

Global Sampling Characteristics and Coverage Complementarity of 12 GNSS Radio Occultation Constellations

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Abstract. This study analyzes observations from COSMIC-2, FY-3, GRACE-C/D, KOMPSAT-5, MetOp-B/C, PAZ, PlanetiQ, Sentinel-6A, Spire, TerraSAR-X/TanDEM-X, TM-1, and YY-1 collected during 1–7 January 2026 to compare their spatial distributions, grid-cell occupancy, area-weighted surface coverage, and local-time sampling; quantify the sampling gains achieved through multi-mission integration; and assess changes in sampling when COSMIC-2 is excluded. This study uses observations from COSMIC-2, FY-3, GRACE-C/D, KOMPSAT-5, MetOp-A/C, PAZ, PlanetiQ, Sentinel-6A, Spire, TerraSAR-X/TanDEM-X, TM-1, and YY-1 during 1–7 January 2026 to compare their spatial distributions, grid coverage, local-time sampling, and retrieval accuracy; it also assesses the benefits of multi-mission integration and the potential effects of COSMIC-2 retirement on the integrated observing capability. The results show that orbital configuration determines latitudinal and local-time sampling, whereas event abundance and constellation size primarily control grid coverage. Large constellations such as YY-1 and TM-1 provide the strongest global continuity, while missions with different orbital inclinations offer complementary sampling across latitude bands. Combining all missions substantially reduces spatial gaps and provides area-weighted global surface coverage of 99.71% and 99.99% at 1.0° and 2.0° resolutions, respectively. Within 6 h windows, the mean area-weighted joint coverage reaches 76.79–98% at 2.0° resolution. Multi-mission integration. The combined observations also broadens local-time sampling cycle. Excluding COSMIC-2 reduces the number of RO events within 5° S–5° N by 21.75%, although the remaining 11 missions retain most of the mid- and high-latitude sampling. These results characterize the sampling complementarity and resilience of the multi-mission observing system, whereas COSMIC-

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2 remains particularly important for equatorial coverage. Therefore, the retirement of COSMIC-2 would reduce equatorial sampling capability and should be considered in the development of future multi-mission GNSS-RO observing systems. Comparisons with ERAS indicate broadly consistent retrieval accuracy among most missions between 10 and 35 km, with larger differences in the lower troposphere. These findings demonstrate the value of integrating missions with diverse orbital configurations and highlight the need to sustain complementary sampling after the retirement of key missions.

1 Introduction

Global navigation satellite system (GNSS) radio occultation (RO) is a space-based sounding technique that uses the refraction, bending, and propagation delay experienced by GNSS signals as they traverse the Earth's atmosphere and ionosphere. These measurements are inverted to obtain vertical profiles of atmospheric refractivity and, subsequently, key physical parameters such as temperature, pressure, water vapor, and ionospheric electron density (Kursinski et al., 1997). GNSS-RO measurements rely on precise timing and phase observations and are only weakly affected by clouds and precipitation. The technique therefore provides all-weather global coverage, high vertical resolution, and strong long-term stability, making it valuable for numerical weather prediction, climate monitoring, and space-weather research (Ho et al., 2012).

GNSS-RO originated with the GPS/MET demonstration mission in the late twentieth century. During its operation, GPS/MET acquired extensive observations and successfully retrieved neutral-atmosphere profiles from 0 to 60 km, demonstrating the feasibility of GNSS-RO atmospheric sounding (Rocken et al., 1997). Subsequent single-satellite missions, including CHAMP (Wickert et al., 2001) and GRACE (Beyerle et al., 2005), advanced RO data processing, retrieval algorithms, and applications. The six-satellite COSMIC-1 constellation, launched in 2006, enabled the first large-scale operational use of GNSS-RO observations and substantially increased the number of global RO profiles, marking an important transition from technology demonstration to operational application (Anthes et al., 2008). Later missions, including the MetOp series (Bonnedal et al., 2010), the FY-3 series (Bai et al., 2014), COSMIC-2 (Schreiner et al., 2020), and Sentinel-6/Jason-CS (Donlon et al., 2021), have provided stable observations and broadened the use of GNSS-RO in numerical weather prediction, climate monitoring, and space-weather research. More recently, low-Earth-orbit small-satellite constellations and commercial missions such as GeoOptics/CICERO, Spire, PlanetIQ, TM-1, and YY-1 have further increased the number and spatial sampling density of RO events, creating a multi-source observing system that combines demonstration missions, operational meteorological satellites, and commercial constellations.

Advances in low-Earth-orbit platforms, spaceborne GNSS receivers, and RO retrieval techniques have transformed GNSS-RO from a small number of demonstration missions into a global system of concurrent missions and constellations. Differences in orbital altitude, inclination, local-time configuration, constellation size, and received signal systems produce distinct global distributions, latitudinal coverage patterns, local-time sampling, and observation densities. Low-inclination missions generally enhance sampling at low and middle latitudes, high-inclination or near-polar missions improve middle- and high-latitude coverage, and large or commercial constellations improve global coverage continuity through higher observation frequencies.

64 For global atmospheric monitoring and data assimilation, the value of RO data depends not only on the retrieval accuracy of
65 individual profiles but also on the spatiotemporal distribution of the observations. Insufficient sampling within particular
66 latitude bands, local-time intervals, or spatial grids can reduce the representativeness of a mission for weather systems, climate
67 background states, and regional atmospheric structures. Compared with a single mission, joint multi-mission observations
68 exploit complementary orbital configurations to reduce spatial gaps, improve uneven local-time sampling, and increase the
69 continuity and stability of global RO observations. A systematic assessment of individual and combined missions in terms of
70 spatial coverage, grid density, and local-time distribution is therefore important.

71 The relevance of RO sampling depends on the intended application. For numerical weather prediction (NWP), observations
72 distributed across the globe within relatively short assimilation windows can constrain spatially varying analysis errors and
73 evolving weather systems. However, forecast impact does not necessarily increase linearly with observation number because
74 it also depends on observation quality, error characteristics, bias treatment, redundancy, and the configuration of the data-
75 assimilation system. Application-specific assimilation experiments, such as those coordinated within the Radio Occultation
76 Modeling Experiment (ROMEX), are therefore required to quantify the actual forecast impact of increased RO sampling
77 (Anthes et al., 2024).

78 For climate applications, stable sampling across latitude and local time is important because incomplete sampling of
79 atmospheric variability, including the diurnal and semidiurnal cycles, can introduce sampling errors into gridded climate
80 records. Changes in the composition and orbital configuration of the RO observing system may also introduce time-dependent
81 sampling differences if they are not properly accounted for (Gleisner et al., 2020). For ionospheric and space-weather
82 applications, electron density and ionospheric irregularities exhibit pronounced dependence on geomagnetic latitude and local
83 time, particularly in the equatorial ionosphere after sunset (Hocke et al., 2002). Multi-mission integration is therefore valuable
84 because complementary orbital configurations reduce spatial and local-time gaps. Nevertheless, the coverage metrics analyzed
85 here describe observational availability and sampling representativeness rather than direct changes in forecast skill, climate-
86 record uncertainty, or space-weather prediction performance.

