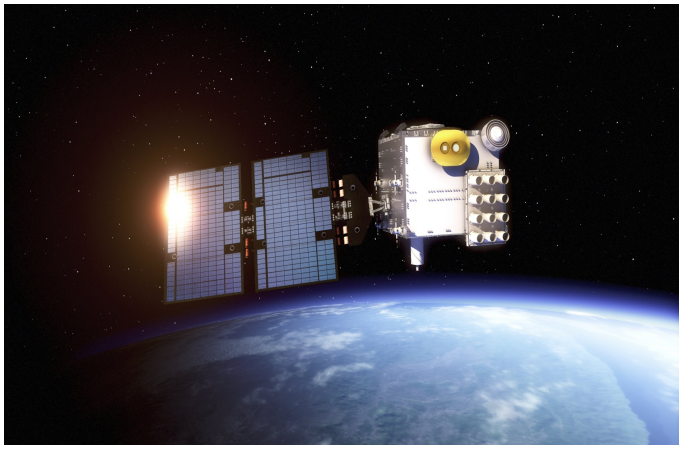


Performance Assessment and Requirement Verification of COSMIC-2 Neutral Atmospheric Radio Occultation Data

Bill Schreiner, Sergey Sokolovskiy, Jan Weiss, John Braun, Richard Anthes, Ying-Hwa (Bill) Kuo, Doug Hunt, Zhen Zeng, Tae-Kwon Wee, Teresa VanHove, Jeremiah Sjoberg, Hannah Huelsing

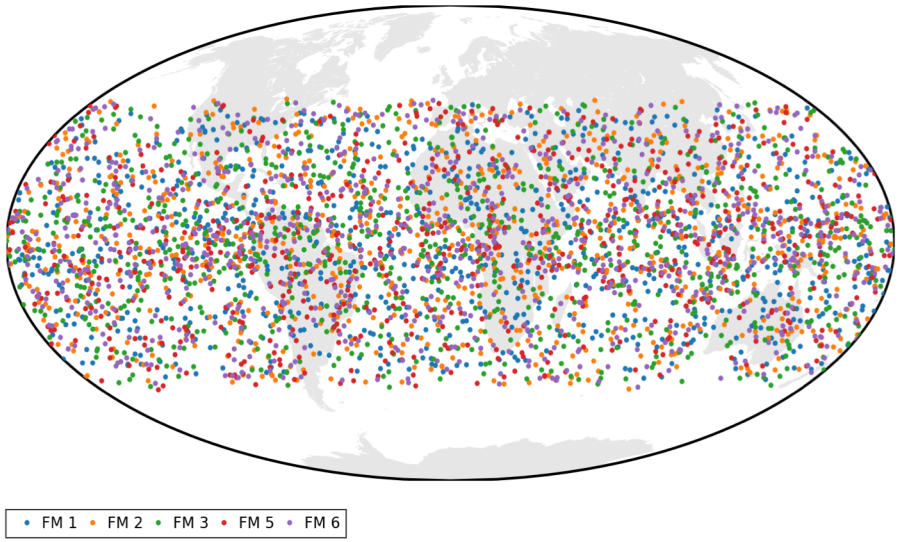
UCAR COSMIC Program

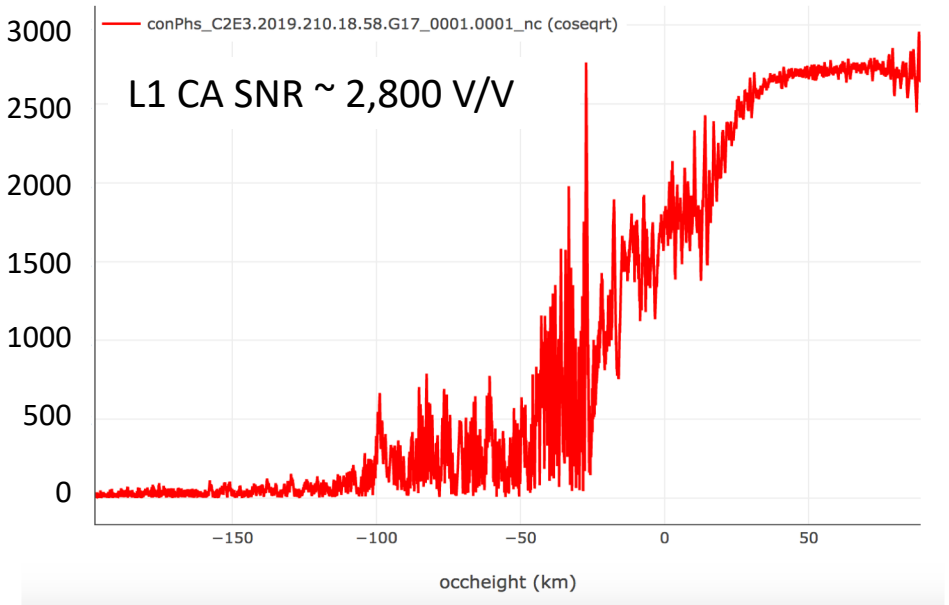
ROMSAF/IROWG-7
Helsingør, Denmark
Sept 19, 2019

Outline

- Overview COSMIC-2 CAL/VAL Plan
- Count and QC performance
- Bending angle performance
  - High altitude BA noise
  - Co-planar collocations
  - Inter-RO (C2 – Metop/K5)
- Refractivity performance
- Tropospheric duct detection
- Conclusions

COSMIC-2 on Aug 22, 2019 – 4,115 profiles





COSMIC-2 GNSS RO CAL/VAL Plan

- Evaluate payload data quality and certify EDR products for use by the community
- COSMIC-2 level-1 requirements (right) specified with COSMIC-1 collocation statistics + margin
- Requirements being verified with combination of COSMIC-2 collocations and comparisons with other observations and models
- COSMIC-2 CAL/VAL team
  - UCAR
  - JCSDA
  - NOAA/NCEP, NOAA/OSPO
  - NOAA/STAR, NOAA/ESRL
  - Taiwan's NSPO and CWB

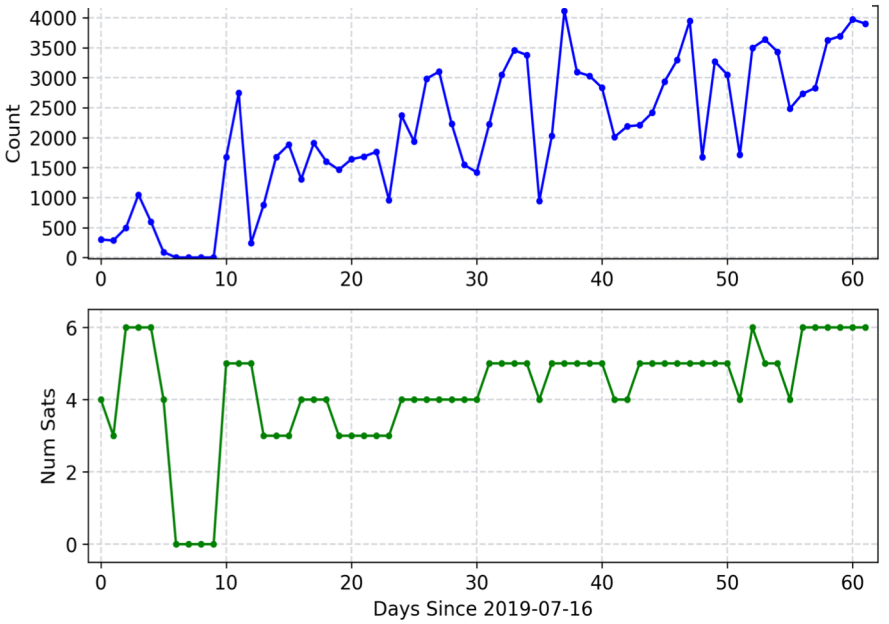
Threshold Requirement Description	Altitude Range [km]	Req't Value
Quality-Controlled Profile Count		4,000/day
Quality Control %		73
Bending angle profile measurement uncertainty [µrad]	0 – 5 km	1,700
	5 – 10 km	300
	10 – 20 km	20
	20 – 30 km	4
	30 – 60 km	2
Refractivity profile measurement uncertainty [N units]	0 – 5 km	3
	5 – 10 km	0.7
	10 – 20 km	0.1
	20 – 30 km	0.03
Dry Temperature profile measurement uncertainty [K]	10 – 30 km	1
Tropospheric duct height (Objective)	0.5 – 5 km	100 m

