PlanetiQ GNSS RO Measurements of the Troposphere and Middle Atmosphere

E. Robert Kursinski

rkursinski@planetiq.com

J. Brandmeyer, A. Botnick, R. Gooch (PlanetiQ)

C. Oliveira, M. Leidner and S. Leroy (AER)

TBD

- DEFINE PERSONNEL REQ
- ~~Rescale ionosphere proposal 140cm 55" height x 90cm 35.4"width~~
- ~~Print it~~
- Fix PlanetIQ and aer on each slide
- Material from JCSDA

- Positions open at PlanetIQ
- Statement about our establishing a European presence

- Nikki Prive

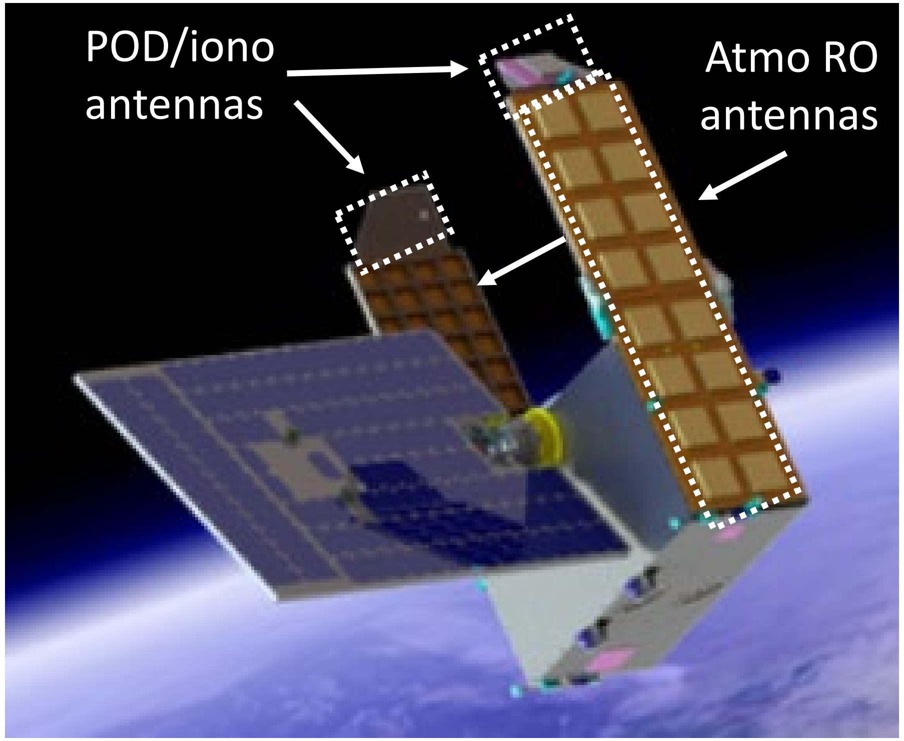
1. Background
2. Overall capability
3. Coverage
4. Data processing
5. Throughput, delay
6. Bending angle perf
7. Refractivity perf vs lat
8. High alt perf
9. Min alt vs lat, season, ocean land etc
10. SNR histogram plots
11. C2 SNR
12. Ducting profile examples
13. Ducting map
14. Ducting vs SNR
15. Ducting vs season
16. RT Data delivery figure
17. The 3 step chart from assimilating METOP => C2 => Spire ~ 11,000 RO
18. Simulations: Harnisch et al., Prive et al
19. Underweighting
20. Free Data availability

Overview

- PlanetIQ is a small commercial company created in 2015 focused on making GNSS Radio Occultation (RO) measurements for weather and climate applications
- Our first successful satellite, GNOMES-2, launched June 30, 2021 into a 515 km 2 AM/PM sun sync orbit and completed commissioning Oct 1, 2021.
- Our second successful satellite, GNOMES-2, launched April 1, 2022 into a 645 km 11 AM/PM sun sync orbit and completed commissioning May 14 1, 2021.
- Our Pyxis GNSS RO receiver on GNOMES-2 is now routinely acquiring occultations from the four GNSS constellations: GPS, GLONASS, Galileo and BeiDou (w/ 1 hour latency easily meeting the 140 minute requirement).
- Here we present initial neutral atmosphere results in terms of bending angle & refractivity profiles made with high signal-to-noise-ratios (SNR) and pole-to-pole coverage.

Antennas

- Four high gain RO antenna columns
  - One pair facing forward
  - One pair facing aft
  - We combine the pairs to increase SNR
- Two POD/iono antennas
  - One forward, one aft
  - Canted back to view limb to overhead



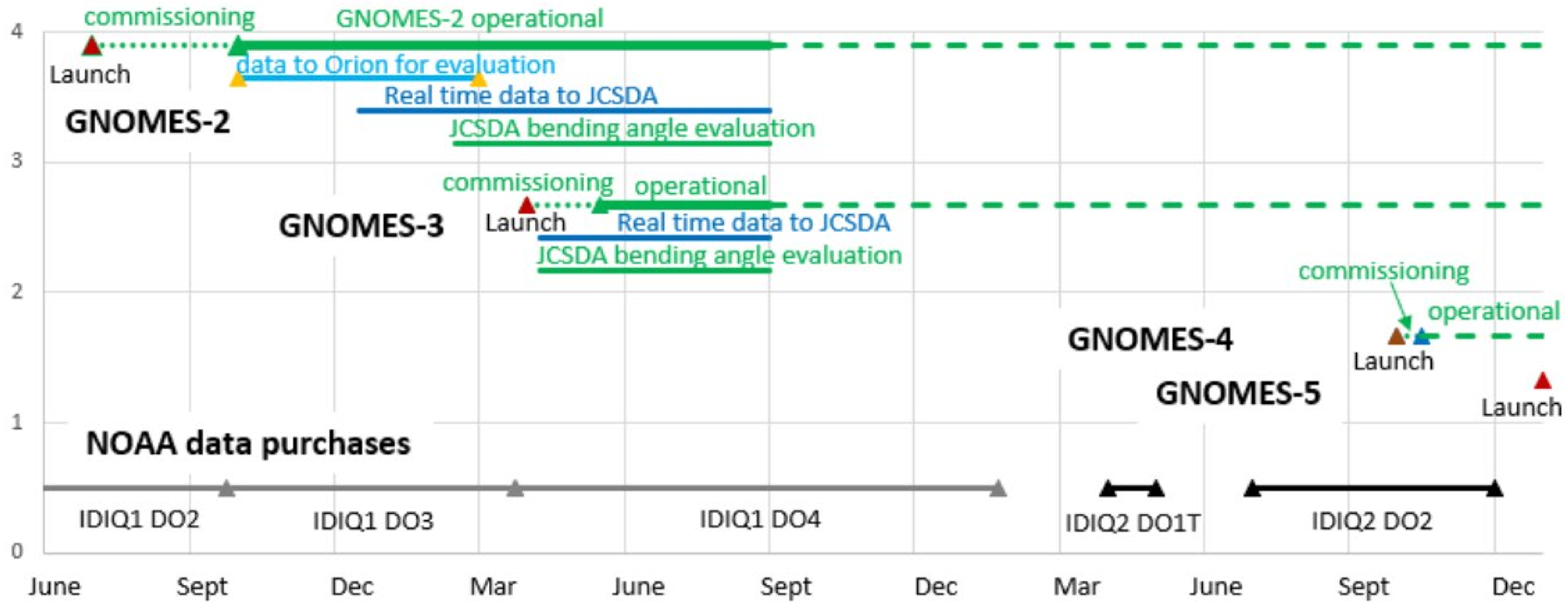
Quantity

- Pyxis tracks all GPS (with L2C), GLONASS, Galileo and BeiDou3 satellites.
- With these ~94 dual frequency sources, Pyxis can acquire 2500 atmospheric and 2800 ionospheric occultations each day.
- Following 90 days of commissioning, GNOMES-2 is routinely generating ~1300 neutral atmosphere and 2700 ionosphere occultations per day.
  - 1300 neutral occultations is roughly 50% of 2500 due to a stuck GNOMES-2 solar panel.

- GNOMES-3 (*with corrected solar panel*) launched April 1, 2022 into a 645 km, 11 AM/PM orbit.
- Together GNOMES-2 + GNOMES-3 will produce a combined 3300 neutral atmosphere and 5600 ionosphere occultations per day beginning in May 2022

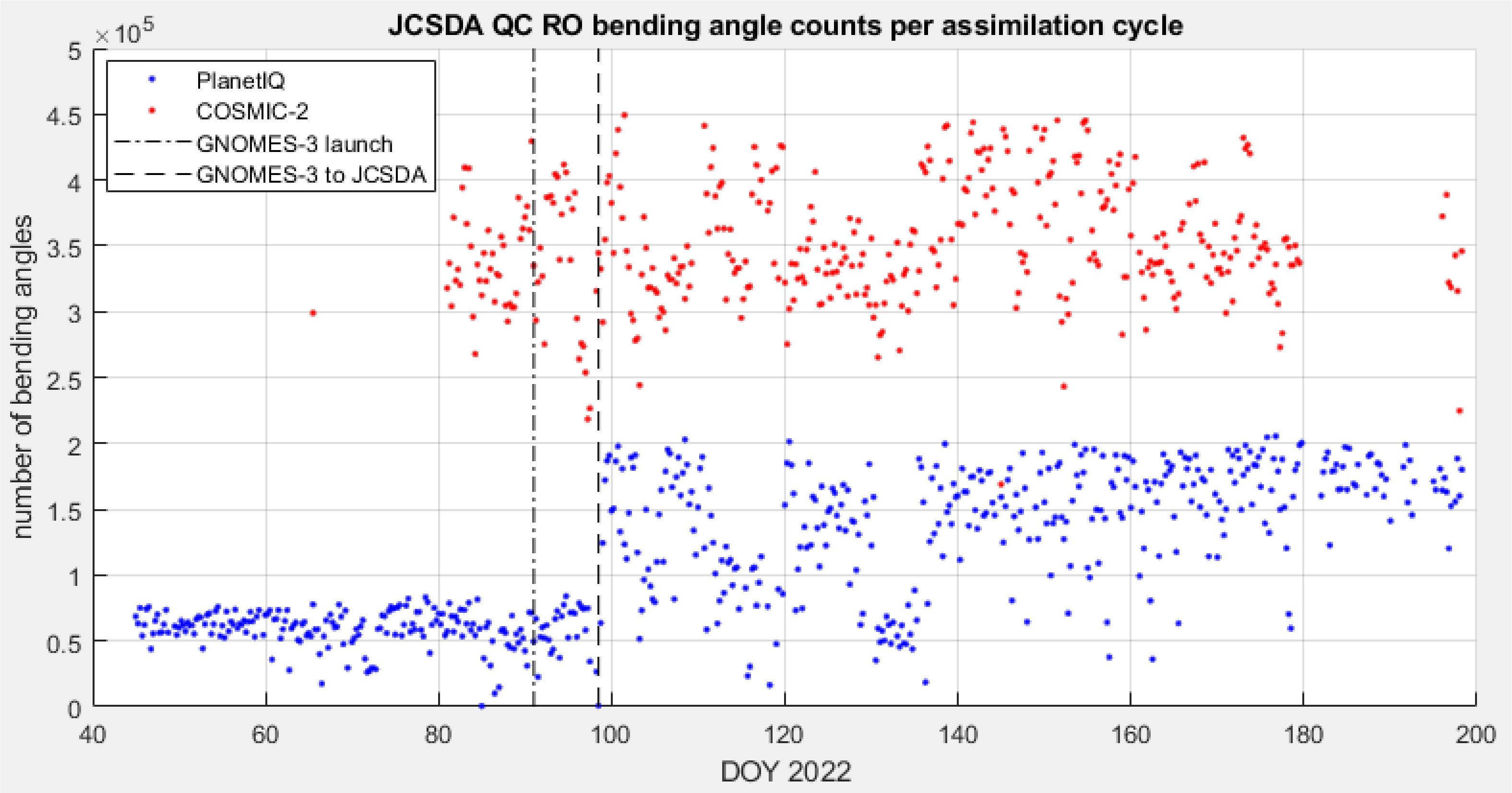
- We are assessing add tracking of 4 QZSS and possibly 15 BeiDou2 satellites
  - (by modifying Pyxis software/firmware **on-orbit**)
  - to increase the combined GNOMES-2 and -3 occultations to ~**4500** neutral and **6700** ionosphere occultations per day.
  - This is comparable to the number of occultations from the 6 COSMIC-2 satellites.

