

Radio Occultation Modeling Experiment (ROMEX)

Determining the impact of radio occultation observations on numerical weather prediction



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ABSTRACT

The international radio occultation (RO) community is conducting a collaborative effort to explore the impact of a large number of RO observations on numerical weather prediction (NWP). This effort, the Radio Occultation Modeling Experiment (ROMEX), has been endorsed by the International Radio Occultation Working Group, a scientific working group under the auspices of the Coordination Group for Meteorological Satellites (CGMS).

ROMEX seeks to inform strategies for future RO missions and acquisitions. ROMEX is planned to consist of at least one three-month period during which all available RO data are collected, processed, archived, and made available to the global community free of charge for research and testing. Although the primary purpose is to test the impact of varying numbers of RO observations on NWP, the three months of RO observations during the first ROMEX period (ROMEX-1, September-November 2022) will be a rich data set for research on many atmospheric phenomena.

The RO data providers have sent their data to EUMETSAT for processing. The total number of RO profiles averages between 30,000 and 40,000 per day for ROMEX-1. The processed data (phase, bending angle, refractivity, temperature, and water vapor) will be distributed to ROMEX participants by the Radio Occultation Meteorology Satellite Applications Facility (ROM SAF). The data will also be processed independently by the UCAR COSMIC Data Analysis and Archive Center (CDAAC) and available via ROM SAF. The data are freely available to all participants who agree to the conditions that the providers be acknowledged and the data are not used for commercial or operational purposes.

SIGNIFICANCE STATEMENT

The paper is significant because it informs the international community about a unique atmospheric dataset that is available for testing in numerical weather prediction models and other research projects, as well as being useful for planning for future RO observations.

CAPSULE

A large set of radio occultation profiles is available for use by the atmospheric sciences community for NWP and other research.

1. Introduction

Radio occultation (RO) is an active remote sensing technique that provides quasi-vertical profiles of density in planetary atmospheres by measuring the phase delay of radio waves emitted by a transmitter and received by a satellite orbiting the planet. Originally used to probe the atmosphere of Mars by Mariner 4 in 1964 (see review by Yunck et al. 2000), it was not until 1995 that the technique was demonstrated for the Earth's atmosphere using Global Positioning System (GPS) for the transmitters and a receiver on a low-Earth orbiting (LEO) satellite in the GPS/Meteorology (GPS/MET) experiment (Ware et al., 1996; Kursinski et al., 1997; Rocken et al., 1997).

Eyre (2008) provides an introduction to RO. As radio waves from a GNSS (Global Navigation Satellite System) transmitting satellites pass through the atmosphere, they are slowed and bent slightly downward. When the waves are received by a low-Earth orbiting (LEO) satellite, the delay in signal is measured by the excess phase compared to what would have been the case in a vacuum. The excess phase measurement can be related mathematically to the bending angle of the ray, which in turn can be used to calculate the refractivity. The refractivity provides information on the temperature, water vapor, and pressure in the stratosphere and troposphere, and on the electron density in the ionosphere. Either bending angles or refractivities can be assimilated in NWP models.

Many RO satellite missions have followed GPS/MET, including CHAMP, GRACE/GRACE-FO, SAC-C/D, TerraSAR-X, TanDEM-X, COSMIC and COSMIC-2, GRAS on METOP-A/B/C, GNOS on FengYun-3C/D/E, C/NOFS, KOMPSAT-5, and PAZ (for a list and brief description of these and other RO missions please see <https://space.oscar.wmo.int/spacecapabilities>). Figure 1 shows the growth in the number of RO profiles per day processed by the UCAR COSMIC Data Center Analysis and Archive (CDAAC, <https://cdaac-www.cosmic.ucar.edu/>) and provided to the research and operational communities. Because of the positive impact of RO data on NWP model forecasts, and the relatively simple and inexpensive technology compared to other remote atmospheric sounding systems from space, the private sector has recently launched RO receivers on commercial satellites and obtained high-quality data for sale to the community. These companies include PlanetiQ, GeoOptics, Muon-Space, and Spire in the U.S. and Aerospace Tianmu and Yunyao Aerospace in China. In 2021, commercial vendors began selling operational RO data to NOAA and EUMETSAT, and now contribute a significant portion of the total number of RO observations being used by the international community.

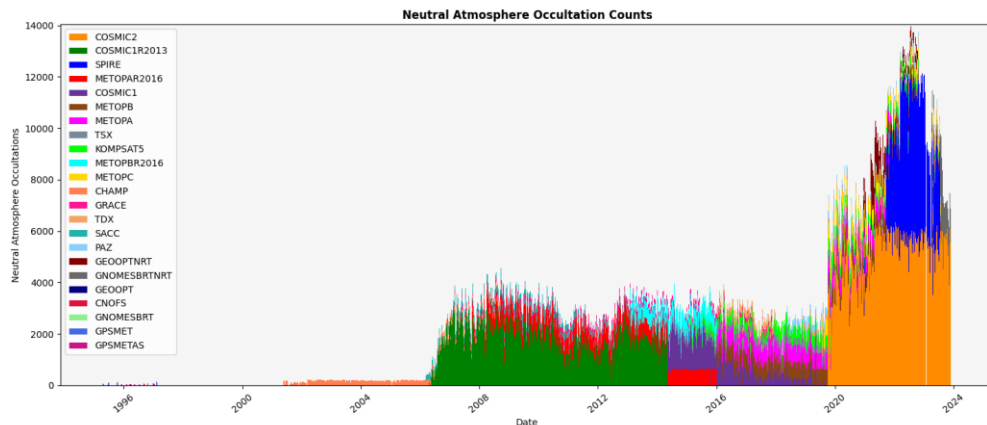


Figure 1: Total number of RO profiles per day (in thousands) processed by UCAR CDAAC since the launch of GPS/MET in 1995. The dates on the abscissa range from 23 August 1994 to 18 March 2024 (Source: Jan Weiss, UCAR COSMIC program, personal communication March 2024. Figure produced by Mike Perotta, UCAR).

A primary, but by no means only, application of RO is NWP. Other important applications include analysis of weather phenomena such as tropical cyclones, fronts, and atmospheric rivers; analysis of upper troposphere/lower stratosphere phenomena, and examination of the planetary boundary layer. Additional applications include climate studies and reanalyses. RO is unique among other sounding systems because it also provides ionospheric observations for space weather applications, including electron density profiles and scintillation events. The many applications of RO in the areas of weather, climate, and space weather are too numerous to list here, and are reviewed by Anthes (2011), Yue et al. (2014), Bonafoni et al. (2019), and Ho et al. (2020).

This paper introduces the Radio Occultation Modeling Experiment (ROMEX), which is a special collection of RO observations available from all sources during a three-month period (September–November 2022) called ROMEX-1. The overarching purpose of ROMEX-1 is to provide timely information that is relevant to planners of future global observing systems and to providers of RO data. An average of approximately 30,000–40,000 RO profiles per day have been obtained for this period, roughly three times the number used currently in operational models, and they are available to the community free of charge for evaluation and testing in regional and global NWP models. These data will also be available for other research purposes, such as case studies of atmospheric phenomena and validation of other datasets. A limitation of the ROMEX-1 data is that only neutral-atmosphere

(troposphere, stratosphere, and lower mesosphere) profiles of bending angles and refractivity are available. If ROMEX-1 is successful, an additional period will be considered that may include space-weather data as well.