Number of Profiles per day

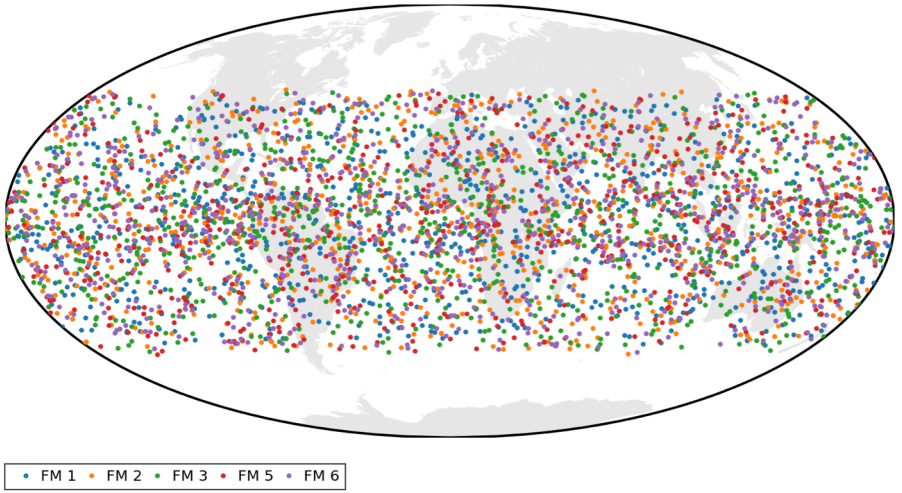
- Requirements:
  - Average Number of Quality-Controlled Profiles per day >= 4,000
  - QC % >= 73%
- To date (2019.198-259) 130,550 QC'd profiles collected
- Average QC Success rate ~ 72 %
- Average QC Success rate last week (2019.253-259)
  - All FMs ~ 73.5%
  - FM1 (v4.3.2) ~ 86% (with L2P rising)
- With 90% QC, COSMIC-2 could approach 6,000 QC'd profiles per day

COSMIC-2 has met count requirement on Aug 22, 2019 with 4,115 occultations, and is currently meeting QC % requirement

COSMIC-2 Daily Occultation Count

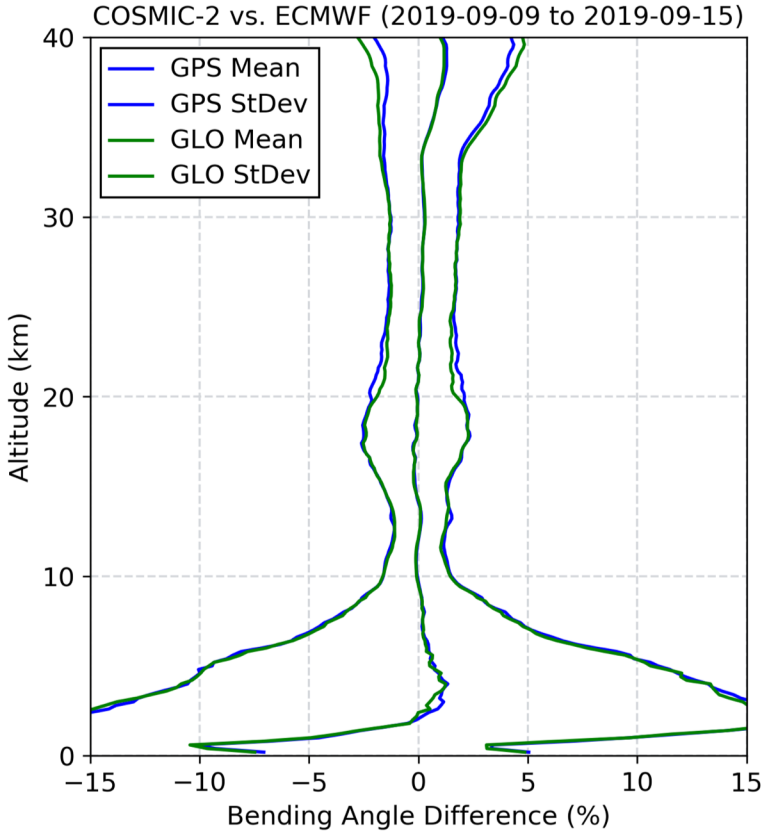


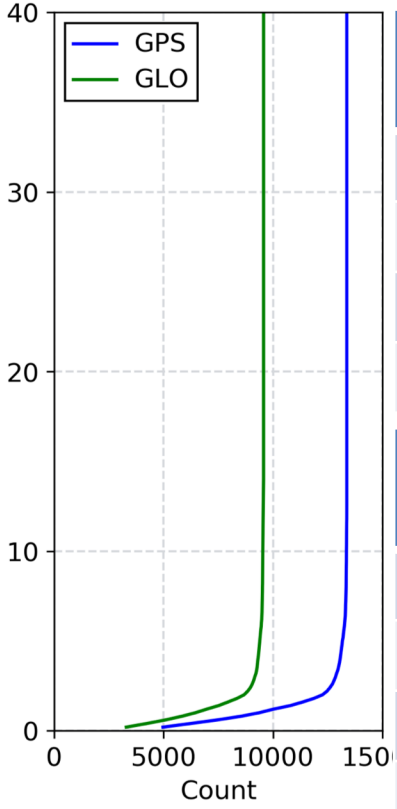
COSMIC-2 on Aug 22, 2019 – 4,115 profiles



Bending Angle Comparison to ECMWF

- GPS, GLONASS data separately for recent week
  - Results very similar for both GNSS





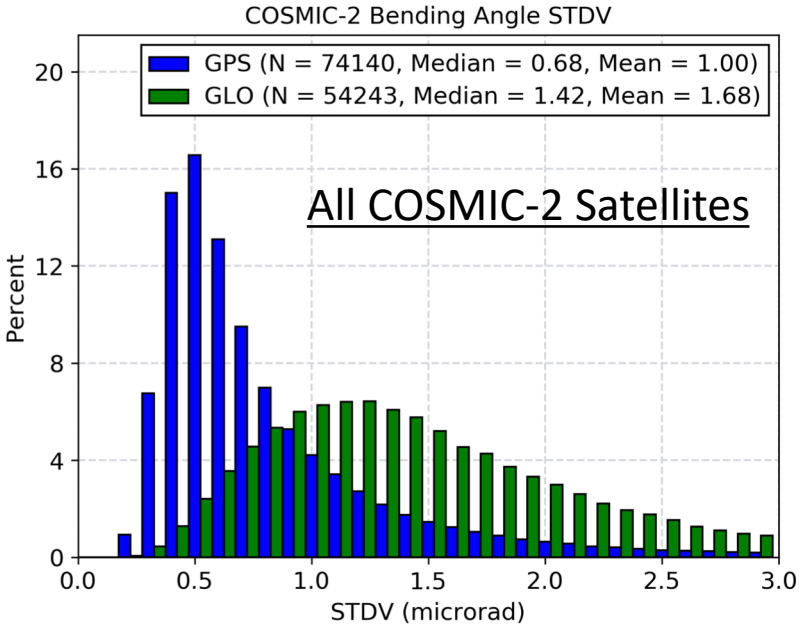
Altitude (km)	Avg Mean GPS (%)	Avg Std Dev GPS (%)
0 - 10	-0.5	9.4
10 - 20	-0.1	1.7
20 - 30	0.1	1.7
30 - 40	0.6	2.2

Altitude (km)	Avg Mean GLO (%)	Avg Std Dev GLO (%)
0 - 10	-0.7	9.4
10 - 20	-0.1	1.7
20 - 30	0.1	1.5
30 - 40	0.6	2.4

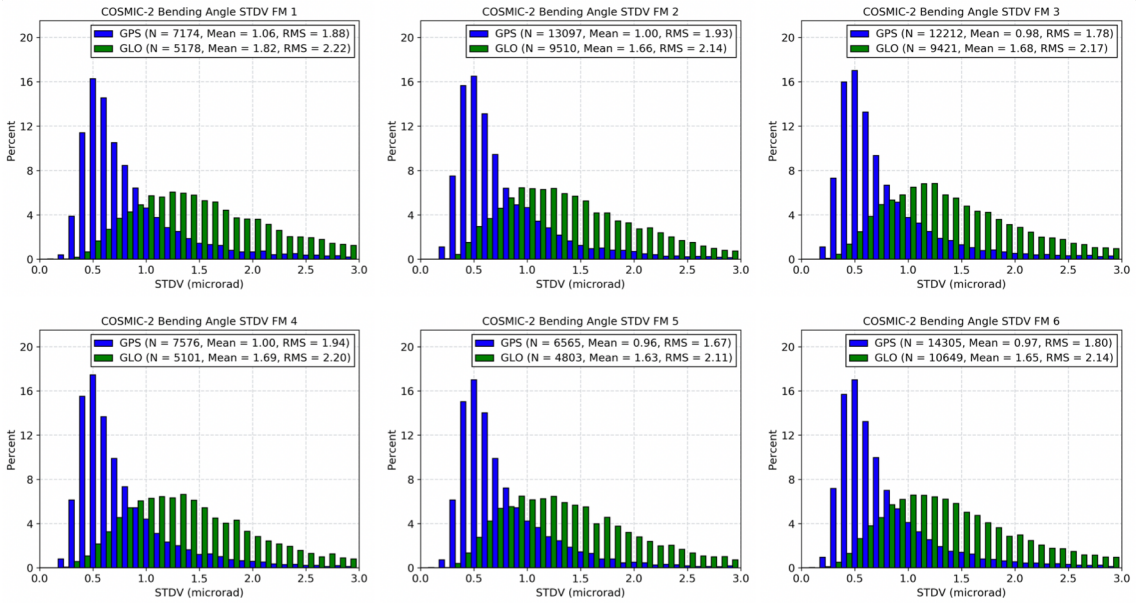
COSMIC-2 data agree with ECMWF as expected without any significant biases