- Our goal is to have 20 satellites on orbit, generating 50,000+ neutral and 60,000+ ionosphere occultations per day.


commissioning
GNOMES-2 operational
Launch
data to Orion for evaluation
Real time data to JCSDA
GNOMES-2
JCSDA bending angle evaluation
commissioning
operational
GNOMES-3
Launch
Real time data to JCSDA
JCSDA bending angle evaluation
commissioning
operational
GNOMES-4
Launch
GNOMES-5
Launch
NOAA data purchases
IDIQ1 DO2
IDIQ1 DO3
IDIQ1 DO4
IDIQ2 DO1T
IDIQ2 DO2
4
3
2
1
0
June
Sept
Dec
Mar
June
Sept
Dec
Mar
June
Sept
Dec

Real time Data flow to JCSDA

- Directory: D:\kursinski021715\SSE\PlanetIQ RO Quality Impact Eval\JCSDA\JCSDA numbers of occs etc
- Code: JCSDA_counts_all.m

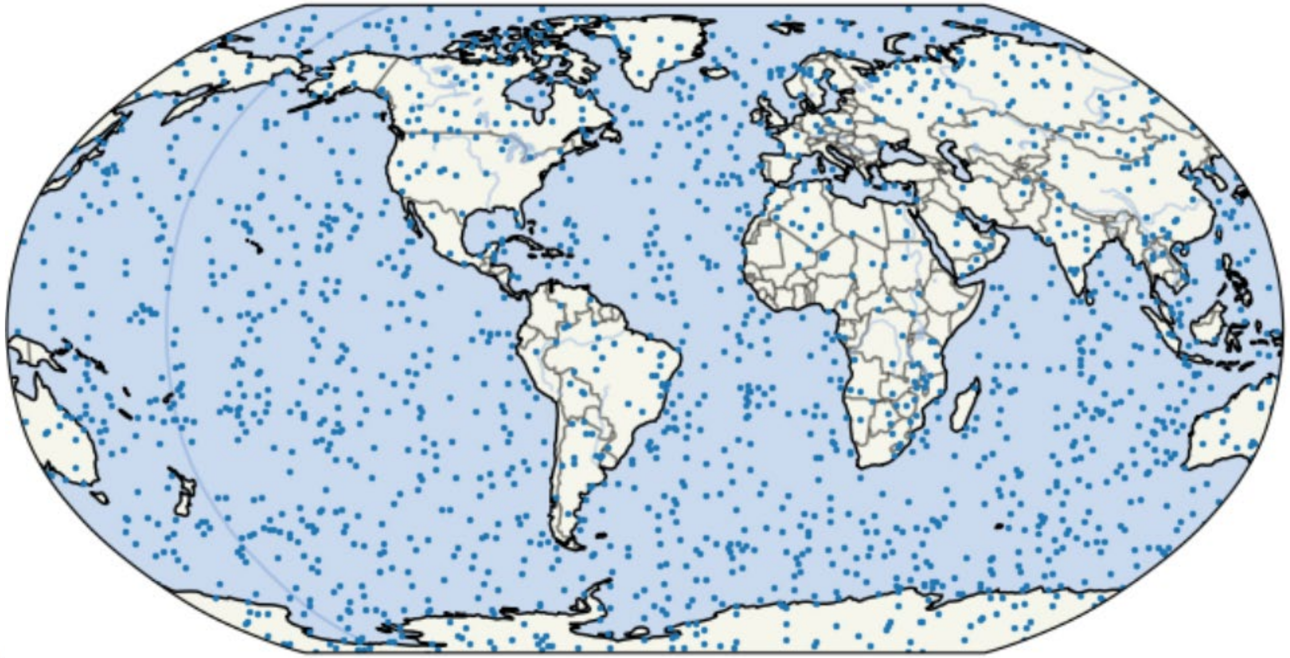


Present PlanetiQ GNSS RO Coverage

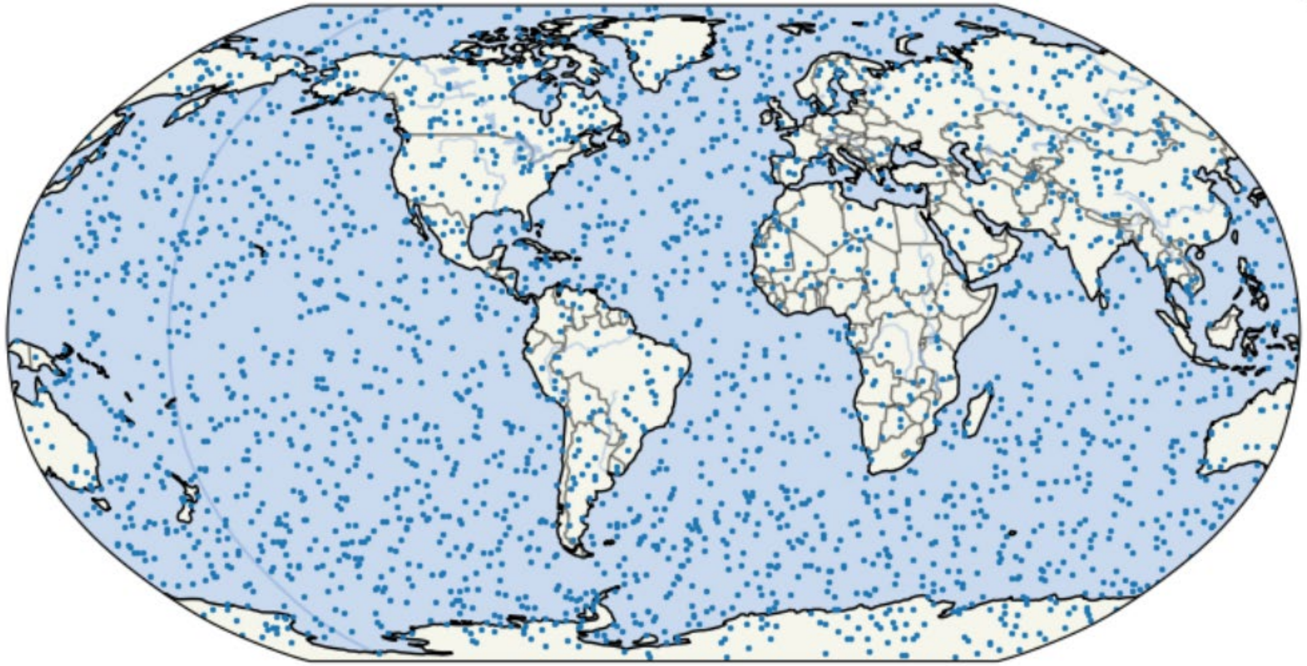
- GNOMES-2 ~1200 occ/day
- GNOMES-3 ~2100 occ/day
- Total: 3,300 occ/day

close to COSMIC 2B

GNOMES-2 Neutral Weather Tangent Points
2022-08-23T20:00 - 2022-08-24T20:00

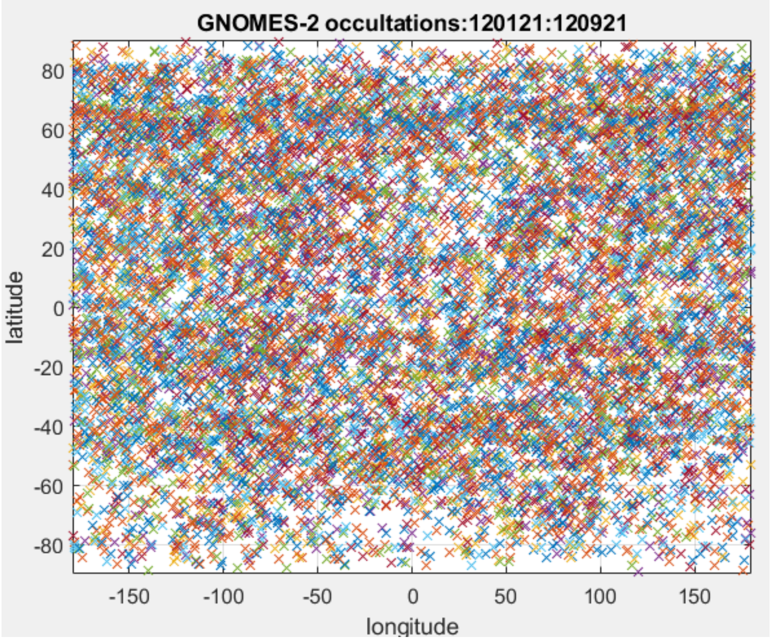


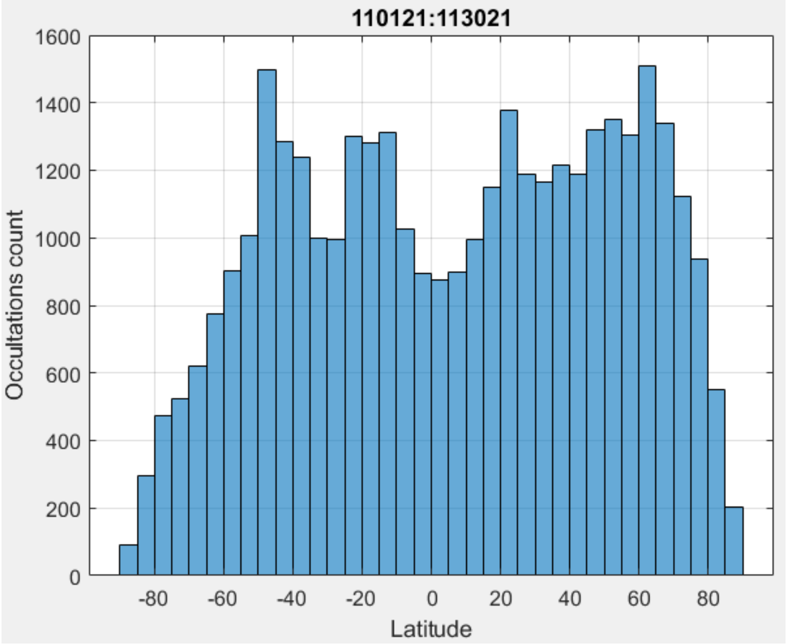
GNOMES-3 Neutral Weather Tangent Points
2022-08-23T20:00 - 2022-08-24T20:00



GNOMES-2 Coverage

- GNOMES-2 provides ~1200 QC'd neutral occultations daily
- Coverage is pole-to-pole centered on 1:30 AM and PM local time.
- The density of occultations is lower at southern high latitudes due to battery charging with the stuck solar panel