The outline of the paper is summarized as follows: Section 2 reviews previous studies showing the impact of RO observation on NWP forecasts using limited numbers of real data and theoretical methods. Section 3 summarizes theoretical studies investigating the impact of future large numbers of RO observation using the Ensemble of Data Assimilations (EDA) technique and Observing System Simulation Experiments (OSSEs). Section 4 projects the number of future RO observations based on current plans by the Coordination Group for Meteorological Satellites (CGMS) and shows that a significant reduction in RO observations is expected to occur beginning before 2030, which indicates the need to begin plans now for a provision of global RO observations to support NWP and other applications. To assist in this planning, ROMEX, described in Section 5 will provide valuable information for CGMS.

2. Impact of RO data on NWP

Numerous studies have shown a large positive impact of a relatively modest number (2500-5000) RO observations on global and regional NWP models, as well as reanalyses, which are widely used for climate studies. Early studies include Healy et al. 2005; Healy and Thépaut 2006; Cucurull et al. 2007; Aparicio and Deblonde 2008; Healy 2008; Poli et al. 2009, 2010; and Rennie 2010. RO observations are important in NWP because of their accuracy and precision, high vertical resolution, and all-weather capability. They can be assimilated without bias corrections and therefore act as anchors to reduce model biases (Bauer et al. 2014; Cucurull et al. 2014). They have their greatest impact in the upper-troposphere-lower stratosphere, the region of the jet stream that is weakly constrained by other observations.

a. Methods to evaluate the impact of different observations and their numbers

Several methods can be used to determine the impact of different types or quantities of observations. Observing System Experiments (OSEs) assess impacts of different observing systems in forecasts using real data (Boukabara et al. 2016) and provide the most reliable method to assess observational impact. Data denial experiments, in which certain real observations are withheld from the forecasts, are a common form of OSEs. The Forecast Sensitivity to Observations Impact (FSOI) quantifies the relative contributions of each of the assimilated observations to model forecasts using an adjoint

or an ensemble approach. Cardinali (2009) and English (2018) compare the FSOI and OSE approaches. The FSOI method measures the response of a single forecast to all perturbations of the observing system, while an OSE measures the effect of a single observation type on all aspects of the forecast. FSOI can be computed quickly on a daily basis, while OSEs require many forecasts and are time and computer intensive. The FSOI method has limitations; for example, it is based on a linearization approximation and is therefore valid for only short-range forecasts (1-3 days), it is affected by the use of a verification state that is correlated with the forecast state, and it depends on the optimality of the data assimilation system. In spite of these limitations, the FSOI method is widely used, and studies show that the ranking of observation types in FSOI is similar to those obtained by OSEs (Cardinali 2009; Candy et al. 2021). FSOI studies consistently show that microwave (MW), infrared (IR), and RO soundings are among the top five observational systems contributing to short-range NWP forecast accuracy (e.g. Cardinali and Healy 2014).

A third technique to evaluate the impact of observations is the Ensemble of Data Assimilations (EDA). EDA combines different quantities of real or simulated observations and the impact of an observing system is quantified by the reduction of uncertainty (“spread” of the forecasts) in the ensemble after adding additional observations (Harnisch et al. 2013). A positive impact of the additional observations is indicated by a reduction in spread. At least for RO, decreased EDA spread values provide a reliable tool to assess the observation impact of RO data in the higher troposphere and stratosphere (Lonitz et al., 2021b).

The above methods are useful in evaluating the impact of real observations. To estimate the potential value of future observations (observations that do not exist), Observing System Simulation Experiments (OSSEs) may be used (Atlas et al. 1985; Hoffman and Atlas 2016; Cucurull et al. 2018; Errico and Privé, 2018; Zeng et al. 2020). In an OSSE, a well-tested numerical model is used to simulate the atmosphere over a period of time. This simulation (called the nature run or truth) is used to simulate any number or type of observations, which are then assimilated in a different model to test their impact on the forecasts. Although OSSEs have provided valuable insights into the relative value of different future observing systems, they are computationally expensive

and have limitations related to the realism of the simulated observations and their errors, and the accuracy of the nature run and the models used in the experiments.

b. Impact of RO observations on global models

The most reliable way of determining the impact of different types or numbers of observations on NWP forecasts is to use real data by adding or deleting observations from an existing set. Data denial experiments carried out by Poli et al. (2008), Bauer et al. (2014), and Boukabara et al. (2016) showed a clear negative impact of a decreased number of RO observations, but these studies were limited by the total number of observations available for testing (fewer than 3,000 profiles per day). As the total number of RO observations increased due to the introduction of COSMIC-2 (launched in 2019) and commercial RO data sets at about the same time (Fig. 1), it became possible to test the impact of varying numbers of RO profiles of 10,000 or more profiles per day.

In 2023, both NOAA and ECMWF assimilated between 10,000 and 14,000 RO profiles per day into their global forecast systems, with approximately a third coming from commercial sources. The acquisition of commercial RO data began with pilot studies in 2016 and progressed to a fully operational data program in 2021. EUMETSAT has also begun purchasing and distributing commercial RO data to augment the government-sponsored data sources by approximately 1,500 profiles per day.

With the assimilation of approximately 10,000 RO global profiles today, RO is often estimated to be among the five most impactful datasets contributing to NWP accuracy. This estimate is derived from several FSOI studies, which determine the relative contributions to forecast accuracy from all datasets assimilated. Figure 2 shows an example from the NASA GEOS-5 forecast model (NASA, 2023) for one year (23 April 2023–21 April 2024). In this study, RO is ranked fifth, behind Geo winds, two microwave sounders, and radiosondes for the entire globe (Fig. 2), and second behind Geo winds in the tropics (not shown), where most of the RO observations were located in this year (the number of RO profiles varied between 4,000–8,000 per day during this period). Another study from ECMWF, using a similar distribution of global observations for April 2024, shows RO ranking third, behind microwave temperature and water vapor (Fig. 3).