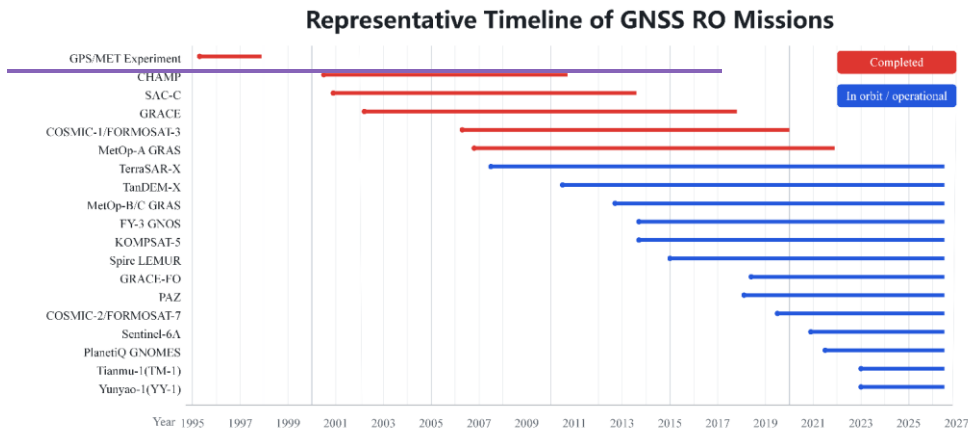
87 This study examines major global GNSS-RO missions, including COSMIC-2, FY-3, GRACE-C/D, KOMPSAT-5, MetOp-
88 BA/C, PAZ, PlanetiQ, Sentinel-6A, Spire, TerraSAR-X/TanDEM-X, TM-1, and YY-1. Using RO observations during 1–7
89 January 2026, we analyze their global spatial distributions, grid-based coverage characteristics, and local-time sampling
90 patterns, and evaluate the improvement in global coverage obtained through multi-mission combinations. Bending-angle and
91 refractivity retrievals are also compared with ERA5 reanalysis fields to support the coordinated use and quality assessment of
92 multi-source GNSS-RO data.

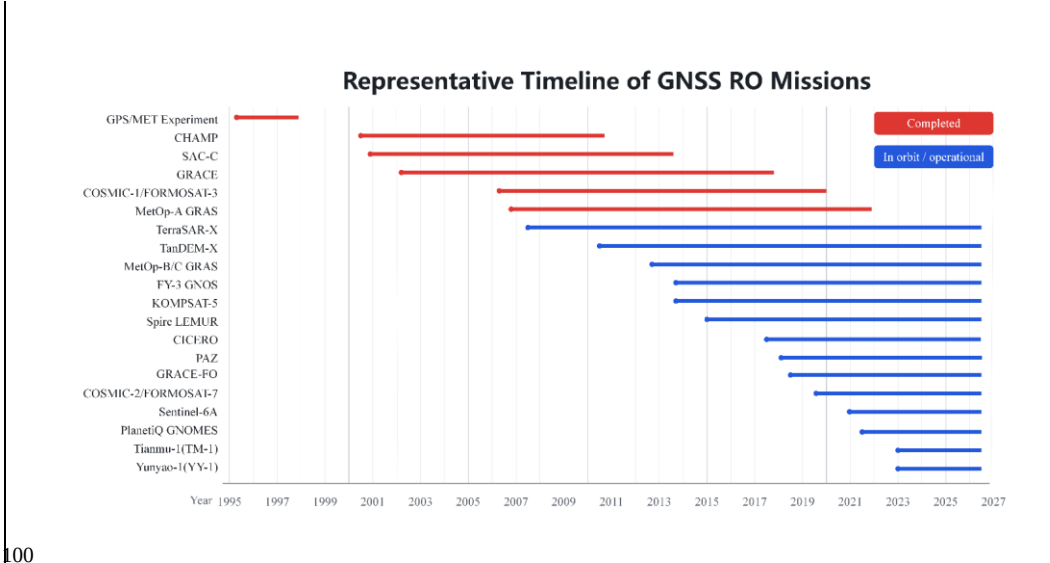
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93 **2 Missions and data**

94 **2.1 GNSS-RO missions**

95 To place the missions within the global observing system, Fig. 1 summarizes the development of GNSS-RO from GPS/MET
96 technology demonstration, through single-satellite and operational constellation missions, to the expansion of commercial
97 constellations. Overall, GNSS-RO has evolved from technology demonstration to operational application and from a small
98 number of individual satellites to coordinated multi-constellation observations.





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COSMIC-2 (Constellation Observing System for Meteorology, Ionosphere and Climate-2) is a next-generation operational GNSS-RO constellation jointly implemented by the United States National Oceanic and Atmospheric Administration and Taiwan. It comprises six low-Earth-orbit satellites launched in June 2019. COSMIC-2 operates in low-inclination, near-circular, non-sun-synchronous orbits at approximately 520-550 km and an inclination of approximately 24 degrees, primarily covering equatorial and low-latitude regions(Schreiner et al., 2020)-(Jaeggi et al., 2021). Its receivers support multi-frequency GNSS RO observations (L1, L2, and L5), and the six-satellite constellation can provide up to approximately 5000 RO profiles per dayeach-satellite-can-acquire-more-than-one-thousand-RO-events-per-day.

Fengyun-3 (FY-3) is China's operational polar-orbiting meteorological satellite series and has carried the GNSS Occultation Sounder (GNOS) since FY-3C (Bai et al., 2014). FY-3D (Du et al., 2019), FY-3E, FY-3F (Miao et al., 2025), and FY-3G (Zhang et al., 2023) occupy different local-time orbits: FY-3E is in a dawn-dusk orbit, FY-3F in a morning orbit, FY-3D in an afternoon orbit, and FY-3G in a low-inclination precipitation-monitoring orbit. Most FY-3 satellites have inclinations near 98 degrees, whereas FY-3G has an inclination near 50 degrees. Their coordinated operation forms the core of China's operational RO observing system.

115 The twin-satellite GRACE mission was launched in 2002 primarily to observe the Earth's gravity field and also carried GNSS
116 receivers for RO observations. The satellites operated in near-polar orbits at approximately 500 km and an inclination of
117 approximately 89 degrees. GRACE RO data contributed to early studies of atmospheric structure and retrieval algorithms
118 (Beyerle et al., 2005). The follow-on GRACE-C/D twin-satellite mission primarily measures static and time-variable gravity
119 fields while continuing GPS RO observations. GF1 and GF2 have provided approximately 500 atmospheric profiles per day
120 since March 2020 and September 2021, respectively, for climate research and numerical weather prediction (Kornfeld et al.,
121 2019; Schmidt et al., 2020).

122 KOMPSAT-5 is a Korean multipurpose satellite launched in 2013. Although its primary payload is synthetic aperture radar
123 (SAR), it also supports GNSS-RO and precise orbit determination. It operates in a near-polar, sun-synchronous orbit at an
124 altitude of approximately 550 km (Roh and Hwang, 2020)(Roh and Hwang, 2020).

125 MetOp-02 (MetOp-A), MetOp-01 (MetOp-B), and MetOp-03 (MetOp-C) were the three first-generation satellites of the
126 EUMETSAT Polar System (EPS). They were launched on 19 October 2006, 17 September 2012, and 7 November 2018,
127 respectively. All three satellites were placed in near-circular, sun-synchronous polar orbits at an altitude of approximately 817
128 km and an inclination of approximately 98.7°. Their nominal mid-morning orbit configuration had descending-node and
129 ascending-node local times of approximately 09:30 and 21:30, respectively. Each satellite was equipped with the GNSS
130 Receiver for Atmospheric Sounding (GRAS), which receives dual-frequency GPS L1/L2 signals and retrieves vertical profiles
131 of atmospheric refractivity, temperature, humidity, and ionospheric electron density (Righetti et al., 2020). MetOp-A was
132 retired in November 2021; therefore, only MetOp-B and MetOp-C were operational during the study period in January 2026.

