PlanetiQ

PlanetiQ Status Report

E. Robert Kursinski

rkursinski@planetiq.com

J. Brandmeyer, I. Scharf, C. McCormick, A. Botnick, B. Houle, T. Triolo, C. Dotts, X. Feng, B. Giesinger, P. McGaugh, C. Palowski, C. Schira

Outline

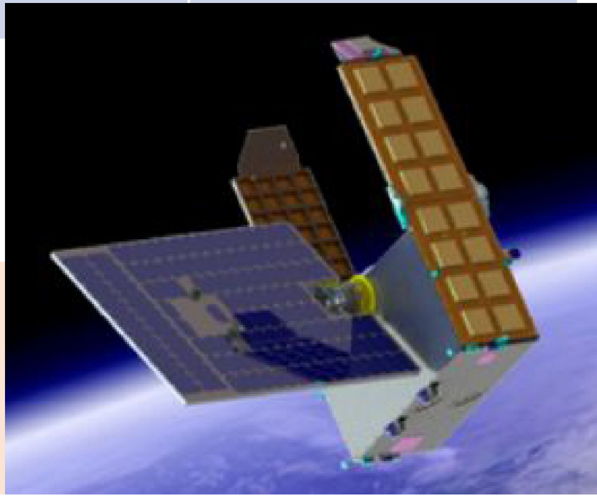
- Summary of PlanetIQ current + near-future capabilities
- Polarized RO first results
- Contracts: NASA, NOAA, and Air Force
- NOAA space weather Ionosphere pilot report
- Increasing the impact of RO in lower troposphere
- We’re hiring

Summary of PlanetIQ capabilities

	Launch	Commission	Neutral atmosphere Occ/day	Ionosphere (total/low latency)	Local time sampling	Altitude (km)	End of life
GNOMES-2	6/30/21	10/1/21	~~1200~~	~~2700 / 925~~	2 AM/PM	460	~4/24 re-entry
GNOMES-3	4/1/22	5/14/22	~~1900~~	~~2700 / 925~~	11 AM/PM	640	9/1/23 radio fail
GNOMES-4	12/1/2023	3 days	2200+	2700/925	10 AM/PM	560	
GNOMES-5	8/16/2024	3 days	2200+	2700/925	10 AM/PM	590	PRO + GNSS-R
Future\Total			**4400+**	**5400 / 1850**			**New capabilities**
Spacecraft 6	1st Qtr 2025		2200+	2700/925	TBD	TBD	PRO + GNSS-R
2025 Total			**6600+**	8100 / 2775			

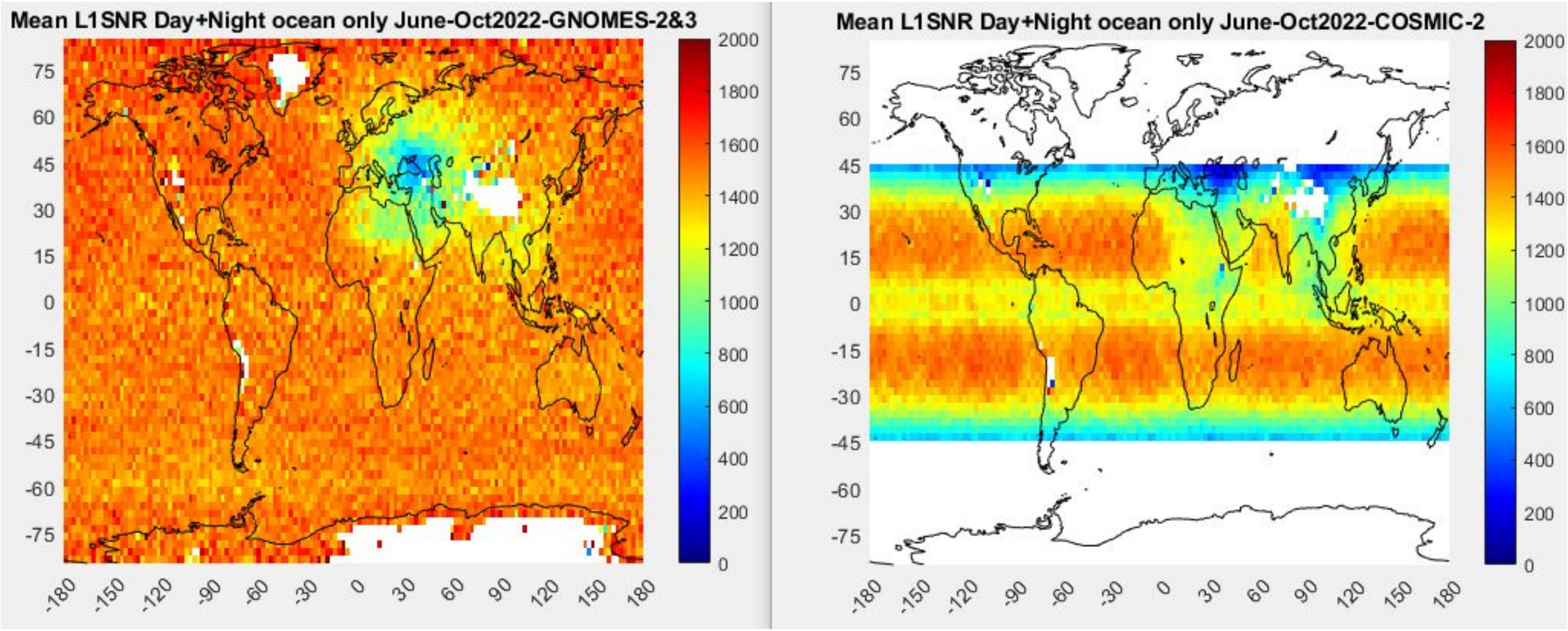
- Receivers track 4 GNSS constellations: GPS (w/L2c) GLONASS, Galileo and BeiDou3
- On RODB2 DO-4 contract with delivery 2200 RO/day to NOAA beginning on Sept 18…
- Satellites 4-6 carry thrusters to adjust the satellites orbits to provide full coverage.
- Full pole to pole coverage, PlanetIQ RO validated by multiple entities
- Flexible and adaptable: modifiable software and firmware on orbit

Goal continues to be 20+ satellites and 50K+ occ/day



PlanetIQ v COSMIC-2 Mean L1 SNRs

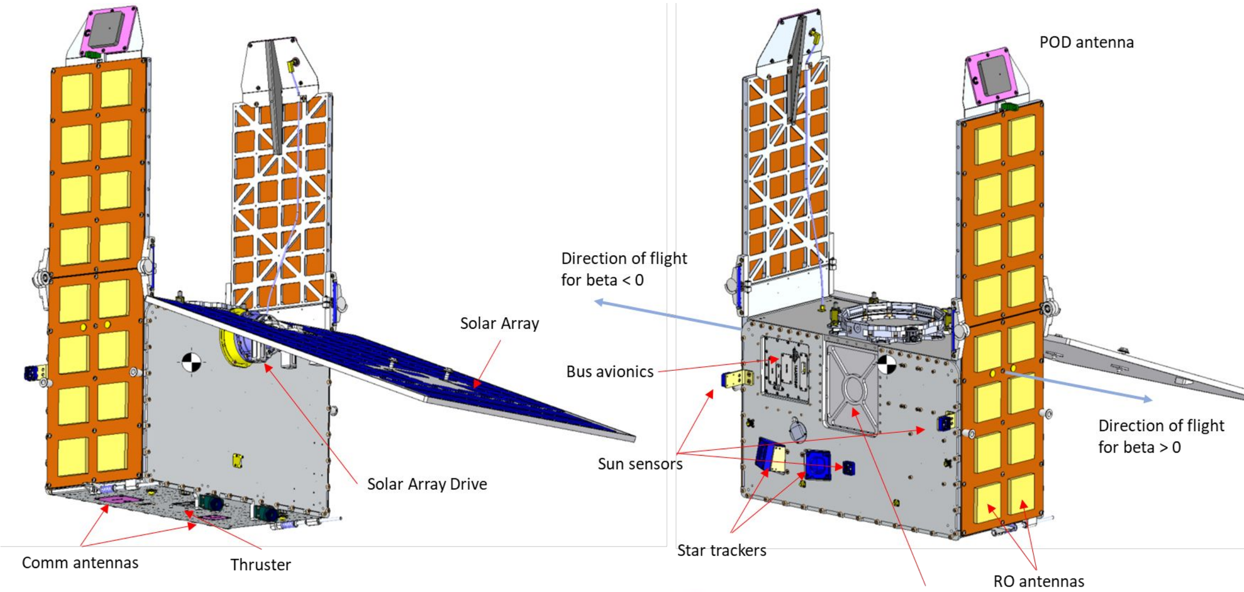
- PlanetIQ SNRs are very high and quite uniform except for degradation over Ukraine



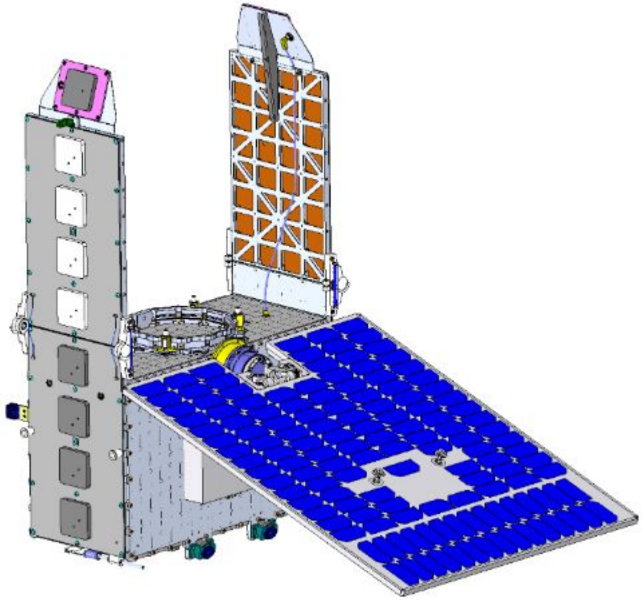
PlanetiQ

Antennas

- RHCP (Satellites 1-4)
  - 6 antennas per spacecraft (2 POD, 4 RO)
  - OL track each of the 2 RO columns separately
  - Then combine them to maximize SNR