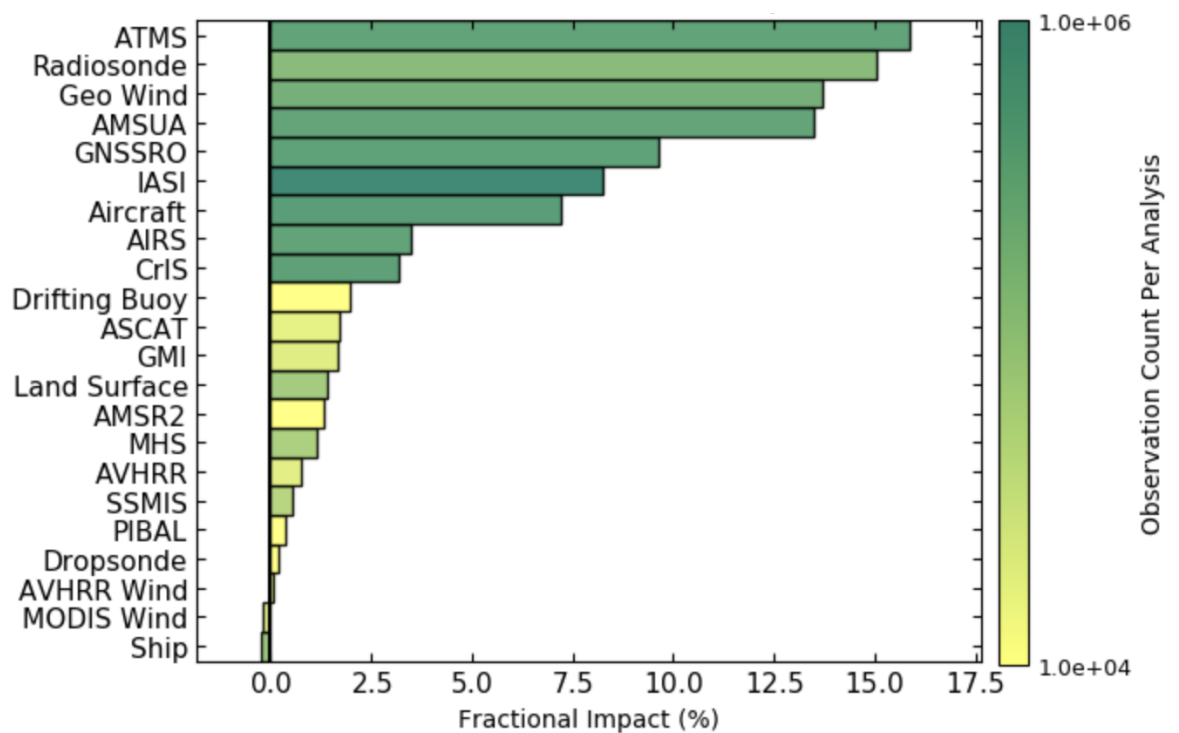


Figure 2. Example of impact results of various observation types, from the NASA GEOS model for one year (23 April 2023-21 April 2024). This figure depicts FSOI, the fractional impact in %, a global measure of 24-h forecast error that combines errors in wind, temperature, specific humidity, and surface pressure with respect to the verifying analysis from the surface to 1 hPa in terms of moist total energy (J/kg). Observation impact is taken to be the difference in this error measure between 24-h forecasts initialized from the analysis and the corresponding background state, where this difference is due entirely to the assimilation of the observations. The observation counts for RO and the other observations per six-hour assimilation period are indicated by the color scale on the right side of the figure. Source: NASA GMAO: [GMAO Observation Impact Monitoring](https://gmao.gsfc.nasa.gov/obs/impact/).

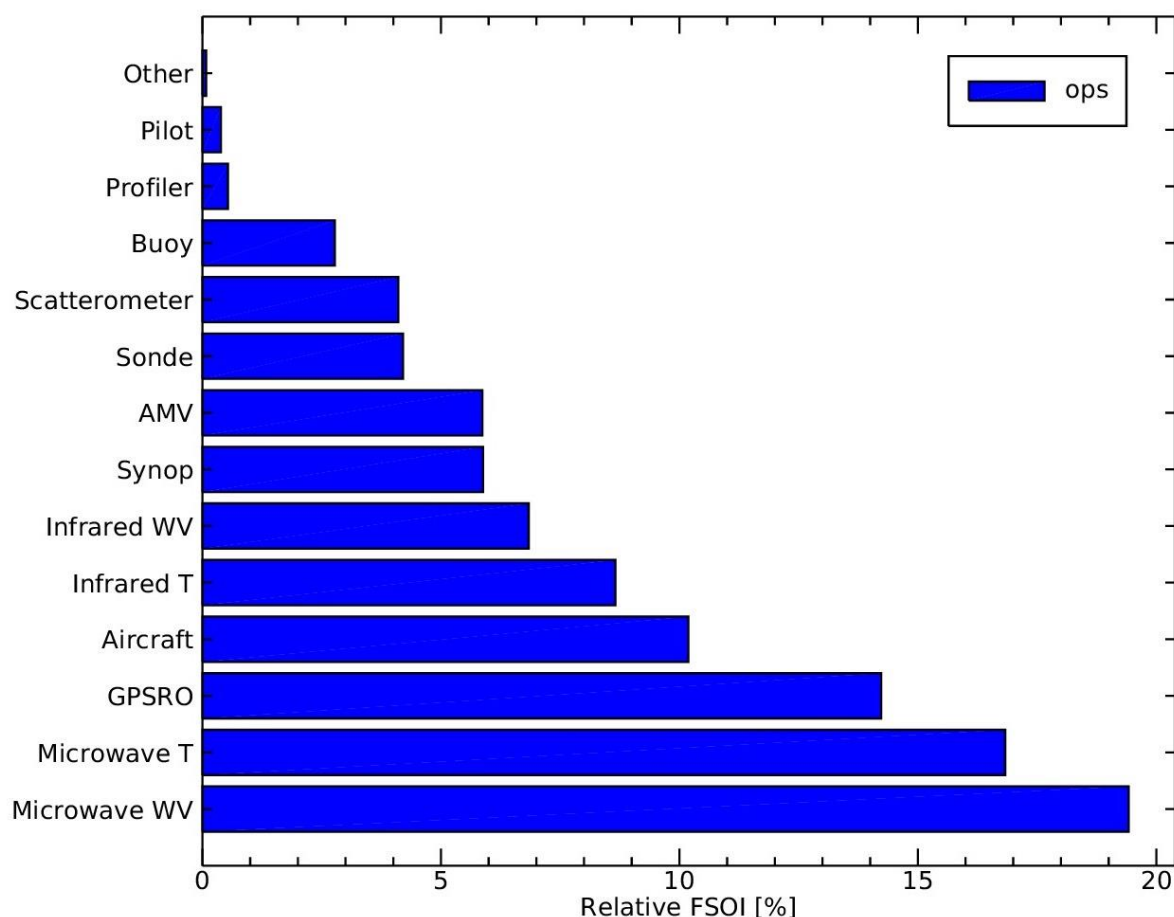


Fig. 3—Relative FSOI in % from ECMWF for 1-31 March 2024 showing relative contributions to forecast accuracy. RO is third in impact. (Source: Katrin Lonitz, ECMWF)

A clear example of the impact of additional RO observations in the operational ECMWF forecast model was evident when about 5,000 COSMIC-2 profiles per day were first assimilated on 21 March 2020, followed a few weeks later by about 6,000 Spire profiles per day on 10 May 2020. The global FSOI impact jumped from about 4% to 10% with the introduction of COSMIC-2 data, and to about 14% with the introduction of Spire data (Fig. 4). A sudden decrease of RO FSOI in August 2020 occurred when the Spire data ended. After that, a slow, irregular increase occurred as EUMETSAT purchased various numbers of Spire data. Figures 5 and 6 show a strong relationship between the impact of RO by the FSOI metric and the number of RO observations, with a correlation coefficient of 0.96. The high correlation indicates that there is no saturation of impact versus number of RO profiles per day over this range of numbers. These real-data results show the value of varying the number of RO observations in an operational NWP model, which is the main goal of ROMEX, but with a much larger number of observations.

