BAMS
Meeting Summary

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

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Eighth International Radio Occultation Working Group Conference

What: More than 300 people from 15 countries met to highlight the data processing and quality assessment of newly available radio occultation (RO) missions and their applications for atmospheric numerical weather prediction, climate sciences, atmospheric studies, and ionospheric studies.

When: 15–20 April 2021

Where: Online

KEYWORDS: Climatology; Data processing/distribution; Global positioning systems (GPS); Instrumentation/sensors; Remote sensing; Satellite observations

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The Eighth International Radio Occultation Working Group (IROWG) of the Coordination Group for Meteorological Satellites (CGMS) was held on 15–20 April 2021. Owing to the COVID-19 pandemic, the workshop was entirely virtual. Four important RO satellite missions have been launched since the seventh meeting of the IROWG in September 2019 (see appendix for list of acronyms). New missions included the Taiwan–U.S. FORMOSAT-7/COSMIC-2 and the ESA–EUMETSAT–U.S. Sentinel-6. The commercial vendors, GeoOptics, Inc. and Spire Global, Inc., also expanded their RO satellite constellation capability to provide more occultation observations.

Each of these missions has different spatial and temporal coverage and tracking systems. With six low inclination (24°) orbit satellites, the COSMIC-2 constellation provides around 5,500 neutral atmosphere profiles distributed from 45°N to 45°S with relatively uniform temporal distribution; both GeoOptics and Spire RO missions provide globally distributed data with their fixed local time coverages. Sentinel-6 provides RO data with global coverage every 10 days. COSMIC-2 is equipped with NASA JPL's TGRS receiver systems, tracking RO signals from the GPS and GLONASS global navigation systems (Galileo is planned in the future). COSMIC-2 signals have a higher SNR with a higher antenna gain, allowing lower penetration. GeoOptics and Spire provide around 500 and 20,000 occultation profiles per day, respectively. The workshop focused on the performance of these missions, the quality of the resulting data, and the development of recommendations for science and operational stakeholders' use of radio occultation data.

The virtual and remote format provided some benefits we had not anticipated that partially compensated for the loss of face-to-face time among colleagues. One benefit was twice the attendance compared to recent previous workshops. More than 300 people registered and attended the 5-day event; nearly 100 oral and poster presentations were shared. We also held a robust facilitated discussion on various working group topics. The presentations, posters, and discussion groups were organized according to the following subgroup topic areas:

- receiver technology and innovative RO techniques,
- numerical weather prediction,
- space weather, and
- climate.

The primary challenges of using GNSS-RO data for the above topic areas and the potential benefit of using high SNR data, like COSMIC-2, were summarized in Ho et al. (2020). Workshop materials are available online at https://cpaess.ucar.edu/events/8409/agenda.

Summary of presentations and session discussions

RO data processing and quality assessment. COSMIC-2, GeoOptics, and Spire receivers at LEO can track the signals emitted by GPS, Galileo, and GLONASS constellations. NOAA operational NWP assimilates COSMIC-2 and approximately 3,000 total additional occultation data from MetOp, *Korea Multi-Purpose Satellite–5 (KOMPSAT-5)*, and Paz daily. The outstanding issues for data assessment for multiple RO missions are (i) how are the RO retrievals related to the emitters; (ii) how high SNR signals may help to improve the penetration; (iii) how high SNR signals may help to improve the RO retrievals; (iv) how to best quantify negative refractivity biases, retrievals accuracy, and retrieval uncertainty; (v) what may be the best way to specify error uncertainty for assimilating RO data into the NWP DA system; and (vi) the spatial and temporal coverage.

D. Master (Spire Global Inc.) and A. Saltman (GeoOptics Inc.) reported the production status of the Spire and Community Initiative for Continuing Earth Radio Occultation (CICERO) GNSS RO Constellation. They reported that the GeoOptics and Spire data quality is similar to COSMIC-2. S.-P. Ho (NOAA STAR) and other STAR scientists reported COSMIC-2 data assessment results. Comparisons of COSMIC-2, Spire, and GeoOptics BA profiles (processed by UCAR) show comparable statistics against the UCAR-provided background and no significant improvement from high SNR. COSMIC-2 high SNR measurements provide slightly deeper penetration depth with slightly better refractivity and water vapor retrievals. STAR scientists also introduced an independent RO processing algorithm using FSI (L. Adhikari). K.-N. Wang (JPL) reported that except for the SNR, the turbulence, horizontal water vapor irregularity, and assumption of symmetric tracking might also affect RO BA retrievals, especially in the lower troposphere. That may partly explain why we did not see significant improvement in COSMIC-2 retrievals compared with Spire and GeoOptics.

