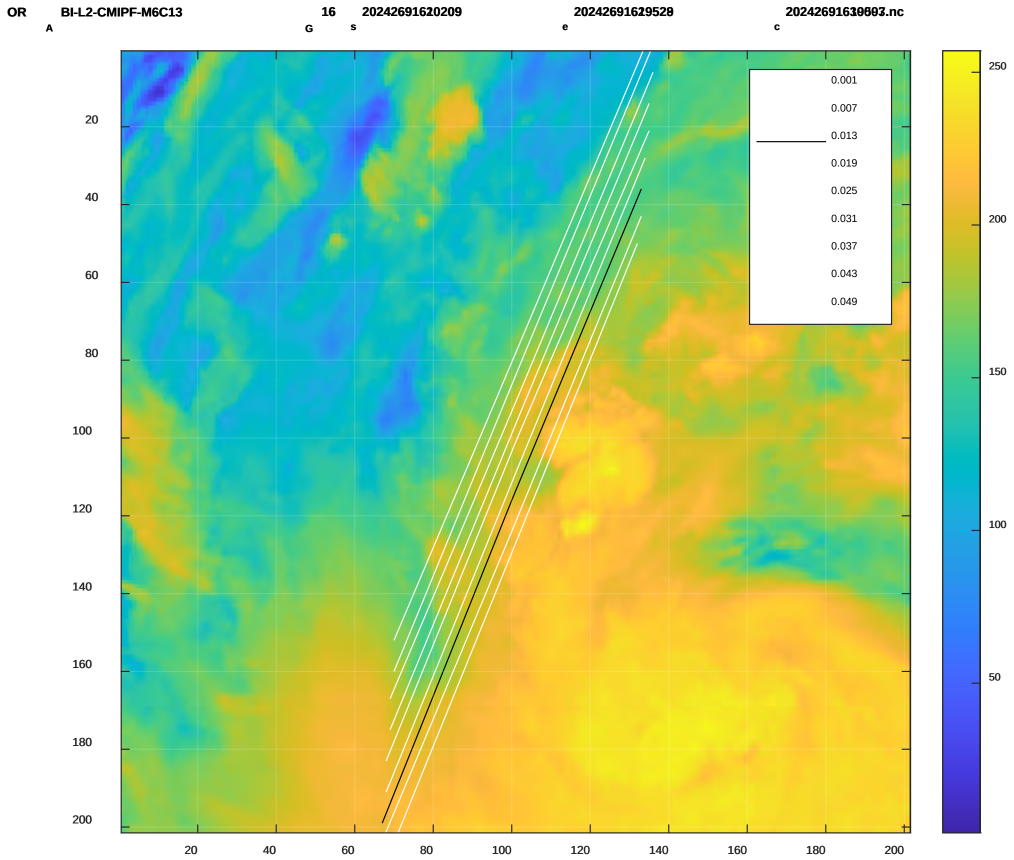


Case Study: Hurricane (animation)



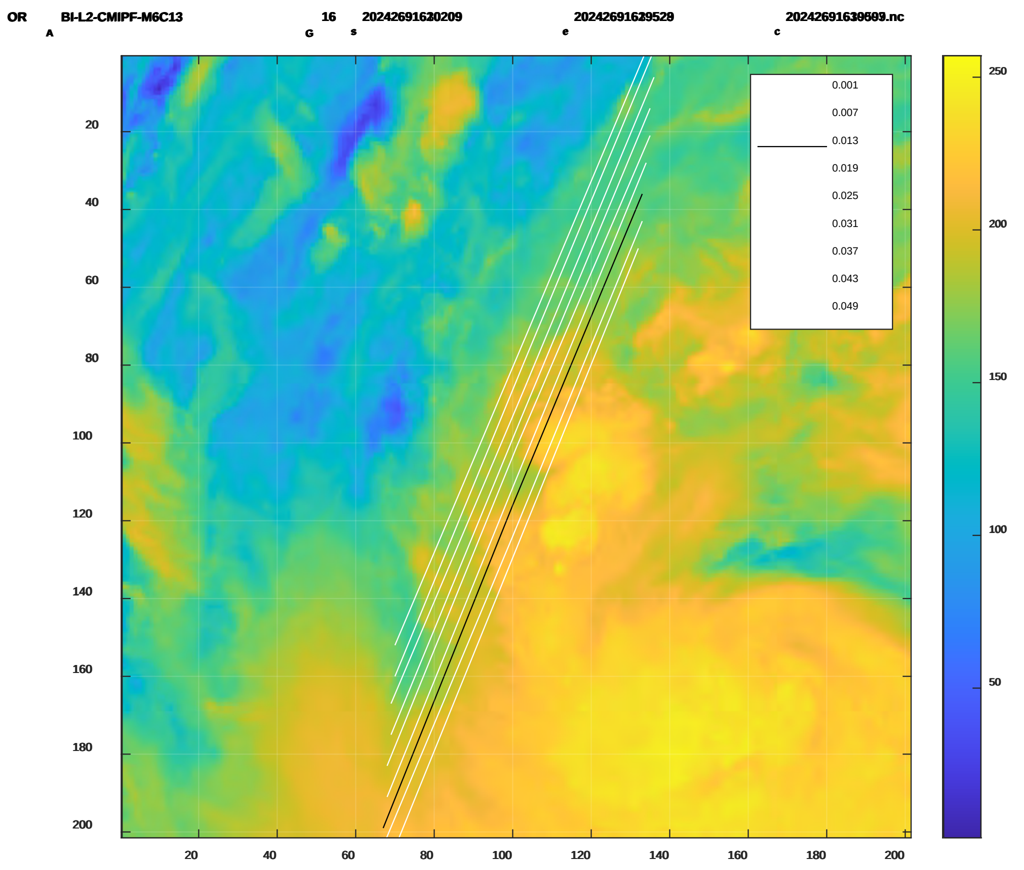
10 min earlier

Case Study: Hurricane (animation)



Closest time

Case Study: Hurricane (animation)

