STAR Seminar

GPS RO Bending Angle Assimilation Using a Limited-ray-path Raytracing Operator and an Impact Multipath Detection Algorithm

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April 2019

Outline

- COSMIC-2 RO data assimilation (DA)
  - ✓ Remaining challenges in RO data assimilation
- Raytracing observation operator of bending angle
  - ✓ A 1D operator —— Abel transform
  - ✓ A 2D raytracing operator —— simulation of a global ray path
- An impact multipath QC to detect multipath simulations
- A 2D limited-ray-path raytracing operator
- RO DA assessing impacts of the impact multipath QC and accuracy of the 2D limited-ray-path raytracing operator
- Summary and future work

GPS RO Data Assimilation

Cost function

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}(H(\mathbf{x})-\mathbf{y}^{obs})^T(\mathbf{O}+\mathbf{F})^{-1}(H(\mathbf{x})-\mathbf{y}^{obs})$$

$\mathbf{y}^{obs}$ — observations assimilated:

- bending angle
- quality control (multipath)

Zou, X., H. Liu and Y.-H. Kuo, 2019a: Occurrence and detection of impact multipath simulations of bending angle. *Quart. J. Roy. Meteor. Soc.*, doi: 10.1002/qj.3520.

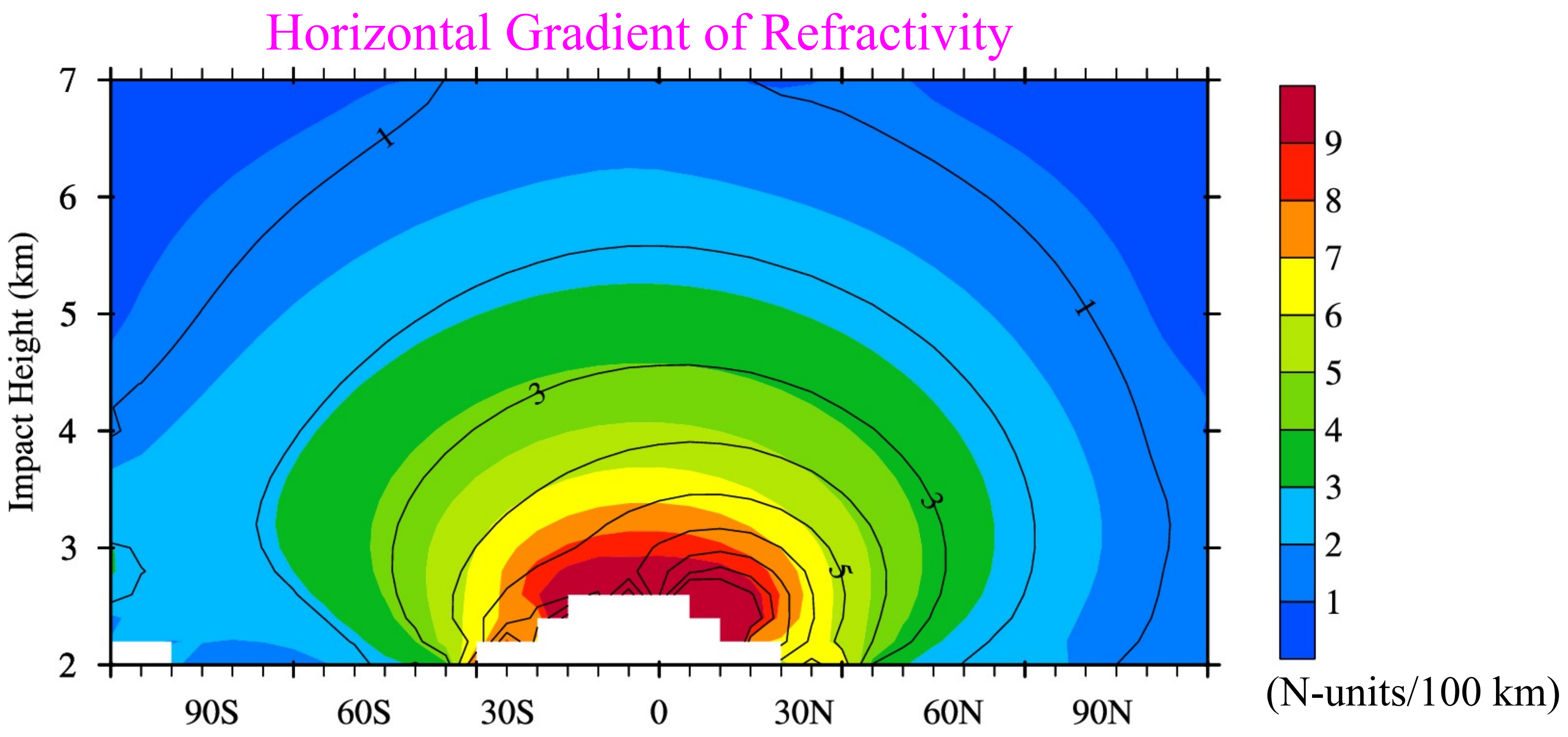
H — observation operator

- 1D, 2D global, 2D regional
- precision versus computational cost

Zou, X., H. Liu and S. Boukabara, 2019b: Bending angle data assimilation using a limited-path-length 2D raytracing operator with an impact multipath quality control in the tropical low troposphere. *Quart. J. Roy. Meteor. Soc.*, (submitted)

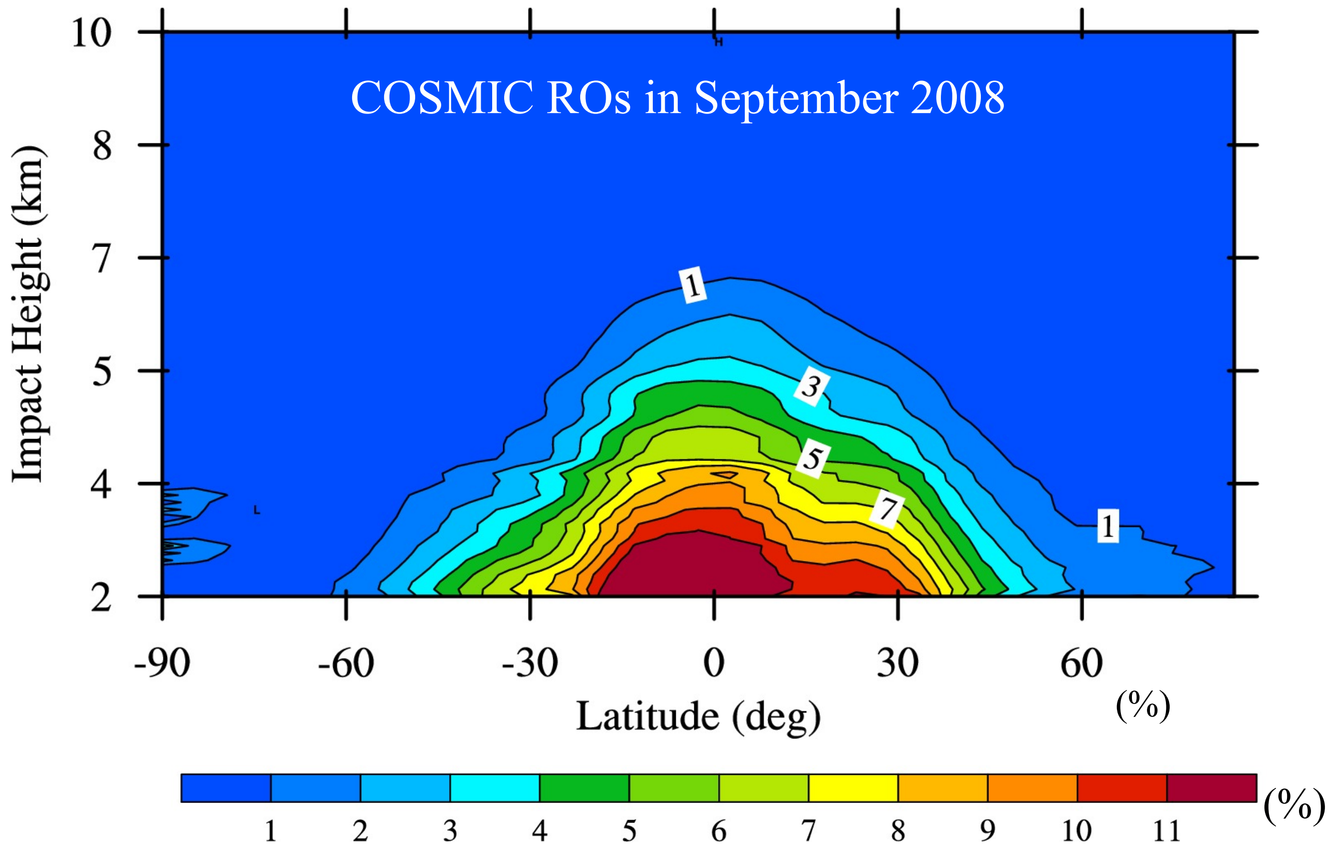
Challenges for COSMIC-2 Data Assimilation

- The COSMIC-2 have more powerful antennas, a twice higher sampling rate (100 Hz), and a three times smaller inclination (24°) than COSMIC, providing many more COSMIC-2 data in the tropics lower troposphere
- The tropical lower troposphere is characterized by large horizontal gradients of refractivity, spherical asymmetry and multipath



COSMIC, MetOp-A/-B, March 19 to April 30, 2017 (mean — color shading, standard deviation — curve)

Variations of Zonal Mean LSW with Latitude and Impact Height

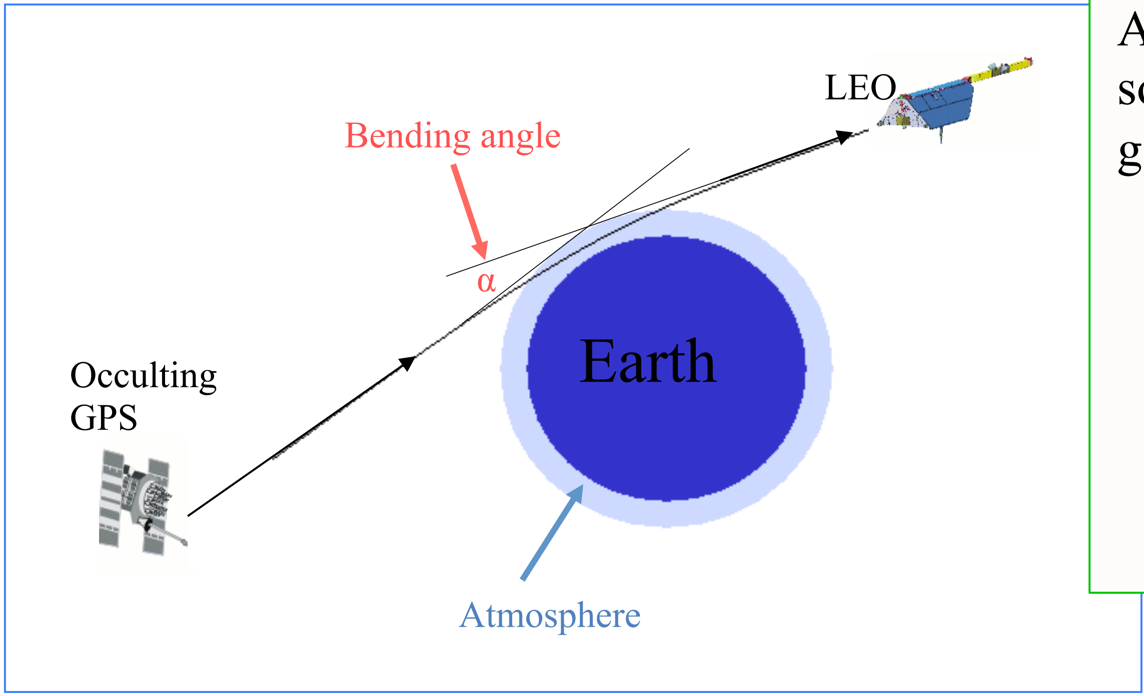


COSMIC data with large uncertainty is found in the tropical lower troposphere.

Liu, H., Y.-H. Kuo, S. Sokolovskiy, X. Zou, Z. Zeng, L.-F. Hsiao and B. C. Ruston, 2018: A quality control procedure based on bending angle measurement uncertainty for radio occultation data assimilation in the tropical lower troposphere. *J. Atmos. Oceanic Technol.*, **35**, 2117-2131.

Local Spectral Width (LSW)

1D and 2D Bending Angle Observation Operators



A non-local 2D observation operator solves the ray trajectory equation a global ray path

$$\frac{d^2\vec{r}}{d\tau^2} = n\nabla n$$

$\vec{r} = (x_1, x_2, x_3)$ — 3D position vector

$d\tau = \frac{ds}{n}$, where s — length of ray

A local 1D observation operator solves an Abel transform

$$\alpha(a) = -2a\int_a^\infty \frac{1}{n\sqrt{\mu^2 - a^2}}\frac{dn}{d\mu}d\mu$$

$\mu = nr$

The 4th International Conference on GPS Radio Occultation (ICGPSRO), Howard International House, Taipei, Taiwan, April 18-20, 2018.

⇓

Liu, H. and X. Zou, 2018: Comparison of GNSS bending angle simulations from the 1D Abel transform and 2D raytracing operators in the tropical lower troposphere. *Journal of Aeronautics, Astronautics and Aviation (JoAAA),* **NSPO Special Issue**, 405-414.

The 2D Raytracing Operator for Bending Angle Assimilation

✓ Zou, X., F. Vandenberghe, B. Wang, M. E. Gorbunov, Y.-H. Kuo, S. Sokolovskiy, J. C. Chang, J. G. Sela, and R. Anthes, 1999: A raytracing operator and its adjoint for the use of GPS/MET refraction angle measurements. *J. Geoph. Res*., **104**, 22,301-22,318.

Zou, X., B. Wang, H. Liu, R. A. Anthes, T. Matsumura, and Y.-J. Zhu, 2000: Use of GPS/MET refraction angles in 3D variational analysis. *Quart. J. Roy. Meteor. Soc*., **126**, 3013-3040.

Liu, H., X. Zou, R. A. Anthes, J. C. Chang, J.-H. Tseng, and B. Wang, 2001: The impact of 837 GPS/MET bending angle profiles on assimilation and forecasts for the period June 20-30, 1995, *J. Geoph. Res*., **106**, 31771-31786.

