Welcome to the first UCAR COSMIC Program Quarterly Newsletter

The COSMIC-2 Radio Occultation Data Revolution is here!

1 INTRODUCTION
The successful launch and operation of the Joint U.S.-Taiwan COSMIC-2 radio occultation (RO) mission brings an exciting new era of atmospheric remote sensing. COSMIC-2 is an operational follow-on mission to COSMIC-1 that has been supported via an international partnership by NOAA, USAF, NSF, and NASA in the US, and by the National Space Organization in Taiwan. The COSMIC-2 constellation of six satellites is regularly providing more than 4,000 RO profiles per day with the highest signal-to-noise ratios ever acquired in orbit. These high signal-to-noise ratio (SNR) data are allowing high accuracy soundings to penetrate closer to the Earth’s surface than any previous RO missions. Figure 1 shows the COSMIC-2 sampling coverage for the day with the highest number of good quality-controlled soundings, a total of 5,556, and illustrates the high sampling density between 45N and 45S latitudes.

Figure 1: COSMIC-2 geographic coverage showing 5,556 high quality occultations on March 27, 2020 (Courtesy: J. Weiss, UCAR).
The main objective of this newsletter is to keep the community up-to-date with “News you can use” to better facilitate science using GNSS (Global Navigation Satellite System) RO observations. This issue focuses on COSMIC-2 neutral atmospheric products (next issue will cover space weather products with COSMIC-2). The section titled Learn about GNSS RO will be a regular newsletter section for the benefit of new data users, and in this issue discusses observational characteristics. A status update of the recently launched COSMIC-2 mission discusses performance of the neutral atmospheric products including the benefits of high SNR, and the accuracy of GNSS RO temperature and water vapor retrievals as deduced from comparisons with radiosondes. Section 4 then describes how to access the recent COSMIC-2 data at the COSMIC Data Analysis and Archive Center (CDAAC) website, as well as data from previously flown missions. The remaining sections include Frequently Asked Questions, Special Announcements, Community Voices where we hear thoughts from community scientists, and useful web pages for GNSS RO users.

2 LEARN about GNSS RO - OBSERVATIONAL CHARACTERISTICS

Observational characteristics of GNSS RO data including high vertical resolution, precision, accuracy and global coverage make it ideal for use in weather forecasting and in research to better understand weather and climate processes. As illustrated in Figure 2, with a GNSS receiver on board a low-Earth orbiting (LEO) satellite, the amplitude and phase of the radio frequency (RF) signals transmitted from GNSS satellites can be measured very precisely as the ray tangent point descends from ~100 km altitude to the surface. Using accurate LEO and GNSS satellite orbits, observational modeling, and sophisticated geometric optics (GO) and wave optics (WO) retrieval algorithms, vertical profiles of bending angles are derived. Profiles of refractivity are then retrieved via an Abel inversion, and subsequently pressure, temperature and water vapor can be derived with additional equations and a priori information. NWP centers currently assimilate profiles of bending angle versus altitude since they are minimally processed, i.e., have minimal retrieval errors, and can be forward-modeled accurately.

The geographic coverage provided by a LEO RO satellite is primarily dependent on the inclination of its orbit. High inclination orbits acquire RO soundings at all latitudes, while lower inclination satellites such as COSMIC-2 (24°) collect soundings confined to the region from 45° N and 45° S. A constellation of six satellites with evenly-spaced orbit planes like COSMIC-2 will also importantly enable full diurnal sampling from approximately 45°
N and 45° S throughout the mission. If you are interested in learning more about GNSS RO, the UCAR COMET Program has published an informative educational module on the science of GNSS RO (2016). Please also see other key GNSS RO publications for more information (Kursinski et al., 1997; Rocken et al., 1997; Anthes, 2011).

