Comparison of COSMIC-2 Radio Occultation Retrieval Products with Vaisala RS41 and RS92 Radiosonde Measurements

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Motivation and Outline

• Understanding the bias and uncertainty between radio occultation (RO) retrievals and radiosonde observations (RAOBs) directly impacts climate studies and numerical weather predictions.

• Comparison of temperature and humidity profile data between
  • Retrieved by University Corporation for Atmospheric Research (UCAR) and NOAA Center for Satellite Applications and Research (STAR) from COSMIC-2 RO data
  • In-situ Vaisala RS41 and RS92 radiosonde observations (RAOB).

• Comprehensive evaluations of the temperature and humidity bias and uncertainty
  • RS41/RS92 RAOB data vs. COSMIC-2 RO data
  • Differences between two COSMIC-2 wet profile retrievals
  • Investigate height and day-night (solar zenith angle) dependence of temperature and humidity biases
COSMIC-2 Radio Occultation (RO) Sensor

- GNSS-RO data are collected by measuring the changes in a radio signal as it is refracted through the atmosphere, allowing derivation of temperatures and moisture in atmosphere’s layers.
- COSMIC-2 was launched on June 25, 2019 as COSMIC-1 follow on.
- Six small satellite-constellation; 24-degree inclination LEO
- Tri-GNSS Radio-occultation System (TGRS) payload; GNSS: GPS and GLONASS
- Enhanced RO signal quality and deeper penetration depth
- On March 16, 2020, data became available for atmospheric and climate studies and NWP applications.

Penetration depths as functions of L1 SNR for multiple RO missions
RS41 and RS92 Radiosonde

- Vaisala RS92 was a primary radiosonde type in the global operational upper-air network
  - Provided the backbone temperature and moisture measurements for NWP and satellite-based sounding sensor validation.
  - Over the past two decades, RS92 was used as a reference sonde in GRUAN.
- Starting in late 2013, RS92 was gradually replaced by Vaisala RS41.
  - Vaisala RS41 is equipped with advanced temperature and humidity sensor technologies
  - Provide improvements in measurement accuracy for temperature, humidity, and pressure and wind parameters throughout the atmosphere.
- Collocated 7-month of COSMIC-2 RO and RS41/RS92 RAOB data are analysed.

## COSMIC-2 Temperature/Humidity Data Products from 1DVAR Retrieval

<table>
<thead>
<tr>
<th>Data Set Name</th>
<th>Provided by</th>
<th>Time Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCAR-WETPf2</td>
<td>UCAR</td>
<td>2019/10/01 to 2020/04/30</td>
</tr>
<tr>
<td>NOAA/STAR WETPrf</td>
<td>NOAA/STAR</td>
<td>2019/10/01 to 2020/04/30</td>
</tr>
</tbody>
</table>

- UCAR WETPf2
  (https://data.cosmic.ucar.edu/gnss-rc/osmic2/nrt/)
- NOAA/STAR WETPrf
  (ftp://ftp.star.nesdis.noaa.gov/pub/smcd/scda/GNSSRO/COSMIC2/wetPrf/)

Difference in 1DVAR retrieval algorithms can cause difference in RO-retrieved temperature and humidity profile.

Inter-comparison with RS41 or RS92 radiosonde measurements helps evaluate such difference.

<table>
<thead>
<tr>
<th>Observation Error</th>
<th>NOAA/STAR 1DVAR</th>
<th>UCAR NRT WETPrf2 1DVAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation Error</td>
<td>Scaled monthly variability of refractivity</td>
<td>Statistical</td>
</tr>
<tr>
<td>Background Error</td>
<td>Monthly variability of T,Q profiles</td>
<td>Consistent with Observation Err.</td>
</tr>
<tr>
<td>Background Error Correlation</td>
<td>Off-diagonal elements set to be zero</td>
<td>Multivariate</td>
</tr>
<tr>
<td>Error Covariance Matrix Resolution and Construction</td>
<td>Five latitude bins; Monthly precomputed on fixed levels</td>
<td>Lat/Lon (10°x10°); Monthly Precomputed on fixed levels</td>
</tr>
<tr>
<td>Observation Operator</td>
<td>Refractivity</td>
<td>Variational Abel Transform</td>
</tr>
<tr>
<td>Initialization a priori model</td>
<td>Global Forecasting System (GFS)</td>
<td>Global Forecasting System (GFS)</td>
</tr>
</tbody>
</table>
Overall comparison of COSMIC-2 Temperature Retrievals with RS41 and RS92 RAOB Measurements

- UCAR vs. NOAA/STAR COSMIC-2 temperature retrievals
  - Very consistent at height above 12.5 km.
  - Main difference occur over the height range 8-11 km with a net difference of ~0.1-0.2 K
- Between 17.8 km and 26.4 km, RS92 RAOB has a warm bias of around 0.1 K in comparison with RS41 RAOB
  - Confirmed by both UCAR and NOAA/STAR COSMIC-2 temperature retrieval
Overall comparison of COSMIC-2 Humidity Retrievals with RS41 and RS92 RAOB Measurements