Zou, X., H. Liu, and R. A. Anthes, 2002: A statistical estimate of errors in the calculation of radio occultation bending angles caused by a 2D approximation of raytracing and the assumption of spherical symmetry of the atmosphere. *J. Atmos. Oceanic Technol*., **19**, 51-64.

Liu, H., and X. Zou, 2003: Improvements to a forward GPS raytracing model and their impacts on assimilation of bending angle, *J. Geoph. Res*., **108**, D17.

Zou, X., H. Liu, R. A. Anthes, H. Shao, J. C. Chang, and Y.-J. Zhu, 2004: Impact of CHAMP occultation observations on global analysis and forecasts in the absence of AMSU radiance data. *J. of the Meteor. Soc. Japan*, **82**, 533-549.

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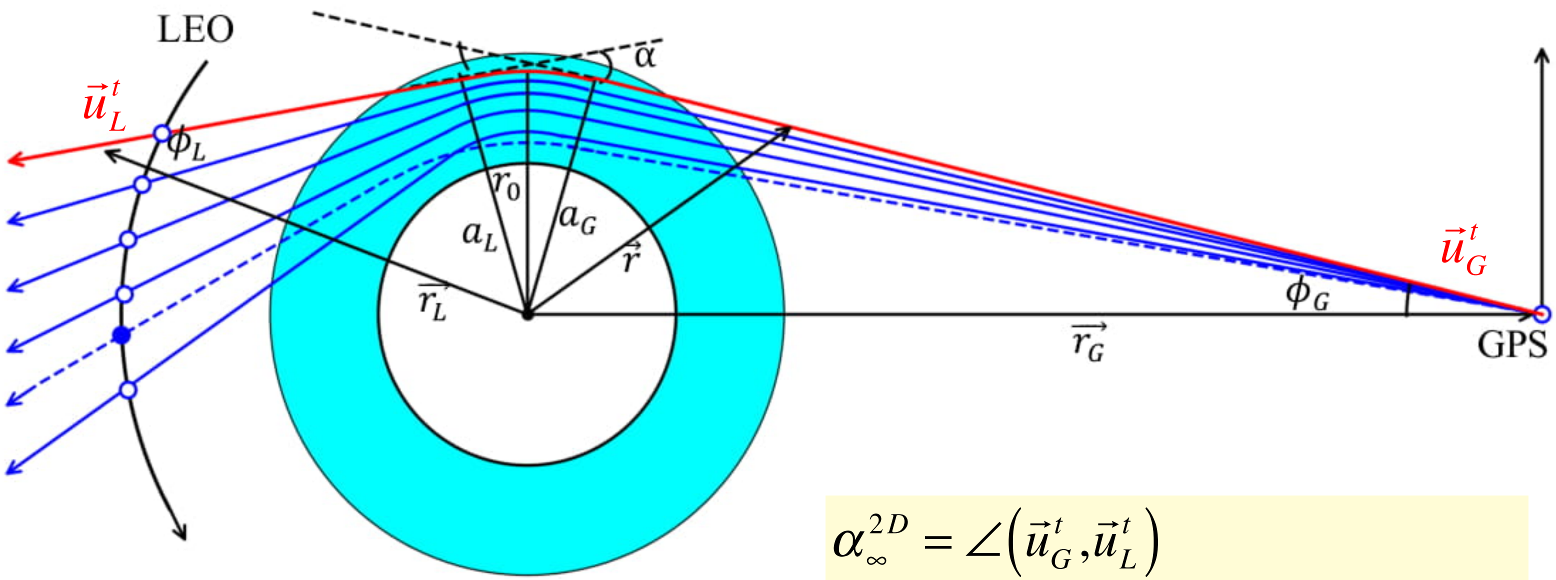
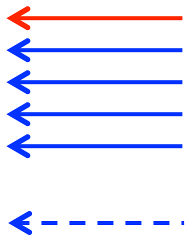
Schematic Representation of an Impact Multipath



$$\alpha_{\infty}^{2D} = \angle\left(\vec{u}_G^t, \vec{u}_L^t\right)$$
$$= \phi_G + \phi_L \mathrm{arcos}\left(\frac{\angle\left(\vec{r}_G, \vec{r}_L\right)}{r_G r_L}\right) - \pi$$

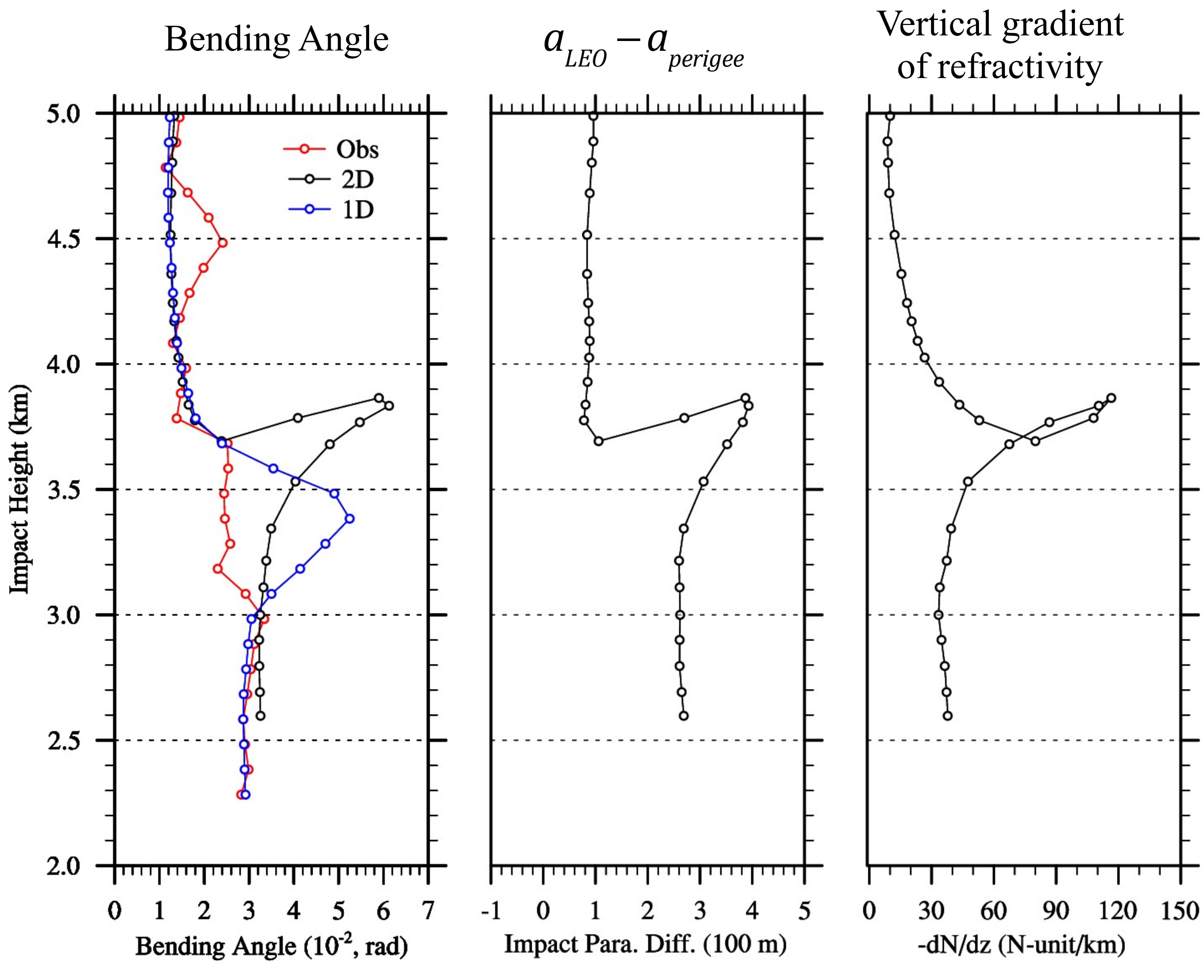
$$\alpha_{s_R}^{2D-\mathrm{limited}} = \angle\left(\vec{t}_{-R}, \vec{t}_R\right)$$



normal ray paths (red and blue solid curves)

a multipath ray (blue dashed curve)

Occurrence and Detection of Multipath Simulations of Bending Angle



A COSMIC RO
(37.9°W, 25.1°S)
1450 UTC
19 March 2017

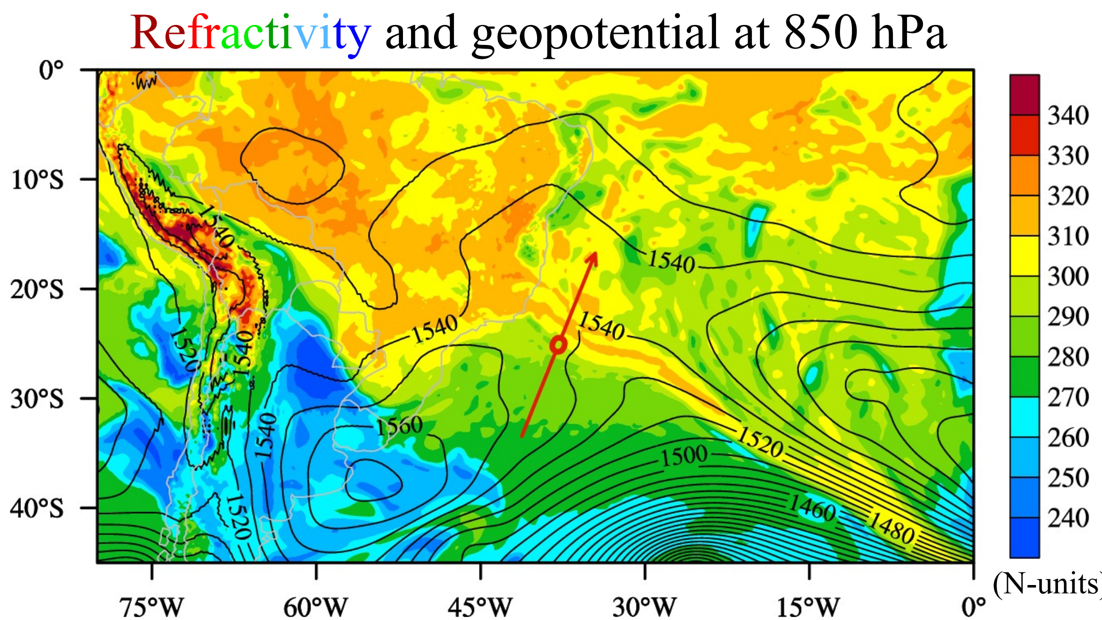
$a_{perigee}$ — impact parameter at the perigee

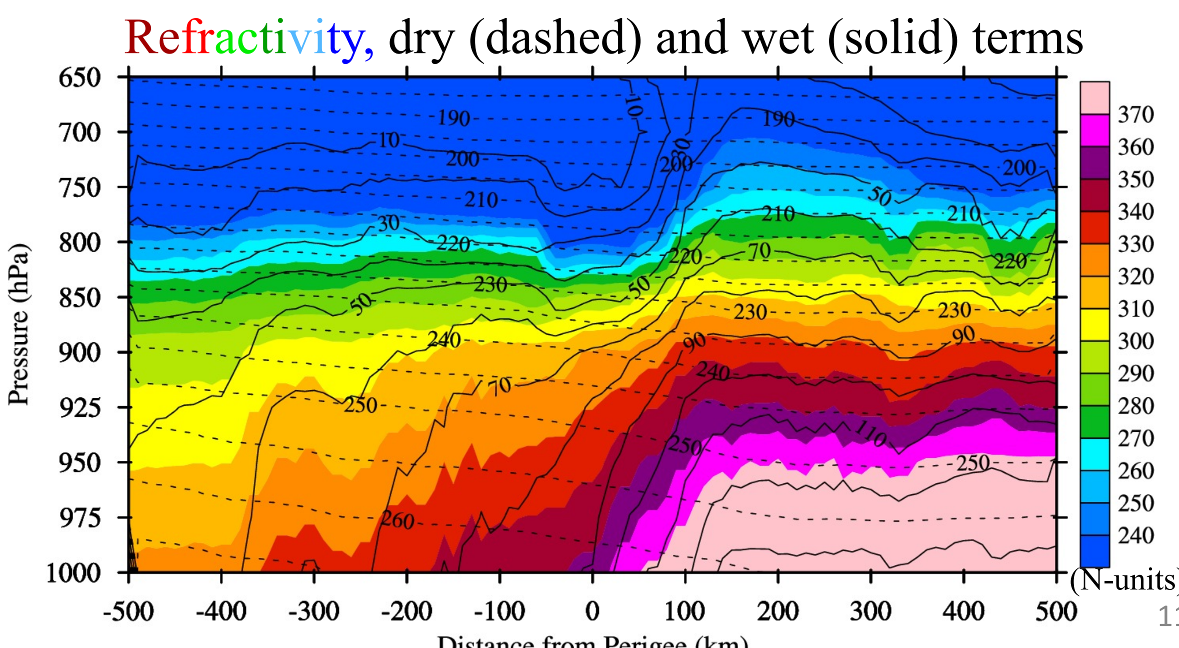
a_{LEO} — impact parameter at the LEO position

- An occurrence of multipath is seen in 2D raytracing simulation
- Differences of impact parameter between perigee and LEO satellite increases from 100 to 400 meters when multipath occurred
- The multipath occurred where the vertical gradient of refractivity increase to ~120 N km^{-1}

Atmospheric State in Which the COSMIC RO with Multipath Occurred

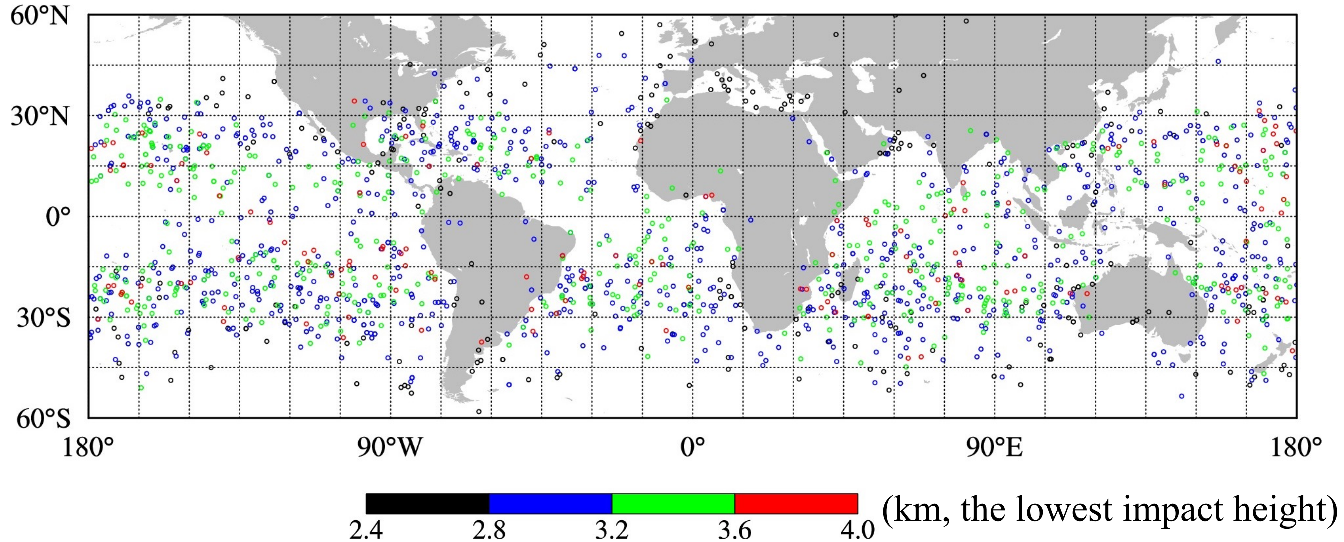
- The RO ray path cut through a narrow belt of maximum refractivity (>300 N-units) that is associated with a trough oriented from southeast to northwest.
- A strong vertical gradient of refractivity co-existed with the belt of maximum horizontal gradient, with a vertical lifting of large refractivity found near the perigees on the LEO satellite side. The strong gradient of refractivity comes mainly from an downward intrusion of the drier water vapor contribution north of the perigee into lower levels.