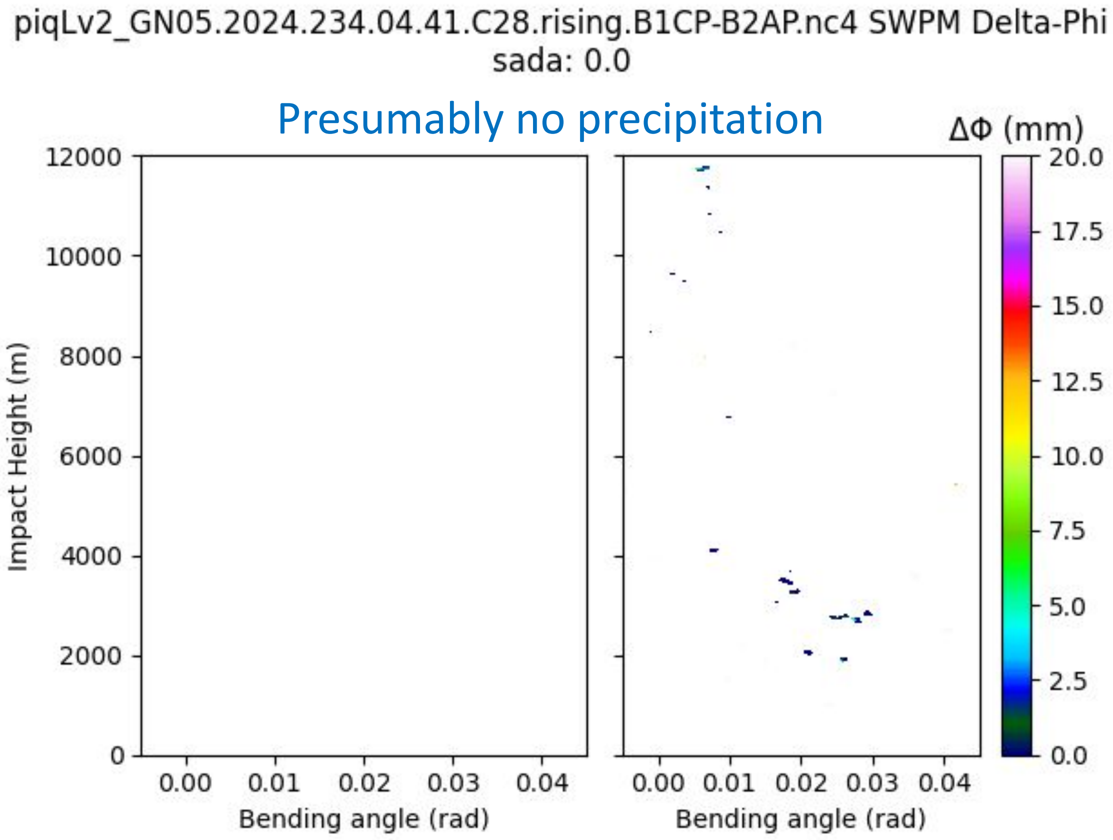
- Dual linear polarization (Satellites 5-6)
  - 4 antennas the same as SC 1-4,
  - One RCP pair replaced with dual linear pol pair
  - OL track H and V polarizations separately
  - Combine H & V to increase SNR for normal RO
  - Calculate differential H-V phase to determine $\Delta\varphi_{precip}$
  - Will be deriving GNSS-R products from this antenna

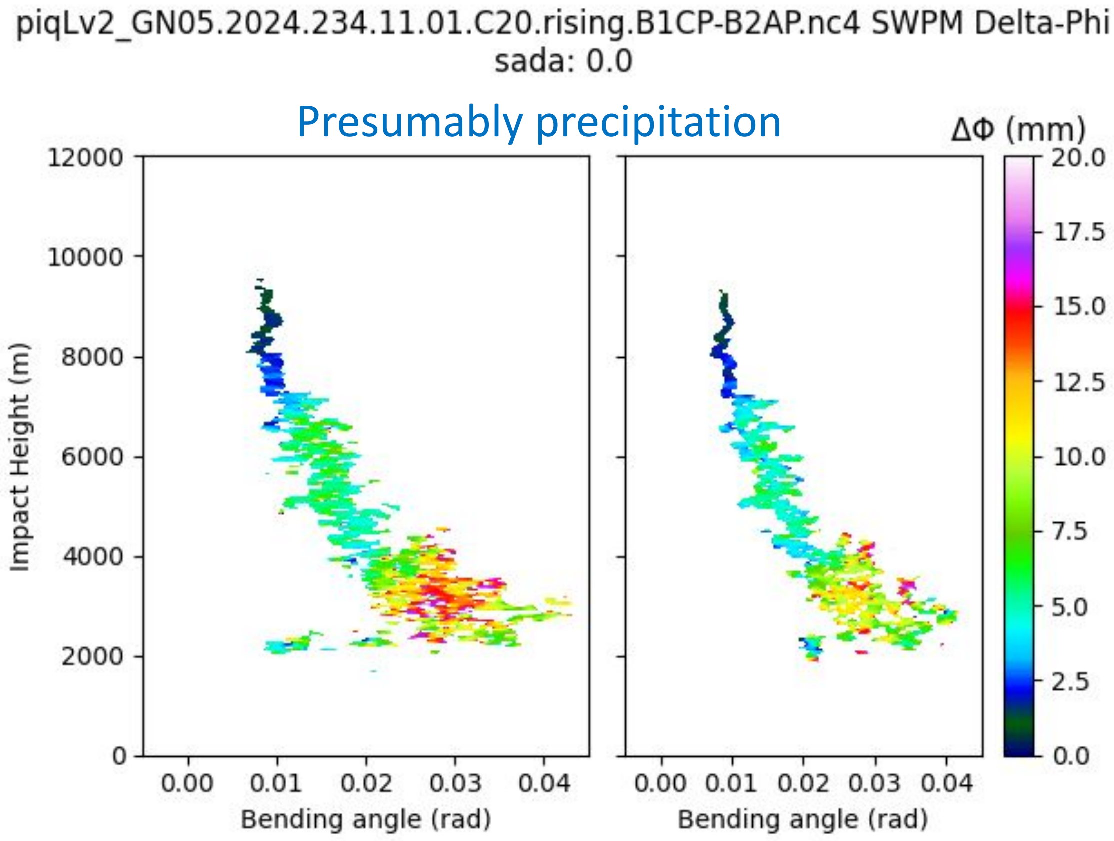


SC 5: Forward facing
SC 6: Aft facing

Our 1st polarimetric RO measurements and retrieval

- GNOMES-5 launched August 16, less than a month ago, with a linear pol antenna
- Just starting to develop dual linear polarization calibration and generate results
- And then validation





PlanetiQ

Contracts

- NASA evaluation contract
- NOAA RODB2 DO-4 data delivery contract
- Air Force contract to increase RO impact in the lower troposphere

PlanetiQ

NOAA & NASA data contracts

Contract	Data Products	Additional comments
NOAA RODB2 Space Weather Pilot	• Level 0, 1a, Level 1b podTc2 & scnPhs • CDAAC then generated Level 1b products	
NOAA RODB2 DO2	• Level 0 & 1a from GNOMES-2 & 3 • CDAAC then generated Level 1b & 2 products	NRT Full SNR "Premium"
NOAA RODB2 DO4	• Level 0 & 1a from GNOMES-4 & 5 • CDAAC then generates Level 1b & 2 products	NRT Reduced SNR "Basic"
NASA initial evaluation	• Level 1b derived from conPhs gen. by AER SatDAAC • includes grazing reflections (not extracted) • Level 2 derived from atmPrf gen. by AER SatDAAC • podTc2 generated and calibrated by PlanetiQ • scnPhs generated by PlanetiQ	Full SNR using final orbits
Future	• Dual polarization differential phase • GNSS-R derived products	

NASA CSDA Evaluation of PlanetiQ Data

- 1st NASA CSDA contract to enable NASA funded PIs to evaluate PlanetiQ data
- Data types
  - Neutral atmosphere
    - Level 1B: High rate carrier phase and SNR (~ 'conPhs')
    - Level 2: Bending angle and refractivity (~ 'atmPrf')
  - Space weather/Ionosphere
    - Calibrated TEC
    - Scintillations: S4, σ_φ and high rate phase and amplitude
    - Sporadic E imbedded in Level 1B neutral atmosphere and ionosphere scintillation files
  - Surface reflections imbedded in Level 1B neutral atmosphere data
  - Dual polarization data will be coming starting June-Oct 2024 (separate evaluation call?)

- Send questions to support@planetiq.com

PlanetiQ

NOAA RODB2 DO-4

- Was on contract with NOAA for RODB2 DO-2
- Shutout on DO-3
- Back on contract with NOAA for RODB2 DO-4 delivering 2200 RO per day from Sept. 18, 2024 to Sept 18, 2025
- PlanetiQ offered two levels of data quality
  - Basic: SNRv= 400 v/v, less expensive
  - Premium: mean SNRv ~1500v/v for dual column RHCP, more expensive
- NOAA chose to purchase Basic quality for DO-4

High altitude noise

- PlanetiQ invested a lot into creating very high SNR RO complete with very high performance reference oscillators
- This should be apparent as better high altitude bending angle performance
- However, in the statistics of the PlanetiQ bending angles at 50 km, processed by UCAR, the performance looks similar to that of Spire, such that the advantages are lost for NWP
- When PlanetiQ estimates the LEO orbits and clock, the performance improvement is there.
- Conclusion: The UCAR leoOrb is adding noise (likely in the clock solutions)
- UCAR is working to fix this

Data Source	Processing	RMS µrad	Fractional @ 50km
Sentinel 6A	EUMETSAT	1.3	5%
PlanetiQ (w/o GLONASS)	PlanetiQ	1.5	6.5%
PlanetiQ w/ GLONASS	PlanetiQ	1.8	7%
COSMIC-2	UCAR	2.0	8%
PlanetiQ w/ GLONASS	UCAR leoOrb	2.2	9.5%
Spire	UCAR	2.3	9.5%

NOAA Space Weather Pilot

- NOAA's report on the 8/1/2022 to 8/1/2023 Space Weather Pilot was just released
- NOAA evaluated TEC, Latency and Scintillations

TEC

- Mostly acceptable TEC data quality, exceeding required 500 TEC profiles per day.
- TEC data validated very well when compared with COSMIC-2 data.
- The absolute TEC accuracy, measured in terms of uncertainty, was slightly higher than 4.5 TEC units root mean square, which marginally exceeded the 4 TEC unit threshold.
- Spatial coverage was good,
- Only one vendor provided decent temporal coverage which is a function of the differences in constellation size and orbital distribution both vendors operated during the SWDP data delivery time period.
- Assimilation of TEC improved Global TEC model near-real-time performance and bias away from ground stations and improved observation density coverage especially away from ground station data.