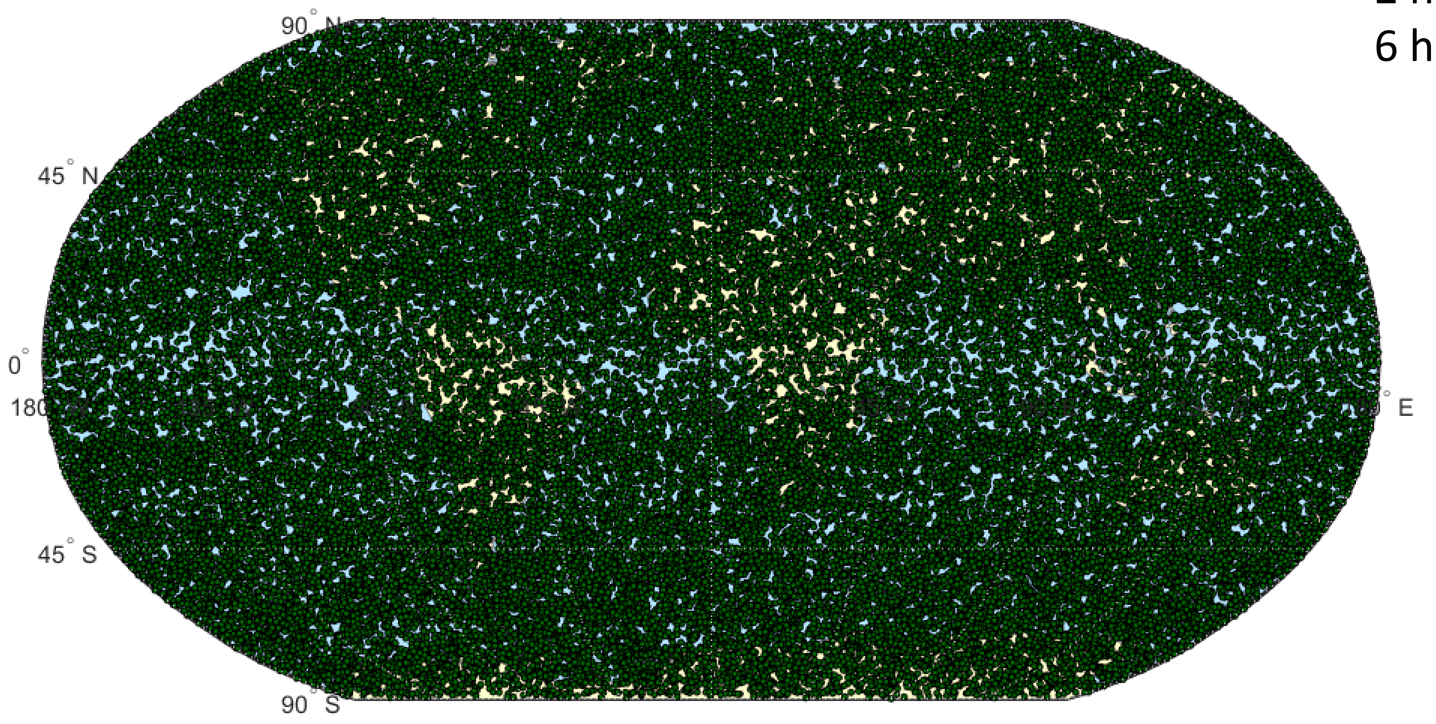




PlanetiQ GNSS RO Coverage with 20 satellites

~60,000 neutral occultations per day

1 hr: 2500
2 hr: 5000
6 hr: 15000

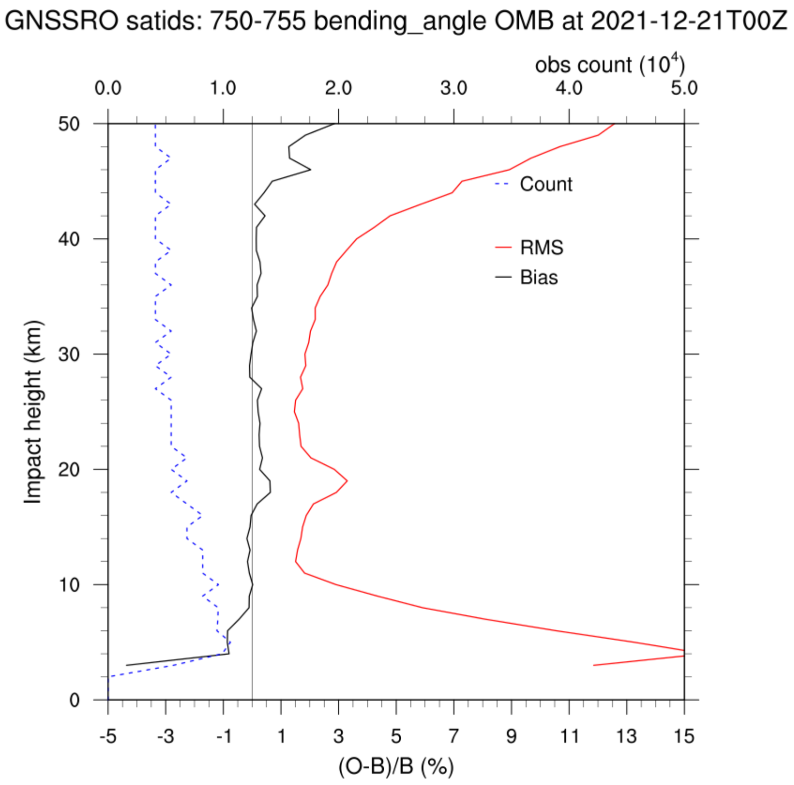


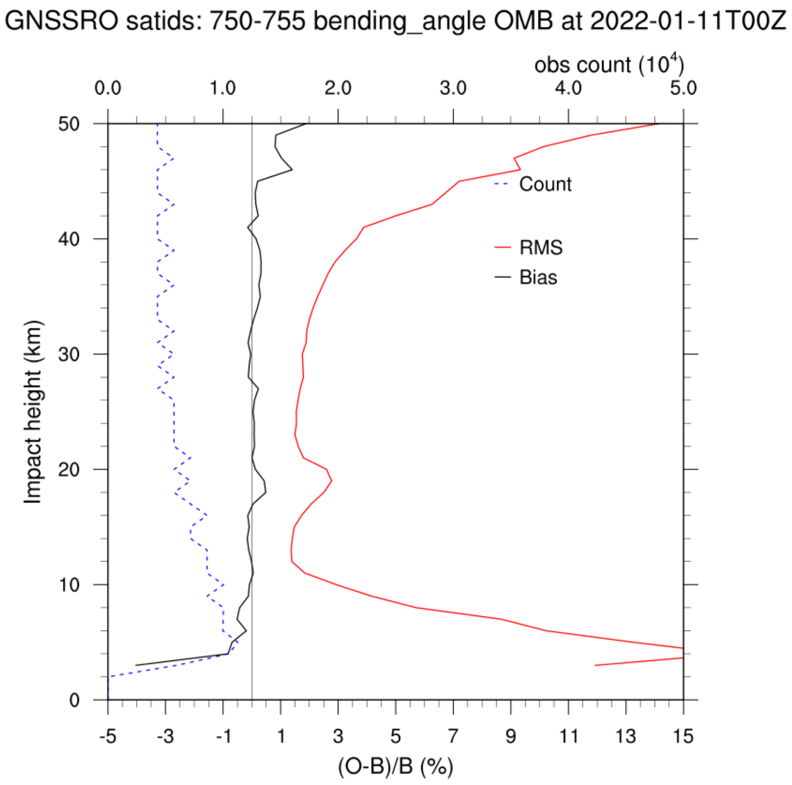
Performance Evaluation

1. Observed minus Background (OmB) COSMIC-2 and PlanetIQ GNOMES-2 bending angle statistics against AF GALWEM, courtesy of JCSDA
2. Fractional refractivity comparisons between GFS 6 hour forecasts and PlanetIQ GNOMES-2 occultations.

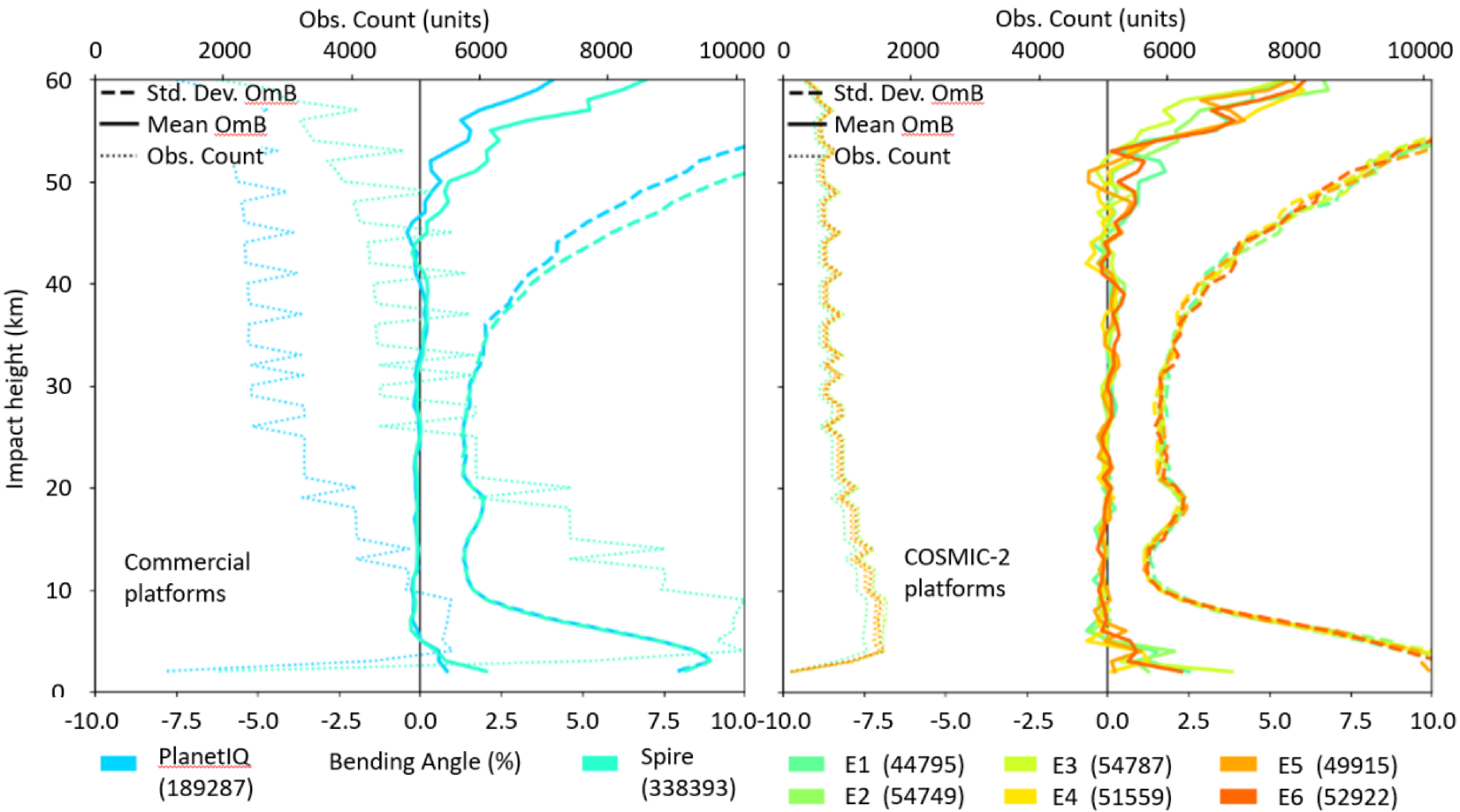
PlanetiQ COSMIC-2 OmB from JCSDA aer

courtesy of Francois Vandenberghe and Ben Ruston



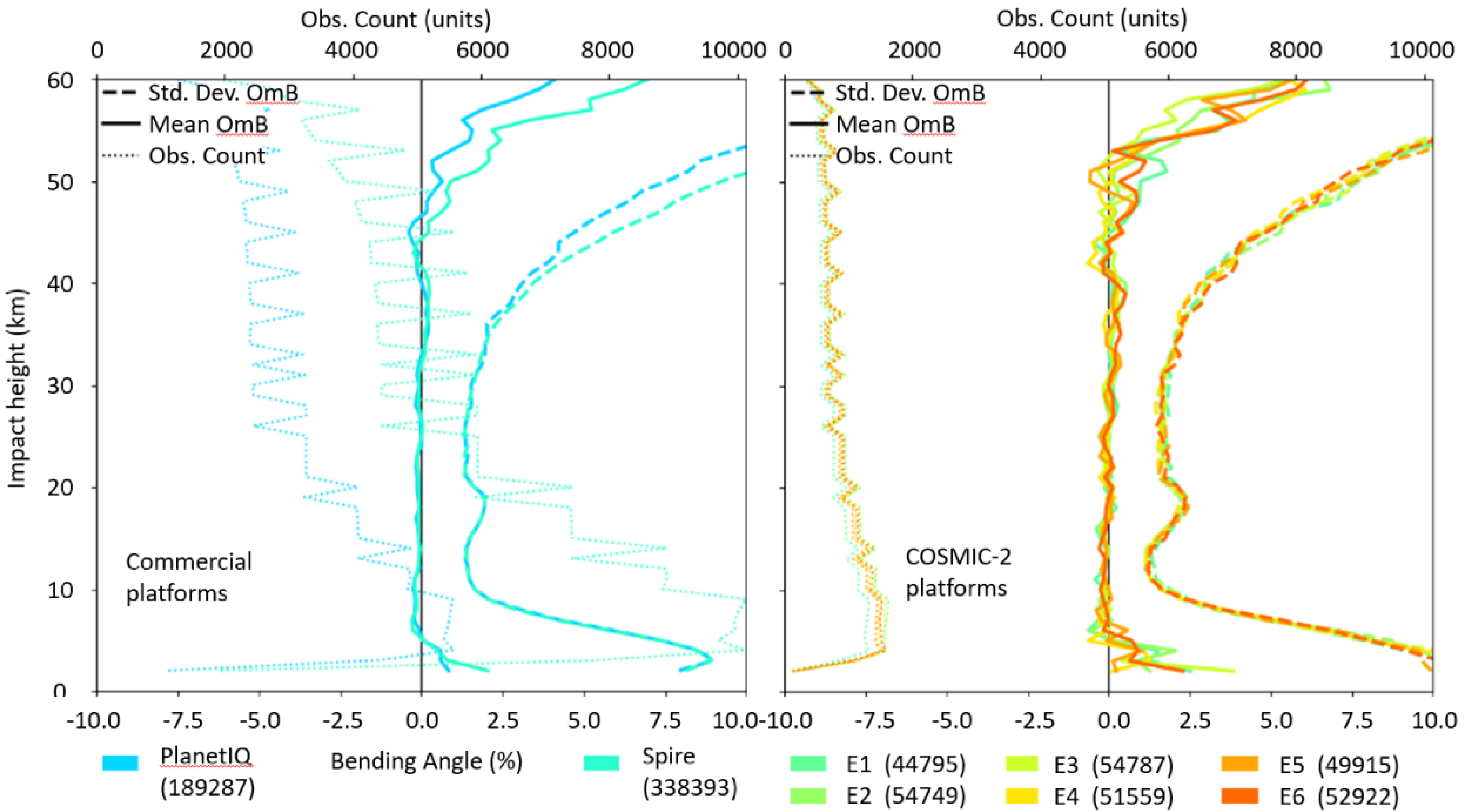


COSMIC-2 OmB statistics
(GALWEM background, MetOffice UFO,
nominal profiles only, no QC


Obs. Count (units)
0
2000
4000
6000
8000
10000
Std. Dev. OmB
Mean OmB
Obs. Count
Impact height (km)
60
50
40
30
20
10
0
Commercial platforms
COSMIC-2 platforms
-10.0
-7.5
-5.0
-2.5
0.0
2.5
5.0
7.5
10.0
Bending Angle (%)
PlanetIQ (189287)
Spire (338393)
E1 (44795)
E2 (54749)
E3 (54787)
E4 (51559)
E5 (49915)
E6 (52922)

