Lessons Learned from the Preparation and Evaluation of Multiple GNSS RO Data for the ROMEX from NOAA/STAR

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Outlines

1. **Motivation**

Using ROMEX data to answer

a. Does higher Signal-Noise-Ratio RO data provide smaller observation errors?

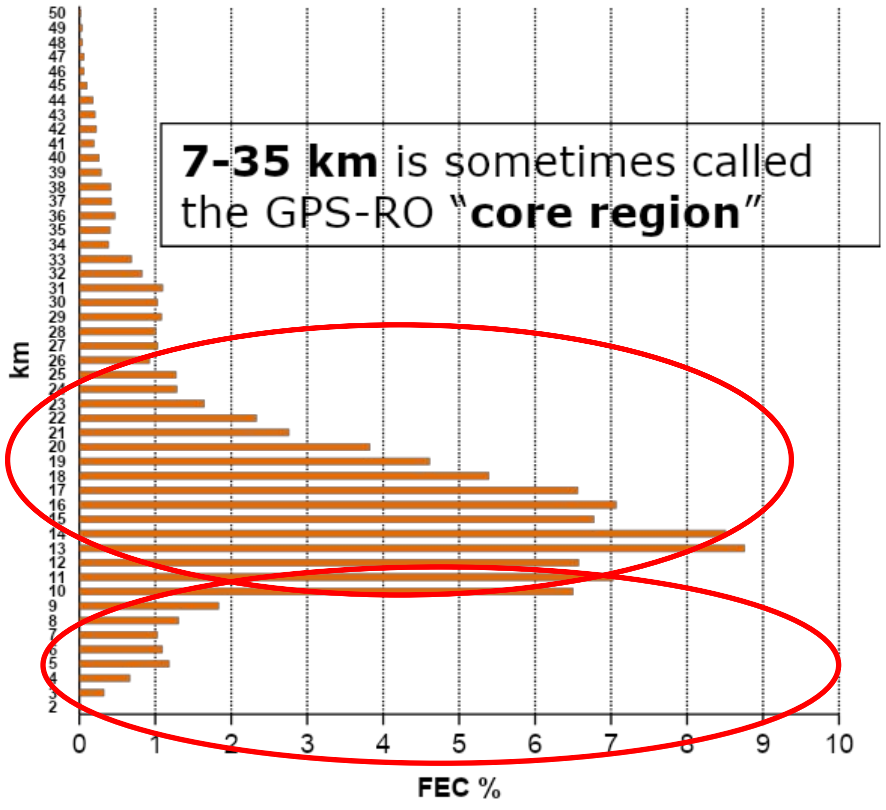
b. Are data from different RO missions of the same quality?

c. Can we still use multiple RO data to construct UT/LS temperature MMC

d. What are the criteria for future NESDIS backbone RO missions?

2. **Approaches**
3. **Results**
4. **Conclusions and Lessons Learned**

Heights where GNSS-RO is reducing the 24hr forecast errors

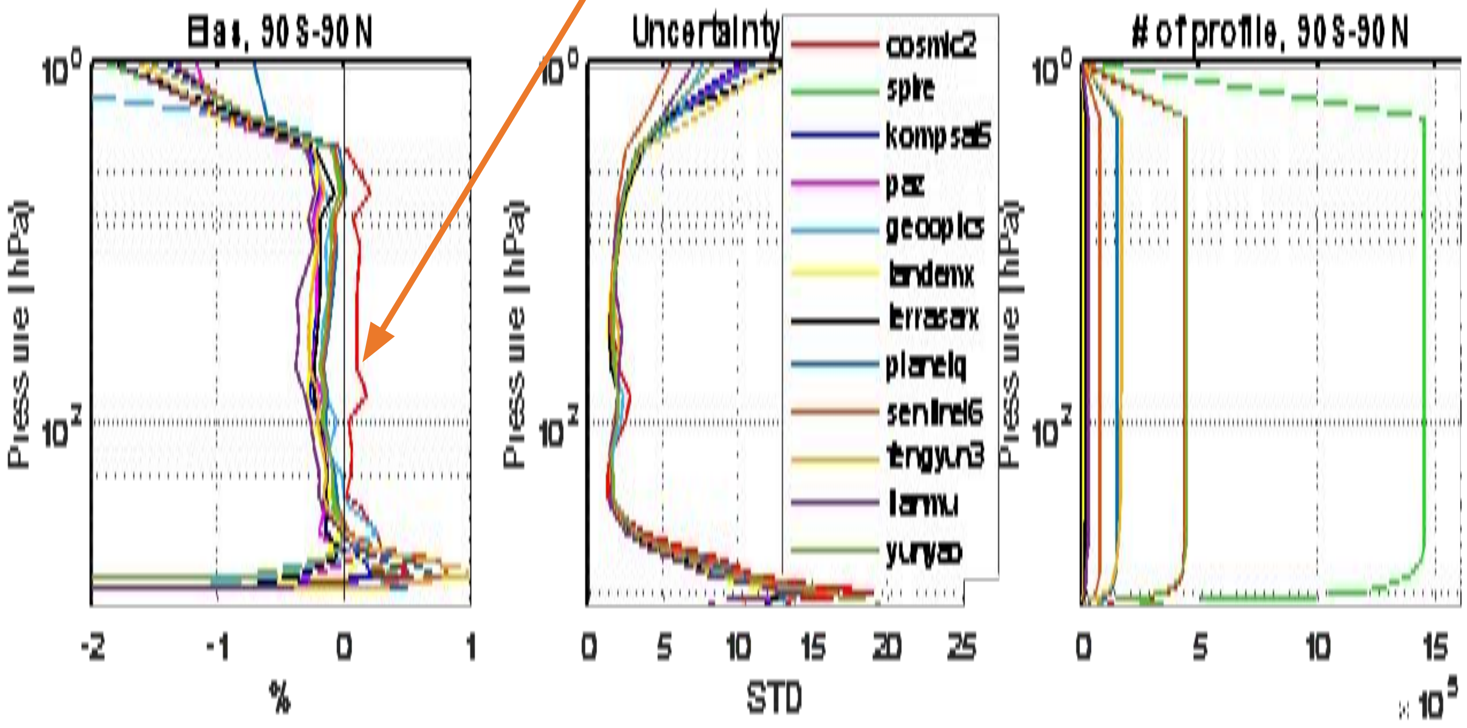


Florian Harnisch, Sean Healy, Peter Bauer, Steve English, Nick Yen, 2013

Ho et al., BAMS (2019)

ROMEX biases vs ERA5

UCAR COSMIC-2 (45N-45S)



My results shows negative biases of ~-0.1 to -0.4 from about 4 km up to 35 km for all ROMEX missions except C2, which shows a positive bias of about 0.05 to 0.10 %. So C2 appears to have a positive bias compared
to the other missions by about 0.3%
(Heights are approximate)

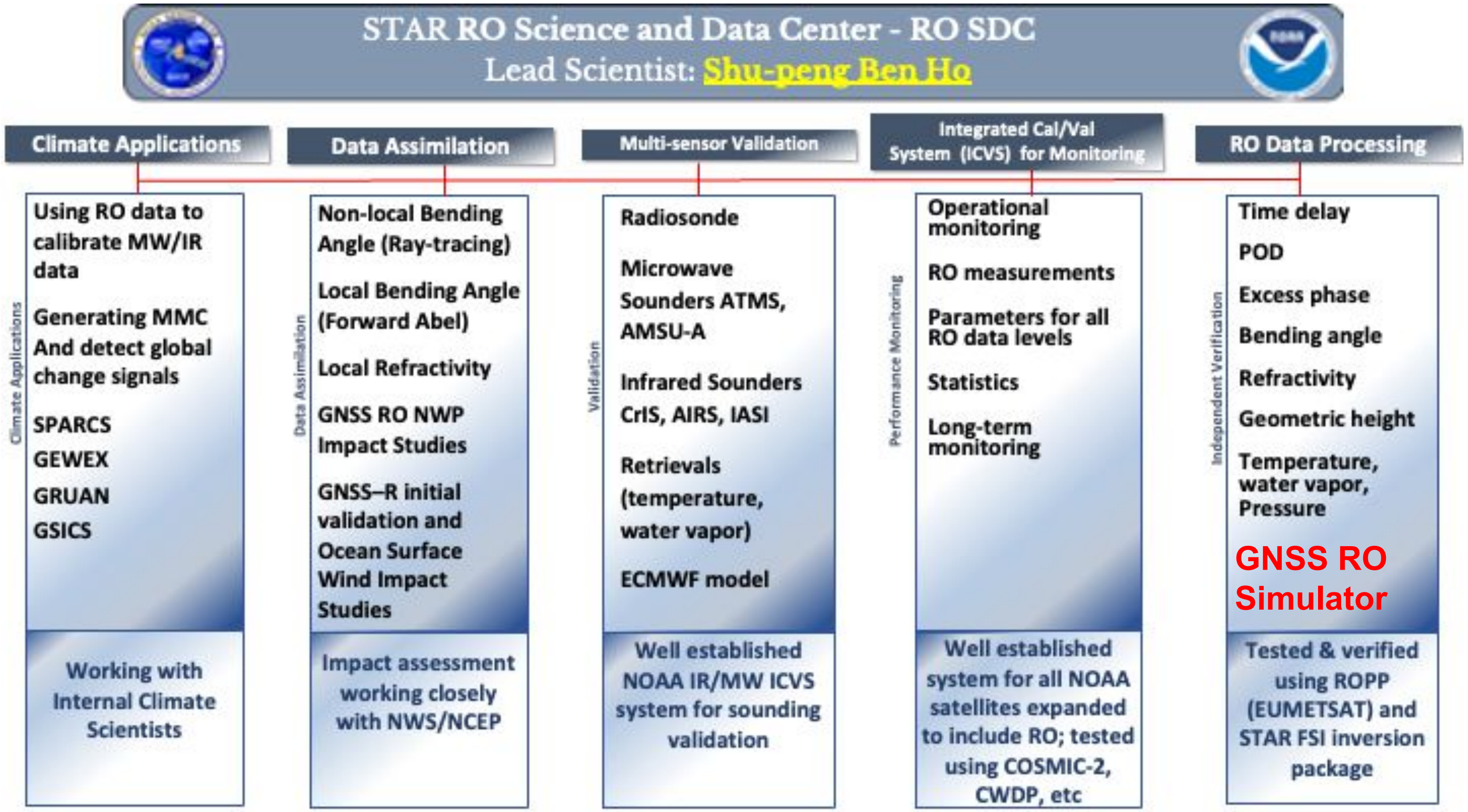
UCAR COSMIC-2 (and others) are used as control runs for ROMEX. Will UCAR COSMIC-2 BA positive biases affect the results for other ROMEX DA experiments ?