133 PAZ (SEOSAR/Paz) is an X-band SAR Earth-observation satellite operated by the Spanish company Hisdesat. It was launched
134 from Vandenberg Air Force Base on a SpaceX Falcon 9 rocket on 22 February 2018. PAZ operates in a sun-synchronous low-
135 Earth orbit at approximately 514 km, with an inclination of approximately 97.44 degrees and an approximately 11-day repeat
136 cycle. It flies in coordination with TerraSAR-X and TanDEM-X to enhance revisit capability. Its ascending-node equator-
137 crossing local time is approximately 18:00 ± 0.25 h (Padullés et al., 2024).

138 GeoOptics operates the Community Initiative for Cellular Earth Remote Observation (CICERO) constellation of low-Earth-
139 orbiting CubeSats, whose deployment began in 2017, to provide commercial GNSS-RO observations. Chang et al. (2022)
140 evaluated the spatial coverage and measurement performance of GeoOptics RO data relative to the COSMIC missions(Chang
141 et al., 2022). However, GeoOptics observations for 1–7 January 2026 were not available through either the GTS or the CMA-
142 authorized data channels used in this study. GeoOptics/CICERO is therefore included in the mission overview but excluded
143 from the quantitative comparison.

144 PlanetiQ is a US commercial remote-sensing company. Its GNSS-RO satellites are typically deployed in sun-synchronous
145 orbits at approximately 620–645 km, with inclinations near 97.8 degrees and orbital periods near 97 min. The typical equator-
146 crossing local times are approximately 06:00/18:00, providing stable solar illumination geometry (Zhran et al., 2024).

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147 Sentinel-6A is a joint European-US operational altimetry satellite launched in 2020 and equipped with a GNSS-RO receiver.
148 Its non-sun-synchronous orbit has an inclination of approximately 66 degrees and provides complementary observations at
149 low and middle latitudes (Paoletta et al., 2025).
150 Spire Global operates a commercial constellation that collects GNSS-RO and GNSS reflectometry data using numerous
151 LEMUR nanosatellites. More than one hundred satellites have been launched, forming one of the world's largest commercial
152 GNSS-RO constellations. The satellites occupy multiple low-Earth-orbit planes, including several sun-synchronous planes, at
153 altitudes of approximately 385-650 km. Orbital inclination and local solar time vary among launch batches (Masters et al.,
154 2020).
155 TerraSAR-X and TanDEM-X are German twin SAR missions that also support GNSS-RO and precise orbit determination.
156 They operate in near-polar, sun-synchronous orbits with an inclination of approximately 97.44 degrees and a designed
157 descending-node local time of 06:00 (Faller et al., 2007).
158 Tianmu-1 (TM-1) is China's first commercial GNSS-RO meteorological constellation. It comprises multiple networked small
159 satellites in low-Earth orbit at approximately 520 km and an inclination near 97 degrees. The receivers support GPS, BDS,
160 Galileo, and GLONASS signals, substantially increasing global RO observation density (Li et al., 2025).
161 Yunyao-1 (YY-1) is an important component of China's new generation of commercial GNSS-RO constellations. The planned
162 system comprises 90 satellites equipped with GNSS-RO instruments by the end of 2026 (Fu and Li, 2021)(Fu and Li, 2021).
163 Its design combines 12 high-inclination orbital planes with six satellites per plane and six low-inclination planes with three
164 satellites per plane. The constellation includes quasi-sun-synchronous orbits near 97 degrees and low-inclination orbits near
165 50 degrees at an altitude of approximately 500 km. This combination of orbital configurations further enhances coverage (Xu
166 et al., 2025).
167 To keep figure legends concise and clear, standardized abbreviations are used for several missions. Table 1 lists the full mission
168 names and abbreviations used in this study.

169 **Table 1. Names and abbreviations of the 12 GNSS-RO mission systems included in the quantitative analysis.**
170 ~~names and abbreviations used in this study.~~

RO Constellation	RO Acronym	Specific Satellite (Data Directory)	RO Constellation	RO Acronym	Specific Satellite (Data Directory)
COSMIC-2	COSMIC-2	C2E1 ₁	FengYun-3	FY-3	FY3D ₁ —FY3E ₁
		C2E2 ₁			FY3F ₁ —FY3G
		C2E4 ₁			
		C2E5 ₁ —C2E6			

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GRACE-C/D	GRACE	GRACE-C, GRACE-D	KOMPSAT-5	KOM5	KOM5
MetOp	MetOp	MetOp01, MetOp 03	PAZ	PAZ1	PAZ1
PlanetiQ	PLAQ	PLAQ	Sentinel-6A	SE6A	SE6A
SPIRE	SPIRE	SPIRE	TerraSAR-X/TanDEM-X	TSX_TDX	TSAR_TDMX
Tianmu-1	TM-1	TM01–TM22	Yunyao-1	YY-1	Y014–Y022, Y025–Y026, Y031–Y040, Y043–Y048, Y055–Y060

2.2 Data sources

This study used GNSS radio occultation (GNSS-RO) observations from 12 global systems during 1–7 January 2026. The data were obtained from the National Meteorological Information Centre (NMIC) in BUFR format and included observations disseminated through the Global Telecommunication System (GTS) and operational products authorized by the China Meteorological Administration from Tianmu and Yunyao companies. The dataset comprised observations from COSMIC-2, FY-3, GRACE-C/D, KOMPSAT-5, MetOp-B/C, PAZ, PlanetiQ, Sentinel-6A, Spire, TerraSAR-X/TanDEM-X, TM-1, and YY-1. It should be noted that the occultation data analyzed in this study represent only the observations accessible through the two aforementioned data channels. The BUFR records include bending angle, impact parameter, occultation tangent-point location, observation time, refractivity, and geometric height. Event latitude, longitude, time, and mission identifier were extracted to analyze global spatial distributions, grid coverage, local-time sampling, and the effects of multi-mission joint observations. Bending angle, refractivity, and geometric height were further used to compare retrieval performance among missions. ERA5 atmospheric reanalysis from the European Centre for Medium-Range Weather Forecasts was used as the reference field for evaluating GNSS-RO retrieval products. ERA5 is the fifth-generation ECMWF global atmospheric reanalysis and provides continuous global estimates of atmospheric, land surface, and oceanic variables (Hersbach et al., 2020). Globally gridded ERA5 data for 1 January 2026 were used at a horizontal resolution of $1^{\circ} \times 1^{\circ}$ and a temporal resolution of 6 h (00:00, 06:00, 12:00, and 18:00 UTC). Temperature, pressure, and specific humidity were used to calculate reference refractivity profiles.

188 These profiles were collocated with the bending angle, refractivity, and geometric height information contained in the GNSS-
 189 RO BUFR data to calculate relative error, mean bias, and root-mean-square error.

190 3 Global distribution characteristics of individual missions

191 3.1 Coverage metrics and statistical methods

192 To quantify the global spatial coverage of each mission at a given spatial resolution, we introduce a grid-coverage metric. The
 193 global study area is first divided into N_r grids at a prescribed latitude-longitude resolution r , and the number of RO events $n_i(r)$
 194 in the i th grid is counted. A grid is considered covered when it contains at least one RO event and is considered blank when it
 195 contains no events:

$$C(r) = \frac{\sum_{i=1}^{N_r} I(n_i(r) \geq 1)}{N_r} \times 100\%, \quad I(n_i(r) \geq 1) = \begin{cases} 1, & n_i(r) \geq 1 \\ 0, & n_i(r) = 0 \end{cases} \quad (1)$$

196 In Eq. (1), $C(r)$ is the global grid-coverage fraction at resolution r , N_r is the total number of grids included at that resolution,
 197 $n_i(r)$ is the number of RO events in the i th grid, and I is the indicator function. The metric is the fraction of all grids containing
 198 RO observations and complements the blank-grid fraction (the fraction of grids without RO events), $1 - C(r)$. Coverage was
 199 calculated at grid resolutions of 0.5, 1.0, and 2.0 degrees to compare global coverage continuity among individual missions
 200 and joint-observation scenarios.