PlanetIQ OmB from JCSDA

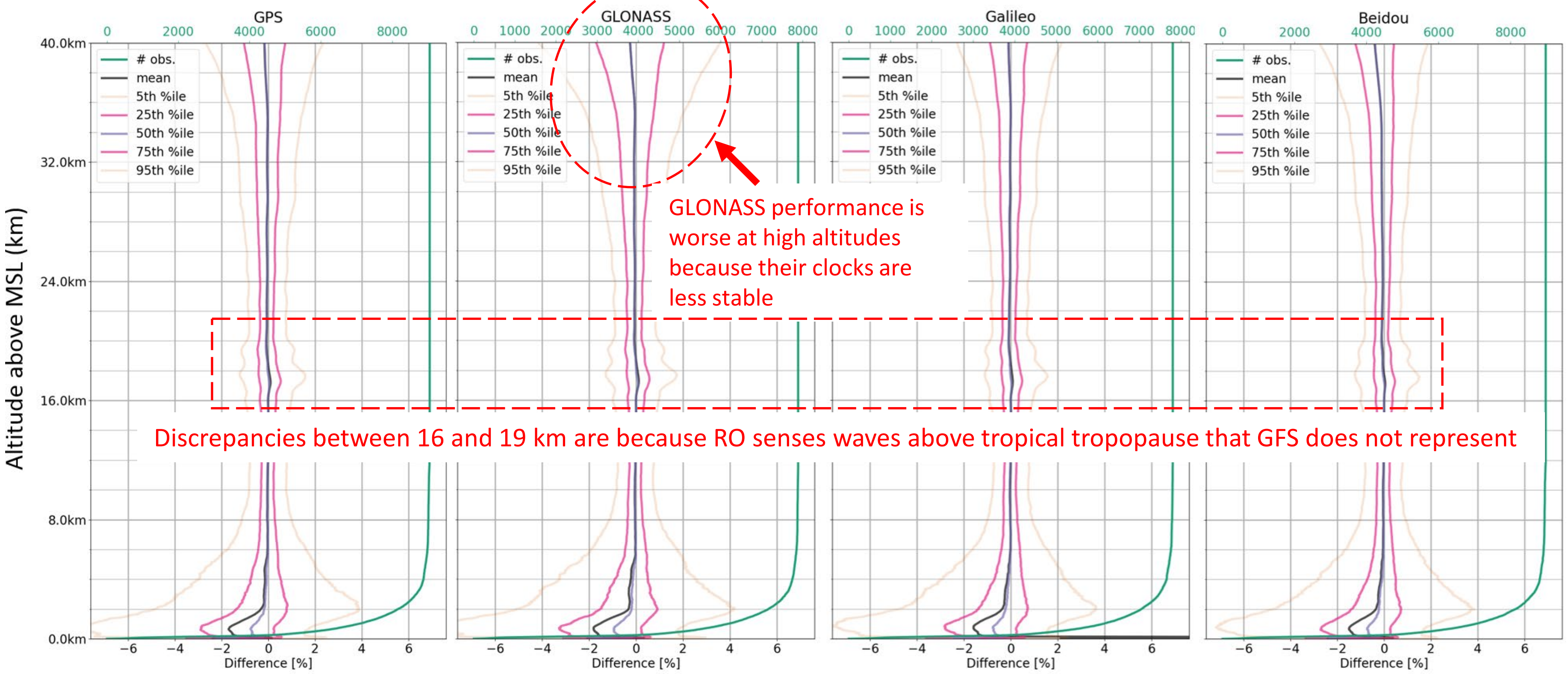
courtesy of Francois Vandenberghe and Ben Ruston



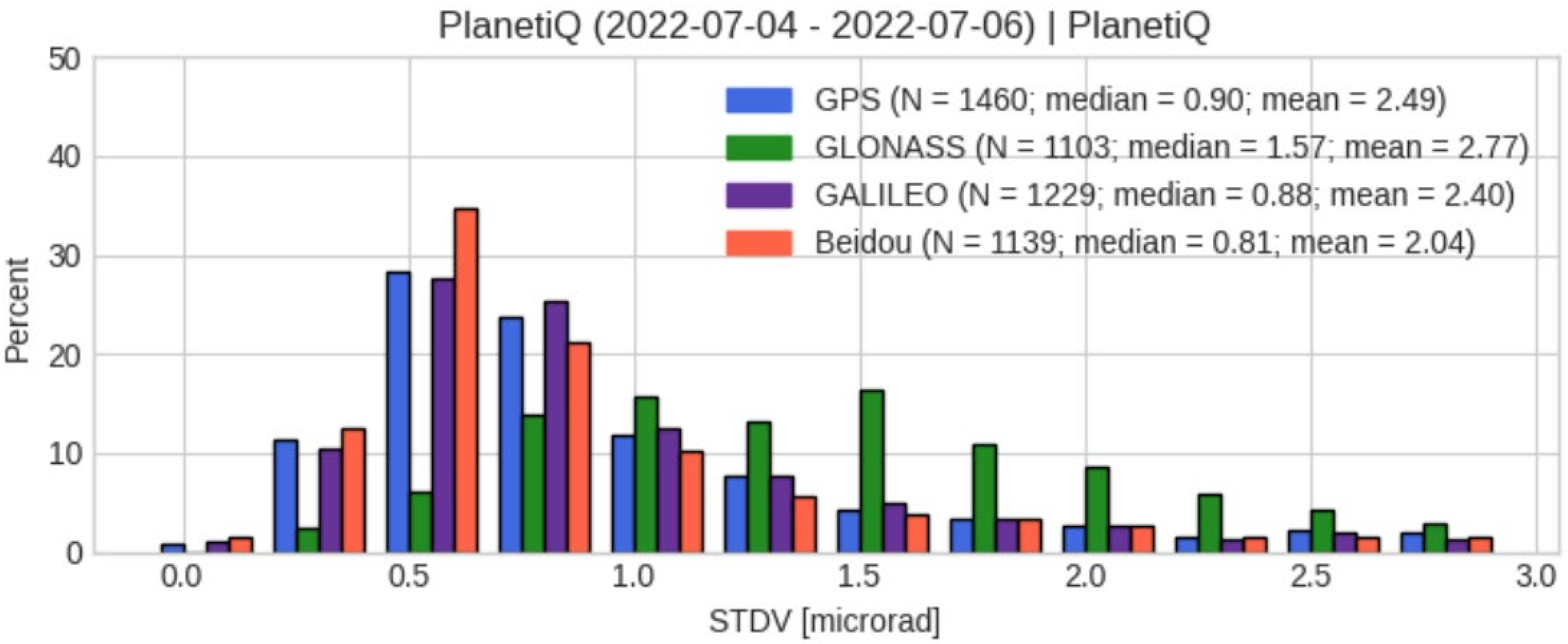
PlanetIQ OmB statistics (NOAA forecast background, RO profiles, w/ QC

Fractional refractivity comparisons against NOAA GFS forecasts

- All occultations are included (Global)
- Altitudes extend from mean sea level (MSL) to 40 km
- Performance is shown in terms of percentiles: 5, 25, 50, 75, 95 and mean
- Very similar performance across the 4 GNSS constellations: GPS (w/ L2C), GLONASS, Galileo and BeiDou3.

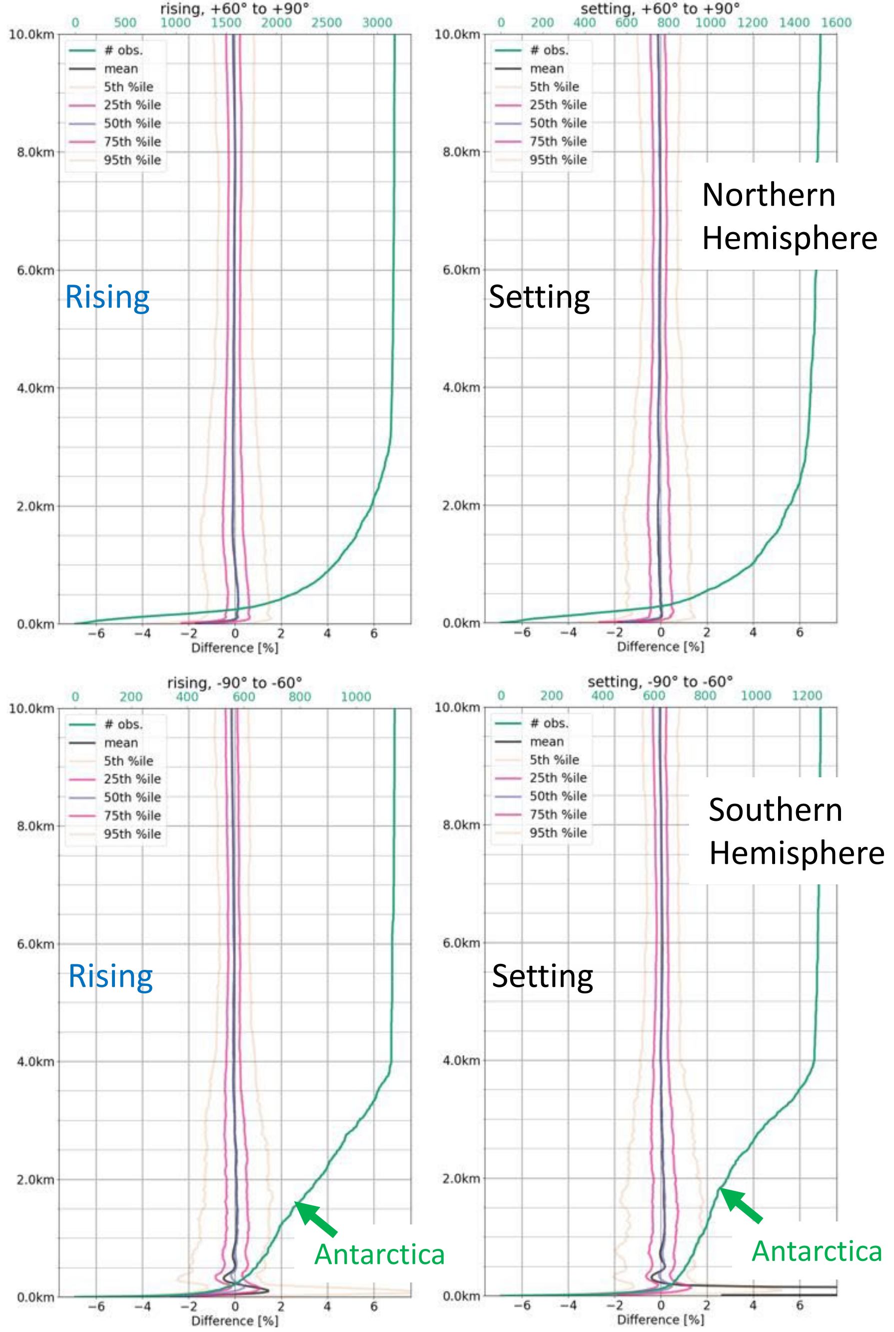


Bending angle performance at high altitude



Performance at high latitudes

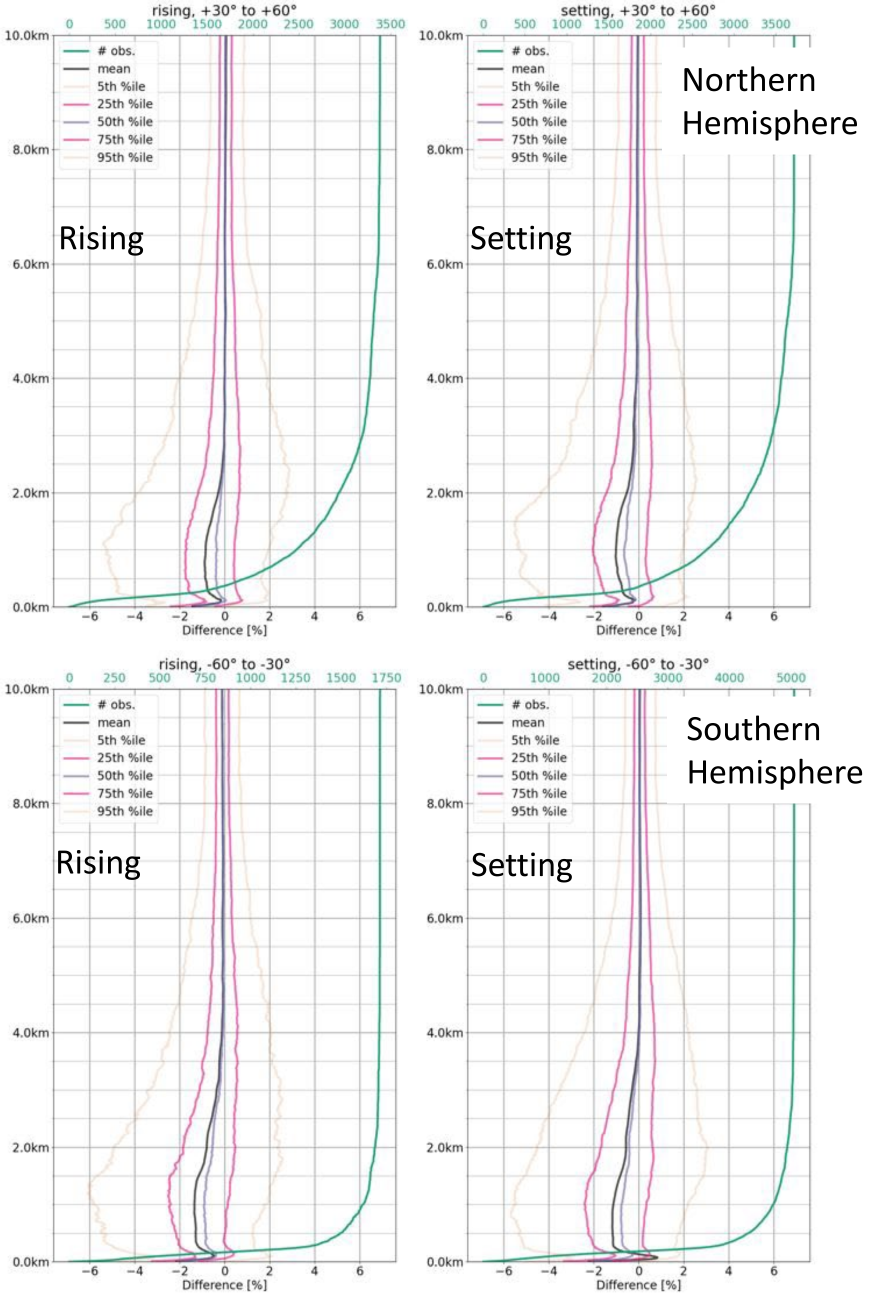
- 60º to 90º Northern vs Southern
- Rising vs setting, MSL to 10 km altitude
- Very similar, low noise performance in both hemispheres, for rising and setting, for all 4 GNSS constellations
- More occultations in northern hemisphere due to battery charging associated with stuck solar panel
- Antarctica topography limits lowest altitudes above sea level at high southern latitudes