We also have new RO missions, including Sentinel-6 (C. Ao, JPL; A. von Engeln, EUMETSAT) and GRACE-FO (T. Schmidt, GFZ). Outstanding issues for RO data processing include (i) determination of the cutoff of SNR, (ii) developing optimal quality control criteria, and (iii) identifying the BA biases in the lower troposphere.

RO applications for meteorology/weather forecasting. M. Farrar, the director of NCEP, reported the current status of NESDIS for assimilating COSMIC-2 data in NCEP's NWP system. He noted that (i) COSMIC-2 observation errors seem slightly more significant than those from other RO missions in the same latitudinal zones and (ii) current quality controls (QCs) in EMC reject most RO data below 700–800 hPa. The current NCEP forecast system showed the impact of COSMIC-2 data for NWP is mainly in the upper troposphere and lower stratosphere (L. Cucurull, OAR NOAA), which are consistent with similar analyses using the U.S. Navy system (B. Ruston, NRL) and ECMWF system (K. Lonitz and S. Healy, ECMWF). However, ECMWF also showed that COSMIC-2 data had improved the water vapor forecasts below 5-km altitude (K. Lonitz and S. Healy, ECMWF), although the uncertainty in the troposphere below 2-km altitude seems large.

Assimilating Spire data improved the GEOS Atmospheric Data Assimilation System; even on top of COSMIC-2, the data improved tropical skills, but the most significant impacts were seen in the Southern Hemisphere (W. McCarty, NASA GSFC). Using the FSOI metric, extra RO data demonstrated a more significant impact on reducing short-term forecast skills than infrared and microwave missions. ECWMF and UKMET performed a 3-month study of the impact of Spire RO assimilated into their forecast models, respectively. Spire RO BA profiles had comparable statistics to other operational systems in the core region. Spire RO had a positive impact across almost all variables. Both centers concluded that Spire data would be used operationally if routinely available.

Outstanding issues include (i) negative refractivity, (ii) how to best assimilate the RO data into the DA system, and (iii) the observation uncertainty of the data.

Applications for climate and atmospheric studies. The broader climate science community increasingly acknowledges the value of GNSS-RO data for climate monitoring. The IPCC has invited IROWG to contribute, and a chapter was included in the Sixth Assessment Report. The high spatial and temporal resolution of COSMIC-2 data allows for studying the tropical atmosphere in unprecedented detail, thereby breaking new ground for atmospheric research, e.g., related to different types of atmospheric waves and the diurnal cycle in the stratosphere. A. Steiner (Wegner Center) provided an overview of the current status of climate monitoring with RO data.

Presentations on RO applications mainly focused on the following areas:

1) Detection of atmospheric change owing to global warming. Several studies by H. Gleisner (DMI), M. Oyola-Merced (JPL), and A. Steiner (Wegener Center) are constructing climate data records (CDRs) using multiple RO missions available in the past 15 years. P. Vergados (JPL) studied the tropical upper tropospheric warming amplification. S. Leroy (AER Inc.) reported on the stratospheric diurnal cycle in RO data and its implications for climate monitoring.
2) Atmospheric variability and wave activity. L. Halperin (MIT) combined RO with MW soundings to detect the marine boundary layer. K. Nelson (Texas A&M University) demonstrated that high vertical resolution RO data could detect the diurnal PBL height variation over land. R. Anthes (UCAR) presented RO observations of Hurricane Dorian (2019). J. Mascio (AER Inc.) assessed the ability of RO data to detect clouds. X. Xu (Wuhan University) reported that RO temperature profiles from multiple missions help detect variations of stratospheric gravity waves. W. Randel (UCAR) used COSMIC-2 data to monitor equatorial waves, diurnal tides, and small-scale thermal variation in the tropical lower stratosphere. Z. Zeng (UCAR) reported on three-dimensional (3D) structures of tropical nonmigrating tides in similar regions. T. Ayorinde (INPE, Brazil) studied gravity wave propagation from the troposphere to the mesosphere. R. Fitzgerald (MIT) demonstrated RO-bases tomography of gravity waves.
3) Monitoring moisture variation in the moist tropical troposphere. D. Wu (NASA Goddard Space Flight Center) investigated the deep refraction of GNSS-RO signals from the moisture boundary layer. I. Polinsky (AER Inc.) retrieved PBL humidity using combined RO and MW data. T. Winning (Texas A&M University) studied how the horizontal inhomogeneity in the PBL would affect the GNSS RO measurement. R. Kursinski (PlanetIQ Inc.) studied the variation of moisture signature and precipitation and ENSO using all available RO data in the past 15 years. He also compared the water vapor histograms among GNSS RO, CMIP6, AIRS, ECMWF, and GFS. J. Haase and M. Murphy (Scripps, University of California) studied atmospheric rivers.