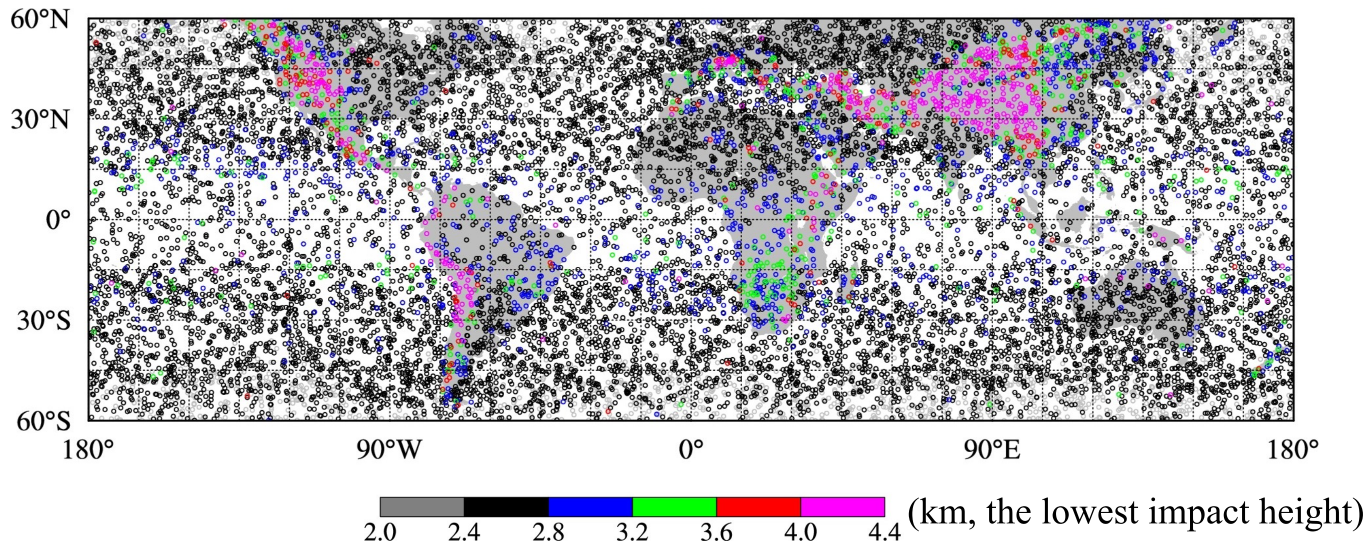


Geographical Distributions of COSMIC ROs (March 19 to April 30, 2017)

ROs whose simulations have multivalued bending angles

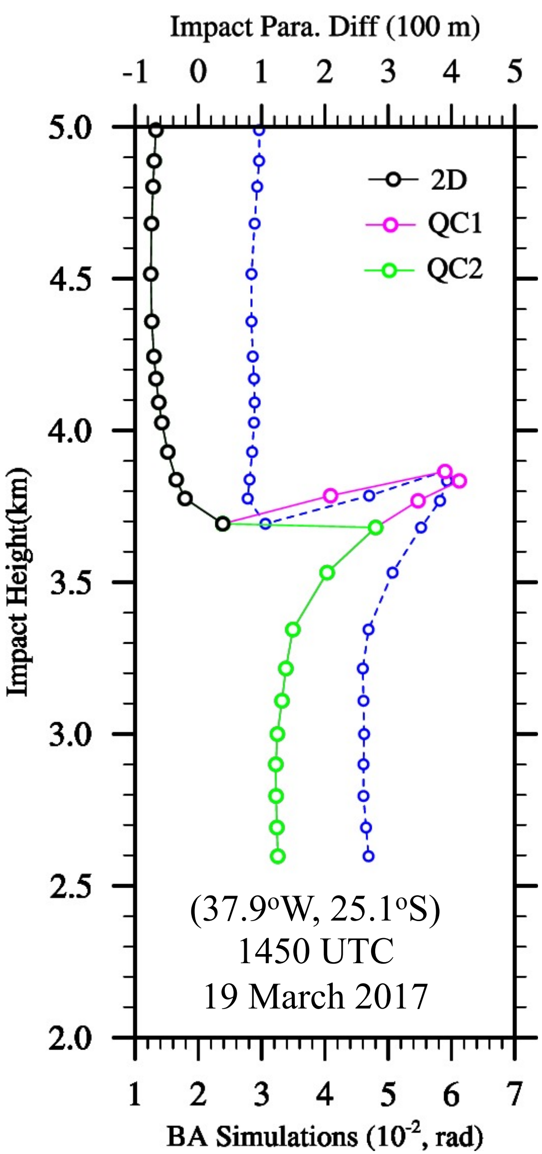


ROs whose simulations give single valued bending angles

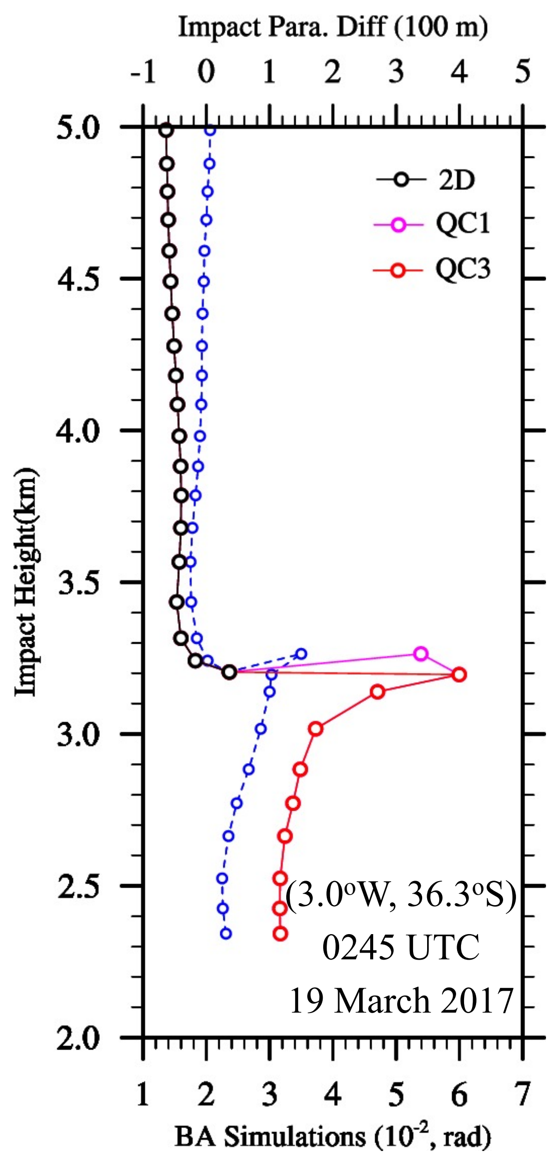


A Three-step QC Procedure for Removing Multivalued Simulations

RO1



RO2

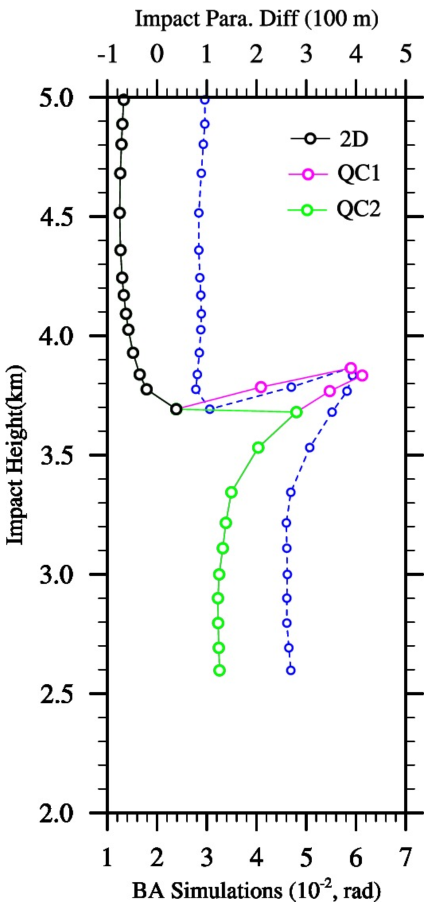


The Impact multipath QC

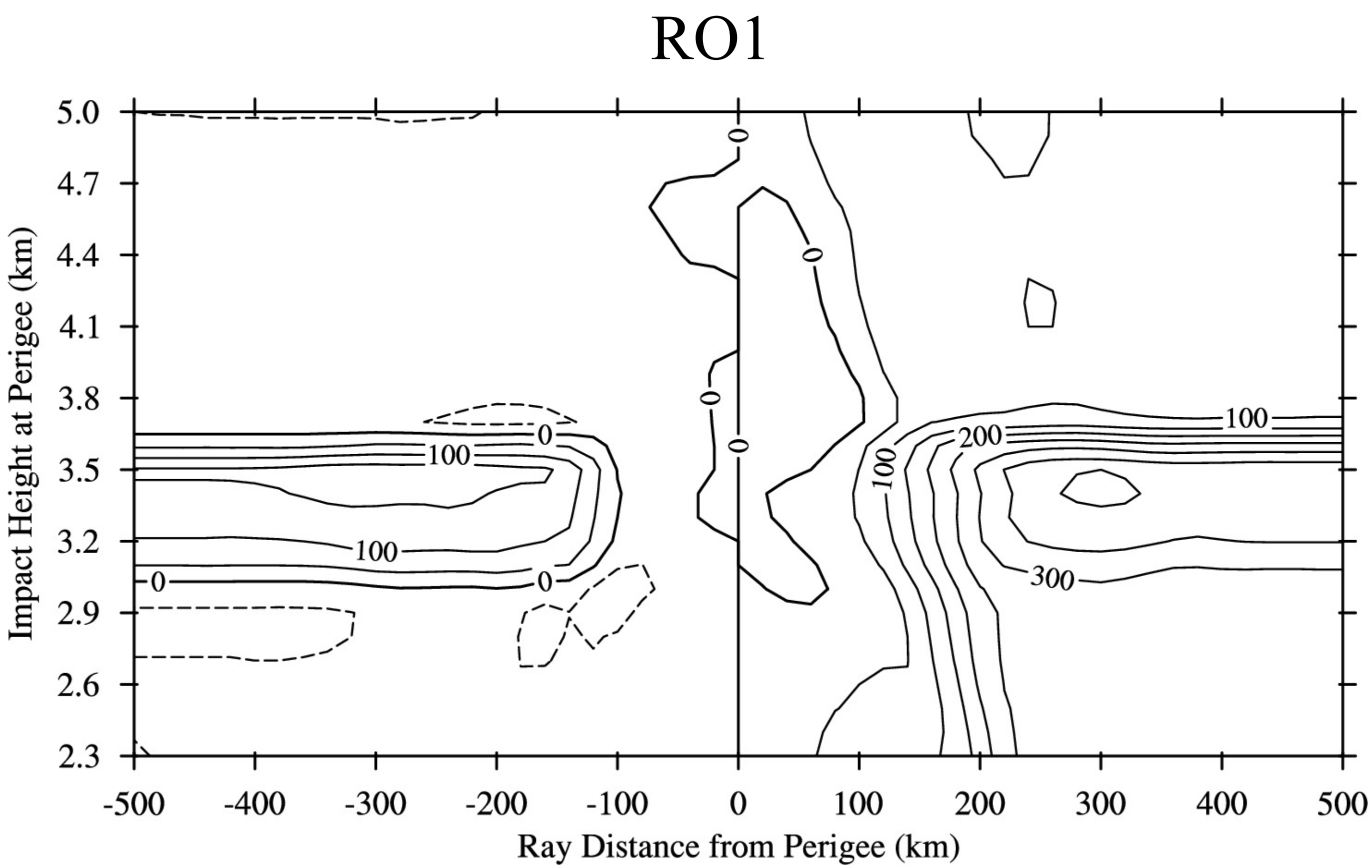
1. QC1 removes data within the layer of the multivalued bending angle simulations
2. QC2 removes additional data points if the differences in the impact parameter between the perigee and the LEO satellite are greater than 200 m
3. QC3 removes all data points below the multivalued levels

