OPAC-IROWG 2022

# Workshop on Occultations for Probing Atmosphere and Climate

## Joint OPAC-7 & IROWG 9

## Programme

Castle Seggau | Austria | September 8–14, 2022

hosted by

Wegener Center

UNI GRAZ

IROWG

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# FOREWORD

Use of the occultation measurement principle for observing the Earth‘s atmosphere and climate has become so broad as to exploit solar, lunar, stellar, navigation and satellite-crosslink signals, to employ the whole electromagnetic spectrum from EUV/UV via VIS/IR to MW and radio, and to utilize all kinds of atmosphere-radiation interaction such as refraction, absorption, and scattering. Use of radio navigation signals from the Global Navigation Satellite System GNSS, enabling accurate refraction-based observations of atmosphere and climate, has become particularly successful over the recent decades, making it a key method for numerical weather prediction and global climate monitoring.

OPAC-IROWG 2022 – the Joint OPAC-7 & IROWG-9 Workshop – follows the objectives of the previous workshops in 2016, 2013, 2010, 2007, 2004, and 2002 for again fostering the advancement and use of this great utility: It aims at providing a casual forum and stimulating atmosphere for scientific discourse, co-operation initiatives, and mutual learning and support amongst members of all occultation-related communities and users of occultation data. The 9th Workshop of the International Radio Occultation Working Group (IROWG-9) integrates perfectly with these aims as its goals are to promote the exchange of scientific and operational information between RO data producers, the research community and the applied user community.

The excellent scientific programme compiled in this book is clearly a very good basis to meet the above aims and all signs are positive that we will experience a great workshop. After difficult Covid-years, we are looking forward to meet again in person – and to celebrate 20 years of OPAC.

I cordially welcome and thank each individual participant for joining OPAC-IROWG 2022 and supporting its success with her/his presence and active contributions. Particularly sincere thanks go to all co-chairs in the Programme Committee and all colleagues in the Local Organizing Committee for their dedicated support and the great teamwork (https://opacirowg2022.uni-graz.at/en/organization/). Many thanks also to all others who provided valuable support in one or another way.

OPAC-IROWG 2022 is co-funded by ESA, EUMETSAT, PlanetiQ, Spire, and WEGC. I am very grateful to these co-sponsors who helped ensure excellent participant benefits for a reasonable registration fee.

I wish all of us a highly interesting and fruitful workshop and an unforgettable week at this beautiful place at Seggau Castle, Leibnitz near Graz, Austria.

**WELCOME TO OPAC-IROWG 2022!**

Ulrich Foelsche
(Workshop Chair
on behalf of the OPAC-IROWG chairs)

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# SCIENTIFIC PROGRAMME

## THURSDAY, SEPTEMBER 8, 2022

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| **08:00-09:00** | **Registration** (and poster mounting time) |
| **09:00-09:30** | **Welcome & Opening Event**<br>Moderator: G. Kirchengast |
| | **Welcome and Remarks by the Organizers**<br>**U. Foelsche** (OPAC-7): Organizational remarks<br>**H. Shao, S. Healy, T. Mannucci** (IROWG-9): IROWG introductory remarks |
| | **Welcome Address**<br>**A. K. Steiner** (Director Host Institute Wegener Center and Research Dean – School of Environmental & Regional Sciences and Education, University of Graz) |
| **09:30-10:30** | **Opening Talks**<br>Moderator: U. Foelsche |
| 09:30-09:50 | GNSS-RO: Where We've Been, Where We're Going *(invited)*<br>**T. Yunck** |
| 09:50-10:10 | Revisiting the 2002 Opening "OPAC: Setting the Scene" Twenty Years Later: A 2022 Reflection on What's Achieved and What's Next *(invited)*<br>**G. Kirchengast** |
| 10:10-10:30 | Radio Occultation in the WMO Integrated Global Observing System *(invited, remote)*<br>**K. Holmlund** |
| **10:30-11:00** | **Coffee Break** (and poster mounting time) |

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| **11:00-12:40** | **Morning Session**<br>**Occultations in NWP 1 – Impact of Commercial Data**<br>Chair: S. Healy |

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| 11:00-11:20 | Status and Future Plans of the Spire Satellite Constellation for Neutral and Ionospheric Radio Occultation Measurements *(invited)*<br>**V. Nguyen**, V. Irisov, O. Nogues-Correig, T. Yuasa, J. Ringer, R. Sikarin, and K. Petty |
| 11:20-11:40 | PlanetiQ GNSS RO Measurements of the Troposphere and Middle Atmosphere *(invited)*<br>**R. Kursinski**, J. Brandmeyer, A. Botnick, R. Gooch, C. Oliveira, M. Leidner, and S. Leroy |
| 11:40-12:00 | Processing of CICERO Radio Occultation data *(invited)*<br>**A. Patelli**, I. Rosso, A. Saltman, and T. Yunck |
| 12:00-12:15 | NOAA Commercial Data Program: Recent RO Purchases and Plans<br>P. Weir, M. McHugh, and **G. Peltzer** |
| 12:15-12:30 | Commercial RO Data Processing Status and Product Validation<br>**M. Sleziak-Sallee**, J-P. Weiss, I. Cherniak, J. Galimore, T. Hager, H. Huelsing, D. Hunt, E. Lauer, G. Romero, and T. VanHove |
| **12:30-12:40** | **Discussion** |

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| **12:40-14:00** | **Lunch Break** (and poster mounting time) |

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| **14:00-15:40** | **Afternoon Session 1**<br>**Occultations in Climate Monitoring and Research**<br>Chair: W. Randel |

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| 14:00-14:40 | Atmospheric temperature change: recent advances and open issues *(invited keynote)*<br>**B. D. Santer**, S. Po-Chedley, Q. Fu, J. C. Fyfe, C. Mears, S. Solomon, A. K. Steiner, F. J. Wentz, and C. Z. Zou |
| 14:40-14:55 | Observing atmospheric temperature change – Advances with GNSS radio occultation<br>**A. K. Steiner**, F. Ladstädter, and M. Stocker. |

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| 14:55-15:10 | GNSS RO providing a detailed view on the thermal structure and changes in Earth's atmosphere<br>**F. Ladstädter**, M. Stocker, K. Yessimbet, and A. K. Steiner |
| 15:10-15:25 | The ROM SAF RO climate data records: recent applications and plans ahead<br>**H. Gleisner**, K. B. Lauritsen, J. K. Nielsen, and S. Syndergaard |
| 15:25-15:40 | Interannual Variability of Tropospheric Moisture and Temperature and Relationships to ENSO using COSMIC-1 GNSS-RO Observations<br>**B. R. Johnston**, W. Randel, and J. J. Braun |

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| **15:40-16:10** | **Coffee Break** |

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| **16:10-17:50** | **Afternoon Session 2**<br>**Occultation Methodology 1 – Recent Missions**<br>Chair: K. B. Lauritsen |

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| 16:10-16:30 | COSMIC-2: Highlights from 3 Years in Orbit *(invited)*<br>**J. P. Weiss** |
| 16:30-16:45 | COSMIC-2/FORMOSAT-7 Program Status<br>**W. Xia-Serafino**, C.-Y. Huang, I. Wheeler, and J.-P. Weiss |
| 16:45-17:00 | COSMIC-1 and COSMIC-2 Processing Updates and Availability<br>**H. Huelsing**, M. Sleziak-Sallee, J. Weiss, I. Cherniak, J. Galimore, T. Hager, D. Hunt, E. Lauer, G. Romero, and T. VanHove |
| 17:00-17:20 | Recent RO activities at EUMETSAT *(invited)*<br>**C. Marquardt**, Y. Andres, L. Butenko, A. von Engeln, F. Martin-Alemany, R. Notarpietro, S. Padovan, S. Paolella, and F. Sancho |
| 17:20-17:35 | New RO missions processed at the EUMETSAT ROM SAF: Sentinel-6 and Spire<br>**S. Syndergaard**, J. K. Nielsen, H. Gleisner, and K. B. Lauritsen |
| 17:35-17:50 | EUMETSAT GRAS reprocessing activities<br>**F. Martin Alemany**, C. Marquardt, A. von Engeln, S. Padovan, S. Paolella, R. Notarpietro, F. Sancho, Y. Andres, and L. Butenko |
| **17:50** | **Thursday Scientific Sessions Adjourn** |

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| **18:15-22:00** | **Get-Together Party** |

# FRIDAY, SEPTEMBER 9, 2022

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| **09:00-10:25** | **Morning Session 1**<br>**Specific Occultation Methods and New Techniques**<br>Chair: T. Yunck *(TBC)* |

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| 09:00-09:20 | GNSS Remote Sensing: Recent Results from GFZ *(invited)*<br>**J. Wickert**, N. Antonoglou, C. Arras, M. Asgarimehr, A. Brack, G. Dick, A. Kepkar, C. Männel, C. Nguyen, M. Ramatschi, T. Schmidt, H. Schuh, M. Semmling, M. Song, R. Thundathil, K. Wilgan, T. Xiao, and F. Zus |
| 09:20-09:35 | Geosynchronous Radio Occultation Processing with GOES<br>**D. Hunt**, S. Gleason, I. Cherniak, I. Zakharenkova, S. Sokolovskiy, D. Freesland, A. Krimchansky, J. McCorkel, and G. Ramsey |
| 09:35-09:55 | A Multi-center exercise on the sensitivity of PAZ GNSS Polarimetric RO for NWP modelling *(invited)*<br>**E. Cardellach**, R. Padullés, F.J. Turk, M. de la Torre Juárez, C.O. Ao, K.-N. Wang, M. I. Oyola, S. Hristova-Veleva, M. J. Murphy, J. S. Haase, D. Hotta, and K. Lonitz |
| 09:55-10:10 | What does Artificial Intelligence tell us about the geophysical information content in GNSS polarimetric RO?<br>**E. Cardellach**, R. Padullés, I. Cobas, and D. Gallego |
| 10:10-10:25 | Balloon-borne GNSS Radio Occultation Sounding from Commercial Off-the-Shelf Receiver<br>**F. Xie**, K. J. Nelson, B. C. Chan, A. Goel, J. Kosh, T. G. R. Reid, C. R. Snyder, P. M. Tarantino |

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| **10:25-10:55** | **Coffee Break** |

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| **10:55-12:30** | **Morning Session 2**<br>**Future Missions**<br>Chair: J. Wickert |

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| 10:55-11:15 | Radio Occultation in NOAA's Next-Generation Environmental Observation Architecture *(invited)*<br>**R. Ullman** |

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| 11:15-11:30 | Preliminary Results of FY-3E GNOS II Mission: GNSS RO and GNSS-R *(remote)*<br>**C. Liu**, Y. Sun, W. Bai, F. Huang, G. Tan, G. Yang, X. Hu, M Liao, Q. Du, X. Wang, X. Meng, J. Xia, C. Yin, P. Hu, and Y. Liu |
| 11:30-11:45 | GRAS-2 RO mission<br>**J. Christensen**, A. Carlström, J. Rasch, and T. Liljegren |
| 11:45-12:00 | Simulation-Retrieval Demonstration of Gravity Wave Tomography by Radio Occultation<br>**S. Leroy**, J. Hegarty, S. Leidner, and R. Fitzgerald |
| 12:00-12:15 | Constellation Design Enabling Augmented and Persistent Radio Occultation with Ultra-Low Latency<br>**C. Barsoum**, W. Xia-Serafino, and W. Gullotta |
| 12:15-12:30 | Technology Roadmap for Future GNSS Radio Occultation and Reflectometry<br>**T. Burger** |

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| **12:30-14:00** | **Lunch Break** (and poster mounting time) |

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| **14:00-15:05** | **Afternoon Session 1**<br>**Occultations in NWP 2 – Tropical Cyclones and more**<br>Chair: H. Shao |

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| 14:00-14:20 | Impact of Radio Occultation Data on the Prediction of Tropical Cyclogenesis *(invited)*<br>**Y.-H. Kuo**, and H.-F. Teng |
| 14:20-14:35 | Optimizing the RO Data Assimilation Approach for the Prediction of Tropical Cyclogenesis with the JEDI/FV3 Global NWP System<br>**H. Zhang**, B. Kuo, H. Shao, and J.-P. Weiss |
| 14:35-14:50 | Can COSMIC-2 bending angle data assimilation improve HWRF tropical cyclone forecasts? A preliminary evaluation using six cases from the 2020 Atlantic hurricane season<br>**W. Miller**, Y. Chen, S.-P. Ho, and X. Shao |
| 14:50-15:05 | Impact of GNSS radio occultation data on the prediction of convective systems associated with a Mei-Yu front<br>**Y.-H. Kuo**, J. Sun, Y. Zhang, Y. Ho, J-S. Hong |

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| **15:05-15:30** | **Coffee Break** |

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| **15:30-17:00** | **Afternoon Session 2**<br>**IROWG**<br>Chair: A. von Engeln |

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| 15:30-16:00 | IROWG: Report from CGMS-50 and Open Actions<br>**T. Mannucci**, **U. Foelsche**, **S. Healy**, and **H. Shao** |
| 16:00-16:10 | Proposed new BUFR Format<br>**N. Bowler** |
| 16:10-16:20 | RO Modeling Experiments (ROMX)<br>**B. Ruston** |
| 16:20-17:00 | Formation of Subgroups and Subgroup Discussions |

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| **17:00-19:00** | **Poster Session**<br>Chair: F. Ladstädter |

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|---|---|---|
| P1 | KMA's Study on Development of GNSS-RO Receiver for Meteorological Measurement<br>**J. Kim**, S. Chung, and D. Kim |
| P2 | Quality control measures in EUMETSAT's RO processing<br>**C. Marquardt,** Y. Andres, L. Butenko, A. von Engeln, F. Martin-Alemany, R. Notarpietro, S. Padovan, S. Paolella, F. Sancho, V. Nguyen, and V. Irisov |
| P3 | Mitigation of TACAN/DME Interferences for L5/E5 Space-Borne GNSS Receivers in LEO with Focus on Radio-Occultation Missions<br>**C. Dulery**, L. Lestarquit, R. Prevost, and M. Iervolino |
| P4 | Empirical look-up tables for polarimetric phase delay to precipitation likelihood using ROHP-PAZ Polarimetric Radio Occultation and SSMIS/GMI Microwave-based estimates of water paths.<br>M. de la Torre Juárez, **K.-N. Wang**, F. J. Turk, R. Padullés, C. O. Ao, and E. Cardellach |
| P5 | COSMIC-2 Ionospheric Product Latency Improvements and Impacts<br>**W. Gullotta**, C. Barsoum, and W. Xia-Serafino |
| P6 | RO studies with the NeQuick ionospheric electron density model<br>**B. Nava** |
| P7 | Sporadic-E morphology from 13 years of COSMIC-1<br>**B. Bergsson**, and S. Syndergaard |

P8 Observations of Ionospheric Disturbances - From Space Weather Events to Tonga Volcano Eruptions
C. Lin, **S.-P. Chen**, P. K. Rajesh, C. Y. Lin, and C. Y. Huang

P9 PlanetiQ GNSS RO Measurements of the Ionosphere
**R. Kursinski**, J. Brandmeyer, R. Gooch, A. Botnick, M. Leidner, C, Oliveir, S. Leroy, and C. Alcala

P10 Real time on board processing of ionosphere signals by TGRS on COSMIC-2
**T. Meehan**, J. Tien, P. Straus, and J. Braun

P11 Localizing Ionospheric Irregularities in GNSS Radio Occultation Signals with Back Propagation Method: Assessment
**V. Ludwig-Barbosa**, J. Rasch, A. Carlström, J. Christensen, T. Sievert, V. T. Vu, and M. I. Pettersson

P12 Effects of background water vapor information on the 1D-Var retrieval of Radio Occultation wet profiles of CDAAC/UCAR and WEGC, during Atmospheric River events
**B. Rahimi** and U. Foelsche

P13 Combining GNSS-RO and microwave sounder in joint retrieval of atmospheric temperature and water vapor structures
**K.-N. Wang**, C. O. Ao, M. G. Morris, G. A. Hajj, F. J. Turk, and A. W. Moore

P14 Detection of the diurnal Variation of the Planetary Boundary Layer Height over Oceans using COSMIC-2 Data
**X. Zhou** and S.-P. Ho

P15 Comparison of COSMIC temperature profiles with MIPAS instrument and EMAC model
**A. Laeng**, MIPAS team, and EMAC team

P16 GNSS Radio Occultation Data in the AWS Cloud: AWS Architecture
**A. McVey**, S. Leroy, S. Leidner, and J. Martin

P17 Implementation of the Super-Refraction Correction for GNSS RO Data at the STAR
**S. Kireev**, Y. Chen, S.-P. Ho, and Y. He

P18 Real-time and retrospective monitoring and evaluation of bending angle with JEDI
**B. Ruston**, H. Shao, F. Vandenberghe, F. Diniz, H. Zhang, and L. Hayden

P19 Initial experiments with vertical smoothing of GNSS-RO bending angles
**N. Bowler**, C. Marquardt, and K. Lonitz

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| P20 | GNSS Radio Occultation interpolated by Machine Learning and Bayesian Interpolation<br>**E. Shehaj**, S. Leroy, K. Cahoy, A. Geiger, L. Crocetti, G. Moeller, B. Soja, and M. Rothacher |
| P21 | Validation of Spire Radio Occultation Retrievals with SNPP ATMS Microwave and Radiosonde Measurements<br>**X. Shao**, S.-P. Ho, Y. Chen, X. Zhou, and B. Zhang |
| P22 | IROWG-8 Virtual Meeting Hosted by NOAA<br>**A. Gonzalez**, R. Ullman, J. Clegg, S.-P. Ho, K. Eaves, S. Yaary, K. Samuel, and J.-P. Weiss |
| P23 | FORMOSAT-7/COSMIC-2 Space Weather Data Products<br>**J. J. Braun**, N. Pedatella, I. Zakharenkova, Q. Wu, I. Cherniak, T. Van Hove, H. Huelsing, R. Heelis, M.-Y. Chou, P. Straus, E. Yizengaw, B. Valant-Weiss, L. Gelinas, C. Carrano, K. Groves, W. McNeill |
| **19:00** | **Friday Adjourn** |
| **19:00-20:00** | **Dinner** |

# SATURDAY, SEPTEMBER 10, 2022

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| **09:00-10:30** | **IROWG Subgroup Working Meetings** |
| **10:30-11:00** | **Coffee Break** |
| **11:00-12:00** | **Consolidation of IROWG Subgroup-Recommendations** |
| **12:00-13:00** | **Lunch Break** |
| **13:00-22:00** | **Excursion to Castle Riegersburg and Dinner*** |

# SUNDAY, SEPTEMBER 11, 2022

Optional excursion to Graz or explore Castle Seggau.*

*** SEE ENCLOSED INFO SHEET!**

# MONDAY, SEPTEMBER 12, 2022

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| **09:00-10:45** | **Morning Session 1**<br>**Methodology 2 – Processing**<br>Chair: J. P. Weiss |

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| 09:00-09:15 | Impact of the GNSS clock rate on Radio Occultation bending angles<br>**S. Padovan**, Y. Andres, S. Paolella, A. Von Engeln, R. Notarpietro, L. Butenko, F. M. Alemany, F. Sancho, and C. Marquardt |
| 09:15-09:30 | Precise Orbit Determination of Low Earth Orbiting Satellites for Climate Applications Including Uncertainty Estimation<br>**J. Innerkofler**, C. Pock, G. Kirchengast, M. Schwärz, A. Jäggi, Y. Andres, and C. Marquardt |
| 09:30-09:45 | On the impact of signal cutoff and smoothing on systematic and random uncertainty in RO retrievals<br>**C. Marquardt**, Y. Andres, L. Butenko, A. von Engeln, F. Martin-Alemany, R. Notarpietro, S. Padovan, S. Paolella, and F. Sancho |
| 09:45-10:00 | L1-L2 bending angle fitting and L2 extrapolation in the troposphere<br>**S. Paolella**, A. Von Engeln, S. Padovan, R. Notarpietro, Y. Andres, F. Martin Alemany, L. Butenko, C. Marquardt, and F. Sancho |
| 10:00-10:15 | Radial asymmetry correction assessment by end-to-end simulations and analysis of RO data<br>**V. Proschek**, M. Schwärz, J. Innerkofler, S. Syndergaard, and G. Kirchengast |
| 10:15-10:30 | Development of excess phase processing algorithm for multi-RO missions and data quality improvements at STAR<br>B. Zhang, S.-P. Ho, J. Dong. **Y. Chen**, X. Shao, and X. Zhou |
| 10:30-10:45 | A one-dimensional variational ionospheric retrieval for truncated GNSS Radio Occultation measurements<br>**S. Healy**, I. Culverwell, and S. Elvidge |

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| **10:45-11:15** | **Coffee Break** |

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| **11:15-12:35** | **Morning Session 2**<br>**Atmospheric Physics and Climate 1 – Hunga Tonga and more**<br>Chair: S. Leroy |

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| 11:15-11:35 | Stratospheric water vapor from the Hunga Tonga volcanic eruption deduced from COSMIC-2 GNSS-RO observations *(invited)*<br>**W. Randel**, B. Johnston, J. Braun, and S. Sokolovskiy |
| 11:35-11:50 | Investigating the atmospheric response to the January 2022 Hunga Tonga eruption through GNSS radio occultations<br>**P. Vergados**, C. O. Ao, and A. J. Mannucci |
| 11:50-12:05 | Wildfire and volcanic signals in the stratosphere observed by radio occultation measurements<br>**M. Stocker**, F. Ladstädter, and A. K. Steiner |
| 12:05-12:20 | Signs of climate variability in double tropopause global distribution from two decades of radio occultation data *(remote)*<br>**A. de la Torre**, P. Alexander, T. Schmidt, P. Llamedo, R. Hierro, A. K. Steiner, and F. Ladstädter |
| 12:20-12:35 | Analysis of UTLS dynamics using GNSS radio occultations: the connection between blocking and sudden stratospheric warming events<br>**K. Yessimbet**, A. Osso, F. Ladstädter, and A. K. Steiner |

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| **12:35-14:00** | **Lunch Break** |

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| **14:00-15:50** | **Afternoon Session 1**<br>**Occultations in Ionosphere and Planetary Science**<br>Chair: T. Mannucci |

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| 14:00-14:20 | COSMIC-2 Capabilities for Monitoring Ionospheric Scintillation *(invited)*<br>**P. Straus**, C. Carrano, K. Groves, W. McNeil, S. Sokolovskiy, I. Zakherenkova, Q. Wu, J. Braun, and E. Yizengaw |
| 14:20-14:35 | Assessment of GRAS ionospheric measurements from Metop-A end-of-life testing campaign<br>**M. Hoque**, L. Yuan, F. S. Prol, M. Hernandez Pajares, R. Notarpietro, A. Von Engeln, and C. Marquardt |

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| 14:35-14:50 | Radio Occultation ionospheric products from GRAS on board Metop EPS satellites: overview and validation<br>**R. Notarpietro**, C. Marquardt, S. Paolella, S. Padovan, Y. Andres, A. Von Engeln, L. Butenko, F. M. Alemany, F. Sancho, M. Hoque, and M. Hernandez Pajares |
| 14:50-15:05 | GNSS-RO for the D- and E-Region Electron Density *(remote)*<br>**D. L. Wu**, D. J. Emmons, and N. Swarnalingam |
| 15:05-15:20 | Use of COSMIC-2 Slant TEC to Validate IRI Estimates of F-layer and Topside Electron Density<br>P. Puhl-Quinn, **S. M. Leidner**, J. V. Eccles, M. David and K. Shurkin |
| 15:20-15:35 | NOAA’s First Commercial Space Weather Data Pilot<br>**M. McHugh**, P. Weir, and G. Peltzer |
| 15:35-15:50 | Radio Holographic Methods for the Inversion of Radio Occultation Measurements from Past and Current Venus Missions<br>**T. Bocanegra-Bahamon**, C. O. Ao, K.-N. Wang, and P. Vergados |