PlanetiQ aer

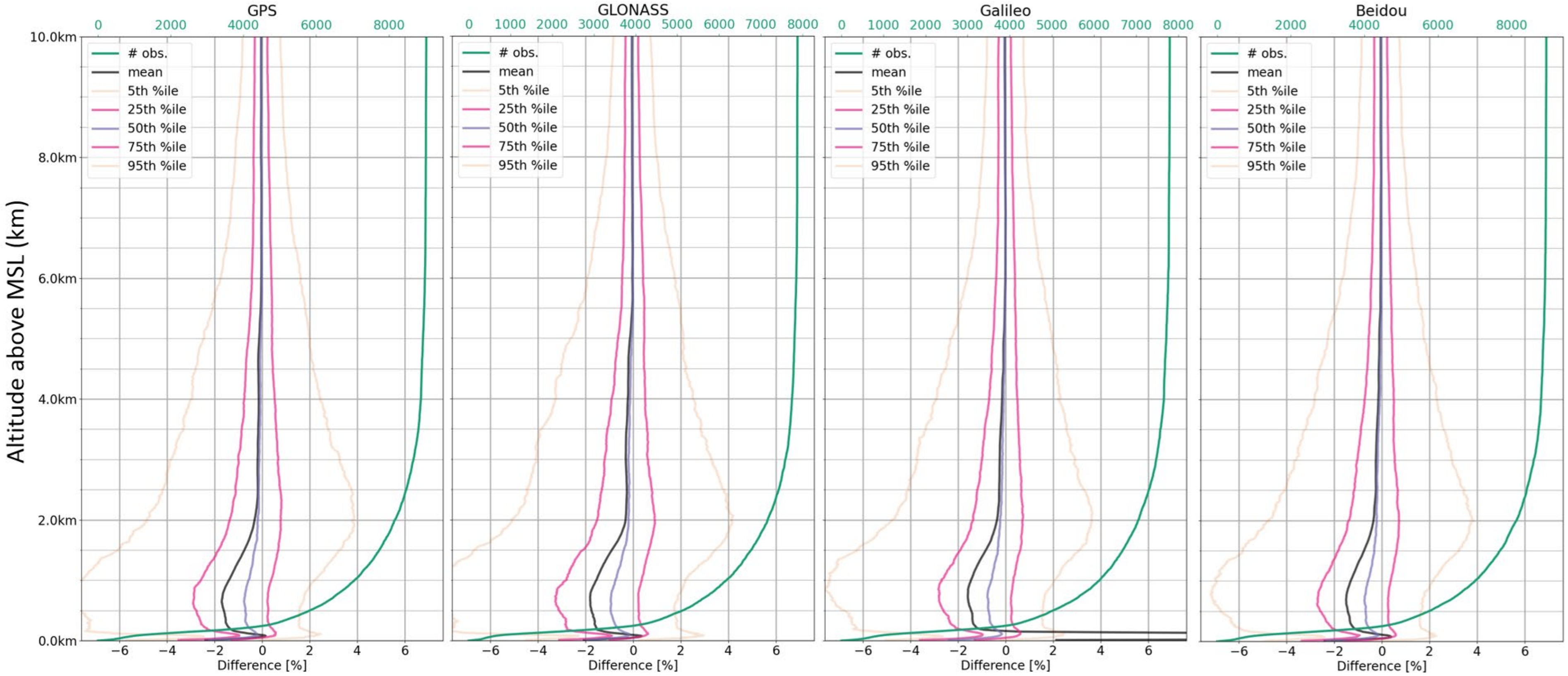
Midlatitude Performance

- 30° to 60° Northern vs Southern
- Rising vs setting, MSL-10 km altitude
- Very similar performance in both hemispheres for rising and setting, across all four GNSS constellations
- Some negative bias and skew is readily apparent at the lowest altitudes
  - This is likely caused by super-refraction or ducting (more on that later)



Tropics

- Low latitude (30S – 30N), 0 to 10 km
- More discrepancies with GFS at lower altitudes due to water vapor variations
- Negative bias and skew are likely associated with ducting



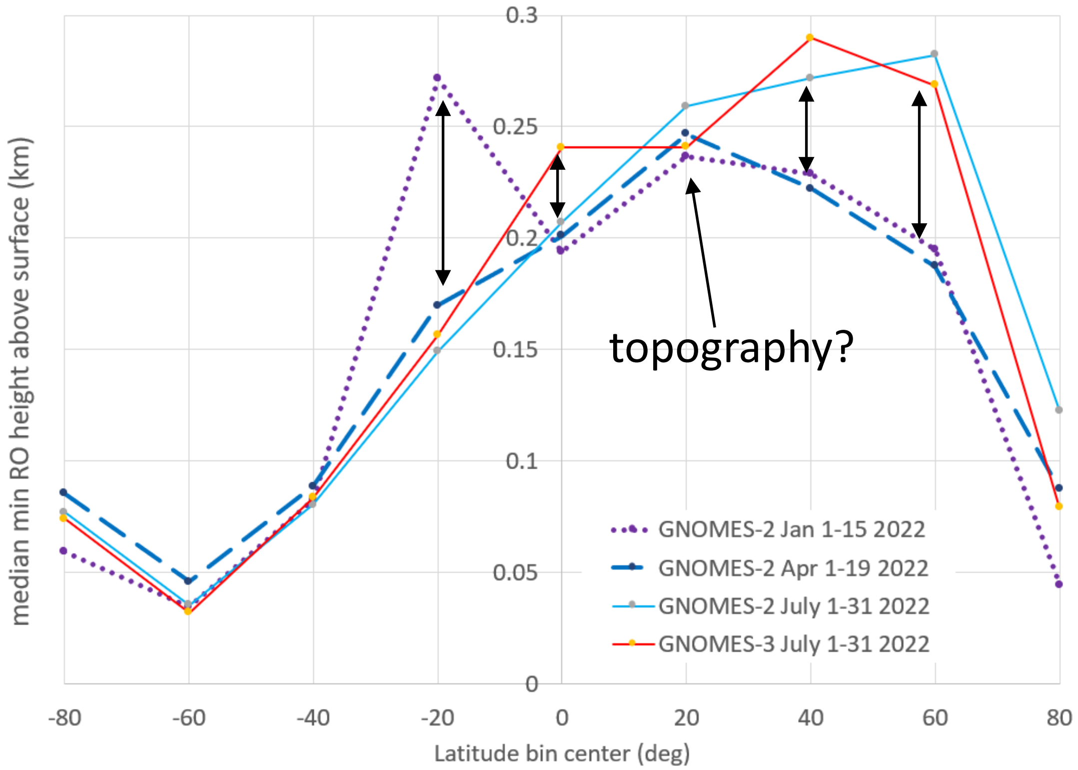
Depth of occultation penetration

A figure of merit is how close are our profiles getting to the surface.

Refractivity profile altitude is relative to sea level

Used 4 km resolution topography to get height relative to surface

Consistent behavior plus convection?



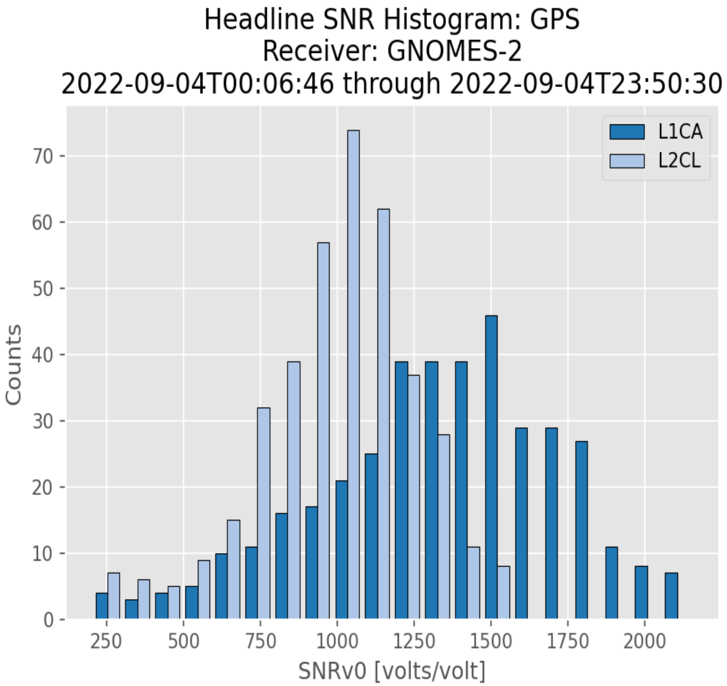
Global median depths (m)

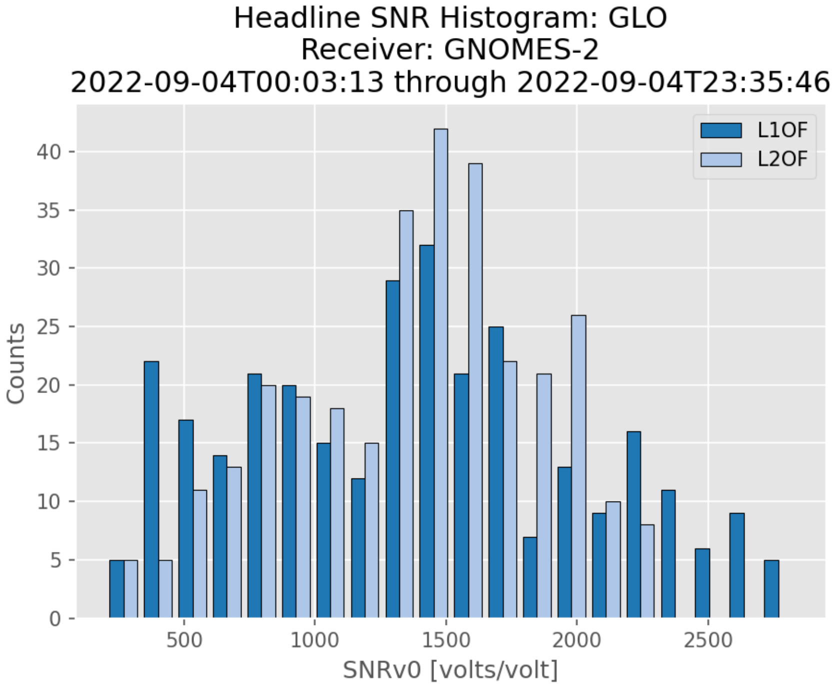
	GNOMES2	GNOMES3
Jan 1-15	147	
Apr 1-19	135	
July 1-31	123	134