2. Approaches
Processing RO data

STAR Science and Data Center

GNSS-R
OSW
Impacts on TCs forecast through data assimilation

PRO data processing

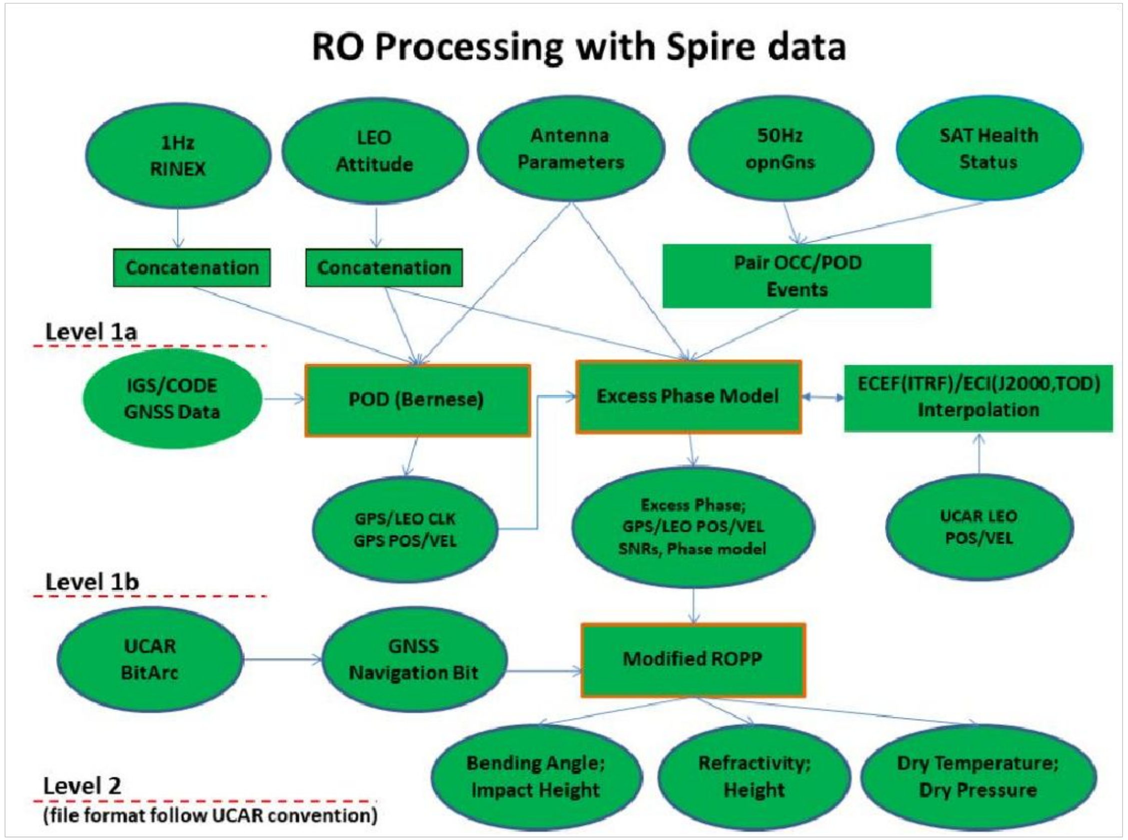


STAR RO Data FTP site: https://gpsmet.umd.edu/star_gnssro/download.html

STAR RO DSC aims to develop enterprise RO processing algorithms for all RO missions, like other NOAA infrared and microwave satellite missions.

STAR ROPP package and STAR Full Spectrum Inversion package

https://gpsmet.umd.edu/RO/web_grouppublication.php and check publications (also see https://www.researchgate.net/profile/Shu-Peng-Ho/publications)



Option 1: Access Data from HTTP server

RO mission	STAR ROPP atmPrf Data on HTTP server	STAR ROPP atmPrf ICVS Monitoring & Doc	STAR 1Dvar wetPrf Data on HTTP server	STAR 1Dvar wetPrf ICVS Monitoring & Doc
COSMIC-2	Near Real Time Post-Processing	ICVS Monitoring ATBD	Near Real Time Post-Processing	ICVS Monitoring ATBD
COSMIC-1	Post-Processing	ICVS Monitoring ATBD	Post-Processing	ICVS Monitoring ATBD
Spire	Post-Processing	ICVS Monitoring ATBD	Post-Processing	ICVS Monitoring ATBD
GRAS Metop-A	Post-Processing	ICVS Monitoring ATBD	Post-Processing	ICVS Monitoring ATBD
GRAS Metop-B	Near Real Time Post-Processing	ICVS Monitoring ATBD	Near Real Time Post-Processing	ICVS Monitoring ATBD
GRAS Metop-C	Near Real Time Post-Processing	ICVS Monitoring ATBD	Near Real Time Post-Processing	ICVS Monitoring ATBD
KOMPSAT-5	Near Real Time Post-Processing	ICVS Monitoring ATBD	Near Real Time Post-Processing	ICVS Monitoring ATBD
PAZ	Near Real Time Post-Processing	ICVS Monitoring ATBD	Near Real Time Post-Processing	ICVS Monitoring ATBD

Option 2: Access Data from FTP server

ftp starro.umd.edu
username: anonymous
cd starro/data/
The directory structure is the same as on the HTTP server in option 1

STAR RO Data FTP site: https://gpsmet.umd.edu/star_gnssro/download.html

See Yong Chen's poster: Processing multiple GNSS RO data at NOAA/STAR using FSI and ROPP: initial results from the ROMEX Missions

3. Results

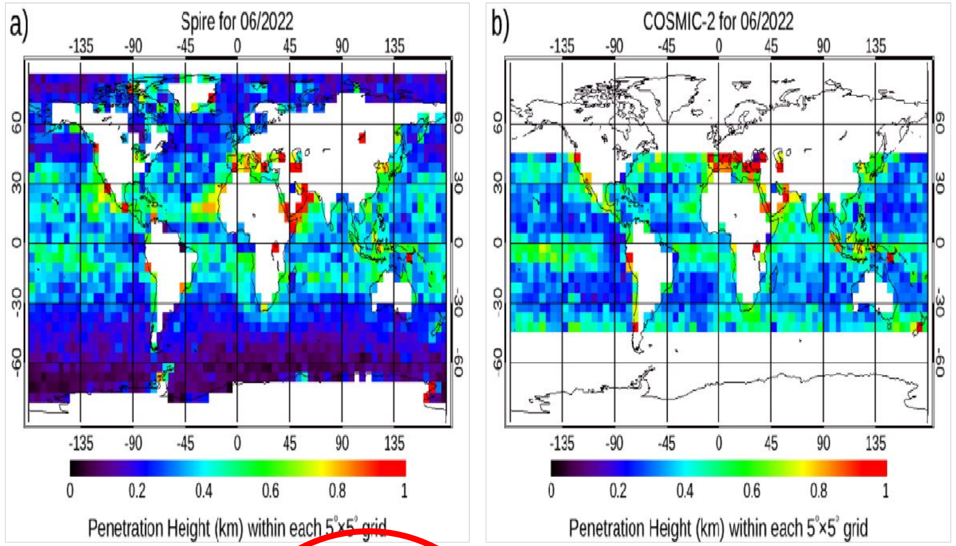
a. Does higher Signal-Noise-Ratio RO data provide smaller observation errors?

The global mean of the lowest penetration height in June 2022 binned into 5°× 5° grid

Spire

COSMIC-2

Penetration Height



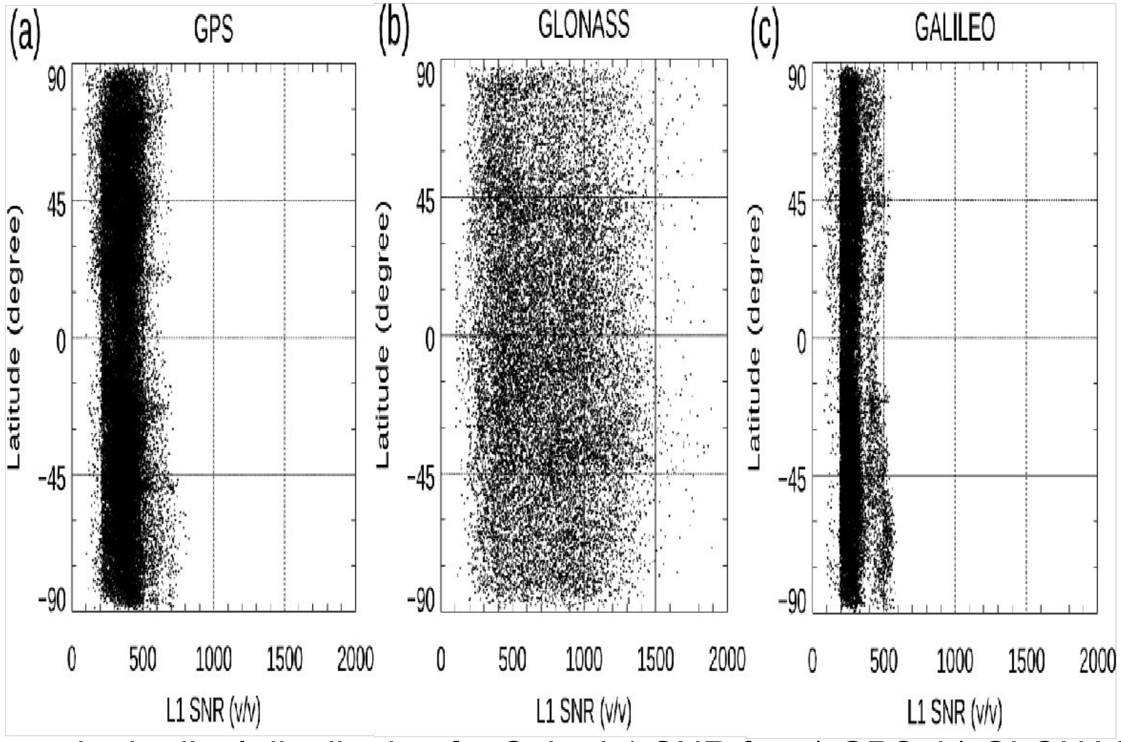
We usually use the SNR to indicate the strength of RO signals in penetrating the lower troposphere (Ho et al., 2023). The lowest penetration height of RO tracking is usually related to the data's SNR and the atmosphere's dryness. However, because the high SNR signals still cannot resolve the combination of i) complexity of water vapor along the track, ii) the turbulence effects, iii) the instrument effect (see Ao et al., 2022), we did not see high SNR RO data improv i) retrieval accuracy, and ii) retrieval uncertainty in the lower troposphere (Ho et al., 2022, 2023).

	10°N-10°S	30°N-10°N	10°S-30°S	45°N-30°N	30°S-45°S	60°N-45°N	45°N-60°S	90°N-60°N	60°S-90°S
COSMIC-2	0.85	0.90	0.75	1.35	1.10				
Spire	0.90	0.90	0.75	0.80	0.55	0.45	0.25	0.45	0.20
KOMPSAT-5	1.85	1.50	1.15	0.40	0.95	0.35	0.40	0.25	0.20
PAZ	2.65	1.85	2.05	0.90	1.30	0.45	0.45	0.35	0.35

The lowest penetration height of 80% of the total data for different RO missions at different latitudinal zones.