201 To further characterize spatial gaps and observation concentration, we also use the blank-grid fraction and mean-grid-event
 202 density. The blank-grid fraction describes the proportion of grids containing no RO events at a given spatial resolution and is
 203 defined as follows:

$$B(r) = 1 - C(r) \quad (2)$$

204 In Eq. (2), $B(r)$ is the blank-grid fraction and $C(r)$ is the grid-coverage fraction. This metric characterizes the spatial extent
 205 without RO observations.

206 In addition to coverage and blank-grid statistics, the average number of RO events within the gridded domain describes the
 207 overall observation concentration. The mean-grid-event density is defined as follows:

$$D(r) = \frac{1}{N_r} \sum_{i=1}^{N_r} n_i(r) \quad (3)$$

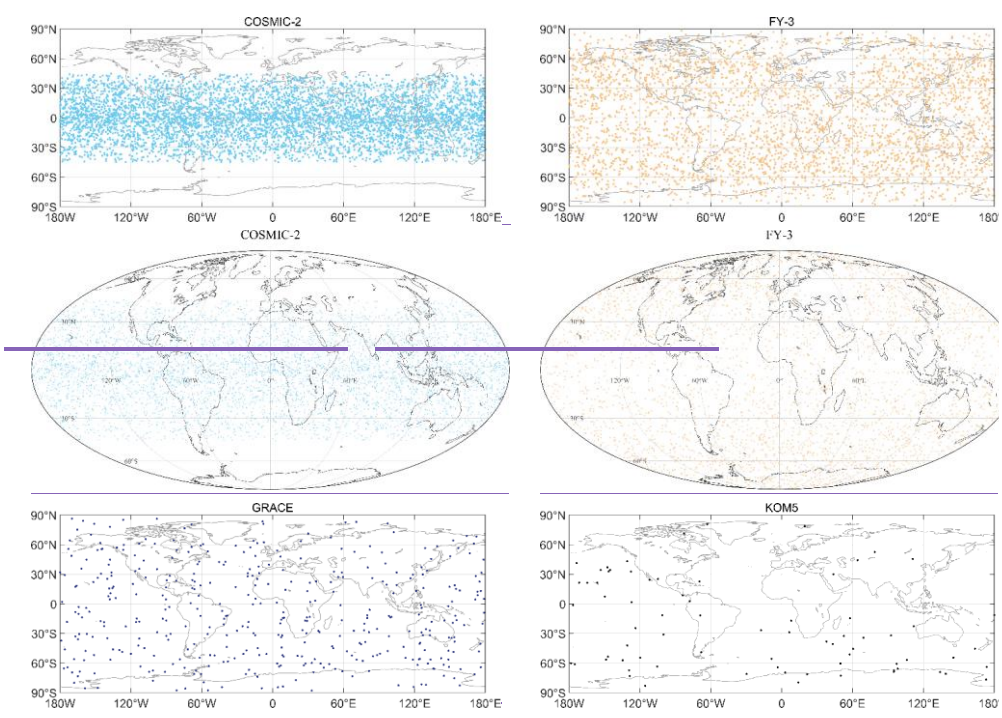
208 In Eq. (3), $D(r)$ is the mean-grid-event density at resolution r and $n_i(r)$ is the number of RO events in the i th grid.

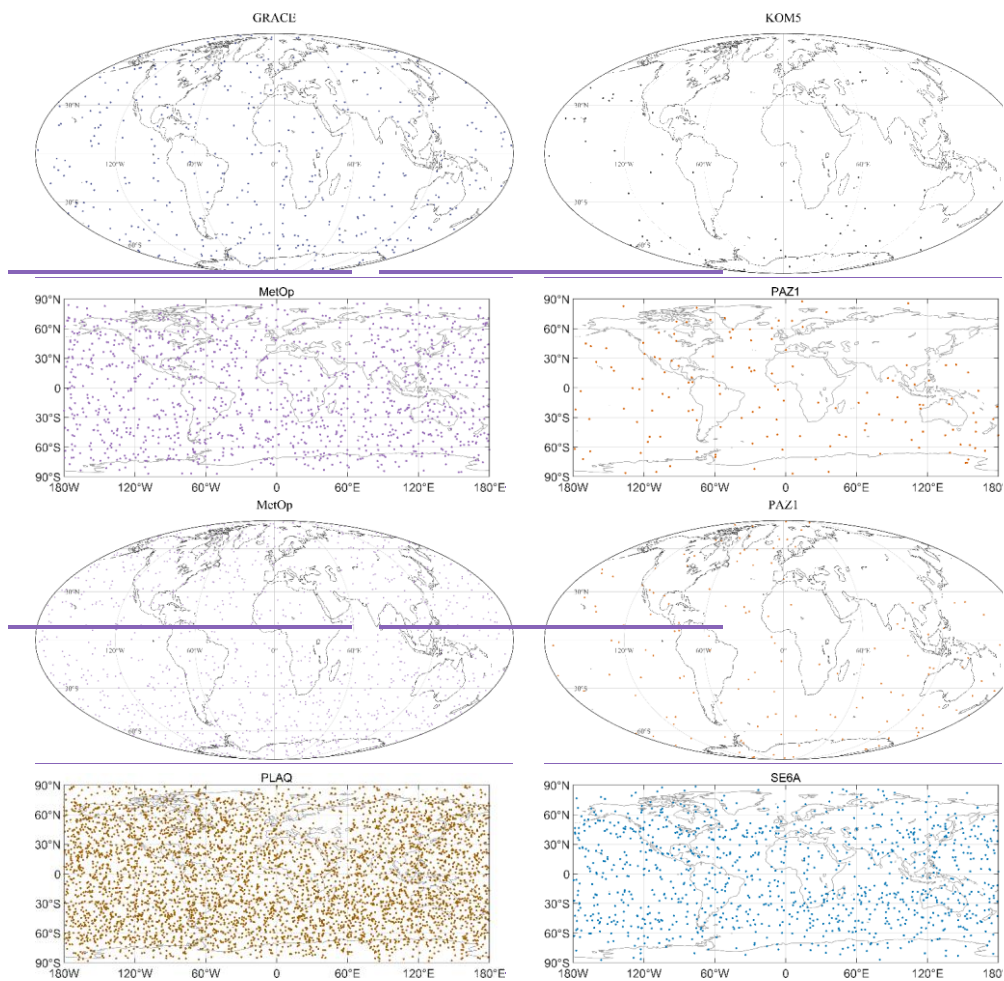
209 To characterize the global spatial sampling of each mission at a prescribed angular resolution r , the study domain was divided
 210 into regular latitude-longitude cells, and the number of RO events $n_i(r)$ in cell i was counted. A cell was considered occupied
 211 when it contained at least one RO event and blank when it contained no events.