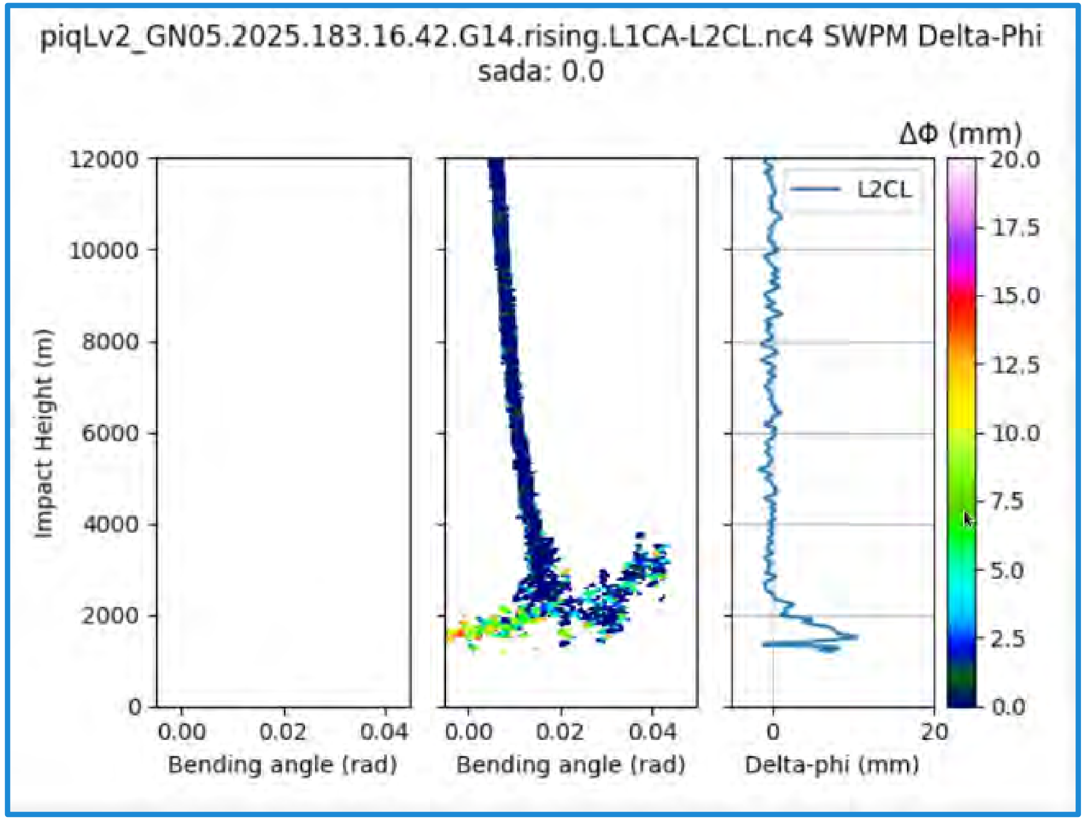


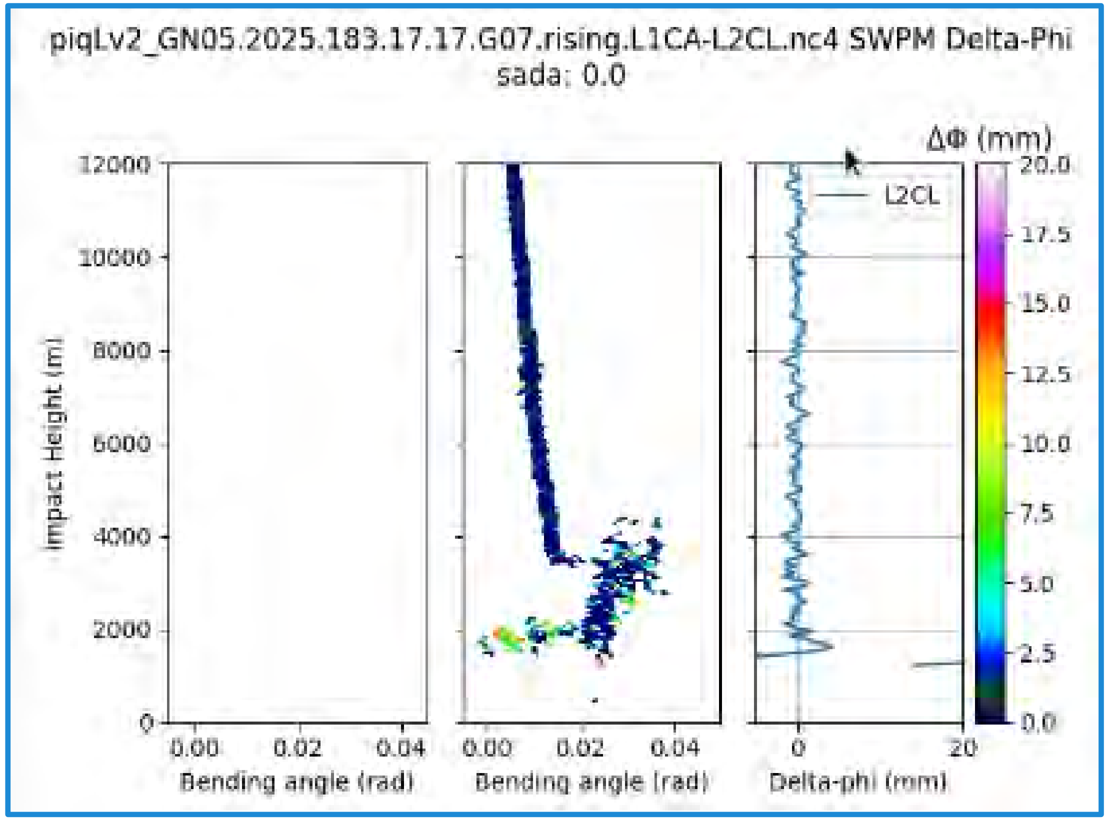
10 min later

Reflections w/ H-V phase shifts w/ no corresponding H-V phase shift in direct signal

What is the explanation?

- Appears to be due to imaginary part (absorption) of permittivity of sea water which is a function of temperature and salinity





Key points summary and conclusions

- Critical need for high SNR GNSS RO for measuring LT/BL:
  - Capturing signatures of large BAs and reducing negative bias in large bending angles
  - Detecting ducting AND frequency of detected ducting increases with higher SNR
  - Acquiring grazing reflections to use in solving the ducting BA vs N ambiguity,
  - High SNR at L1 & L2 critical to isolating geometric optics solutions among diffraction (speckle) noise
  - Deeper penetration extending closer to surface
- Recognizing and utilizing the information content
  - Occultations are not 1D profiles in the LTBL, rather each occultation is really a series of ~2D planes sliding through the LTBL as the ray slowly ascends or descends overall
  - A lot of mesoscale information is contained in these occultations, Can see active convection
  - Properly interpreting the occultation information in the LTBL will reduce the RO uncertainty
- **RO resolution**: Vertical: ~ 100 m, Along-track: ~ 100km, Cross-track: $\geq$ 1.4 km
- Coincident polarized RO to measure precipitation such as in Typhoon rainbands