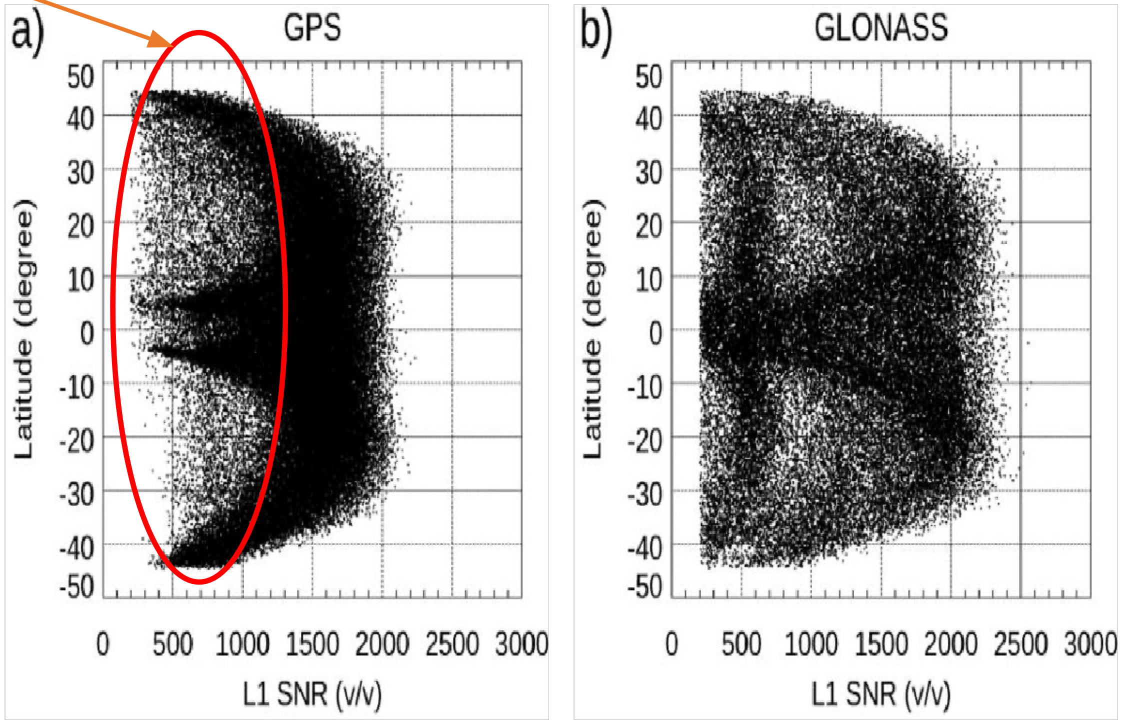
the information of the antenna gain pattern related to the viewing geometry

Small SNRs are mainly from larger viewing azimuth angle (see page 7, and see paper below)



Latitudinal distribution for Spire L1 SNR for a) GPS, b) GLONASS, and c) GALILEO

Spire

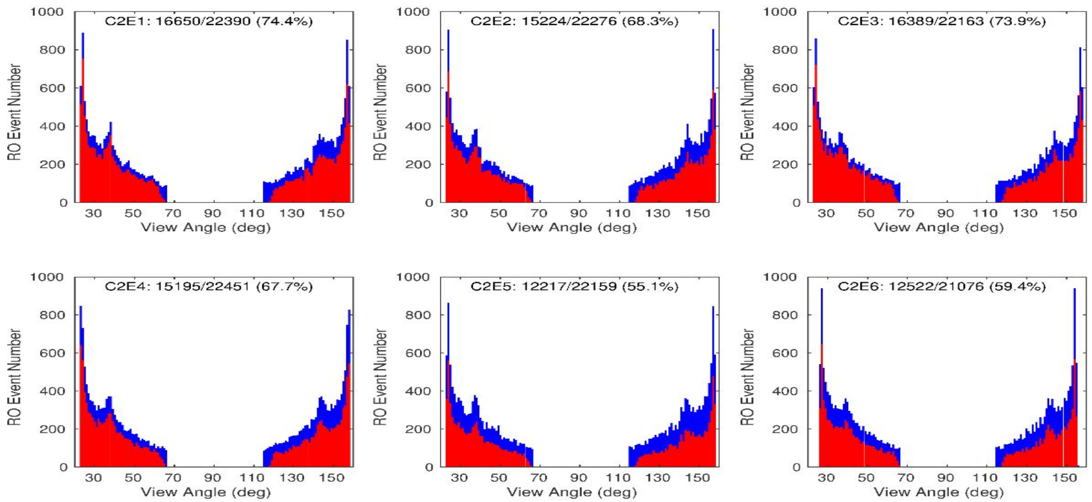


Latitudinal distribution for COSMIC-2 L1 SNR from February 15 to March 15, 2022, for a) GPS and b) GLONASS.

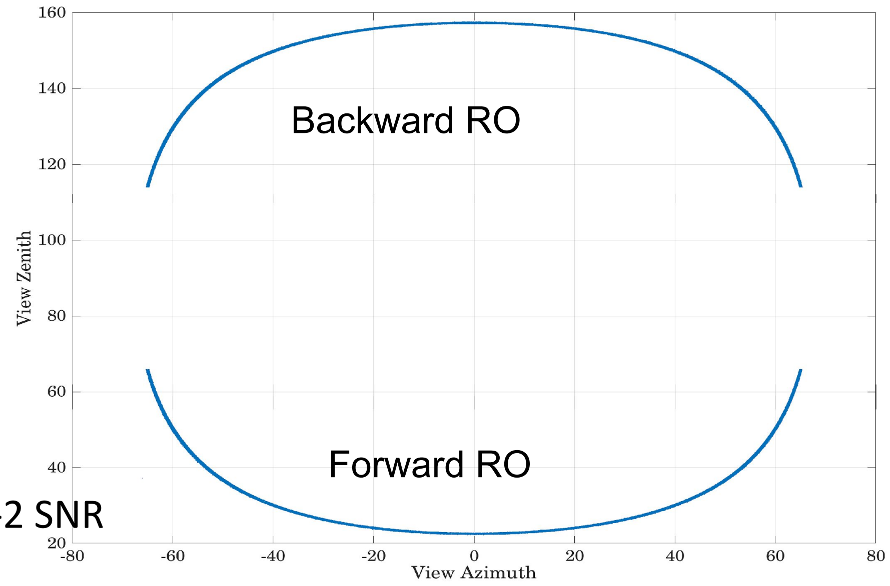
COSMIC-2

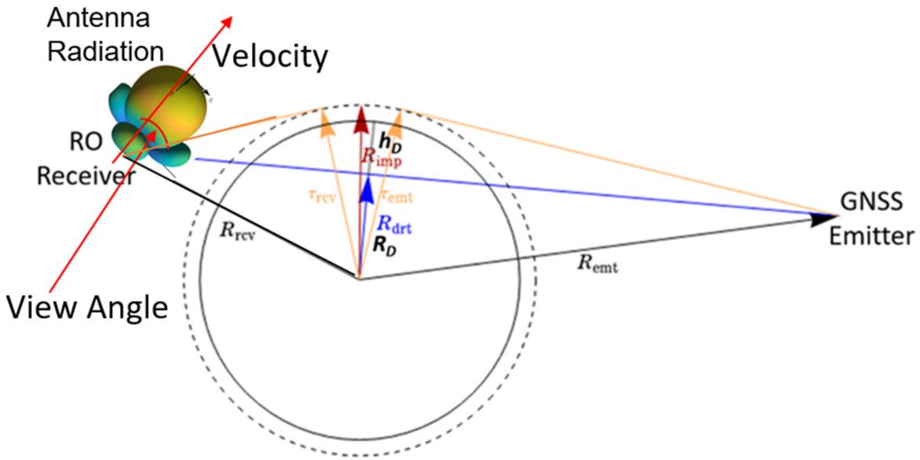
Ho, S.-p.; Zhou, X.; Shao, X.; Chen, Y.; Jing, X.; Miller, W. Using the Commercial GNSS RO Spire Data in the Neutral Atmosphere for Climate and Weather Prediction Studies. *RemoteSens.* **2023**, *15*, 4836. https:// doi.org/10.3390/rs15194836

COSMIC-2



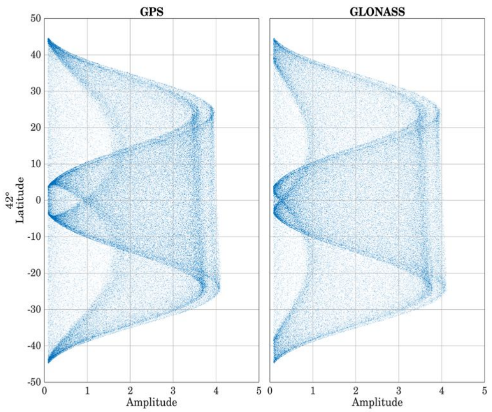
Relationship between View Zenith and View Azimuth Angle for RO Limb Sounding

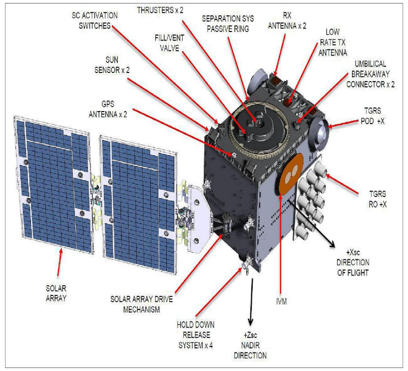


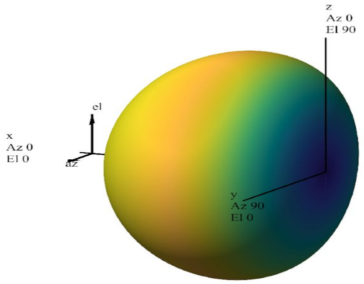


Simulated Distribution of COSMIC-2 SNR

(3x4 Phase Array Antenna)