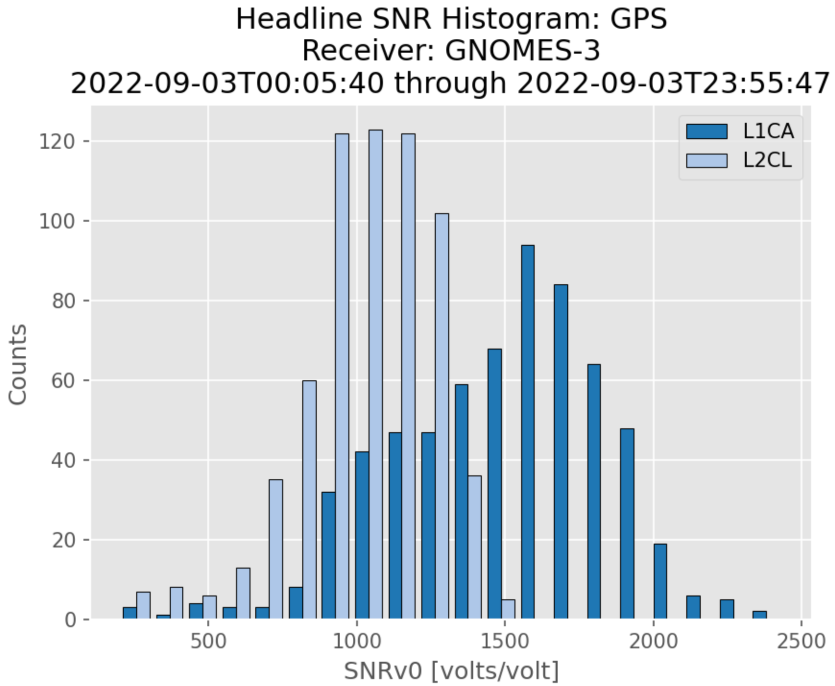
July 1-31 N. Pacific: 75

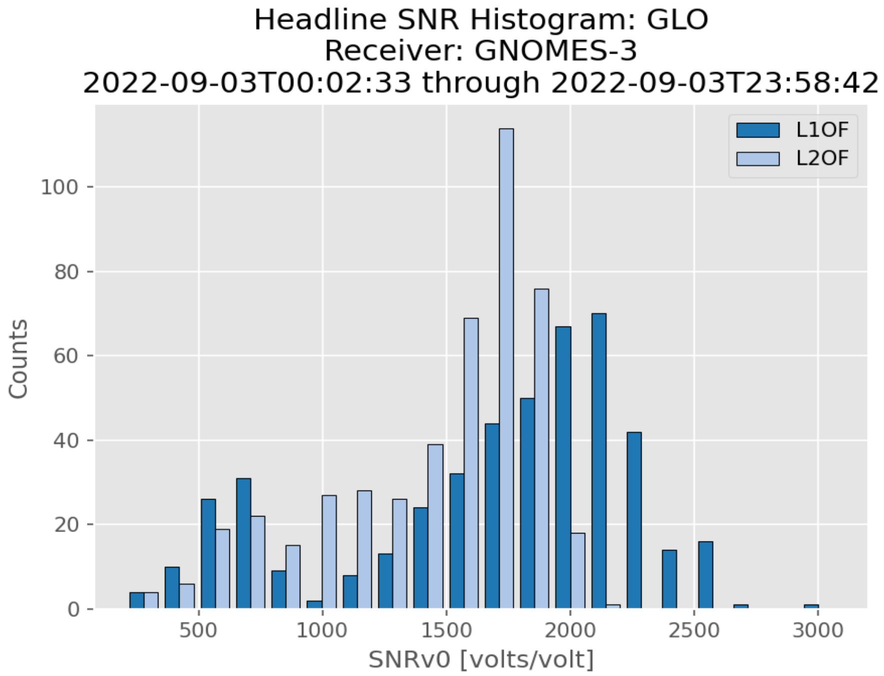
SNR SNR SNR

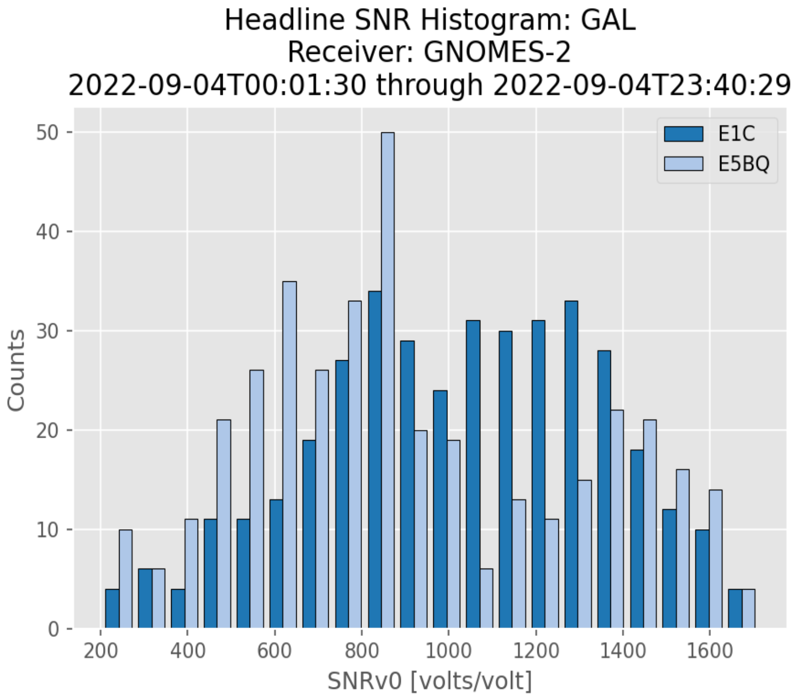
- Overall statistics

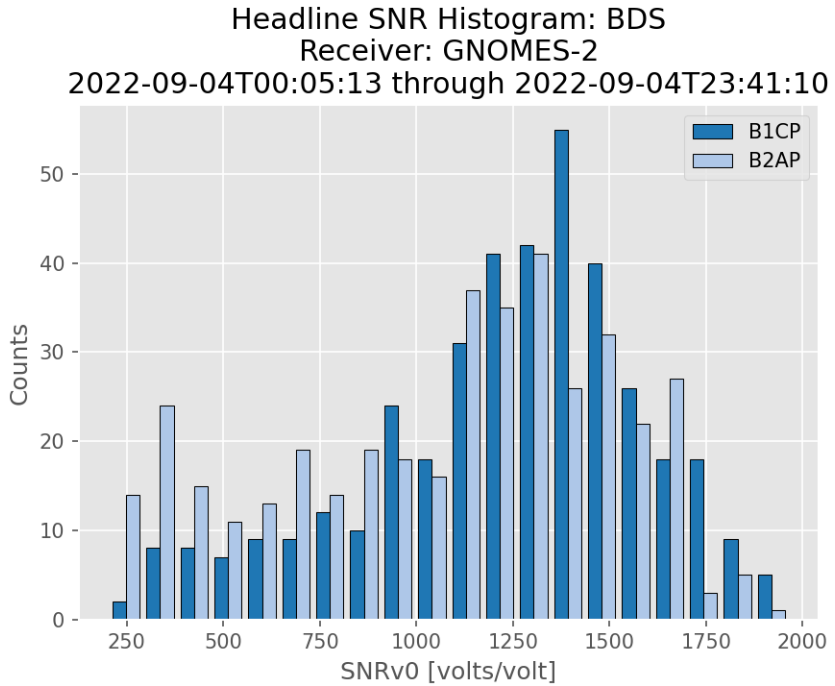

Headline SNR Histogram: GPS
Receiver: GNOMES-2
2022-09-04T00:06:46 through 2022-09-04T23:50:30
L1CA
L2CL
Counts
SNRv0 [volts/volt]

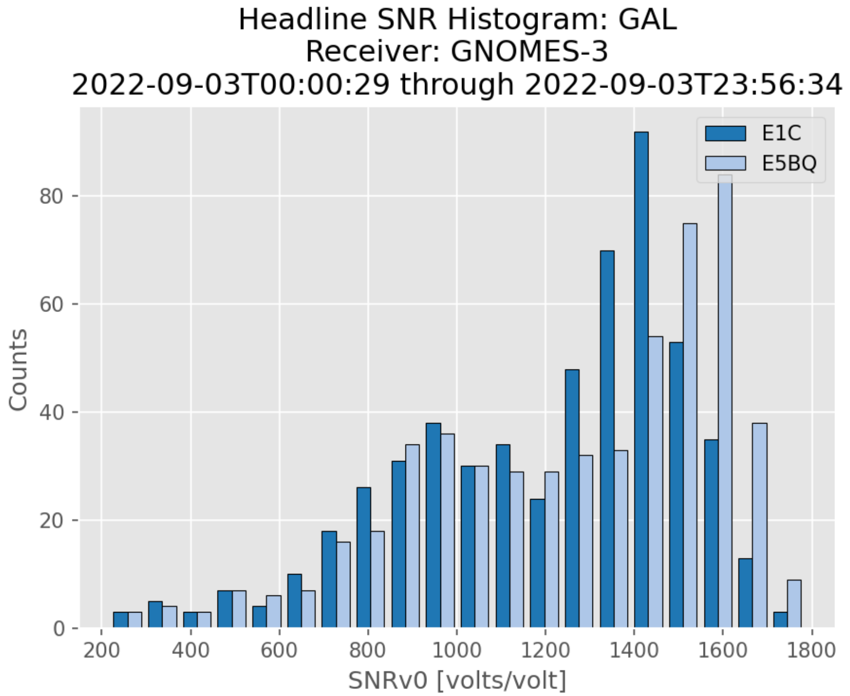

Headline SNR Histogram: GLO
Receiver: GNOMES-2
2022-09-04T00:03:13 through 2022-09-04T23:35:46
L1OF
L2OF
Counts
SNRv0 [volts/volt]

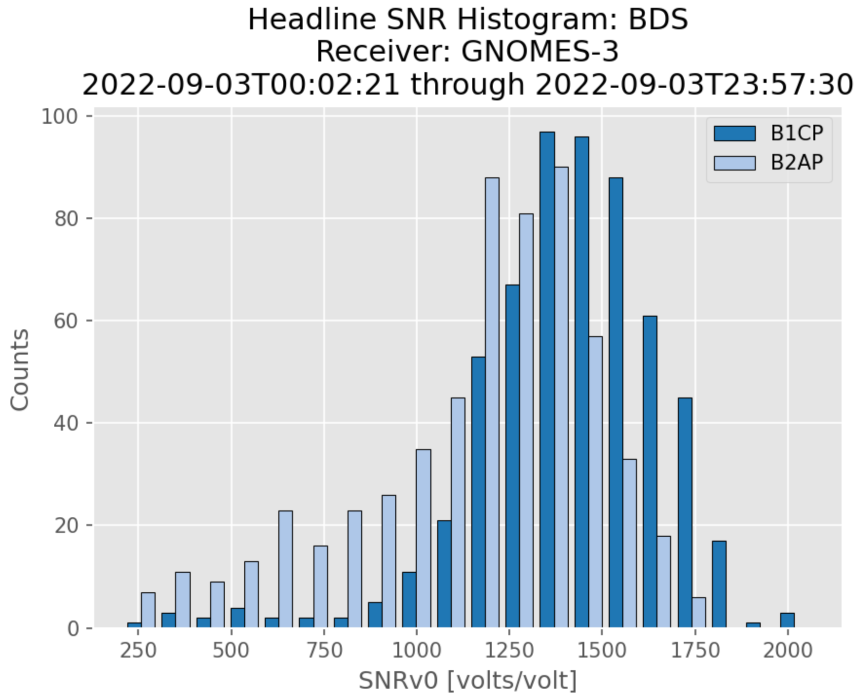

Headline SNR Histogram: GPS
Receiver: GNOMES-3
2022-09-03T00:05:40 through 2022-09-03T23:55:47
L1CA
L2CL
Counts
SNRv0 [volts/volt]


Headline SNR Histogram: GLO
Receiver: GNOMES-3
2022-09-03T00:02:33 through 2022-09-03T23:58:42
L1OF
L2OF
Counts
SNRv0 [volts/volt]


Headline SNR Histogram: GAL
Receiver: GNOMES-2
2022-09-04T00:01:30 through 2022-09-04T23:40:29
E1C
E5BQ
Counts
SNRv0 [volts/volt]


Headline SNR Histogram: BDS
Receiver: GNOMES-2
2022-09-04T00:05:13 through 2022-09-04T23:41:10
B1CP
B2AP
Counts
SNRv0 [volts/volt]


Headline SNR Histogram: GAL
Receiver: GNOMES-3
2022-09-03T00:00:29 through 2022-09-03T23:56:34
E1C
E5BQ
Counts
SNRv0 [volts/volt]


Headline SNR Histogram: BDS
Receiver: GNOMES-3
2022-09-03T00:02:21 through 2022-09-03T23:57:30
B1CP
B2AP
Counts
SNRv0 [volts/volt]

- Ho et al 2020
- Volz 2022 quoted 1514 v/v.

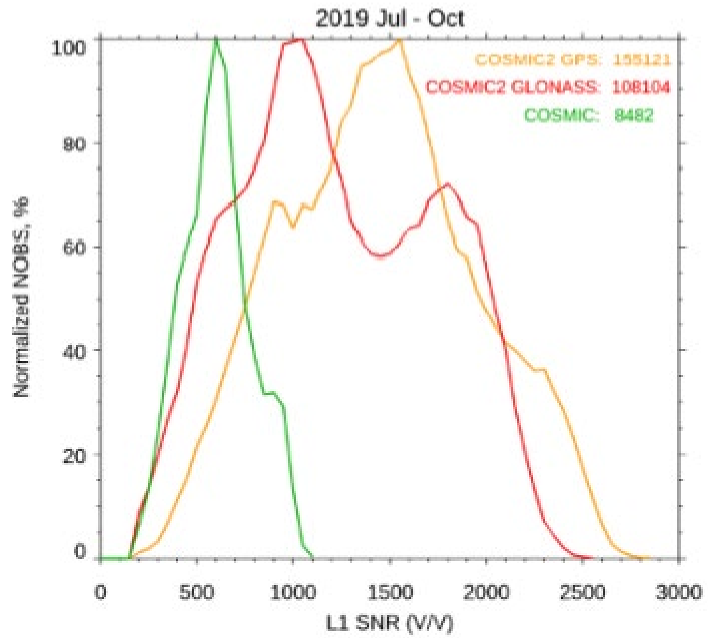
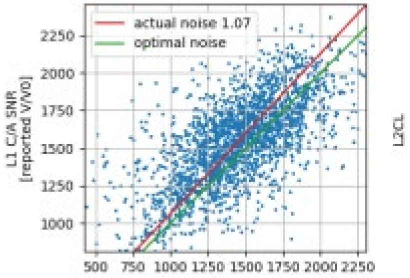
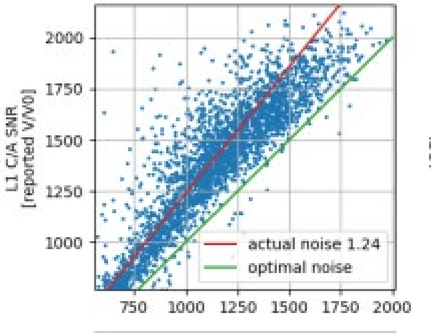


Figure 1. The histograms of the normalized accumulation (in %) L1 SNR for COSMIC (in green line), COSMIC-2 with GPS emitter (in orange line), and COSMIC-2 with GLONASS emitter (in red). The SNR is computed from the average SNR values from 60 km to 80 km geometric height range of the L1 signal. We normalized the lines to the maximum of the sample number of the SNR bin. The mean L1 SNR for COSMIC is equal to 700 *v/v*, where that for COSMIC-2/GLONASS samples and COSMIC-2/GPS samples are equal to 1100 *v/v* and 1250 *v/v*, respectively. All the data are collected from June to October 2019.