High Altitude Bending Angle Uncertainty

- STDV is the standard deviation of the difference between climatological bending angle and RO bending angle between 60-80km
- This altitude range is chosen to avoid most atmospheric and ionospheric effects to measure the inherent noise of the RO data



Each of the Six COSMIC-2 Satellites

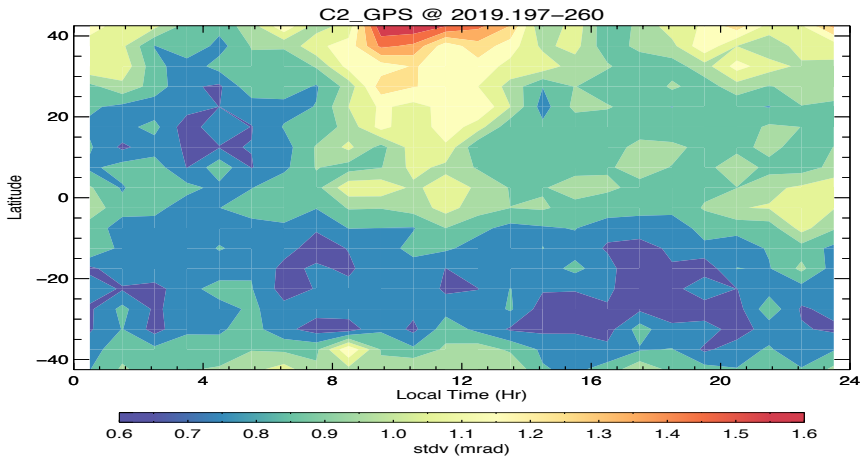


COSMIC-2 meets 2.0 µrad requirement for high altitude bending angle uncertainty for each satellite.

Courtesy: Jan Weiss

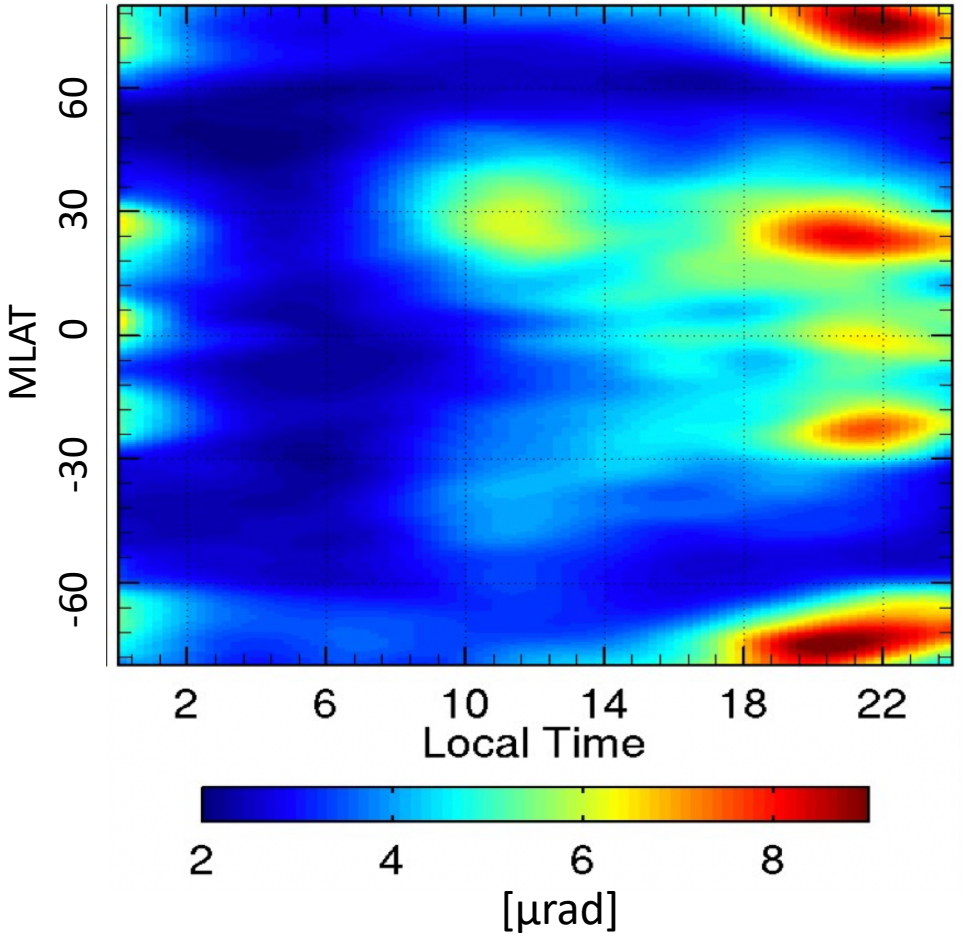
STDV variation with latitude and local time

COSMIC-2 STDV vs. LAT and LT



Only C2_GPS samples with stdv < 5 mrad are included herein

COSMIC-1 STDV vs MLAT and LT (Yue et al., 2015)



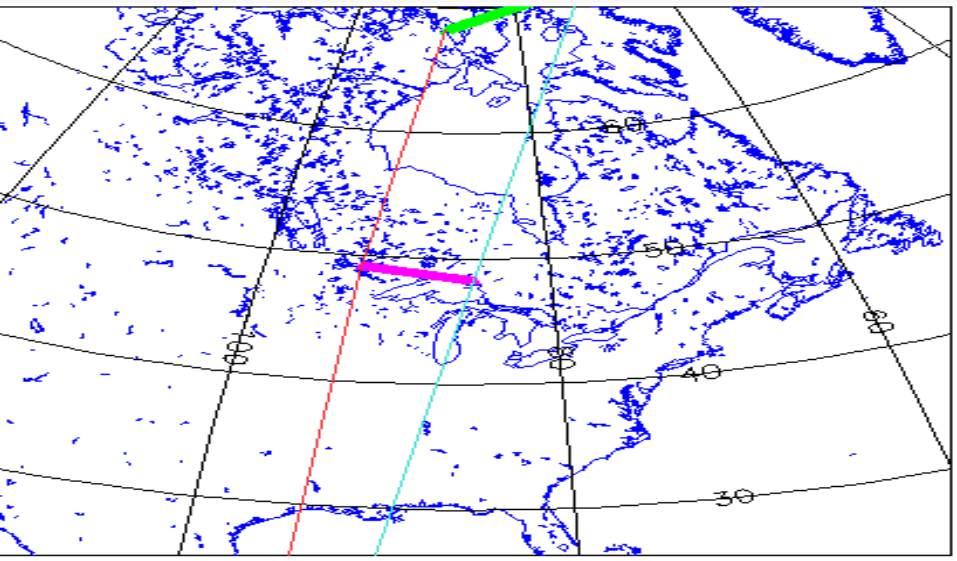
COSMIC-1 and COSMIC-2 STDV see similar latitude and local time dependence