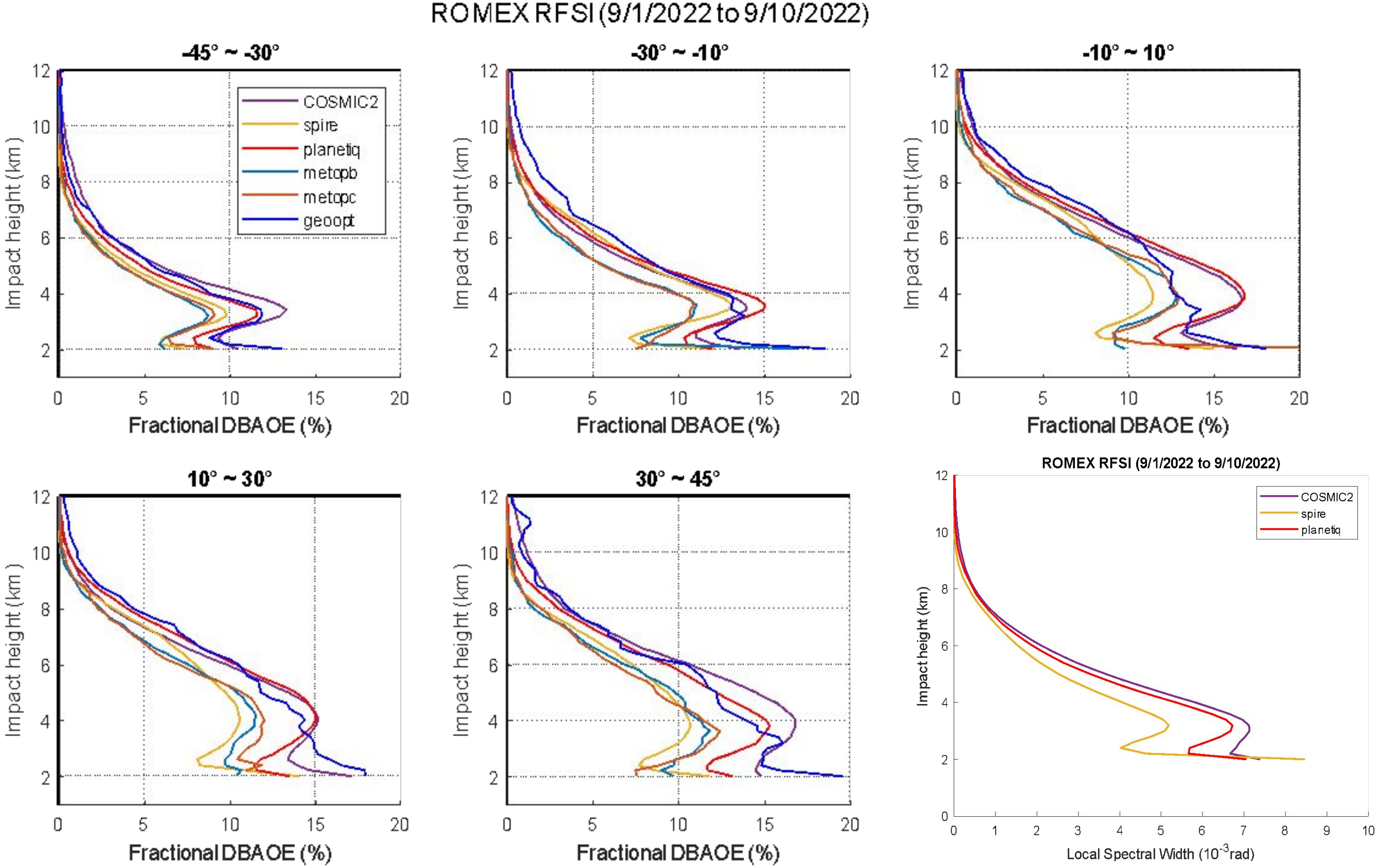




See Tom Liu's poster: A Completed Simulation Tool to Explore the Optimal Configuration for the NOAA's Future GNSS RO Architecture Missions

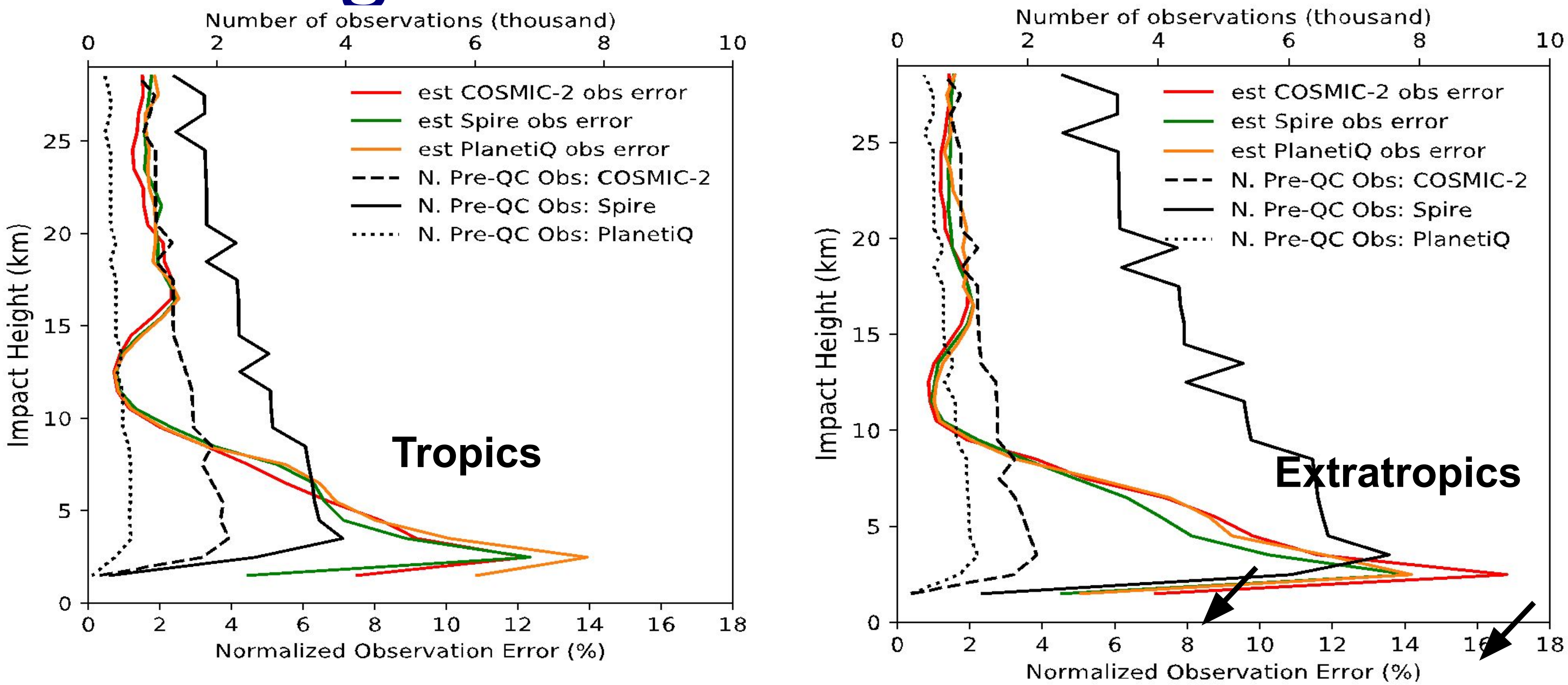
b. Are data from different RO missions of the same quality?

DBAOE latitudinal distribution



(see Xin Jing's poster: Characterizing the Uncertainty of GNSS RO Bending Angles in the Lower Troposphere with the Local Spectral Width Analysis)

Diagnosed Observation Errors

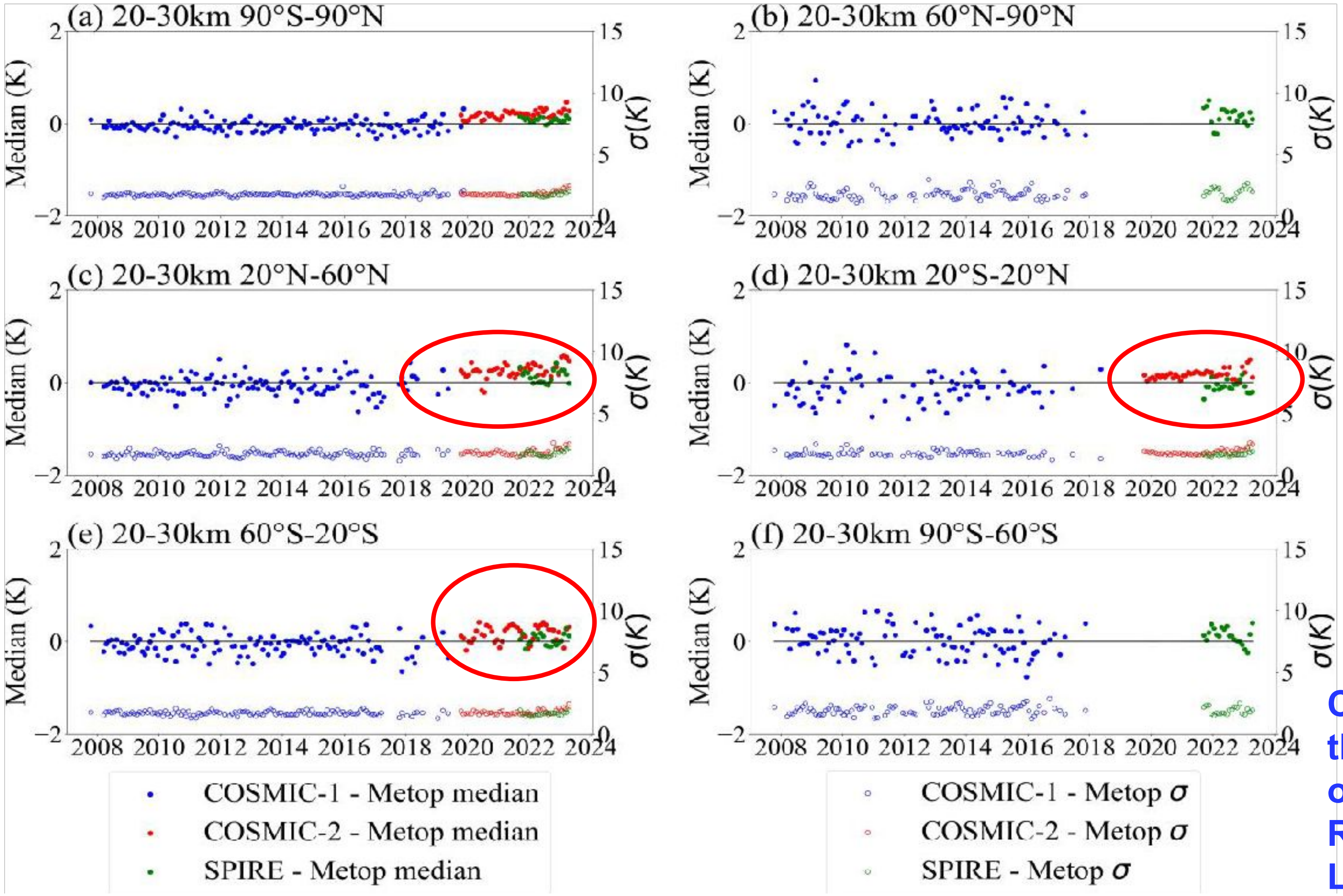


- Use Desroziers et al. (2005): $\widetilde{\sigma_i^o}^2 = \frac{(d_b^o)_i^T (d_a^o)_i}{p_i} = \sum_{j=1}^{p_i}(y_j^o - y_j^b)(y_j^o - y_j^a)/p_i$