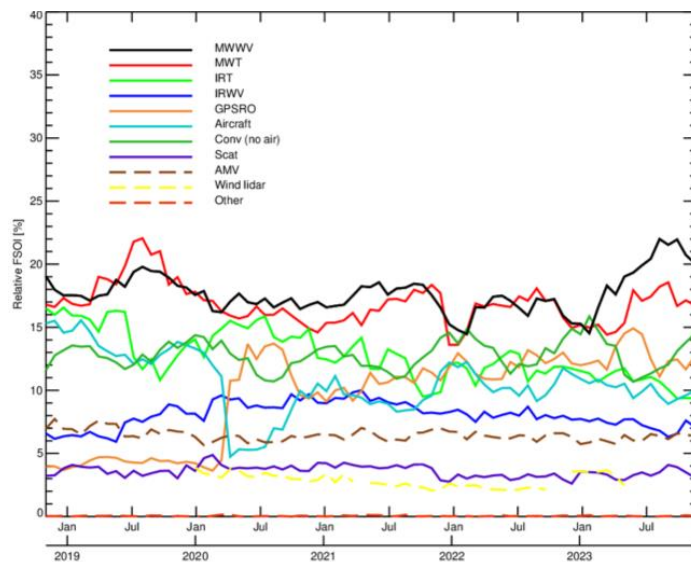


Fig. 4: Global FSOI for all the observations assimilated by ECMWF from November 2018 to November 2023. The orange time series shows the % contribution to the total error reduction by RO. Approximately 5,000 COSMIC-2 profiles were assimilated beginning on 21 March 2020 and another 6,000 Spire profiles beginning 10 May 2020. The Spire observations were discontinued on 10 August 2020. The other observations shown in the figure include microwave water vapor (MWWV), microwave temperature (MWT), infrared temperature (IRT), infrared water vapor (IRWV), aircraft, conventional observations (non satellite, includes radiosondes and surface data), scatterometer winds (Scat), atmospheric motion vectors (AMV), wind lidar and all other types (Source: Sean Healy, ECMWF).

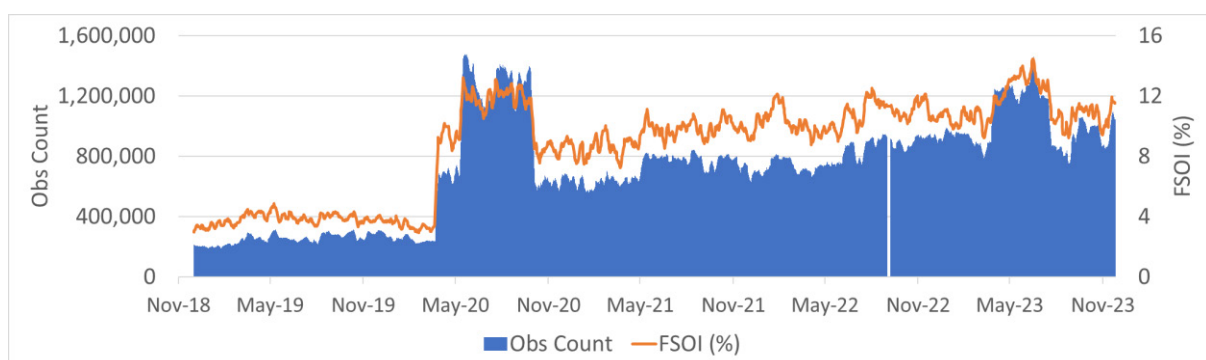


Fig. 5: Time series of the FSOI for all RO observations assimilated by ECMWF (orange) and total number of RO observations assimilated in each 12-h period (blue). Note that these are

number of RO observations, not profiles, per 12-h period. (Produced by Jon Starr, UCAR, based on data provided by Sean Healy and Alan Geer, ECMWF)

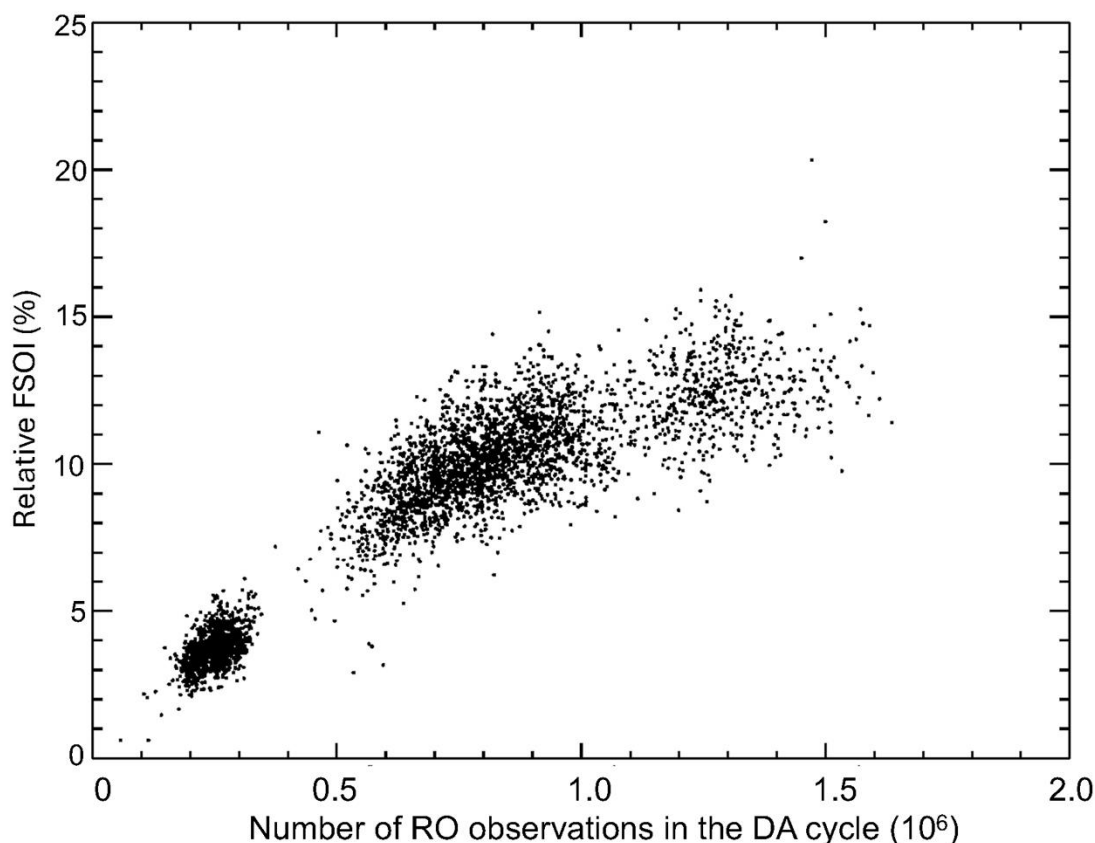


Fig. 6: Scatter plot of daily RO relative FSOI versus number of RO observations in millions assimilated per 12 hours at ECMWF for time period shown in Figs. 4 and 5. (Source: Sean Healy and Alan Geer, ECMWF).

3. Future RO needs-determining the optimal number of RO observations

As shown above, the current large impact of RO on NWP is directly related to the increase in the number of observations available for assimilation up to the number tested (~12,000 profiles per day). Several studies have been made to estimate the effect of additional RO data well beyond the numbers currently available. Harnisch et al. 2013 used the EDA method to investigate the impact of increasing the number of RO profiles to 128,000 profiles per day and found no saturation of impact up to this very large number (Fig. 7).