PLANETiQ

Latency

Issues

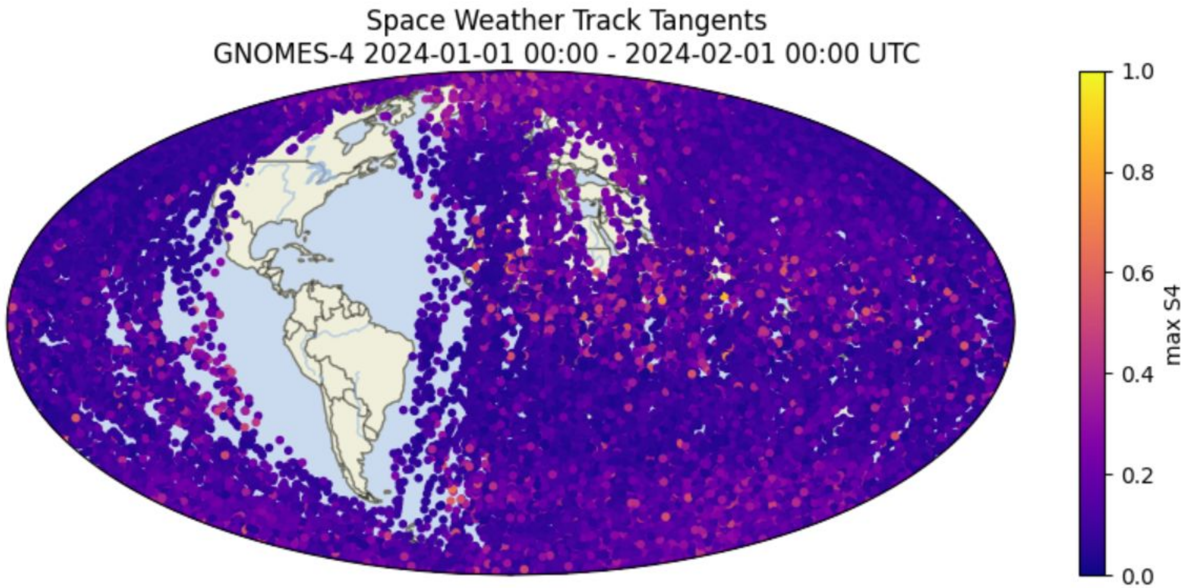
- NOAA reported PlanetiQ's median delivery latency as 52 minutes.
  - How did NOAA calculate this number?
- We provided 500 TEC per day in podTc2 files that met the 30 minute median latency but NOAA apparently used all of the POD data in deriving the latency.
- PlanetiQ developed its own TEC calibration capability which NOAA chose not to use which would have shortened the processing time
  - We would like a joint effort to evaluate the PlanetiQ calibration against the UCAR TEC calibration

Table 1. Daily median Absolute TEC latency for the Space Weather Data Pilot (Period: Mar 1 - Apr 30 2023)
Product Creation Time is when the product is ready for dissemination to SWPC.

Vendor	Observation to NCCF Delivery Time	Data Check and Dissemination (NCCF to UCAR)	UCAR Processing Time	Observation to UCAR Product Creation Time
Spire	28.6 mins	3 mins	33.1 mins	64.7 mins
PlanetiQ	51.8 mins	3 mins	9.1 mins	63.9 mins

Latency

- Approximately 40% of our ionosphere measurements meet the 30 minute median latency when PlanetiQ does the TEC calibration processing



- Figure shows the coverage of the low latency ionosphere observations
- Gap over Americas is due to the locations of our 2 current ground stations
- That gap can largely be closed by adding a ground station in NW Canada, if there is demand to do so
- We have also begun development of a real time sat-sat link to bring data down in seconds to meet DoD's 10 minute latency requirements

PLANETiQ

Scintillations

- Radio signals passing through small scale ionosphere structure experience phase and amplitude scintillations which RO can monitor globally
- Our receiver continually generates amplitude and phase statistics, S4 and σ_φ.
- When scintillations are detected, the receiver downlinks high rate data to allow geolocating where small scale structure lies along the ray path
- We have suggested a better scintillation trigger threshold that captures weaker scintillations and avoids downlinking high rate unnecessarily
    - We'll write a brief paper on this

For 50 Hz sampling, consider the following weak-signal and strong-signal cases.

SNR (dB-Hz)	SNRv0	S4_thermal	S4_rmse	COSMIC-2 S4 trigger	1% CFAR S4 Trigger
35	80	0.177	0.0056	0.675	0.196
53	632	0.022	0.00071	0.085	0.025

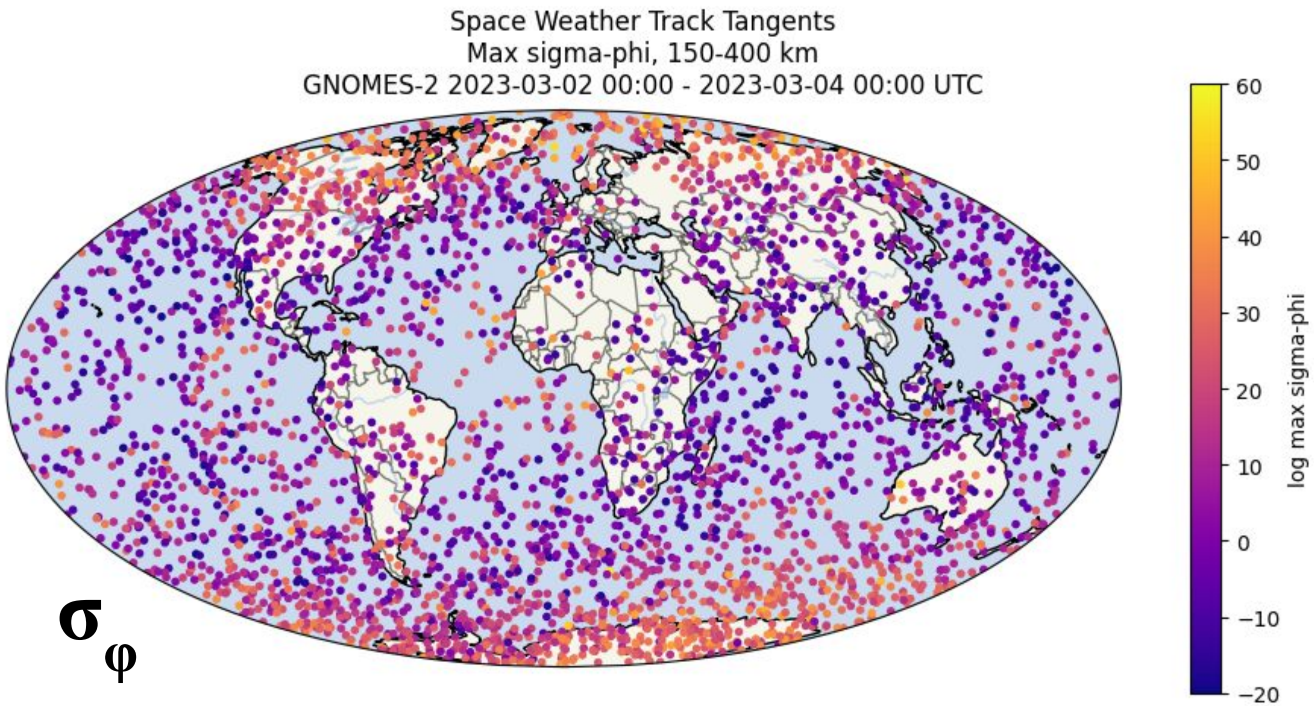
- More frequent and quicker interactions would be beneficial for both the vendor and the customer

constant false-alarm rate (CFAR)