The main issues discussed in the climate section included (i) the uncertainty and accuracy of moisture retrievals from different RO missions for climate studies and (ii) how different temporal and spatial sampling among RO missions may affect the quality of RO CDRs.

Applications in the ionosphere. Presentations on the ionosphere and space weather applications of GNSS RO during the IROWG-8 primarily focused on COSMIC-2. This is due, in part, to the significant advance in observing the low-latitude ionosphere enabled by the COSMIC-2 mission. The advances in ionospheric research enabled by COSMIC-2 and previously by COSMIC were summarized by J. Y. Liu (NCU). Several presentations focused on the validation of COSMIC-2 space weather data products. P. Strauss (Aerospace Corporation) provided a general overview of the validation of the COSMIC-2 TGRS, IVM, and RFB space weather science products. N. Pedatella and Q. Wu (NCAR/UCAR) provided detailed presentations on validating GPS and GLONASS absolute TEC and localization of ionospheric irregularities.

Applications of GNSS RO ionosphere observations were shown in several presentations. C. H. Lin (NCKU) presented results based on the assimilation of COSMIC-2 observations to generate a 3D Global Ionosphere Specification (GIS). With the assimilation of COSMIC-2 observations, the GIS helped study the ionosphere variability due to lower atmosphere forcing and geomagnetic activity. D. Emmons (Air Force Institute of Technology) compared RO observations of sporadic-E layers to those obtained by ground-based ionosondes. The ionosphere responses to geomagnetic storms using topside TEC observations were presented by N. Swarnalingham (NASA/CUA).

V. Nguyen (Spire Global Inc.) and R. Notarpietro (EUMETSAT) presented overviews of the ionosphere observations from Spire and *MetOp-A*, respectively. The Spire constellation currently provides space-weather data products, including TEC, electron density profiles, and high-rate scintillation data. The extension of *MetOp-A* GRAS observations to 300-km altitude was feasible and of scientific value, demonstrating that GRAS instruments may provide ionospheric data products in the future.

Several topics were identified on GNSS RO observations for ionosphere and space weather applications. This includes 1) understanding the accuracy of irregularity localization techniques; 2) assimilation of RO observations into ionosphere models as well as the potential usage of ionospheric assimilative models to provide ionospheric corrections for improved neutral atmosphere inversions; and 3) improved electron density inversions.

Conclusions and recommendations

The increasing RO observations from COSMIC-2, commercial missions, and new international RO missions significantly impact NWP, climate and atmospheric research, and ionosphere studies. The GPS RO technique has evolved to become a true GNSS RO technique, where signals from all GNSS constellations are exploited.

The recently launched GeoOptics and Spire missions seem to provide RO data with consistent quality with those from COSMIC-2. The SNR of RO signals mainly affects the penetration depth and observation uncertainty above 30-km altitude. Both COSMIC-2 and commercial GNSS-RO data demonstrate a high impact on NWP. The increasing RO sample numbers from all RO missions improve their impacts on NWP. This impact increases with the number of high-quality profiles—without any sign of “saturation.” With similar stability and data quality from multiple RO missions, we may explore the diurnal atmospheric phenomena that were unavailable before. GNSS-RO data with high spatial and temporal resolution allow for unprecedented studies of atmospheric and ionospheric phenomena. Better penetration into the lowest kilometers allows for studying the planetary boundary layer—including tropospheric water vapor. GNSS-RO climate data advanced climate change monitoring and contributed to the IPCC Sixth Assessment Report.