Zou et al., 2019a, *QJRMS*

Variations of Impact Parameter along Simulated Ray Paths



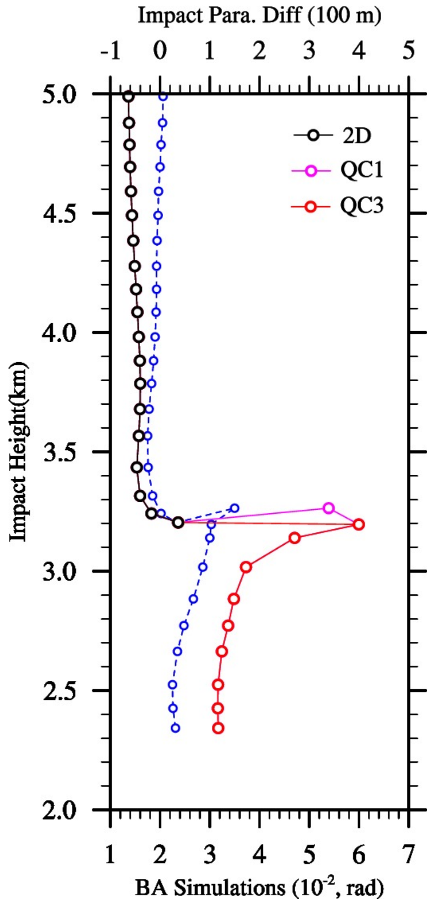
RO1

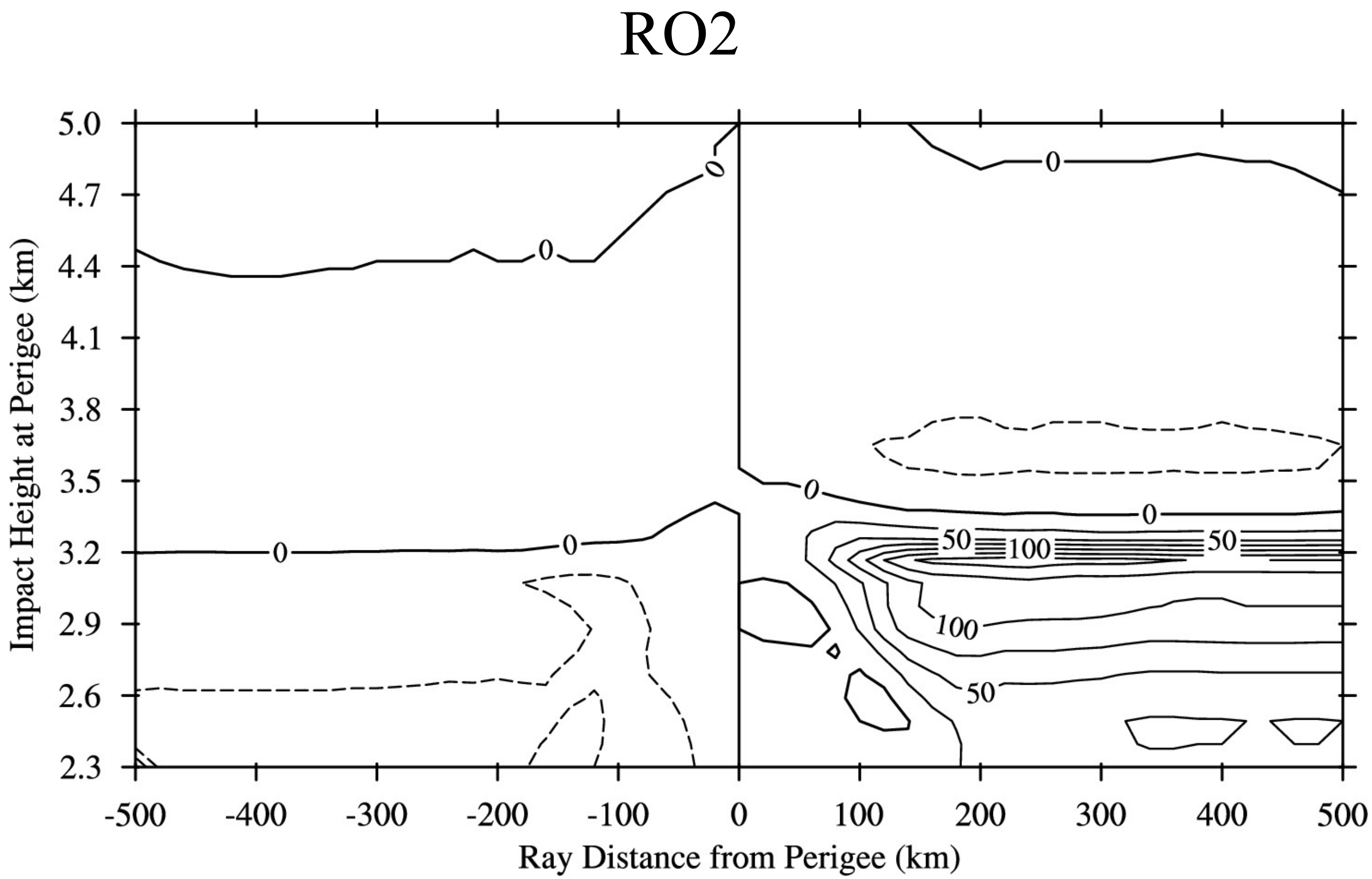


RO1
(37.9°W, 25.1°S)
1450 UTC
19 March 2017

- Large deviations of the impact parameter from their values at the perigees are confined within 400-km impact height.
- The GPS and LEO satellite positions are on the left and right sides of the x-axis, respectively.

Variations of Impact Parameter along Simulated Ray Paths

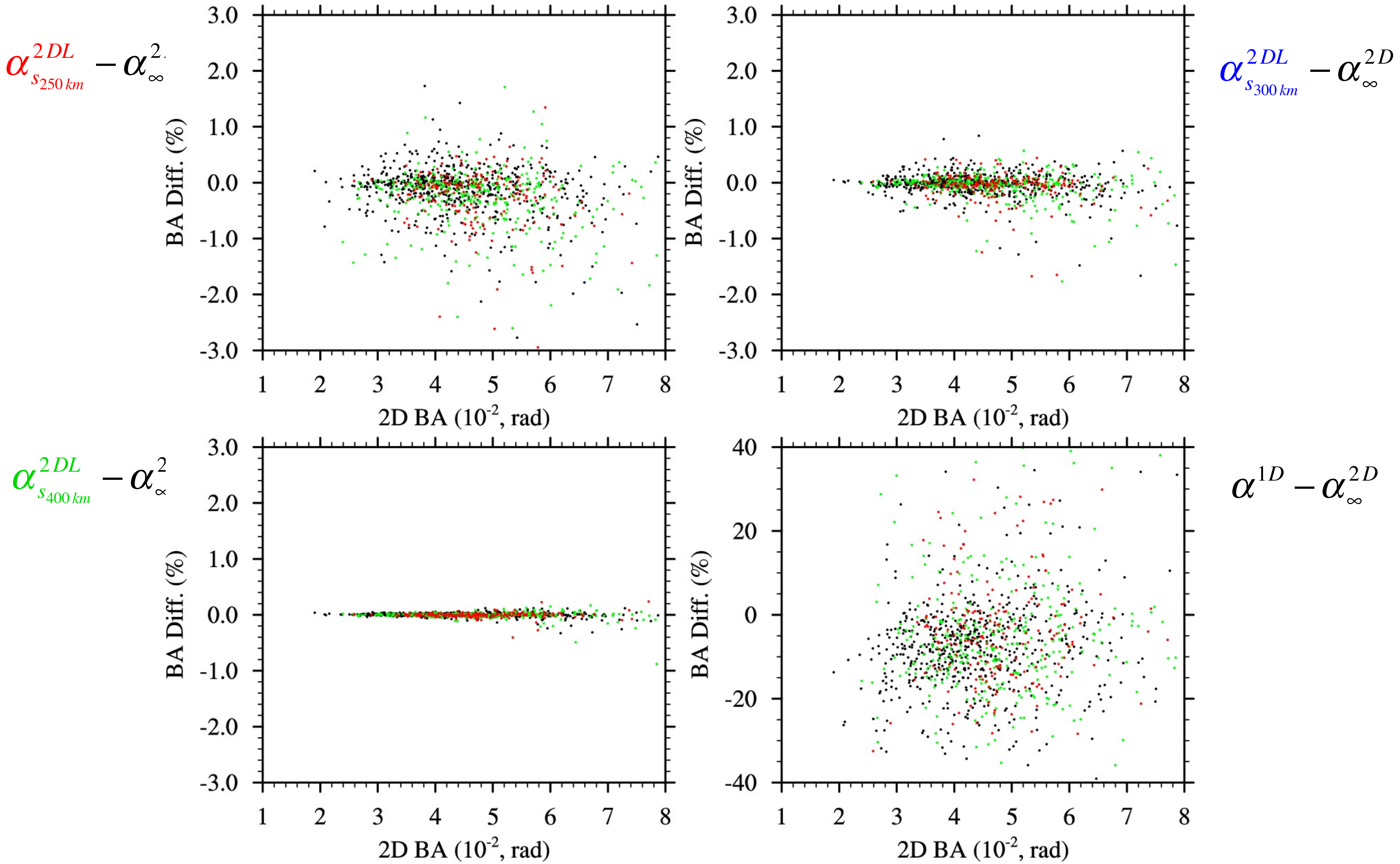




RO2
(3.0°W, 36.3°S)
0245 UTC
19 March 2017

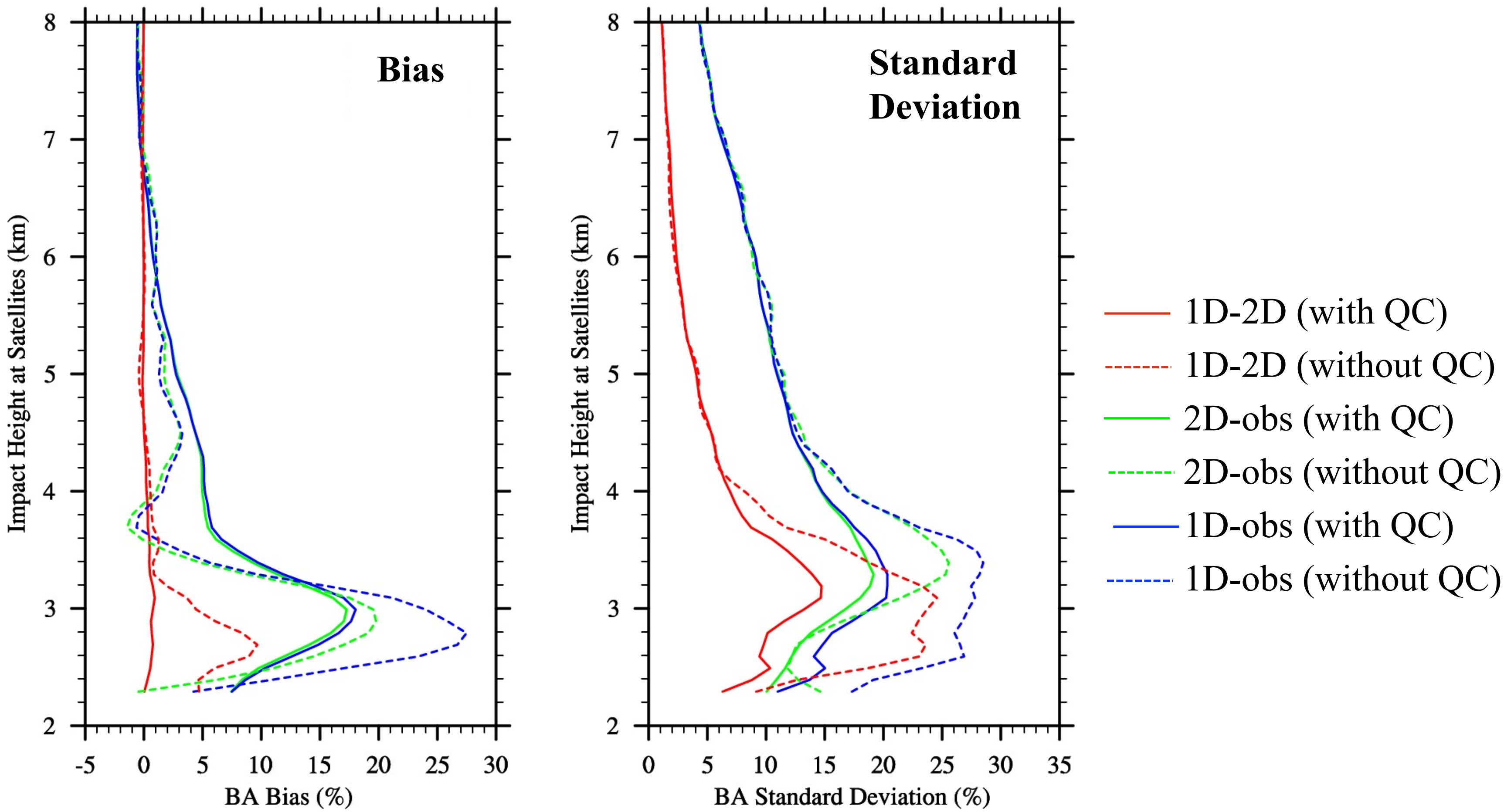
- Large deviations of the impact parameter from their values at the perigees are confined within 400-km impact height.
- The GPS and LEO satellite positions are on the left and right sides of the x-axis, respectively.

The Limited Ray Path Operator for multipath Simulations



All rays whose impact heights are within 3–3.3 km of all COSMIC ROs within (30°S, 30°N) from 19 March to 30 April 2017 that fails the QC1 step.