3 COSMIC-2 MISSION STATUS and PERFORMANCE

COSMIC-2 was launched on 25 June 2019. Each satellite carries an advanced Tri-GNSS RO System instrument (TGRS) developed by NASA’s Jet Propulsion Laboratory. The TGRS includes a high-gain beam-forming RO antenna, and is achieving the highest SNR of RO measurements to date (>2500 V/V L1CA in a 1 Hz band) with an average of about 1,500 V/V, about twice higher than the average from COSMIC-1 of ~750-800 V/V. COSMIC-2’s high SNR improves the RO retrieval quality throughout the entire profile, penetration of soundings lower into the troposphere, detection of sharp atmospheric boundary layer (ABL) tops, and detection of super-refraction (SR) at the sharp top of the ABL. Reliable detection of SR, a key science goal for the mission, should positively impact the assimilation of RO data into NWP models and also lead to more impactful scientific applications of RO data. For more information, please see Anthes and Schreiner (2019) and Schreiner et al. (2020).
COSMIC-2 is now regularly producing more than 4,000 high-quality atmospheric profiles daily that are being made available free of charge for NWP operations via the Global Telecommunications System (GTS) and to scientists for research studies via the CDAAC website (see section on COSMIC-2 Data Access below). Several operational NWP centers are already assimilating COSMIC-2 data and showing positive impact. Recent results from NCEP are described in a recent JCSDA (Joint Center for Satellite Data Assimilation) Newsletter article (Shao, H., 2020), and ECMWF has also posted a newsletter article about COSMIC-2 (Healy, S., 2020). By May 2021, the COSMIC-2 satellites will be deployed into six evenly-spaced orbit planes, COSMIC-2 is expected to produce more than 5,000 quality-controlled high vertical resolution profiles per day.

3.1 COMPARISON of COSMIC-2 TEMPERATURE and WATER VAPOR PROFILES with RADIOSONDES

Here we show an initial validation of GNSS RO temperature and moisture profiles by comparing them to independent radiosonde profiles. These GNSS-RO-based atmospheric soundings are retrieved with the One-Dimensional Variational (1DVAR) method, which optimally combines an RO bending angle profile with a priori model information to estimate temperature and moisture profiles independently. Figure 3 shows a statistical comparison of COSMIC-2 1DVAR products (heavy black lines) with co-located (within 1 hour and 100 km) radiosonde (RS92 and RS41) observations in the Tropical Western Pacific region for the period October 1, 2019 – May 19, 2020. Corresponding NCEP (red dashed) and ECMWF (blue dashed) operational short-term (of varying range, 0-12h) forecasts interpolated to the time and location of COSMIC-2 soundings are also plotted. The bias and standard deviation show very good agreement between the COSMIC-2 and radiosonde profiles, which is on average even better than the agreement of both model forecasts with radiosondes. These high accuracy and high vertical resolution 1DVAR temperature and moisture soundings from COSMIC-2 are extremely well-suited for atmospheric science studies in the tropics and sub-tropics.
4 COSMIC-2 and OTHER RO MISSION DATA ACCESS

The CDAAC processes GNSS RO mission data in three modes: 1) near real-time (NRT) if available, 2) post-processing with better GNSS orbits and clocks with a latency of ~6 weeks, and 3) re-processing with consistent algorithms and software approximately every three years. Data from all three modes of processing for all past and current RO missions are available from the CDAAC website.

Near real-time COSMIC-2 provisional neutral atmosphere profile data were initially released to the community on Dec 10, 2019. Validated neutral atmospheric data are published daily since March 6, 2020. Provisional ionosphere products are available since April 1, 2020.

On the date of this newsletter, COSMIC-2 data processed in NRT are published on a daily basis, as summarized in Table 1. Details about available COSMIC-2 data are maintained at: https://www.cosmic.ucar.edu/what-we-do/cosmic-2/data/

Data may be retrieved free of charge from our open https server using tools such as curl or wget. We are working to make the COSMIC-2 data available via Unidata’s Local Data Manager (LDM) software.
### Table 1: Summary of COSMIC-2 intermediate retrieval products.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>BRIEF DESCRIPTION</th>
<th>CDAAC Level/Filename/format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precise orbits</td>
<td>LEO orbit and clock solutions</td>
<td>Level1b/leoOrb/SP3</td>
</tr>
<tr>
<td>Excess phase</td>
<td>Atmospheric excess phase</td>
<td>Level1b/conPhs/netCDF</td>
</tr>
<tr>
<td>Neutral atmospheric retrieval</td>
<td>Retrieval for bending angle, refractivity, dry temperature, pressure</td>
<td>Level2/atmPrf/netCDF</td>
</tr>
<tr>
<td>1DVAR retrieval</td>
<td>1DVAR variational retrieval of temperature, water vapor</td>
<td>Level2/wetPr2/netCDF</td>
</tr>
<tr>
<td>WMO RO BUFR</td>
<td>Binary format containing RO and 1DVAR retrieval information</td>
<td>Level2/bfrPrf/WMO BUFR</td>
</tr>
<tr>
<td>S4 and total electron content</td>
<td>Onboard computed S4 scintillation amplitude index and relative total electron content</td>
<td>Level 1b/podTc2/netCDF</td>
</tr>
<tr>
<td>Electron density</td>
<td>Electron density profiles</td>
<td>Level 2/ionPrf/netCDF</td>
</tr>
</tbody>
</table>