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| **15:50-16:20** | **Coffee Break** |

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| **16:20-17:55** | **Afternoon Session 2**<br>**Occultations in NWP 3 – Processing-Assimilation-Forecasting Advances**<br>Chair: N. Bowler |

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| 16:20-16:40 | Status update of GNSS-RO data assimilation efforts at NOAA *(invited)*<br>**L. Cucurull**, D. Kleist, H. Liu, J. Guerra, X. Li, and B. Johnston |
| 16:40-16:55 | Status of GNSS-RO in global data assimilation at DWD<br>**H. Anlauf** |
| 16:55-17:10 | Recent developments on the assimilation of GNSS-RO bending angles in the Météo-France 4D-Var system<br>**D. Raspaud** |
| 17:10-17:25 | A Forecast Sensitivity to Observation Impact of traditional and commercial occultation data with Environment. Canada's forecast system<br>**J. M. Aparicio** and D. Lobon |
| 17:25-17:40 | Impact on ECMWF forecast by assimilating Spire bending angles<br>**K. Lonitz**, S. Healy, and C. Marquardt |

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| 17:40-17:55 | Status of near-real-time processing of GNSS radio occultations from the Sentinel-6 Michael Freilich satellite<br>**C. Galley** and C. Ao |
| **17:55** | **Monday Scientific Sessions Adjourn** |
| **19:00-20:00** | **Dinner** |
| **20:00-22:00** | **Wine Tour** |

# TUESDAY, SEPTEMBER 13, 2022

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| **09:00-10:25** | **Morning Session 1**<br>**Occultation Methodology 3 – Errors and Solutions**<br>Chair: S. Syndergaard |
| 09:00-09:20 | Errors in RO observations: what causes them and how can we estimate them? *(invited)*<br>**R. Anthes**, J. Sjoberg, S. Syndergaard, and X. Feng |
| 09:20-09:35 | Generalized Three Cornered Hat applied to three independent refractivity data sets<br>**J. K. Nielsen**, H. Gleisner, K. B. Lauritsen, and S. Syndergaard |
| 09:35-09:50 | Residual ionospheric errors in radio occultation data and latest news on two correction techniques<br>**J. Danzer**, C. Liu, and G. Kirchengast |
| 09:50-10:10 | ROM SAF radio occultation activities and future developments *(invited)*<br>**K. B. Lauritsen** |
| **10:05-11:00** | **Coffee Break** |
| **11:00-12:30** | **Morning Session 2**<br>**Radio Occultation Data for Climate Monitoring**<br>Chair: R. Anthes |
| 11:00-11:15 | STAR GNSS RO Processing, Validation, and Monitoring System: Validation of the Spire Data Products and their Applications for Numerical Weather Prediction and Climate Studies<br>**S.-P. Ho**, X. Zhou, Y. Chen, W. Miller, and B. Zhang |
| 11:15-11:30 | Sentinel-6A Non-Time-Critical Radio Occultation Products by EUMETSAT<br>**A. von Engeln**, S. Paolella, S. Padovan, R. Notarpietro, Y. Andres, F. Martin Alemany, L. Butenko, C. Marquardt, and F. Sancho |
| 11:30-11:45 | GNSS radio occultation excess phase processing for climate applications including uncertainty estimation<br>**J. Innerkofler**, G. Kirchengast, M. Schwärz, C. Marquardt, Y. Andres, and C. Liu |

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| 11:45-12:00 | OPAC 2022 Radio occultation processing at the Wegener Center: Validation and uncertainty evaluation of rOPS long-term data records<br>**M. Schwärz**, V Proschek, J. Innerkofler, A. Leuprecht, E. Wappis, and G. Kirchengast |
| 12:00-12:15 | Assessment of the Consistency and Stability of CrIS Infrared Observations Using COSMIC-2 Radio Occultation Data Over Ocean<br>**Y. Chen**, C. Cao, X. Shao, and S. Ho |
| 12:15-12:30 | GNSS Radio Occultation in the AWS Cloud: Background<br>**S. Leroy**, A. McVey, S. Leidner, J. Martin, H. Zhang, D. Hunt, S. Sokolovoskiy, C. Ao, K.-N. Wang, M. Oyola-Merced, H. Gleisner, S. Syndergaard, and K. Lauritsen |

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| **12:30-14:00** | **Lunch Break** |

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| **14:00-15:45** | **Afternoon Session 1**<br>**Occultations in NWP 4 – Understanding Errors and Validation Studies**<br>Chair: **L. Cucurull** |

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| 14:00-14:15 | Characterizing the radio occultation bending angle uncertainty in the lower troposphere using end-to-end simulations<br>**K. N. Wang**, C. O. Ao, S.-P. Ho, L. Cucurull |
| 14:15-14:30 | Assimilating Radio Occultation Profiles with Vertical Error Correlations<br>**K. Bathmann** and D. Zupanski |
| 14:30-14:45 | Estimates of GNSS-RO bending angle covariance information<br>N. Semane and **S. Healy** |
| 14:45-15:00 | Using ensemble spread as a measure of GNSS-RO impact: real and simulated data<br>**K. Lonitz** and S. Healy |
| 15:00-15:15 | GRACE-FO radio occultation data processing – a validation study<br>**T. Schmidt**, P. Schreiner, J. Wickert, B. A. Iijima, C. O. Ao, J. Tien, and T. Meehan |
| 15:15-15:30 | A Study of Quality Control and Observation Error Models for RO Data Assimilation<br>**H. Shao**, H. Zhang, L. Hayden, J. Sjoberg, B. Ruston, R. Anthes, J.-P. Weiss, and B. Kuo |

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| 15:30-15:45 | First results from two-dimensional bending angle operator for airborne radio occultations<br>**P. Hordyniec**, J. S. Haase, B. Cao, M. J. Murphy, and S. Healy |
| **15:45-16:15** | **Coffee Break** |
| **16:15-17:50** | **Afternoon Session 2**<br>**Atmospheric Physics and Climate 2 – Dynamics and Variability**<br>Chair: C. Marquardt |
| 16:15-16:35 | Planetary Boundary Layer Profiling from COSMIC-2, Sentinel-6, and Spire GNSS Radio Occultation *(invited)*<br>C. O. Ao, **P. Vergados**, and K.-N. Wang |
| 16:35-16:50 | The ROHP-PAZ Polarimetric Radio Occultation research dataset and its applications<br>**R. Padullés**, E. Cardellach, S. Oliveras, C. O. Ao, F. J. Turk, K.-N. Wang, M. Oyola, M. de la Torre Juárez, J. P. Weiss, D. Hunt, and S. Sokolovskiy |
| 16:50-17:05 | Validation of monthly wind fields derived from GPS radio occultation data<br>**I. Nimac**, J. Danzer, and G. Kirchengast |
| 17:05-17:20 | Madden-Julian Oscillation observed in COSMIC-2 radio occultation data<br>**Z. Zeng** |
| 17:20-17:35 | The Relationship between Stratospheric Gravity Wave Potential Energy and Tropospheric Parameters over South America inferred from COSMIC-2 and METOP Radio Occultation Measurements<br>**T. T. Ayorinde**, C. M. Wrasse, H. Takahashi, C. A. O. B. Figueiredo, D. Barros, S. O. Lomotey, P. Essien, and A. Vestena Bilibio |
| 17:35-17:50 | Absolute momentum fluxes in the stratosphere with GNSS radio occultation data<br>**T. Schmidt**, A. de la Torre, and P. Alexander |
| **17:50** | **Tuesday Scientific Sessions Adjourn** |
| **18:00-19:00** | **Dinner** |
| **19:00-21:00** | **Cloud computing and RO data in the AWS Open Data Registry**<br>**Side-workshop (S. Leroy)** |

# WEDNESDAY, SEPTEMBER 14, 2022

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| **09:00-09:40** | **Morning Session 1**<br>**Preparing for IROWG-10**<br>Chair: R. Ullman |
| 09:00-09:20 | GNSS-RO Observations at Scale - Potential RO Data from the SkyKraft Constellation *(invited)*<br>**J. Andrews** |
| 09:20-09:40 | Pre-planning of IROWG-10 |
| **09:40-10:10** | **Coffee Break** |
| **10:10-12:00** | **Morning Session 2**<br>**IROWG Recommendations to CGMS**<br>Chairs: **U. Foelsche** and **H. Shao** |
| 10:10-11:10 | **Reporting of IROWG Subgroups**<br>Subgroup co-chairs/rapporteurs |
| 11:10-12:00 | **Main IROWG Recommendations**<br>Moderated by IROWG co-chairs |
| **12:00-12:10** | **Workshop Wrap-up & Farewell** |
| **12:30-14:00** | **Lunch (optional)** |

# ABSTRACTS

## GNSS-RO: WHERE WE'VE BEEN, WHERE WE'RE GOING

**T. Yunck**
GeoOptics, Inc.

It has been 20 years since the first OPAC meeting in Graz, 34 years since the GNSS-RO technique was first proposed – before many current RO scientists were born. While much progress has been made, a great deal more is yet to come. Happily, the rate of progress is, at last, rapidly increasing. The next few years will see a blossoming and expansion of RO and closely related techniques far surpassing all that has gone before.

GNSS-RO has a rich history, emerging from a chance collaboration by GPS geodesists in the 1980s with the preeminent, pioneering planetary radio scientist from the early 1960s – a continuous thread going back 60 years. Only now, however, as a result of continuing and dramatic technology advances, have we had the means to take RO to its farthest horizons: not just mapping the 3D refractive structure of the atmosphere in unprecedented detail but evolving to address a sweeping variety of today's environmental sensing needs, all with a pocket-size device of, by ordinary flight standards, negligible cost.

This talk will offer a historical tour of GNSS-RO going back to its earliest roots, marking key milestones as it grew from a niche pursuit by a cloistered cadre of planetary scientists to become a mainstream Earth science discipline. We will show that, notwithstanding this progress, the past has been prologue, the RO revolution is just getting underway. We will survey the various technical offshoots of the RO sounding concept to embrace everything from gravity mapping to surface vector winds, ocean circulation, vegetation canopy, soil moisture and more, coming online in the next few years.

# REVISITING THE 2002 OPENING "OPAC: SETTING THE SCENE" TWENTY YEARS LATER: A 2022 REFLECTION ON WHAT'S ACHIEVED AND WHAT'S NEXT

**G. Kirchengast**

Wegener Center for Climate and Global Change (WEGC) and Institute for Geophysics, Astrophysics, and Meteorology/Institute of Physics, University of Graz, Graz, Austria

Twenty years ago in September 2002, I was opening the first International Workshop on Occultations for Probing Atmosphere and Climate (OPAC1) in Graz, Austria, with a twelve-slides welcome & introduction presentation "OPAC: Setting the Scene". A written version derived from that presentation also served, under the same title, as the introductory article to the Springer Proceedings Book that well documented the status of and plans in the OPAC field at that time.

In this talk I will use the original 2002 presentation, intentionally unmodified, and relations to the associated introductory article in the Proceedings Book, to reflect from my view on what we as "OPAC-IROWG scientific community" have achieved with reference to that scene painted in 2002 and what's next if we refresh the scene.

My overall aim for sharing reflections in this way is twofold: 1.) to contribute a bit to (re)vitalizing our broader awareness of the enormous utility that occultation data bear for applications in climate monitoring and research, atmospheric (re)analysis and numerical weather prediction, atmospheric physics, dynamics and chemistry, and also in the fields of ionospheric, space weather and planetary science. 2.) to contribute a bit to (re)raising our awareness on which of our research and application activities perhaps deserve highest and collective priority, if measured in terms of their value for user communities, and which are more driven by personal preferences and interests, including research topic inertia, and hence appear more off-track from user needs.

# RADIO OCCULTATION IN THE WMO INTEGRATED GLOBAL OBSERVING SYSTEM

**K. Holmlund**

World Meteorological Organization, Space Systems and Utilization

(Abstract available online or no abstract available.)

# STATUS AND FUTURE PLANS OF THE SPIRE SATELLITE CONSTELLATION FOR NEUTRAL AND IONOSPHERIC RADIO OCCULTATION MEASUREMENTS

**V. Nguyen** (1), V. Irisov (1), O. Nogues-Correig (1), T. Yuasa (1), J. Ringer (1), R. Sikarin (1), and K. Petty (1)

(1) Spire Global, Inc.

Spire Global operates one of the largest constellations of satellites in the world and is currently the largest commercial producer of satellite-based GNSS Earth observation products. It now operates an expanding constellation of over 120 satellites in low-earth-orbit, of which, more than 40 are capable of collecting signals from GNSS constellations such as GPS, GLONASS and Galileo. The Earth observations that can be derived from measurements collected by Spire's GNSS science receiver include neutral atmospheric profiles from radio occultation (RO), ionospheric estimates of total electron content and scintillation, and Earth surface characteristics using near-nadir and grazing angle reflected GNSS signals.

As of May 2022, Spire produces over 17000 quality-controlled RO profiles and millions of ionospheric observations each day with low latency. Over the past few years, Spire's RO and other Earth observation data have been evaluated by NOAA, NASA, NRL, USAF, ESA, EUMETSAT, ECMWF, and the UK Met Office, all with positive results. Due to the past and current demonstrative impact of the data, Spire's RO data are now continuously delivered to organizations such as EUMETSAT and NOAA for further processing and assimilation into operational weather forecast models.

This talk will provide an overview of the status and capabilities of the Spire satellites and describe the collection and processing of neutral RO and ionospheric measurements. Statistics obtained internally and from third-party evaluators will also be shown to demonstrate the comparable quality of Spire GNSS measurements to other satellite missions. The operational deliveries to EUMETSAT and NOAA will also be highlighted. Finally, the presentation will outline future plans for the Spire Earth observation satellite constellation.

# PLANETIQ GNSS RO MEASUREMENTS OF THE TROPOSPHERE AND MIDDLE ATMOSPHERE

**R. Kursinski** (1), J. Brandmeyer (1), A. Botnick (1), R. Gooch (1), C. Oliveira (2), M. Leidner (2), and S. Leroy(2)

(1) PlanetIQ, Golden, CO, USA
(2) AER, Lexington, MA, USA

PlanetIQ now has two operational satellites, GNOMES-2 and 3, on orbit, GNOMES-2 in a 525 km, 2 pm sun synchronous orbit and GNOMES-3 in a 640 km 11 am/pm SSO. Each satellite carries our new Pyxis GNSS RO receiver which measures neutral atmosphere and ionosphere occultations by tracking approximately 91 GPS, GLONASS, Galileo and BeiDou3 satellites at present.

On GNOMES-2, a stuck solar panel is limiting the number of neutral occultations to approximately 60% of what the receiver is designed to acquire. GNOMES-3 is acquiring more than 1800 occultations per day and together GNOMES-2 and 3 acquire 3000+ occultations of the troposphere and middle atmosphere each day, with full pole to pole coverage. That number will continue to rise as more GNSS satellites come on line and as we continue to optimize the acquisition of GNSS RO signals. Our plan is to launch 20 satellites providing 50,000+ occultations per day by end of 2025.

Our system acquires neutral atmosphere occultations with signal to noise ratios (SNR) comparable to or higher than COSMIC-2 to enable routine tracking to the surface across the globe and the ability to identify and account for the effects of ducting or super-refraction. Our processing is a fully automated version of the UCAR GNSS RO processing system that runs continuously on the cloud to deliver data well within the NOAA operational NWP requirements.

We will present a summary of our neutral atmosphere results in terms of bending angle, refractivity, pressure, temperature and humidity profiles, demonstrating pole to pole coverage and high signal-to-noise-ratios (SNR).

We will present comparisons with sondes, forecasts/analyses and reanalyses, demonstrating performance comparable to COSMIC-2.

We will also present results regarding depth of penetration and detection of ducting/super-refraction.

# PROCESSING OF CICERO RADIO OCCULTATION DATA

**A. Patelli** (1), I. Rosso (1), A. Saltman (2), and T. Yunck (2)

(1) GeoOptics Switzerland SA
(2) GeoOptics Inc.

The GeoOptics constellation of low orbit 6U CubeSats (CICERO) has been operational since 2018, producing hundreds of thousands of high quality GNSS radio occultations (RO) from GLONASS and GPS signals, and recently from Galileo as well. Under the CWDP program, GeoOptics is one of the private companies that provides RO data to NOAA for operational weather forecasting.

GeoOptics has been developing a processor for RO data (GeoPRO), which converts the raw acquired measurements into phases, pseudoranges, excess phases, bending angle, refractivity and BUFR, and is now operating the NASA/JPL GipsyX positioning software for precise orbit determination. A comparison with the independent processing of the raw GeoOptics data performed by NOAA/UCAR was assessed. By using the bending angle (BA) as metrics for quality assessment, we find good agreement between NOAA/UCAR and GeoOptics, demonstrating the maturity of the GeoOptics processing.

The CICERO constellation has recently expanded and an update on the current status, as well as plans for future missions, will be presented.

# NOAA COMMERCIAL DATA PROGRAM: RECENT RO PURCHASES AND PLANS

P. Weir, M. McHugh, and **G. Peltzer**

NOAA NESDIS

The National Oceanic and Atmospheric Administration (NOAA) is using commercially available Earth observing data to respond to the ever-growing demand for environmental information and satisfy NOAA observational requirements potentially at a lower cost than government-provided alternatives.

In 2016, NOAA National Environmental Satellite, Data, and Information Services (NOAA/NESDIS) initiated the Commercial Weather Data Pilot (CWDP). The CWDP evaluated satellite-based commercial data, including global navigation satellite system (GNSS) radio occultation (RO) data, for use in weather models and other systems. In 2020, NOAA/NESDIS concluded the commercial sector was ready to provide RO data to NOAA for operational use and initiated a Commercial Data Program to manage the acquisition, ingestion, use, and dissemination of these data. As of Summer 2022, NOAA/NESDIS has issued a series of contracts for the operational delivery of near-real-time RO profiles for numerical weather prediction (NWP) and space weather applications.

In this presentation we will discuss the current state and future direction of RO purchases from the NOAA Commercial Data Program. We will review of the scope and specifications of NOAA's most recent purchases including technical requirements, data volumes, data quality, latency, temporal and spatial distribution, data licensing, and other requirements. Results from examinations of the data will be presented, including system performance, impact analyses, anomalies, and lessons learned. Finally, we will describe the plans and scope of future NOAA commercial RO purchase activities.

# COMMERCIAL RO DATA PROCESSING STATUS AND PRODUCT VALIDATION

**M. Sleziak-Sallee**, J.-P. Weiss, I. Cherniak, J. Galimore, T. Hager, H. Huelsing, D. Hunt, E. Lauer, G. Romero, and T. VanHove

University Corporation for Atmospheric Research (UCAR)

The COSMIC Data Analysis and Archive Center (CDAAC) is an end-to-end processing and analysis system for ground- and space-based Global Navigation Satellite System (GNSS) measurement data focusing on radio occultation (RO) applications. We process data and publish products from a variety of space missions in near-real-time (NRT) and post-processing modes. We present the status of commercial RO data processed in NRT as part of NOAA's Commercial Weather Data Program, including data from Spire and GeoOptics satellites. We evaluate data quantity, latency, and quality metrics for neutral atmosphere (e.g. bending angle vs. numerical weather prediction model comparisons) and space weather products (e.g. slant total electron content leveling and distributions). Commercial RO data products are delivered to operational centers for assimilation into weather and space weather analysis and prediction systems, and are made freely available via a public data interface. We also look ahead to future commercial RO data processing and development activities.

# ATMOSPHERIC TEMPERATURE CHANGE: RECENT ADVANCES AND OPEN ISSUES

**B. D. Santer**, S. Po-Chedley, Q. Fu, J. C. Fyfe, C. Mears, S. Solomon, A. K. Steiner, F. J. Wentz,, and C. Z. Zou

(1) Joint Institute for Regional Earth System Science and Engineering, University of California at Los Angeles, Los Angeles, California
(2) Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, Livermore, California

This lecture provides an overview of recent progress in improving scientific understanding of the size, rate, and causes of atmospheric temperature changes. It focuses on three areas. The first area is a brief summary of relevant findings from recent assessment reports and synthesis publications. The second area explores the use of covariance relationships – such as relationships between changes in tropical temperature and water vapor, or between changes in temperatures at different atmospheric layers – to evaluate the physical consistency of independently monitored aspects of observed climate change. These tropical covariance relationships are tightly constrained in CMIP5 and CMIP6 simulations, despite large model differences in climate sensitivity, historical external forcings, and the amplitude of natural internal variability. The same tropical covariance relationships diverge markedly in available observational data sets. If model results and physically based expectations are credible, there is potential for using such well-understood covariance properties to reduce observational uncertainties in tropical temperature and moisture trends.

The third and final area of my talk covers the intersection between climate change detection and attribution research and model representation of key modes of natural internal variability. Concerns have been expressed about the possibility that multidecadal internal variability could significantly hamper the identification of human influence on the annual cycle of tropospheric temperature. Using results from large initial condition ensembles, it is shown that the identification of a human fingerprint on the annual cycle is robust to model differences in the amplitude and phasing of major modes of multidecadal internal variability. This robustness arises because internal variability patterns are distinctly different from the patterns of response to anthropogenic forcing.

# OBSERVING ATMOSPHERIC TEMPERATURE CHANGE – ADVANCES WITH GNSS RADIO OCCULTATION

**A. K. Steiner** (1), F. Ladstädter (1), and M. Stocker (1)

(1) Wegener Center for Climate and Global Change, University of Graz

The troposphere and stratosphere play an essential role in many climate aspects such as the global radiative balance, the transfer of energy, and the exchange of water vapor, ozone and other constituents. Atmospheric observations are crucial for understanding climate change. Large efforts have been made on establishing climate data records. Satellite measurements have been merged to provide records of layer-averaged temperatures from 1979 to present. Profile information on atmospheric temperature is available from limb viewing satellite sounders, lidars, and radiosondes. With more than 20 years of measurements available, the GNSS radio occultation record has become an essential part of recent assessments on atmospheric temperature changes.

We present an update of atmospheric temperature trends from observational records since 1979. Over the past decades, significant cooling trends have been observed in the stratosphere while the troposphere has warmed. Since the late 1990s, cooling of the lower stratosphere has slowed due to the recovery of the ozone layer, while tropospheric warming has increased. These changes led to a rise of the tropopause as observed over the Northern hemisphere. We discuss recent atmospheric temperature changes in the upper troposphere and lower stratosphere and the contribution of GNSS RO observations to their understanding. Results underpin the need for long-term RO atmospheric observations for climate monitoring and freely available data for climate research.

# GNSS RO PROVIDING A DETAILED VIEW ON THE THERMAL STRUCTURE AND CHANGES IN EARTH'S ATMOSPHERE

**F. Ladstädter** (1), M. Stocker (1), K. Yessimbet (1), and A. K. Steiner (1)

Wegener Center for Climate and Global Change, University of Graz, Graz, Austria

GNSS radio occultation (RO) has now monitored Earth's atmosphere for more than 20 years. With that, RO becomes increasingly valuable for analyzing the rapid changes of the atmospheric climate system. The vertical resolution of RO is one key advantage compared to many other atmospheric observation systems. For decades, observations of upper-air temperature have either lacked the necessary vertical resolution, or the horizontal coverage. This has resulted in limited knowledge about the important transition zone around the tropopause. Latest climate observations from RO reveal a significant warming of the atmosphere. The tropical upper troposphere has already warmed about 1 K in the 21st century alone, and the stratospheric trend structure indicates a possible change in stratospheric circulation. We improve the effective horizontal resolution by using a gridding strategy involving a fixed surface area combined with weighting profiles according to their distance to the respective grid cell center. We provide a detailed view on changes and phenomena on monthly mean fields as well as close to the minimal possible temporal and spatial resolution.