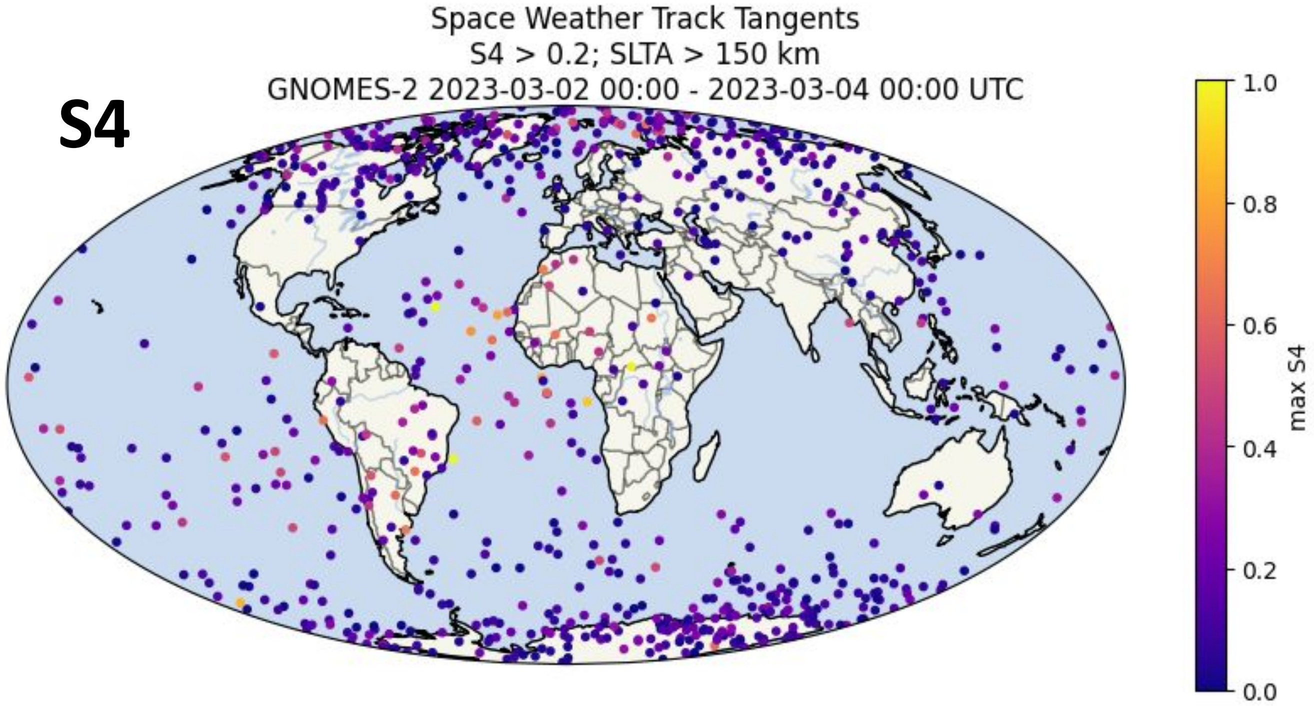
Scintillations

- NOAA is concerned that high latitude scintillation events are under detected using S4 criterion
- They are interested in using sigma-phi (σ_φ) to detect these events.
- Preliminary examination of our data indicates σ_φ may indeed be better for these detections
- Because of our very high quality oscillators, we can measure sigma-phi in real time and download the high rate data needed to geo-locate the

σ_φ



S4



PlanetiQ Improving RO impact in the lower troposphere

TOWARD A GLOBAL PLANETARY BOUNDARY LAYER OBSERVING SYSTEM

THE NASA PBL INCUBATION STUDY TEAM REPORT

National Academy of Sciences (NAS) 2017 Decadal Survey stated that observing the Planetary Boundary Layer (PBL) is a top priority because (1) of its critical importance for understanding and predicting weather and climate and (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

GNSS RO uniquely features for PBL observations

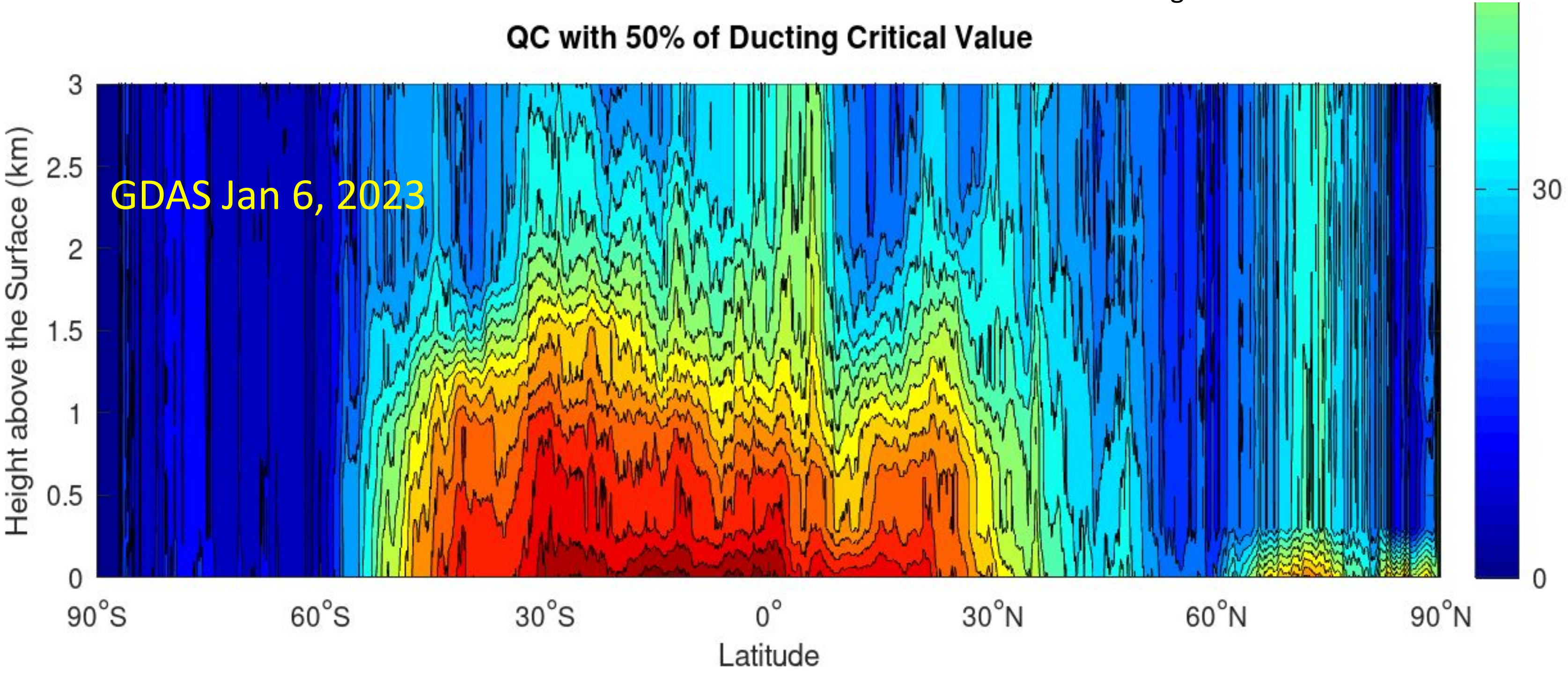
- **PlanetIQ Goal**: Work to get GNSS RO PBL information into NWP systems to improve present environmental knowledge and forecasting skill for weather and climate and more realistic re-analyses for understanding and predicting climate change
- Accurately profiling the PBL via GNSS RO with minimal bias requires very high SNR
  - Additional challenges in doing so:
    1. Numerical instabilities when assimilating sharply peaked bending angles near PBL top
    2. Large bending angles are being underestimated
    3. Ducting causes a negative bias in GNSS RO PBL profiles

Rejection of RO data in lower troposphere

NWP systems reject RO data when the forecast dN/dz approaches ducting (SR) conditions

- Figure shows % of RO data rejected when GFS forecast dN/dz exceeds 50% SR
- From 50S to 30N below ~1.2 km, more than 60% of the RO observations will be rejected for the 50% SR rejection criterion
- This check is to avoid an instability in the DA system

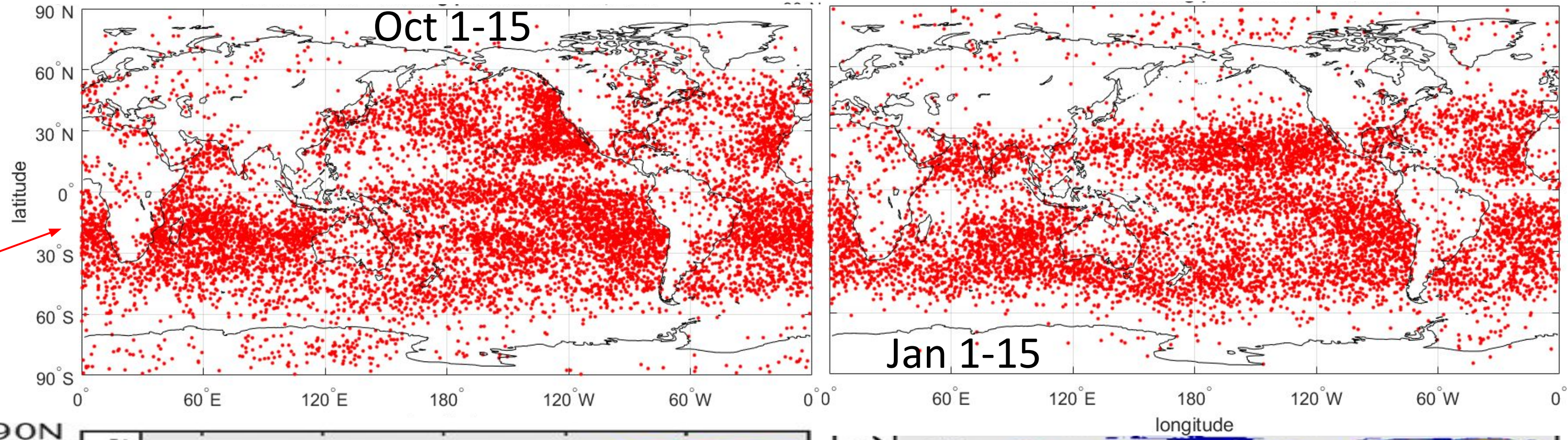
% Rejection when $|dN/dz_{GFS}| > 0.5\ |dN/dz_{ducting}|$