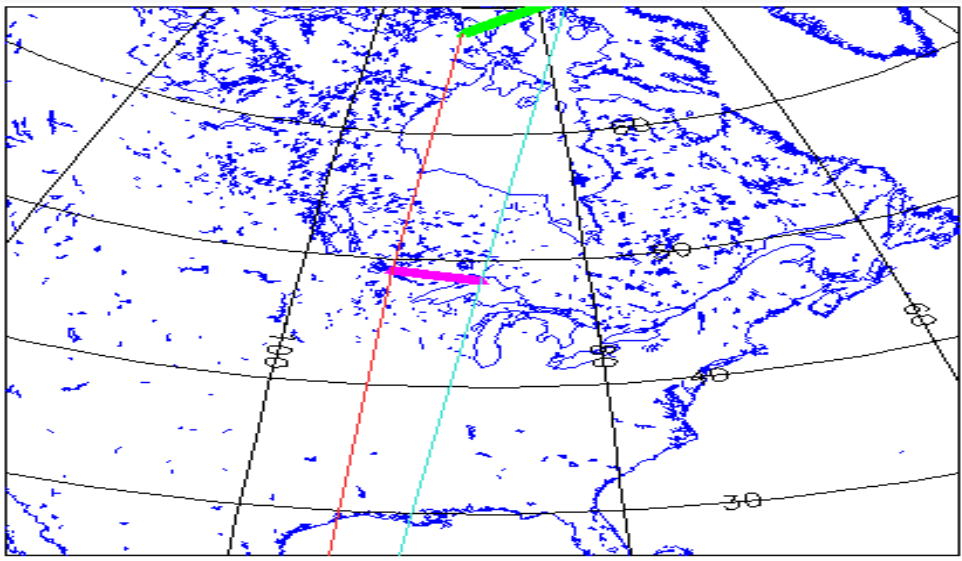
Courtesy: Z. Zeng

Precision from COSMIC-2 Collocations

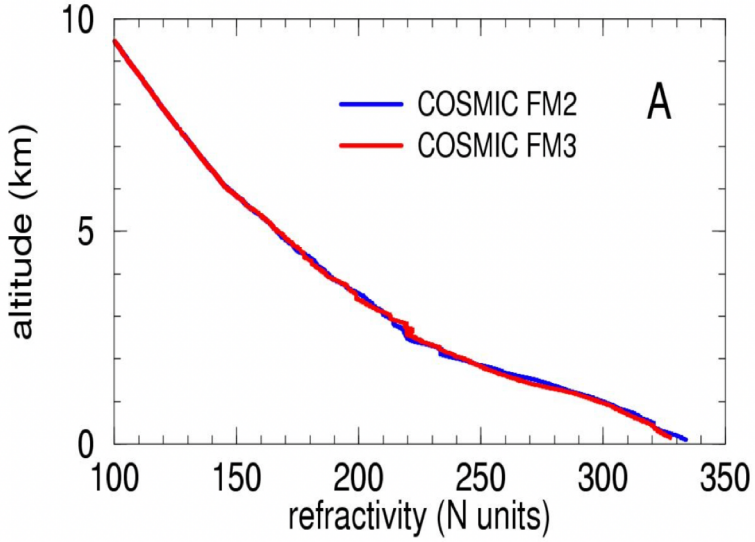
- The following results were computed from COSMIC-2 data at the UCAR CDAAC
- Date range = 2019.197-247
- Rising and Setting
- GPS and GLONASS
- L2C and L2P (setting only, rising marked bad)
- Non-beam forming
- Ionospheric extrapolation height of 20 km
- Only atmPrf GOOD profiles
- Found collocated matches
  - ~40 pairs for 10 km TPs
  - ~280 pairs with 20 km TP separation used for this analysis

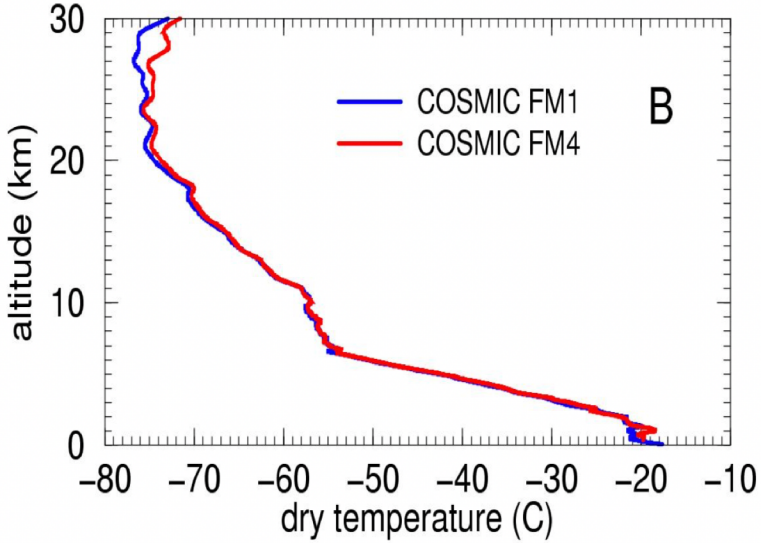
Co-Planar Collocated Occultations





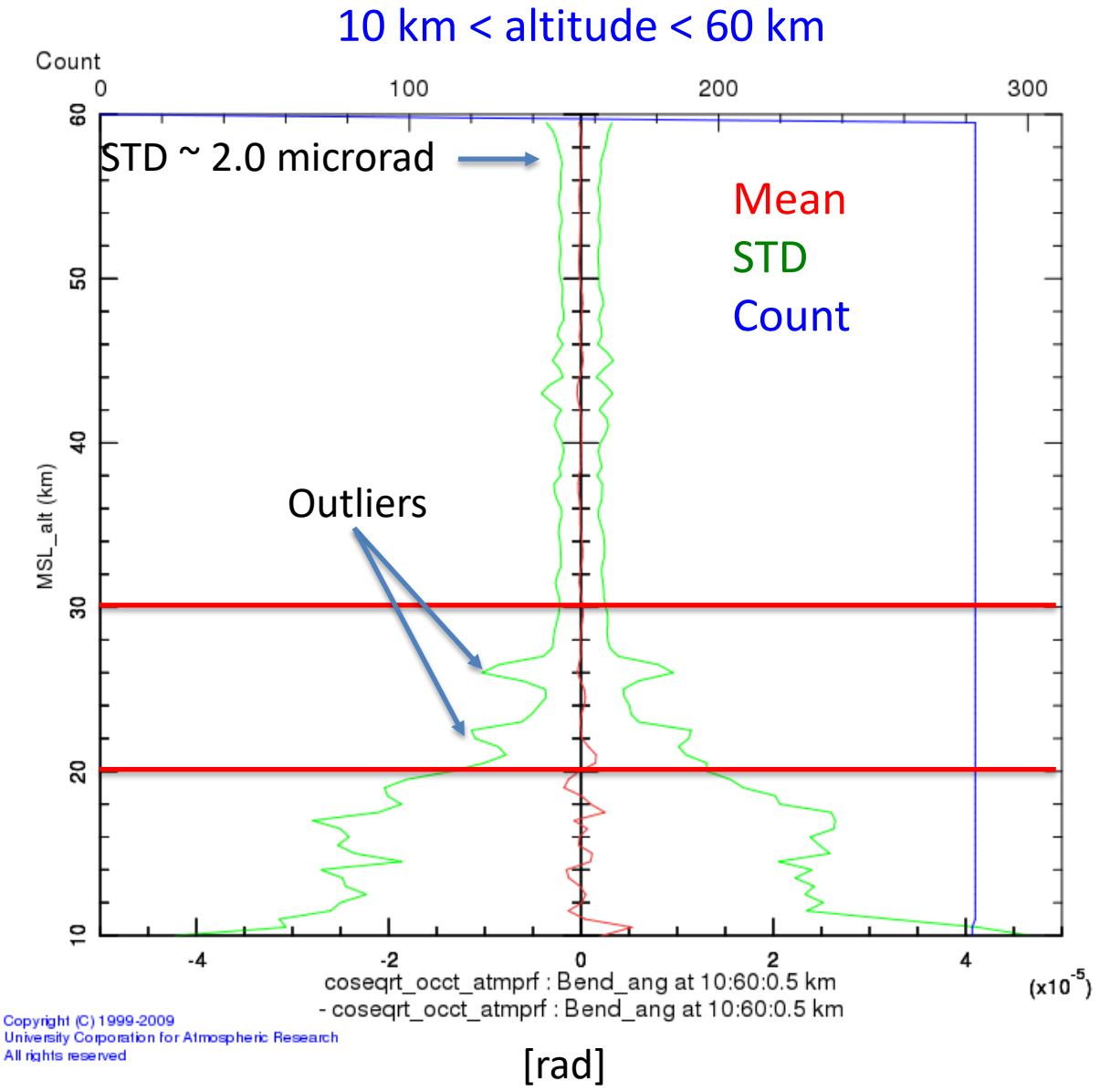
Ray path at end of occultation
LEO satellite sub-point
Ray path at start of occultation
Ray path periqee sub-point