Space weather

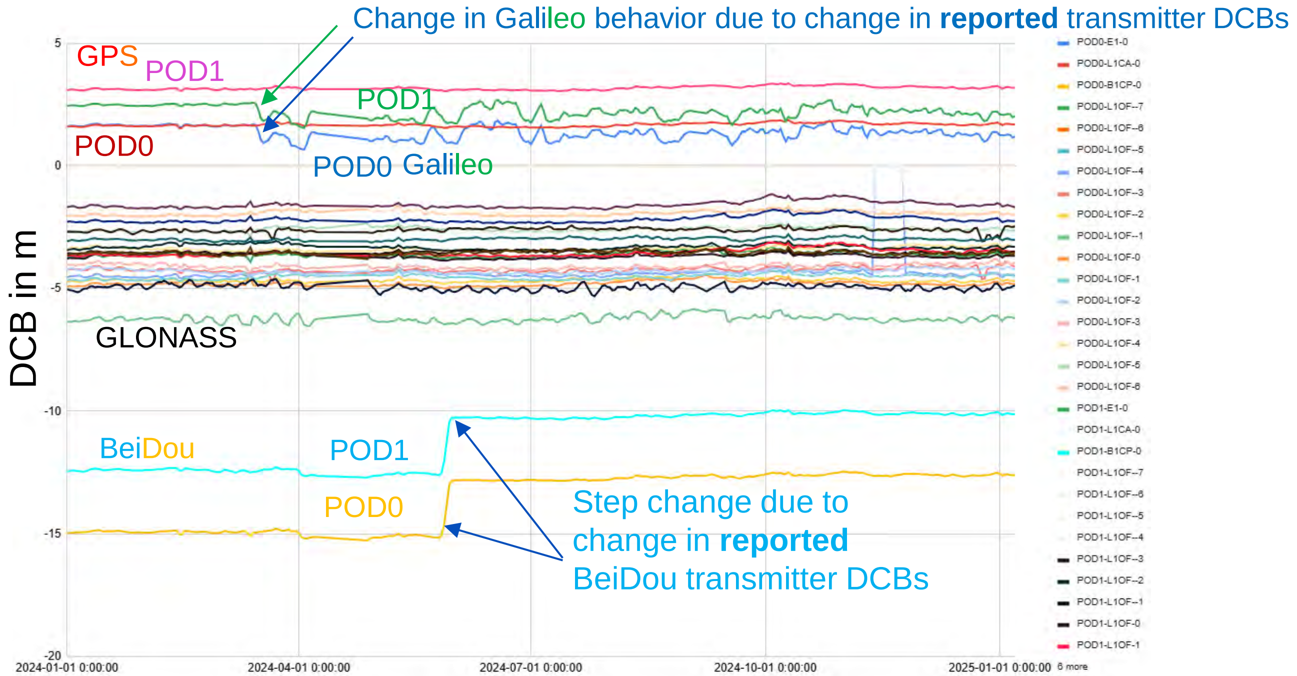
Data Type	Has NASA purchased?
Total Electron Content (TEC)	• Yes
Scintillations	• Yes
Sporadic E layers (Es)	• Imbedded in high-rate, high SNR data NASA has purchased. • Es extraction under development
Electron Density Profiles (EDP)	• No, Under development

TEC Calibration

- The TEC PlanetiQ delivers to BC is the differential phase TEC leveled to match the differential ranging TEC following estimation and removal of local multipath and transmitter & receiver differential code biases (DCB).

- Figure shows stability of our GNOMES-4 receiver **DCB** estimates for our two POD antennas for GPS, Galileo, BeiDou3 & GLONASS
  - using broadcast xmtr DCBs
- GPS very stable & smooth
- BeiDou stable & smooth except for a step
- Galileo transmitter DCB estimation changed in March 2024
- GLONASS is noisier due to coarser ranging precision and less averaging due to FDMA