# THE ROM SAF RO CLIMATE DATA RECORDS: RECENT APPLICATIONS AND PLANS AHEAD

**H. Gleisner** (1), K. B. Lauritsen (1), J. K. Nielsen (1), and S. Syndergaard (1)

(1) Danish Meteorological Institute

Many studies have by now demonstrated the accuracy of GNSS Radio Occultation (RO) data, and their usefulness as a stable climate reference. Homogeneity of the data records are obtained by reprocessing of the data using uniform processing software throughout the length of the climate record. Version 1 of the ROM SAF Climate Data Record (CDR), based on Metop, CHAMP, GRACE, and COSMIC data, covers a continuous 15-year period from 2002 to 2016 and is extended in time by an Interim CDR (ICDR) which is regularly updated nearly up to present time. The combined time series is now long enough (> 20 years) for studies of climate variability and for detection of climate trends.

We here present aspects of the RO climate data records and discuss a few results from recent climate applications. We show that the observed RO bending-angle trends closely match predictions made 15 years ago using the HadGEM1 climate model and a plausible IPCC emissions scenario, suggesting that RO bending angles provide a valuable observational data source for climate model development and evaluation. We also discuss the first contribution by the RO community to the IPCC 6th Assessment Report, providing important information on the temperature trends in the tropical upper troposphere and lower stratosphere (UTLS) region. Moreover, we discuss monitoring of the Arctic stratosphere, in particular build-up of extremely cold stratospheric conditions leading to formation of Polar Stratospheric Clouds and increased ozone depletion.

Finally, we outline the plans for the next ROM SAF reprocessing and the expected developments of the ROM SAF climate data records.

# INTERANNUAL VARIABILITY OF TROPOSPHERIC MOISTURE AND TEMPERATURE AND RELATIONSHIPS TO ENSO USING COSMIC-1 GNSS-RO OBSERVATIONS

**B. R. Johnston** (1), W. Randel (2), and J. J. Braun (3)

(1,2,3) University Corporation for Atmospheric Research - COSMIC Program Office

(1) National Oceanic and Atmospheric Administration - Atlantic Oceanographic & Meteorological Laboratory

(2) National Center for Atmospheric Research - Atmospheric Chemi

Interannual variability of tropospheric moisture and temperature are key aspects of Earth's climate. In this study, monthly mean specific humidity (q) and temperature (T) variability is analyzed using 12 years of COSMIC-1 (C1) radio occultation retrievals between 60°N-60°S, with a focus on the tropics. Tropical interannual variability is dominated by El Niño-Southern Oscillation (ENSO). Systematic increases and decreases in zonal mean q and T are observed during the 2009-10 and 2015-16 El Niño events and 2007-08 and 2010-11 La Niña events, respectively. ENSO patterns in q and T are isolated using linear regression, and anomaly magnitudes increase with altitude, reaching a maximum in the upper troposphere. Upper troposphere q anomalies expand from the tropics into the midlatitude lower stratosphere, and the T vertical structure is consistent with a moist adiabatic response. C1 results are compared with a free-running simulation from NCAR's Whole Atmosphere Community Climate Model (WACCM), forced by observed sea surface temperatures, to evaluate model behavior in an idealized setting. WACCM ENSO variations in q and T generally show consistent behavior to the C1 observations, with somewhat smaller magnitudes. Case studies are conducted for major ENSO events during the study period. The spatial variability of q is closely aligned with outgoing longwave radiation (OLR, a proxy for deep convection) anomalies. For example, mid-tropospheric q increases over 100% and OLR decreases over 50 W m-2 over the central Pacific during the 2015-16 El Niño, and substantial regional q and T anomalies are observed throughout the tropics and midlatitudes for each event.

# COSMIC-2: HIGHLIGHTS FROM 3 YEARS IN ORBIT

**J.-P. Weiss**

University Corporation for Atmospheric Research (UCAR)

(Abstract available online or no abstract available.)

# COSMIC-2/FORMOSAT-7 PROGRAM STATUS

**W. Xia-Serafino** (1), C.-Y. Huang (2), I. Wheeler (3), and J.-P. Weiss (4)

(1) National Oceanic and Atmospheric Administration (NOAA)

(2) Taiwan National Space Organization (NSPO)

(3) United States Space Force

(4) University Corporation for Atmospheric Research (UCAR)

We present program status and recent highlights for the FORMOSAT-7/COSMIC-2 (COSMIC-2) mission. The COSMIC-2 mission is jointly managed by NOAA and Taiwan's National Space Organization (NSPO), consisting of six satellites in a 24-degree inclination orbit at ~550km altitude. The primary payload is the JPL developed Tri-GNSS Radio-occultation System (TGRS). Tracking data from two upward looking choke-ring antennas are used for orbit and clock determination as well as ionospheric total electron content retrieval. The US and Taiwan data processing centers receive level-0 data from a set of downlink stations and process them into higher level weather and space weather products for use by operational weather and space weather centers worldwide. Across all satellites, COSMIC-2 is providing typically more than 5000 neutral atmosphere profiles and nearly 12,000 ionospheric total electron content arcs and occultations per day with median latencies under 30 min. In this presentation we summarize spacecraft, instrument, and ground segment status, mission operations, available data products, product latency, recent program milestones, and future development plans.

# COSMIC-1 AND COSMIC-2 PROCESSING UPDATES AND AVAILABILITY

**H. Huelsing**, M. Sleziak-Sallee, J. Weiss, I. Cherniak, J. Galimore, T. Hager, D. Hunt, E. Lauer, G. Romero, and T. VanHove

UCAR COSMIC

The COSMIC-1 mission had global coverage and lasted from mid-2006 until early 2020. This data has been available to the public in various formats, including near real-time, post-processed, and re-processed. It was recently determined that the reprocessed dataset could be improved and this effort began in 2021. The COSMIC-2 system of satellites launched in June 2019 and has equatorial coverage. The near real-time version of this dataset has been available to the general public since early 2020. Recent work has been done to post-process this dataset and make it available to the general public. This presentation will discuss the changes to both datasets and display comparisons with their older counterparts as well as model-produced datasets. The availability of these newer datasets to the research community will also be discussed.

# RECENT RO ACTIVITIES AT EUMETSAT

**C. Marquardt**, Y. Andres, L. Butenko, A. von Engeln, F. Martin-Alemany, R. Notarpietro, S. Padovan, S. Paolella, and F. Sancho

EUMETSAT

Since the last IROWG meeting, the radio occultation landscape at EUMETSAT has evolved:

- In August 2021, a pilot procurement programme of commercial RO data started, with raw data being procured from Spire Global. Since February 2022, EUMETSAT is the first public agency globally disseminating commercial RO data without restrictions, including NRT dissemination of bending angle data through the Global Telecommunication System (GTS).

- In late 2021, the Sentinel-6 / Jason-CS RO instrument became operational; EUMETSAT is providing a "Non-Time Critical" processing of the data from the US TriG instrument flown onboard the satellite.

- Also in February 2022, the GRAS instruments onboard the Metop-B and -C satellites were reconfigured to perform measurements in the lower ionosphere; initial versions of operational ionospheric products including scintillation indices based on the 50 Hz carrier phase and amplitude measurements are expected to be available later in 2022.

In this presentation, we summarise these activities and provide an outlook for the future.

# NEW RO MISSIONS PROCESSED AT THE EUMETSAT ROM SAF: SENTINEL-6 AND SPIRE

**S. Syndergaard** (1), J. K. Nielsen (1), H. Gleisner (1), and K. B. Lauritsen (1)

Danish Meteorological Institute, Copenhagen, Denmark

The Radio Occultation Meteorology Satellite Application Facility (ROM SAF), which is a decentralised processing centre under EUMETSAT, recently started offering data products based on the processing of Sentinel-6 and Spire missions. In both cases the ROM SAF products are based on bending angles provided by EUMETSAT, which are further processed to refractivity, dry temperature, and 1D-Var products at the ROM SAF. For Sentinel-6, also monthly means of all variables are provided as globally gridded products.

We compare the statistics against ECMWF forecasts for the two missions, and focus on differences depending on the GNSS signals being tracked. For example, early versions of the Sentinel-6 data processing revealed that an increased clock rate in the processing of GLONASS occultations significantly reduced standard deviations at high altitudes. Generally, the data quality of both missions is on par with that of Metop.

Sentinel-6 provides 800-900 occultations per day, and so-called non time critical (NTC) data provided by the ROM SAF are regularly made available to users with about two weeks latency. A limited amount of Spire data from the ROM SAF have been made available to a few NWP centers for testing and feedback, and the ROM SAF is currently working toward becoming operational in near real-time (NRT) with about 1500 occultations per day from Spire. Progress and status will be given in the presentation.

# EUMETSAT GRAS REPROCESSING ACTIVITIES

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GRAS (GNSS Receiver for Atmospheric Sounding) is the European GNSS receiver on-board of Metop-A/B/C satellites, belonging to the EUMETSAT Polar System (EPS) satellites series. Since the first satellite (Metop-A) was launched in 2006, EUMETSAT operationally provides Near-Real-Time Radio Occultation (NRT-RO) data for climate monitoring and numerical weather prediction centres.

EUMETSAT provides Operational Radio Occultation products of the Metop GRAS instruments via an in-house operational processor. This operational processor is based on a science prototype software called YAROS (Yet Another Radio Occultation Software) also developed at EUMETSAT.

In addition to the operational processing, EUMETSAT also performs regular reprocessing activities to provide complete and consistently processed datasets not only from its own GRAS instruments, but also third-party missions such as CHAMP, GRACE and COSMIC. Improvements developed for successive reprocessing rounds include both bug fixes and algorithm improvements which also find their way into the operational processing of GRAS and other RO missions such as Sentinel-6 NTC and Commercial Spire RO data.

In this context, we want to present some of the main work done in preparation of the next reprocessing activities. Specially, we want to focus on the inclusion of a yaw-steering model (i.e. the LEO satellite's attitude) into the occultation processing, which helped to reduce a rising vs setting bias in GRAS data observed above 50 km altitude for different parts of the orbit.

In addition to this, we will also present the impact of other processing updates on the data characteristics of reprocessed GRAS data. A tentative schedule for the 2022/23 reprocessing of multiple RO missions is also provided.

# GNSS REMOTE SENSING: RECENT RESULTS FROM GFZ

**J. Wickert**, N. Antonoglou, C. Arras, M. Asgarimehr, A. Brack, G. Dick, A. Kepkar, C. Männel, C. Nguyen, M. Ramatschi, T. Schmidt, H. Schuh, M. Semmling, M. Song, R. Thundathil, K. Wilgan, T. Xiao, and F. Zus

Deutsches GeoForschungsZentrum

During the recent two decades ground and satellite based GNSS based remote (GNSS-RS) sensing methods evolved into a versatile and powerful tool for Earth System Research on different spatiotemporal scales with operational applications. Large regional and global GNSS ground networks and 100+ space-borne receivers provide unique atmospheric/ionospheric data and observations of the Earth's surface. This receiver infrastructure will be further developed during the coming years and become the base for increased importance of GNSS-RS techniques for Earth Observation. One of the leading institutions for these developments is the German Research Centre for Geosciences GFZ at Potsdam. Beside various scientific activities to further develop and improve GNSS-RS techniques, GFZ also advances related, in part operational, applications for weather/climate and ionosphere research with cooperation partners. We briefly review recent developments in GNSS Remote Sensing at GFZ with focus on ground and satellite based atmosphere/ionosphere sounding and reflectometry.

# GEOSYNCHRONOUS RADIO OCCULTATION PROCESSING WITH GOES

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We present processing strategies and results for ionospheric radio occultation (RO) retrievals from the NOAA/NASA GOES-16 and GOES-17 GPS navigation receivers. These are the first published RO retrievals from a geosynchronous GNSS receiver.

Radio occultation from geosynchronous orbit holds the potential to provide unique temporal and spatial atmospheric measurements not possible from ground and low earth orbit space-based receivers, including new observations of the upper ionosphere. Notably, the GOES geosynchronous satellites provide an "eye in the sky" pattern of Earth coverage, which can potentially achieve predictable twice-a-day observations at roughly the same location for each of the GPS constellation satellites orbiting below it.

Details of the processing at UCAR are presented. Challenges which had to be overcome include:

1. Poor geometry for orbit determination and tracking compared with LEO
2. Single frequency, GPS-only receiver
3. Extremely high rate of clock drift on the receiver with frequent noisy clock corrections

Several strategies for dealing with the high clock rate are discussed, including a novel approach using a consensus of multiple reference satellites. Comparisons of individual profiles with the IRI ionospheric model and COSMIC-2 retrievals are shown, as are statistical comparisons with IRI.

# A MULTI-CENTER EXERCISE ON THE SENSITIVITY OF PAZ GNSS POLARIMETRIC RO FOR NWP MODELING

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A better understanding of the thermodynamics of heavy precipitation events is necessary towards improving weather and climate models and quantifying the impact of climate variability on precipitation. However, there are limited observations available to assess the model structure within heavy precipitation conditions. Recently, it has also been shown that the Radio Occultations Through Heavy Precipitation (ROHP) GNSS polarimetric radio occultation (GNSS PRO) observations are highly sensitive to hydrometeors above the freezing layer, which expands the potential uses of the GNSS PRO dataset for weather-related science and applications.

An exercise is presented to analyze the sensitivity of PRO observations for NWP modeling applications. The ROHP experiment now provides over four years of coincident thermodynamic and precipitation information with high vertical resolution within regions with thick clouds. Murphy et al. (2019) simulated GNSS airborne polarimetric RO (GNSS PRO) events along an atmospheric river. These were modeled by the community WRF mesoscale model using two different microphysical parameterization schemes. The GNSS PRO observables simulated with the two schemes differed significantly, more than the actual GNSS PRO precision. The new exercise presented here reproduces this methodology for spaceborne data, using different global and regional NWP models, and it analyzes the results and divergences with the help of actual GNSS PRO data acquired aboard the PAZ satellite.

The objectives of the activity are: (1) To compare simulated GNSS PRO observables, generated with models from different centers and different microphysics schemes, against actual PAZ GNSS PRO observables. Can the models reproduce the main features of the actual data? (2) To assess whether different models/schemes result in different GNSS PRO observables, and whether these differences are larger than the measurement uncertainty. This effort provides insight on future methods to assimilate the PRO profile alongside other conventional (non-polarimetric) RO data. (3) To examine the utility of PAZ GNSS PRO observations for model validation and diagnosis.

The exercise includes comparisons with ECWMF reanalysis ERA-5 model, the operational NWP at the Japan Meteorological Agency, and a near-real-time implementation of the WRF regional model over the northeastern Pacific produced at the Center for Western Weather and Water Extremes (CW3E) called West WRF, among others.

# WHAT DOES ARTIFICIAL INTELLIGENCE TELL US ABOUT THE GEOPHYSICAL INFORMATION CONTENT IN GNSS POLARIMETRIC RO?

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Machine learning algorithms build a model based on sample data, capable to make predictions without being explicitly programmed to do so. In the field of GNSS polarimetric RO (GNSS PRO), these algorithms can be used to find patterns and relationships between different variables, even before any physical model is foreseen.

In this study, we present a set of investigations done with PAZ GNSS PRO observables (the vertical profile of polarimetric phase shift, DeltaPhi(h)) and their thermodynamic profiles (T(h), p(h), q(h)), sometimes complemented with ancillary (non-RO) information such as the average rain rate or infrared brightness temperatures. Both forward and backward relationships are studied: Can the thermodynamic profiles predict the polarimetric phase shift vertical profile? Are the polarimetric observables sufficient for predicting the rain rate? When is it necessary to complement with ancillary data? Which ancillary data provides useful information? In which range of altitudes these relationships and patterns are stronger? The answer to these questions might help (1) understanding the GNSS PRO observables; (2) designing optimal forward/backward models; and (3) assessing uses and applications of the GNSS PRO.

Different classifiers and regressors are tested, playing with different subsets of variables. For example, it is found that presence of rain (> 1 mm) can be classified with 92% sensitivity and 85% total accuracy, or that vertical profiles of T,p,q can predict the vertical profiles of GNSS PRO polarimetric phase shift between 6 and 14 km altitude with accuracies between 85% and 90%.

# BALLOON-BORNE GNSS RADIO OCCULTATION SOUNDING FROM COMMERCIAL OFF-THE-SHELF RECEIVER

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The lack of high-resolution atmospheric thermodynamic structure observations inside or near the weather events (e.g., storms, hurricane etc.) impedes our understanding of the physical processes and the predicting capability in numerical weather prediction models. The spaceborne GNSS radio occultation (RO) sounding has demonstrated high impact on weather prediction by providing high vertical resolution, all-weather soundings, but with limited regional sample density per receiver. On the other hand, the RO receiver onboard the long-duration, high-altitude balloon platform could offer unprecedented temporal and spatial sampling density over targeting region of interest. In this study, the commercial off-the-shelf (COTS) GNSS receivers developed by the Night Crew Labs (NCL) were successfully deployed on high-altitude balloon platforms. The highly compact, low-cost COTS receiver equipped with close-loop tracking shows promise for offering high-quality RO sounding from the balloon platform height in the lower stratosphere (~18km) down to the mid-troposphere (~4 km). The bending angle and refractivity retrievals from two balloon flight campaigns (World View and ZPM-1) were analyzed and compared to the near-coincident ERA5 global reanalysis. The BRO refractivity retrievals show overall near-zero median difference for World View, but much larger difference (~3%) for ZPM-1 as compared to ERA5 data. In the future, the COTS RO payloads onboard long-duration balloon platforms are worth further improvement for dense atmospheric soundings to improve the regional weather forecasts.

# RADIO OCCULTATION IN NOAA'S NEXT-GENERATION ENVIRONMENTAL OBSERVATION ARCHITECTURE

**R. Ullman**

National Oceanic and Atmospheric Administration

Beginning with the COSMIC-1 and continuing to present international government and commercial missions, NOAA has assimilated Radio Occultation (RO) data into operational weather models. Contemporary RO data is also assimilated into space weather models to assist in space weather impact prediction. For weather, climate and space weather, RO is recognized as an integral and essential measurement type by the U.S. National Weather Service (NWS). This presentation will discuss the provision of RO data in NOAA's future satellite observing architecture. NESDIS has set an objective to provide RO observations with global spatial distribution and regionally with good temporal distribution. NESDIS anticipates that up to half of the observations will be made with government deployed assets and the remainder through competitively selected commercial providers. NESDIS will continue to engage with the users of RO data to understand their validated needs and new applications. NESDIS will also engage with the developers of RO instrumentation to understand how this crucial measurement type can be improved and extended.

# PRELIMINARY RESULTS OF FY-3E GNOS II MISSION: GNSS RO AND GNSS-R

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The GNOS II payload onboard the FengYun-3E (FY-3E) meteorological satellite launched on July 5, 2021 is the upgraded GNSS remote sensor of GNOS onboard FY-3C and FY-3D. It has both the GNSS radio occultation (GNSS RO) and GNSS reflectometry (GNSS-R) functions that can monitor atmosphere, ionosphere and the Earth surface simultaneously. In particular, the observations of the FY-3E GNOS II sensor mainly involves the Earth's atmospheric refractivity, temperature, humidity, pressure, ionospheric electron density profiles, and the ocean surface wind speed, which is an additional data product.

Firstly, this presentation will introduce the FY-3E GNOS II GNSS RO atmospheric and ionospheric results, comparing with the corresponding data from the models (e.g., ECMWF, NCEP, IRI, etc.), the other missions such as the MetOp, COSMIC, especially the FY-3C and FY-3D GNOS missions. The GNOS RO data quality consistency of different FengYun-3 meteorological satellites i.e., FY-3C/-3D/-3E, as well as different GNSS systems i.e., GPS and BDS will be analyzed.

Secondly, the retrieval algorithm and validation results of the ocean surface wind product will be presented. The GNSS-R L1 product of GNOS II is the 122x20 non-uniform delay-Doppler map. The delay resolution is 1/8 chip near the specular point and 1/4 chip away from the specular point. The Doppler resolution is 500 Hz. The L2 ocean surface winds are retrieved by geophysical model functions related to the delay-Doppler map average (DDMA) and Leading-Edge Slope (LES) observables computed from the L1 DDM. The retrieved L2 winds are validated by comparing to the ECMWF model and HY-2B, HY-2C scatterometer winds. The results are also analyzed by different GNSS systems (GPS and BDS). Furthermore, the preliminary results for the retrieval of sea ice coverage and soil moisture will be presented. The sea ice coverage retrieval results are validated by the OSI SAF product and the soil moisture retrieval results are validated by the SMAP data.

Finally, the additional value of the combination of the GNSS RO and GNSS-R techniques in one payload will be investigated and analyzed.

# GRAS-2 RO MISSION

**J. Christensen** (1), A. Carlström (1), J. Rasch (1), and T. Liljegren (1)

(1) Beyond Gravity

Beyond Gravity is committed to provide high quality radio occultation data to the world community. Based on our heritage with the GRAS-1 instrument on the first generation MetOp satellites and our GRAS-2 instrument on MetOp-SG, we are now developing a mission with dedicated satellites, where RO data with the same quality as from MetOp-SG will be offered on a commercial basis. The mission will be based on our top-of the line GRAS-2 instrument, designed to meet EUMETSAT needs for the next decades. This will be flown on small satellites with proven reliability to support a high-end RO mission with outstanding availability, dependability and performance. We will present our mission and the latest results from the instrument development with measurements of neutral bending angle to an accuracy of 0.3 microradians from the three GNSS constellations of GPS, Galileo, and Beidou.

# SIMULATION-RETRIEVAL DEMONSTRATION OF GRAVITY WAVE TOMOGRAPHY BY RADIO OCCULTATION

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(1) Verisk Atmospheric and Environmental Research; (2) Virginia Polytechnic Institute

Internal gravity waves propagate from the troposphere into the stratosphere and above transporting and depositing momentum as they go, driving the quasi-biennial oscillation, modulating the Brewer-Dobson circulation, dragging the mesosphere and inducing an inter-hemispheric meridional circulation, and forcing propagating disturbances in the ionosphere. They exist over a broad range of scales and are easily detected in GNSS radio occultation as small vertical scale fluctuations in retrieved temperature. Because RO is a limb sounding technique, however, their horizontal structure cannot be probed nor their frequency detected; hence, with a single RO sounding it is impossible to infer the vertical flux of horizontal momentum transported by a detected wave. With the new era of high-performance RO instruments in microsatellite and nanosatellite form factor, it is now possible to fly close-formed constellation of RO satellites affordably. If such a constellation is deployed correctly, it could systematically obtain cluster of RO soundings in the atmosphere spaced about 100 km in the horizontal and separated by no more than 10 minutes in time. Clusters like this cannot only be used to detect the amplitude and vertical wavelength of an internal gravity waves but also the horizontal wavevector of the same wave. With this information, one can infer the momentum flux transported by the wave.

We constructed a simulation-retrieval demonstration system for this proposed technique for observing the momentum flux transported by small scale internal gravity waves. We ran the Model for Prediction Across Scales to generate a physical spectrum of internal gravity waves with 15 km global and 3 km regional resolution centered in the Western Pacific Warm Pool and with 200-meter vertical resolution the stratosphere. Deep convection is produced and internal gravity waves generated by the deep convection are readily apparent. We simulate a realistic distribution of RO soundings with a 6-satellite close-flying formation and simulate RO amplitude and phase data using a wave optics propagator. We then execute a dry temperature retrieval using canonical transform, estimate the vertical wavelength and horizontal wavevector, and infer the momentum flux transported by the detected gravity waves in each cluster. We will present the results of this demonstration and the prospects for deployment of a gravity wave tomography mission.