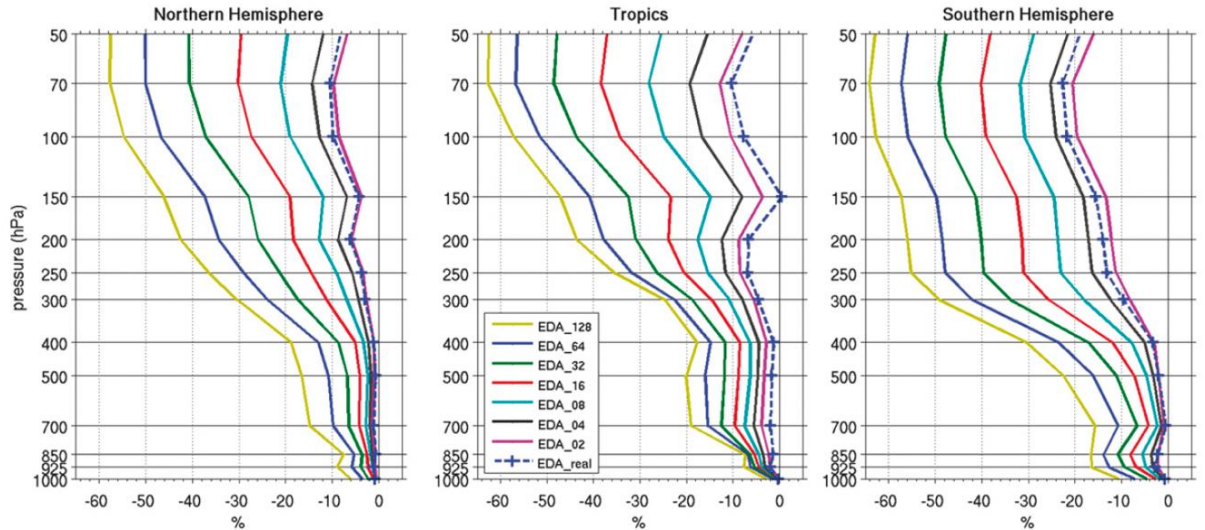


Fig. 7: Vertical profiles (y-axis is pressure in hPa on a log scale) of normalized difference of EDA spread (%) for temperature averaged over the Northern Hemisphere (left), tropics (middle) and Southern Hemisphere (right) for the period 8–15 August 2008. Larger negative values indicate reduced uncertainty of the forecasts and a positive impact. (Fig. 4 from Harnisch et al. 2013)

Privé et al. (2022) investigated the potential impact of a large number of RO profiles on global NWP forecasts using OSSEs carried out with the GEOS (Global Earth Observing System) model. The nature run was the GEOS-5 model with 72 vertical levels and 7-km horizontal resolution. The forecast model was a version of GEOS using the same 72 vertical levels and 25-km horizontal resolution (horizontal grid spacing). The analysis quality, forecast skill and FSOI were analyzed and shown to improve with the addition of RO observations up to 100,000 profiles per day. These OSSEs showed the impact of different numbers of RO profiles in maps of temperature, winds, and specific humidity and these all showed improvements with increasing numbers of RO profiles. Figure 8 shows that with 50,000 and above, RO becomes the dominant satellite data source in reducing forecast errors, especially in the tropics. However, although saturation had not been reached at the maximum of 100,000 profiles per day, the improvement in model performance for each additional 25,000 increment in number of profiles beyond the first 25,000 increment decreased, suggesting, similar to Harnish et al., that there is a “knee” (maximum in curvature) in the benefit versus cost curve.

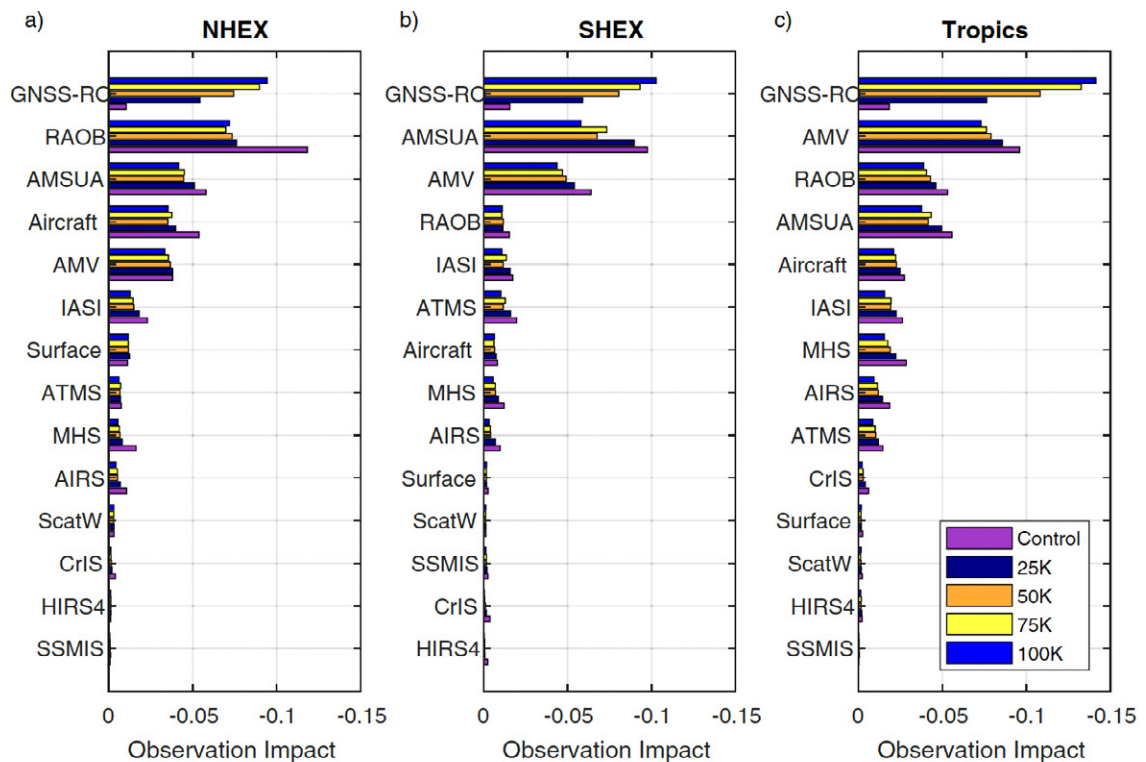


Fig. 8. FSOI impact (24-h wet energy norm in J/kg) for different numbers of RO profiles per day for northern hemisphere (NHEX), southern hemisphere (SHEX) and Tropics (Fig. 22 from Privé et al. 2022)

Although the Harnish et al. (2013) and Privé et al. (2022) studies are independent studies using different methods and show the same results (increasing impact of RO profiles up to 100,000 per day), they are based on simulated data. Confirmation of these theoretical results are needed using OSEs with real data. Lonitz et al. (2021a) confirmed these results in part by using COSMIC-2, Spire, and other RO sources to show that increasingly large positive impacts were attained on nearly all forecast metrics for RO profiles up to at least 10,000 profiles per day. ROMEX will allow testing of the theoretical results up to an average of 35,000 profiles per day using real data.

The numerous positive results from the above impact studies and others prompted the International RO Working Group (IROWG) in 2015 to recommend acquiring a baseline of at least 20,000 RO profiles per day with complete global and local-time coverage. Others have suggested that 30,000 profiles per day may be closer to an optimum number when considering benefit versus cost. The related cost-benefit curve will depend on the price per profile, as well as the impact per profile. While recognizing the potential for commercial RO companies to provide some of these data, the IROWG at its meeting in September 2022

recommended a government-sponsored backbone: *“IROWG recommends operational Global Navigation Satellite System (GNSS) RO mission for continuous global climate observations to be established and maintained as a backbone to ensure continuity and long-term availability of climate quality RO measurements with global coverage and full local time coverage.”*

An independent working group of the NOAA Science Advisory Board, the Environmental Information and Services Working Group (EISWG), supported the concept of a backbone in its first recommendation: *“NOAA should employ a backbone approach to integrating alternative-source observations, with the nature of that backbone determined through a process involving a formal decision and implementation framework.”* (EISWG, 2023).