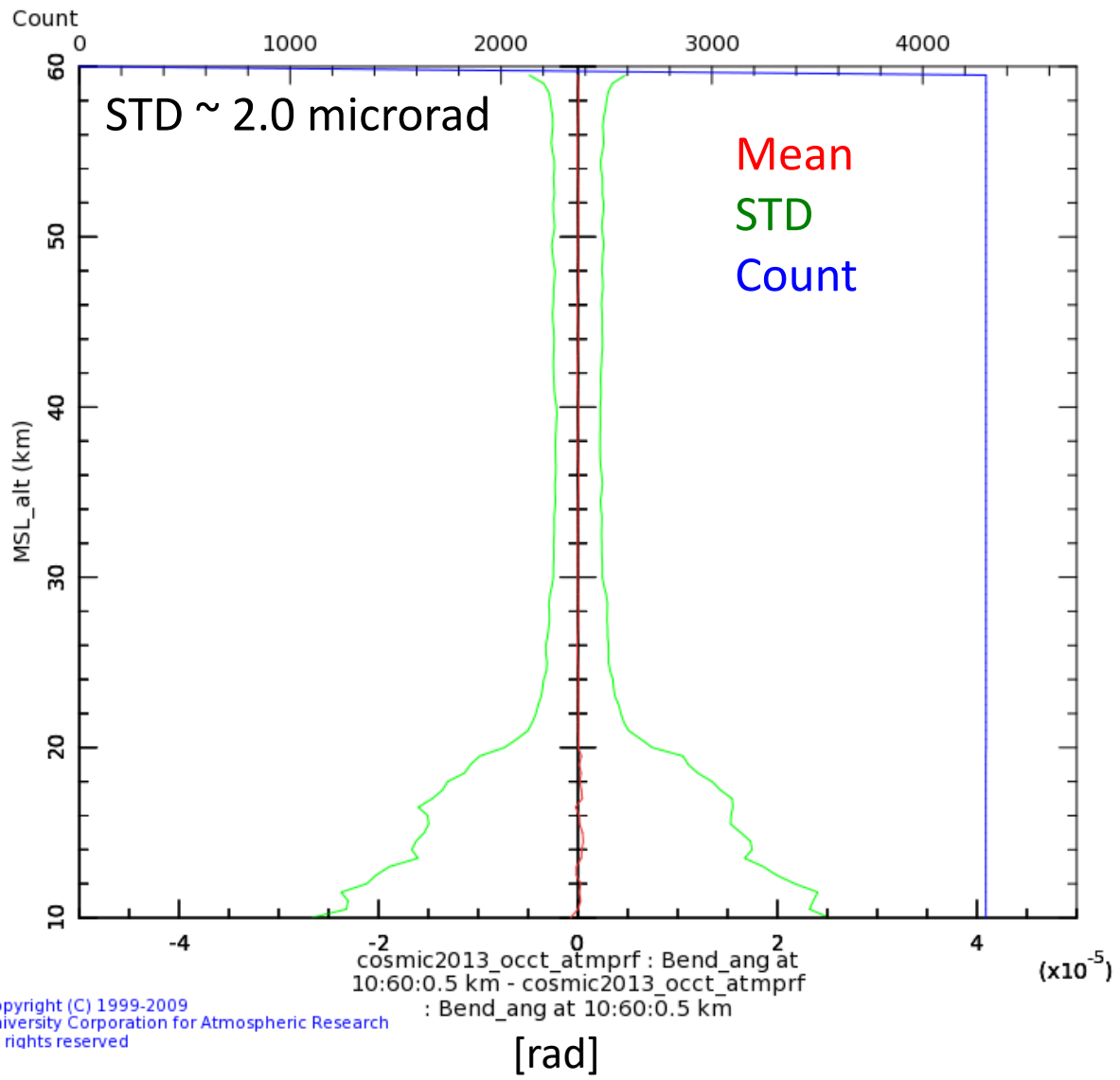
COSMIC-2 BA Collocation Stats

- Statistical comparison of collocated COSMIC-2 soundings with horizontal separations of the estimated tangent points < 20 km
- 2019.197-247
- GPS and GLONASS
- Only quality-controlled profiles used



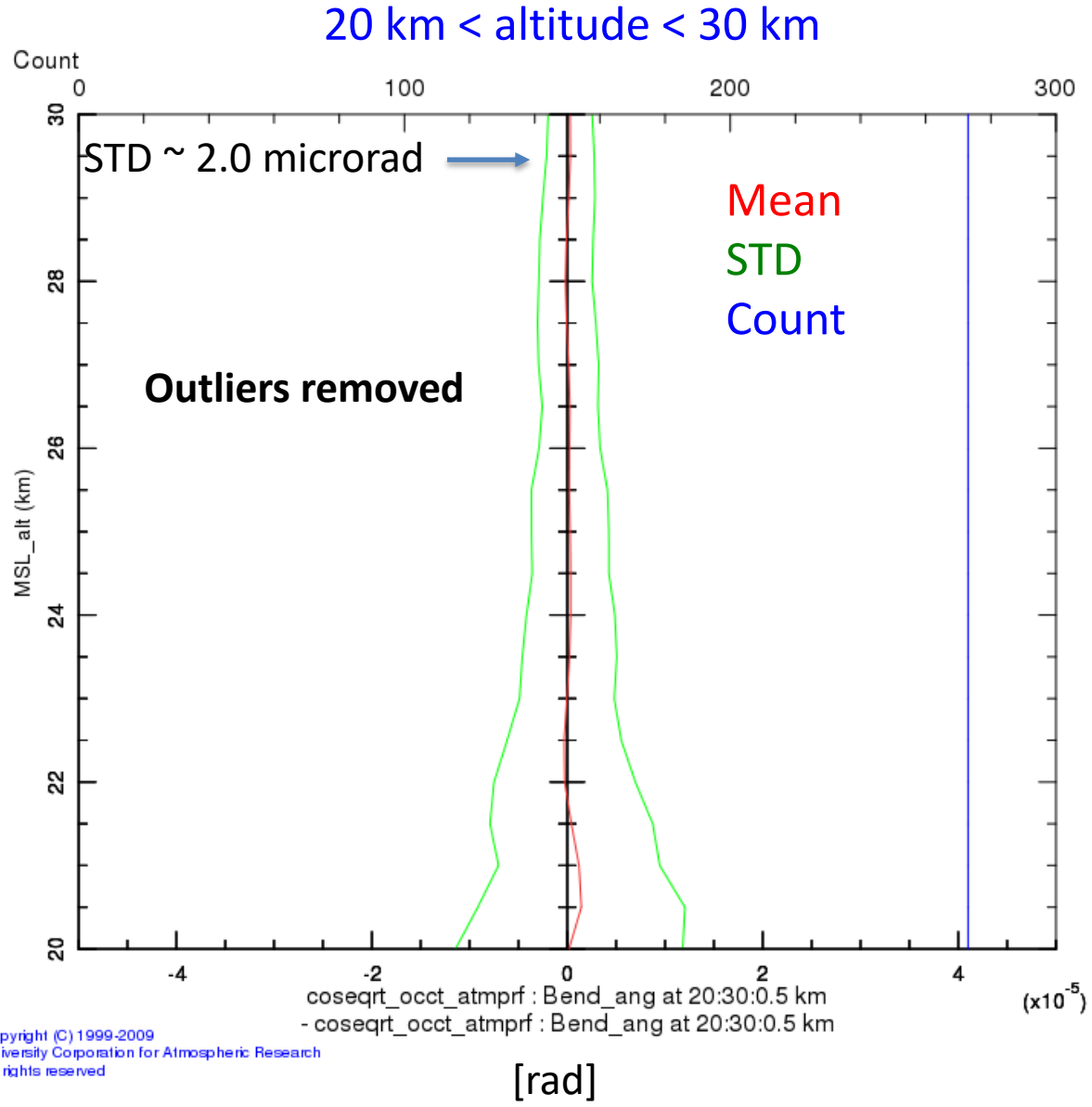
COSMIC-1 BA Collocation Stats

- Global statistical comparison of collocated COSMIC-1 soundings with horizontal separations of the estimated tangent points < 10 km
- 2006.200-365
- FM3-FM4 pairs
- Only quality-controlled profiles used