- UCAR and NOAA/STAR COSMIC-2 humidity retrievals are in general consistent in the troposphere, especially above 4.8 km.
- Systematic near-surface (below 4.2 km) wet biases in the RO retrievals relative to RS41/RS92 RAOB humidity data
  - May indicate the negative refractivity biases owing to super-refraction in RO retrievals (Ho et al., 2020)

<table>
<thead>
<tr>
<th>Retrieval</th>
<th>( \mu(\Delta H) ) (( \sigma(\Delta H) )) (g/kg) (below 4.2 km)</th>
<th>( \mu(\Delta H) ) (( \sigma(\Delta H) )) (g/kg) (4.8-8.4 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCAR WETPf2</td>
<td>-0.28(1.24)</td>
<td>0.01(0.50)</td>
</tr>
<tr>
<td>STAR WETPrf</td>
<td>-0.33(1.33)</td>
<td>0.01(0.54)</td>
</tr>
<tr>
<td>UCAR WETPf2</td>
<td>-0.21(1.25)</td>
<td>0.05(0.58)</td>
</tr>
<tr>
<td>STAR WETPrf</td>
<td>-0.23(1.37)</td>
<td>0.06(0.63)</td>
</tr>
</tbody>
</table>
Compared with both UCAR and NOAA/STAR COSMIC-2 temperature retrievals:

- ~0.1 K warm biases in the RS41 nighttime measurements over the height from 17.8 to 26.4 km.
- The day-night difference for RS41 and RS92 measurements compared with UCAR and NOAA/STAR retrievals are both small (mean temperature bias difference < 0.1 K) over 17.8 to 26.4 km.
- Temperature bias difference below 11 km between UCAR and NOAA/STAR retrievals can be mainly due to the difference in the 1DVAR retrieval algorithms, particularly the treatment of the a priori background model over this height region.
The RS92 warm biases (~0.15–0.25K) between 17.8 km and 26.4 km occur mainly during the daytime.

May be traceable to the remnant error after applying the correction to the daytime temperature for RS92.

Over the height region from 12.5 to 16.5 km, the temperature bias difference among UCAR and NOAA/STAR temperature retrievals and RS41/RS92 RAOB measurements are minimal (mostly < 0.05 K) with no significant (< 0.05 K) daytime and nighttime difference.

Consistency in temperature data among two COSMIC-2 retrievals and two RAOBs over this height region.

Below 11 km, RS92 does show day-night bias difference while RS41 does not.
Day and Nighttime Humidity Bias Comparison: UCAR and NOAA-STAR COSMIC-2 Humidity Retrieval vs. RS41 Measurement

- UCAR and NOAA/STAR COSMIC-2 humidity retrievals are, in general, very consistent in the troposphere, significantly above 4.2 km over lands.
- Systematic wet biases below 4.2 km in the RO retrievals relative to RAOB humidity data.
- Consistency in Day/Night humidity difference below 4.2 km between UCAR COSMIC-2 and RS41 RAOB data.
Day and Nighttime Humidity Bias Comparison: UCAR and NOAA-STAR COSMIC-2 Temperature Retrieval vs. RS92 Measurement

- Day-night humidity difference below 4.2 km in RS92 RAOBs when compared to COSMIC-2 retrievals, mainly due to the wet biases in the nighttime RS92 data.
- The mean humidity difference between RS41 and RS92 below 4.2 km is about 0.07-0.10 g/kg, due to a slight daytime dry bias in RS92 relative to RS41.
Summary

• In this study, the temperature and humidity data independently retrieved by UCAR and NOAA/STAR from COSMIC-2 RO data are compared with in-situ Vaisala RS41 and RS92 RAOB data.

• Collocated 7-month of COSMIC-2 RO and RS41/RS92 RAOB data are analyzed to investigate the height and day-night dependence of temperature and humidity biases.
  
  • UCAR and NOAA/STAR COSMIC-2 temperature retrievals are consistent above 12.5 km.
  • Warm biases in RS92 data compared to RS41 data over the height region above 17.8 km, mainly due to the warm daytime bias in RS92 data.
  • Main temperature difference between UCAR and NOAA/STAR retrievals is 0.1-0.2 K over 8-11 km, which is due to difference in the variational retrieval algorithms.
  • Over 8-11 km, the relative temperature difference between COSMIC-2 retrievals and RS41/RS92 RAOBs are more significant than other heights.
  • UCAR and NOAA/STAR COSMIC-2 humidity retrievals are in general consistent in the troposphere, especially above 4.8 km.
  • Systematic wet biases below 4.2 km in the RO retrievals relative to RAOB humidity data.
  • Day-night humidity bias difference below 4.2 km due to wet biases in the night-time RS92 data.

• The RO vs. RAOB comparison helps quantify the temperature and humidity biases among different radiosonde sensor types and different RO retrieval algorithms.