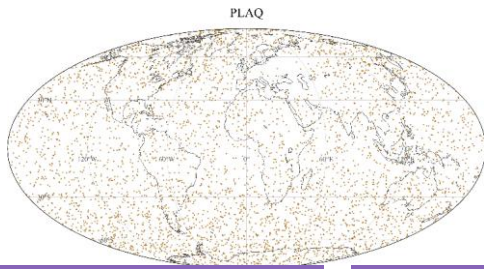
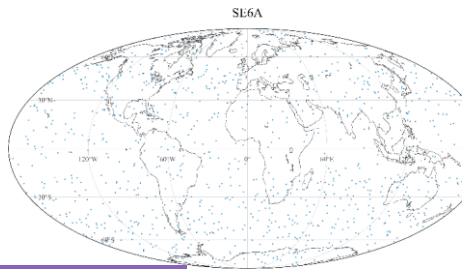
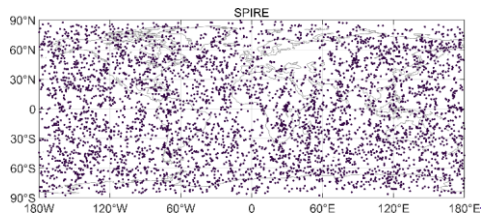
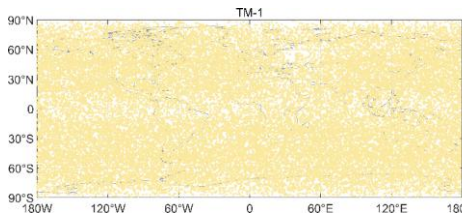
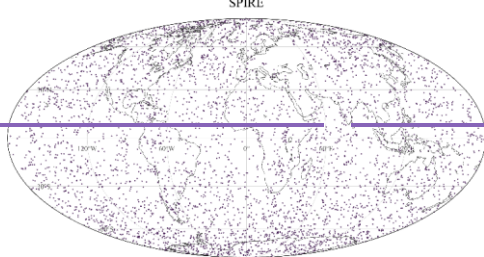
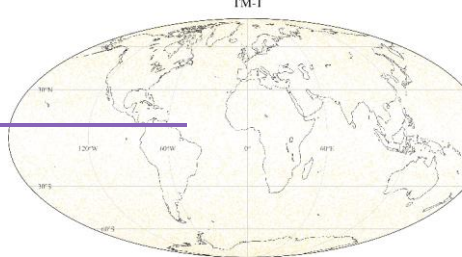
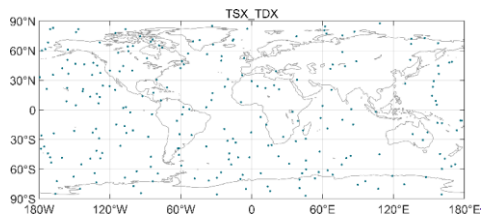
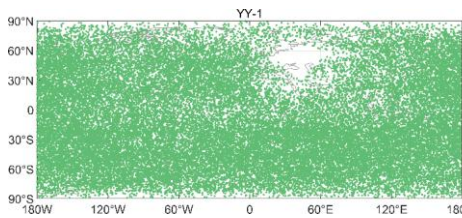
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238 partly reflect regional GNSS interference. Using normalized RO signal-to-noise ratios at deeply occulted heights ($H_{sl} <$
239 140km), Wu (2024) identified enhanced jamming signatures over the Mediterranean, Eastern Europe, and the Middle East,
240 with the enhancement extending toward Russia in 2022 and interpreted as likely related to the Russo-Ukrainian War (Wu, 2024).
241 However, Wu detected jamming signatures rather than directly demonstrating a reduction in the number of retrieved
242 atmospheric RO profiles. The gaps identified here may also result from quality-control screening, data transmission, or data-
243 access limitations; therefore, their cause cannot be determined from the present dataset alone. Localized data gaps apparent in
244 some mission distributions, particularly over the Russia–Ukraine region, may be associated with regional signal interference,
245 quality-control screening, or data-reception limitations; however, this interpretation remains tentative and requires independent
246 verification.

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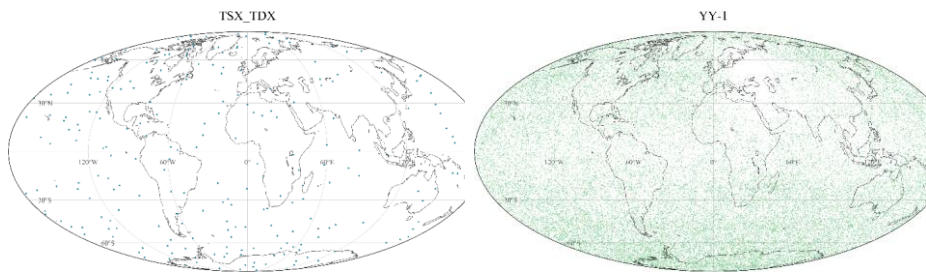


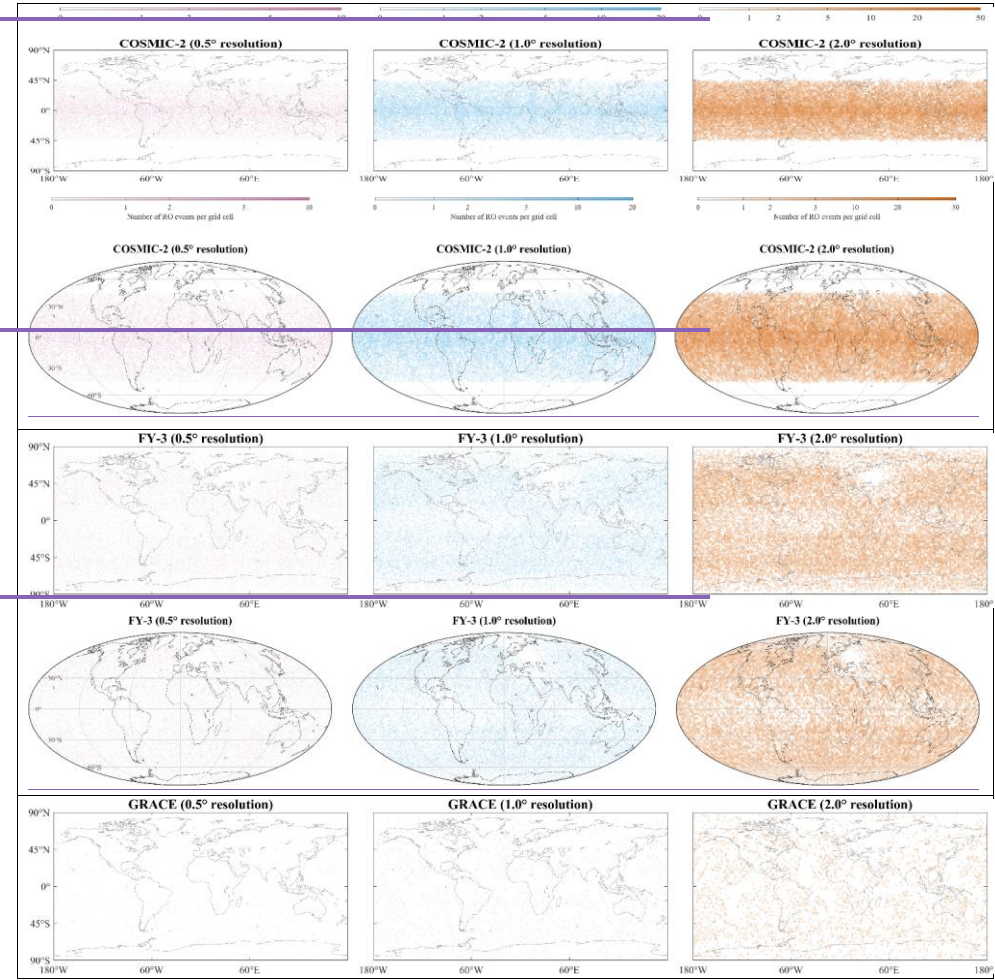
Figure 2. Global distribution of radio occultation events from individual missions on 1 January 2026. The distributions are shown using a Mollweide equal-area projection.