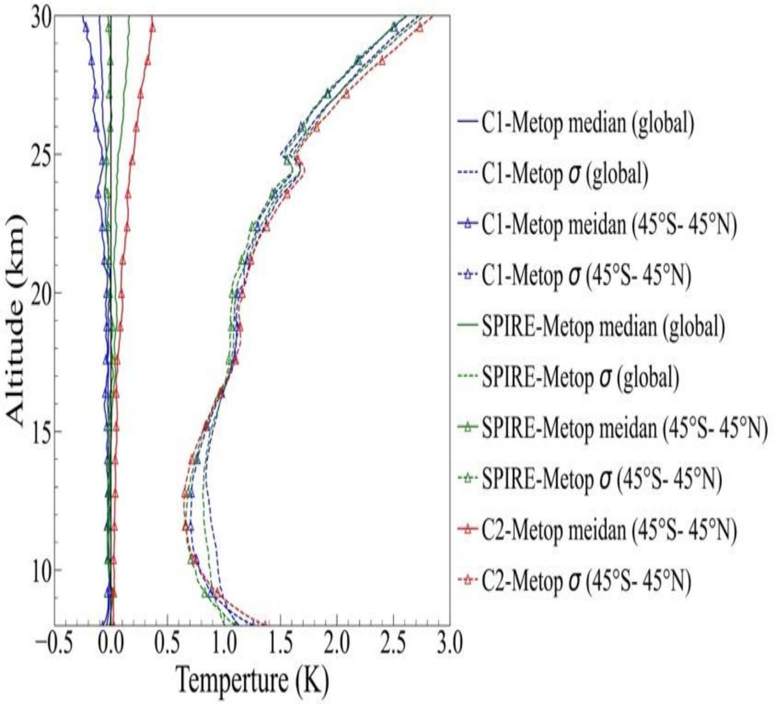
(see Will Miller's talk: Does Assimilating PlanetIQ and Spire GNSS RO Bending Angles Improve HAFS Forecasts of Four 2022 Atlantic Hurricanes? An Evaluation in Support of the ROMEX Experiment)

C. Can we still use multiple RO data to construct UT/LS temperature MMC

i) RO-RO comparisons



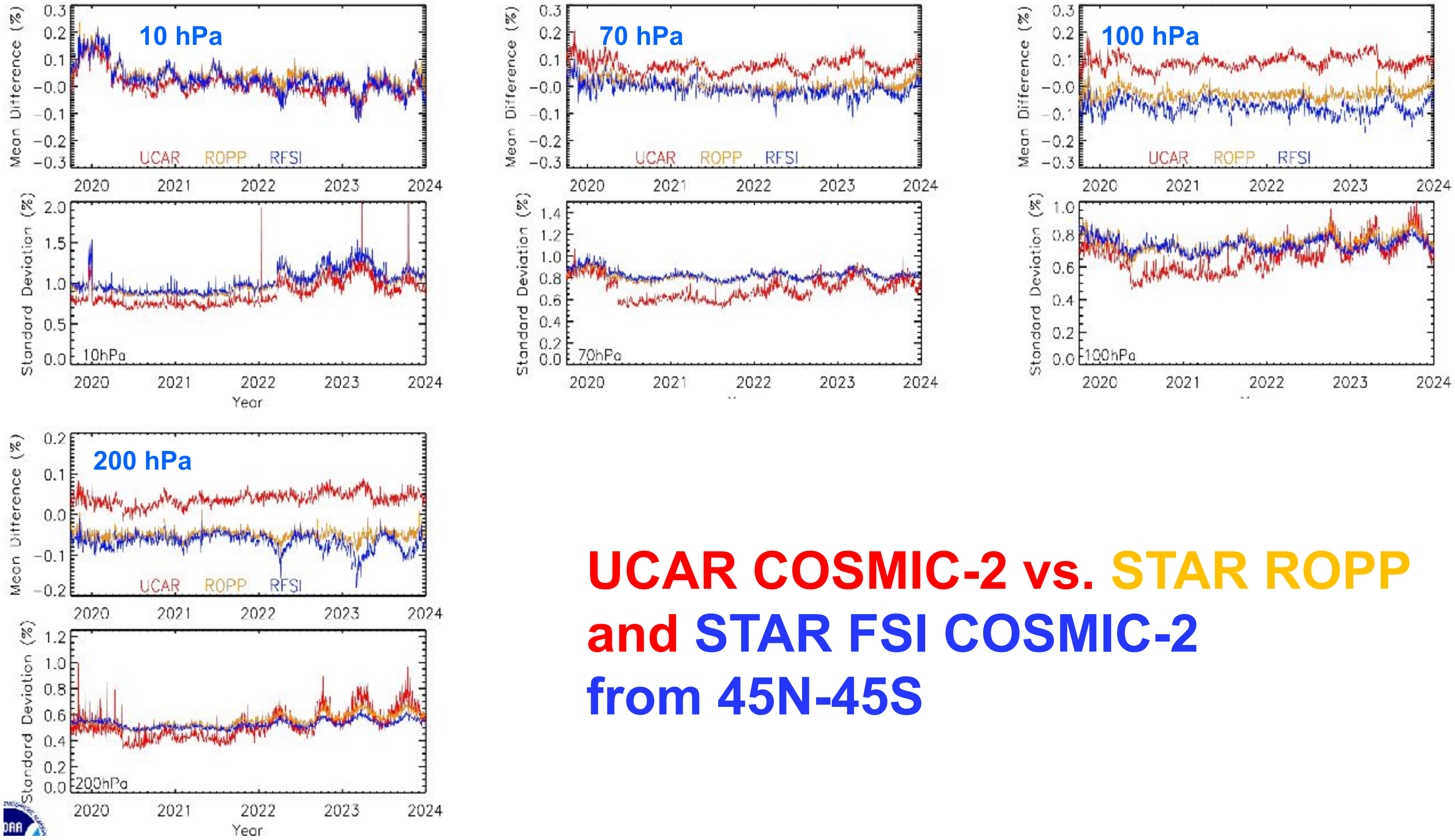
RO – Metop GRAS



Jun Zhou et al., 2024 (JGR)

Check Jun Zhou's poster: Investigating the Impact of Residual Ionospheric Error on GNSS RO Temperature Climate Data Records in the Upper Troposphere and Lower Stratosphere (UTLS)

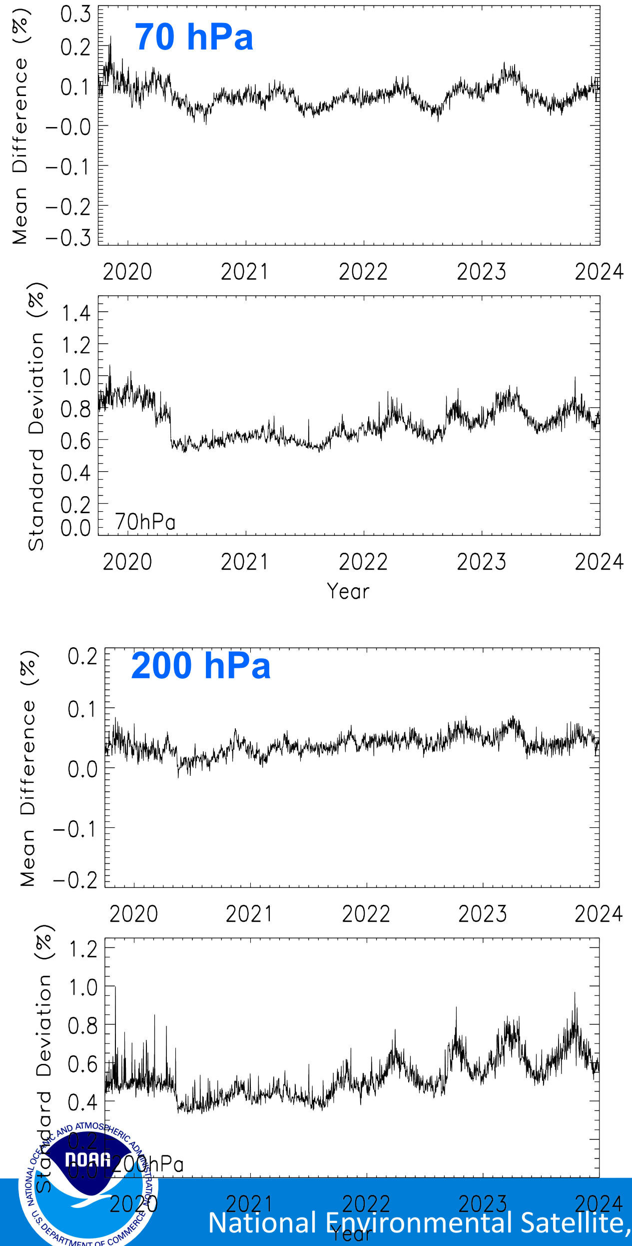
COSMIC-2 Time Series Refractivity Compared to ERA-5



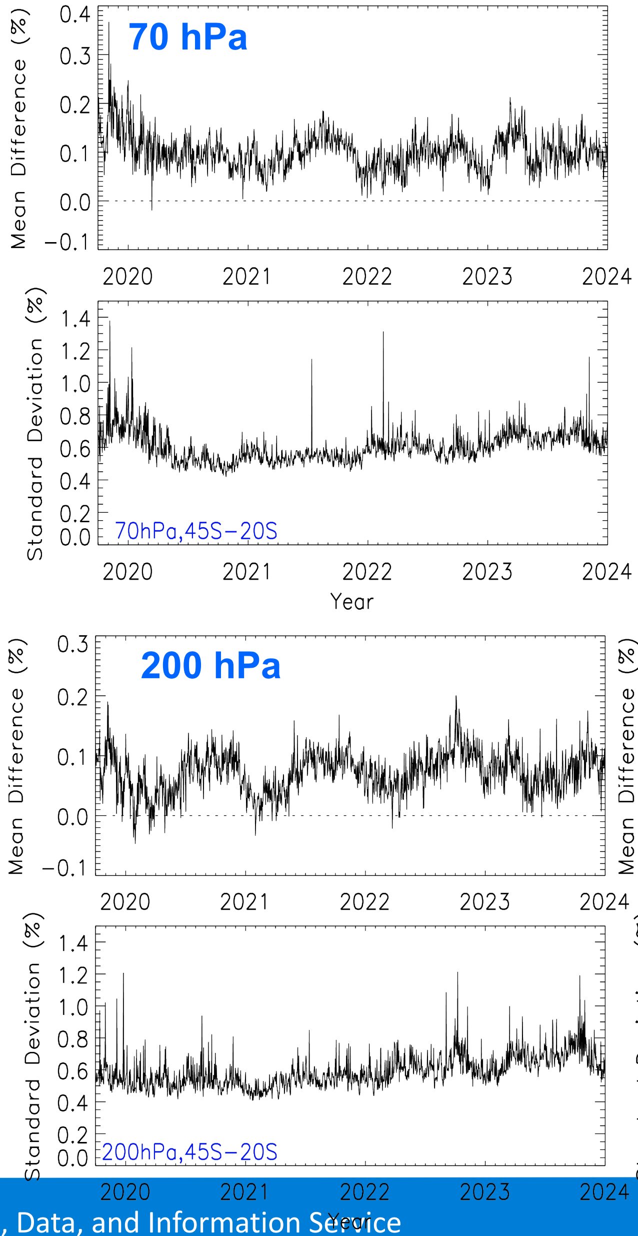
UCAR COSMIC-2 vs. STAR ROPP and STAR FSI COSMIC-2 from 45N-45S