Data from other missions processed at CDAAC are currently available via our legacy interface (via [https://cdaac-www.cosmic.ucar.edu](https://cdaac-www.cosmic.ucar.edu), free of charge but a simple registration is required). We intend to gradually make available more datasets via the simpler interface already used for COSMIC-2.

### 5 SPECIAL ANNOUNCEMENTS

#### 5.1 The DECOMMISSIONING of COSMIC-1 after 14 YEARS of SERVICE

The last of the six tiny COSMIC/FORMOSAT-3 (i.e., COSMIC-1) satellites that were launched into space 14 years ago – and then went on to prove that the wealth of accurate atmospheric data that can be gleaned from existing GPS signals can improve operational weather forecasts – was officially decommissioned on April 30, 2020 outliving its original planned lifespan by a dozen years.

Throughout its lifetime, COSMIC-1 made an astounding 7 million vertical atmospheric profiles available to the operational and research communities. These data demonstrably boosted forecast accuracy and were referenced in more than 550 peer-reviewed scientific publications. In all, more than 5,000 users have accessed COSMIC data from over 100 countries.
After 14 years, the UCAR COSMIC Program sends our fondest farewell to the COSMIC-1 satellites, but they won’t be forgotten as the community will continue to use their data for scientific research. We would also like to sincerely thank the National Space Organization of Taiwan for providing and operating the spacecraft, the Jet Propulsion Laboratory for providing the RO instruments, and US agencies (NSF as lead, NASA, NOAA, USAF, and ONR) for supporting the mission.

5.2 CDAAC REPROCESSING SCHEDULE
UCAR reprocesses all available GNSS RO mission data approximately every three years with consistent software and algorithms to provide the most accurate and stable RO data-set for science studies. The CDAAC system and retrieval software have undergone many improvements and are now ready to start a major reprocessing effort. Reprocessing the full COSMIC-1 mission has started and is expected to complete in late 2020. Remaining RO missions will be reprocessed after COSMIC-1 is finished and should be complete in 2021.

6 FREQUENTLY ASKED QUESTIONS
In this section we present some of the most popular Frequently Asked Questions (FAQ) about GNSS RO. If you have a question about GNSS RO or CDAAC, please visit the CDAAC web forum (sign up here) and ask a question. The CDAAC team will answer your question as soon as possible.

FAQ #1: “Is it true that GNSS RO does not provide data in the moist lower troposphere?”
Answer: No, GNSS RO data do provide extremely valuable information in the lower troposphere. For example, approximately 50% of COSMIC-2 profiles reach within 200 m of the surface. However, early RO missions such as GPS/MET and CHAMP only penetrated down to ~5-7 km in the tropics due to on-board tracking limitations.

FAQ #2: Does RO work in clouds and precipitation?”
Answer: Yes, the L-band microwave RO signals are minimally affected by clouds and precipitation. GNSS RO operates under all weather conditions.
FAQ #3: “I am interested in temperature and water vapor, not refractivity or bending angles. How can RO help me?”

**Answer:** Since GNSS RO is sensitive to the combined effects of temperature and moisture, i.e. refractivity or air density, we perform a 1-D variational retrieval (1DVAR) to obtain estimates of both temperature and water vapor by optimally combining the RO data with a priori NWP model information. These 1DVAR temperature and moisture profiles are still very accurate as shown in section 3 and are useful for science studies.

7 COMMUNITY VOICES

In this section we ask community members to share some of their thoughts and experiences about GNSS RO, how they were introduced to it, and how they have used it for scientific studies. For this newsletter we have asked Rick Anthes, a pioneer that promoted and led the initial GPS/MET proof-of-concept mission, to share his thoughts on how it all started.