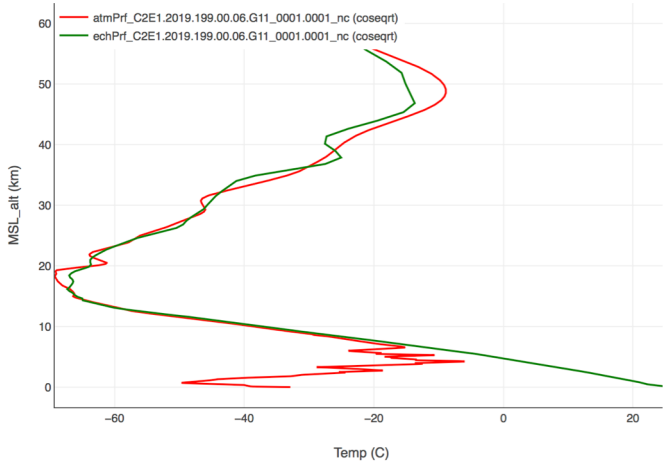
COSMIC-2 BA Collocation Stats

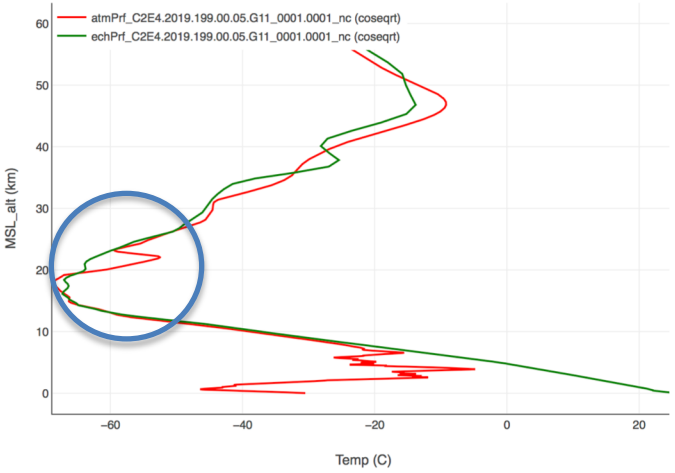
- Global statistical comparison of collocated COSMIC-2 soundings with horizontal separations of the estimated tangent points < 20 km
- 2019.197-247
- GPS and GLONASS
- Only quality-controlled profiles used



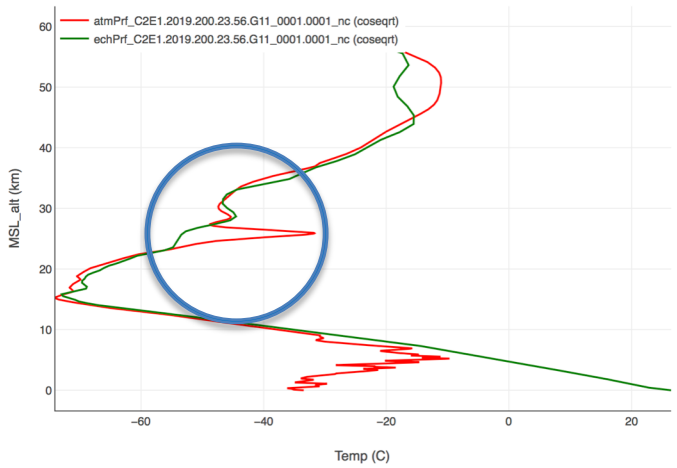
COSMIC-2 GPS L2P Outliers

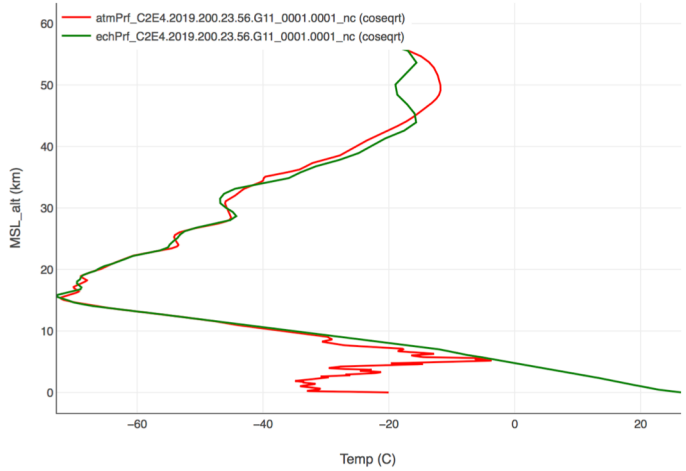
Outlier pair 1





Outlier pair 2

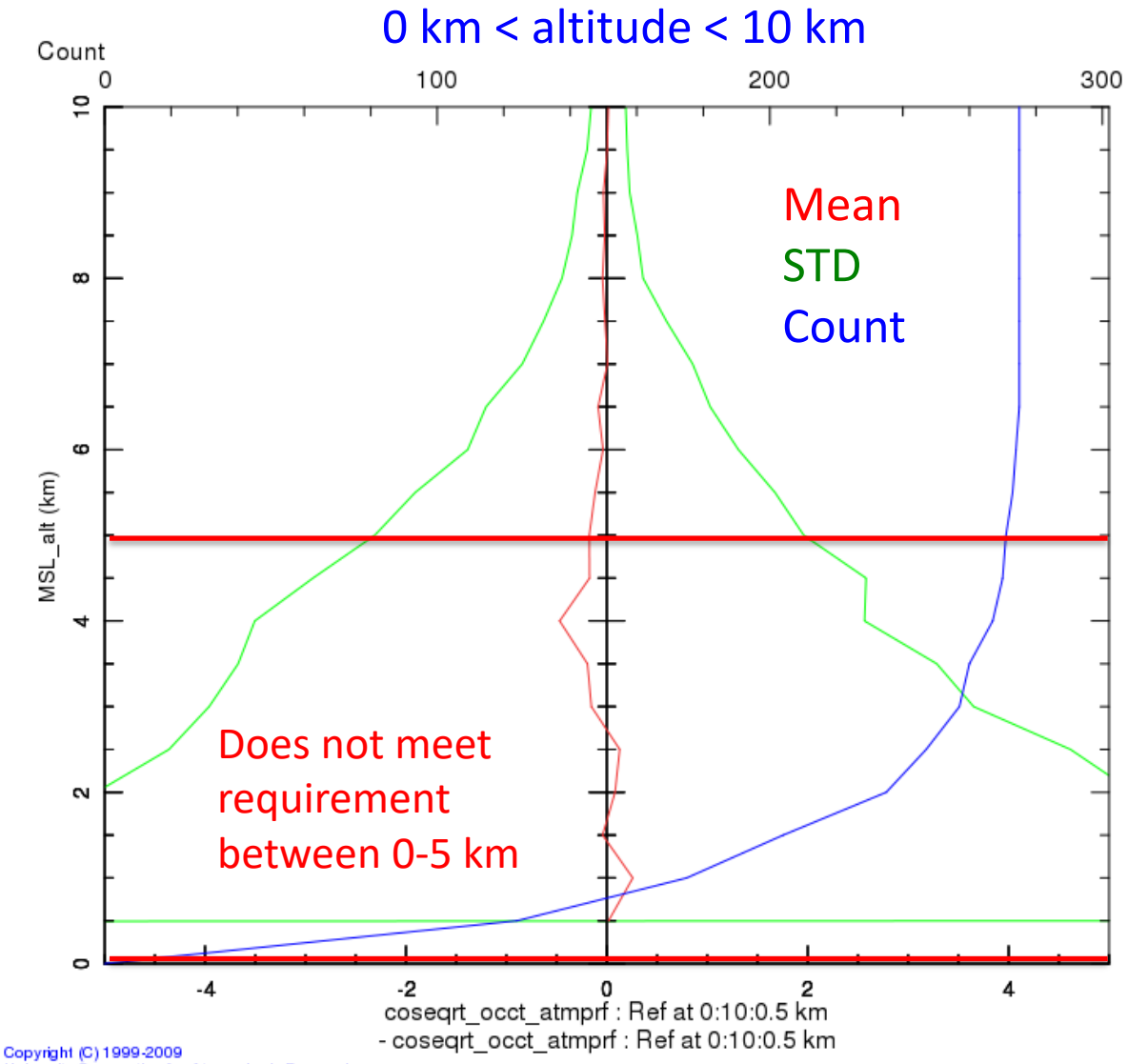




Two COSMIC-2 outliers passed QC. Further investigation needed.