UCAR COSMIC-2

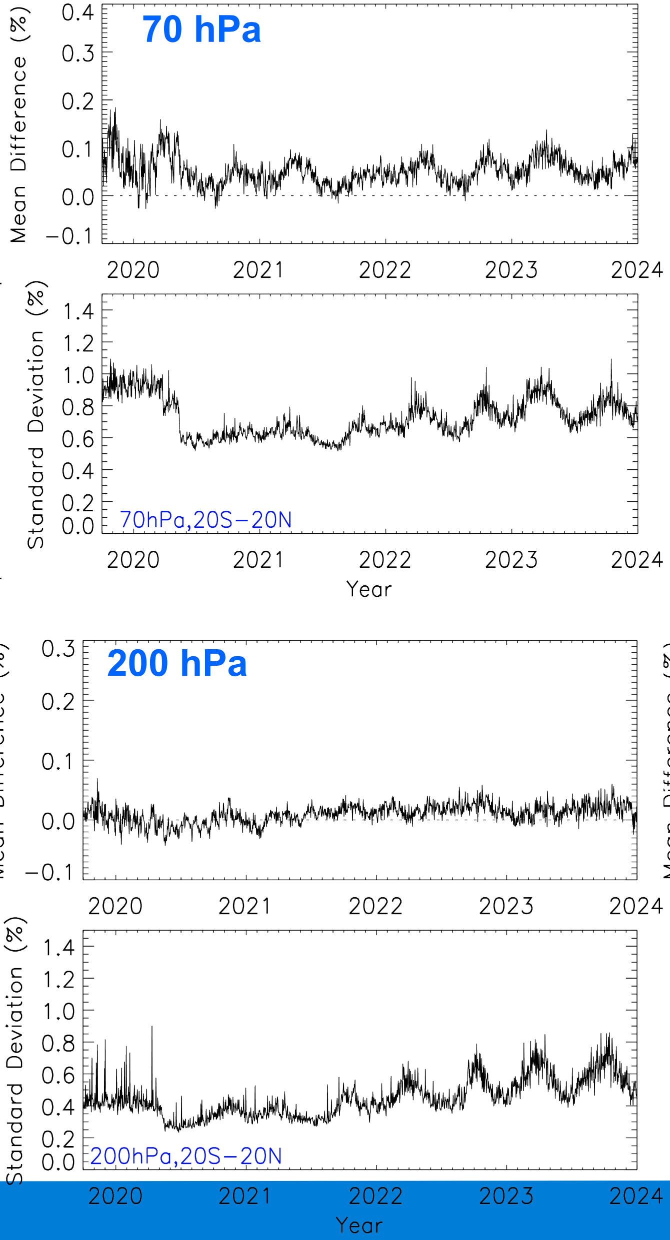
Refractivity 45S-45N



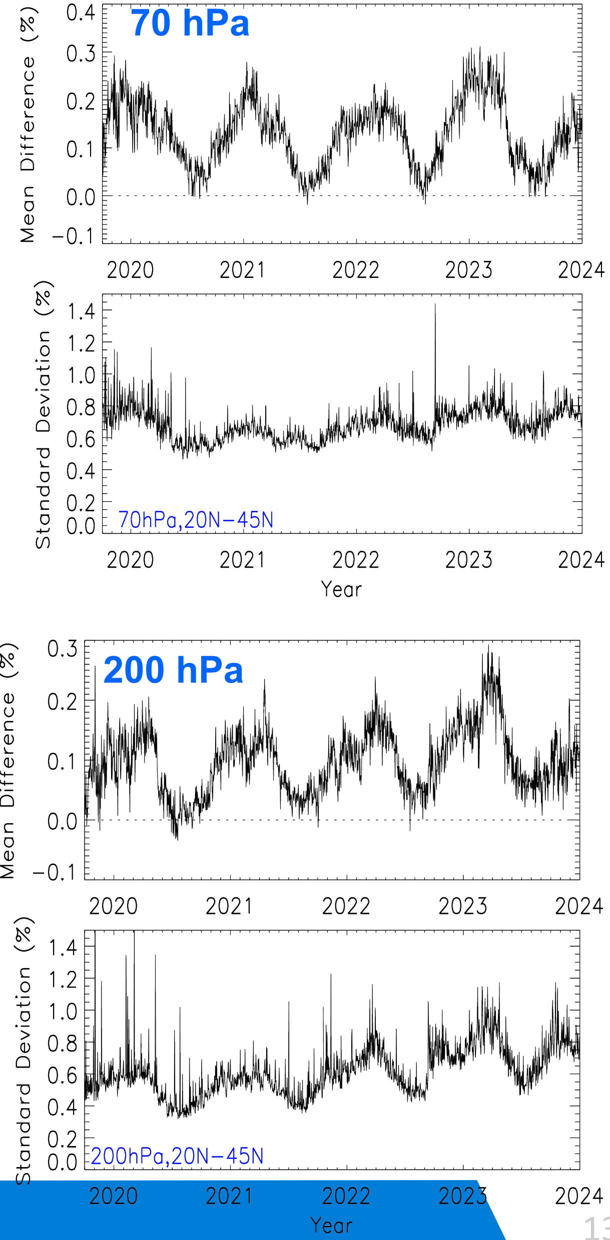
Refractivity 45S-20S



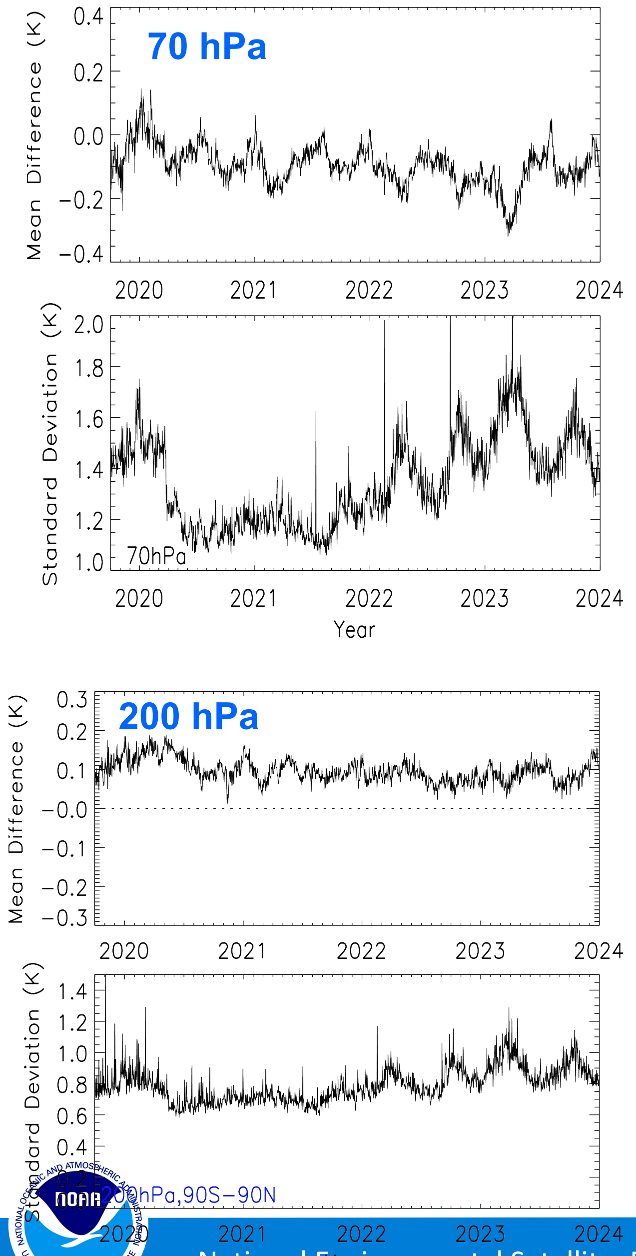
Refractivity 20S-20N



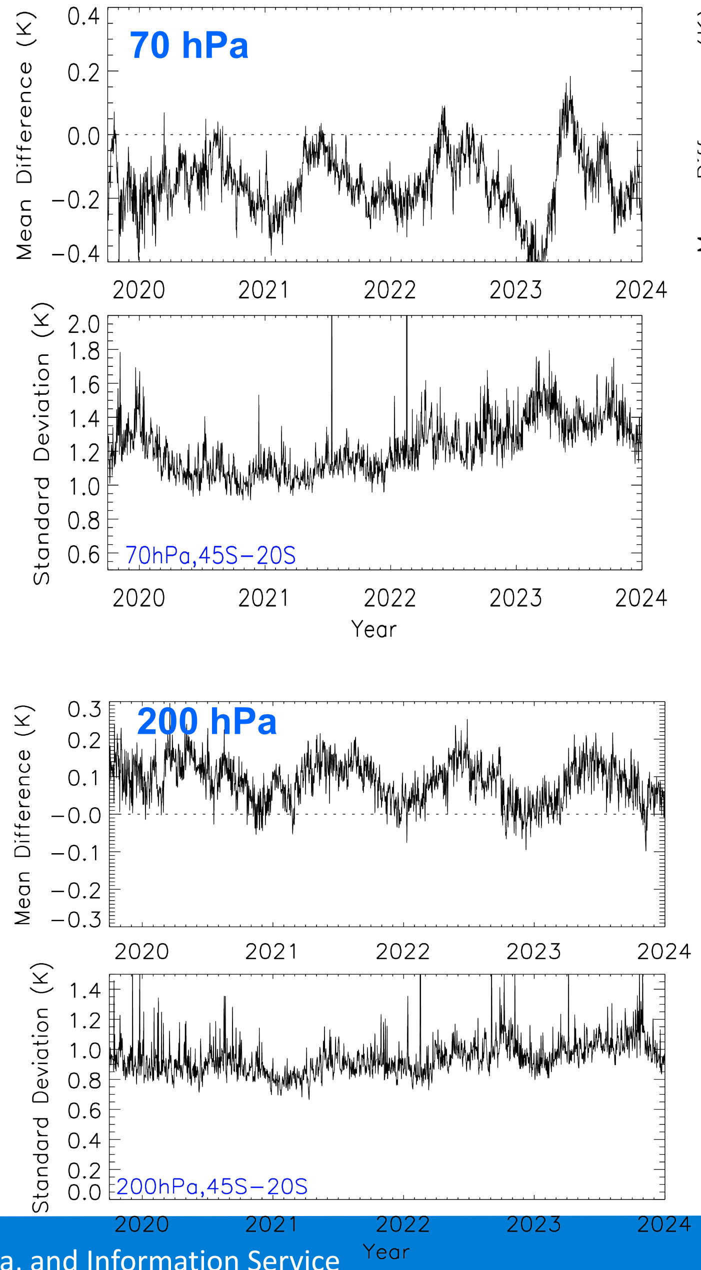
Refractivity 20N-45N



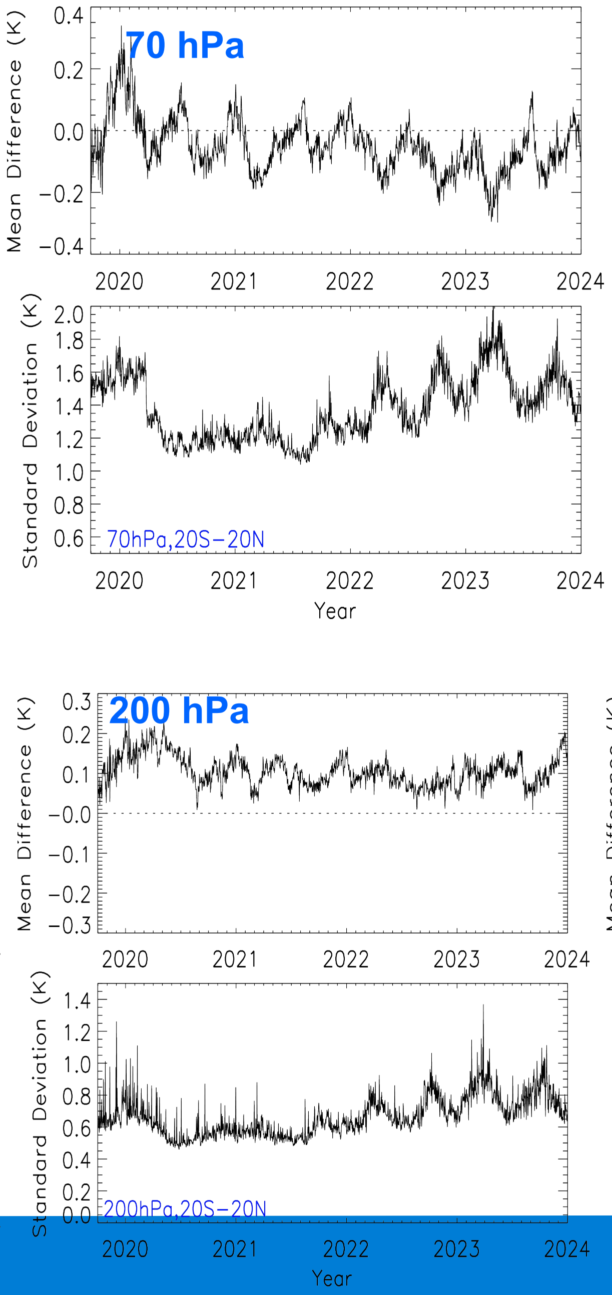
Temperature 45S-45N



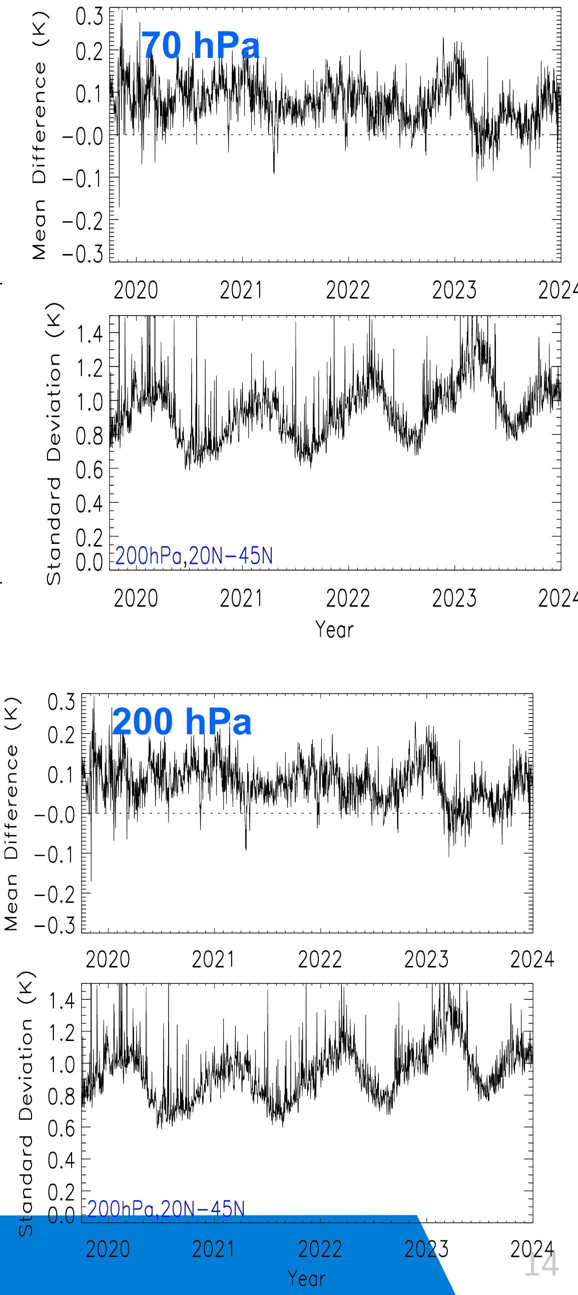