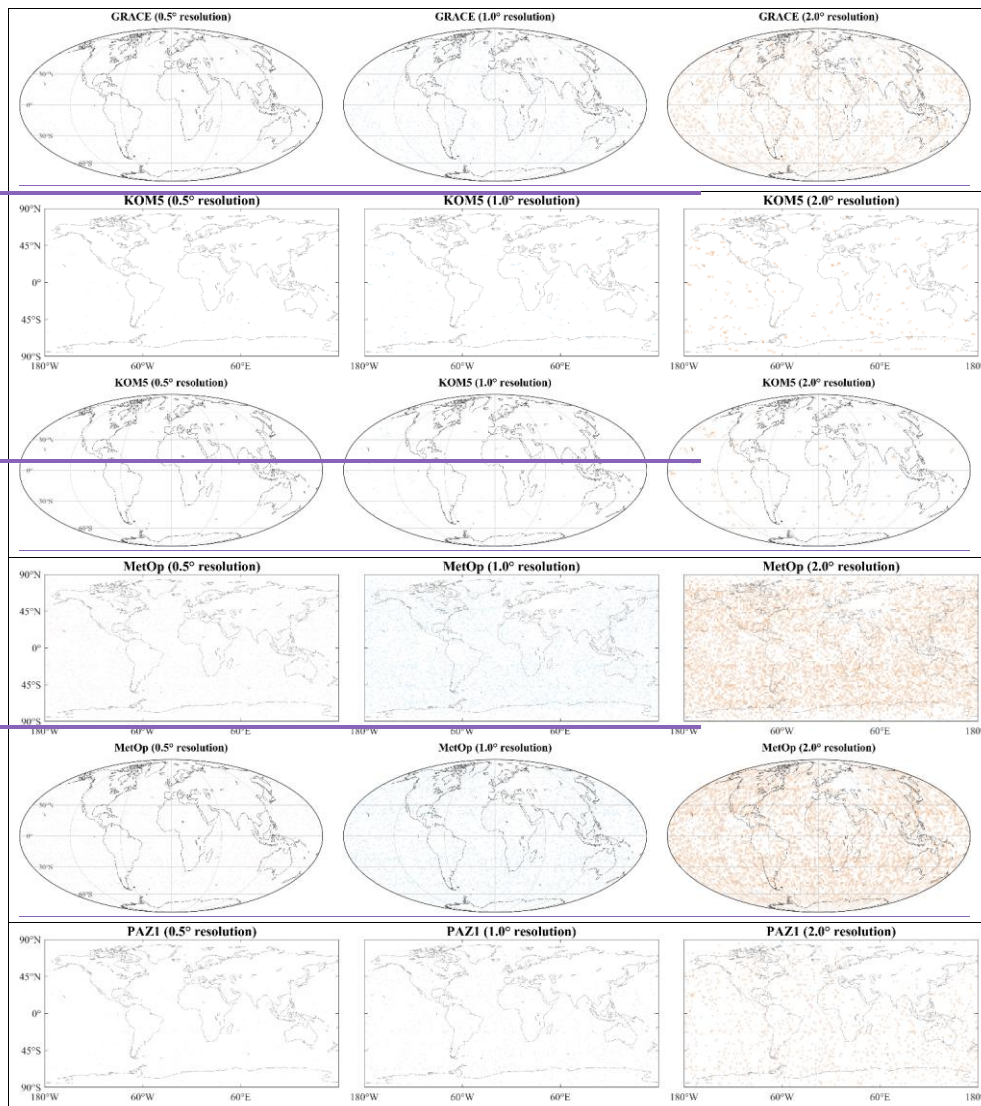
3.3 Grid-based spatial distributions

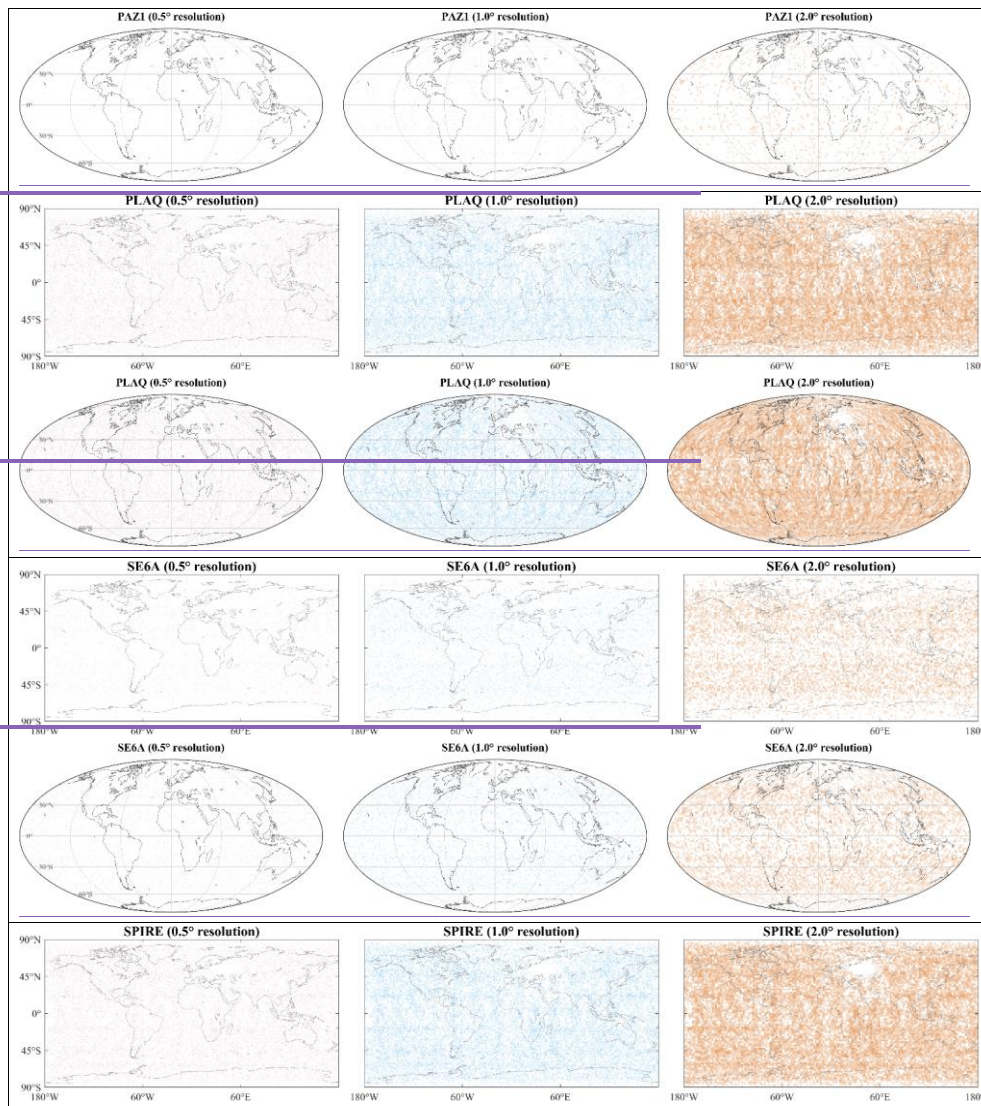
Figure 3 presents the gridded counts of GNSS-RO events during for 1–7 January 2026 at spatial resolutions of 0.5°, 1.0°, and 2.0°. For all missions, the fraction of zero-event grids decreases as grid size increases, and the seven-day accumulation substantially improves spatial continuity relative to the daily distribution. At 0.5° resolution, TM-1 and YY-1 occupy substantially larger fractions of the latitude–longitude grid than the other missions, with blank-grid fractions of 41.60% and 39.28%, respectively, whereas all other missions retain blank-grid fractions above 88%. At 1.0° resolution, TM-1 and YY-1 approach near-global continuity, with blank-grid fractions decreasing to 6.25% and 9.38%, respectively. At 2.0° resolution, TM-1 provides the most spatially continuous coverage, with only 0.69% blank-grid cells and 16,089 nonzero grids, while YY-1 follows closely with 2.55% blank-grid cells and 15,787 nonzero grids. YY-1, however, exhibits the largest strongest-local event density event count per grid cell, with a maximum of 64 events in a single 2.0° grid and 2,002 grids containing at least 30 events; the corresponding values for TM-1 are 42 events and 294 grids. The selected heatmap limits of 15, 40, and 70 events for the 0.5°, 1.0°, and 2.0° maps, respectively, remain above the observed maxima for all missions, so the color scaling preserves the full density range event-count range without saturation. Based on blank-grid fractions, nonzero-grid continuity, and maximum grid-level event density event count per grid cell, the 12 systems can be broadly classified into three tiers. The broad-coverage tier comprises TM-1 and YY-1, which provide the most extensive and continuous global sampling across all three resolutions. The intermediate tier includes PlanetiQ, Spire, FY-3, COSMIC-2, MetOp-B/C, and Sentinel-6A. Within this tier, PlanetiQ, Spire, and FY-3 show relatively strong 2.0° coverage, with blank-grid fractions of 19.53%, 20.81%, and 26.44%, respectively. COSMIC-2 shows a different pattern: its 2.0° blank-grid fraction is higher at 52.34%, but its sampling is concentrated within low latitudes, where the maximum number of events in a single 2.0° grid reaches 19. MetOp-B/C and Sentinel-6A remain less continuous, with 2.0° blank-grid fractions of 62.30% and 65.13%, respectively. The sparse tier comprises GRACE-C/D, TerraSAR-X/TanDEM-X, PAZ, and KOMPSAT-5. Their 2.0° blank-grid fractions remain high, at 84.11%, 87.72%, 92.51%,