# CONSTELLATION DESIGN ENABLING AUGMENTED AND PERSISTENT RADIO OCCULTATION WITH ULTRA-LOW LATENCY

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(1) The Aerospace Corporation
(2) NOAA

The use of global navigation satellite systems (GNSS) is the status quo for space-borne radio occultation (RO) architectures. The Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (COSMIC-2) represents the state of the art satellite constellation designed and utilized primarily for GNSS-RO. For next generation systems, greater global distributions, lower latencies, and reduced costs are all objectives of interest. With the technical maturation of space-to-space communications, this creates a moment of opportunity for RO systems – by leveraging intersatellite communications links in long trailing satellite formation flight, persistent occultation between two satellites can be controlled as a design parameter associated with satellite ground tracks. Simultaneously, collected data may be backhauled through the space layer via direct readout services on meteorologically allocated spectrum bands, thus eliminating the need for large global ground networks to achieve lower latency.

This work leverages multi-objective optimization using genetic algorithms to examine a trade space of satellite constellations by design parameter. The design parameters considered include orbital parameters, latency performance, penetration depth and variation of occultation point, global distribution of observation, communications geometries, and data throughput rates. Additionally, various communications bands are explored for their fitness for both satellite communications and radio occultation.

# TECHNOLOGY ROADMAP FOR FUTURE GNSS RADIO OCCULTATION AND REFLECTOMETRY

**T. Burger**

European Space Agency

GNSS Radio Occultation (GNSS-RO) is meanwhile operationally used e.g. for numerical weather prediction. Many groups have supported this in various ways, from technology and processing developments through instruments to best ways to incorporate radio occultation measurements into applications.

The moderate RF hardware complexity needed for GNSS RO receivers allows a very efficient combination with the New Space approach for affordable highly integrated and miniaturised cubesat design. Consequently, a production type of RO receiver is manifesting, with limited performance as needed by the application, and integral part of the cubesat system. There are now several commercial satellite constellations for GNSS RO, providing worldwide coverage at a good re-observation rate. Their measurement quality can be sufficient to allow use in operational applications.

Still, high-end receivers with superior performance on larger satellites continue to be meaningful; they serve as reference and support future evolution of observables, processing, and products.

The portfolio of measurement types from GNSS RO continues to grow. Polarimetric RO (e.g. ROHP-PAZ) and grazing angle GNSS altimetry (GAA) are examples. The step from GAA to reflectometry using steeper reflections (GNSS-R) requires an additional LHCP Nadir RF chain for specular reflected and forward scattered signals from Earth, and GNSS-R specific processing capability preferably integrated in the receiver digital frontend. TDS-1 and CyGNSS are examples of GNSS-R missions. The ESA Scout mission HydroGNSS kicked off in 2022 aims to collect an exhaustive portfolio of GNSS-R measurements including dual frequency, co/crosspol, and coherent channel, to support the extraction of Earth surface properties like presence of ice, freeze/thaw, vegetation, inundation, and more.

ESA supports GNSS-RO and GNSS-R through development targets and activities adjusted to this scenario, targeting space related technology aspects but also evolution of observables and measurement techniques, and evaluation of products. This paper provides an overview of ongoing and discussed new activities and their rationale. Hardware oriented developments are more aimed towards high performance receivers, comprising RF chains, flexible digital GNSS frontends, and receiver demonstrators to prepare for flight opportunities. Beyond that, ESA is regularly working together with scientific and application partners on data modelling, verification, quality and use.

# IMPACT OF RADIO OCCULTATION DATA ON THE PREDICTION OF TROPICAL CYCLOGENESIS

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(2) National Taiwan University

Tropical cyclones are one of the most devastating severe weather systems that are responsible for huge loss of lives and properties every year. Accurate prediction of tropical cyclogenesis by numerical models has been a significant challenge, largely because of the lack of observations over the tropical oceans. In this paper, we study the impact of GPS radio occultation data on the prediction of tropical cyclogenesis using the regional WRF modeling and data assimilation system.

First, we investigate the impact of radio occultation (RO) data on the prediction of 22 tropical cyclones that formed in the monsoon environment and 13 tropical cyclones that formed in the Easterly environment from 2006 to 2010. We found that the synoptic-scale environment for the monsoon tropical cyclone is moister, and the model has a better skill in predicting the formation of these storms when the GPS radio occultation data are not assimilated. Because the synoptic-scale environment for the Easterly tropical cyclones is drier, tropical cyclones that form in such environment tend to be more sensitive to the quality of moisture analysis. As a result, the assimilation of GPS radio occultation has a much bigger impact for tropical cyclones that form in the Easterly environment.

Second, we assess the impact of RO data (80% from COSMIC-2) on the prediction of 9 developing and 23 non-developing storms in September – October 2019. We found that the assimilation of RO data increases the probability of detection from 0.44 to 0.78 and reduces the false alarm rate from 0.73 to 0.53. We found that the assimilation of RO data improves the analysis of moisture and vorticity fields, leading to more accurate forecast of tropical cyclogenesis.

# OPTIMIZING THE RO DATA ASSIMILATION APPROACH FOR THE PREDICTION OF TROPICAL CYCLOGENESIS WITH THE JEDI/FV3 GLOBAL NWP SYSTEM

**H. Zhang**, B. Kuo, H. Shao, and J.-P. Weiss

University Corporation for Atmospheric Research

The accurate prediction of tropical cyclone (TC) formation is critically important for TC monitoring and disaster prevention. However, it has been a challenge for global NWP models to accurately predict the genesis of TCs due to a number of factors, including the lack of traditional observations in open oceans where TCs form.

With 6,000 radio occultation (RO) profiles per day over the low latitudes, the COSMIC-2 (C2) mission provides a great opportunity to improve the prediction of tropical cyclogenesis. C2 RO measurements are of higher signal-to-noise ratio (SNR) than observations from other RO missions, and penetrate deeper in the lower troposphere. They can provide valuable information on the water vapor distribution close to the surface. The high-quality C2 RO observations can potentially improve the prediction of tropical cyclogenesis. However, many details of data assimilation, such as data quality control, observation error specification, and observation operators can affect the results of RO data assimilation.

In this work we will conduct NWP experiments with the Joint Effort for Data assimilation Integration (JEDI) system and the NCEP operational Finite-Volume Cubed-Sphere Dynamical Core (FV3) forecast model (JEDI/FV3). JEDI offers flexible configurations for RO data assimilation (DA) in terms of quality control, observation error, and forward operator. We will conduct a series of sensitive experiments with various configurations with a goal to optimize the assimilation of COSMIC-2 RO data for the prediction of TC genesis. Results of multiple TC cases will be presented.

# CAN COSMIC-2 BENDING ANGLE DATA ASSIMILATION IMPROVE HWRF TROPICAL CYCLONE FORECASTS? A PRELIMINARY EVALUATION USING SIX CASES FROM THE 2020 ATLANTIC HURRICANE SEASON

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The joint US-Taiwan FormoSat-7/Constellation Observing System for Meteorology Ionosphere and Climate-2 (COSMIC-2) mission, launched in June 2019, consists of six Global Navigation Satellite System (GNSS) radio occultation (RO) receiver satellites. We present a preliminary evaluation of COSMIC-2 RO bending angle data assimilation (DA) in the regional Hurricane Weather Research and Forecasting (HWRF) model through cycled forecasting experiments run retrospectively on six Atlantic hurricane cases from the active 2020 season. Each hurricane case is run using two HWRF configurations: (i) Control, which assimilates a rich set of in-situ and remote sensing observations, including microwave and infrared radiances, but withholds COSMIC-2 RO observations; and (ii) C2, which assimilates COSMIC-2 observations but is otherwise identical to Control. Our offline HWRF configuration assimilates COSMIC-2 bending angles using a local forward operator developed for the operational Global Forecasting System (GFS) model, and its COSMIC-2 RO observation error and quality control (QC) settings have been tuned for COSMIC bending angle assimilation in the GFS.

Results show that COSMIC-2 observation-minus-background characteristics resemble those recently reported for the GFS model background in the tropics. However, we find suboptimal COSMIC-2 bending angle observation error settings for some height layers as well as a large ~ 30 % COSMIC-2 observation rejection percentage in the lower troposphere. Considering a composite set of 108 Control and C2 HWRF 126-h forecast pairs, we find that COSMIC-2 DA has an overall limited impact on HWRF track forecasts, likely resulting in part from HWRF system design limitations. However, C2 intensity forecasts, on average, show a ~ 5-12 % improvement in relative skill over Control intensity forecasts; these differences are statistically significant for forecast lead times t = 36, 54, 60, and 108-120 h. We conclude with a single forecast example from the Hurricane Hanna (2020) cycled experiment, showing how the assimilation of two COSMIC-2 profiles close to the TC center during Hanna's early development period locally enhances 700-850 hPa layer relative humidity in the C2 analysis. Comparing C2 and Control forecasts initialized from this analysis cycle, we find that the C2-forecast Hanna intensifies more quickly in better agreement with National Hurricane Center Best Track data, coincident with its more rapid inner-core convective organization.

# IMPACT OF GNSS RADIO OCCULTATION DATA ON THE PREDICTION OF CONVECTIVE SYSTEMS ASSOCIATED WITH A MEI-YU FRONT

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During the seasonal transition period between Spring and Summer, a quasi-stationary front, known as the Mei-Yu front, can be found over Southern China, extending through Taiwan to Japan. The Mei-Yu front is characterized by a strong moisture gradient, but with a relatively weak temperature contrast. Mesoscale convective systems often develop along the Mei-Yu front and produce heavy rainfall. On 21-22 May 2020, a series of convective systems developed along the Mei-yu front. These convective systems moved eastward across the Taiwan Strait. They interacted with the steep topography of Taiwan's Central Mountain Range and produced severe flooding for southwestern Taiwan. Because of the lack of observations over the ocean, accurate prediction of these convective systems and the associated precipitation is a significant challenge.

Since the launch in June 2019, the FORMOSAT-7/COSMIC-2 has been providing ~6,000 GNSS RO data from 40S to 40N, which can be very valuable for the prediction of severe weather systems. In this paper we examine the impact of COSMIC-2 GNSS RO data on the prediction of this heavy rainfall event. Using a configuration of the Weather Research and Forecasting (WRF) Model similar to that of Taiwan's Central Weather Bureau with 15/3 km nested grids, we performed continuous assimilation of conventional observations and COSMIC-2 data starting from 0000 UTC 18 May 2020. We then performed short-range (12-h) forecast experiments at 3 hr intervals. Our results showed that the assimilation of COSMIC-2 RO data using a nonlocal excess phase operator significantly improved the moisture analysis over the South China Sea, the structure and movement of the Mei-Yu front over the Taiwan Strait, and the organization of the convective systems ahead of the Mei-Yu front. As a result, short-range (6-h) rainfall prediction over Taiwan was improved significantly. Averaged over 12 forecasts, the precipitation skill scores increased by 30% for high precipitation thresholds. The structure and the distribution of the precipitation are also much more consistent with the observation. Additional sensitivity experiments showed that the use of a local refractivity observation operator had a much reduced impact. These results suggest that the COSMIC-2 GNSS RO data, when properly assimilated, have the potential to improve the prediction of mesoscale convective systems. Detailed analysis will be presented to gain physical insights on how GNSS RO improves the prediction of convective systems associated with the Mei-Yu front.

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# KMA'S STUDY ON DEVELOPMENT OF GNSS-RO RECEIVER FOR METEOROLOGICAL MEASUREMENT

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The National Meteorological Satellite Center (NMSC) of the Korea Meteorological Administration (KMA) has been carrying out the missions of Korean meteorological satellite development, observation operation, data collection, and data service for weather forecasting. And NMSC also has been supporting satellite data to Numerical Modeling Center of the KMA for data assimilation since 2011. NMSC provide not only meteorological products of satellite but also ground and space based Global Navigation Satellite system (GNSS) data for Numerical Weather Prediction (NWP) model. In many previous studies, it is known that GNSS-Radio Occultation (RO) data contributes to increasing the effect of forecasting accuracy by being applied to the NWP model. Meanwhile, as GNSS-RO data is gradually observed through commercial satellites and their service rate is increasing, we started research on receiver development to secure data stably in the future. We first conducted a basic investigation on the GNSS-RO receiver to be used for the weather observation mission. Then, the research necessary for the design of the payload, receiver, and antenna was conducted and drafts ware derived. The KMA will develop the GNSS-RO receiver in line with the actual LEO satellite development plan in the future, and prepare to be mounted on the satellite. In this presentation, we will also show some effective results on the KMA's NWP model of the GNSS-RO data.

P2

# QUALITY CONTROL MEASURES IN EUMETSAT'S RO PROCESSING

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(1) EUMETSAT
(2) Spire Global

In this poster, we provide an overview of the quality control measures implemented in EUMETSAT's processing for both operational and reprocessed radio occultation data. At present, this affects the operational processing chains for EPS/GRAS and commercial RO/Spire data as well as the Non-Time Critical products of Sentinel-6/RO. In the reprocessing context, data from CHAMP, GRACE, COSMIC and COSMIC-II are affected (or will be in future reprocessing activities). We present examples for some of these checks, especially when configured differently for different missions, and show the number and percentage of profiles being affected.

For commercial RO data provided by Spire Global, we briefly discuss quality control measures implemented by Spire as far as they affect which raw data is being delivered to EUMETSAT prior to processing.

P3

# MITIGATION OF TACAN/DME INTERFERENCES FOR L5/E5 SPACE-BORNE GNSS RECEIVERS IN LEO WITH FOCUS ON RADIO-OCCULTATION MISSIONS

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(1) CNES
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At their design time, GPS L5 and GALILEO E5a/E5b signals compatibility with TACAN/DME was studied for aeronautical users with altitude limited up to 40,000 feet, but not for space-borne users.

For space-borne GNSS receivers in Low Earth Orbit (LEO), if the larger free space losses lead to weaker received TACAN/DME signals, the number of beacons in visibility is much higher, reaching in the worst locations a total over 200 with more than half of them having a peak power above or close to the noise floor, making time blanking a poor mitigation means. Therefore, other mitigation techniques performances need to be assessed in order to determine which techniques are best suited.

A simulation tool has been developed to compute the post correlation C/No degradation due to TACAN/DME on a LEO with and without mitigation means enabled. The equivalent post-correlation noise (No) increased due to TACAN/DME is simulated using the Spectral Separation Coefficient (SSC) methodology to emulate the effect of GNSS signal de-spreading in the receiver correlation process. The part of the useful signal carrier suppressed by the application of time blanking and/or frequency notch filtering is taken into account in the simulation.

This study is focusing on radio-occultation (RO) missions which are the more sensitive to TACAN/DME interferences. Indeed, a medium-gain antenna (9–18 dB typical) is steered toward the earth limb resulting in having many TACAN/DME transmitters inside its main lobe. In this configuration, the C/No degradation can reach up to 13.8 dB in the absence of mitigation over the European TACAN/DME hotspot.

Several mitigation techniques have been included in the simulation tool: time domain pulse blanking, Frequency Domain Adaptive Filtering (FDAF) and hybrid blanking.

As anticipated, pulse blanking does not perform well at the LEO orbit. It can be actually worse than doing nothing when there is a large number of TACAN/DME transmitters in visibility since it leads to a high loss in useful GNSS signals during the blanking process. Hybrid time domain and frequency domain methods are more effective when frequency notch filtering is applied over a limited time window. For FDAF, windows have fixed boundaries, independently of the presence of interfering pulses, whereas in the hybrid method, time windows are centered on the detected pulses. The hybrid blanking method has the best performances with a worst degradation which can be reduced to 1.8 dB over the European hotspot.

P4

# EMPIRICAL LOOK-UP TABLES FOR POLARIMETRIC PHASE DELAY TO PRECIPITATION LIKELIHOOD USING ROHP-PAZ POLARIMETRIC RADIO OCCULTATION AND SSMIS/GMI MICROWAVE-BASED ESTIMATES OF WATER PATHS.

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Results from forward propagation ray tracing of Radio Occultation (RO) through the atmosphere were compiled from coincident observations from the ROHP-PAZ experiment and the SSMIS/GMI passive microwave radiometer (MWR). DPR were inverted into precipitation profiles before using Bayesian retrievals of passive MWR water vapor at the location of PAZ RO. The MWR based information was used to estimate the total water path traversed by the RO ray trajectories. RO temperatures were used to separate between ice and liquid water. With those classifications empirical look-up-tables were created to relate water path, ice path, and polarimetric phase difference, $\Delta\phi$, observable is presented as a function of height.

The results were fitted to several functions that relate $\Delta\phi$ with water path for each value of refractivity at each height. A logistic function provided the best analytical approach to describe polarimetric phase differences to precipitation likelihood at each height.

For retrieval purposes, where one does not know a priory the type of cloud encountered, nor the phase of the water droplets, a cluster analysis was explored to find ways to discriminate the different types of precipitating clouds. This cluster classification uses only retrieved quantities like $\Delta\phi$ and refractivity to establish criteria that would help separate ice from liquid water contributions to the polarimetric phase difference.

Finally, we explored profiles that did not match these empirical look-up-tables. We try to find criteria to indentify the cause in either uncertainties in the MWR retrieval, or actual anomalous behavior in PRO profiles.

P5

# COSMIC-2 IONOSPHERIC PRODUCT LATENCY IMPROVEMENTS AND IMPACTS

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(3) NOAA NESDIS OPPA

COSMIC-2 has a mission requirement to provide ionospheric Total Electron Content (TEC) with a maximum daily median latency of 30 minutes. In addition, 30-minute latency for TEC is also a significant boundary for operational utility of TEC data. As of July 2021, the mission was only achieving a daily median latency of 34-36 minutes, not meeting that requirement. A concerted effort was initiated by the COSMIC-2 team to improve the latency and meet the requirement.

Over the past year, significant changes were made to numerous parts of the COSMIC-2 ground architecture. The targeted areas for improvement were reduction of the time between a TEC observation and a downlink and reduction in the time following a downlink and data arrival at the COSMIC-2 processing centers. Reduction in the time between a TEC observation and a downlink was achieve through two methods. First, the elevation masks were adjusted at ground sites to expand their effective coverage areas to capture additional passes. Second, scheduling was adjusted to increase the effective number of passes at non-dedicated sites. The amount of time between a downlink and data arrival at the centers was achieved by changing the scheduled downlink lengths.

COSMIC-2 has achieved a daily median TEC latency of 26-28 minutes since the initiation of reduction efforts and is now meeting its mission requirement. Even more significantly, the number of TEC profiles achieving sub-30 minute latency has dramatically improved, increasing the impact of COSMIC-2 data at operational space weather centers. Moving forward, additional latency reduction strategies may be implemented to further improve the system and potentially could reduce the daily median latency to under 20 minutes.

# RO STUDIES WITH THE NEQUICK IONOSPHERIC ELECTRON DENSITY MODEL

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NeQuick is a three-dimensional and time dependent ionospheric electron density model developed at the former Aeronomy and Radiopropagation Laboratory of the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy with the collaboration of the Institute for Geophysics, Astrophysics and Meteorology of the University of Graz, Austria. It is a quick-run model particularly designed for trans-ionospheric propagation applications that has been conceived to reproduce the median behavior of the ionosphere. It allows calculating the electron concentration at any given location in the ionosphere and thus the Total Electron Content (TEC) along any ground-to-satellite ray-path by means of numerical integration. In this contribution specific cases related to the use of the NeQuick in Radio Occultation (RO) studies will be presented. As examples, the simulations performed to assess the effects of the spherical symmetry assumption for the ionosphere electron density in RO data inversion and the implementation of a model-assisted RO data inversion method based on data ingestion into NeQuick will be illustrated. The usage of RO-derived TEC and electron density profiles for the model validation will be also considered.

P7

# SPORADIC-E MORPHOLOGY FROM 13 YEARS OF COSMIC-1

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We have analyzed 13 years of radio occultation data from the first Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC-1) mission with a focus on scintillations originating in ionospheric sporadic-E (Es) layers. To identify the Es irregularities, we applied the algorithm developed by Zeng and Sokolovskiy (2010). The analysis enabled the statistical global mapping of Es occurrence in space and time at very high resolution, and allowed an investigation of the statistical variation of Es height and thickness with seasons, solar activity, local time, and latitude. Important new results are that Es height and thickness varies with seasons and solar activity, with different behavior in the morning and in the evening. The evening Es height and thickness varies significantly with solar activity, apparently having lower mean height and larger mean thickness when the activity is high. We interpret that as a tendency for the evening Es to be more tilted with respect to the local horizon.

# OBSERVATIONS OF IONOSPHERIC DISTURBANCES - FROM SPACE WEATHER EVENTS TO TONGA VOLCANO ERUPTIONS

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The global low-latitude ionosphere observations given by the Tri-GNSS radio occultation system (TGRS) and ion velocity meter (IVM) onboard the FORMOSAT-7/COSMIC-2 (F7/C2) have been applied to study the ionosheric responses to the moderate geomagnetic storms. Results show that the ionosphere responses are much greater than expectation as the moderate storms could double or triple the electron density, which was only possible during major magnetic storms under higher solar activity conditions. On January 15th 2022, the Tonga volcano eruption unleashed a strong global atmosphere perturbations and coincided with a moderate geomagnetic storm. The ensuing thermospheric variations created a rare display of extreme poleward-expanding conjugate plasma bubbles in rate of total electron content indices over 100-150°E, also causing ion-density fluctuations in IVM measurements reaching ~40°N geographic latitude. This was preceded by an unusually strong pre-reversal enhancement (PRE) of low latitude ionosphere as seen from the global ionospheric specification (GIS) which is constructed based on the TGRS observations. The GIS further revealed sharp decrease of equatorial ionization anomaly (EIA) crest density due to the storm impact. The enhanced F-region wind over EIA by the negative storm, when combined with volcano induced E-region westward disturbance wind, apparently intensified the PRE. In presence of the strong PRE, seed perturbations from volcano induced variations triggered the super plasma bubble activity.

# PLANETIQ GNSS RO MEASUREMENTS OF THE IONOSPHERE

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PlanetIQ now has two operational satellites on orbit. The first, GNOMES-2, has been operational since October 1, 2021 in a 525 km, 2 pm sun synchronous polar orbit. The second launched April 1, 2022 into an 11 AM 640 km SSO and has been operational since April 8.

Each satellite carries our new Pyxis GNSS RO receiver which tracks GPS, GLONASS, Galileo and BeiDou satellites, to acquire approximately 2700 daily ionospheric occultations, with pole-to-pole coverage. The number of ionosphere occultations from 2 PlanetIQ satellites is comparable to that from COSMIC-2's 6 satellites.

Total electron content (TEC) is derived from Pyxis dual frequency ranging and carrier phase data, along all available signal paths through the ionosphere for assimilation into space weather specification/forecasting systems. This includes removal of local multipath and phase leveling. We also derive electron density profiles. 50 Hz and higher rate data is available to characterize sporadic E layers with very high vertical resolution. The receiver measures S4 to characterize amplitude scintillations from 50 Hz and higher rate data. Shortly we will also deliver sigma-phi to characterize the phase scintillations as well as downlink the full complex signal for those occultations where S4 exceeds 0.3 to enable location of ionospheric turbulence along the signal paths.

Presently we are using two high latitude ground stations to deliver our data. We will be adding additional ground stations to reduce the latency. We are presently working to maximize the number of ionosphere observations that meet NOAA's 30 minute median latency specification for space weather measurements. Eventually, with additional ground stations, we can reduce median latency to 20 minutes or less.