Temperature 45S-20S



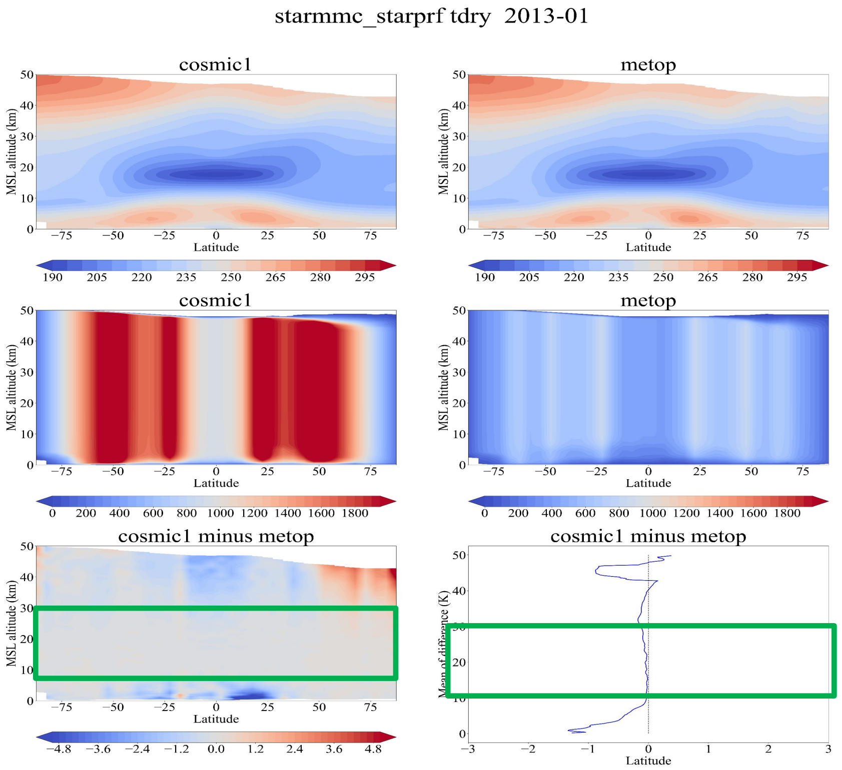
Temperature 20S-20N



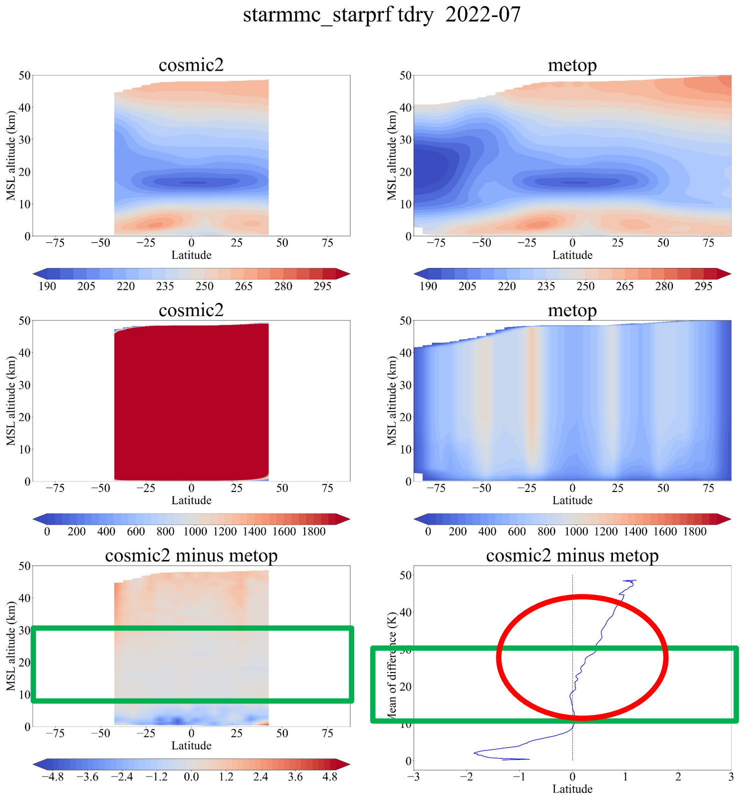
Temperature 20N-45N



ii) MMC comparisons in one month



Range of the difference between 8-30 km: -0.13 ~ -0.01 K



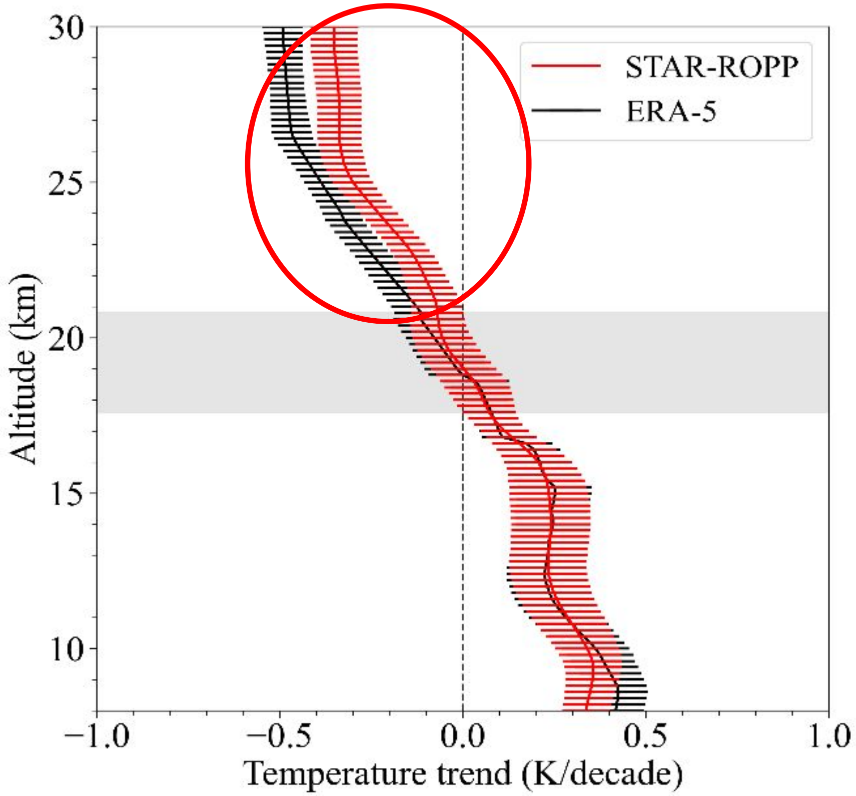
Range of the difference between 8-30 km: -0.07 ~ 0.45 K