POD0 and POD1 are the two POD antennas on GNOMES-4



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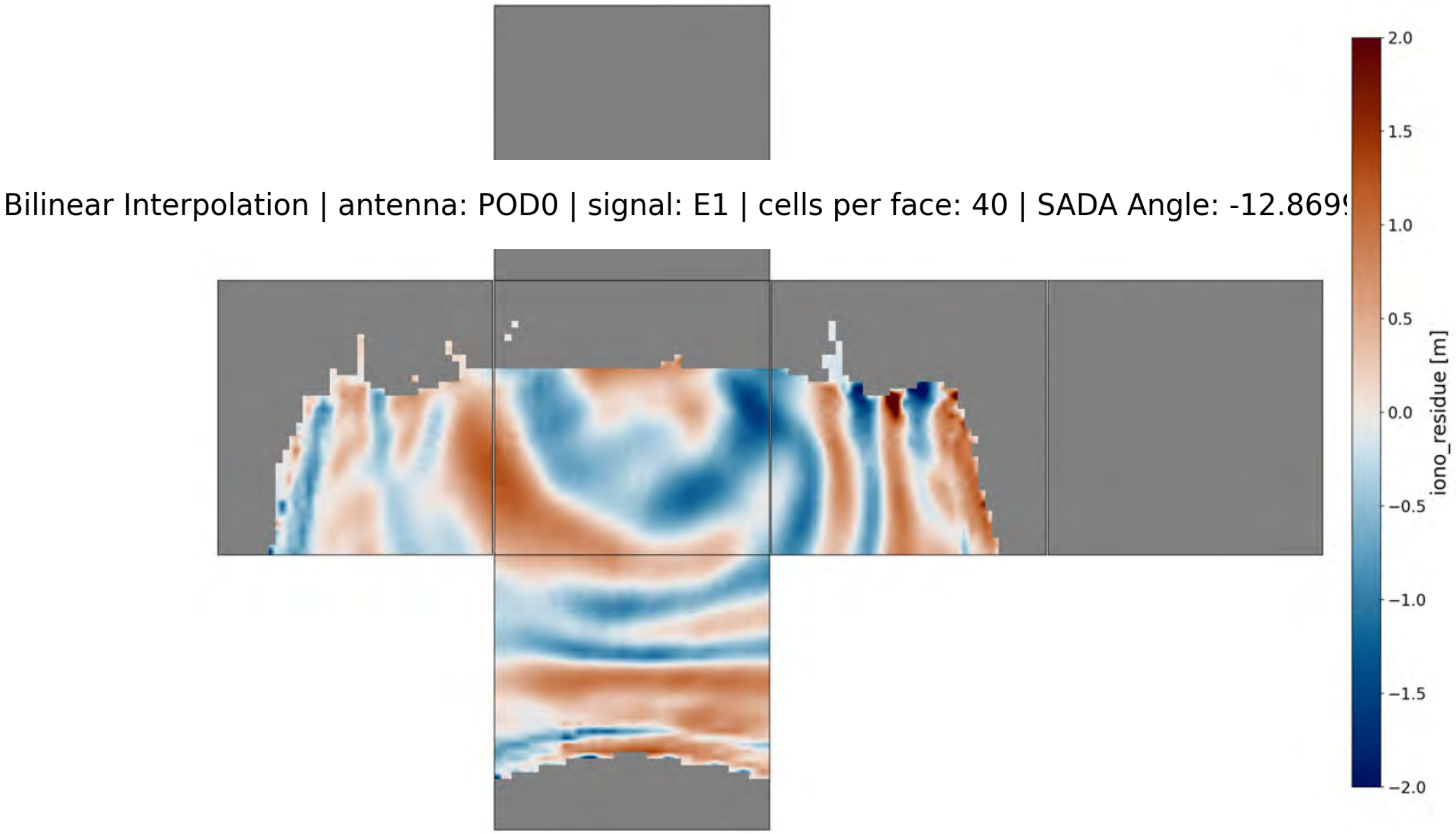
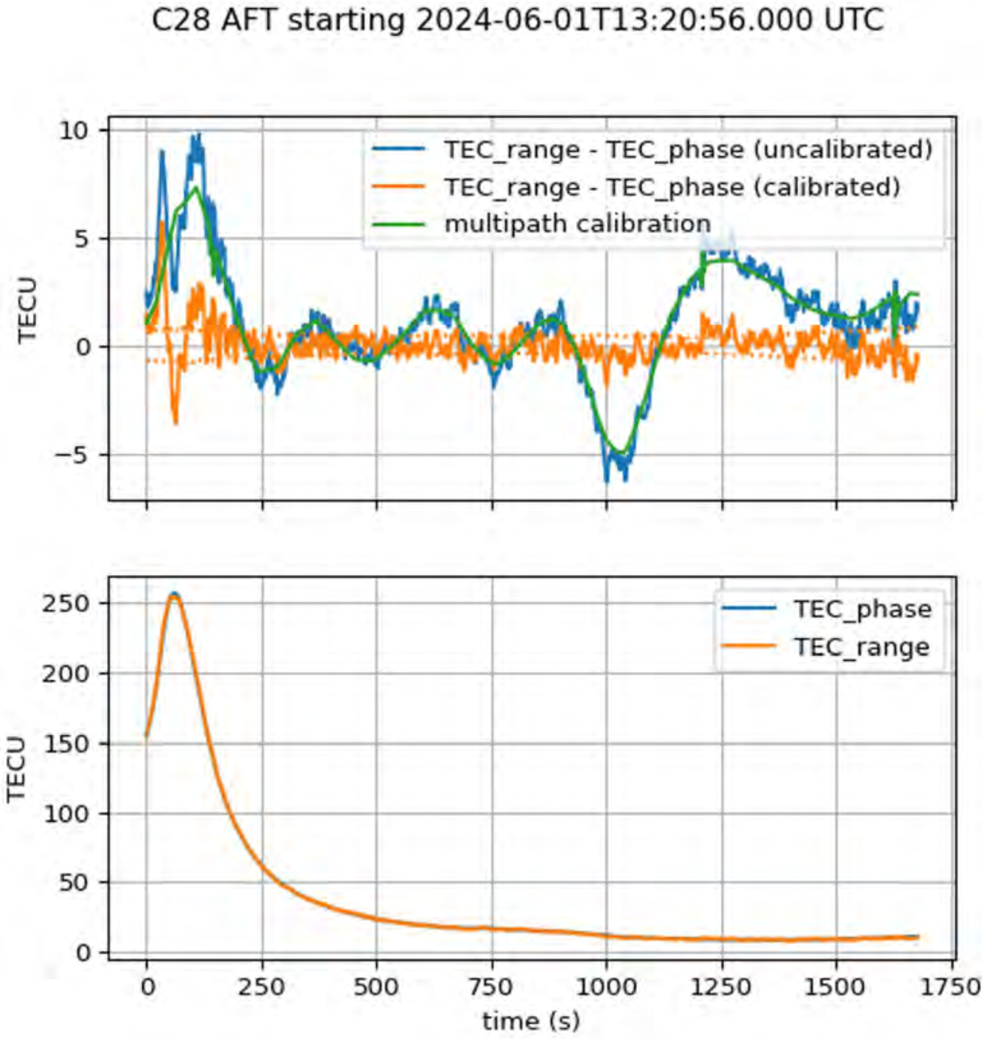
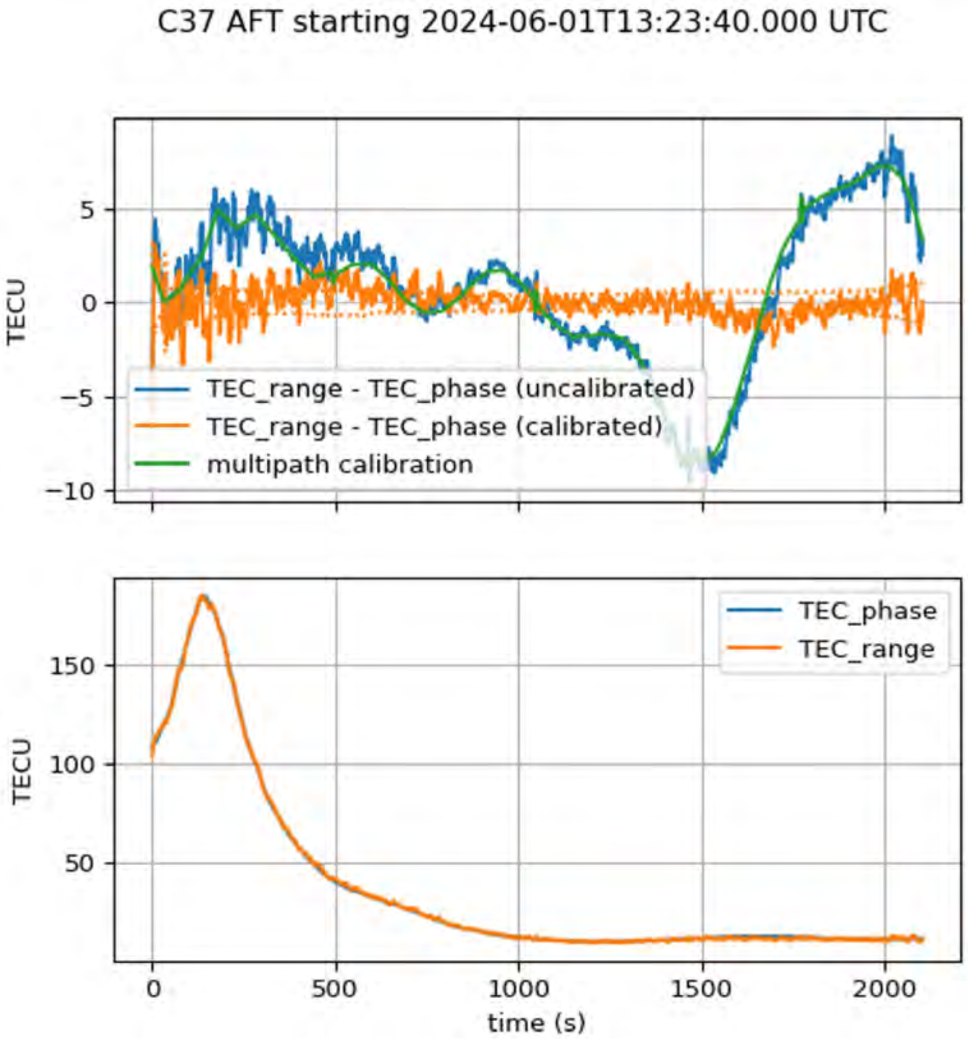
TEC Multipath Calibration