We plan to deploy 20+ satellites by end of 2025 to acquire 60,000+ daily ionospheric occultations, with full global and diurnal coverage, delivering 1250 occultations every half hour, and an unprecedented, continuous, 4D characterization of the global ionosphere.

We will present a summary of initial measurement, calibration and validation results.

# REAL TIME ON BOARD PROCESSING OF IONOSPHERE SIGNALS BY TGRS ON COSMIC-2

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The TriG GNSS Receiver System (TGRS) employs a mixture of on board and ground-based signal processing methods to meet the objectives for low-latency space weather observations. There are continuous phase, range and SNR measurements from two wide field of view antennas to obtain TEC and scintillation measurements. Over the three years since the launch of the six satellite COSMIC-2 constellation, the TGRS on board firmware has been upgraded many times to improve these measurements.

Although the observation metrics are identical between the GPS and GLONASS tracking, TGRS tracks GPS in a traditional closed-loop fashion while GLONASS is tracked with a quasi-open loop method. The latter provides somewhat better immunity from sharp signal changes through lower layers of the atmosphere. On board firmware is configured by command to select 50-100 Hertz high rate scintillation products to be sent to the ground. Selection criteria vary based on per-orbit data volume, altitude region, scintillation index among others. This presentation will describe the various features of the COSMIC-2 TGRS as applied to space weather observations.

P11

# LOCALIZING IONOSPHERIC IRREGULARITIES IN GNSS RADIO OCCULTATION SIGNALS WITH BACK PROPAGATION METHOD: ASSESSMENT

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The presence of electron density gradients along the ray path during GNSS radio occultation (GNSS-RO) measurements may disturb the signal amplitude and phase strongly, in a phenomenon called scintillation.

Such small-scale irregularities contribute to the high-order terms of the residual ionospheric error (RIE) and are driven, for example, by the occurrence of equatorial plasma bubbles (EPB).

From the modelling perspective, spectral analysis of the sampled signal can better characterise the ionospheric irregularities compared to the intensity of disturbance quantified by scintillation indices. As a complement to the spectral analysis, the back propagation (BP) method can estimate the average location of the irregularity patches.

This approach is based on the Huygens-Fresnel diffractive integral, where the signal amplitude is backpropagated to different auxiliary planes. The diffraction effects are gradually reversed during the process, and the placement estimate is given at the auxiliary plane, where the BP amplitude has minimal fluctuation. The BP method has been previously applied in GNSS-RO measurements showing promising results in the location estimate of ionospheric irregularities but often without complementary data to validate the estimations.

In this work, a control case collocated with other remote sensing techniques was replicated in wave optics propagator (WOP) simulations to assess the capability and accuracy of the estimate obtained with the BP method. In addition, a few more test cases were designed to assess the BP method regarding size, intensity and placement of single and multiple irregularity regions.

The results indicate that the accuracy partly depends on the resolution of the auxiliary planes, the intensity of the disturbance created by the irregularities, the receiver noise level and - in the scenario of multiple bubbles - on the inter-distance between multiple bubbles.

P12

# EFFECTS OF BACKGROUND WATER VAPOR INFORMATION ON THE 1D-VAR RETRIEVAL OF RADIO OCCULTATION WET PROFILES OF CDAAC/UCAR AND WEGC, DURING ATMOSPHERIC RIVER EVENTS

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The Global Navigation Satellite System Radio Occultation (GNSS-RO) limb-sounding technique provides a new source of open-ocean soundings of high vertical resolution profiles of water vapor, temperature and, pressure in all weather conditions throughout the depth of the atmosphere. In recent years, the RO technique has emerged as a powerful and relatively inexpensive approach to overcome some problems of traditional data sources. Atmospheric Rivers (ARs) represent narrow (<~ 1000km wide) and long (>~ 2000 km) narrow bands of anomalously high atmospheric water vapor fluxes which can be characterized using Integrated Water Vapor (IWV) measurements. IWV can be derived directly from the Special Sensor Microwave Imager/Sounder (SSMI/S) with high horizontal resolution, or by using the high vertical resolution GNSS RO retrieved moist profiles. In this study, the GNSS-RO 1-Dimensional Variational (1D-Var) retrieved moist profiles from WEGC and UCAR will be evaluated during different AR events. These two centers have been proven to be providing high-quality and consistent RO refractivity and dry atmospheric profiles in the troposphere. However, since the retrieval of moist profiles uses additional information combined with RO observations, the decisions of centers to use what kind of climatological model and how they estimate observation and background information can lead to discrepancies of their moist products. We carefully selected six AR events

from different parts of the globe in both hemispheres at different times to investigate both latitudinal variations of RO moist profiles and consider changes and updates in GNSS RO wet profiles. We also compare 1D-Var specific humidity profiles of the two centres with Retrieval-to A priori Error Ratio (RAER) as well as specific humidity sigma profiles to analyze how background data influence retrieved moist profiles during the AR events. Finally, we analyze the IWV values of the retrieved RO moist profiles with SSMI/S IWV to investigate how GPS RO and SSMI/S observations can be used together to study the low-level moisture distribution associated with the AR events.

P13

# COMBINING GNSS-RO AND MICROWAVE SOUNDER IN JOINT RETRIEVAL OF ATMOSPHERIC TEMPERATURE AND WATER VAPOR STRUCTURES

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Global Navigation Satellite System – Radio Occultation (GNSS-RO) and passive Microwave Radiometer (MWR) are two complimentary spaceborne sounding observations for atmospheric science research. GNSS-RO provides high vertical resolution (~200m) refractivity and bending angle measurements, and the L-band signals it uses can penetrate heavy cloud cover without depending on surface emissivity. However, GNSS-RO suffers from low along-track horizontal resolution (~200km). The temperature and moisture are also coupled in the GNSS-RO retrieval process, and for decoupling the a-priori information or auxiliary observations are required. On the other hand, MWR has much better horizontal resolution (~20km). Its brightness temperature (TB) measurements in numerous frequency bands can be related to the temperature and water vapor structure in the atmospheric column. However, MWR is limited by poor vertical resolution (>2km), precipitation, and surface characteristic uncertainty over land.

In this study we present two joint retrieval approaches to combine the GNSS-RO and MWR measurements. First, an optimal estimation method, 1DVar, is implemented to combine the collocated GNSS-RO refractivity or bending angle and MWR TB observations in 1D. The GNSS-RO/MWR observations can be modeled by an Abel integral and a Radiative Transfer Model (RTM) that considers atmospheric absorption, scattering, and surface reflection and emission. By applying 1DVar to the simulated data this method is shown to reduce GNSS-RO temperature and retrieval biases at the top of PBL, and simultaneously capture the fine-scale water vapor variability that MWR cannot resolve. Results of combining the data from COSMIC-2 and Suomi-NPP missions will be demonstrated. Second, a tomographical 2D combination approach over the GNSS-RO occultation plane has been explored. The simulation results from WRF show that this new concept can better resolve the complex 2D moisture structure than what is possible from either measurement alone. The accuracy and resolution of both joint retrieval methods will be further discussed.

P14

# DETECTION OF THE DIURNAL VARIATION OF THE PLANETARY BOUNDARY LAYER HEIGHT OVER OCEANS USING COSMIC-2 DATA

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NOAA STAR

The planetary boundary layer (PBL) is an essential component of the troposphere. It controls rapid exchanges of heat, moisture, and chemical constituents between the surface and free atmosphere. A fundamental variable of the PBL is the top height (PBLH). The PBL structure is complicated, and the PBLH usually exhibits a strong diurnal cycle associated with the daily variation of solar radiation.

Utilizing the strength of Global Navigation Satellite System (GNSS) Radio Occultation (RO) with the high vertical resolution (~ 200 meters) and deeper penetration (50% of profiles penetrate to below 500 meters), the PBLH can be identified as the layer at the sharp atmospheric density changes near the surface. COSMIC-2 provide more than 4000 atmospheric bending angle profiles per day over the tropical and sub-tropical regions from 45°N - 45°S. COSMIC-2 constellation consists of 6 Leo satellites, covering relatively uniform local time than other currently operating RO missions.

In this work, the COSMIC-2 BA data from October 2019 to Dec. 2021 processed by UCAR are used to detect the PBLH. A sharpness parameter, defined by the relative minimum refractivity gradient, is used to identify the less distinguished vertical changes related to the ambient cloud and other non-PBL atmospheric structures. A Locally Weighted Scatterplot Smoothing (LOWESS) approach is deployed to eliminate high-frequency BA variation in the original COSMIC-2 BA profiles. We define the local minimum in the BA lapse rate in 50 meters intervals between 0.5 km to 3 km altitude as the PBLH. CALIPSO provides high-resolution vertical profiles of aerosols and clouds. In situ observations have intensively validated the cloud-top layer determined by CALIPSO. The accuracy of CALIPSO cloud-top height is within 100 meters. The global CALIPSO data provide a unique opportunity to validate the RO-derived PBLH in regions dominated by marine PBL clouds. We compared the COSMIC-2 derived PBLH with those collocated low cloud top heights detected by the CALIPSO. We focus our comparison on a well-known stratocumulus cloud-dominated region (25S to 15S and 85W to 70W). This study showed that over this region, the diurnal variation of PBLH determined from the RO observations is consistent with those from CALIPSO, which brings us confidence in the COSMIC-2 derived PBLH on the overall ocean and land and combination of all GNSS RO missions.

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# COMPARISON OF COSMIC TEMPERATURE PROFILES WITH MIPAS INSTRUMENT AND EMAC MODEL

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We use COSMIC GPS RO data as absolute reference for validation of satellite derived and modelled temperature fields. We present comparison of COSMIC temperature profiles with profiles measured by MIPAS (Michelson Interferometer for Passive Atmospheric Sounding) instrument. The MIPAS data Version 8 are retrieved with KIT Scientific Level 2 processor and are delivered with complete error characterisation, which allows simultaneous estimation of the natural variability of atmospheric temperature from COSMIC and MIPAS data. COSMIC temperature profiles are also compared with those modelled by EMAC (ECHAM5 MESSy Atmospheric Chemistry) model.

# GNSS RADIO OCCULTATION DATA IN THE AWS CLOUD: AWS ARCHITECTURE

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Verisk Atmospheric and Environmental Research

Multiple independent centers and retrieval systems have processed GNSS radio occultation data beginning with GPS/MET in 1995. Each center has processed different subsets of those data, but the retrieval algorithms have been nonhomogeneous in time as have the formats of the output data themselves. Moreover, there has been no universally agreed upon definition for the identification of a unique RO sounding, making matchups of RO retrievals difficult. Finally, access to RO data has proven limited because of the volume of data, constraints on bandwidth, and inadequate metadata on RO soundings. In order to enable easier and more efficient use of RO data for scientific studies, we at Verisk Atmospheric and Environmental Research (AER) have new standardized formats for RO data, translated repositories of RO data from UCAR COSMIC Project Office, the NASA Jet Propulsion Laboratory (JPL), and the Radio Occultation Meteorology Satellite Application Facility (ROM SAF) into the new formats, assigned unique identifiers to each RO sounding, and developed a database that enables RO sounding matchups between different contributing processing centers and allows for highly efficient subsetting of RO data according to geolocation, time, mission, transmitter, receiver, geometry (rising v. setting), and contributing processing center. Using Amazon Web Services (AWS) we were able to process and catalogue over 17 million RO soundings in a matter of a few days at minimal cost. We also developed an automated system that routinely checks for new RO data and then retrieves and processes them to keep the dataset current with a latency of approximately 2 months. All processes require a complex system that simultaneously translates incoming data and interacts with the database. To meet these objectives, we developed an AWS architecture to enable easy updates and efficient processing. AWS services used include Batch, DynamoDB, S3, ECR, Lambda, and IAM. This presentation will dive into detail on the AWS architecture and discuss the hurdles we had to overcome.

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# IMPLEMENTATION OF THE SUPER-REFRACTION CORRECTION FOR GNSS RO DATA AT THE STAR

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(2) NOAA/STAR

With high vertical resolution and all-weather sensing capability, the RO-derived atmospheric variables are applied widely for weather forecasting and detecting long-term climate signals. However, the super-refraction (SR) phenomenon, caused by sharp gradients of temperature and moisture in the Planetary Boundary Layer (PBL), is frequently observed in subtropical regions over oceans. SR results in systematic underestimating of the RO refractivity in and below PBL. It leads to the negative bias of RO retrieved water vapor compared to in-situ RAOB data and atmospheric profiles derived from microwave and infrared sounders. The NOAA/STAR RO inversion algorithm to convert refractivity into atmospheric pressure, temperature, and moisture profiles is recently enhanced with the ability to process SR cases. Under SR conditions, the refractivity should be corrected before using it in the retrieval. This is a challenging problem because a) in RO measurements, there is no information about the refraction index in the SR layer; b) the infinite number of corrected refractivity profiles satisfy the given bending angle; c) identification of the SR conditions can only be done from the bending angle or refractivity profile in the processing of actual data; d) the proper choice of correction is an ambiguous and arguable issue. We present how these challenges are met in the STAR RO-SR retrieval algorithm. To build a family of SR-corrected refractivity profiles, we implemented the approach proposed by F. Xie. We use RAOB data from the VOCALS campaign as references to simulate the SR refractivity. Then we apply the refractivity correction and retrieve the atmospheric variables for each family member. We use Global Forecasting System 6 hours forecast as the first guess for retrieval. The particular water vapor profile, which provides the minimal deviation of Total Precipitable Water from the first guess, is picked as the final retrieval. To validate the results, moisture profiles are compared with VOCALS RAOB data (123 pairs of SR cases total). After statistical averaging, the bias of humidity, retrieved from corrected refractivity, is about -0.3 g/kg for altitudes below 1.5 km, while it is in the range from -2 to -1 g/kg for retrievals from non-corrected refractivity. We will present the algorithm application to actual COSMIC observations, collocated with the VOCALS data. Results show that the STAR RO-SR algorithm significantly reduces the negative bias of moisture in PBL.

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# REAL-TIME AND RETROSPECTIVE MONITORING AND EVALUATION OF BENDING ANGLE WITH JEDI

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(3) UCAR/JCSDA Postdoctoral fellow

The Joint Center for Satellite Data Assimilation (JCSDA) is the lead developer of the Joint Effort for Data assimilation Integration (JEDI). This system is being designed as an object-oriented flexible architecture to enable multiple modeling systems to share a common data assimilation framework. The system has been enabled with multiple operators for simulating the bending angle for assimilation into NWP models. The NOAA Bending Angle Model (NBAM), the EUMETSAT Radio Occultation Processing Package (ROPP), and the UK Met Office operator. This enables the ability to compare multiple options for bending angle simulation within a common structure and also for improvements to more easily be transferred from system to system. In our poster we will show some of the monitoring capabilities including operational governmental, as well as, commercial constellations, using the publicly available NOAA FV3 model short-range forecasts as background states and largely focusing on the NBAM operator. Bending angle means in time, zonal average, and statistics by rising/setting and by the transmitter are helpful for the current and future missions to identify issues and strategize for future improvements.

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# INITIAL EXPERIMENTS WITH VERTICAL SMOOTHING OF GNSS-RO BENDING ANGLES

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(3) ECMWF

Initial experiments with GNSS-RO bending angle observations from Spire posed a problem. While the ECMWF NWP system showed better results when using observations which had been processed by EUMETSAT, the Met Office NWP system performed better with Spire-processed observations. Two main differences were noted between the two sets of observations: a different bias in the troposphere and the level of vertical smoothing applied. EUMETSAT have subsequently revised the processing to nearly eliminate the bias in the troposphere, relative to both Met Office and ECMWF models. Thus, the question remains – how does the vertical smoothing of the observations affect its utility in NWP?

To answer this question we aim to run a set of NWP experiments with different levels of vertical smoothing. These experiments aim to shed light on what effect smoothing has on forecasting systems, and whether there is a preferred level of smoothing. As a possible explanation we put forward the possibility that high-resolution observations can introduce grid-scale noise in the NWP analysis that may detrimentally affect the model forecast. Thus, it may be beneficial to smooth the observations to the resolved scale of the model. Other observation types use thinning and super-obbing to address these issues – do those methods offer useful tools to the GNSS-RO community?

# GNSS RADIO OCCULTATION INTERPOLATED BY MACHINE LEARNING AND BAYESIAN INTERPOLATION

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GNSS radio occultation (RO) is a space-based remote sensing technique that profiles microwave refractivity, temperature, and pressure in the atmosphere by measuring the refractive bending of signals transmitted by the Global Navigation Satellite Systems (GNSS) transmitters as they transect the Earth's limb. Long-term stability, all-weather capability, and high accuracy make RO very attractive to the meteorological community. Indeed, RO profiles at a global scale are routinely assimilated into numerical weather prediction models. However, constructing RO-based climatologies is complicated because the sampling density is non-uniform and so low that it does not resolve synoptic variability in the atmosphere.

Bayesian interpolation (BI) is a state-of-the-art approach to construct RO climatologies in which the occultation data are fit — but not over-fit — using spherical harmonics as basis functions on constant height surfaces. In this presentation, we investigate a neural network machine learning (ML) algorithm to generate maps of RO-retrieved products based on sparse RO data. We produce RO climatologies using ML and compare them to the performance of BI. Furthermore, we train the ML models using the residuals of BI in a combined BI+ML approach. We map microwave refractivity on six constant geopotential height surfaces (2, 3, 5, 8, 15 and 20 km), representing diverse atmospheric dynamical regimes. We focus most of our evaluation at the lowest layer (i.e., 2-km), where RO is sensitive to small horizontal scale structures associated with boundary layer clouds and correlated variations in water vapor density. We use the forecasts of the operational numerical weather prediction system of the European Centre for Medium-range Weather Forecasts (ECMWF) as a nature run, interpolate the forecasts to the times and locations of COSMIC-2 RO data over a period of 10 days, apply BI-only and ML-only, and combined BI+ML to map the simulated data. Then the results are compared to the gridded products of ECMWF to evaluate the performances of these three approaches. COSMIC-2 produces approximately 3500 RO soundings daily spanning 46°S to 46°N latitude only.

We find that the performances of BI in interpolating RO data and of ML in interpolating RO data are comparable; however, we find that ML when applied to the residuals of BI offers further improvement in interpolating RO data in the form of increased temporal and horizontal resolution. BI is able to provide maps of refractivity at a cadence of a few days whereas BI+ML provides maps of refractivity at a cadence of 3 hours. The posterior uncertainties in microwave refractivity at each iso-height surface for BI-only are 10.9, 9.1, 5.3, 1.6, 0.6 and 0.3 N-unit. The posterior uncertainties for the same for BI+ML are 8.7, 6.6, 3.6, 1.1, 0.3 and 0.2 N-unit.

# VALIDATION OF SPIRE RADIO OCCULTATION RETRIEVALS WITH SNPP ATMS MICROWAVE AND RADIOSONDE MEASUREMENTS

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The Global Navigation Satellite System (GNSS) radio occultation (RO) data play an essential role in numerical weather prediction (NWP) and climate change monitoring. Spire RO data were provided to NOAA under the Commercial Weather Data for RO (CWD-RO) project to evaluate the commercial RO data quality. To ensure the data quality from Spire is consistent with other RO missions and is not significantly deviated from observations by NOAA's satellite, we need to quantify their accuracy and retrieval uncertainty carefully. In this work, the Spire Wet Profile (wet temperate and humidity profiles) data from 2021-09 to 2022-03 (Delivery Order-3) processed by the University Corporation for Atmospheric Research (UCAR) are evaluated through comparison with Suomi National Polar-orbiting Partnership (SNPP) Advanced Technology Microwave Sounder (ATMS) microwave sounder measurements and collocated radiosonde measurements. Observations from RO, microwave sounders such as ATMS, and radiosonde are all assimilated into NWP. The inter-consistency among Spire RO, SNPP ATMS, and radiosonde data is critical in improving the global weather forecasts and monitoring/predicting severe weather events, and still remains challenging to be quantitively characterized. Through the Community Radiative Transfer Model (CRTM) simulation, the microwave sounder SNPP ATMS and Spire RO measurements are compared over the ATMS sounding channels CH07 to CH14 (temperature channels) with weighting function peak height from 8 to 35 km and CH19 to CH22 (water vapor channels) with weighting function peak heights ranging from 3.2 to 6.7 km. Biases of the evaluated channels' brightness temperature (BT) are within ±0.6 K, indicating the consistency between CRTM-simulations using Spire data and ATMS data. For the ATMS moisture channels CH19-21, the Spire versus ATMS BT biases are consistent within 0.1 K. In the Spire retrievals versus RS41radiosonde observations (RAOB) inter-comparison study, the height-dependent mean temperature/humidity biases and their associated uncertainties are evaluated. In general, over the height region between 8 km and 26 km, the RS41 RAOBs match Spire temperature profiles very well with temperature biases < 0.04 K. Below 4 km, the Spire humidity retrievals deviate from RS41 RAOBs with increasing negative humidity biases approaching the surface, which can be attributed to the negative refractivity biases due to the super-refraction conditions. The RAOB data quality can be affected by the solar illumination correction. Spire data also provide an opportunity to serve as a reference.

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# IROWG-8 VIRTUAL MEETING HOSTED BY NOAA

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The eighth International Radio Occultation Working Group meeting was held on 15- 20 April 2021. Travel and gathering restrictions imposed by the COVID-19 pandemic forced NOAA and UCAR to innovate by hosting a completely virtual meeting. Despite the challenging logistics, IROWG-8 provided a forum for sharing recent programmatic developments, operational and scientific results, technology advancements, and community-building measures. In addition to two parallel serial speaker presentation tracks, the virtual meeting featured a virtual poster session and four concurrent facilitated sessions for in-depth discussion among the RO community to develop recommendations on future direction and use of RO technology for environmental applications. Attendees widely praised the virtual meeting as a model for facilitated science workshops. This poster will describe NOAA and UCAR planning and organization of the IROWG-8 meeting, including the technologies that the team used and the lessons learned in hosting the first virtual international Radio Occultation Working Group meeting.

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# FORMOSAT-7/COSMIC-2 SPACE WEATHER DATA PRODUCTS

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The The FORMOSAT-7/COSMIC-2 mission significantly extends the capabilities of ionosphere monitoring from space. The mission payload is the Tri-GNSS Radio Occultation System (TGRS), designed by the Jet Propulsion Laboratory (JPL). Science payloads include the Ion Velocity Meter (IVM) designed by the University of Texas at Dallas (UTD), and the Radio Frequency Beacon (RFB)designed by SRI. The payloads provide a range of observation types relevant space weather applications including GNSS limb and overhead TEC, electron density profiles, amplitude/phase scintillation (TGRS), in-situ ion density, composition, and velocities (IVM), and TEC between the satellite and ground-stations (RFB). Data collected from the constellation of satellites can resolve large, medium, and small-scale ionospheric structures. This presentation summarizes the space weather data products available for operations and research applications.

# IMPACT OF THE GNSS CLOCK RATE ON RADIO OCCULTATION BENDING ANGLES

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Measuring the bending angle of a signal travelling through the Earth's atmosphere, between a GNSS satellite and a LEO spacecraft, requires an accurate knowledge of the position and velocity of the two space vehicles during the radio occultation (RO) event. The GNSS positions and clocks are provided as auxiliary files, while the Precise Orbit Determination (POD) of the LEO is a necessary step of the bending angles retrieval process. At EUMETSAT, the POD software embedded in the RO operational processors for the EPS missions (Metop-B and -C) and Sentinel-6A use a zero-differencing approach to estimate the LEO orbits and clocks.

The GNSS space vehicles have revolution periods in excess of 10 hours and their orbits, which are relatively smooth, are typically provided at a 15-minute rate. The GNSS clocks are needed to synchronize the receiver clock when performing the LEO POD. Being GNSS clocks more affected by random variations, a smaller sampling interval is required to obtain accurate interpolations, as needed by the bending angles retrieval process.