Impact Multipath QC on Biases and Standard Deviations



- Multipath causes negative biases of 1D simulations from the 2D simulations in the tropical lower atmosphere (below about the 3.3-km impact height)
- Bending angle simulations between 1D and 2D operators have no bias after the QC
- Multipath causes larger negative biases for the 1D than 2D simulations
- After the QC, the negative biases for the 1D and 2D simulations have similar magnitudes
- Standard deviations of all differences shown are significantly reduced after the QC

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- The limited-ray-path operator for the impact multipath QC
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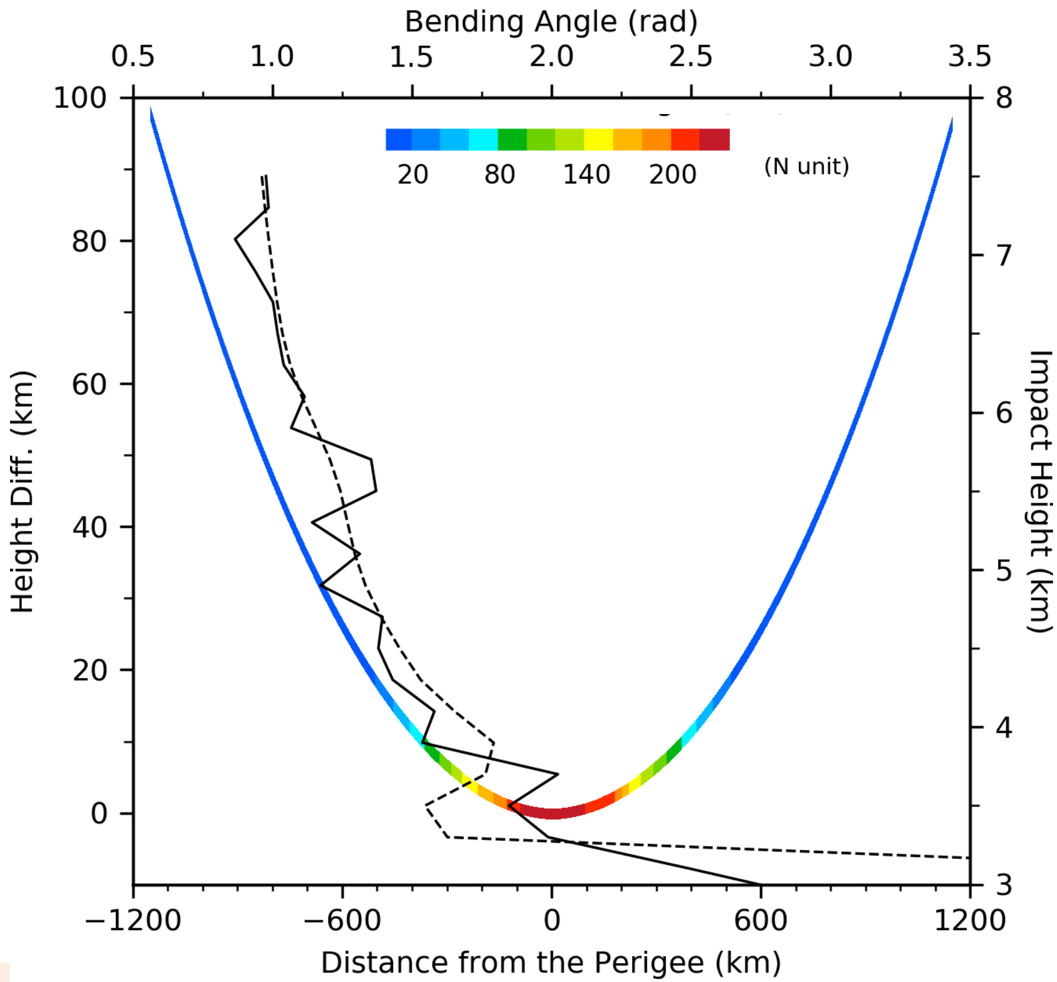
A Limited-Ray-Path Raytracing Operator

— An Approximation to the 2D Raytracing Operator

COSMIC RO:
located at (19.9°N, 134.3°E),
1110 UTC 19 March 2017

A ray path simulated by the 2D raytracing operator for the above COSMIC observed bending angle at the 3.3-km impact height at the perigee.

The NCEP GFS analysis is used as the input atmospheric state to the 2D bending angle simulation.



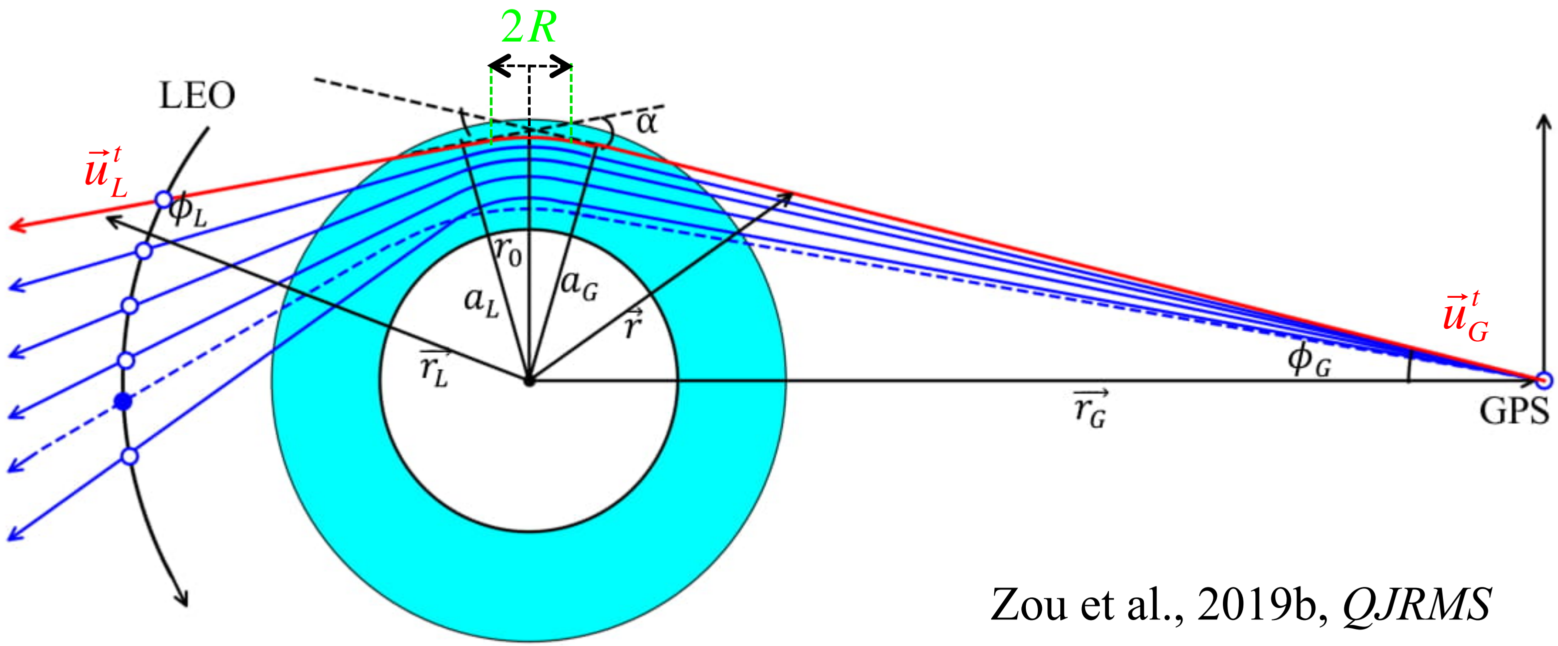
- Variation of refractivity along the ray path (color shading)
- Variation of impact height of the ray path (y-axis)
- COSMIC observed bending angle observed profile (solid black curve)
- GFS simulated bending angle observed profile (solid dashed curve)

Derivation of bending Angle from a Limited Ray Path

$$\alpha_{\infty}^{2D} = \angle\left(\vec{u}_G^t, \vec{u}_L^t\right) = \phi_G + \phi_L \arccos\left(\frac{\angle\left(\vec{r}_G, \vec{r}_L\right)}{r_G r_L}\right) - \pi$$

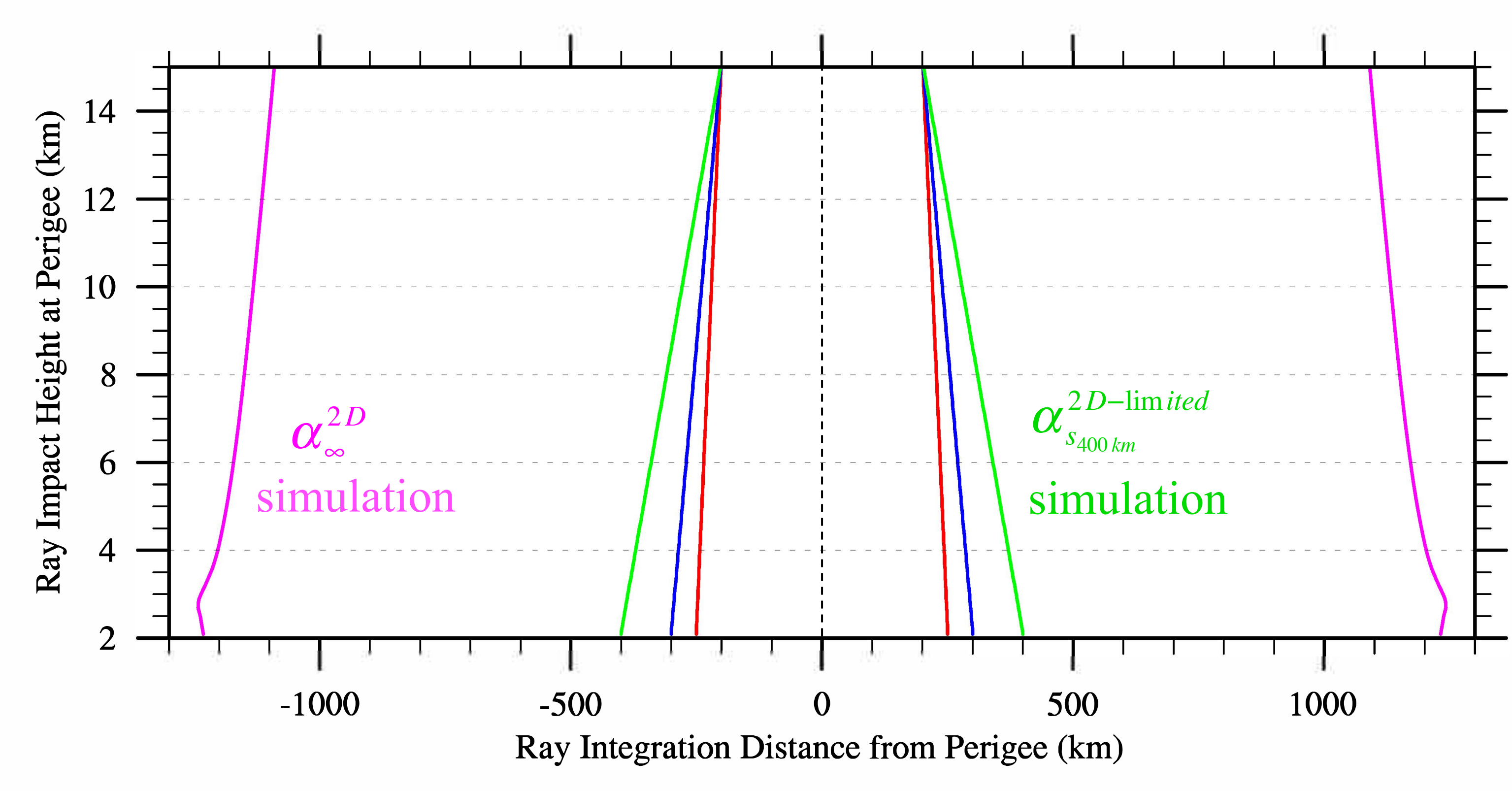
→

$$\alpha_{s_R}^{2D\,\mathrm{limited}} = \angle\left(\vec{u}_{-R}^t, \vec{u}_R^t\right) = \phi_{-R} + \phi_R \arccos\left(\frac{\angle\left(\vec{r}_{-R}, \vec{r}_R\right)}{r_{-R} r_R}\right) - \pi$$



Zou et al., 2019b, *QJRMS*

Assuming Three Different Limited Ray Path Lengths

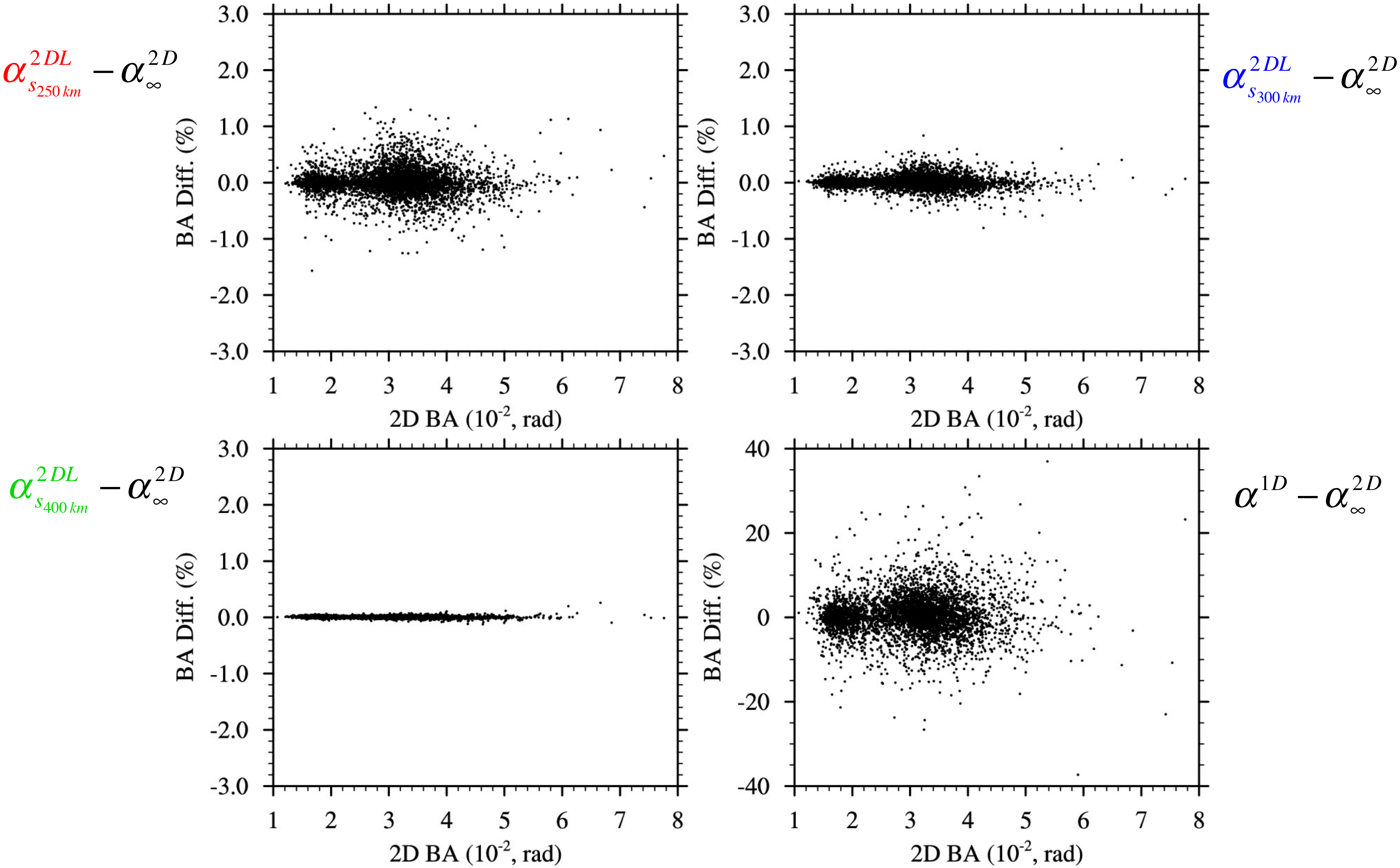


The three setups of the limited-ray-path 2D raytracing operators on the horizontal distances from the perigee:

	250 km (red)		200 km
2-km impact height:	300 km (blue)	15-km impact height:	200 km
	400 km (green)		200 km

All three setups reduce linearly to 200 km at the 15-km impact height.