4. Planning for the future

Over the past decade, NOAA has been planning for its future satellite observing systems, beginning with the NOAA Satellite Observing System Architecture (NSOSA) study (Volz et al. 2016; NOAA 2018; Maier et al. 2021). The Maier et al. (2021) study estimated the cost-effectiveness of over 180 possible constellations on NWP, as well as many other user needs. Critical input to this study included the Environmental Data Record Value Model, which was developed by the Space Platform Requirements Working Group (Anthes et al. 2019). In this study, RO was the second highest priority (behind 3D winds) for improvement over the NOAA Program of Record 2025 in weather- and climate-related observations. The high priority of RO was based on two main factors—the large impact of RO on NWP and a projected future gap in RO observations.

Figure 9 shows the near real time monthly mean daily RO profiles available so far or as expected in the future as of January 2024 according to EUMETSAT; future numbers are based on mission requirements. The numbers plotted here represent data from publicly funded open-access data, i.e. the current backbone of publicly operated RO missions, as well as the current commercial data procured with a global license by either NOAA or EUMETSAT. Even though there is a significant amount of commercial data available for purchase and future acquisitions are now being planned, the number acquired from commercial vendors so far has been limited. Figure 9 shows a clear shortfall from the recommended 20,000 profile baseline. This discrepancy will become even larger in the next 10 years, since COSMIC-2 is expected to end and the CGMS (Coordination Group for

Meteorological Satellites) partners have no plans yet for government-sponsored follow-on RO missions (Fig. 10). Meanwhile, the commercial data continue to pose uncertainties in terms of availability, open data access, full traceability, global and local time coverage, and long-term reliability.

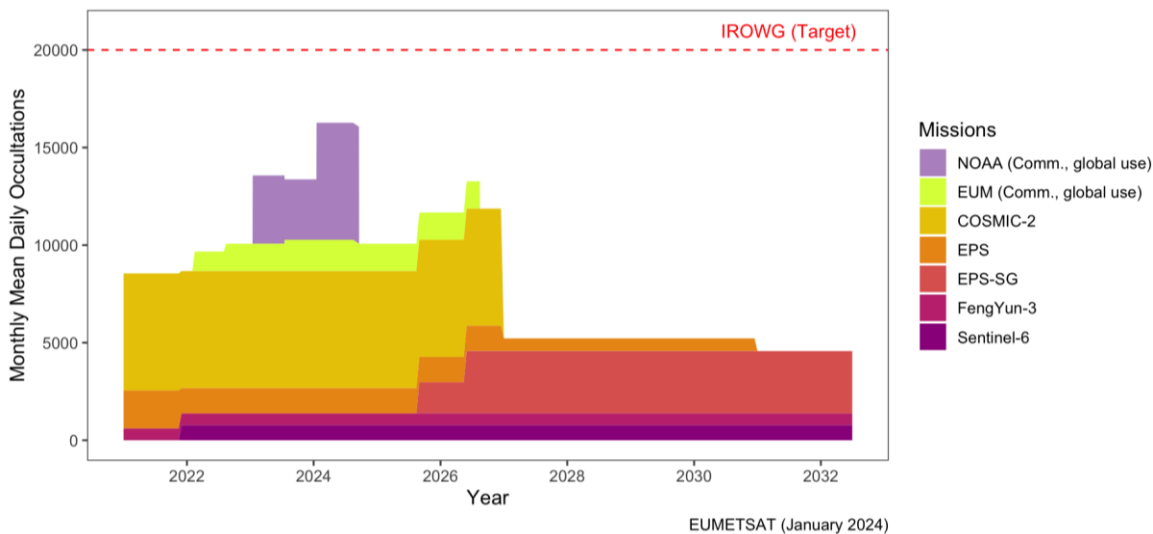


Fig. 9: Current and expected daily number of RO profiles provided in near-real time (NRT) based on the requirements for the listed set of ongoing and known upcoming public missions and their planned lifetimes. The figure also includes the current commercial data procured with a global license by either NOAA or EUMETSAT. (Source: EUMETSAT)



Figure 10: Top-level risk assessment of Earth Observations. The risk is highest for radio occultation observations. (CGMS WGIII report, 2023)

Thus, despite numerous independent studies showing the large impact of RO observations on NWP, one of the most important applications of satellite meteorology, the number of RO observations is already below the base number recommended by the IROWG. There is a further risk of a decreasing number of RO observations in the future, and there are no plans yet for a stable provision of RO observations that are freely available to the community. The results from ROMEX, showing the value of up to 35,000 RO profiles per day, will test the theoretical estimates in previous studies and provide valuable information for members of the CGMS as they plan for the future.

5. The Radio Occultation Modeling Experiment

ROMEX-1 will make available the largest volume of RO data ever collected to the international community free of charge for testing in NWP models and other science and applications research. The RO data from all known government and commercial providers have been collected for a three-month period September–November 2022, which overlaps the Northern Hemisphere tropical cyclone season. A second ROMEX period during the Northern Hemisphere winter will be considered if the first period is successful.

The ROMEX concept was endorsed by the Ninth International Radio Occultation Workshop (IROWG-9) on 8–14 September 2022 in Leibnitz, Austria and presented to the CGMS-51 Working Group II (WGII) meeting on 14 April 2023 and the CGMS-51 at its plenary meeting 26–28 June 2023. The IROWG NWP community has approval from their respective institutions to perform forecast experiments with the additional RO measurements over the ROMEX-1 period.

a. Questions to be addressed by ROMEX

High-level questions that can be addressed by ROMEX include:

What is the impact of increasing the number of RO observations in NWP models? Is there an optimum number of RO profiles per day? With 30,000–40,000 profiles per day, the experiments can measure improvements up to these numbers in different operational NWP models.

How should RO observations be distributed around the globe and in local time?

Should the tropics or other specific latitudes receive relatively more focus? How important is uniform local-time sampling to NWP and climate applications?

Are there systematic differences in the RO sources and their processing algorithms?

Issues include the value of higher signal-to-noise ratio, latency, differences between GNSS sources and differences between processing algorithms.

How can we exploit the various aspects of RO quality such as penetration depth and detection of superrefraction? How can these attributes be exploited in NWP and other applications? Quantifying these quality aspects into data requirements is an important topic, especially for commercial purchases.

How can the impact of RO data be increased, especially in the moist lower troposphere?

The greatest value of RO data has been in the upper troposphere/lower stratosphere, but RO observations provide much information on water vapor in the lower troposphere and numerous studies have shown a large impact of RO on tropical cyclone development and heavy precipitation events (Chen et al. 2020; Chang and Yang, 2022). ROMEX can provide data to improve the impact of RO data in the moist lower troposphere.

How can RO data be most effectively used to observe the atmospheric boundary layer?

Observing and understanding the atmospheric boundary layer (ABL) was one of the highest priorities in the most recent NASA Decadal Survey (NASEM, 2018). RO observations have been shown to be useful in determining the ABL height and the presence of super refraction (Kalmus et al. 2022; Sokolovskiy et al. 2024). Three months of RO data with global and all local time coverage provide a unique data set for global ABL studies.

b. ROMEX project details

A ROMEX web site has been established under the auspices of the CGMS IROWG: <https://irowg.org/ro-modeling-experiment-romex/>. This site provides organizational details of ROMEX and how users may access and use the data. A ROMEX Steering Committee has been established (the authors of this paper) and questions or requests for information can be addressed to any of its members.