For this study we process a month-long batch (September 2021) of RO data from the RO receiver onboard Sentinel-6A. As auxiliary GNSS products, we use JPL-generated orbits and high-rate clocks (1 Hz) for both the GPS and GLONASS constellations. We test the impact of different down-sampling of the GNSS clock data on the LEO POD solutions and on the RO bending angles retrieval processing. The resulting L1B products from the different data sets, resulting from different down-sampling values, will be assessed by estimating the number of degraded and failed occultations and by comparing them with forward-modelled ECMWF bending angle profiles.

# PRECISE ORBIT DETERMINATION OF LOW EARTH ORBITING SATELLITES FOR CLIMATE APPLICATIONS INCLUDING UNCERTAINTY ESTIMATION

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Global Navigation Satellite System (GNSS) radio occultation (RO) is a highly valuable remote sensing technique for probing the Earth's atmosphere, due to its global coverage, high accuracy, long-term stability, and essentially all-weather capability. In order to ensure the highest quality of essential climate variables (ECVs), derived from GNSS signal tracking by RO satellites in low Earth orbit (LEO), the orbit positions and velocities of the GNSS transmitter and LEO receiver satellites need to be determined with high and proven accuracy and reliability. Wegener Center's new Reference Occultation Processing System (rOPS) hence integrates uncertainty estimation at all stages of the processing.

Here we present the setup for precise orbit determination (POD) within the rOPS, which routinely and in parallel performs the LEO POD with the two independent software packages Bernese GNSS software (v5.2) and NAPEOS (v3.3.1), employing two different GNSS orbit data products. This POD setup enables mutual consistency checks of the calculated orbit solutions and is used for position and velocity uncertainty estimation, including estimated systematic and random uncertainties. For LEOs enabling laser tracking, we involve position uncertainty estimates from satellite laser ranging. Furthermore, we intercompare the LEO orbit solutions with solutions from other leading orbit processing centers for cross-validation.

We carefully analyzed multi-month, multi-satellite POD result statistics and find a strong overall consistency of estimates within LEO orbit uncertainty target specifications of 5 cm in position and 0.05 mm/s in velocity for the CHAMP, GRACE-A, and Metop-A/B missions. In 92% of the days investigated over two representative 3-month periods (July to September in 2008 and 2013) these POD uncertainty targets, which enable highly accurate climate-quality RO processing, are satisfied. The moderately higher uncertainty estimates found for the remaining 8% of days (about 5–15 cm) result in increased uncertainties of RO-retrieved ECVs. This allows identification of RO profiles of somewhat reduced quality, a potential benefit for adequate further use in climate monitoring and research.

# ON THE IMPACT OF SIGNAL CUTOFF AND SMOOTHING ON SYSTEMATIC AND RANDOM UNCERTAINTY IN RO RETRIEVALS

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EUMETSAT

It is probably generally accepted that subjective choices in the setup of a RO processing chain impact the statistics of RO retrievals (e.g., bending angles) when compared to Numerical Weather Prediction data or co-located retrievals from other RO instruments. On the other hand, data from different RO missions or data providers are often compared statistically, with the results subsequently being used to infer the relative merits of *instruments*, or to derive uncertainty estimates which are assumed to be valid for RO data products in general. Also, requirements for instrument performance (or commercial data buys) are regularly expressed in terms of the statistical properties of end products.

Such analyses or requirements do not take the contribution of data processing details into account. We analyse the impact of two such choices - the cutoff of carrier phase signals in the noise-only region of deep occultations and the amount of vertical smoothing applied to bending angles - on both bias and standard deviation against NWP short-range forecasts as well as the penetration of retrievals into the lower troposphere for EPS/GRAS and Spire bending angle data. While we focus on the impact on tropical tropospheric bending angle statistics where we find the largest effect, we also show the variation of statistics due to these modifications in other latitude bands and altitude regions.

Based on the results of several experiments, we conclude that

- Upper altitude SNR is not much related to the penetration of retrievals into the lower troposphere;

- Data exhibiting high carrier phase noise levels (or low SNR) can be processed to exhibit random uncertainty statistics similar to or better than “normally” processed low-noise missions, but at the cost of significantly larger vertical error correlations (and possibly, positive biases in the lower tropical troposphere);

- Simply comparing first-order statitics between different instruments and/or processing scenarios without taking into account the vertical correlations introduced by smoothing hardly allow making judgements on the relative benefits of the said instruments and/or processing approaches.

# L1-L2 BENDING ANGLE FITTING AND L2 EXTRAPOLATION IN THE TROPOSPHERE

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In Radio Occultation (RO) processing, the modeling of the ionospheric effects on the GNSS frequencies L1, L2 and L5 is crucial to avoid undesired biases in the retrieved neutral bending angle profiles. At EUMETSAT we adopt a linear fitting of the L1-L2 difference, which is based on a Chapman layer bending angle profile. The extrapolation of the L2 profile in troposphere, where the L2 signal drops out, is the current approach adopted in the operational RO processors for the RO experiments onboard Metop B and C, Sentinel-6A (S6A), and the SPIRE constellation.

After the activation of TriG GNSS-RO receiver onboard the S6A satellite on November 28th 2020, the early bending angle retrievals showed non-physical neutral bending angles close to the altitude where the L2 bending angle tracking was lost. This, through the ionospheric correction, had a negative impact on the neutral bending angle profiles. This effect was observed in both GPS and GLONASS occultations. To compensate for this, before performing the ionospheric correction, the EUMETSAT S6A RO Non Time Critical (NTC) processor currently uses a simple algorithm removing all L2 data below the altitude at which the absolute L1-L2 difference is larger than a threshold. However, with the increasing solar activity of solar cycle 25, a large bias in the L1-L2 difference led the algorithm to often cut the L2 signal too high, where the signal was still meaningful. This bias effect looks to be affecting the processing of occultations from S6A, Metop and COSMIC-2, more than the ones from Spire satellites.

With the goal of using as much physical data as possible and more accurately remove the non-physical part, we performed an investigation of the possible approaches to improve the fitting of L1-L2 differences and the resulting L2 bending angles cutoff and extrapolation that would work with all RO receivers operated by EUMETSAT. We present the results of this investigation and a way forward, by comparing the resulting L1B products against forward-modeled ECMWF products

# RADIAL ASYMMETRY CORRECTION ASSESSMENT BY END-TO-END SIMULATIONS AND ANALYSIS OF RO DATA

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The retrieval of atmospheric profiles from radio occultation (RO) measurements assumes local spherical symmetry of the atmosphere about the (mean) tangent-point location of RO events, for instance in the Abel integral used in refractivity retrieval and the hydrostatic integral used in pressure retrieval. However, since the real atmosphere is not exactly spherically stratified, and also since tangent-point trajectories are not vertical but rather 3D curves, the symmetry assumption in retrieval algorithms introduces errors when the retrieved profiles are interpreted (or used) as in-situ measurements.

We find that longitudinally horizontal gradients are small, in general, and that the main contribution to statistical biases from horizontal variations comes from the RO signal ray-paths in the latitudinal direction. A residual error correction based on estimating the along-ray asymmetry and accounting for the obliqueness of the tangent-point trajectory hence seems a valuable algorithmic feature.

Based on Syndergaard et al. (2005), who published a refractivity mapping operator for assimilation of RO data for numerical weather prediction purposes, we investigated the application of this mapping operator for such a residual error correction within Wegener Center's new Reference Occultation Processing System (rOPS). We used ray-traced bending angle profiles under suitable simulation conditions (orbit geometry, (a)symmetric atmosphere) for end-to-end simulations through ECMWF analysis fields. Additionally, we used real RO bending angle data as input to the assessment. Based on the ECMWF fields and the mapping operator, and retrieving refractivity and (dry-)atmospheric profiles of pressure and temperature assuming spherical symmetry, we analyzed the error correction statistically. We find highest bias correction potential in the mid-latitude and polar regions, where salient latitudinal refractivity gradients occur. The correction clearly enables improved accuracy across the stratosphere and into the upper troposphere, while its effect at the lowest altitudes is difficult to assess.

# DEVELOPMENT OF EXCESS PHASE PROCESSING ALGORITHM FOR MULTI-RO MISSIONS AND DATA QUALITY IMPROVEMENTS AT STAR

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ESSIC/CISESS, University of Maryland

With recent addition of CubSATs (i.e., Spire, GeoOptics, PlanetIQ) to the GNSS RO family, more and more RO receivers with different sensing quality deployed into space to detect the atmosphere path delays of the GNSS signals. While the processing algorithms are generally similar for all missions, the sensor-dependent L1a observations and mission-specific requirements require special processing and customized interfacing software for each sensor. The comparisons between various missions are generally consistent above 8 km altitude. However, the differences are usually not negligible below 8 km. The bending angle retrieval quality in the lower atmosphere is often correlated with the open-loop technique.

Recent RO satellites (COSMIC-2, Spire and GeoOptics) can receive the GPS and GLONASS signals. While COSMIC-2 are also designed to track Galileo satellite signals, there are no actual occultation data tracking Galileo satellites yet. Spire satellites have occultation profiles from tracking the Galileo satellites. Current daily RO profiles assimilated into NWP models are far less than saturation. Inclusion of different GNSS systems in occultation can double or triple daily RO profile numbers. which can potentially improve the NWP weather forecasting skills. However, processing RO observations from receivers under new GNSS systems poses difficulties and challenges for the RO L1a to L2 data conversion. The differences in dealing with GLONASS and Galileo systems from GPS are mainly due to the signal frequency, SNR level, satellite clock system, satellite orbital accuracy, and the receiver differences. These differences can contribute to the error propagation in the RO data processing from the Precise Orbit Determination (POD) to the excess phase calculation. Including GLONASS satellites in POD may result in a different POD solution; processing occultation from Galileo signals also poses difficulty in dealing with the simulation of the open-loop phase model, signal frequency, navigation bit removal, signal smoothing/filtering, etc.

In this study, we characterize RO receivers regarding the SNR values, clock stability, number and orientation of the POD and RO antennas, satellite orbits, and the receiver open-loop model through multiple RO missions at NOAA-STAR. We compare algorithm differences in RO processing (carrier phase to bending angle) from different RO missions and quantify the difference and uncertainty in the POD, excess phase, and bending angle. We also quantify the impacts of the receiver update and decay on the bending angle time series.

# A ONE-DIMENSIONAL VARIATIONAL IONOSPHERIC RETRIEVAL FOR TRUNCATED GNSS RADIO OCCULTATION MEASUREMENTS

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A new one-dimensional variational (1D-Var) retrieval approach for ionospheric GNSS radio occultation (GNSS-RO) measurements is described. The approach maps a one-dimensional ionospheric electron density profile, modelled with multiple ``VaryChap'' layers, to bending angle space. The use of ionospheric bending angles is discussed.

This approach potentially circumvents the need to for a Differential Code Bias (DCB) estimate when using the measurements.

This new, general retrieval method is applicable to both standard GNSS-RO retrieval problems, and the truncated geometry of EUMETSAT's Metop Second Generation (Metop-SG), which will provide GNSS-RO measurements up to 500 km above the surface. The 1D-Var approach has been tested with COSMIC-2 and Metop-A extension campaign measurements, and compared with other retrieval approaches.

The 1D-Var retrieval code is included in the EUMETSAT ROM SAF's ROPP-11.0 software package.

# STRATOSPHERIC WATER VAPOR FROM THE HUNGA TONGA VOLCANIC ERUPTION DEDUCED FROM COSMIC-2 GNSS-RO OBSERVATIONS

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The eruption of the Hunga Tonga – Hunga Ha'apai (HTHH) volcano on January 15, 2022 injected large amounts of water vapor directly into the stratosphere. While normal background levels of stratospheric water vapor are not detectable in radio occultation measurements, effects of the HTHH eruption are clearly observed as anomalous refractivity profiles from COSMIC-2, suggesting the possibility of detecting the HTHH water vapor signal. In order to separate temperature vs. water vapor effects on refractivity, we use co-located temperature observations from the Microwave Limb Sounder (MLS) to constrain a simplified water vapor retrieval. Our results show enhancements of water vapor above 1000 ppmv in the stratosphere (~25-30 km) following the HTHH eruption, with propagating patterns that follow the dispersing volcanic plume. The stratospheric water vapor profiles derived from radio occultation are in reasonable agreement with limited radiosonde observations.

# INVESTIGATING THE ATMOSPHERIC RESPONSE TO THE JANUARY 2022 HUNGA ERUPTION, TONGA THROUGH GNSS RADIO OCCULTATIONS

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In the upper troposphere lower stratosphere (UTLS), Global Navigation Satellite System (GNSS) Radio Occultations (ROs) provide accurate air temperatures (< 0.5 K) every ~200 m vertically. We use RO observations on 01/15/2022 to investigate the thermodynamic response and dynamic coupling of the Hunga volcanic eruption in Tonga with the Earth's lower-to-middle atmosphere. We analyze spatially and temporally collocated RO soundings from Sentinel-6A, the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC-2), and Spire spacecraft. We find that, within 450 km and < 3 hours after the eruption, the UTLS region exhibits distinct ~7–8 km vertical wave oscillations that induce ± 8.0 K (peak-to-peak) temperature perturbations. This signature is captured by both COSMIC-2 and Spire, independently. Additionally, southwest of the eruption site, Sentinel-6A and COSMIC-2 reveal extreme tropospheric dryness with superimposed wave activity, which is absent North of the Hunga volcano, Tonga location. We will conclude by highlighting the importance of RO soundings in investigating the dynamic coupling of natural hazard events with the Earth's lower atmosphere, which opens up a plethora of atmospheric physics applications for societal benefits.

# WILDFIRE AND VOLCANIC SIGNALS IN THE STRATOSPHERE OBSERVED BY RADIO OCCULTATION MEASUREMENTS

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Extreme events such as wildfires and volcanoes not only have harmful effects on vegetation, human infrastructure and lives, but can also significantly impact the Earth's atmosphere by emitting large quantities of aerosols. Although the absorptive capacity of aerosols emitted by volcanoes and wildfires is very different, both can have large impacts, especially in the stratosphere where they remain for months to years. Yet little is known about their effects on the atmospheric temperature structure and climate.

Using radio occultation data, we analyzed two of the largest wildfires of the last decade. We found significant local warming of the lower stratosphere by up to 10 K within the aerosol plumes emitted by the wildfires immediately after they emerged. The impact on the lower stratospheric climate persisted for several months and reached up to a remarkable 3.5 K in the case of the 2019/20 Australian wildfires. This is stronger than any signal from minor volcanic eruptions in the last two decades.

The recent massive eruption of the Hunga Tonga–Hunga Ha'apai volcano not only sent strong shock waves around the globe, but also set a new record for plume height, transporting aerosols up to an altitude of more than 50 km into the mesosphere. However, compared to the high explosiveness of this eruption, only a small amount of aerosols has been released, equivalent to that of a moderate volcanic eruption. This raises the question, about the impact of the eruption on important atmospheric parameters such as temperature, and what other traces it left in the upper atmosphere.

In our presentation, we will compare the signals from wildfires with those from volcanic eruptions on atmospheric parameters such as temperature. Further we highlight some of the key benefits of radio occultation data for studying the atmospheric impact of these types of extreme events.

# SIGNS OF CLIMATE VARIABILITY IN DOUBLE TROPOPAUSE GLOBAL DISTRIBUTION FROM TWO DECADES OF RADIO OCCULTATION DATA

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From GPS radio occultation observations between 2001 and 2018, a detailed record of well-resolved, accurate and globally distributed double tropopause (DT) occurrences was retrieved at the Wegener Center in Graz. A multiple linear regression analysis is applied at each latitude-longitude grid point to relate the distribution of monthly TDs (response variable) with several predictor variables and model coefficients. Different features are proposed, in particular, the variability expected from the first annual harmonics, SOI, solar flux, OLR, QBO, SAM and tradewind indexes. Data at each grid point are separated into two sets (training and test). The model performance of both sets is evaluated from the mean square error, as the difference between the observed and predicted values, normalized by the number of observations. A heuristic approach is applied to select the appropriate features, checking the correlations between the response variable and the explanatory variables. Different transformations, base expansions and interactions of the predictors are tested to improve the predictive power of the model. The combination of features that provides the best model performance while counteracting overfitting problems is evaluated. In addition to the different mechanisms proposed so far of possible DT generation, the radiation of inertia gravity waves by the geostrophic imbalance in the presence of the subtropical jet is analyzed. This is accomplished by considering the cross stream Rossby number as an additional feature.

# ANALYSIS OF UTLS DYNAMICS USING GNSS RADIO OCCULTATIONS: THE CONNECTION BETWEEN BLOCKING AND SUDDEN STRATOSPHERIC WARMING EVENTS

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A better understanding of the dynamics in the upper troposphere and lower stratosphere (UTLS) is essential for improving surface weather predictability. In this study, we focus on wave propagation in the UTLS and its role in the connection between blocking and sudden stratospheric warming (SSW) events. We analyse the properties of the quasi-geostrophic Eliassen-Palm (E-P) flux in the UTLS using vertically high-resolved Global Navigation Satellite System radio occultation (GNSS RO) observations. These results demonstrate that GNSS RO observations provide detailed information on vertical structure in the UTLS and are suitable for observing atmospheric circulation. The E-P flux we obtain with GNSS RO is in good agreement with the E-P flux theory. We show that SSWs are preceded by enhanced E-P flux propagating upward in the UTLS, for cases associated with blocking events over the Euro-Atlantic region. This is consistent with the existing literature. For SSW cases where wave reflection takes place, downward propagation of E-P flux leads to blocking over the North Pacific.

# COSMIC-2 CAPABILITIES FOR MONITORING IONOSPHERIC SCINTILLATION

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The COSMIC-2 program has demonstrated new methods for monitoring ionospheric scintillation using the radio occultation (RO) technique that provide substantial improvements relative to past ground-based systems that can only provide localized knowledge. COSMIC-2 is able to provide maps of the presence or absence of the ionospheric irregularities that cause scintillation throughout the equatorial region at all longitudes and refresh these maps on time scales that approach the growth rates of the underlying instabilities. The All Clear product, based on 1 Hz Signal-to-Noise Ratio (SNR) occultation observations, indicates which longitude sectors can be confidently stated to be scintillation-free, whereas the Bubble Map product, derived from a combination of 50-100 Hz carrier phase and SNR observations, specifies regions in which irregularities have been detected. Two different irregularity geolocation algorithms underly the Bubble Maps. These algorithms utilize back-propagation techniques to localize irregularities to an accuracy of ~1° in longitude. All of these products and algorithms have been validated by the COSMIC-2 space weather Cal/Val team. In addition, the team has also investigated the possibility of augmenting the Bubble Maps using data from the Ion Velocity Meter (IVM) sensors on the COSMIC-2 spacecraft. IVM measures the in-situ density along the satellite tracks and can be used to localized irregularity regions as long as they extend up to the COSMIC-2 altitude. Important factor enabling the successful COSMIC-2 scintillation capabilities are COSMIC-2’s equatorial, low inclination orbits and the program’s low data latency. These factors must be considered by future RO sensing programs seeking to replicate or improve upon the COSMIC-2 baseline capability.

# ASSESSMENT OF GRAS IONOSPHERIC MEASUREMENTS FROM METOP-A END-OF-LIFE TESTING CAMPAIGN

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The GRAS instrument on-board of the Metop satellites of the EUMETSAT Polar System (EPS) programme uses the radio occultation (RO) technique to obtain information about the temperature and humidity profiles. RO soundings are also capable of providing information on the vertical structure of the electron density if the measurements cover an appropriate height range (e.g., 90 - 500 km). In the framework of the Metop-A end-of-life testing campaign, the EUMETSAT conducted an ionospheric extension experiment enabling the GRAS instrument to extend its vertical measurement range for ionosphere soundings (up to 300 and 600 km height) for a two months period during summer 2020. During the test campaign a large set of GNSS radio occultation measurements (e.g., carrier phases and pseudoranges) had been recorded by onboard GRAS instrument. The ionospheric measurements were taken with impact parameter height below 600 km and 300 km whereas the Metop-A was flying at an orbit height of about 800 km which makes the electron density reconstruction very challenging.

A study called GIMA (assessment of GRAS Ionospheric Measurements for ionospheric model Assimilation) has been undertaken to complement the GRAS instrument assessment by processing RO observations to ionospheric products. Ionospheric electron density profiles were generated up to the Metop-A orbit height using an adaptive topside ionosphere/plasmasphere model technique. The impact of the limitation in the vertical measurement range on the data quality of the retrieved parameters has been investigated.

A comprehensive validation study is done by comparing the key ionospheric parameters (NmF2, hmF2, NmE) obtained from Metop-A extension campaign with other RO mission reconstructions (e.g., COSMIC-2, Fengyun-3D) and ground vertical sounding observations (ionosonde stations from GIRO network). The investigation shows an overall very good agreement of Metop-A electron density reconstructions with other independent data. Furthermore, the suitability of used electron density extrapolation is checked for operational use with respect to memory use and timeliness.

# RADIO OCCULTATION IONOSPHERIC PRODUCTS FROM GRAS ON BOARD METOP EPS SATELLITES: OVERVIEW AND VALIDATION

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Main objective of EUMETSAT is to monitor weather, climate and climate changes from space. In the last few years there has been also an increased interest in EUMETSAT's user community for ionospheric monitoring and space weather.

In the framework of the Metop-A end-of-life technology test campaign, EUMETSAT approved the extension of the GRAS vertical measurement's range into the lower and mid ionosphere (up to 300 km and up to 600 km) for a two months period experiment, during summer 2020. The experiment was successful. GRAS was able to provide a good set of ionospheric occultations without impacting the provision of occultation data to NWP centres and to users.

Metop-A reached its end-of-life and was deorbited in November 2021 but, thanks to the good results achieved, both the GRAS receivers on-board Metop-B and C have been configured on February 2022 to collect operationally data up to 300 km. There are also plans to provide operationally ionospheric occultation data to the users, starting from the end of 2022.

This contribution presents an overview of the ionospheric monitoring activities at EUMETSAT in the framework of its current and future radio occultation missions. In particular, it will provide details about the ionospheric products (ionospheric bending angles profiles, amplitude and phase scintillation indexes profiles and topside TEC) that EUMETSAT plans to generate and to make available to the users. Moreover, during 2021/2022 EUMETSAT funded a study (GIMA: Assessment of GRAS Ionospheric measurements for Ionospheric model assimilation), with the purpose of complementing the GRAS instrument assessment with an ionospheric data assessment, including processing of relevant ionospheric data for their future assimilation into ionospheric models. This contribution will also provide a summary of the results obtained within this study.

# GNSS-RO (RADIO OCCULTATION) FOR THE D- AND E-REGION ELECTRON DENSITY

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The D (60-90 km) and E-region (90-150 km) ionosphere plays an important role in radio communication/navigation for its absorption of high-frequency (HF) and reflection of very low frequency (VLF) radio waves. The D-region, also known as the mesosphere in the neutral atmosphere, is arguably one of the most critical interfaces between the lower atmosphere and the ionosphere. The D/E-region ionosphere is often strongly perturbed by planetary waves from the lower atmosphere as well as by local irregular small-scale dynamic and electromagnetic instability. Sporadic E (Es) is a good example as strong transient disturbances to the background Ne profile at 90-120 km. It is difficult to measure the D/E-region electron density (Ne) from space because of its low concentration and large vertical gradient. This talk will induce a novel observing technique, the GNSS radio occultation (RO), for profiling the lower-ionospheric Ne. Rapid advances in low-cost SmallSat/CubeSat constellations such as COSMIC and Spire have greatly improved the spatiotemporal sampling of Ne. The new GNSS-RO Ne observations reveal many interesting features that led to new science questions on the diurnal, seasonal, solar-cycle, and magnetic-field-dependent variations of Ne in the lower ionosphere.