- Average many measurements at the same signal frequency in the antenna coordinate system and the multipath signature emerges
- Example of Galileo multipath pattern on POD0 antenna



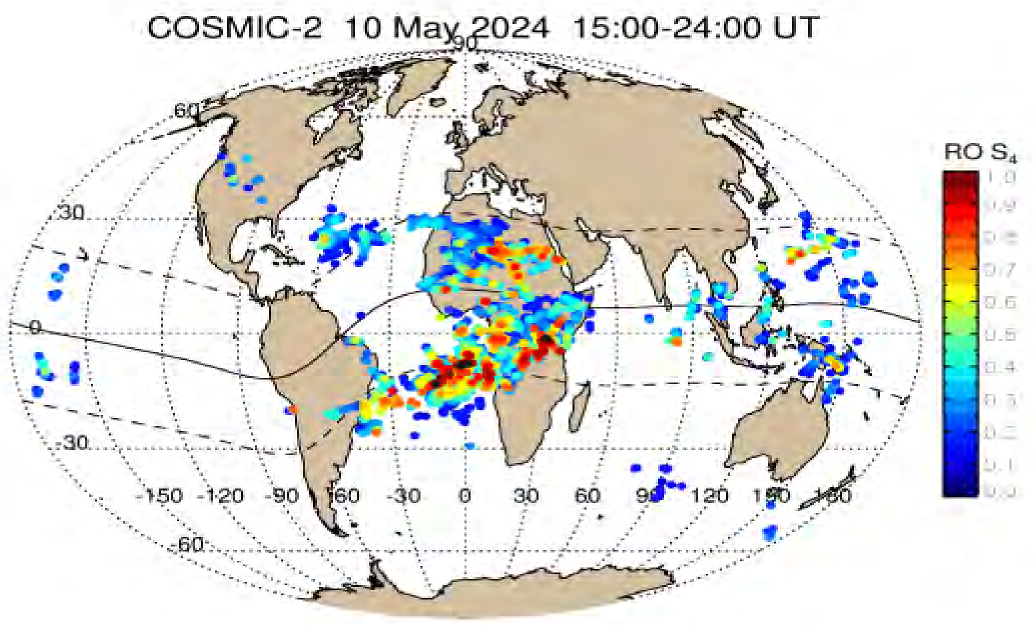
TEC Multipath Removal Examples

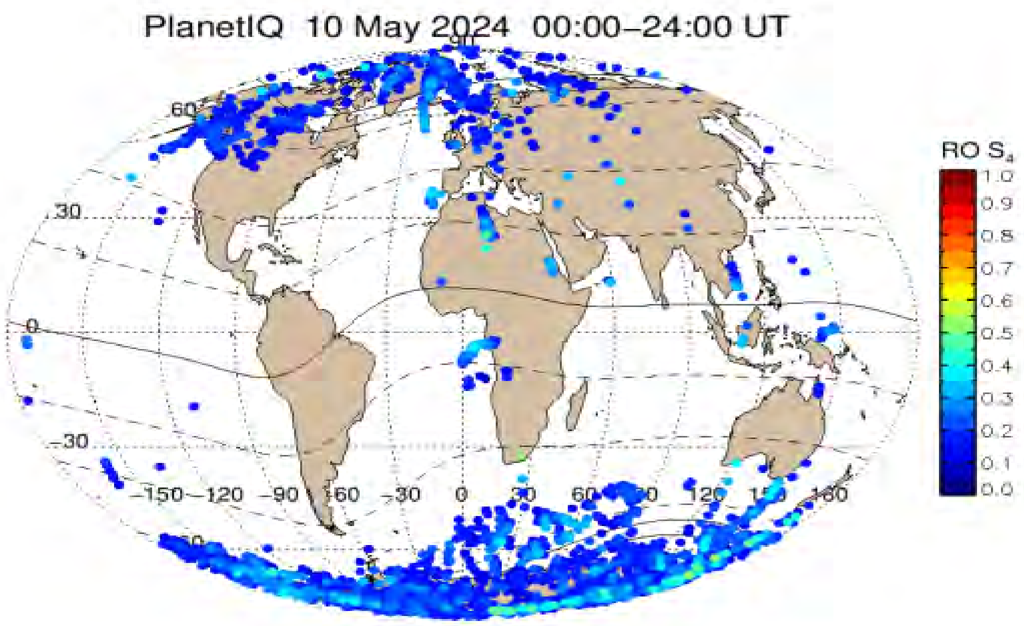




Scintillations: Global Geolocations During Gannon Storm

- COSMIC-2 satellites fly in equatorial orbits favorable for geolocating irregularities in the equatorial zone at all local times.
- Present PlanetiQ satellites are in sun-synchronous polar orbits ~22-23LT favorable for geolocating irregularities at mid- and high-latitudes, but misses some early post-sunset activity (often the strongest scintillation events) at low latitudes.
- BC's preliminary results of the geolocation analysis for May 10, 2024 are shown below demonstrating successfully geolocations at high latitudes