EUMETSAT and ROM SAF (<https://rom-saf.eumetsat.int/>) are taking the lead to collect, process, store, and redistribute the ROMEX data. EUMETSAT is managing an agreement with the data providers. As part of the data use agreement, users of ROMEX data are required to sign a data license with EUMETSAT for the terms and conditions of using the data. EUMETSAT has performed security checks, processed, and reformatted the data in BUFR format, and the data are available through ROM SAF; variational retrievals of temperature and water vapor profiles will also be made available to the ROMEX participants. Individual data processing centers may also receive the lower-level data from EUMETSAT under mutual agreement.

The ROMEX excess phase data obtained by EUMETSAT will also be processed independently by the UCAR COSMIC Data Analysis and Archive Center (<https://cdaac-www.cosmic.ucar.edu/>) and made available to the research community via the ROM SAF. In addition to bending angles and refractivity, CDAAC will provide vertical profiles of temperature and specific humidity using a one-dimensional variational approach (Wee et al. 2022), as well as local spectral width, which is a measure of uncertainty of the RO observations in the troposphere (Liu et al. 2018; Zhang et al. 2023; Sjoberg et al. 2023).

All of the RO data for the ROMEX-1 period have been delivered to EUMETSAT. The daily numbers by the main data providers are shown in Fig. 11. A list of the providers and their contributions is presented in Table 1. The existing data providers were able to provide data sets to ROMEX beyond what have been available to real-time operations at NWP centers accessible either through the global telecommunications system (GTS) or under the commercial purchase contracts of NOAA, NASA, and/or EUMETSAT. For example, Spire Global Inc. provides nearly 17,000 profiles per day for the ROMEX studies.

It is noteworthy that two of the data providers are contributing data that are relatively new to the RO community. These are Yunyao Aerospace, a private company in Tianjin China and China Aerospace Science and Industry Corporation subsidiary Xiyong Microelectronics Park. The latter produces GNSS radio occultation profiles for research and operations with its Tianmu satellites. During the first ROMEX period, Yunyao is the second largest data provider, with up to 5,400 profiles per day (Table 1). There are no published reports yet on the processing and evaluation of the Yunyao data, but the authors of this paper have discussed the processing with Yunyao scientists (Cheng Yan, personal communication) and carried out a preliminary assessment; the data are comparable in quality to other well-

evaluated missions such as COSMIC-2 and MetOp. Data from the Tianmu satellites were limited to a few hundred profiles per day (not shown in Fig. 11) since the ROMEX period is during its pre-launch period with only one satellite available, but might provide a significantly larger number of occultations during a second ROMEX period.

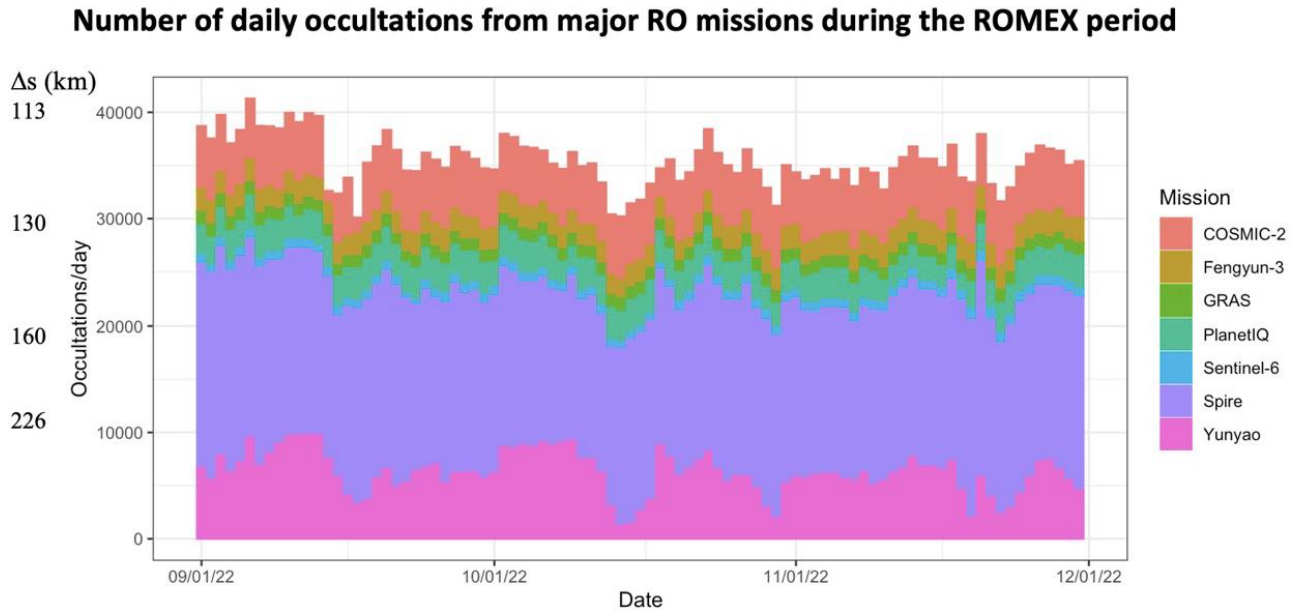
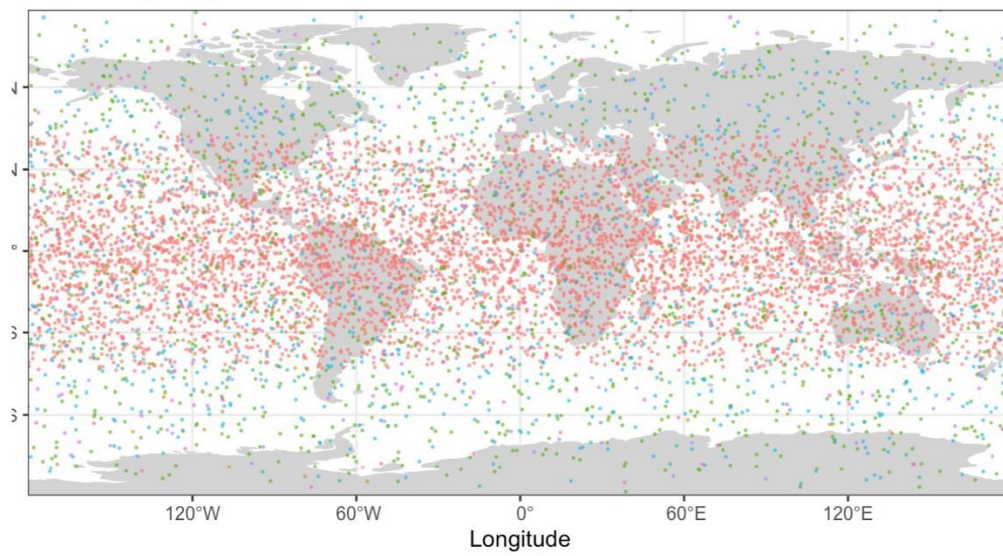