Comparison with COSMIC-2 SNRs

- c

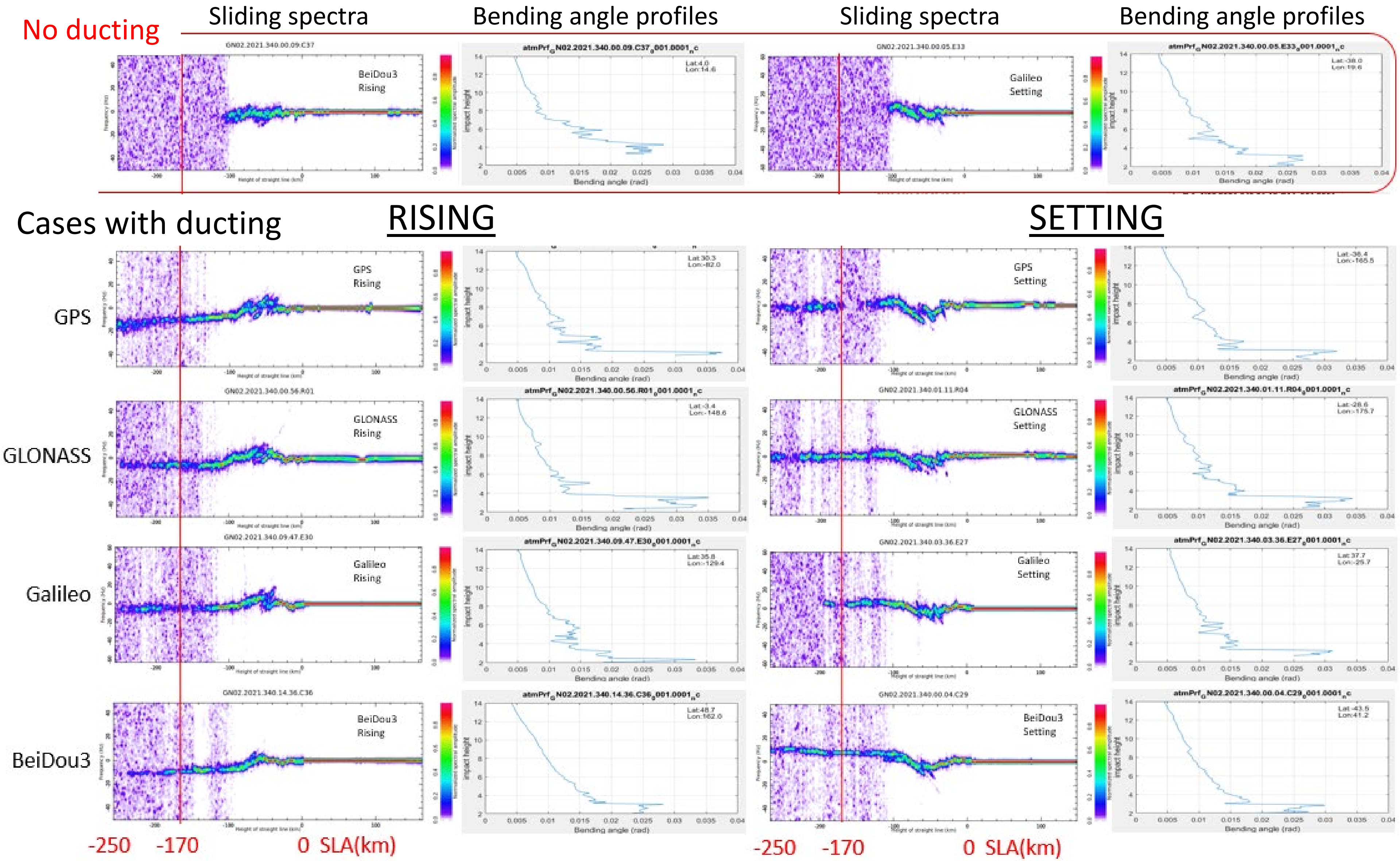




Super-refraction (SR) or Ducting

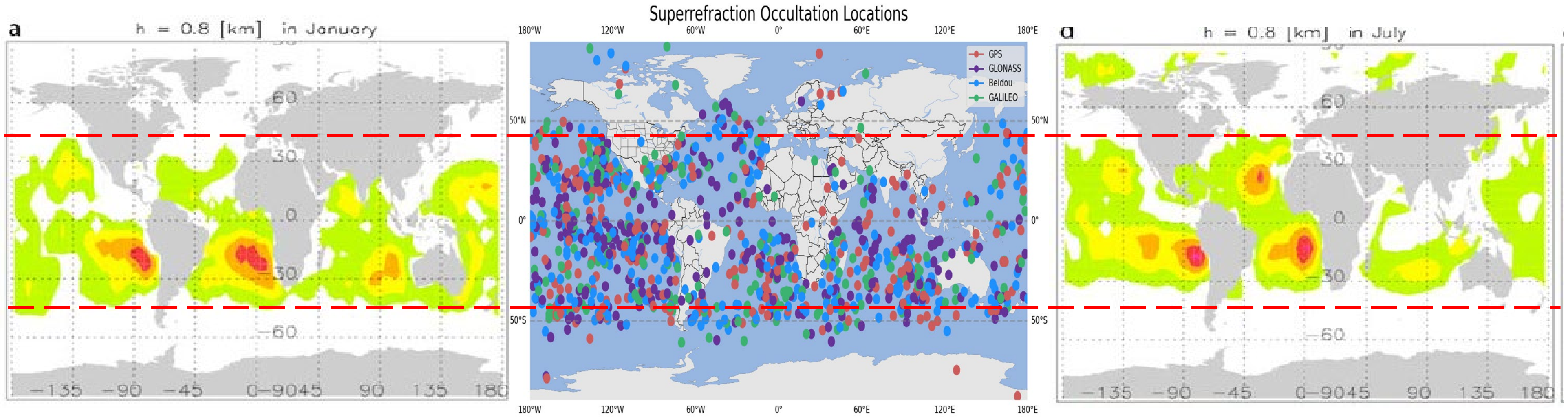
- Ducting: vertical gradient of refractivity is so large that the radius of curvature of the occultation ray path is less than the radius of the Earth.
- Occurs frequently at vertical transition between the free troposphere and planetary boundary layer (PBL), particularly over the oceans.
- Super-refraction causes a negative bias in the refractivity derived from RO bending angle profiles (Xie et al., 2006).
- Xie et al. 2006 retrieval approach derives refractivity from bending angles under SR conditions that greatly reduces or eliminates the bias.
- Using that method requires knowing whether or not SR is present in each profile.
- Sokolovskiy et al. (2014) showed that assessing each occultation to determine whether SR is present requires RO measurements made with very high SNR.
- We designed PlanetIQ's GNSS RO receiving system to produce a high percentage of SNRs of 2000 V/V comparable to or higher than COSMIC-2.

Detecting ducting in PlanetIQ occultations



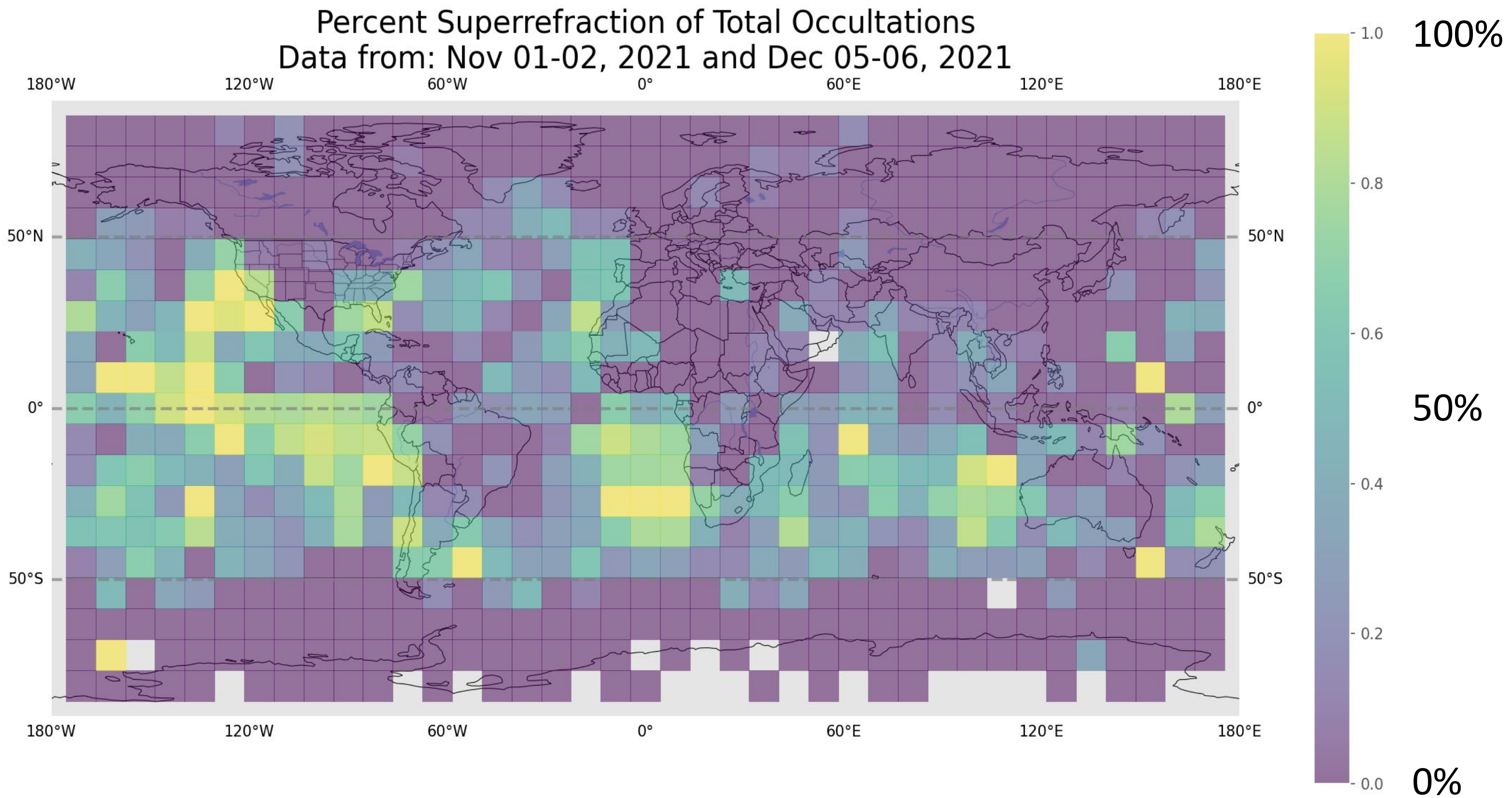
Detecting Super-refraction (SR) in PlanetIQ occultations

- Using the Sokolovskiy-based SR detection criteria of signal presence below -170 km straight line altitude (SLA), we identified PlanetIQ occultations containing SR.
- Center figure shows occultations with SR from four days: Nov 1-2 and Dec 5-6, 2021.
- For comparison, left and right figures from Xie et al. 2010 show regions of ducting based on COSMIC negative biases relative to ECWMF for Jan. and July respectively.
- 23% of all PlanetIQ occultations contain SR, including 46% between 30°S and 45°S.
- SR apparently seldomly occurs over land,
- The regions where SR is present are generally consistent with the Xie et al. (2010) results, with the exception that SR extends over a wider range of latitudes.