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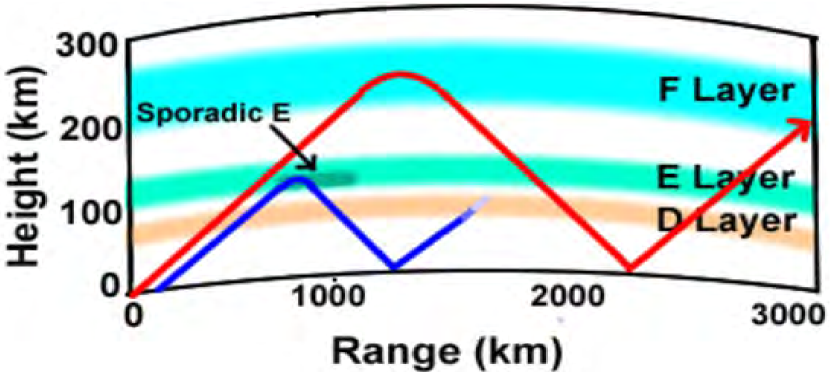
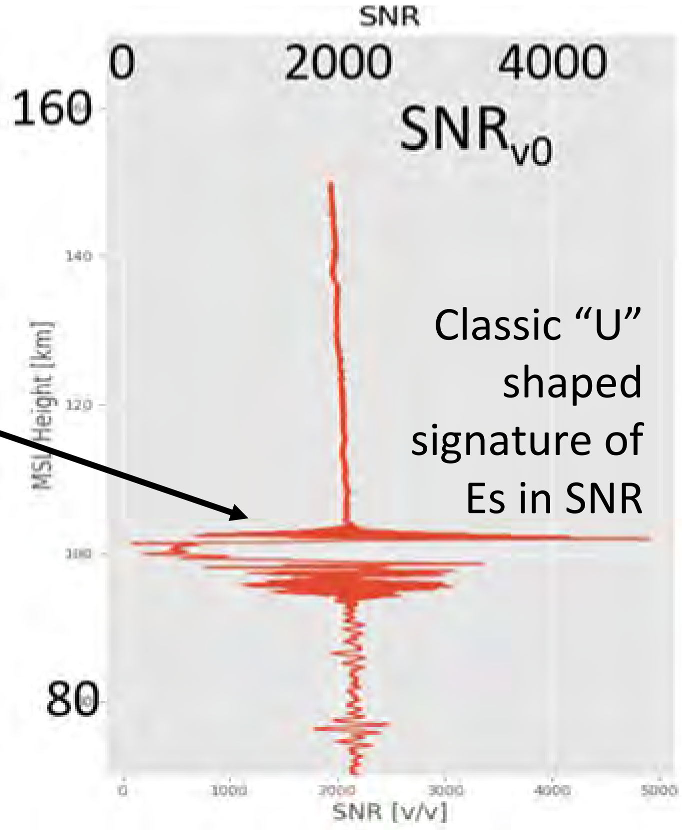
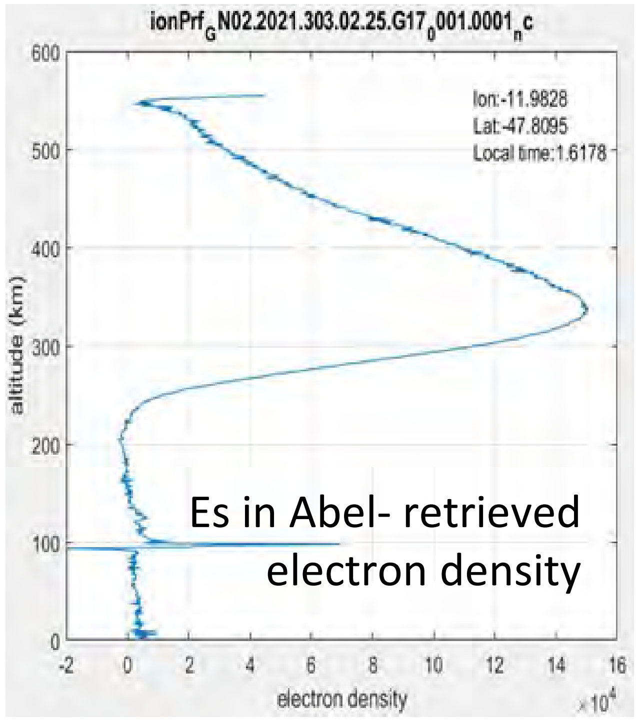
Sporadic E (Es) layers

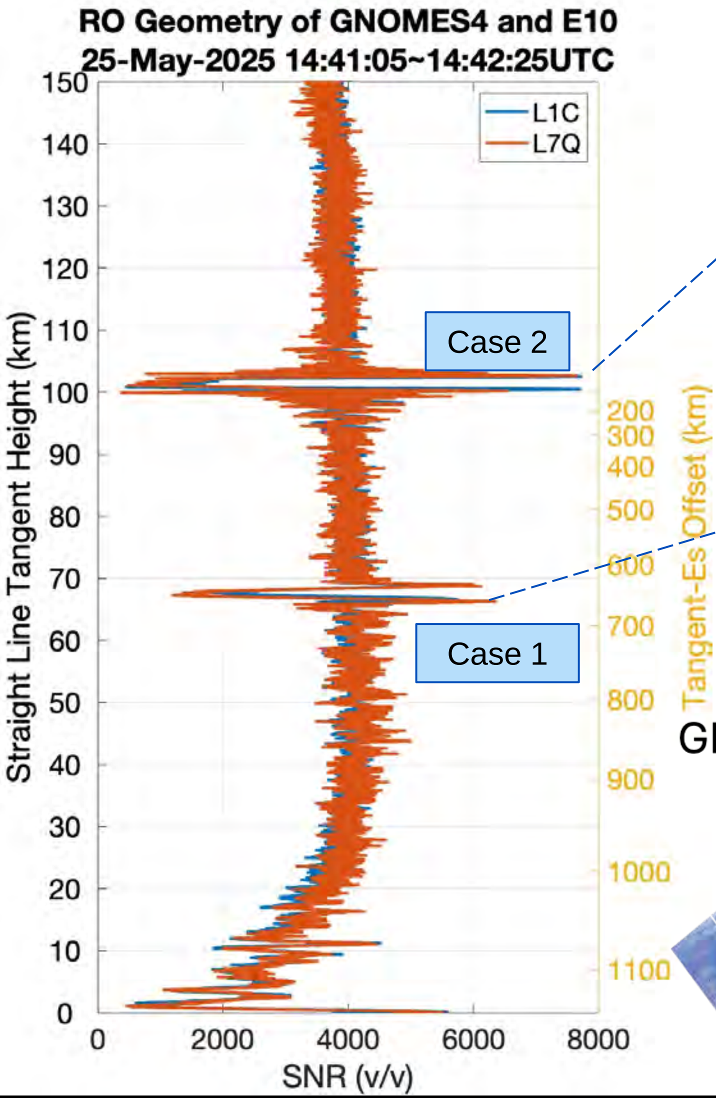
- Es layers strongly affect and alter HF propagation which is critical for communications and OTH radar
- Sporadic E layers occur frequently in our RO measurements
- RO is best way to characterize Es globally
- Es layers cause classic "U" shape in SNR near 100 km making Es readily detectable via S4 index in the 90 to 120 km altitude range