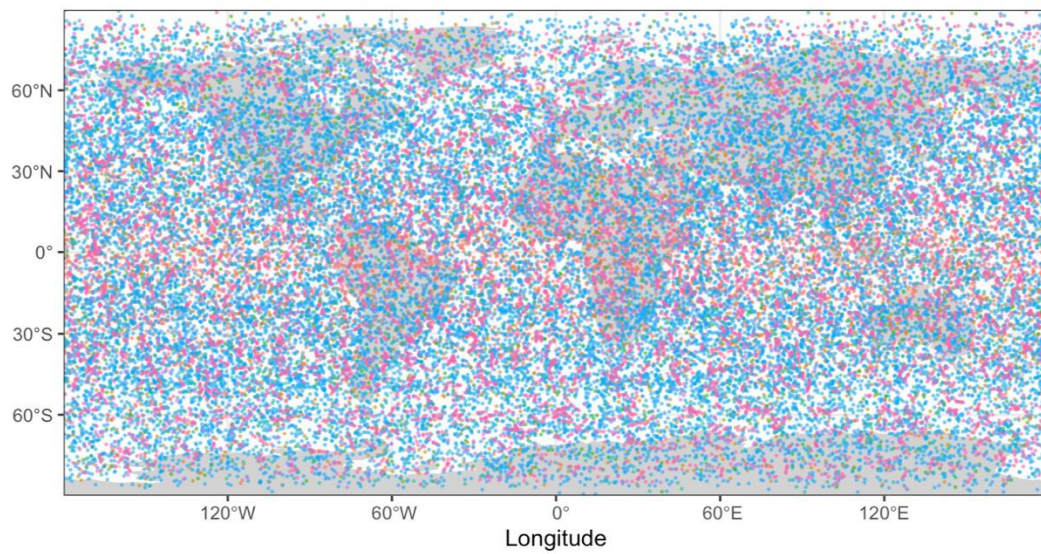
Figure 11: Number of daily RO profiles from major RO missions during the ROMEX-1 period (1 September-30 November 2022). Approximate average horizontal spacing between observations indicated by Δs on left of figure. Colors indicate the contribution by the various missions, stacked on top of each other. Additional missions not shown are GeoOptics, TerraSar-X, Tandem-X, Kompsat-5 and Tianmu (Source: EUMETSAT).

Figure 12 (top) shows the global distribution of RO profiles from the ROMEX-1 baseline case, consisting of COSMIC-2, MetOp, Kompsat-5, Sentinel-6, PAZ, Tandem-X and TerraSAR-X on 1 September 2022 (about 7,000 profiles). The middle panel of Fig. 12 shows the distribution of all RO profiles in ROMEX-1 on the same day (about 35,000 profiles). The bottom panels shows all the ROMEX-1 profiles versus latitude and local time. The predominance of missions in the same polar orbit, which concentrates the observations near the same local time, is evident.

Baseline (1 Sep 2022)



All ROMEX (1 Sep 2022)



All ROMEX (1 Sep 2022)

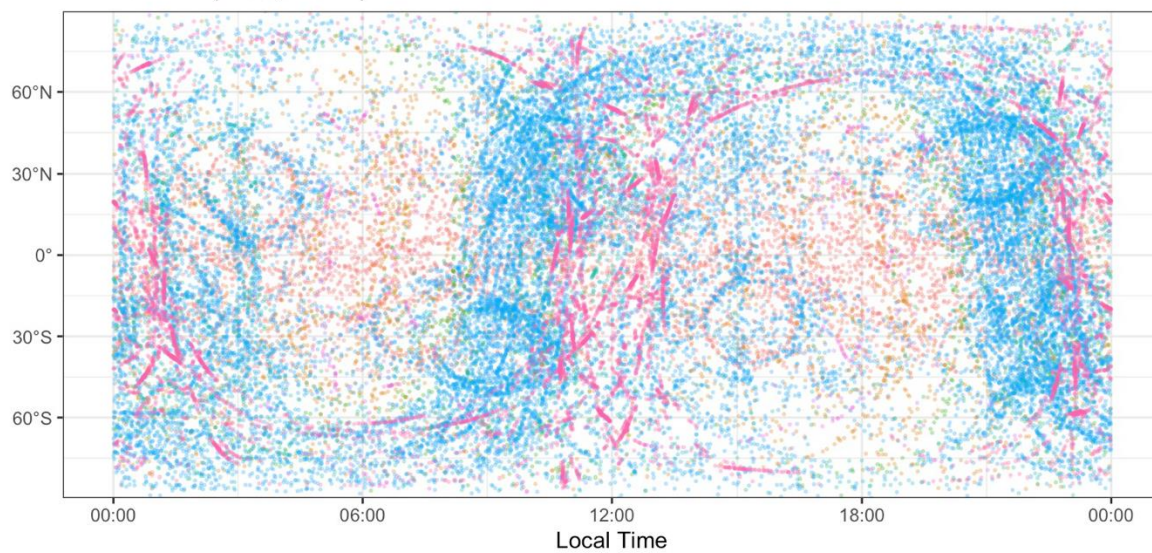


Figure 12: Global distribution of ROMEX missions on 1 September 2022. Colors denote occultations from different missions, e.g. red dots indicate COSMIC-2; light blue and green dots denote occultations from MetOp, Sentinel-6 and smaller missions in the baseline data, other colors denote Spire (blue), Yunyao (magenta) and other data. Top: profiles in the Baseline (~7K) consisting of COSMIC-2, MetOp, Kompsat-5, Sentinel-6, PAZ, Tandem-X and TerraSAR-X on 1 September 2022. Middle: all ROMEX-1 vs. latitude and longitude on the same day. Bottom: All ROMEX-1 vs. latitude and local time on the same day.

Table 1	
Mission	RO/day
Spire	16,750
Yunyao	5,400
COSMIC-2	4,900
PlanetiQ	2,750
Fengyun-3 (GNOS)	1,950
Metop (GRAS)	1,150
Sentinel-6	850
Tianmu	270
Other (GeoOptics, Kompsat-5, PAZ, TerraSAR-X, TanDEM-X)	500
ROMEX-1 total	34,520

Table 1: Average number of RO profiles per day acquired by EUMETSAT from the data providers and available for ROMEX-1 after quality control by processing center (available at ROM SAF).

6. Summary

Numerous studies have shown a large impact of radio occultation in NWP model forecasts for real observations numbering approximately 10,000 profiles per day. With these numbers, RO consistently ranks in the top five of observations contributing to global NWP accuracy, and even higher in the tropics. Theoretical studies have shown significant additional impact up to at least 100,000 profiles per day. ROMEX-1 is providing approximately 35,000 RO profiles per day for a three-month period (September–November 2022), and these are available free of charge to the community for testing in global and regional models. The data are also available for other scientific studies in weather and climate.

ROMEX-1 will provide additional guidance to NOAA, EUMETSAT and other CGMS organizations for planning their future observational systems. Figures 9 and 10 clearly show this need, as a significant gap in RO observations is projected in less than ten years. With an end-of-life of COSMIC-2 and one of the EUMETSAT satellites as early as 2027, planning for follow-on missions and/or acquisitions must begin now.

The ROMEX-1 data have been collected and processed by EUMETSAT and are available to the community via the ROM SAF. The data are also being processed independently by UCAR CDAAC and are also available to the community. Early results were reported at the first IROWG ROMEX workshop hosted by EUMETSAT 17–19 April 2024 in Darmstadt, Germany, with additional results reported at the next IROWG workshop 12–18 September 2024 in Boulder, Colorado.

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Data Availability Statement

The EUMETSAT figures are based on global licensed data so they are available through the WMO GTS service and archives at various NWP centers. ROMEX data are available through ROM SAF under the ROMEX terms and conditions (see Section 5b for details). The sources for the data used to create the figures is given in the figure captions.

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