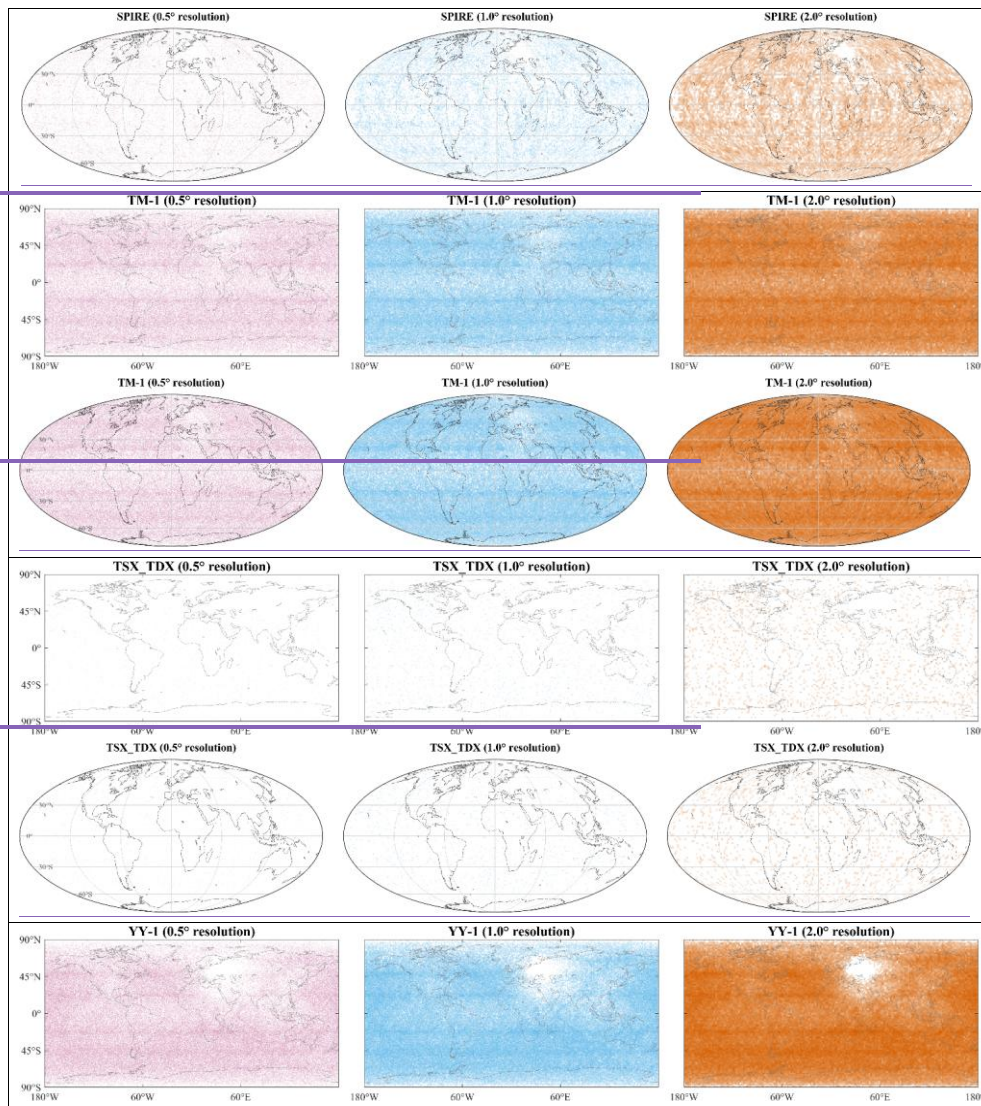
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271 and 98.16%, respectively, indicating that their observations are still spatially discontinuous even after seven-day accumulation.
272 Overall, the seven-day results show that TM-1 and YY-1 dominate the global-gridded event-count distributionevent-density
273 field, PlanetiQ, Spire, FY-3, and COSMIC-2 provide useful supplementary coverage with mission-specific spatial patterns,
274 and the remaining smaller missions contribute more localized and sparse observations.









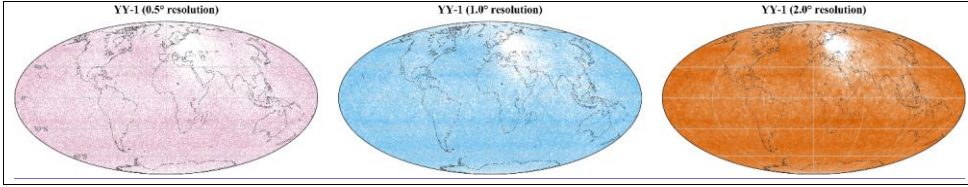


Figure 3. Gridded spatial distributions of radio occultation events from individual missions during 1–7 January 2026. [Colors represent the raw number of events within each latitude–longitude cell and are not normalized by physical cell area.](#)