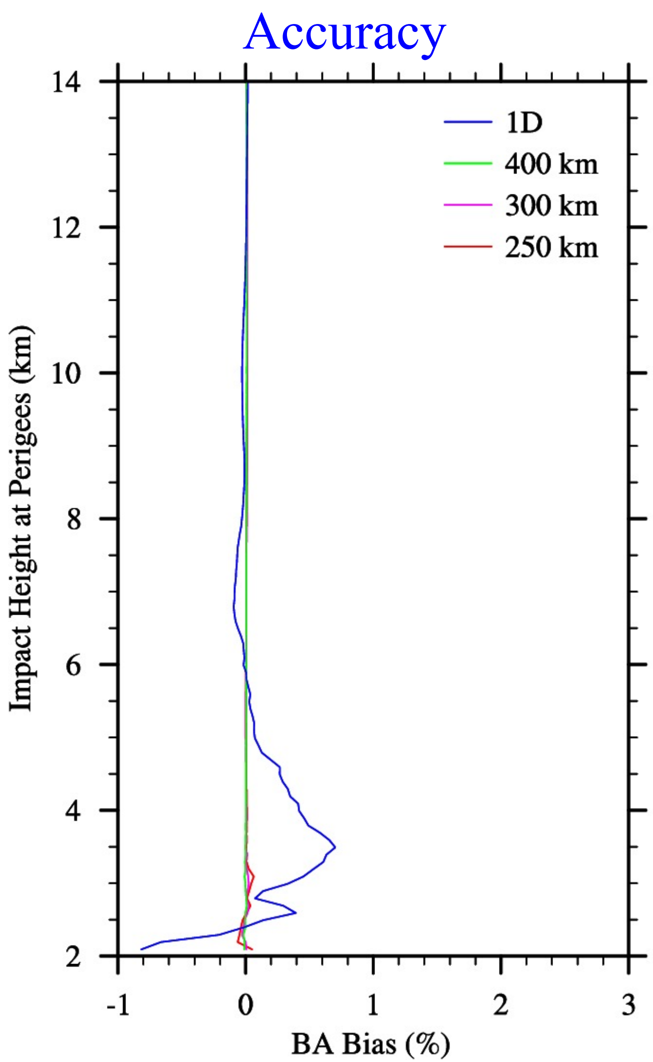
Accuracy of the Limited Ray Path Operators

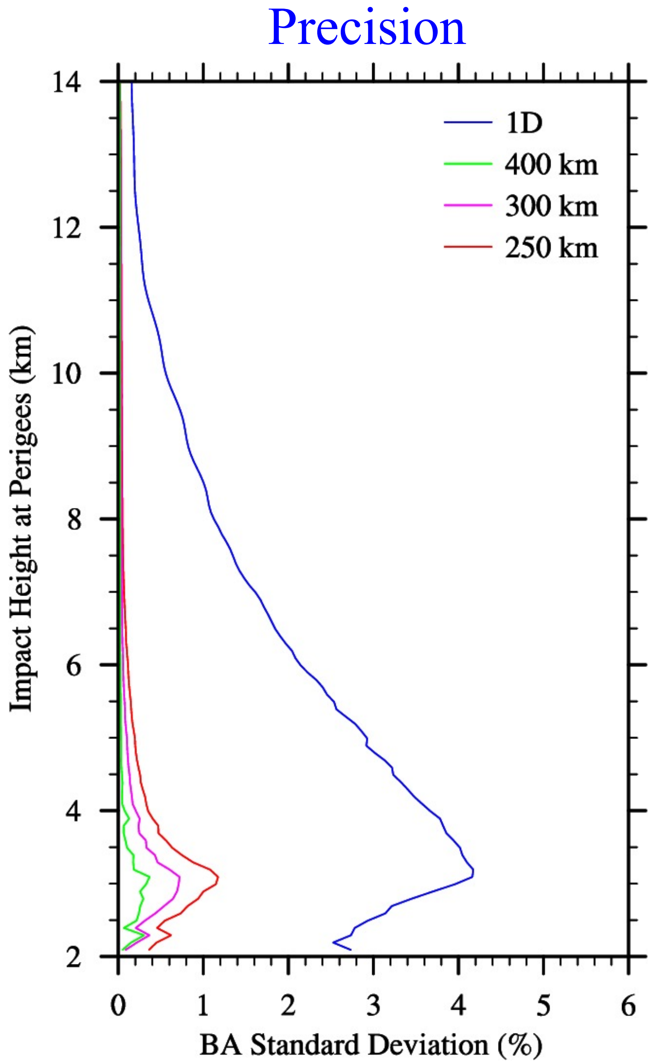


All rays whose impact heights are within 3–3.3 km of all COSMIC ROs within (30°S, 30°N) from 19 March to 30 April 2017 that pass the QC1 step.

Accuracy and Precision of Limited-Ray-Path Raytracing Operators

Fractional differences of bending angle between the limited-path-length raytracing operators (±250, ±300, and ±400 km) and 1D simulations and the 2D full-path-length raytracing simulations: $\alpha^{2Dlimited} - \alpha^{2D}$ $\alpha^{1D} - \alpha^{2D}$





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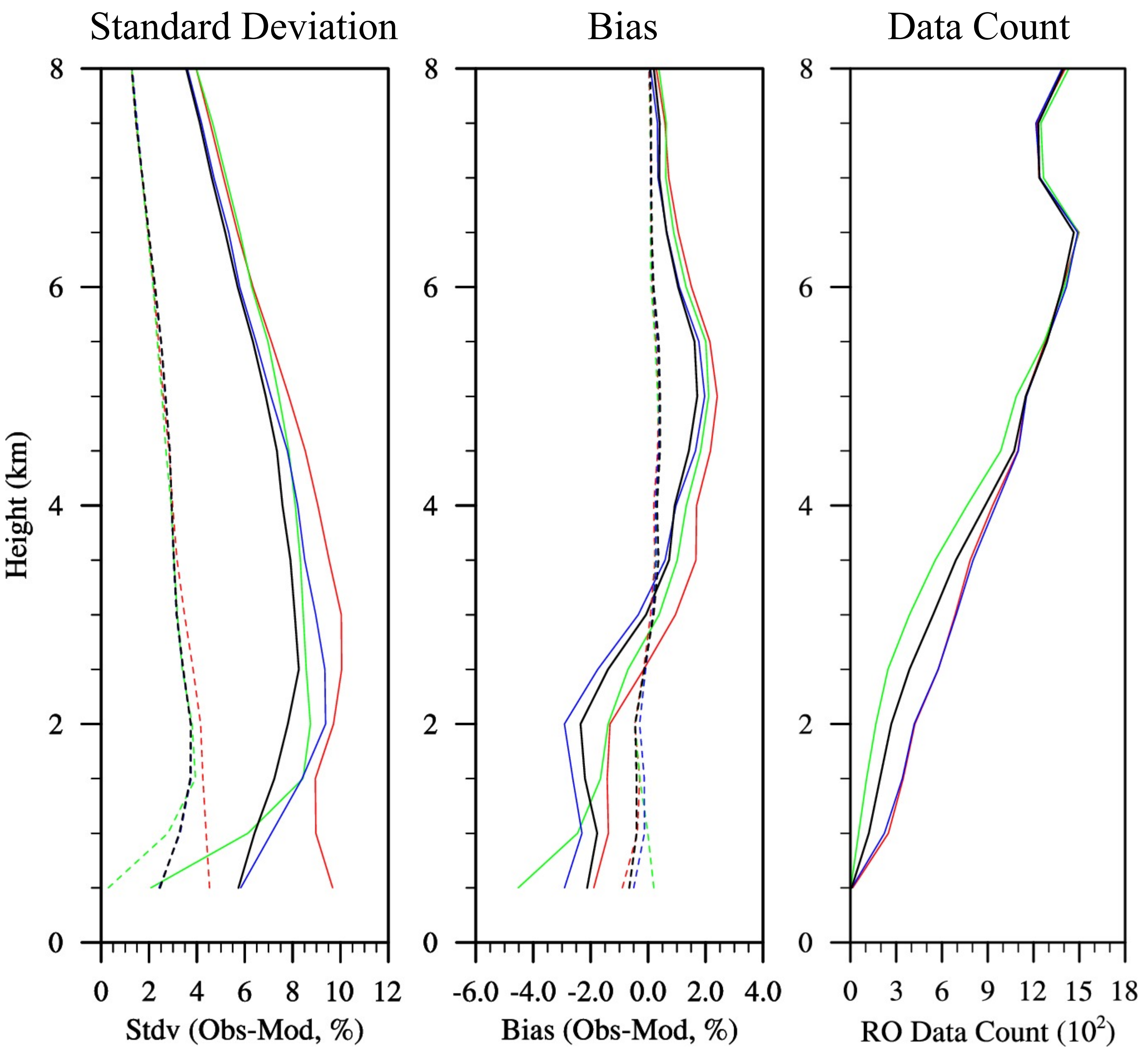
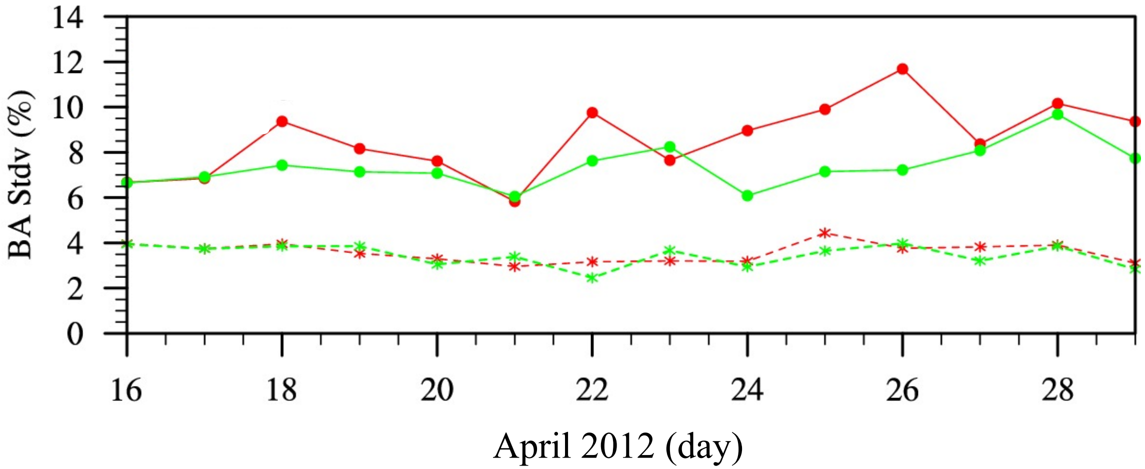
Fit to COSMIC Observation Retrievals of Bending Angle



DA period:
16 to 30 April 2012

Impact of Multipath QC on COSMIC Data Assimilation

$\sigma(\alpha^{\text{2D-limited}} - \alpha^{obs})$

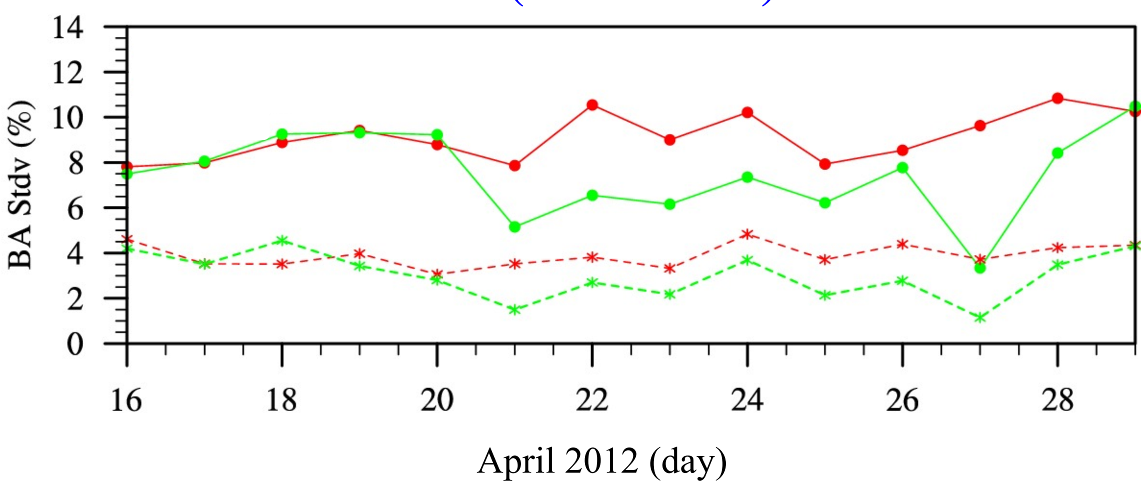


The fit of background fields to bending angle COSMIC observations.