# USE OF COSMIC-2 SLANT TEC TO VALIDATE IRI ESTIMATES OF F-LAYER AND TOPSIDE ELECTRON DENSITY

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Total electron content (TEC) estimated by COSMIC-2 measurements are used as a validation data set for ionospheric structures produced by the International Reference Ionosphere (IRI) model plus an assumed plasmasphere. The limb-viewing geometry of COSMIC-2 satellites receiving GPS signals allows for examination of layered properties of the ionosphere, whereas the near-nadir viewing geometries of COSMIC-2 allow for estimates of topside electron density. The 1 Hz estimates of Total Electron Content (TEC) along COSMIC-2 acquisition data arcs permit a fine-grained dividing of different layers of the ionosphere and evaluation of those same structures estimated by IRI. To make a comparison between COSMIC-2 and IRI models of the ionosphere, spatial and temporal colocation is required, as well as integration along the COSMIC-2 transmitter-receiver line of sight within the IRI model field of electron density.

The presentation will briefly compare and contrast the two ionospheric data sources, COSMIC-2 and IRI, describe the method for integration along the line-of-sight, and finally present summary statistics and results for two, 6-day periods where detailed comparisons were performed.

# NOAA'S FIRST COMMERCIAL SPACE WEATHER DATA PILOT

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The Commercial Weather Data Pilot (CWDP) program was authorized by the Weather Research and Forecasting Innovation Act of 2017. The first two Pilot studies (2016 and 2018) evaluated commercial radio occultation (RO) data sources. This led to NOAA's first operational commercial satellite data purchase in 2020, and commercial RO data have been part of the operational data stream going into the National Weather Service Global Forecast System since May 2021.

After the conclusion of the second Pilot round, the PROSWIFT Act (Public Law 116-181, 2020) was signed into law and set forth provisions to improve the Nation's ability to forecast space weather events and mitigate the effects of space weather. In response, the CWDP Program issued a Request For Information focused on commercial sources of space weather data. Eleven responses were received, detailing a variety of capabilities. Evaluations of these responses considered 1) the degree to which the proposed space weather data types would meet NOAA requirements including benefits to partners and downstream users, 2) the readiness level of the data type and the company to participate in a Pilot study and 3) the readiness of NOAA systems and resources for ingesting, evaluating, and using the data in the near term. Based on the results of the evaluations, a decision was made to proceed with a Pilot study of ionospheric measurements from GNSS RO sensors in FY2022.

In this presentation, we will discuss the status of NOAA's first CWDP Space Weather Data Pilot program, including the requirements, schedule, plans for executing the Pilot, and the anticipated uses and benefits of the space weather products from commercial radio occultation data.

# RADIO HOLOGRAPHIC METHODS FOR THE INVERSION OF RADIO OCCULTATION MEASUREMENTS FROM PAST AND CURRENT VENUS MISSIONS

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The radio occultation (RO) technique has been used by multiple planetary spacecraft to characterize planetary neutral atmospheres and ionospheres [e.g., 1,2,3,4]. While the RO technique was conceived in the framework of planetary missions, the emergence of Global Positioning System (GPS) RO for sensing the Earth's atmosphere [5] and their increasingly widespread use in numerical weather prediction has spurred new developments in techniques that can in turn be applied to process planetary RO data and enhance their science returns.

We present preliminary results of implementing novel radio holographic methods [6], widely used in GPS RO processing for sensing the Earth's moist tropical troposphere, to past and current Venus' missions: NASA's Magellan, ESA's Venus Express (VEX), and JAXA's Akatsuki. The main advantages of using this approach are higher (sub-Fresnel) vertical resolution [7], the possibility of resolving the signal when multi-path interference is present, and cancellation of the refractive defocusing effect. These improvements enhance investigations on the role of local waves in the vertical transport of heat and mass and their impacts on the global circulation of Venus' atmosphere. Additionally, by processing radio occultation data spanning four decades, we will enable the analysis of the temporal variation of the profiles, with an extended coverage of spatial and solar illumination conditions.

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# STATUS UPDATE OF GNSS-RO DATA ASSIMILATION EFFORTS AT NOAA

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The launch of COSMIC-2 in June 2019 brought the next-generation of RO observations, with dense equatorial coverage and higher signal-to-noise ratio. The Commercial Weather Data pilot project has provided additional RO observations from the commercial sector, with further needs for a timely operational implementation. The current RO observing system now requires a holistic approach to improve RO impact in numerical weather forecasting at NOAA. These efforts include testing of new RO data sources as well as improvements in data assimilation algorithms, with enhanced forward operators, quality control procedures and error structures.

During this talk, recent, current, and planned efforts to improve the impact of RO observations in the operational global system at NOAA will be presented. Furthermore, ongoing work towards the assimilation of COSMIC-2 into the next generation of NOAA’s hurricane system will be discussed.

# STATUS OF GNSS-RO IN GLOBAL DATA ASSIMILATION AT DWD

**H. Anlauf**

Deutscher Wetterdienst

This talk will review the current status of using GNSS-RO in DWD's data assimilation for the ICON global model. We will present results on the impact in particular from the addition of COSMIC-2 and also describe the observation error model in use that is guided to some extent by the Desroziers method and also differentiates by LEO and by GNSS. The dependence of observation error on GNSS turned out to be particularly significant for COSMIC-2, but is also relevant for the optimal use of bending angles from Spire as processed and received via EUMETSAT.

# RECENT DEVELOPMENTS ON THE ASSIMILATION OF GNSS-RO BENDING ANGLES IN THE MÉTÉO-FRANCE 4D-VAR SYSTEM

**D. Raspaud**

Météo-France/CNRS, DESR/CNRM

The GNSS-RO bending angles have been operationally assimilated in the Météo-France global model ARPEGE since 2007, firstly with the FORMOSAT-3/COSMIC constellation, CHAMP and GRACE. They are currently assimilated up to 50 km and the tangent point drift is taken into account. A two-dimensional bending angle observation operator is about to be used in operation in 2022.

The presentation will focus on recent developments regarding the use of new observations and the ongoing revision of GNSS-RO observation uncertainties.

With the recent availability of new GNSS-RO data on GRACE-C and SENTINEL-6 in addition to SPIRE commercial data provided by EUMETSAT, a significant amount of observations has been added to the ARPEGE four-dimensional variational (4D-Var) data assimilation system. The assimilation of these new observations shows a positive impact in terms of objective forecast skill scores.

A revision of GNSS-RO observation uncertainties has also been initiated. A series of experiments aims to assess the impact on the forecast kills of varying observation uncertainties with several parameters such as satellite identifier or latitude in addition to the tangent point height of the observation.

# A FORECAST SENSITIVITY TO OBSERVATION IMPACT OF TRADITIONAL AND COMMERCIAL OCCULTATION DATA WITH ENVIRONMENT. CANADA'S FORECAST SYSTEM.

**J. M. Aparicio** and D. Lobon

Environment and Climate Change Canada

During NOAA's Delivery Order 4 period (spring 2022), a near-real time parallel system (non operational) was prepared at Environment Canada, to test the effect under global assimilation of all available occultation data, including the recent Sentinel-6A, and commercial sources, under conditions equivalent to actual operations. We find a generally positive impact of all data sources, as measured against several independent measures, although with some interesting negative impacts that are worth considering. These impacts will be discussed. The comparative effect of the different sources on the performance of the forecast system was analyzed in more detail with a Forecast Sensitivity (FSOI) study, whose main results will be presented.

# IMPACT ON ECMWF FORECAST BY ASSIMILATING SPIRE BENDING ANGLES

**K. Lonitz** (1), S. Healy (1), and C. Marquardt (2)

(1) ECMWF
(2) EUMETSAT

We have conducted different observing system experiments (OSEs) to assess the impact of Spire bending angles, processed by EUMETSAT. First is an OSE assimilating additionally about 1,000 Spire occultations per day for three months in 2022 into the ECMWF system. We found, that adding Spire data to the 4D-Var system clearly improves forecast scores. For example, forecast scores in temperature are very much improved by about 1.0% at 500hPa at day 3 in the southern hemisphere. Fits to independent observations sensitive to temperature and wind improve largely when adding Spire. For example, fits to radiosonde temperature and wind profiler observations at 150hPa improve by 0.2%, globally.

The second OSE assimilates up to 10,000 additional Spire occultations per day, which brings the total of GNSS-RO profiles to around 18,000, which is close to the daily number targeted by the International Radio Occultation Working Group. These experiments with a large volume of GNSS-RO observations show a large positive impact on the forecast scores, demonstrating the potential power of this observation type. Furthermore, more subtle impacts from the assimilation of GNSS-RO can be detected more easily. One interesting feature through the addition of a large number of GNSS-RO data is the improvement in the fit to wind observations in the troposphere and stratosphere, especially in the Tropics. In addition, the assimilation of a high number of observations enables us to investigate the sensitivity of temperature and humidity forecast scores to the presence of GNSS-RO observations in the lower troposphere.

# STATUS OF NEAR-REAL-TIME PROCESSING OF GNSS RADIO OCCULTATIONS FROM THE SENTINEL-6 MICHAEL FREILICH SATELLITE

**C. Galley** (1), and C. Ao (1)

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The Sentinel-6 Michael Freilich satellite was launched on November 21, 2020 as the first of two satellites to continue high-precision ocean altimetry measurements. As a secondary mission, the spacecraft carries a JPL radio occultation instrument to track GNSS satellites rising and setting across the Earth's limb. The occultations are processed at JPL's GDGPS operations centers in near-real-time (NRT) and have been distributed via NOAA in the BUFR format to numerical weather prediction centers on WMO's Global Telecommunication Service since Aug 24, 2021. We review the NRT processing system and discuss its performance, including issues encountered and future work.

# ERRORS IN RO OBSERVATIONS: WHAT CAUSES THEM AND HOW CAN WE ESTIMATE THEM?

**R. Anthes** (1), J. Sjoberg (1), S. Syndergaard (2) and X. Feng (1)

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GNSS radio occultation (RO) bending angle and refractivity observations have both random and bias errors. The sources of these two types of errors are different and vary with many factors associated with the GNSS and LEO (low-Earth Orbiting) satellites, RO receiver, retrieval errors, and atmospheric structure. Accurately estimating RO errors is important in applications of RO, in particular numerical weather prediction (NWP) and climate research and monitoring. The effect of bias and random errors on these two applications is somewhat different, with biases being especially significant in climate applications. Random errors are impactful in NWP, but are less so in climate applications because they tend to cancel in the mean when large data sets are used.

Since the earliest days of RO, it has been recognized that RO observations have small biases, except in the lowest levels of the troposphere where superrefraction can produce large biases. For NWP, the biases above the atmospheric boundary layer are considered small enough that RO observations may be assimilated without bias corrections. They may also be used to correct the larger biases in radiance measurements. For climate, however, even the small biases of RO observations can be important.

This presentation reviews the sources of RO errors and several methods of estimating random error statistics, including direct comparison with other observations or models, the Desroziers method, and the three-cornered hat (3CH) method. The Desroziers method is widely used in data assimilation and uses the model background and analysis fields. The 3CH method estimates the uncertainties of three independent data sets simultaneously by using any three collocated independent data sets. Under certain conditions the Desroziers and 3CH methods give identical results. We present examples of RO bending angle and refractivity error standard deviation profiles.

In data assimilation, RO observations are weighted inversely according to their estimated random errors (uncertainties). Historically, statistical error models have been employed, which can vary with latitude, mission, or atmospheric state. Dynamic error models have been proposed in which the uncertainties of individual RO observations vary with a parameter of the occultation profile itself (e.g. local spectral width) or atmospheric state (e.g. mean temperature). A hybrid approach for estimating uncertainties in RO observations in NWP data assimilation is proposed.

# GENERALIZED THREE CORNERED HAT APPLIED TO THREE INDEPENDENT REFRACTIVITY DATA SETS

**J. K. Nielsen** (1), H. Gleisner (1), K. B. Lauritsen (1), and S. Syndergaard (1)

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A generalization of the Three Cornered Hat method provides a way to estimate error covariance matrices for three independent data sets, measuring the same physical property. Here we apply this method to three collocated refractivity data sets: 1) Refractivity profiles from Radio occultation data (Metop and COSMIC), 2) refractivity derived from GRUAN processed RS92 sondes, and 3) refractivity profiles from ERA5 forecast fields. Various sources of representativeness error affecting the achieved uncertainty estimates are discussed and assessed systematically. The differences in vertical representation of the refractivity among the three data sets are analyzed by applying sequences of vertical smoothing, and examining the resulting uncertainty estimates of the three data sets. The least vertically resolved data set, in this case ERA5, determines the lowest vertical scale where the Three Cornered Hat can be expected to yield the most accurate results. The estimated refractivity uncertainties of all three refractivity data sets are stated with reference to this vertical scale.

The estimated RO refractivity uncertainties agree with theoretical estimates in the UTLS. In the lower troposphere the estimated uncertainty decreases with latitude, and the results suggest that the refractivity uncertainty applied in the current ROM SAF 1D-Var algorithm could be deflated. It is also found that the applied error correlation length may be reduced considerably at mid latitudes.

# RESIDUAL IONOSPHERIC ERRORS IN RADIO OCCULTATION DATA AND LATEST NEWS ON TWO CORRECTION TECHNIQUES

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Radio occultation (RO) data show high quality from the upper troposphere to the middle stratosphere (about 5 km to 35 km altitude). Above about 35 km, the impact of residual errors in the data rises due to measurement noise and an increasing impact of the ionosphere. While the measurement noise is handled in the RO retrieval by using a high-altitude initialization and some lowpass filtering of the data, the contribution of the ionosphere is corrected to first order by a dual-frequency linear combination of RO bending angles.

In the past years, the RO community has put significant effort into improving the quality of RO data towards higher altitudes including the upper stratosphere. In this respect, higher-order ionospheric correction techniques have played an increasing role in research. The residual ionospheric errors in bending angles can vary with the solar activity cycle between about 0.01 μrad up to more than 0.1 μrad, at altitudes near 35 km. This can amount to temperature biases of more than 0.5 K at these altitude levels.

After introducing the topic along the lines above, I will focus in this presentation on the two latest correction techniques, the kappa-correction and the bi-local correction. A main advantage of the kappa-correction is that it is easy and fast to apply, depending only on the solar radio flux index as external auxiliary information. So far, it was tested in simulation studies and more recently on real observed RO data. The bi-local correction, on the other hand, includes not only effects of the ionosphere in a more comprehensive manner, but also geomagnetic information, for modeling the higher-order geomagnetic term.

A comparison study has shown that the large-scale ionospheric variations were captured about equally well by both corrections, while the smaller geomagnetic impact played a somewhat increased role in low-orbit RO missions, such as CHAMP or GRACE, and in particular for regional averages, where it may contribute systematic bias effects. Ongoing research focuses on a more detailed profile-to-profile intercomparison based on extended time periods, more refined study of the impact of the geomagnetic term, as well as of the inbound and outbound electron density asymmetries along the RO ray paths.

# ROM SAF RADIO OCCULTATION ACTIVITIES AND FUTURE DEVELOPMENTS

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The Radio Occultation Meteorology Satellite Application Facility (ROM SAF) is a decentralized operational processing facility under EUMETSAT. The objectives of the ROM SAF are to develop, generate, disseminate and archive operational GNSS radio occultation products for NWP, Climate and Space Weather applications.

The products are derived from measurements by RO instruments onboard the EUMETSAT missions Metop, Metop-SG and Sentinel-6A Michael Freilich, RO data from Spire processed by EUMETSAT, and data from other RO missions for reprocessing. ROM SAF produces reprocessed Climate Data Records (CDRs) extended in time by Interim Climate Data Records (ICDRs) for users requiring a higher degree of homogeneity of the RO data sets. The ROM SAF also maintains the Radio Occultation Processing Package (ROPP) that contains software modules that aid users wishing to process, quality control and assimilate radio occultation data from any radio occultation mission into NWP and other models.

The present contribution contains an overview of R&D plans for CDOP 4 (Continuous Development and Operations Phase 4), covering the period March 2022 to February 2027. CDOP 4 commitments include the continued provision of operational RO data for NWP and climate applications. In addition, for Metop-SG Day 2 ionosphere products (scintillations, electron density profiles) for space weather applications will be developed and produced operationally about one year after the launch of the first Metop-SG satellite. New releases of CDRs and ICDRs will include addition of uncertainty estimates and ingestion of new RO missions. For ROPP the plan includes development of forward models for assimilation of polarimetric and airborne RO measurements and development of a forward model for future LEO-LEO microwave occultations.

The Leading Entity of ROM SAF is the Danish Meteorological Institute (DMI), with four Cooperating Entities: ECMWF (European Centre for Medium-Range Weather Forecasts) in Reading, UK, Bologna, Italy, Bonn, Germany; IEEC (Institut D'Estudis Espacials de Catalunya), Barcelona, Spain; Met Office, Exeter, United Kingdom; and Wegener Center, University of Graz, Graz, Austria. Information about ROM SAF products and services are available at http://rom-saf.eumetsat.int

# STAR GNSS RO PROCESSING, VALIDATION, AND MONITORING SYSTEM: VALIDATION OF THE SPIRE DATA PRODUCTS AND THEIR APPLICATIONS FOR NUMERICAL WEATHER PREDICTION AND CLIMATE STUDIES

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Global Navigation Satellite System (GNSS) Radio Occultation (RO) is becoming an essential component of National Oceanic and Atmospheric Administration (NOAA) observation systems.

NOAA has operationally assimilated the RO observations from the current NOAA mission (i.e., Constellation Observing System for Meteorology, Ionosphere, and Climate-2 (COSMIC-2)) and partners' missions (i.e., Challenging Minisatellite Payload, Korea Multi-Purpose Satellite-5 (KOMPSAT-5), Meteorological Operational satellite (MetOp) series -A/-B/-C Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS)) into the National Centers for Environmental Prediction (NCEP) numerical weather prediction (NWP) systems. NOAA is also purchasing RO Commercial Weather Data (CWD) from commercial vendors (i.e., GeoOptics, Inc. and Spire Global, Inc.) and assimilating the CWD into its NWP systems. To optimize the usage of RO data in data assimilation systems, it is necessary to quantify the accuracy and the uncertainty of the RO-derived atmospheric profiles, especially in the lower troposphere, understand the sources of uncertainty and optimize the data impacts on NWP.

In the past three years, the Center for Satellite Applications and Research (STAR) has developed capabilities as a GNSS RO processing and science center. This is to develop the ability as a national satellite center to perform NOAA operational processing and NOAA science development, support, archive, and steward for the operational processing and data quality monitoring. To better quantify how the observation uncertainty from clock error and geometry determination may propagate to bending angle and refractivity profiles, STAR has developed the GNSS RO Data Processing and Validation System. We will use this system to assess the Spire product quality. In this study, we first describe STAR RO Data Processing System, which includes: i) STAR's conversion of Spire carrier phase to excess phase, ii) bending angle inversion algorithm, and iii) one-dimension variational approach to convert refractivity to temperature and moisture profiles. We then provide the validation of the STAR's processed results for the Spire mission. We demonstrate the usefulness of Spire data for the numerical weather prediction system through data assimilation and quantify their impacts and present the potential climate and atmospheric applications using Spire data among measurements from all available RO missions.

# SENTINEL-6A NON-TIME-CRITICAL RADIO OCCULTATION PRODUCTS BY EUMETSAT

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The Sentinel-6 / Jason-CS satellite was launched on 21 November 2020. Its prime focus is on altimetry measurements, but it also carries a radio occultation receiver. One week after launch, the TriG GNSS-RO instrument was switched on. The receiver tracks occultations from two GNSS, GPS and GLONASS. It has a requirement to provide at least 770 quality controlled occultations per day, but in general exceeds that.

Contrary to other operational radio occultation missions, two product streams are available from the GNSS-RO instrument: (1) Near-Real-Time (NRT), provided by NASA/JPL; (2) Non-Time-Critical (NTC), provided by EUMETSAT / ROM SAF. The NRT service has a timeliness of up to 3h, the NTC one is formally following the timeliness of altimeter products, with a requirement of 60 days. In reality, data is though available not later than 2-3 weeks.

This presentation focusses on the NTC product stream, which is provided for climate and re-analysis applications. It makes use of delayed GNSS orbit/clock information to obtain improved bending angle and higher processing level products. An overview of available products and auxiliary data is given, validation against the NRT stream as well as other operational missions like Metop/GRAS and COSMIC-2 are shown, comparisons of GPS versus GLONASS occultation quality analysed, some instruments issues are briefly discussed, and an outlook for future improvements will be given.

# GNSS RADIO OCCULTATION EXCESS PHASE PROCESSING FOR CLIMATE APPLICATIONS INCLUDING UNCERTAINTY ESTIMATION

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Satellite-based remote-sensing observations of the free atmosphere constitute an important backbone for atmospheric and climate science as well as for providing climate benchmark data. Measurement data from Global Navigation Satellite System (GNSS) radio occultation (RO) qualify to produce benchmark data records, as they provide highly accurate, global, and long-term stable datasets for essential climate variables (ECVs). However, this requires a rigorous processing from the raw occultation measurements to ECVs, with narrow uncertainties. In order to fully exploit this potential, Wegener Center's Reference Occultation Processing System (rOPS) includes uncertainty estimation in both precise orbit determination and excess phase processing.

Here we specifically introduce the L1a excess phase processing system, as a first step in the overall RO profiles retrieval, which extracts the atmospheric excess phase from raw SI-tied measurements. The excess phase processing includes integrated quality control and uncertainty estimation. This requires a complex framework of various subsystems, which we first introduce in this presentation, before discussing the implementation of core algorithms. The quality control, supported by forward-modeled excess phase profiles, removes or alternatively flags excess phase profiles of insufficient or degraded quality. Additionally, we discuss the components of the estimated random and systematic uncertainty profiles, computed per RO event, which serve as starting point for the subsequent uncertainty propagation through L1b and L2a/L2b processors.

To evaluate the resulting excess phase profiles, we investigated Metop-A/B/C RO data for three-monthly periods for a robust statistical analysis. In a sensitivity analysis of the excess phases, we focused on three different atmospheric layers (from troposphere to upper stratosphere), investigating differences between various datasets, the influence of different orbit and clock inputs, as well as cross-platform consistency of the different Metop satellites. Independent validation and inter-comparison with excess phase data from EUMETSAT and UCAR revealed subtle discrepancies but overall good agreement. We also discuss first results from excess phase processing of FY-3C/D RO data in comparison to excess phase profiles from NSSC. The goal of all efforts is to establish reliable long-term data records including uncertainty estimation for the benefit of climate applications.

# OPAC 2022 RADIO OCCULTATION PROCESSING AT THE WEGENER CENTER: VALIDATION AND UNCERTAINTY EVALUATION OF ROPS LONG-TERM DATA RECORDS

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Wegener Center's new reference occultation processing system (rOPS) aims to process raw global navigation satellite system (GNSS) radio occultation (RO) measurements along the complete RO retrieval chain into profiles of essential climate variables (ECVs). We base this solution on the SI-traceability of GNSS RO data, which are available from a range of RO mission since 2001 and scheduled long-term into the future.

rOPS is the core processing system of the Wegener Center Occultation and Climate Analysis System, supported in its development also by colleagues from EUMETSAT Darmstadt, UCAR Boulder, DMI Copenhagen, ECMWF Reading, AIUB Berne, NSSC/CAS Beijing, and others. It aims to rigorously implement traceability, and the related quantification of accuracy and precision, by processing along the full Level 1 and Level 2 chain from the SI-tied raw data to the ECVs (temperature, pressure, and tropospheric water vapor profiles) as well as integrating a complete uncertainty propagation, for both, estimated random and systematic uncertainties.