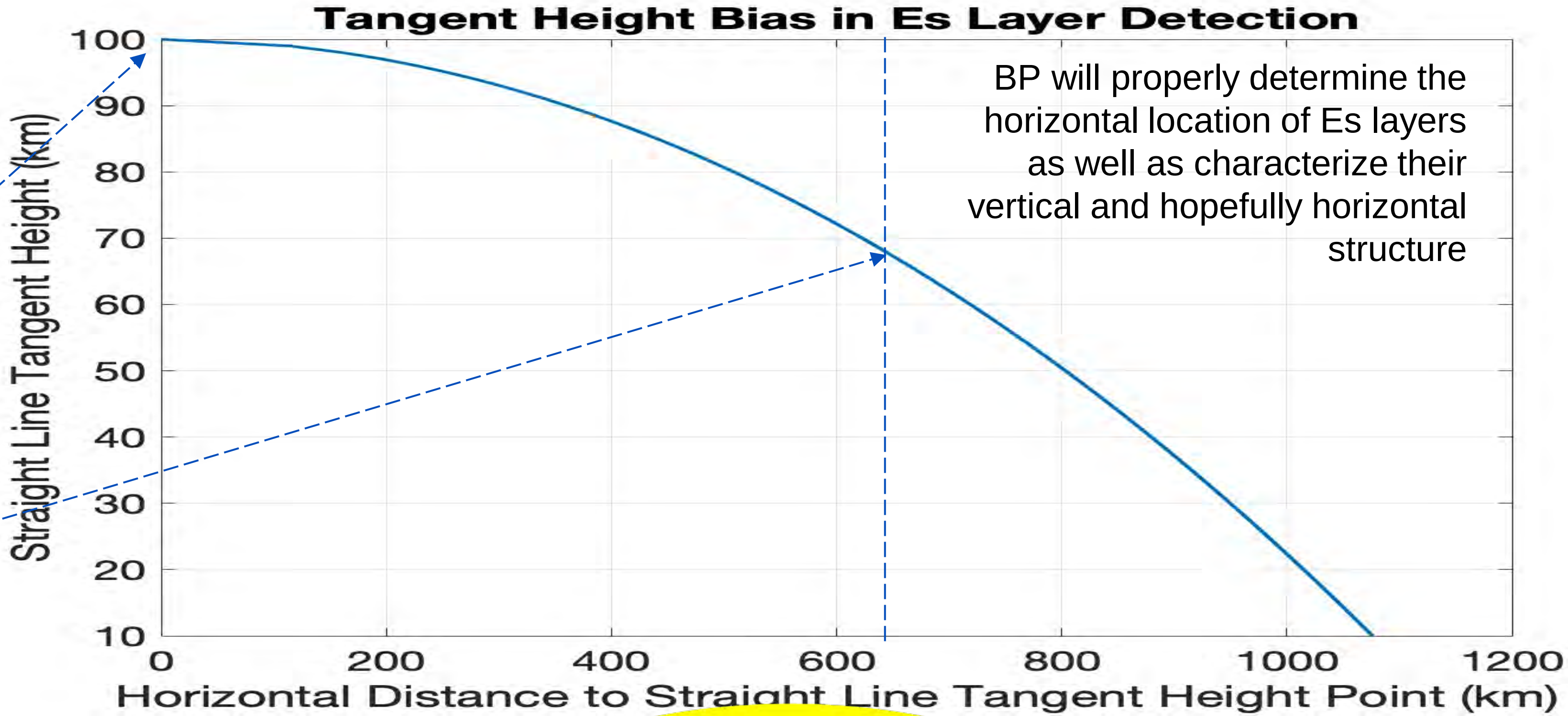




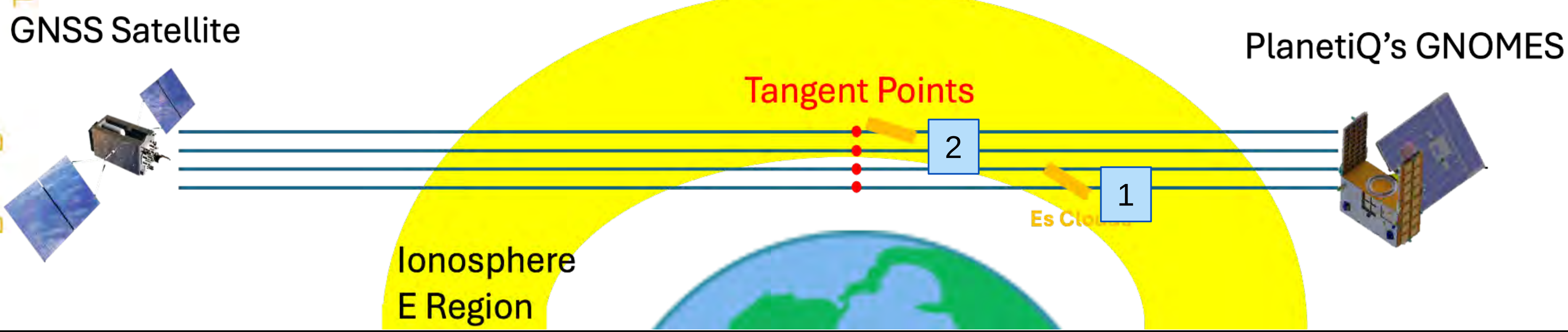


Horizontal location of Es

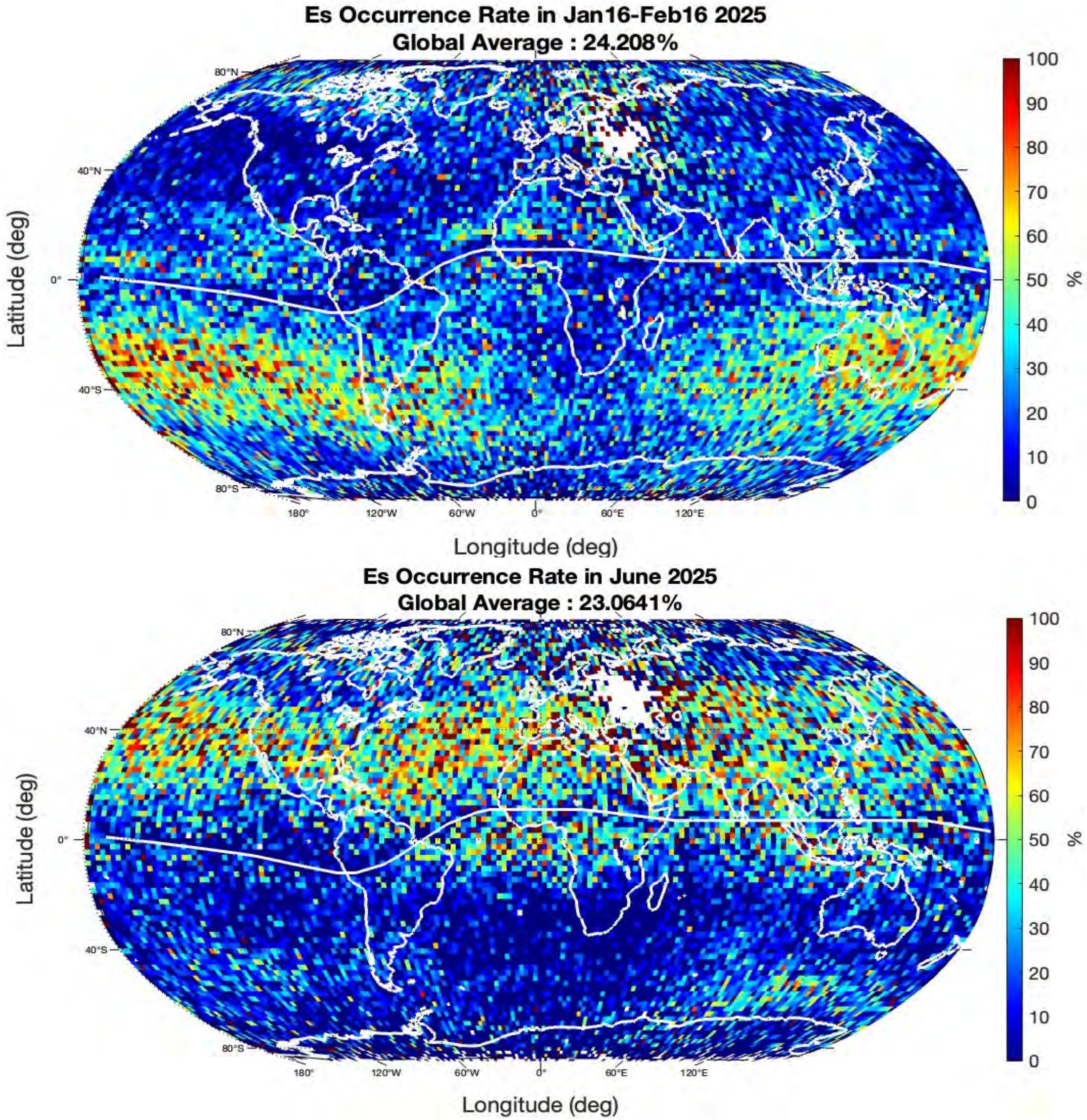




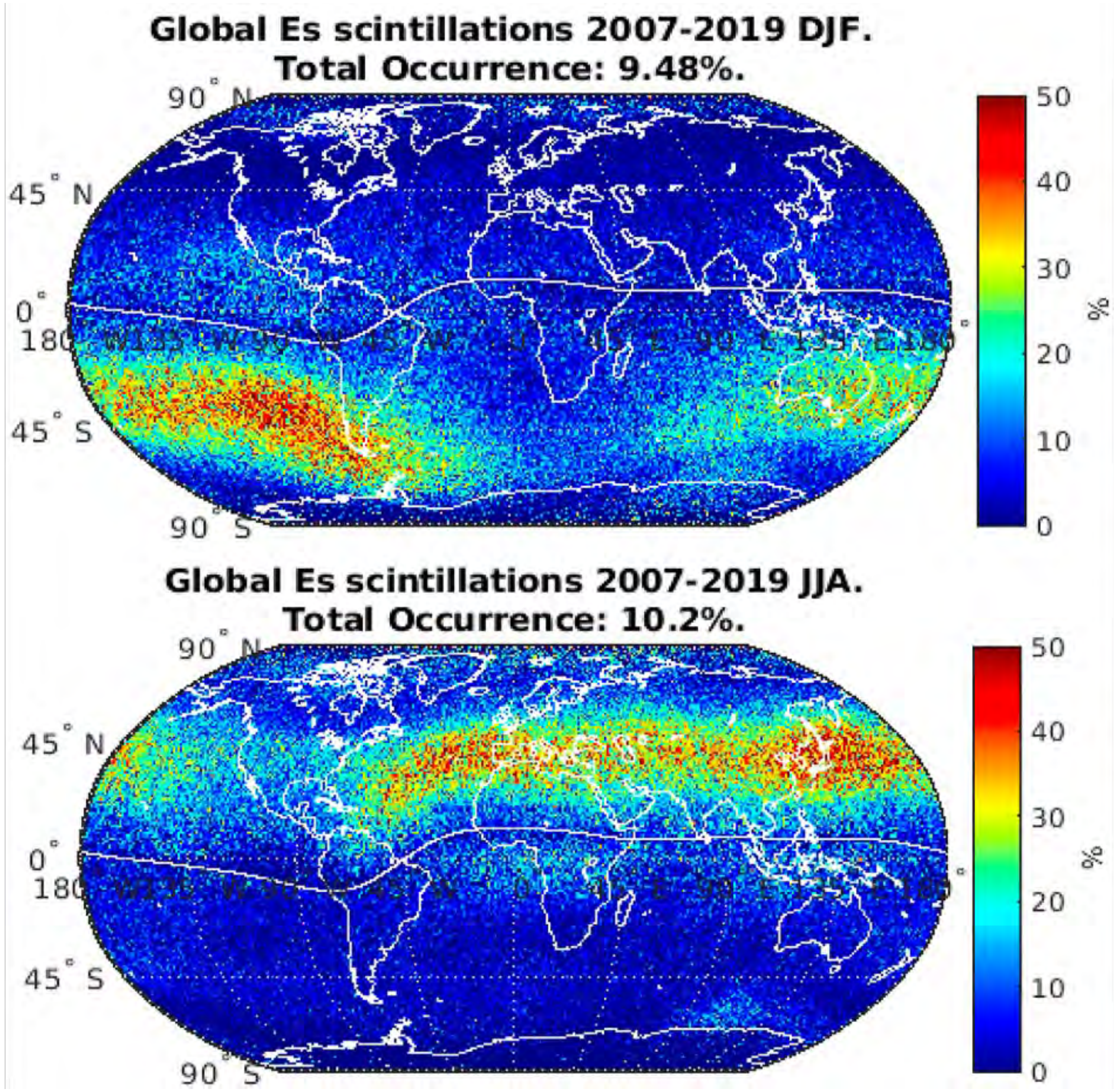
BP will properly determine the horizontal location of Es layers as well as characterize their vertical and hopefully horizontal structure



Compare to Bergsson et al.(2022) — Seasonal Pattern



~2.5x more frequent than previous estimates



Future items

- Specific & relative humidity
- Grazing reflections
- Electron density profiles (EDP)
- Es detection & geolocation
- Jamming
- Eventually GNSS-R w/ DDMs

That’s all folks

- We have a powerful set of instruments on orbit with more coming.
- These are flexible instruments, modifiable within limits on orbit.
- We want to know what the customers/PI’s want so we can decide how best to focus our resources.
- Please **leave your email in the poll** if you want to be informed of PlanetiQ webinars or to have further discussions

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Thank You

rkursinski@planetiq.com

Acronyms

- BA Bending angle
- EDP Electron density profiles
- Es Ionospheric sporadic E layer
- GDAS NOAA global data assimilation system
- HF High Frequency (3-30 MHz)
- IH Impact height
- LTBL Lower troposphere / boundary layer
- N Refractivity
- NWP Numerical weather prediction
- SNR Signal to noise ratio
- SWPM Sliding window phase matching
- TC Tropical cyclone
- TEC Total electron content
- UTLS Upper troposphere/lower stratosphere
- WO Wave optics (as opposed to geometric optics)

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References

- Feng et al., 2020
- Kursinski et al. 1997
- Kursinski and Gebhardt, 2014
- Sievert et al., 2021
- Sokolovskiy et al., 2014
- Wang et al., 2020
- Xie et al., 2006

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