$\sigma(\alpha^{model} - \alpha^{obs})$

A-O with multipath QC
A-O without multipath QC
B-O with multipath QC
B-O without multipath QC

$\sigma(\alpha^{\text{1D}} - \alpha^{obs})$



Model domain:
(90°E-180°E, 18°S-28°N)
DA cycling:16-30 April 2012

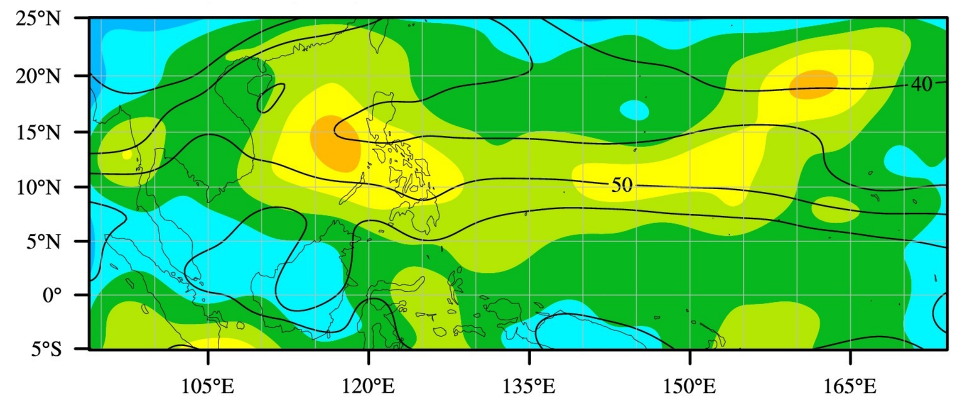
Details of the WRF/DART used in this study can be found in

Anderson, J. L., and coauthors, 2009: The Data Assimilation Research Testbed: A community data assimilation facility. *Bull. Amer. Meteor. Soc.*, **90**, 1283-1296.

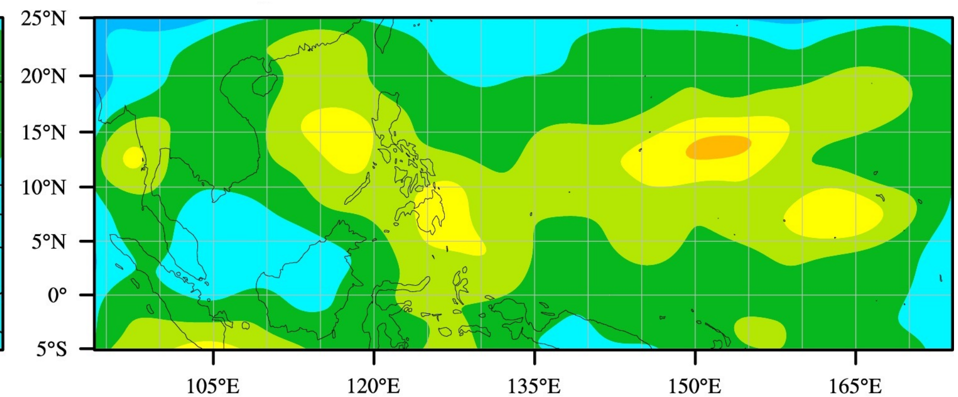
Impact of Multipath QC on 48-h Forecasts of PW

Verification with ECMWF analyses in terms of standard deviations

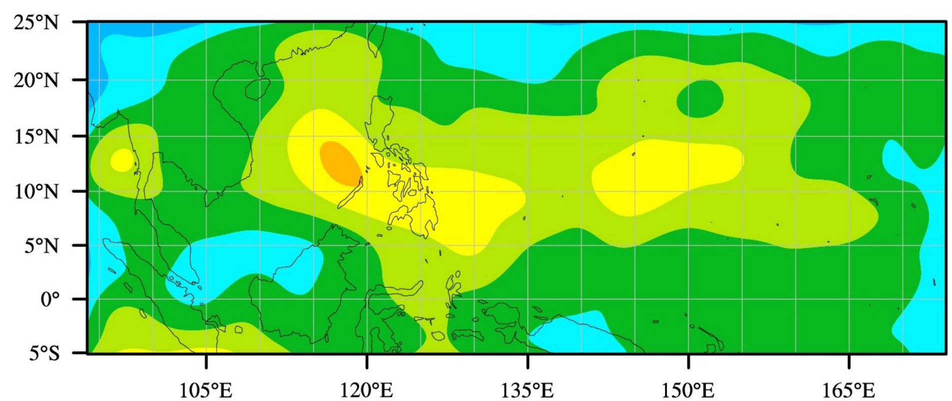
1D operator without QC



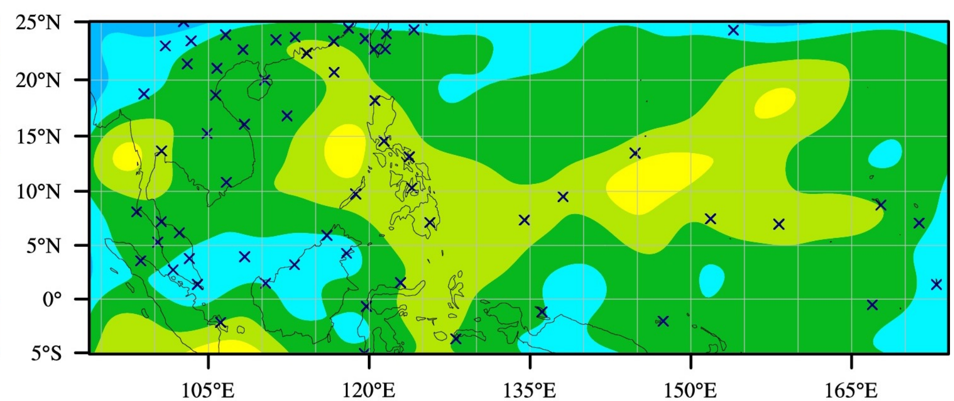
1D operator with QC



2D-limited operator without QC



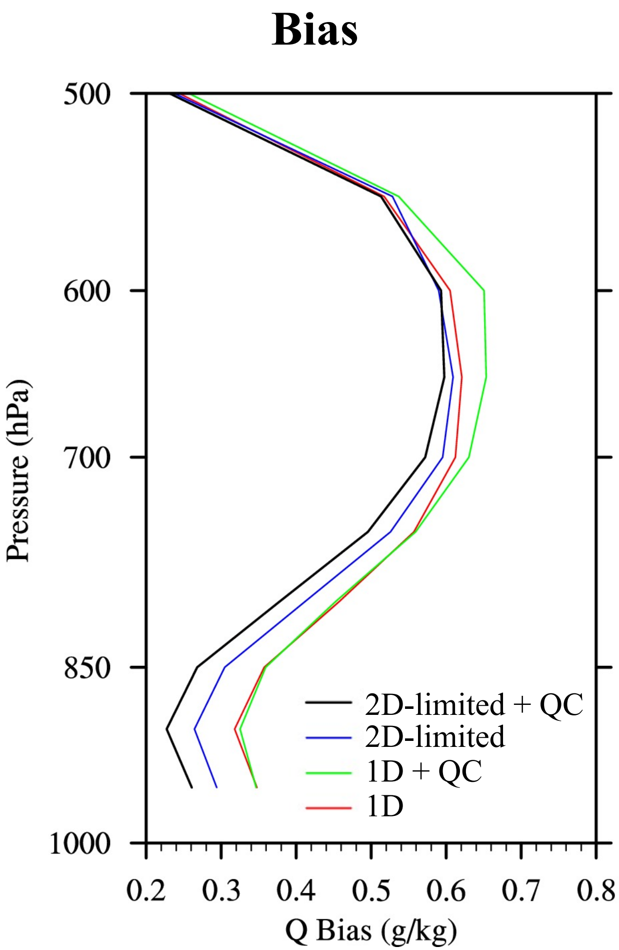
✓ 2D -limited operator with QC

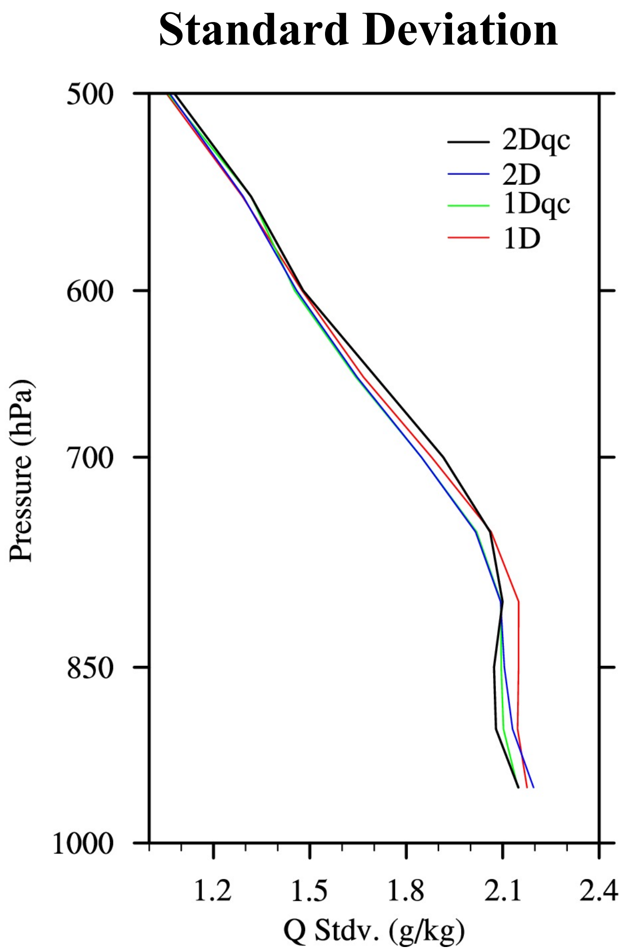


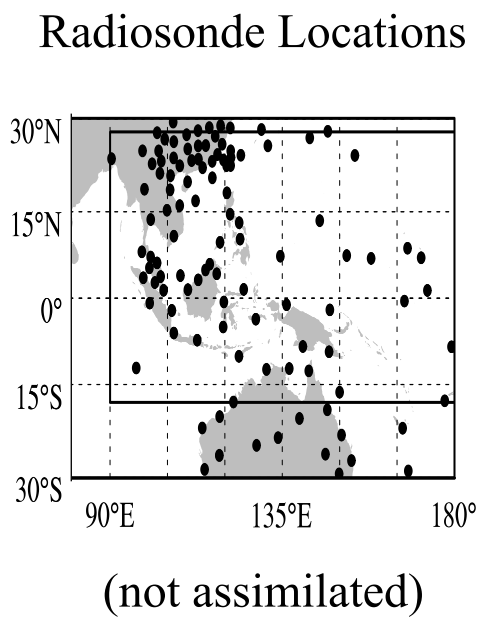
Cross Symbols are radiosonde locations.

Impact of Multipath QC on COSMIC Data Assimilation

Verification with radiosonde data for 24-h forecasts of water vapor mixing ratio



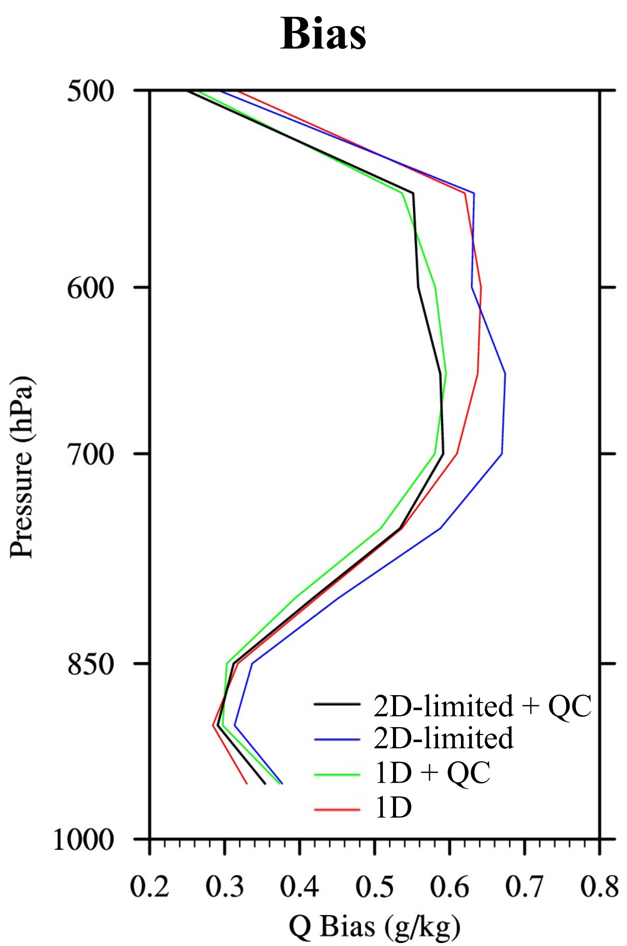


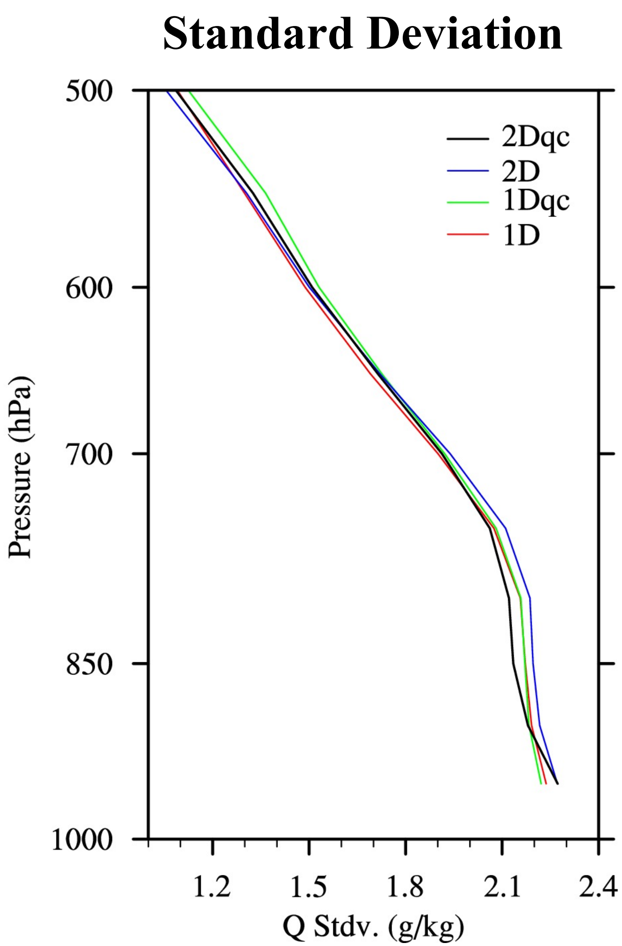


The COSMIC bending angle assimilation using the 2D limited-ray-path raytracing operator with the impact multipath QC incorporated produced the best accuracy and highest precision of the 24-h forecasts of water vapor mixing ratio among four experiments.