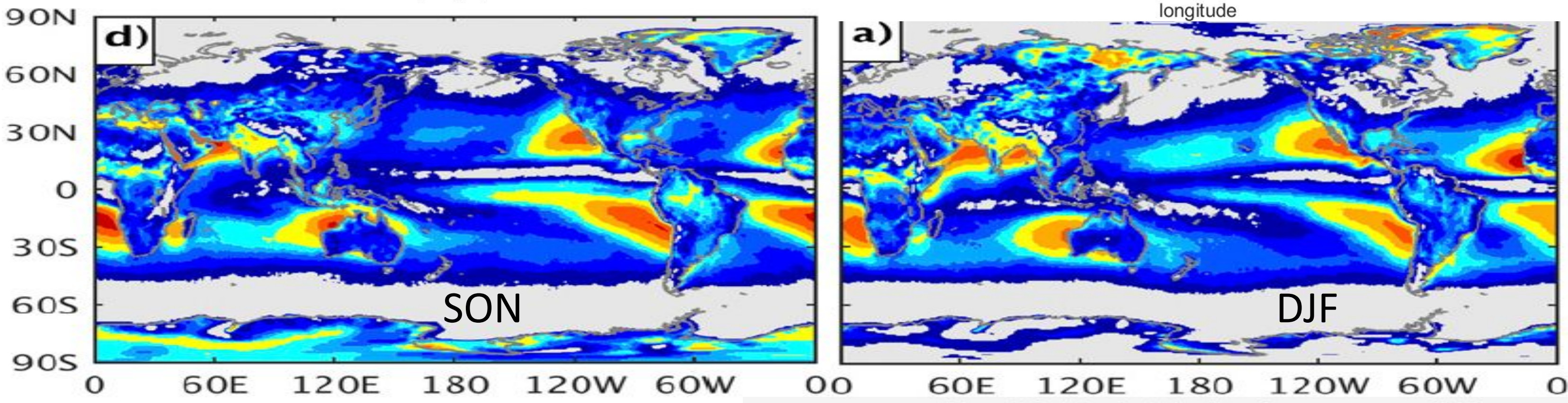


We must develop better ways that enable NWP systems to ingest more RO data in the lowermost troposphere/PBL

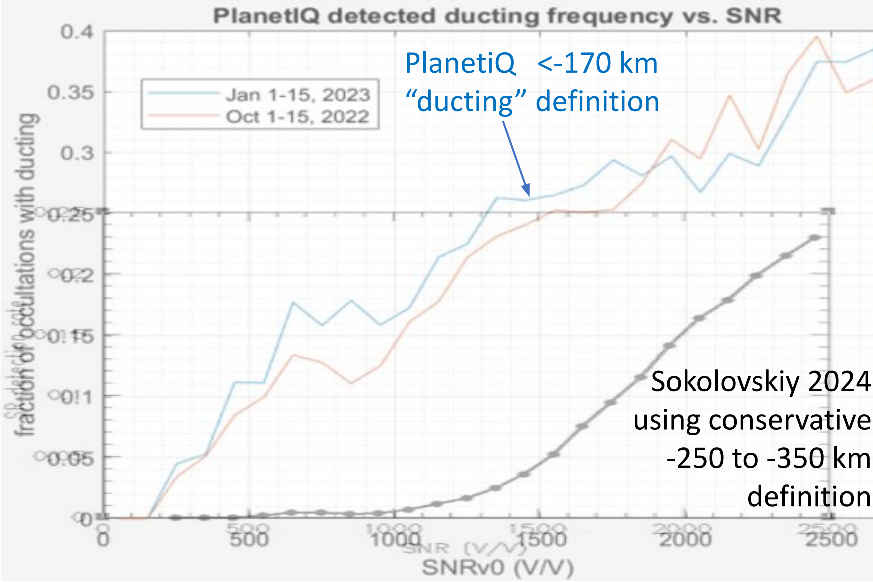
Frequency of large bending angles & ducting

- Occultations with large bending angles & 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 … thermal inversions /km(!)





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



PlanetiQ Lower troposphere AF contract

- Given NWP's limited use of high SNR RO in the lower troposphere and boundary layer, we are have taken the initiative to develop and implement the measurement, retrieval and forward operator capabilities needed to enable NWP to utilize the data
- This work is under a contract with the AF
- Working with JCSDA to implement the NWP portion in JEDI

Problem	Solution
Underestimated large bending angles	Better retrievals of large bending angles using very high SNR RO observations at 2 or more frequencies and phase matching
Determine whether ducting is present	Detect ducting using very high SNR RO observations (Sokolovskiy et al 2014)
Ducting nonunique BA ⇔ N relation	Xie et al (2006) method plus grazing surface reflections (Aparicio et al., Wang et al.)
Assimilation instability in near ducting conditions	Use the nonlocal pseudo excess phase FO (Sokolovskiy et al.; 2005) which is based on Syndergaard et al. (2003, 2005)

Summary

- We have developed a very high SNR GNSS RO system presently generating 4400+ high SNR neutral occultations via our 2 satellites with 1 more coming
- We are now producing Pol-RO observations and have begun the work of calibrating them
- We will be generating GNSS-R data in the near future
- We are now on NOAA and NASA data contracts
- NWP is presently making only limited use of RO data in the lowermost troposphere due to challenges associated with assimilating that data.
- We are attacking the lower troposphere/boundary layer impact challenge with funding from the AF
- We welcome others to be involved with that effort to enable full utilization of GNSS RO's unique PBL information in NWP analyses, forecasts and re-analyses

PLANETiQ

Other PlanetiQ IROWG talks and posters

Perspectives on GPSMET & COSMIC	Talk	Kursinski	Thursday 13:55
New PlanetiQ Level-2 Data Processing and Validation	Talk	Brandmeyer et al.	Friday 10:20
PlanetiQ lower troposphere results	Talk	Kursinski et al.	Tuesday 11:05
First PlanetiQ Polarized RO results	Poster	Kursinski et al.	Session 1
Broadcast GNSS Transmitter Orbits & Clocks for NRT RO Processing	Poster	Brandmeyer et al.	Session 1
PlanetiQ Space Weather update	Poster	Kursinski et al.	Session 2

PlanetiQ is hiring!

- Signal processing
- GNSS RO
- GNSS PRO
- GNSS-R
- Space weather
- NWP
- AI

rkursinski@planetiq.com

Impact of large numbers of RO on NWP

- Two simulations showed high # of RO greatly improve NWP analyses/forecasts
  - Harnisch et al. (2012, 2013) ECMWF EDA (up to 128Kocc/day)
  - Prive' et al. (2022) at NASA GMAO OSSE (up to 100Kocc/day)
- Simulations are now being verified using real RO data: Gov't + **commercial**
  - Aparicio (ECCC) showed similar impact scaling adding Spire + PlanetIQ RO to Gov't RO.

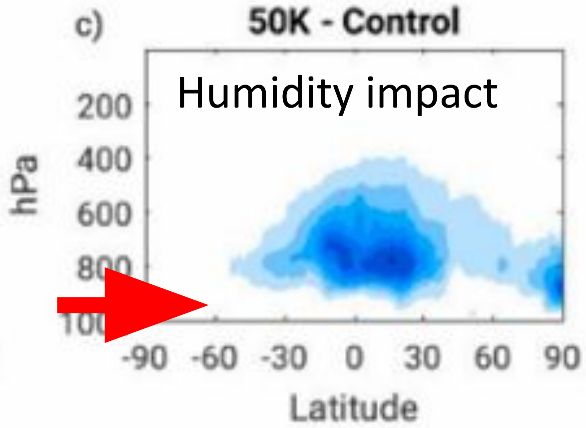
Power law: $$\frac{FSOI_2}{FSOI_1} = \left(\frac{\#_2}{\#_1}\right)^a$$

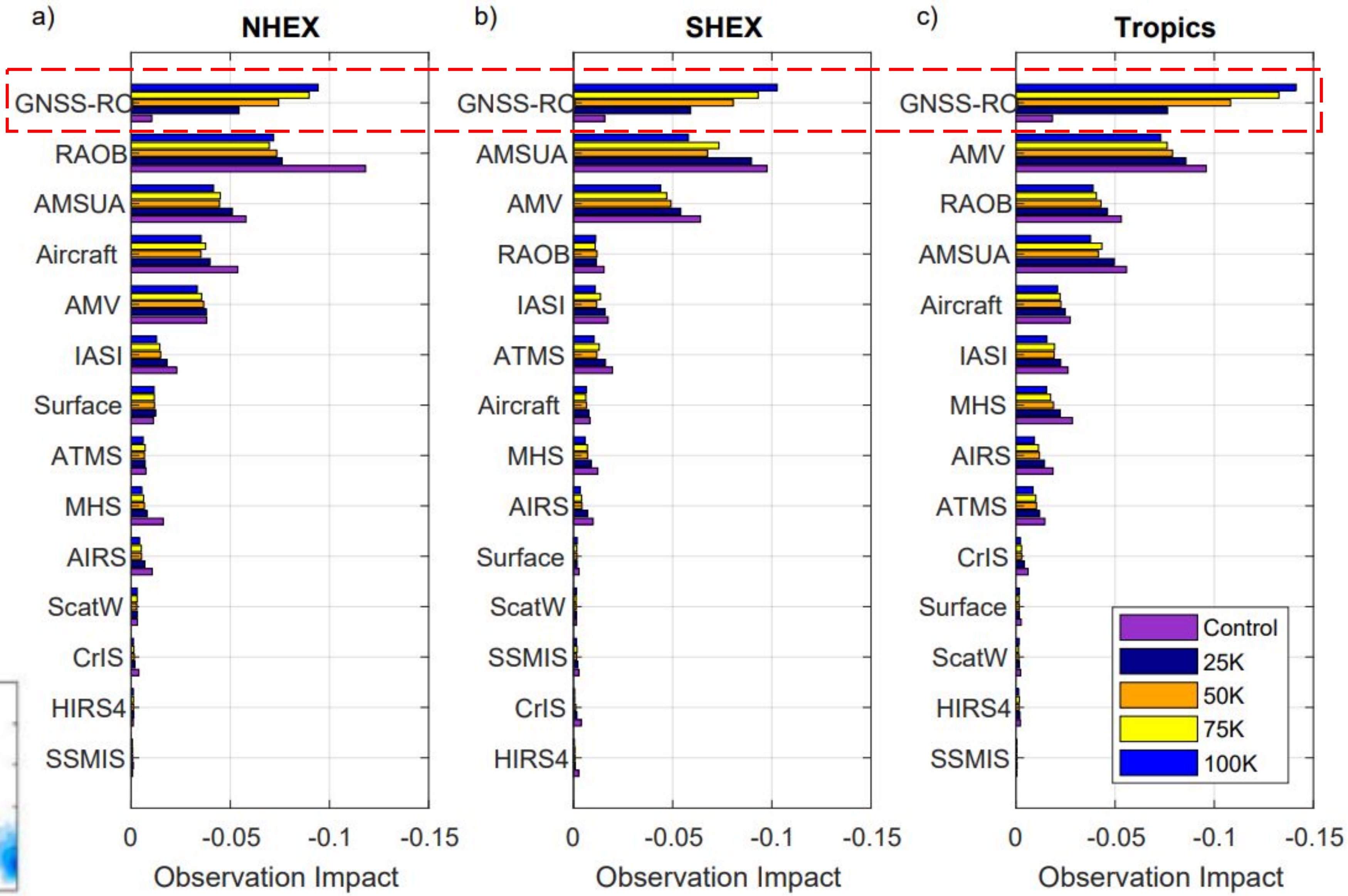
Study	Initial # RO	Final # RO	exponent
Prive (sim)	3000	25000	0.7
Aparicio (**real**)	8500	19000	0.7