Overall, the community aims to ensure the long-term continuity of the GNSS-RO measurements and to maximize the number of high-quality GNSS-RO observations, providing good spatial and local time coverage, which can be freely exchanged. The provision and funding of long-term archiving of the raw GNSS-RO data and all the metadata are essential for climate studies, reanalysis, and climate data reprocessing. Specifically, the researchers need access to the raw data, not just retrieved products. The researchers also need access to information about the instrument’s performance. Multiple centers must have all the information required to process and reprocess GNSS-RO from government-sponsored and commercial missions.

Therefore, there is strong support for a "backbone" of agency-funded GNSS-RO missions with long-term commitment.

The workshop had the following main recommendations:

1) IROWG stresses the importance of free, timely, and unrestricted access in real time to essential RO data and unrestricted access to archive raw data (including auxiliary data). IROWG reaffirms that all providers of RO observations should classify these as necessary in WMO Resolution 40. According to the WMO Unified Data Policy (Res. 1), approved in 2021, RO data should be regarded as "core data."
2) IROWG recommends that WMO and CGMS coordinate any GNSS-RO data purchases. Specifically, we suggest convening a meeting of all agencies considering procuring these data to discuss if, how, and when the current 20,000 daily targets will be met with global and full local time coverage.
3) IROWG recommends that CGMS encourages technology and retrieval developments for improving planetary boundary layer profiling from GNSS-RO and their utilization in NWP data assimilation—and the further exploration of RO-derived water vapor as a climate variable.
4) IROWG recommends that CGMS encourages ongoing and future GNSS RO and non-RO missions, including potential commercial providers of RO observations, to incorporate a complete set of ionospheric measurements.

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Appendix: Acronyms

AIRS	Atmospheric Infrared Sounder
BA	Bending angle
CICERO	Community Initiative for Continuing Earth Radio Occultation
CDR	Climate data record
CGMS	Coordination Group for Meteorological Satellites
CMIP6	Coupled Model Intercomparison Project phase 6
COVID-19	Coronavirus disease 2019
CUA	Catholic University of America
DA	Data assimilation
DMI	Danish Meteorological Institute
ECMWF	European Centre for Medium-Range Weather Forecasts
EMC	Environmental Modeling Center
ENSO	El Niño–Southern Oscillation
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FORMOSAT-7/COSMIC-2	Formosa Satellite Mission 7/Constellation Observing System for Meteorology, Ionosphere, and Climate Mission 2
FORMOSAT-3/COSMIC	Formosa Satellite Mission 3/Constellation Observing System for Meteorology, Ionosphere, and Climate
FSI	Full-spectrum inversion
FSOI	Forecast sensitivity to observation impact
GEOS	Goddard Earth Observing System
GFS	Global Forecast System

GFZ	German Research Centre for Geosciences
GLONASS	Globalnaya Navigatsionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GIS	Global Ionosphere Specification
GPS	Global positioning system
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
GRAS	GNSS Receiver for Atmospheric Sounding
GSFC	Goddard Space Flight Center
INPE	National Institute for Space Research
IPCC	Intergovernmental Panel on Climate Change
IROWG	International Radio Occultation Working Group
IVM	Ion velocity meter
JPL	Jet Propulsion Laboratory
LEO	Low-Earth orbit
MetOp-A	*Meteorological Operational Satellite-A*
MIT	Massachusetts Institute of Technology
MW	Microwave
NASA	National Aeronautics and Space Administration
NCAR	National Center of Atmospheric Research
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NCKU	National Cheng Kung University
NCU	National Central University in Taiwan
NRL	U.S. Naval Research Laboratory
NWP	Numerical weather prediction
OAR	Oceanic and Atmospheric Research
OPPA	Office of Projects, Planning, and Analysis
QC	Quality control
UCAR	University Corporation for Atmospheric Research
UKMET	United Kingdom Meteorological Office
PBL	Planetary boundary layer
RFB	Radio frequency beacon
RO	Radio occultation
Smallsat	Small satellite
SNR	Signal-to-noise ratio
STAR	Center for Satellite Applications and Research
TEC	Total electron content
TGRS	Tri-GNSS Radio Occultation System
WMO	World Meteorological Organization

Reference

Ho, S.-P., and Coauthors, 2020: The COSMIC/FORMOSAT-3 Radio Occultation Mission after 12 years: Accomplishments, remaining challenges, and potential impacts of COSMIC-2. *Bull. Amer. Meteor. Sci.*, **101**, E1107–E1136, https://doi.org/10.1175/BAMS-D-18-0290.1.