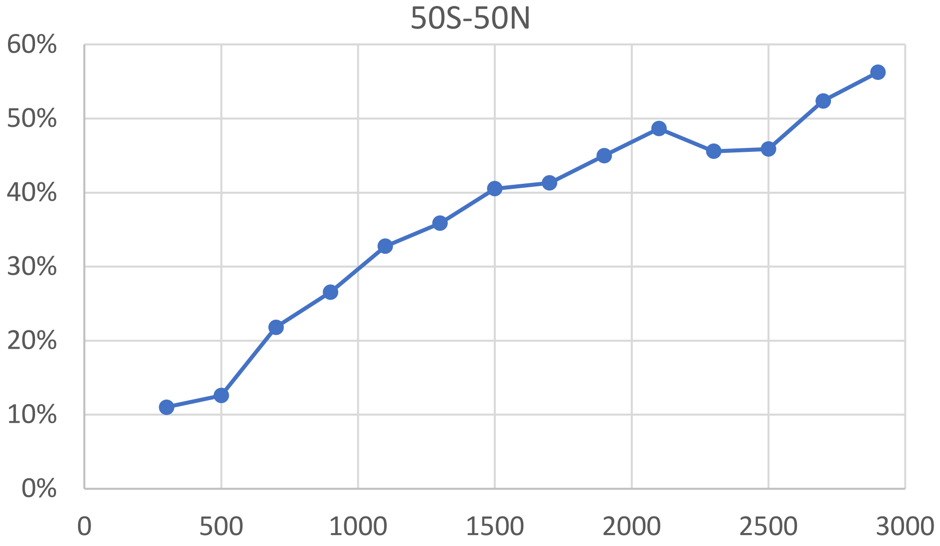


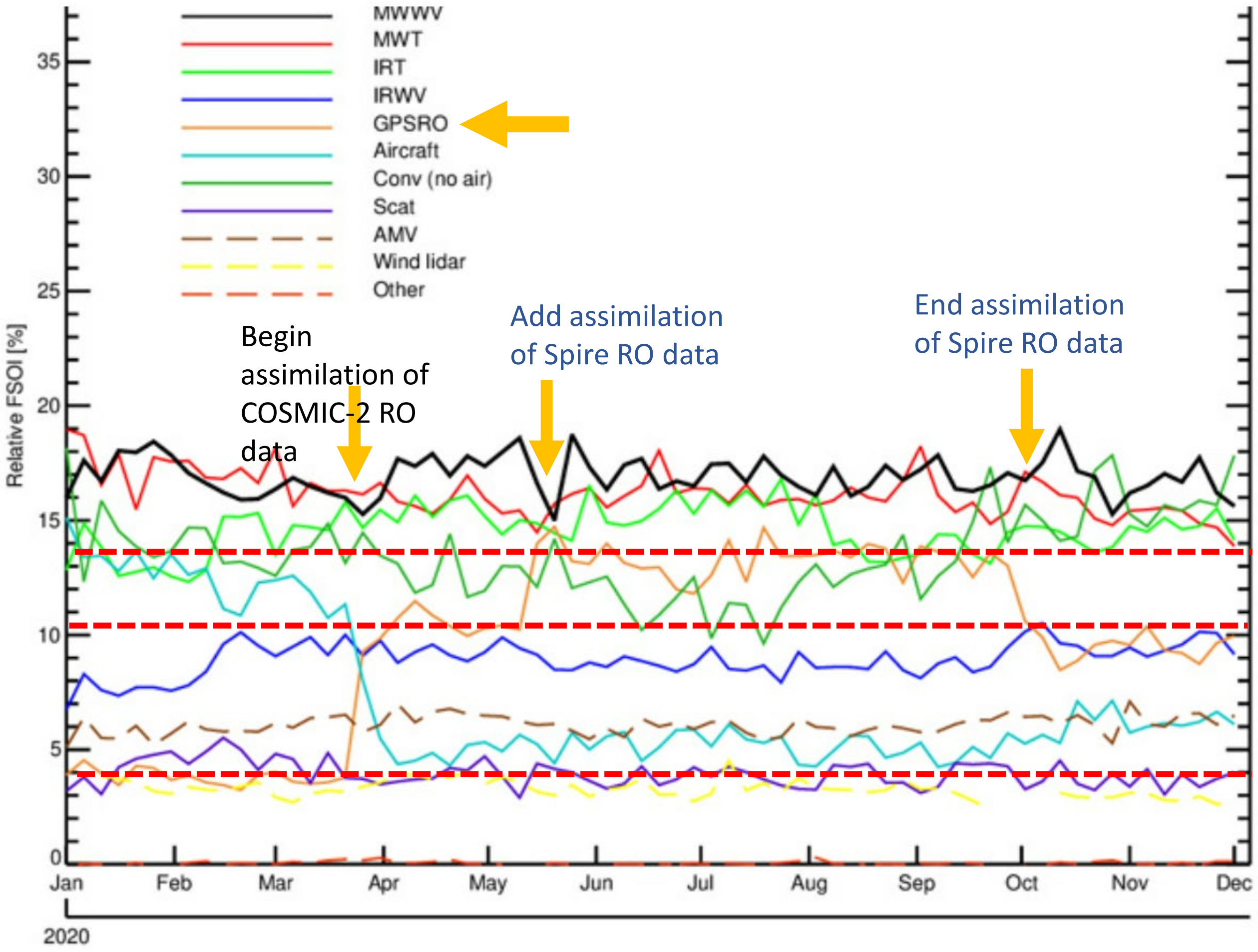
Frequency of SR

- Preliminary % of PlanetIQ occultations containing SR vs location
- Clearly higher over oceans and off west coasts of continents
- Need to automate this to obtain a larger sample



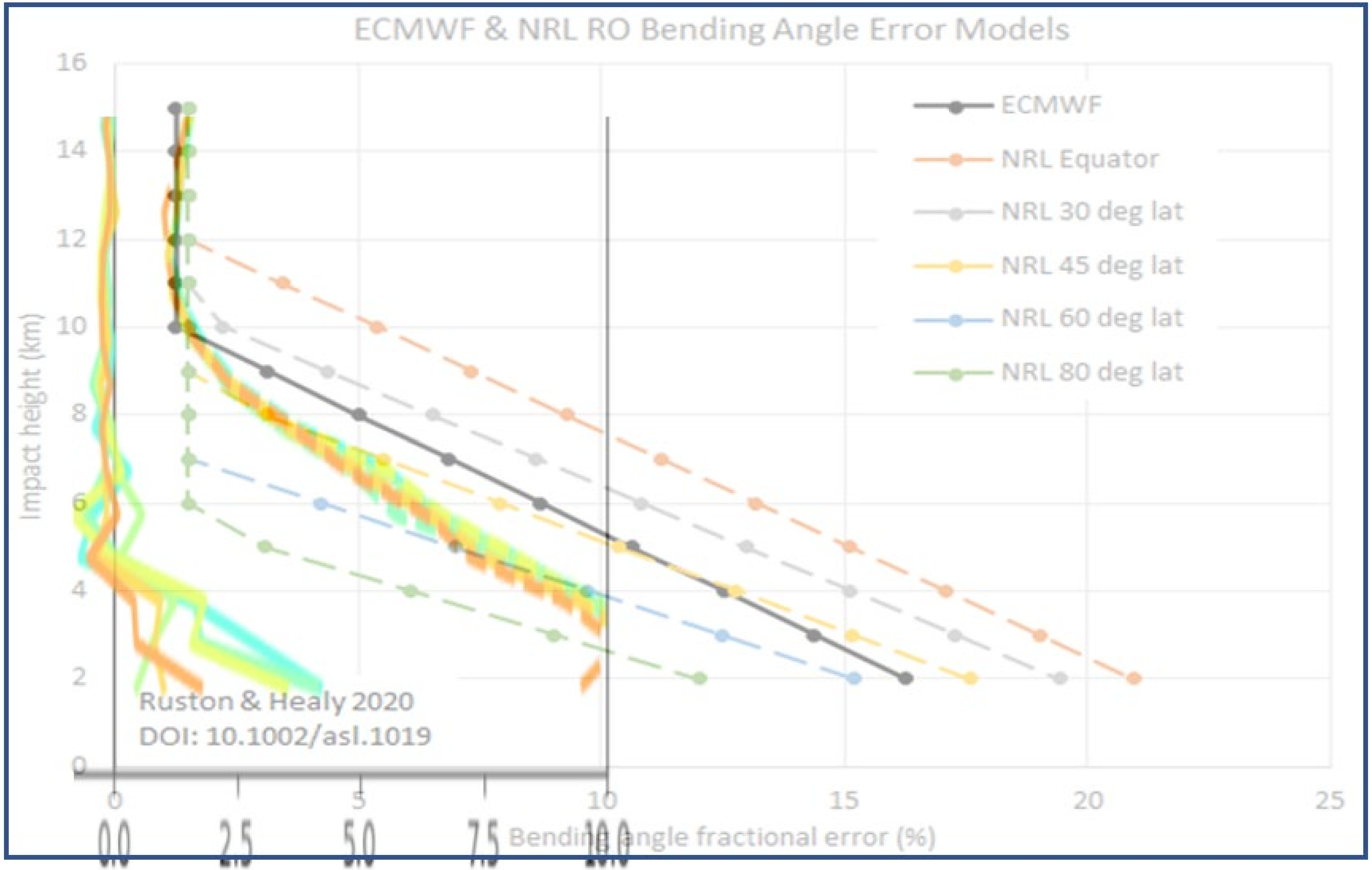
- V





Sean Healy (ECMWF) noted that with 11,000 RO being assimilated, RO is approaching being the most impactful data set

- 1/(16/10)^2= 40% of weight
- 1/(21/10)^2= 21% of weight



Summary

- GNOMES-2 is routinely producing 1200 globally distributed QC'd neutral occultations which look good
- GNOMES-3 coming in April => 3800 daily neutral occultations combined from GNOMES-2 and 3
- This will increase to 4500 as BDS2 + QZSS are added, comparable to COSMIC-2 but with global distribution
- Developing 20 sat constellation => 60K occ/day in 3 years
- SR occurs frequently over the oceans up to 60^{o} latitude as well as over the Arctic ocean
- Making full use of the unique high SNR RO information in the lowermost troposphere requires (1) automated detection of SR and (2) new NWP Forward operator that accounts for SR

- We are making our data available for evaluation
- We are working to establish a European presence expected in 3 months enabling us to sell to EUMETSAT

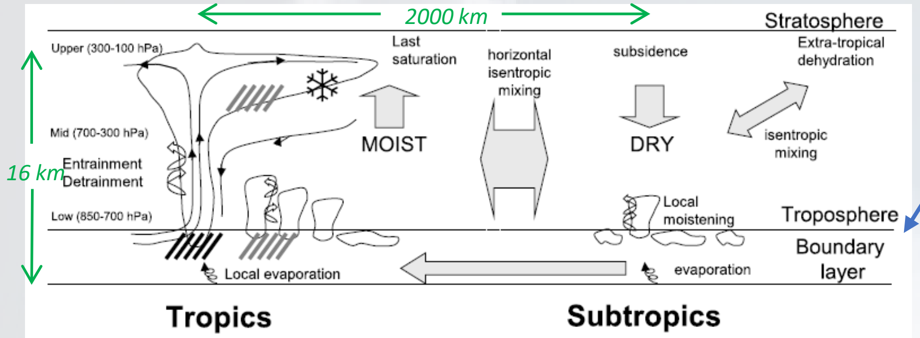
Thank you and any questions?

rkursinski@planetiq.com

Additional slides

Quality – the Super-refraction Challenge

Routine profiling to the surface requires very high SNR

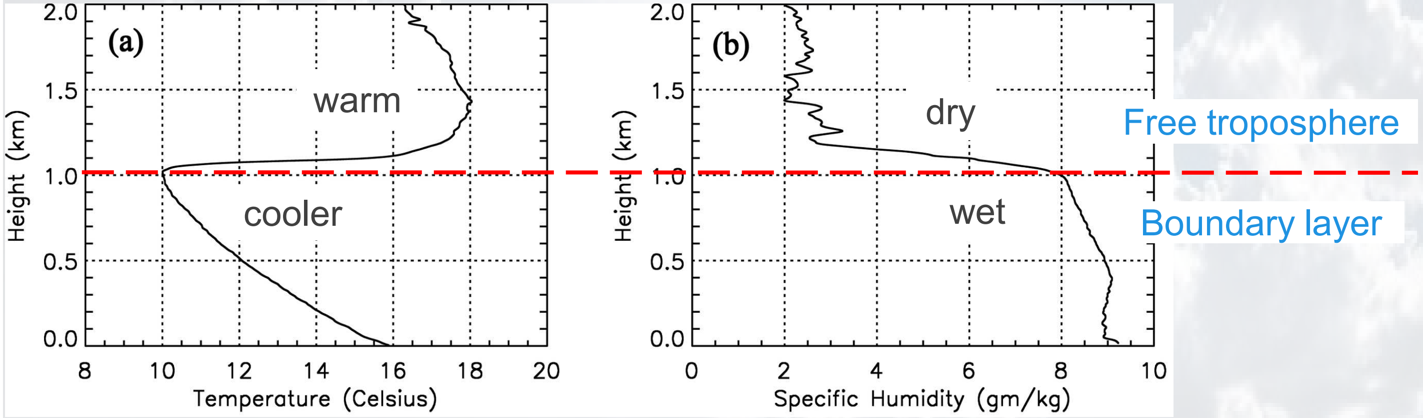


Super-refraction:
Very large refractivity gradients occur at transition between dry free troposphere & wet boundary layer.

- Causes radius of curvature of ray path bending to become smaller than radius of Earth.

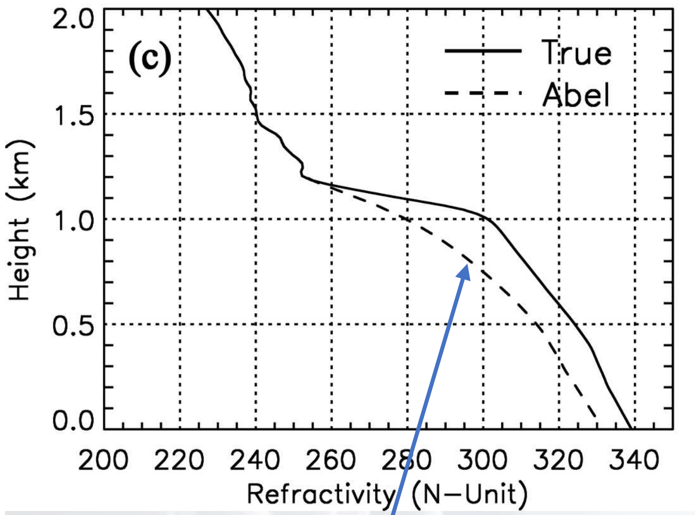
⇒ Systematic underestimate of refractivity.

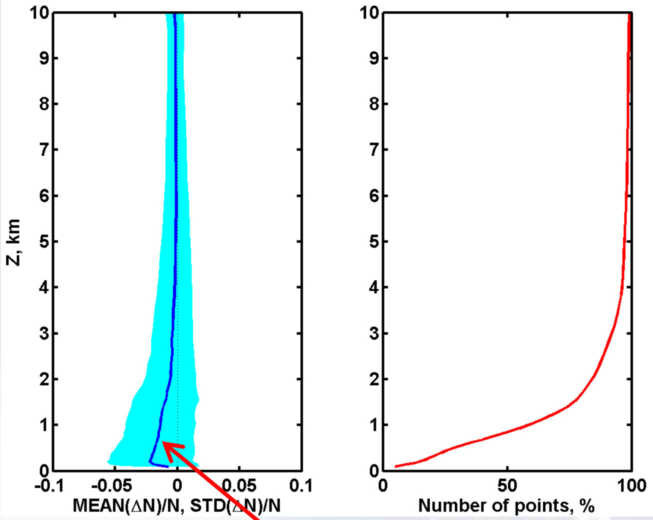
⇒ **NWP centers don't use RO data in lowermost troposphere**



PlanetiQ

Quality - Super-refraction Challenge





Systematic underestimate of refractivity results when the standard “Abel” retrieval is used in the presence of Super-Refraction

- Systematically underestimated refractivity assimilation would cause underestimate of severe weather. *Very bad*!!
- To avoid this, NWP centers simply don’t assimilate RO data in lowermost troposphere

Two-part solution:

1. We developed a retrieval method that correctly accounts for effects of super-refraction
2. We need to know when SR is occurring which requires very high SNR.