*My introduction to radio occultation - “the most accurate thermometer from space”*

My introduction to radio occultation began in November 1991 when I was President of UCAR. Randolph (Stick) Ware, who was Director of the UNAVCO program, which had just joined UCAR the month before, came into my office and said we had a great opportunity to launch the first satellite to measure Earth’s atmosphere from space using a technique called radio occultation. I had never heard of radio occultation (RO) and I had no experience whatsoever with satellite measurements; most of my scientific career up until now had been involved with building mesoscale models. I was skeptical, but Stick was persuasive so I promised him a few thousand dollars from the UCAR General Fund to hold a small workshop with remote sensing experts to discuss the concept of what became the mission known as GPS/MET (GPS Meteorology).

The principle of RO had been known for many years since scientists at Stanford University and JPL flew a radio receiver on the Mariner IV flyby of Mars in July 1965 to provide vertical temperature profiles of Mars’ atmosphere. As the Mariner IV satellite orbited behind Mars (was occulted by the planet) and the radio waves that they transmitted passed through the planet’s atmosphere on their way to Earth, the waves were slowed and bent by the atmosphere. The resulting changes in frequency could be precisely measured and used to calculate refractivity, which could be used to calculate a vertical profile of temperature structure of the Martian atmosphere.
One of the first people I consulted on the potential of RO was my friend and colleague, the late Ben Herman (1929-2018) who was an expert in remote sensing at the University of Arizona. Ben looked into the theory and told me that GPS/Met was an experiment worth trying. With support from NSF (the Earth Sciences and Atmospheric Sciences Division) and under the leadership of Mike Exner and the support of Tom Meehan of JPL, who provided the receiver, we obtained the first RO observations of Earth’s atmosphere on April 9, 1995, six days after the Orbital Sciences launch of MicroLab-1.

The first GPS/Met sounding was in the tropics and showed an extremely sharp tropopause, as well as evidence of gravity waves in the stratosphere and a realistic temperature profile that extended from about 8 km to 30 km. GPS/Met produced many global soundings over the next two years, proving the concept of GPS RO from a low-Earth orbiting satellite to provide useful information on temperature, water vapor, and electron density for use in weather, climate and space weather research and numerical weather prediction. It led to other successful RO missions such as the German CHAMP (Challenging Mini-satellite Payload) mission launched on July 15, 2000. Based on the success of GPS/MET, CHAMP and other early RO missions, Taiwan and the U.S. developed the COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) mission, which was launched on 15 April 2006 and was only recently decommissioned (see announcement above). Many studies of RO observations by hundreds of scientists around the world have proved the value of RO as an important complement to infrared and microwave soundings of Earth’s atmosphere, supporting science and contributing significantly to the accuracy of operational numerical weather prediction. Its high vertical resolution, precision and accuracy through much of the troposphere and stratosphere has led to the claim “the most accurate and precise thermometer from space.”

I hope that this first COSMIC newsletter will encourage additional scientists to become familiar with the unique properties of RO data and will find these data, especially the new COSMIC-2 data that are providing an unprecedented data set for studying the tropics, useful to support their research and operational activities.

Rick Anthes, COSMIC Program Office, UCAR
5 June 2020
8 USEFUL WEBPAGES to VISIT

UCAR COSMIC-2 Page: https://www.cosmic.ucar.edu/what-we-do/cosmic-2/
COSMIC-2 Data Page: https://www.cosmic.ucar.edu/what-we-do/cosmic-2/data/
CDAAC Special Announcements Page: https://cdaac-www.cosmic.ucar.edu
CDAAC Data Users Web Forum Sign-up Page: https://docs.google.com/forms/d/e/1FAIpQLSfM_2-b4ABH34diLkQEU8iU9g7fTxcGhI0_C3xlh197tMnA/view-form
UCAR COMET GNSS RO Educational Module: https://www.meted.ucar.edu/training_module.php?id=1092#.Xt6U8i2ZPYo
JCSDA Provisional COSMIC-2 Page: https://www.jcsda.org/cosmic2-prov-release
EUMETSAT ROM SAF Monitoring Page: https://www.romsaf.org/monitoring/

9 REFERENCES