  - **ROMEX** will demonstrate this further, hoping to get to >30K real occ/day
- Confirms large numbers of RO via commercial RO yield "big impact for the buck"
- At 20Kocc/day, GNSS RO is nowhere near saturated. At 25K-30K occ/day RO promises to become the most impactful obs data set in terms of FSOI

Prive et al. (2022) NASA RO OSSE

- Similar conclusion to Harnisch et al (2013) EDA results
- GNSS RO becomes most impactful data set at
  - **50Kocc/day in NH**
  - **~40Kocc/day in SH**
  - **~25Kocc/day in Tropics**
- COSMIC1 vertical sampling
- Underestimate of impact? not making use of lowermost troposphere





J. Aparicio (2023)

Verifications VI: 24h FSOI, Global weighted, dry norm

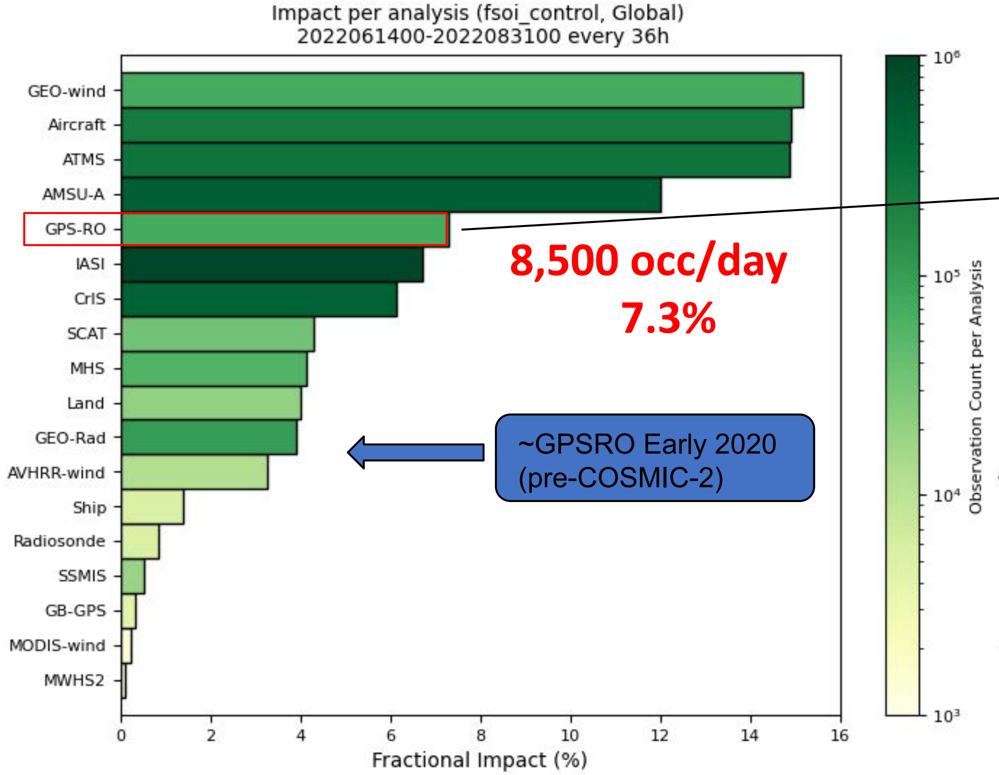
Test with all available data included

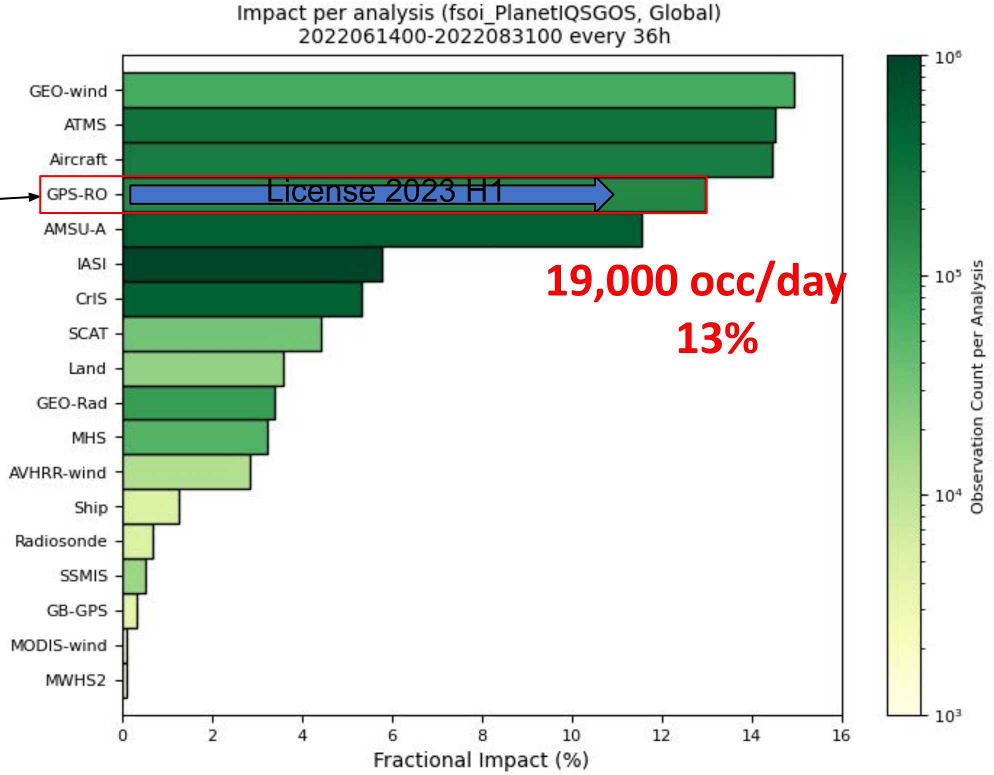
GPSRO advanced **ahead of AMSU-A**

Note: only 2/3 of the **new data** here will be available (licensed) in Jan-Jun 2023

Ballpark estimation for operationally available in 2023 H1 marked in the arrow

In late 2023, volume may be higher than test shown here. To follow.



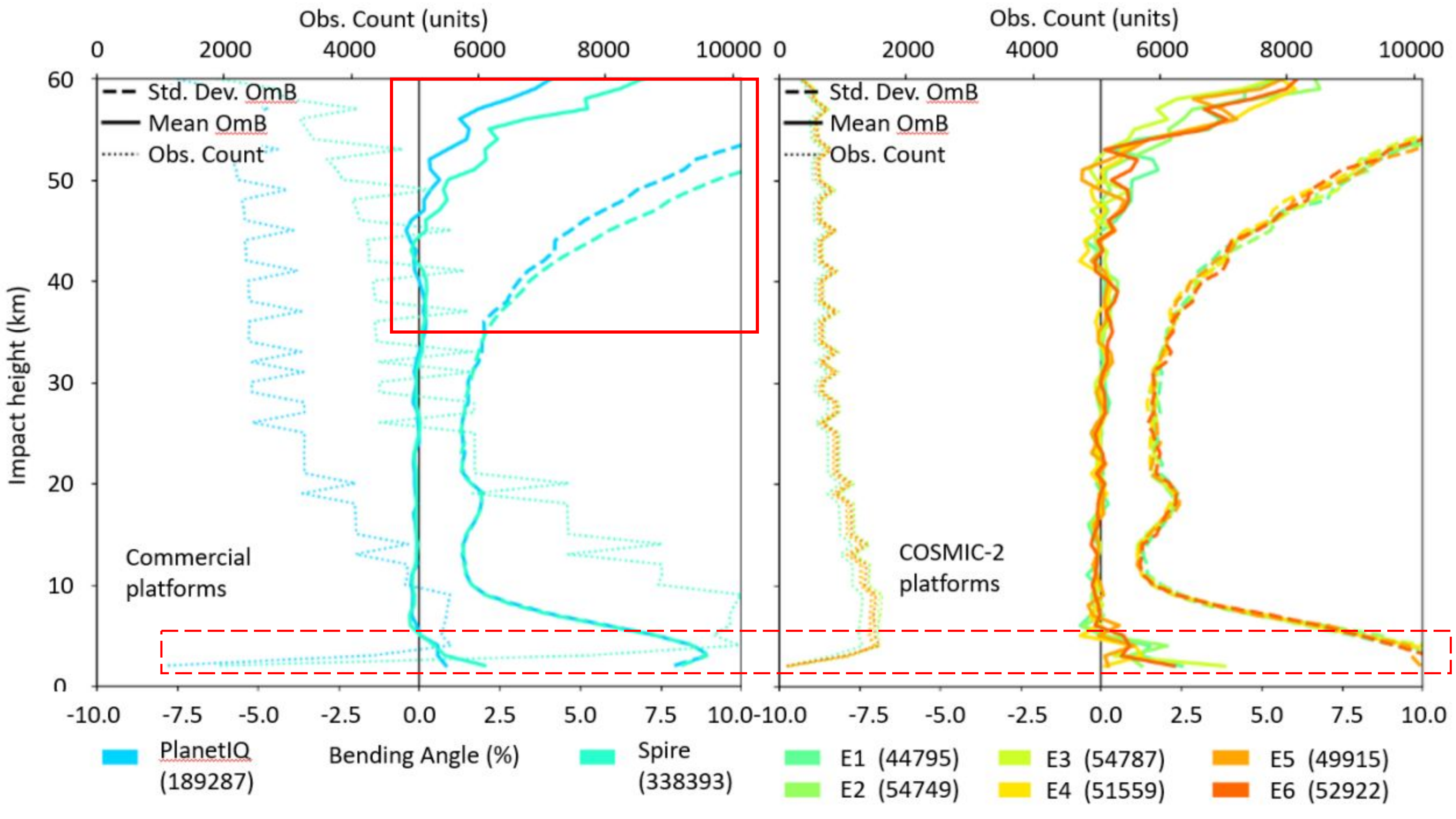


Underestimate of impact? not making use of lowermost troposphere

Added Sentinel-6A (since approved), GeoOptics, Spire, PlanetIQ

PlanetIQ OmB from JCSDA

courtesy of Francois Vandenberghe and Ben Ruston



1. Commercial data performs similar to Gov't data
2. Better than Spire at high altitudes
3. Comparable at low altitudes (*more on this later*)