In this presentation we start with a brief introduction of the design of the rOPS. Subsequently, we show validation and verification results of rOPS long-term data records from different RO missions compared to other high-quality datasets (e.g., radiosondes, ERA-5, datasets from other RO-provider). The focus of this inter-comparison study lies in the evaluation of the consistency among the different datasets, using the capabilities of rOPS, in particular the integrated uncertainty propagation. This allows us to track the uncertainties throughout the processing chain and to inspect them for intermediate retrieved profiles as well as for the final ECV result profiles.

# ASSESSMENT OF THE CONSISTENCY AND STABILITY OF CRIS INFRARED OBSERVATIONS USING COSMIC-2 RADIO OCCULTATION DATA OVER OCEAN

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The accuracy of brightness temperature (BT) from the Cross-track Infrared Sounder (CrIS) onboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite and NOAA-20 is estimated using the Constellation Observing System for Meteorology, Ionosphere, and Climate 2 (COSMIC-2) Radio Occultation (RO) data as input to the Community Radiative Transfer Model (CRTM). The matchup criteria between RO and CrIS observations are time less than 30 minutes, a distance less than 50 km, and over oceans to reduce the collocation and simulation uncertainty. Based on the information provided in the CrIS and RO observations, only upper temperature sounding channels with weighting function peak height (WFPH) above 200 hPa (~12 km) at CrIS longwave infrared (LWIR) and shortwave infrared (SWIR) bands and water vapor channels at CrIS mid-wave infrared (MWIR) band with WFPH above 500 hPa (~6.3 km) are selected for comparison. The purpose is to minimize the impacts from the surface emission, cloud absorption/scattering, and atmospheric gaseous absorption. The absolute differences between CrIS observation and simulation using RO data as input are less than 1.0 K for the majority of those selected channels. The double differences between CrIS observations on NOAA-20 and S-NPP using CRTM simulations as transfer references are very stable. They range from -0.05 K to 0.15 K at LWIR channels and -0.20 K to 0.10 K at SWIR channels during the two years from 1 October 2019 to 30 September 2021. For MWIR channels, the double differences range from -0.15 K to 0.25 K but have significant variations at both daily mean and monthly mean time series. The results provide ways to understand the qualities of RO retrieval and CrIS measurements: RO data can be used to assess the consistency and stability of CrIS observations quantitatively, and CrIS measurements have the quality to assess the RO retrievals quality and stability. The results in this study demonstrate that the comparison approach can quantify the long-term stability for i) S-NPP CrIS, ii) NOAA-20 CrIS, and iii) between S-NPP CrIS and NOAA-20 CrIS. This approach can also quantify the CRTM simulation error at the $CO_2$ 4.3 μm band due to the nonlocal thermodynamic equilibrium (NLTE) effects during daytime by using the high accuracy and high stability of the RO temperature profiles. Due to the high accuracy and high stability of the CrIS observations, the BT difference in the daily time series can be used to detect the times for algorithm updates in the UCAR COSMIC-2 1DVAR system, which results in differences in bias characteristics.

# GNSS RADIO OCCULTATION IN THE AWS CLOUD: BACKGROUND

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The amount of GNSS radio occultation (RO) data that has accumulated since the proof-of-concept mission GPSMET/FORMOSAT-3 has hit approximately 20 million soundings. At least three fully functional and independent RO retrieval centers have processed these data; they have processed the data with algorithms that have been nonhomogeneous in time; the formats of the output are not only different amongst the retrieval centers but they are non-homogeneous even for a single center; the existing data formats are incompletely documented; no agreed upon standard for identifying a unique RO sounding exists; and different retrieval centers process different subsets of the RO data that have been recorded. The current paradigm of analyzing the data by downloading them onto local servers is proving increasingly cumbersome because of the amount of data, inadequate download interfaces and subsetting capabilities, and limits on bandwidth. We set out to address these problems by hosting as much RO data as are available and processed by as many independent retrieval centers as wish to participate. Current contributors are UCAR, JPL, and the ROM SAF. The data are hosted in the Amazon Web Services Open Data Registry, available for simple browsing, and the data formats are documented in Github. The data are free to browse and download.

We have defined new, AWS-native data formats into which we have translated all contributions of RO data: calibratedPhase contains excess phase, amplitude, and orbit data; refractivityRetrieval contains bending angle, refractivity, and dry atmosphere retrieved data; and atmosphericRetrieval contains pressure, temperature, water vapor, and height retrieved data. Translating required extended study of the details of the various generations of data formats, investigating details of RO retrieval systems, and documenting RO receiver tracking algorithms. Unique identifiers were assigned to RO soundings, and soundings and their metadata recorded in a database to force RO sounding matchups across retrieval centers. The resulting database can be used to select RO soundings depending on transmitter, mission, geolocation, time, sounding geometry, and contributing retrieval center. The result is an archive that enables efficient handling of the data especially when working in an AWS computing environment.

We will discuss details of the archive, problems solved, some simple science applications, and its capabilities in this presentation.

# CHARACTERIZING THE RADIO OCCULTATION BENDING ANGLE UNCERTAINTY IN THE LOWER TROPOSPHERE USING END-TO-END SIMULATIONS

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Radio Occultation (RO) technique has been widely used in numerical weather forecasting because of its unbiased nature, all-weather capability, and high vertical resolution. However, recent studies show that RO bending angle observations in the lower troposphere suffer from strong fluctuation and negative biases, which could fail the quality controls (QCs) in the data assimilation (DA) process. These significant bending angle uncertainties persist even in high SNR RO missions, such as COSMIC-2. The high QC rejection rate could significantly reduce RO impacts on weather forecast skills and the capability to resolve the complex moisture structure within the lower troposphere and planetary boundary layer (PBL).

The COSMIC-2 statistics show that the bending angle retrieval is mostly negative-biased compared to the NCEP reanalysis below the altitude where a sharp humidity change is present. In contrast, the bias is gradually reduced below the top of PBL. These observation errors could be attributed to several interconnected causes: instrument noise, sampling bandwidth, open-loop tracking model bias, atmospheric turbulence, and vertical smoothing applied to the bending profile retrieval.

This study used the end-to-end multiple phase screen (MPS) simulation to better characterize the bending angle error in the moist lower troposphere. The primary observation error sources can be identified by conducting the Monte-Carlo sensitivity test to the MPS simulated bending angle and comparing it with the actual retrieval. The initial results show that the bending angle bias and uncertainty observed in the RO data can be reproduced by including realistic levels of noise and refractivity fluctuations from atmospheric turbulence. We examined how the simulated biases and uncertainty change at different SNR conditions. In addition, an observation-only bias detection method using a spectrogram approach on the impact parameter domain will also be discussed.

# ASSIMILATING RADIO OCCULTATION PROFILES WITH VERTICAL ERROR CORRELATIONS

**K. Bathmann** and D. Zupanski

Spire Global, Inc

Radio occultation observations from global navigation satellite systems are of increasing benefit to numerical weather prediction through data assimilation. Complementary to radiance observations from infrared and microwave sounders, they are globally available at high vertical resolution and are not impacted by clouds or precipitation. However, RO observations are at comparatively lower horizontal resolution. Spire Global operates a large constellation of cubesats capable of measuring upwards of 20,000 RO profiles daily, and strives to increase this number to 100,000 profiles, creating a dense network of RO observations at higher horizontal resolution. Assimilating RO bending angle observations presents unique challenges and handling the increasing number of available observations requires care. This presentation will examine strategies for assimilating a dense network of RO bending angle observations, including accounting for vertical error correlations, thinning, and quality control tuning. The forecast impact of assimilating Spire RO observations into the Unified Forecast System (UFS) through the Gridpoint Statistical Interpolation (GSI) will be tested under these configurations.

# ESTIMATES OF GNSS-RO BENDING ANGLE COVARIANCE INFORMATION

N. Semane (1) and **S. Healy** (1)

ECMWF

In Radio occultation data assimilation at ECMWF, the prescribed observation uncertainties associated with bending angles are assumed uncorrelated. In this work, we estimate the error covariances based on the diagnostics of Desroziers et al. 2005. Covariances from different GNSS-RO missions will be presented and compared.

The covariance matrix estimates will be made available routinely in the ROMSAF webpage.

# USING ENSEMBLE SPREAD AS A MEASURE OF GNSS-RO IMPACT: REAL AND SIMULATED DATA

**K. Lonitz** (1) and S. Healy (1)

(1) ECMWF

At ECMWF we have performed ensemble data assimilation (EDA) experiments and Observing System Experiments (OSEs) using an extensive set of GNSS-RO observations, using real and simulated data. This is done to study the spread-skill relationship and compare to previously performed theoretical studies. Results show that adding real data from Spire or COSMIC-2 reduces the spread for temperature by about 9% at 10hPa in the southern hemisphere, whereas adding Spire and COSMIC-2 reduces the spread by 14%. In the tropics the addition of COSMIC-2 has the largest effect on reducing the spread by about 13% at 10hPa, whereas Spire reduces the spread by 5%. In general, the spread in temperature reduces with more real GNSS-RO data being added, with the larger reductions happening in the stratosphere. When we compare this reduction in ensemble spread by adding new GNSS-RO data with fits to radiosonde observations, it can be seen that both measures are qualitatively consistent. Comparing the change in ensemble spread using real data with simulated one, shows many similarities. We also have run sensitivity experiments changing the observation errors of the simulated data to understand their impact on the ensemble spread.

The challenges when studying ensemble spread values and comparing them with forecast error statistics or observations are numerous. For example, one must be fully aware that for the EDA experiments the variability of the perturbations does not grow sufficiently through the forecast (under-dispersive) in some regions and height levels. This means the EDA can underestimate the impact of the addition of GNSS-RO data in these areas. Furthermore, the evaluation of forecast error statistics depends on the choice of analysis as a reference, which has limitations. Also, the model resolution of the experiments does matter for which scales can be captured at the various height levels. Nevertheless, in the tropics where most of the GNSS-RO data is located, a linear relationship between ensemble spread and variance in first guess (FG) departures can be seen at higher altitudes. Here, ensemble spread and variance in FG departures can be used to see the effect from adding GNSS-RO data which shows a reduction in their values.

# GRACE-FO RADIO OCCULTATION DATA PROCESSING – A VALIDATION STUDY

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The major objective of the GRACE Follow On (GFO) mission with its two satellites GF1 and GF2 is to obtain precise global and high-resolution models for both the static and the time variable components of the Earth's gravity field. Additional goal is the continuation of the GPS radio occultation (RO) measurements from the predecessor GRACE, successfully performed between 2006 and 2017.

The GRACE/GRACE FO data contribute to the global RO dataset consisting of several missions provided by different centres since the pioneering GPS/MET mission in 1995/97.

Beside climate applications, GFO data are used for the assimilation in numerical weather forecast models by the leading weather service centres.

After several on-board software updates and raw data reader improvements since March 2020 rising occultations from GF1 and since September 2021 setting occultations from GF2 are continuously available. Both satellites provide about 500 atmospheric profiles daily.

The RO data are processed based on different measured observables: For different GPS satellites combinations of L1CA/L2P, L1CA/L2C, or L1CA/L5 amplitude and phase measurements are available.

In this study results of GFO processing and validation are presented. Bending angle, refractivity, and temperature data are compared with ECMWF operational analyses and ERA5 data. The quality of the different measured variables is evaluated for different geographical regions. In addition, GFO data are compared with co-located COSMIC-2 and Spire radio occultations.

# A STUDY OF QUALITY CONTROL AND OBSERVATION ERROR MODELS FOR RO DATA ASSIMILATION

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The Joint Effort for Data assimilation Integration (JEDI) system is the next-generation data assimilation system for JCSDA and its partners, including NOAA. This system incorporates multiple forward operators and observation error models for Global Navigation Satellite System (GNSS) radio occultation (RO) data assimilation based on current operational capabilities at NOAA, NRL, Met Office, and ECMWF. Therefore, it possesses a wealth of operational capabilities and offers an excellent platform to evaluate various aspects of RO data assimilation with a goal of developing an optimal configuration in support of operational NWP.

This paper introduces the latest RO advancement at JCSDA using the JEDI system, and addresses issues that affect the performance of the RO data assimilation, including the observation error specification and quality control. Recently, a new observation error model, based on the Three-Cornered Hat (3CH) method, has been incorporated into the JEDI system through the collaboration between JCSDA and the UCAR/COSMIC team. This is an addition to four existing RO error models from NOAA, NRL, Met Office, and EUMETSAT. This study evaluates the performance of this new observation error model in comparison with the operational NOAA GDAS observation error model and optimizes its performance with additional data quality indicators using JEDI.

# FIRST RESULTS FROM TWO-DIMENSIONAL BENDING ANGLE OPERATOR FOR AIRBORNE RADIO OCCULTATIONS

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Atmospheric River Reconnaissance (AR Recon) campaigns collect targeted observations of significant winter weather events contributing to long duration heavy precipitation and flooding on the U.S. West Coast. Airborne radio occultations (ARO) together with dropsonde observations are key datasets for studying vertical moisture structures in such frontal systems. However, in order to improve forecasts of atmospheric rivers based on ARO, an observation operator needs to be developed to allow assimilation of ARO geophysical variables into numerical weather prediction models. A two-dimensional (2-D) operator is preferred due to the nature of ARO measurements as well as significant horizontal inhomogeneities associated with atmospheric river events. This goal has been achieved by modifying the existing "state-of-the-art" spaceborne RO operator provided in the forward module of ROM SAF Radio Occultation Processing Package (ROPP). The developed operator simulates ARO bending angles using two-dimensional background information from ECMWF ERA5 fields. Since ARO measurements are characterized by significant horizontal drift of tangent points with altitude, especially in the upper levels near the aircraft, the corresponding forward modeling errors are mitigated by taking into account the tangent point drift. Observed minus Background (O-B) statistics based on observations collected during intensive operating periods sampling an impactful AR in 2021 are used to assess error properties of the ARO bending angles. Both the full bending angle from satellite to aircraft and the "partial" bending angle corresponding to the geometrically symmetrical section of the atmosphere below the aircraft have been considered in the forward modeling experiments. Simulations with the two-dimensional operator are compared with results in a spherically symmetrical atmosphere to assess the significance of horizontal gradients. The achieved error characteristics are further supported by direct comparison of ARO and dropsonde profiles in terms of refractivity. The density of ARO observations within the highly variable AR environment provides sufficient data to demonstrate a distinct advantage in using the 2-D operator for the simulations, which is anticipated to carry through to improved forecasts of AR precipitation compared to a 1-D operator.

# PLANETARY BOUNDARY LAYER PROFILING FROM COSMIC-2, SENTINEL-6, AND SPIRE GNSS RADIO OCCULTATION

C. O. Ao, **P. Vergados**, and K.-N. Wang

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An important application of GNSS-RO that has emerged in the past decade is its ability to profile the moist thermodynamical structure of the Earth's planetary boundary layer (PBL) at high vertical resolution. Studies performed using COSMIC and similar missions have revealed its unique capabilities and limitations. Global PBL heights exhibit spatial, diurnal, seasonal, and interseasonal variabilities that can be used to extend in-situ observations and assess climate models.

A new generation of data, including COSMIC-2 and Sentinel-6 that have improved receiver tracking and higher SNRs, are now available for PBL investigations. We will present results that show how these measurements have improved the PBL profiling performance over the previous missions and how this varies with SNRs. At the same time, we have investigated the quality of PBL profiling from Spire GNSS-RO data available from the NASA Commercial Data Acquisition Program (CSDAP) and compared these results with COSMIC-2 and Sentinel-6. Together, the combined COSMIC-2, Sentinel-6, and Spire data provide significantly better observation coverage than COSMIC, with better PBL penetration. This allows us to study the PBL height and vertical structure with improved spatial and temporal resolution.

# THE ROHP-PAZ POLARIMETRIC RADIO OCCULTATION RESEARCH DATASET AND ITS APPLICATIONS

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After more than 4 years on orbit, the Radio Occultations and Heavy Precipitation aboard PAZ satellite (ROHP-PAZ) experiment has already demonstrated the ability of polarimetric radio occultations (PRO) to detect precipitation. In fact, PRO have shown potential not only in rain detection, but also in precipitation characterization and in sensing the associated vertical cloud structures. PAZ PRO $\Delta\phi$ observable profiles were made available in 2020 trough the ICE servers (https://paz.ice.csic.es), and more recently through the JPL (https://genesis.jpl.nasa.gov).

A new re-processing of the PRO observations is being carried out with the aim to make it public during the second half of 2022. In addition to a better treatment of the rainy observations, the new re-processed profiles will come with an extensive collocation dataset that will allow the users to address scientific studies much more easily. These will take into account the limb-sounding geometry of the observations, performing the collocations directly into the RO rays obtained through a ray-tracer. These collocations include observations like the 30-minute geostationary 10.8 μm brightness temperature, GPM IMERG surface precipitation, microwave brightness temperatures from the numerous overpasses by the satellites in the GPM constellation, radar reflectivities from the GPM core satellite and the NEXRAD ground based weather radars, among others. Furthermore, the collocation algorithms are designed so that more external observations can be easily included.

In addition to the exact collocations as described above, external databases are also checked so that coincidences with Tropical Cyclones, Mesoscale Convective Systems and other relevant precipitating systems are identified nearby PAZ observations.

In this presentation, we will show a brief overview of the re-processing of the ROHP-PAZ data, with emphasis in the differences between the $\Delta\phi$ profiles obtained from UCAR's CDAAC excess phases and from those obtained from JPL excess phases. After that, examples of the coincident datasets will be presented. Results will include statistics gathered from the differentiation of different precipitation regimes (e.g. stratiform vs convective), identification and validation of cloud top height determination, and comparison with other relevant parameters obtained from the collocated observations.

# VALIDATION OF MONTHLY WIND FIELDS DERIVED FROM GPS RADIO OCCULTATION DATA

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For the purposes of detailed horizontal and vertical wind field analysis, monthly-mean wind fields were derived from radio occultation (RO) measurements. The wind fields were validated in comparison with European Centre for Medium-Range Weather Forecasts ERA5 reanalysis data.

For estimating wind fields outside of the tropics, the geostrophic wind approximation was used. In equatorial regions, due to the Quasi-Biennial Oscillation, thermal wind balance could be used to estimate mean (zonal) stratospheric winds. For both approximations, wind fields were derived from monthly-mean geopotential height fields on isobaric surfaces with 2.5°x2.5° horizontal resolution, in the period from 2007 to 2020.

We examined the geographic and vertical range of validity of both approximations for wind field derivation by inter-comparing to the 'true' ERA5 wind data. Evaluating the systematic and random aspects of differences, we investigated in which regions the RO-derived geostrophic and thermal wind balances hold reasonably well (within ±2 m/s accuracy) and otherwise break down. Also, a long-term data record validation between RO and ERA5 winds was performed, analyzing the consistency of the approximate and 'true' wind fields at the decadal time scale.

# MADDEN-JULIAN OSCILLATION OBSERVED IN COSMIC-2 RADIO OCCULTATION DATA

**Z. Zeng**

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With the launch of an equatorial constellation of six satellites called COSMIC-2 (Formosa Satellite-7/Constellation Observing System for Meteorology, Ionosphere, and Climate-2), on average there are more than 4,000 high quality radio occultation (RO) measurements per day over 40S-40N. Such unprecedented dense measurements of the tropical atmosphere enables investigating the full cycle of individual Madden-Julian Oscillation (MJO) events. In this study, a MJO event is selected based on the daily averaged outgoing longwave radiation (OLR), a proxy of deep convection associated with MJO, over the eastern equatorial Indian Ocean (10S to 10N and 75E to 95E). Temperature and specific humidity profiles from COSMIC-2 RO are used to depict both the propagation and three-dimensional thermodynamic structures of all MJO cases during three boreal winters from 2019/2020 to 2021/2022. MJO impacts on tropopause and tides are also investigated.

# THE RELATIONSHIP BETWEEN STRATOSPHERIC GRAVITY WAVE POTENTIAL ENERGY AND TROPOSPHERIC PARAMETERS OVER SOUTH AMERICA INFERRED FROM COSMIC-2 AND METOP RADIO OCCULTATION MEASUREMENTS.

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The study shows the first direct and independent relationship between the stratospheric gravity wave (SGW) activities, the precipitable water vapour (PWV), the tropopause height (TPH), and the cold-point height (CPH) over South America from the COSMIC-2 and METOP radio occultation measurements during the year 2020 and 2021. The South American continent comprises the tropical region, the Andes mountain range, and the mid-latitude climates. The seasonal mean of the potential energy (Ep ), the PWV, and the tropopause parameters height (TPH and CPH) were obtained to investigate the relationship between the SGW Ep and the tropospheric parameters (PWV, TPH, and CPH). A good correlation of variability was found between the precipitable water vapour (PWV) and the lower stratospheric gravity wave Ep in summer over the tropical region. In the tropical and subtropical winter. Our result showed a negative correlation between the PWV and the SGW Ep in the stratosphere. We found a direct link between the PWV and the gravity waves in the tropical region and an anti-correlation between the PWV and the gravity waves in the subtropical region. A significantly low water vapour (PWV <10 mm) and relatively high gravity wave activity (Ep >8 kJ/kg) around the Andes Mountains towards the East. The tropopause and the cold-point temperature showed an anti-correlation (r > -0.6 ) with SGW over the South American tropics. There is a negative or no correlation between the SGW Ep and tropospheric parameters in winter. The SGW activities in the tropical region showed an impact on the structure of the tropopause parameters which could as a result of the convective activity in this region. The SGW Ep climatology showed a less or no SGW activity was observed in the summer and a higher SGW activity in the winter in the subtropical regions, especially over the Andes mountain.

# ABSOLUTE MOMENTUM FLUXES IN THE STRATOSPHERE WITH GNSS RADIO OCCULTATION DATA

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A previous feasibility study with COSMIC data showed that triples of radio occultation (RO) temperature data can be used to derive gravity wave (GW) parameters including horizontal wavelengths and thus the vertical flux of horizontal momentum (shortly momentum flux, MF) in the lower stratosphere (20-40 km).

The spatio-temporal arrangement of these triples is limited because at all locations of the single temperature profiles the same GW must be observed. The limiting values are typical in the order of $\Delta d \leq 250$ km for the distance and $\Delta t \leq 15$ minutes for the time interval between involved measurements. Appropriate numbers of triples were only available from the beginning of the COSMIC mission when all six satellites were close in orbit (May to October 2006).

The new COSMIC-2 data from the early phase 2019/2020 in combination with Metop and Spire data since end of 2020 allow a continuation and update of this early study with an improved continuous database, i.e., number of triples.

Beside the geometrical constraint the background separation from the measured temperature profile is challenging. For this separation, i.e., the detrending of large-scale processes from the measured temperature profile, several methods exist. In this study we use the RO data itself and in addition ERA5 re-analysis data from ECMWF. Differences between both detrending approaches (datasets) will be discussed and the results will be compared with MF estimations from other satellite missions.

# GNSS-RO OBSERVATIONS AT SCALE – POTENTIAL RO DATA FROM THE SKYKRAFT CONSTELLATION

**J. Andrews**

Skykraft

Australian company Skykraft proposes to use its forthcoming constellation of over 200 small satellites for GNSS-RO observations. The full constellation would observe in excess of 500,000 GNSS-RO events per day and will provide real-time global communication of processed results, with archiving of raw results. Highlighting the potential from GNSS-RO observations at scale, Skykraft is interested in feedback on science requirements for the receivers and antennas for future flights. The existing spacecraft design, launching in November 2022, includes 12 GNSS-RO receivers per satellite. The on-board GNSS-RO processing algorithms can also be open source and iteratively improved by the global community.

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