COSMIC-2 N Collocation Stats

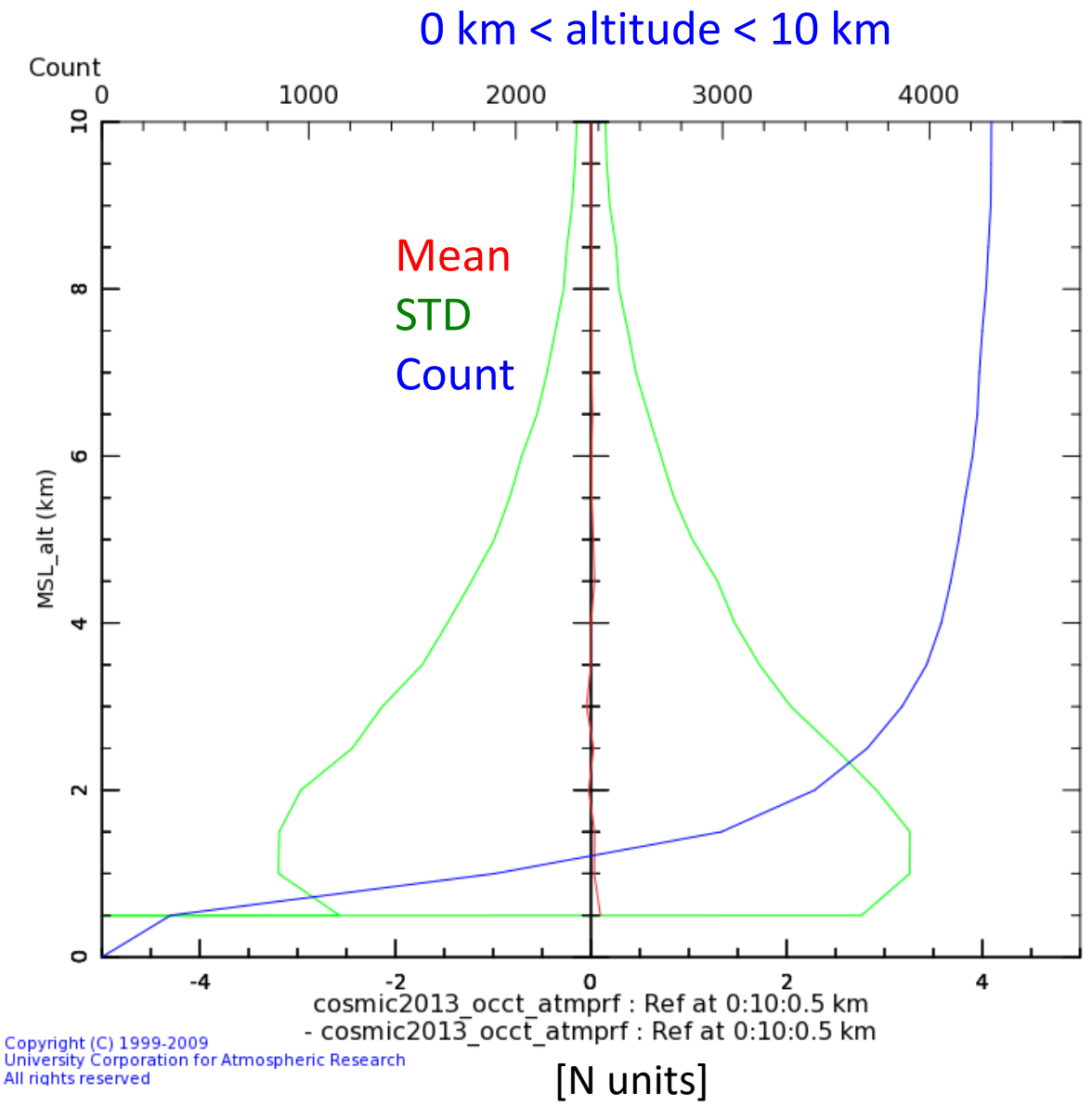
- Global statistical comparison of collocated COSMIC-2 soundings with horizontal separations of the estimated tangent points < 20 km
- 2019.197-247
- GPS and GLONASS
- Only quality-controlled profiles used



[N units]

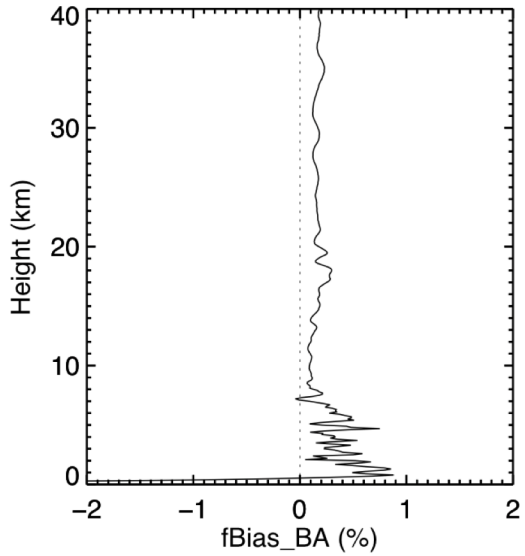
COSMIC-1 N Collocated Statistics

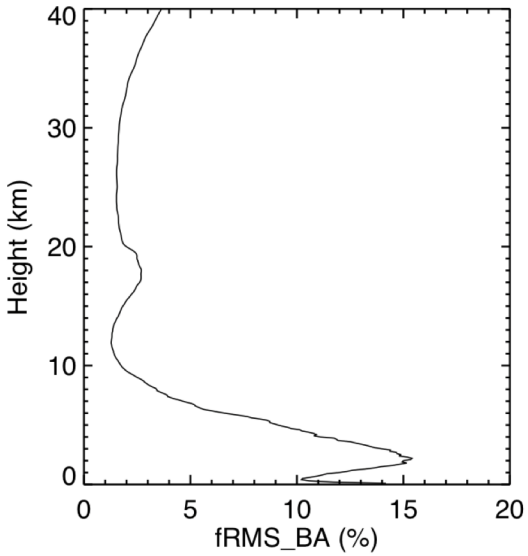
- Global statistical comparison of collocated COSMIC soundings with horizontal separations of the estimated tangent points < 10 km
- 2006.200-365
- FM3-FM4 pairs
- Only quality-controlled profiles used ('bad flag = 0')



Inter-RO (C2 – Metop/K5) Stats

2019.197-2019.234

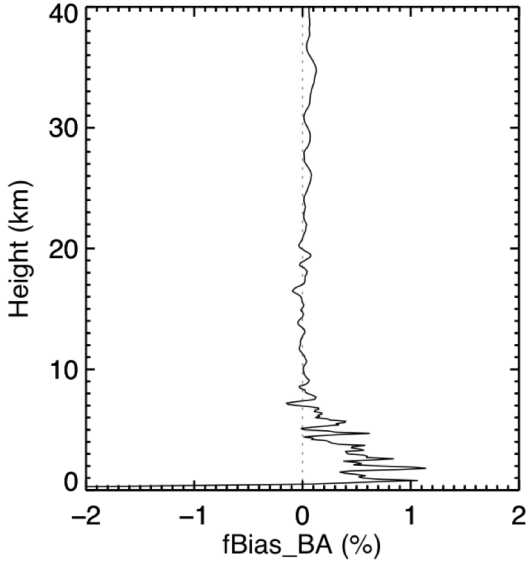


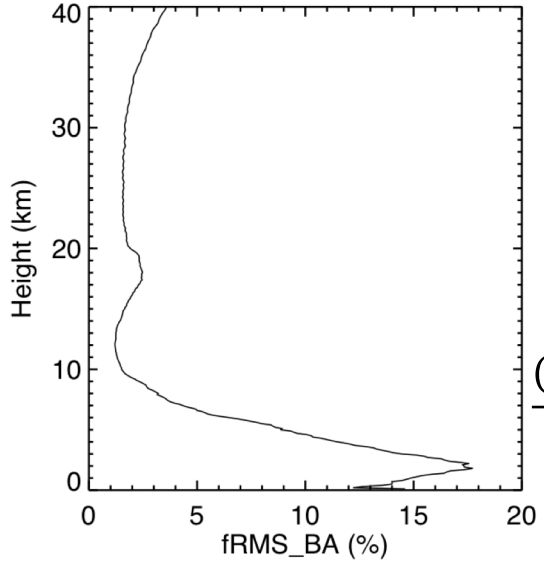


Before sampling correction,
9518 pairs within 300km/3hrs

$$Fractional\ diff = \frac{(C2_{RO} - Multi_{RO})}{C2_{ech}}$$

No significant bias between COSMIC-2 and Metop's/KOMPSAT-5 above 8 km





After Sampling Correction,
9518 pairs within 300km/3hrs

$$Fractional\ diff = \frac{(C2_{RO} - Multi_{RO}) - (C2_{ech} - Multi_{ech})}{C2_{ech}}$$