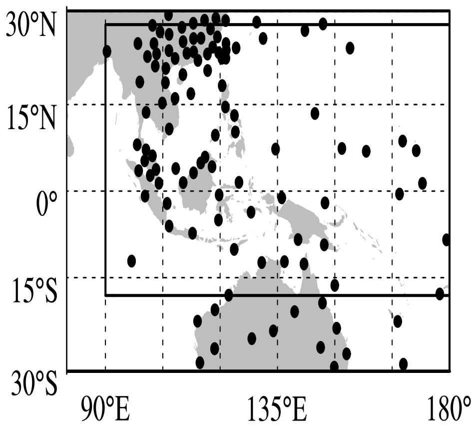
Impact of Multipath QC on COSMIC Data Assimilation

Verification with radiosonde data for 48-h forecasts of water vapor mixing ratio





Radiosonde Locations



(not assimilated)

The COSMIC bending angle assimilation using the 2D limited-ray-path raytracing and 1D operators with the impact multipath QC incorporated produced the best accuracy and highest precision of the 48-h forecasts of water vapor mixing ratio among four experiments.

Summary

- The new opportunity provided by COSMIC-2 to have many more ROs in the moist tropical lower troposphere could only be realized when multipath propagation can be effectively detected by a 2D raytracing operator for RO data assimilation

- A limited-path-length raytracing operator — Integration of the ray equation over a limited ray path length (250-400 km away from the perigee) gives the highest accuracy (bias≈0) and precision (std.<1%) for both simulations and data assimilation

- The physically based quality control on the occurrence of multipath simulations improved COSMIC data assimilation results (analyses and forecasts of water vapor) using either the 1D or the 2D observation operators of bending angle in the tropical lower troposphere

More details related to this talk can be found in the following refereed journal papers

Zou, X., H. Liu and Y.-H. Kuo, 2019: Occurrence and detection of impact multipath simulations of bending angle. *Quart. J. Roy. Meteor. Soc.*, doi: 10.1002/qj.3520.

Zou, X., H. Liu and S. Boukabara, 2019: Bending angle data assimilation using a limited-path-length 2D raytracing operator with an impact multipath quality control in the tropical low troposphere. *Quart. J. Roy. Meteor. Soc.*, (submitted)

Liu, H. and X. Zou, 2018: Comparison of GNSS bending angle simulations from the 1D Abel transform and 2D raytracing operators in the tropical lower troposphere. *Journal of Aeronautics, Astronautics and Aviation (JoAAA),* NSPO Special Issue*,* 405-414. doi: *10.6125*/JoAAA.201812_50(4).06.

Future Work to Explore COSMIC-2 Science Value

Investigate tropical cyclone genesis from and model "vortex" initialization of tropical disturbances that involve into tropical depressions, tropical storms and then hurricane intensities by using COSMIC-2 data together with other satellite data in deep ocean.

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List of Zou's publications on GPS RO related research

1. Zou, X., Y.-H. Kuo, and Y.-R. Guo, 1995: Assimilation of atmospheric radio refractivity using a nonhydrostatic adjoint model. *Mon. Wea. Rev.*, **123**, 2229-2249.
2. Ware, R., M. Exner, D. Feng, M. Gorbunov, K. Hardy, B. Herman, Y.-H. Kuo, T. Meehan, W. Melbourne, C. Rocken, W. Schreiner, S. Sokolovski, F. Solheim, X. Zou, R. Anthes, and S. Businger, 1996: GPS sounding of the atmosphere from low earth orbit: Preliminary results. *Bull. Am. Meteor.Soc.*, **77**, 19-40.
3. Rocken, C., R. Anthes, M. Exner, D. Hunt, S. Sokolovskiy, R. Ware, M. Gorbunov, W. Schreiner, D. Feng, B. Herman, Y.-H. Kuo, and X. Zou, 1997: Analysis and validation of GPS/MET data in the neutral atmosphere. *J. Geophy. Res.*, **102**, 29,849-29,866.
4. Kuo, Y.-H., X. Zou, and W. Huang, 1997: The impact of GPS data on the prediction of an extratropical cyclone: An observing system simulation experiment, *J. Dyn. Atmos. Ocean.*, **27**, 439-470.
5. Kuo, Y.-H., X. Zou, S. J. Chen, W. Huang, Y.-R. Guo, R. A. Anthes, M. Exner, D. Hunt, C. Rocken, and S. Sokolovskiy, 1998: A GPS/MET sounding through an intense upper-level front. *Bull. Am. Met. Soc.*, **79**, 617-626.
6. Zou, X., F. Vandenberghe, B. Wang, M. E. Gorbunov, Y.-H. Kuo, S. Sokolovskiy, J. C. Chang, J. G. Sela, and R. Anthes, 1999: A raytracing operator and its adjoint for the use of GPS/MET refraction angle measurements. *J. Geophy. Res.*, **104**, 22,301-22,318.
7. Zou, X., B. Wang, H. Liu, R. A. Anthes, T. Matsumura, and Y.-J. Zhu, 2000: Use of GPS/MET refraction angles in 3D variational analysis. *Quart. J. Roy. Meteor. Soc.*, **126**, 3013-3040.
8. Liu, H., X. Zou, R. A. Anthes, J. C. Chang, J.-H. Tseng, and B. Wang, 2001: The impact of 837 GPS/MET bending angle profiles on assimilation and forecasts for the period June 20-30, 1995. *J. Geophy. Res.*, **106**, 31771-31786.
9. Zou, X., H. Liu, and R. A. Anthes, 2002: A statistical estimate of errors in the calculation of radio occultation bending angles caused by a 2D approximation of raytracing and the assumption of spherical symmetry of the atmosphere. *J. Atmos. Oceanic Technol.*, **19**, 51-64.

11. Shao Hui, and X. Zou, 2002: On the observational weighting and its impact on GPS/MET bending angle assimilation. *J. Geophy. Res.*, **107**, ACL 19, 1-28.

12. Liu, H., and X. Zou, 2003: Improvements to a forward GPS raytracing model and their impacts on assimilation of bending angle. *J. Geophy. Res.*, **108**, D17, 4548.

List of Zou's publications on GPS RO related research (cont.)

13. Zou, X., H. Liu, R. A. Anthes, H. Shao, J. C. Chang, and Y.-J. Zhu, 2004: Impact of CHAMP occultation observations on global analysis and forecasts in the absence of AMSU radiance data. *J. of the Meteor. Soc. Japan*, **82**, 533-549.
14. Zou, X. and Z. Zeng, 2006: A quality control procedure for GPS RO data. *J. Geophy. Res.*, **111**, D02112, doi: 10.1029/2005JD005846.
15. Zeng, Z and X. Zou, 2006: Application of principle component analysis to CHAMP radio occultation data for quality control and a diagnostic study. *Mon. Wea. Rev.,* **134**, 3263-3282.
16. Shao, H., X. Zou, and G. A. Hajj, 2009: Test of a non-local excess phase delay operator for GPS RO data assimilation. *J. Applied Remote Sensing*, **3**(1), 033508, 16 pages.
17. Lin, L., X. Zou, R. Anthes and Y.-H. Kuo, 2010: COSMIC GPS cloudy profiles. *Mon. Wea. Rev.*, **138**, 1104-1118. doi: 10.1175/2009MWR2986.1.
18. Yang, S. and X. Zou, 2012: Assessments of cloud liquid water contributions to GPS RO refractivity using measurements from COSMIC and CloudSat. *J. Geophy. Res.*, **117**, D06219, doi:10.1029/2011JD016452.
19. Zou, X., S. Yang, and P. Ray, 2012: Impacts of ice clouds on GPS radio occultation measurements. *J. Atmos. Sci.*, **67**(12), 3670-3682.
20. Yang, S. and X. Zou, 2013: Temperature profiles and lapse rate climatology in altostratus and nimbostratus clouds derived from GPS RO data. *J. Climate*, **26,** 6000-6014.
21. Zou, X., L. Lin and F. Weng, 2014: Absolute calibration of ATMS upper level temperature sounding channels using GPS RO observations. *IEEE Trans. Geo. Remote Sensing*, **52**(2), 1397-1406.
22. Chen X. and X. Zou, 2014: Post-launch calibration of AMSU-A upper-air sounding channels using GPS RO data. *J. Geophy. Res.*, **119**, 3924-3941. doi 10.1002/2013JD021037.
23. Yang, S. and X. Zou, 2017: Lapse rate characteristics in ice clouds inferred from GPS RO and CloudSat observations. *Atmos. Res.*, **197**, 105-112. doi: 10.1016/ j.atmosres.2017.06.024.
24. Liu, H., Y.-H. Kuo, S. Sokolovskiy, X. Zou, Z. Zeng, L.-F. Hsiao and B. C. Ruston, 2018: A quality control procedure based on bending angle measurement uncertainty for radio occultation data assimilation in the tropical lower troposphere. *J. Atmos. Oceanic Technol.*, **35**, 2117-2131. doi: 10.1175/JTECH-D-17-0224.1.

List of Zou's publications on GPS RO related research (cont.)

25. Yang, S., X. Zou and P. S. Ray, 2018: Comparison of TC temperature and water vapor climatologies between Atlantic and Pacific Oceans from GPS RO observations. *J. Climate*, **31**, 8557-8571. doi: 10.1175/JCLI-D-18-0074.1.

26. Zou, X. and X. Tian, 2018: Hurricane warm core retrievals from AMSU-A and remapped ATMS measurements with rain contamination eliminated. *J. Geophy. Res.,* doi: 10.1029/2018JD028934.

27. Liu, H. and X. Zou, 2018: Comparison of GNSS bending angle simulations from 1D Abel transform and 2D raytraing operators in the tropical lower troposphere. *J. Aero., Astro. Avia.*, NSPO Special Issue, 71-80. doi: 10.6125/JoAAA. 201809_50(4).06.

28. Zou, X. and X. Tian, 2019: Comparison of ATMS striping noise between NOAA-20 and S-NPP and noise impact on hurricane warm core retrieval of Typhoon Jelawat (2018). *IEEE J-STARS*, doi: 10.1109/JSTARS.2019.2891683.

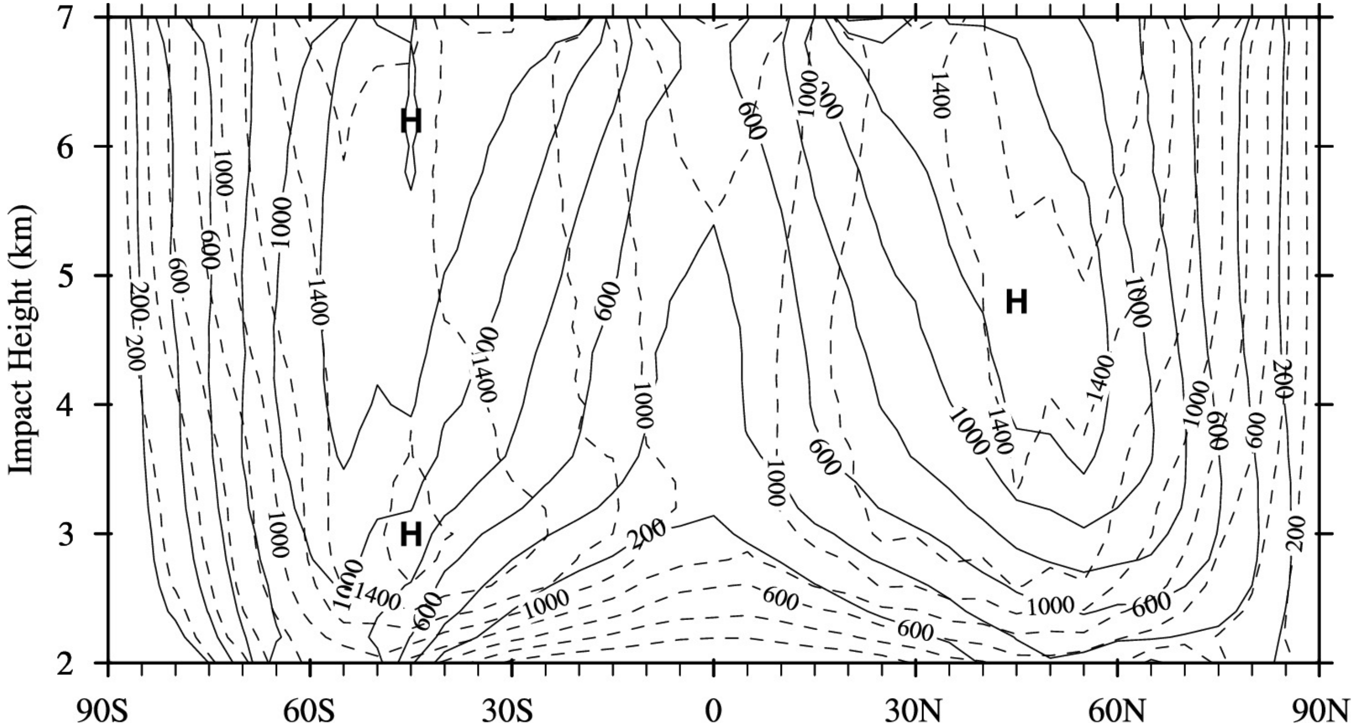
29. Zou, X., H. Liu and Y.-H. Kuo, 2019: Occurrence and detection of impact multipath simulations of bending angle. *Quart. J. Roy. Meteor. Soc.*, doi: 10.1002/qj.3520.

30. Zou, X., H. Liu and S. Boukabara: Bending angle data assimilation using a limited-path-length 2D raytracing operator with an impact multipath quality control in the tropical low troposphere. *Quart. J. Roy. Meteor. Soc.*, (submitted)

Major research topics covered in the above publications:

- GPS RO data assimilation (observation operators, observation errors, assimilation)
- GPS RO data for post-launch calibration of microwave observations
- Contributions of cloud liquid water content and ice water content to GPS RO data
- Use of GPS RO for hurricane warm core retrieval
- Hurricane structures derived from GPS RO data

Data Count for Slide 4



Zonally average RO profile counts when (O-1D)>0 (solid curve) and (O-1D)<0 (dashed curve) during the time period from March 19 to April 30, 2017. The statistics are averaged in each 5^{o} latitude and 200-m height box.