- Bias between C2 and Metop from 20-30 km is much larger than that between C1 and Metop.
- Compared to C1 and Metop in 2013-01, C2 and Metop in 2022-07 have much larger sampling number which should result in less residual sampling error.
- The large bias between C2 and Metop is likely caused by residual ionospheric error.

iii) Construction of temperature climate data records in the upper troposphere and lower stratosphere using multiple RO missions from 2006 to 2023

RO mission	Data coverage
SPIRE	Sep 2021 to Jul 2023
COSMIC2	Oct 2019 to Jul 2023
COSMIC1	Apr 2006 to Apr 2020
Metop-A	Oct 2007 to Nov 2021
Metop-B	Feb 2013 to Mar 2023
Metop-C	Jul 2019 to Feb 2023

With COSMIC-2

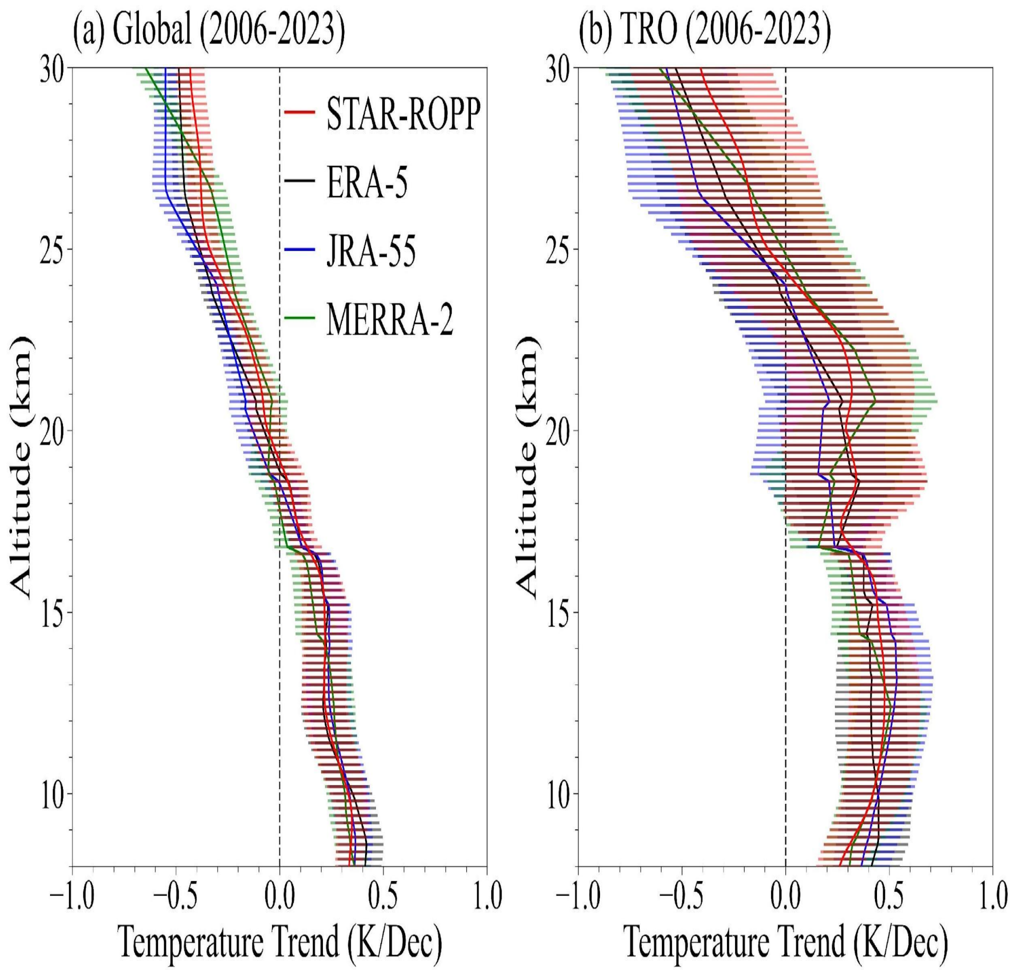


Vertically resolved temperature trends were estimated from STAR-ROPP (red) and ERA-5 (black) data sets. Error bars represent the trend uncertainty at the 95% confidence level. The shaded area denotes the altitude levels where temperature trends are insignificant.

iv) Construction of temperature climate data records in the upper troposphere and lower stratosphere using multiple RO missions from 2006 to 2023

RO mission	Data coverage
SPIRE	Sep 2021 to Jul 2023
COSMIC1	Apr 2006 to Apr 2020
Metop-A	Oct 2007 to Nov 2021
Metop-B	Feb 2013 to Mar 2023
Metop-C	Jul 2019 to Feb 2023

No COSMIC-2



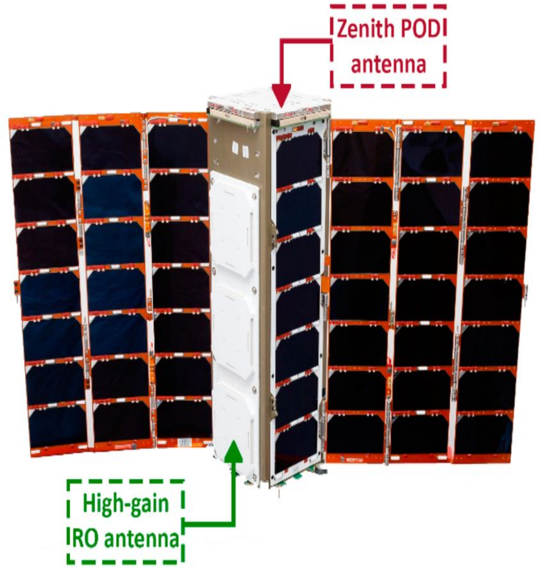
4. Conclusions

Q. What are the criteria for future NESDIS backbone RO missions?

RO backbone (ROBB) vs. others

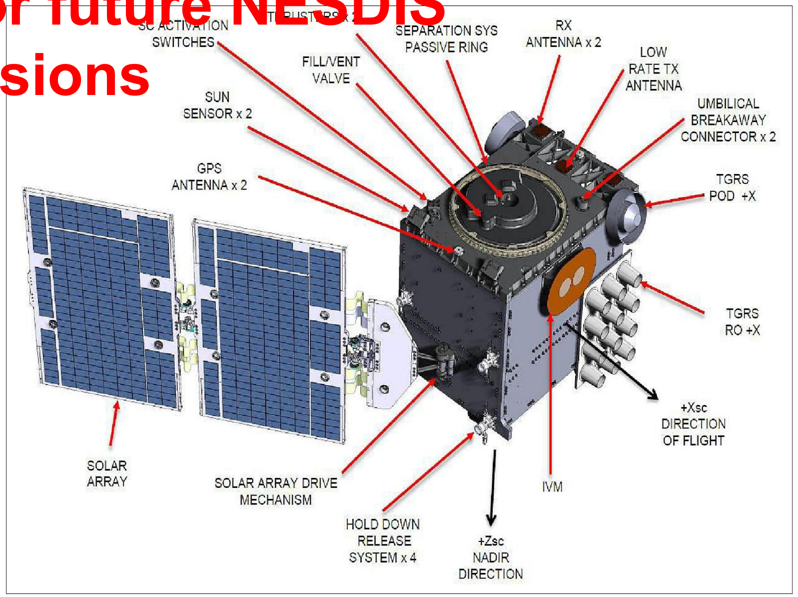
- anchor for weather
- anchor for climate
- anchor for space weather

a. SNR effects in the lower troposphere and UT/LS
b. Antenna Geometry matters
c. Not all the RO missions are in the same quality and are suitable to be used as climate benchmark
d. The criteria for future NESDIS backbone RO missions



Spire

COSMIC-2



References

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Ho, S.-P., X. Zhou, X. Shao, Yong Chen, Xin Jing, William Miller, 2023: Using the Commercial GNSS RO Spire Data in the Neutral Atmosphere for Climate and Weather Prediction Studies, *Remote Sensing. 2023, 15(19), 4836*, https://doi.org/10.3390/rs15194836

Ho, S.-P., Nick Pedatella, Ulrich Foelsche, Sean Healy, Jan-Peter Weiss, Richard Ullman, 2022: Using Radio Occultation Data for Atmospheric Numerical Weather Prediction, Climate Sciences, and Ionospheric Studies and Initial Results from COSMIC-2, Commercial RO Data, and Recent RO Missions, *Bulletin of the American Meteorological Society, 01 Sep 2022*, DOI: 10.1175/BAMS-D-22-0174.1

Ao et al., (2022), Exploitation of New Approaches of Using COSMIC-2 Data in Numerical Weather Prediction in the Moist Troposphere, Final report for CISESS task code: XSXS_COSMIC_19. 2022.

Jun Zhou et al., 2024 (JGR): Construction of Temperature Climate Data Records in the Upper Troposphere and Lower Stratosphere Using Multiple RO Missions from 2006 to 2023 at NESDIS/STAR

Ho, S.-p.; Zhou, X.; Shao, X.; Chen, Y.; Jing, X.; Miller, W. Using the Commercial GNSS RO Spire Data in the Neutral Atmosphere for Climate and Weather Prediction Studies. *RemoteSens.*2023,*15*,4836. https:// doi.org/10.3390/rs15194836