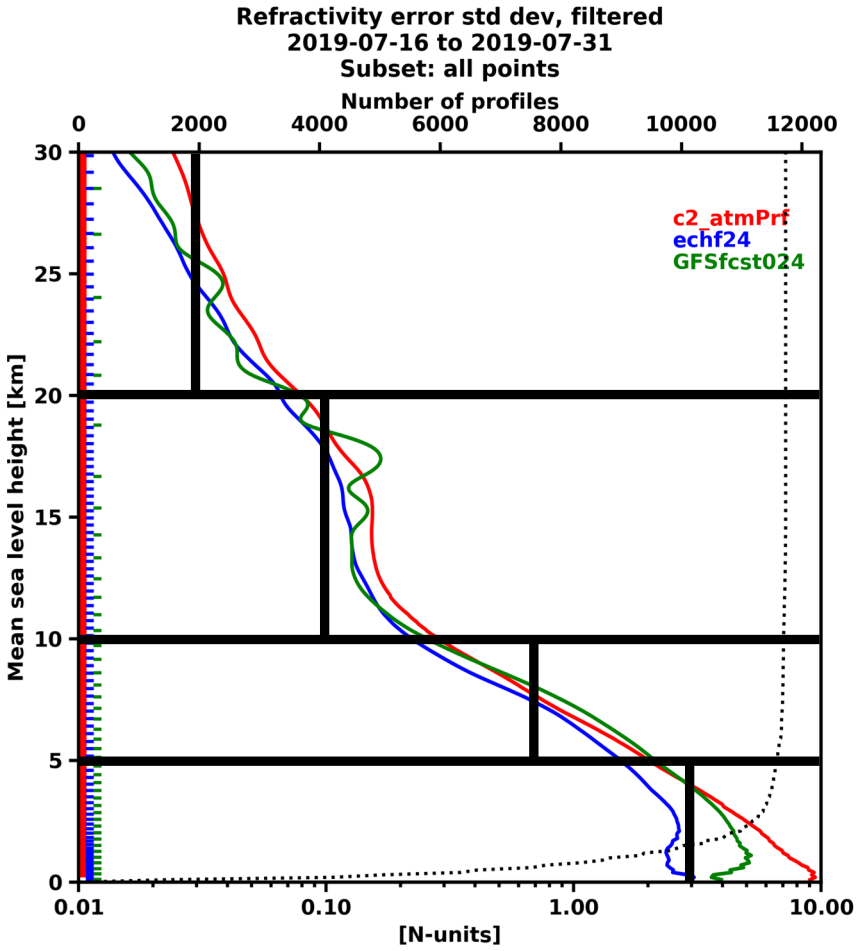
Courtesy: Z. Zeng

Three-Cornered Hat Error Statistics

- Established: history in atomic clock (Gray and Allan 1974), SST (O'Carroll et al. 2008) error estimations
- Error standard deviation estimates for C2, and co-located EC and GFS 24 hour forecasts
- Black lines show the C2 neutral atmosphere requirements
- See Reference:
  - Anthes and Rieckh (2018), DOI:10.5194/amt-11-4239-2018

Initial COSMIC-2 3CH estimates are similar with model estimates, but do not meet requirements for refractivity. Investigation ongoing.

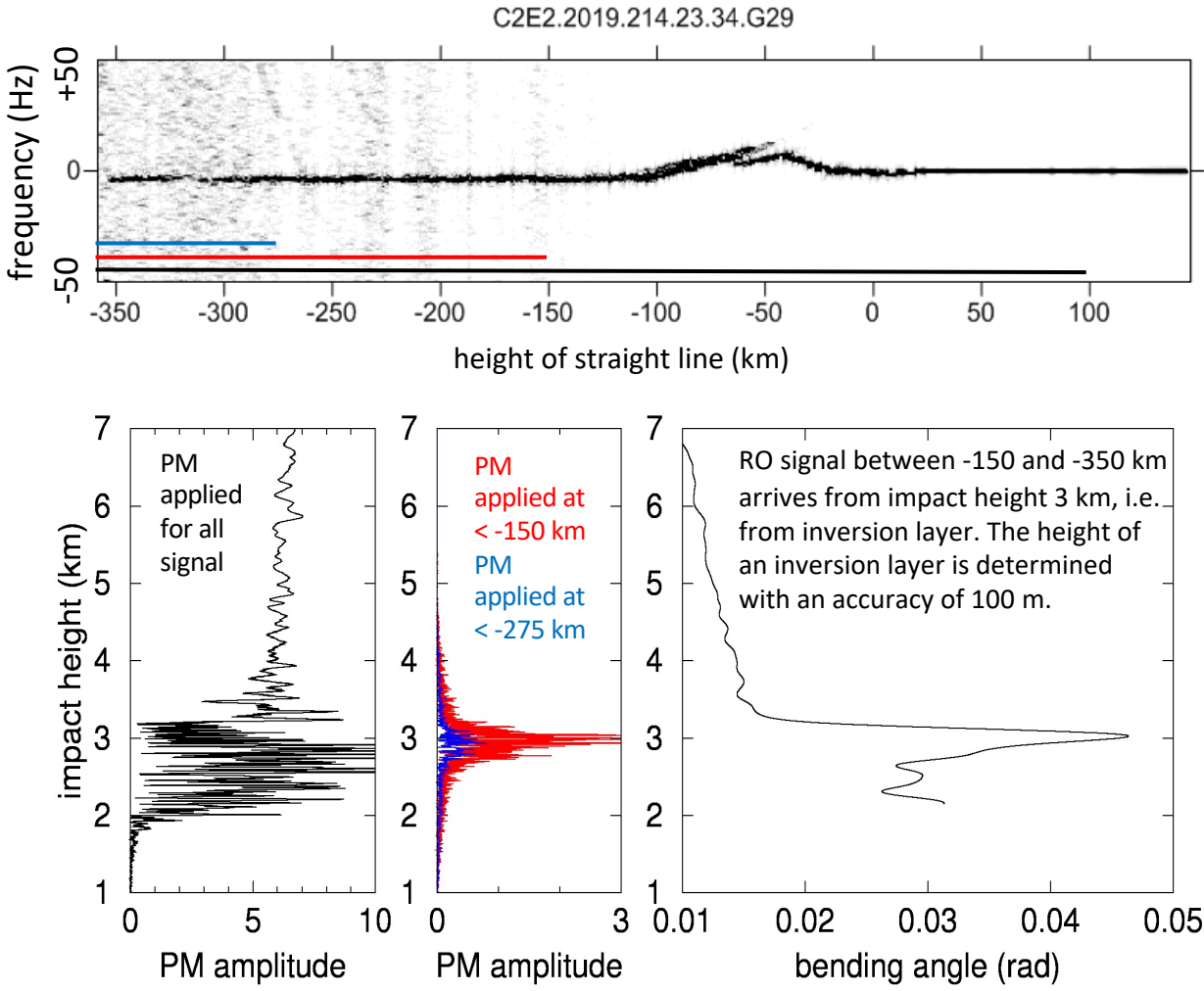
3CH estimates for
C2 wetPrf (unaltered refractivity) + EC forecast + GFS forecast



Courtesy: J. Sjoberg and R. Anthes

Tropospheric Duct Height Detection

- Sokolovskiy et al. 2014 determined via wave-propagation modelling that super-refractive ducts can be reliably detected with SNR > 2000 V/V by examining existence of deep signals
- The accuracy of the determination of duct height (requirement = 100 m) is defined by the sub-Fresnel vertical resolution with the application of WO methods, which is known to be 50-100 m. Thus the requirement is met.
- The amplitude of WO transform applied for deep part of RO signal is used only for the estimation of the impact height from which the signal is arriving. Once the maximum of the distribution points to a single inversion layer, the accuracy of that pointing does not need quantification.



COSMIC-2 has detected super-refractive ducts with an accuracy of 100 m

Courtesy: S. Sokolovskiy

COSMIC-2 GNSS RO Level1 Req. Verification

Requirement Description	Altitude Range [km]	Requirement Value	C-2 Current Best Estimate	Margin [%]	Comment
Quality-Controlled Profile Count		4,000	4,115 on Aug 22, 2019	2.9	Only one day
Quality Control %		73	73.5	0.7	For (2019.253-259)
Bending angle profile measurement uncertainty [µrad]	0 – 5 km	1,700	1555.9	8.5	Meets req
	5 – 10 km	300	234.1	22.0	Meets req
	10 – 20 km	20	15.9	20.5	Meets req
	20 – 30 km	4	3.5	12.5	Meets req w outliers removed
	30 – 60 km	2	1.6	20.0	Meets req
Refractivity profile measurement uncertainty [N units]	0 – 5 km	3	3.1	-3.3	Does not meet req
	5 – 10 km	0.7	0.5	28.6	Meets req
	10 – 20 km	0.1	0.076	24.0	Meets req
	20 – 30 km	0.03	0.028	6.6	Meets req
Dry Temp profile meas. Uncertainty [K]	10 – 30 km	1	0.68	32.0	Meets req
Tropospheric duct ht	0.5 – 5 km	100 m	50 - 100 m	-	COSMIC-2 detected ducts

Conclusions

- The COSMIC-2 CAL/VAL plan is underway
- COSMIC-2 has met 4,000 QC'd profiles per day on one day, and is currently meeting QC percentage requirement
- COSMIC-2 is meeting ALL level-1 requirements when 2 outlier profiles are removed, except
  - COSMIC-2 refractivity requirement for 0 < alt < 5km is not being met
- COSMIC-2 STDV has latitude and local time dependence
- COSMIC-2 has detected initial super-refractive ducts with high SNR data
- Future work includes continuing analysis, debugging tracking and retrieval issues and tuning QC algorithm

Acknowledgement

- Thanks to the FORMOSAT-7/COSMIC-2 Program partners!

Backup Slides