PlanetIQ OmB statistics vs NOAA forecast background, RO profiles, w/ QC

PlanetiQ

Refractivity vs NOAA forecast

aer

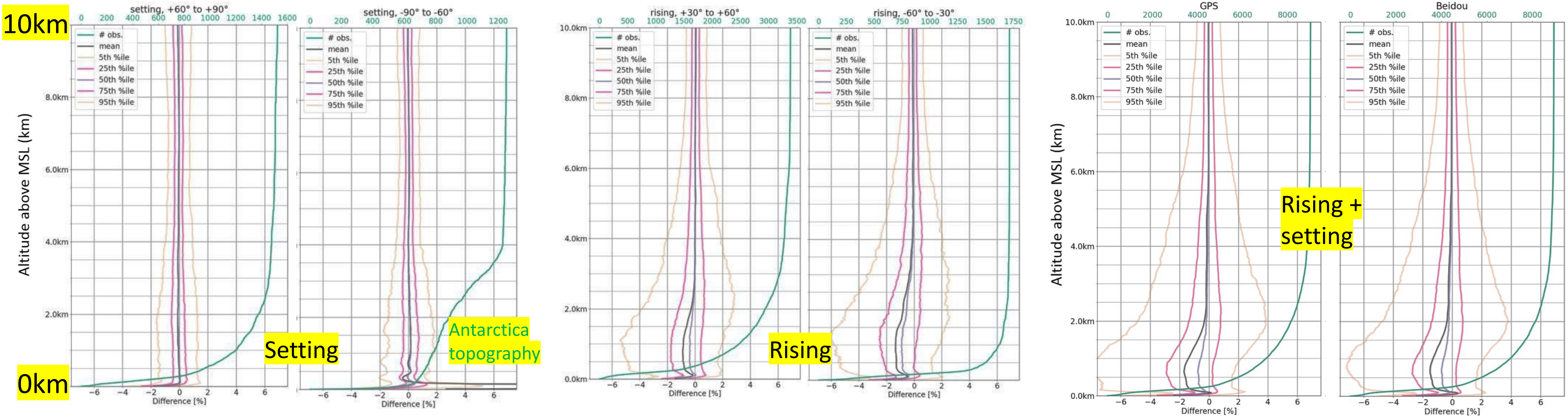
- Performance in percentiles: 5, 25, 50, 75, 95 and mean
- Little difference across GNSS constellations and between rising and setting occultations
- **Typical of high quality GNSS RO**

Some negative bias and skew apparent at lowest altitudes caused by horizontal structure and ducting (more later)

Northern Hemisphere **High Lat** Southern Hemisphere

Northern Hemisphere **Mid-Lat** Southern Hemisphere

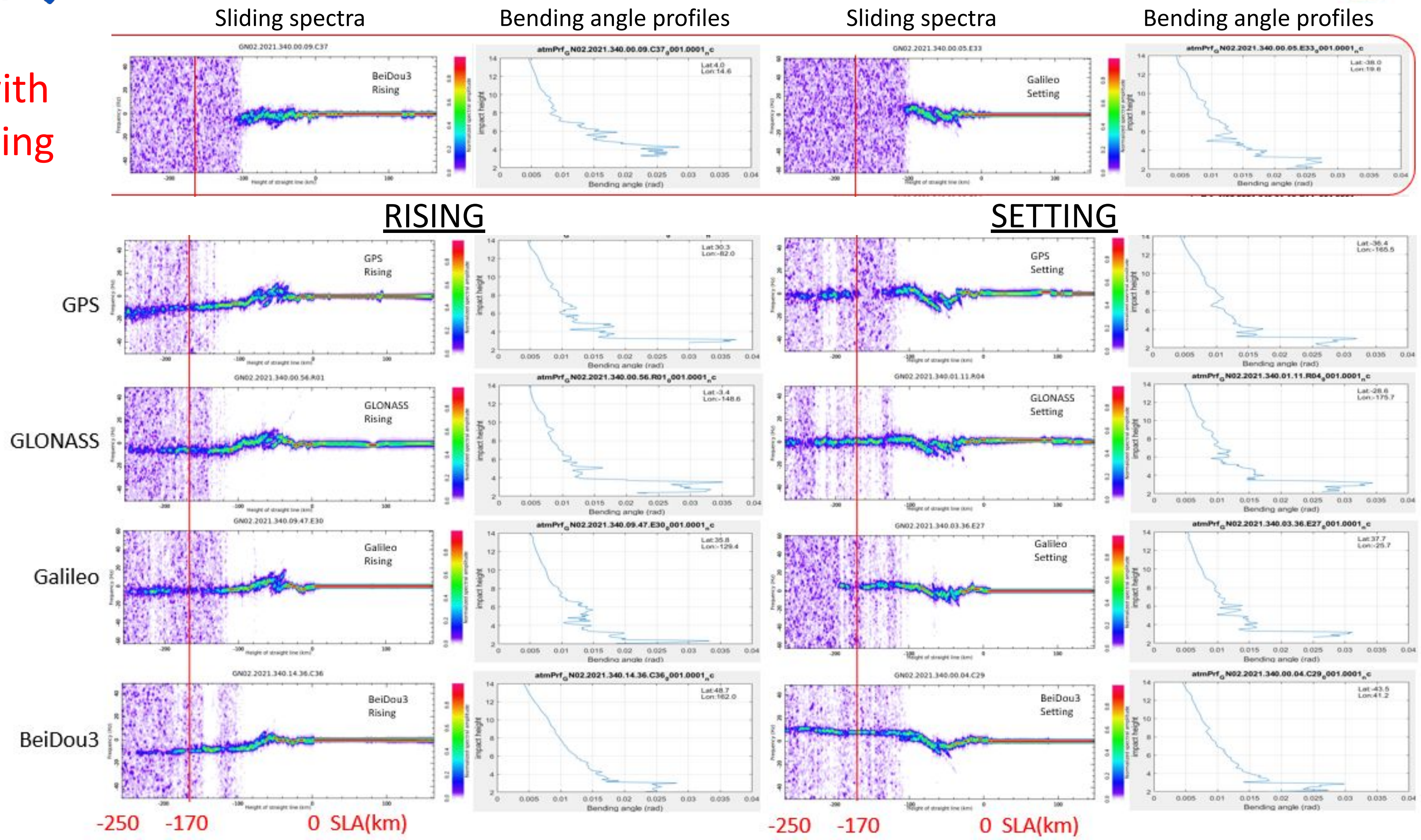
GPS **Low-Lat** BeiDou3



Detecting ducting in PlanetIQ occultations

Cases with No ducting

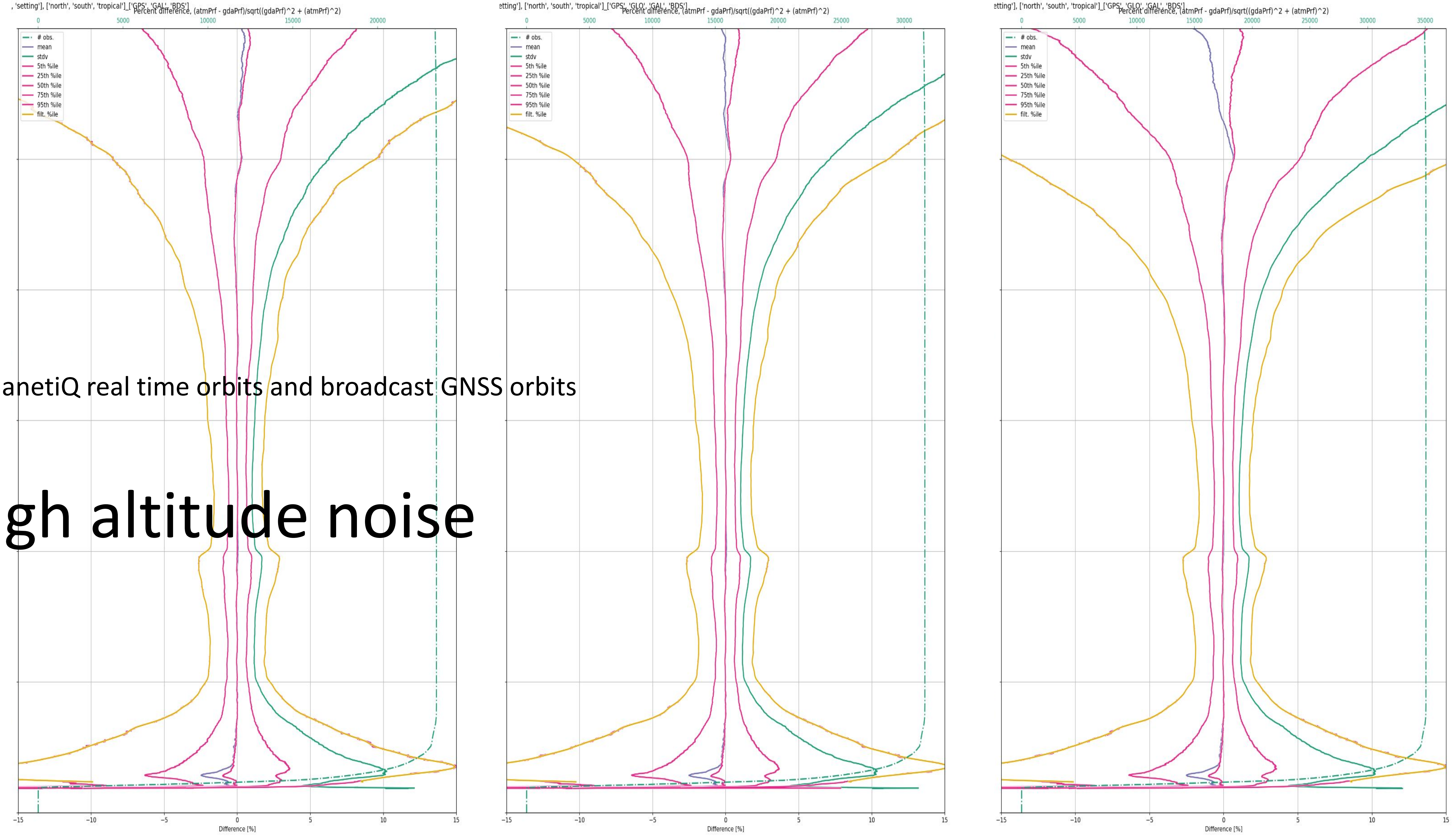
Cases with ducting



Based on Sokolovskiy et al. 2014

PlanetiQ real time orbits and broadcast GNSS orbits

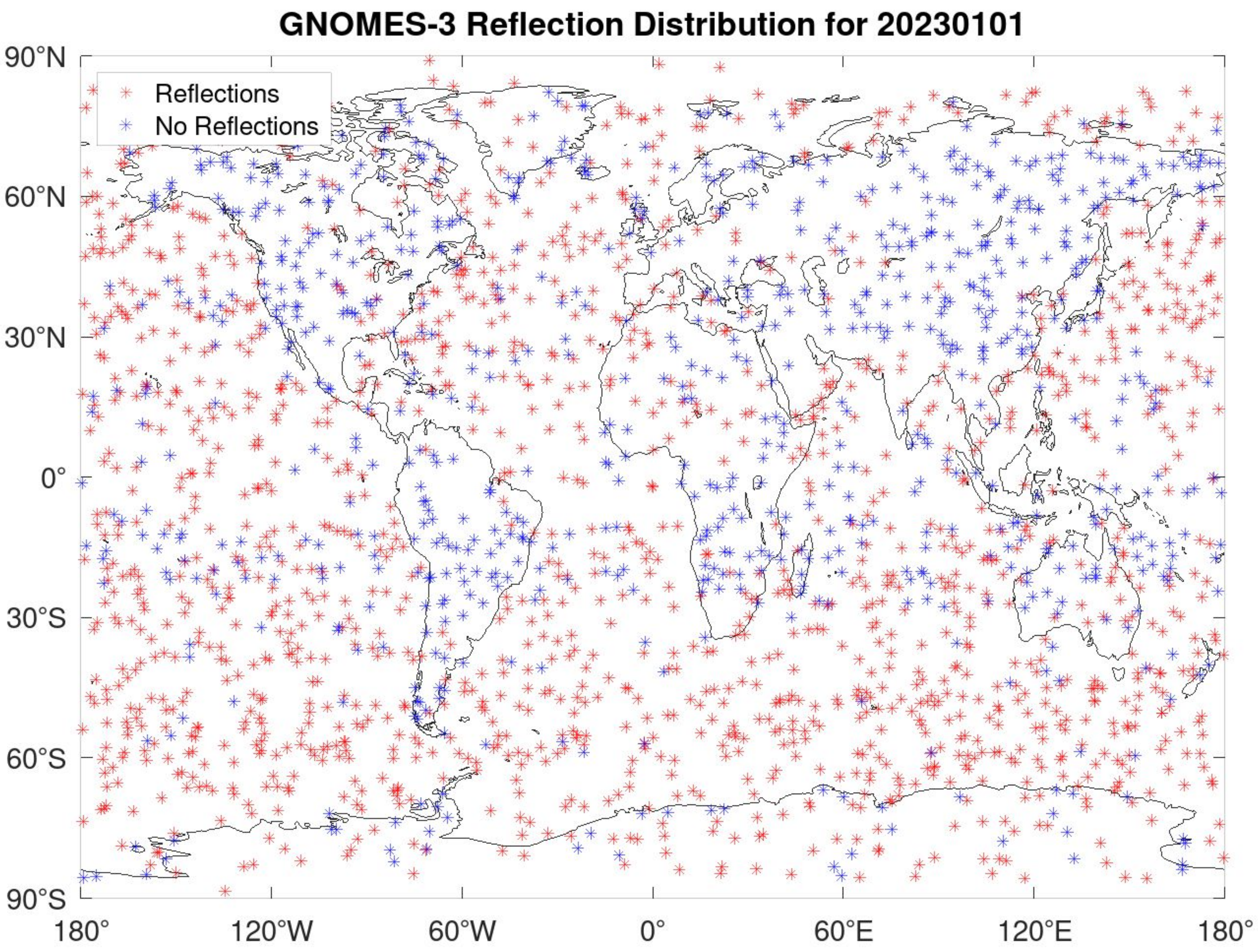
High altitude noise



PlanetiQ

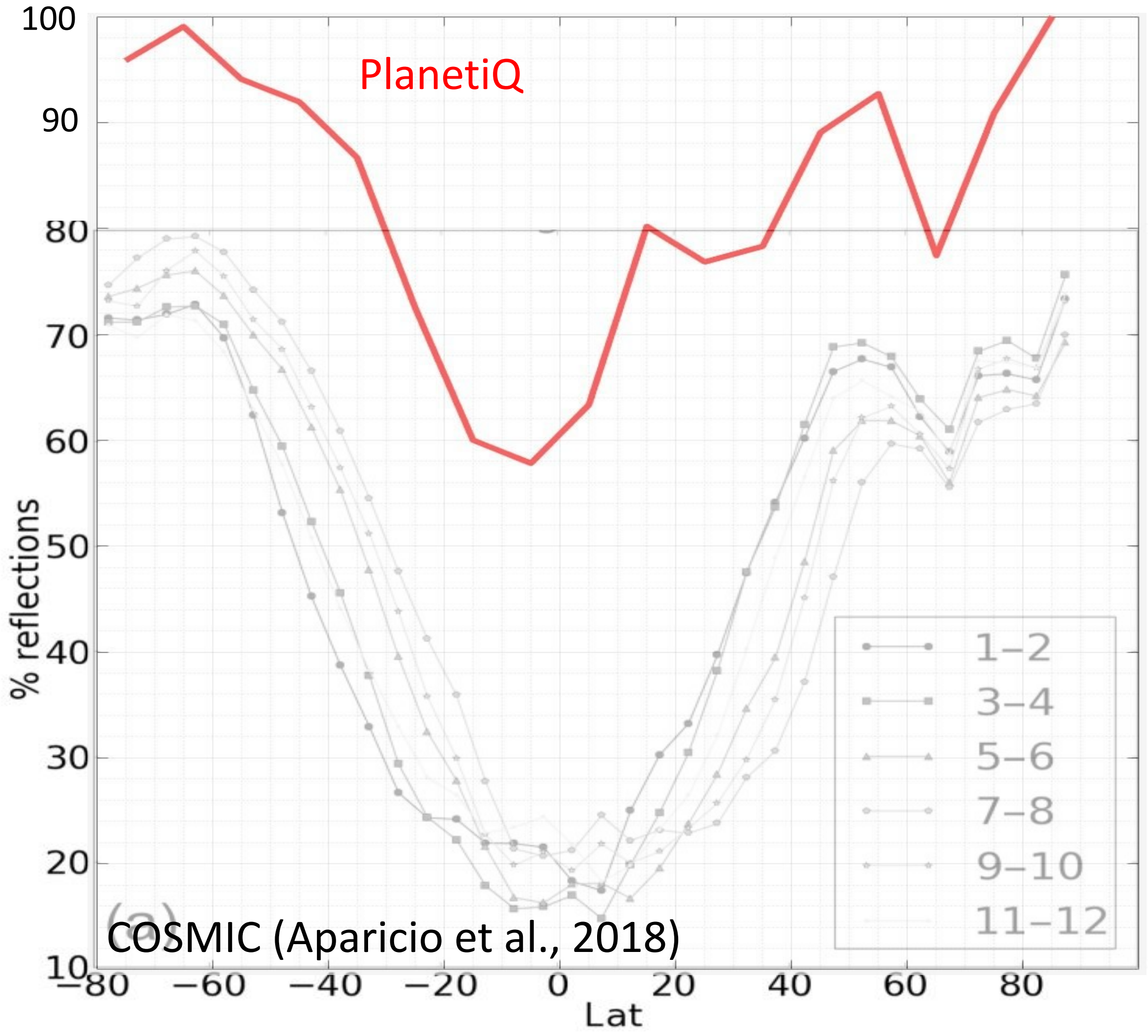
Grazing surface reflections

- GNOMES-3 occultations from Jan 1, 2023 and which occultations also have grazing surface reflections and which do not.
- Many more reflections over the oceans as expected.
- Some interesting reflections over land



Fraction of occ's over oceans with grazing surface reflections

- Black lines are % COSMIC occultations over oceans where grazing reflections were observed (Aparicio et al., 2018)
- Red line is % of GNOMES-3 occultations over oceans in Jan 2023 where grazing reflections were observed
- GNOMES-3 observes a significantly higher % of occultations with ocean reflections than observed with COSMIC
    - Particularly at low latitudes
- The higher % is presumably due to the significantly higher SNR of PlanetiQ RO observations



PlanetiQ 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**.