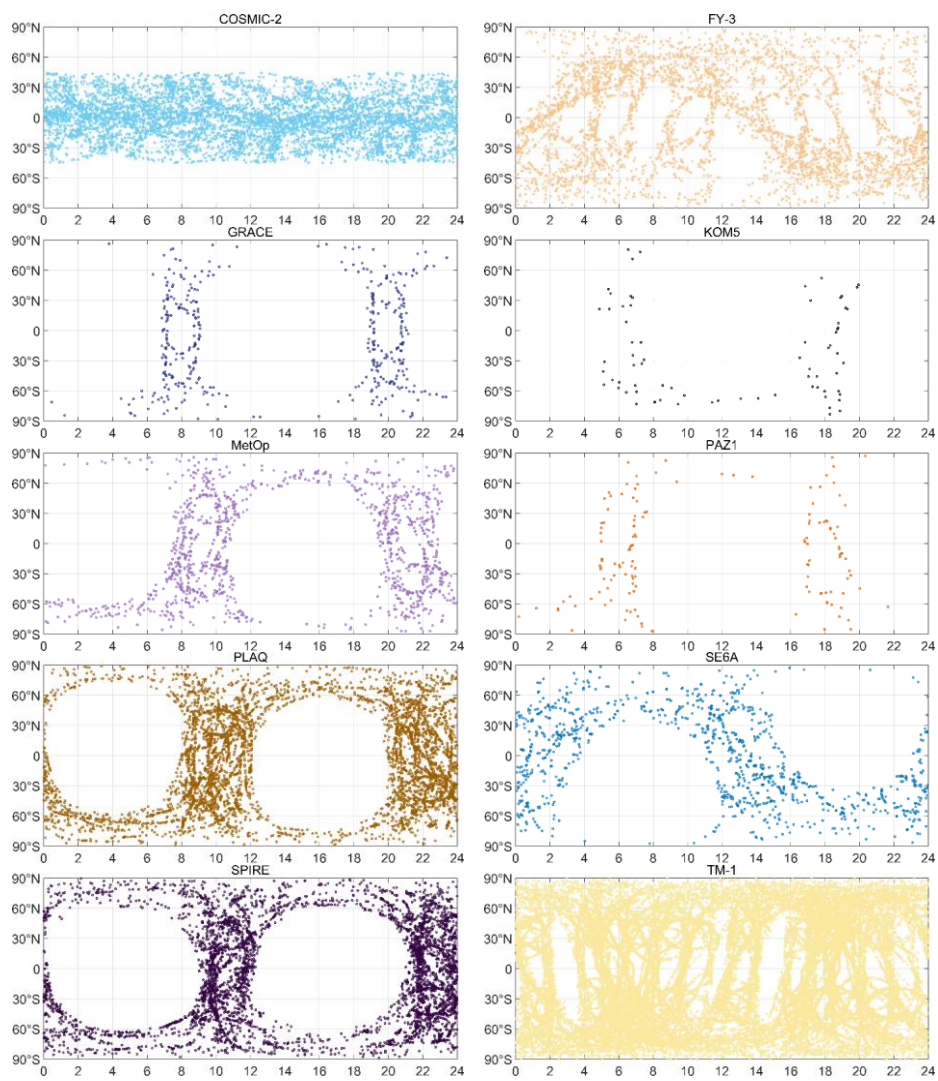
3.4 Local-time distributions

To analyze within-day temporal sampling, the UTC time of each event was converted to local time at the tangent point. Local time depends on both UTC and tangent-point longitude. Because the Earth rotates by approximately 15 degrees per hour, local time was calculated as follows:

$$LT = \left(UTC + \frac{\lambda}{15^\circ} \right) \bmod 24 \quad (45)$$

In Eq. (45), LT is the local time of an RO event, UTC is the event time in coordinated universal time, and longitude is positive eastward and negative westward.

Figure 4 shows the local-time distributions of the global RO systems. The low-inclination COSMIC-2 configuration provides broad local-time sampling at low and middle latitudes. The local-time distributions of FY-3D, FY-3E, and FY-3F correspond to their descending-node local times, while low-inclination FY-3G produces curved bands that supplement low-latitude sampling. Sentinel-6A exhibits a similar curved-band pattern. The near-polar GRACE-C/D configuration produces nearly meridional distributions near 01:30, 11:30, 13:30, and 23:30 local time. Too few KOMPSAT-5 events are available to identify a clear pattern. MetOp-B/A/C events cluster near 08:00–10:00 and 20:00–22:00, while TerraSAR-X/TanDEM-X and PAZ events cluster near 05:00–07:00 and 17:00–19:00, consistent with their approximately 06:00 descending-node local times. Spire events primarily occur near 10:00–12:00 and 22:00–24:00. PlanetiQ has many events concentrated near 08:00–12:00 and 20:00–24:00, although the cause of this pattern requires further investigation. TM-1 includes sun-synchronous satellites with different descending-node local times, providing observations throughout the day but retaining gaps associated with LEO-GNSS geometry. Many YY-1 sun-synchronous satellites have descending-node local times between 02:00 and 08:00, producing concentrated sampling, while YY-1 satellites 18–20 supplement low-latitude gaps. Overall, mission-specific orbital objectives and local-time configurations produce pronounced sampling biases, particularly because many near-sun-synchronous satellites are concentrated near 08:00–12:00 local time.



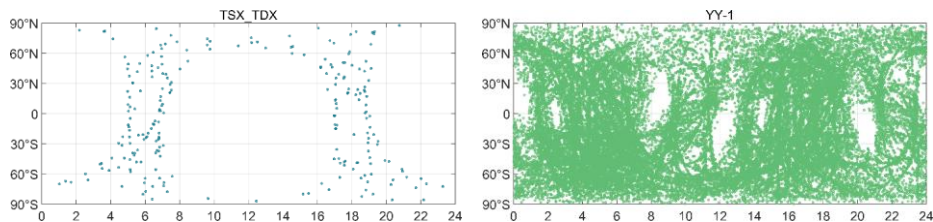
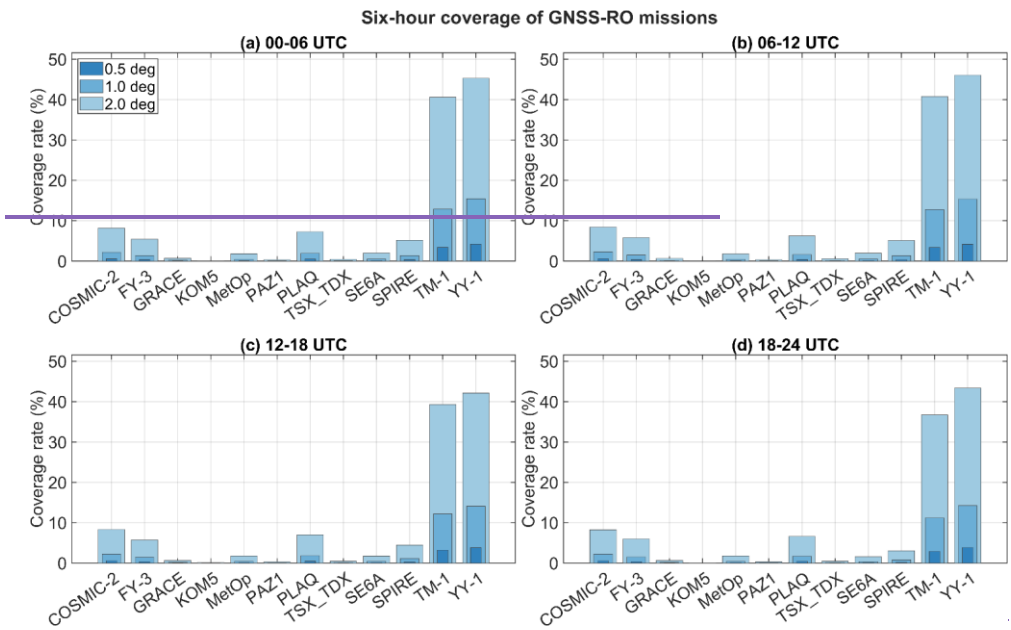


Figure 4. Local-time distributions of radio occultation events from individual missions on 1 January 2026.

3.5 Coverage within 6 h time windows

To assess coverage on the time scale commonly used for numerical weather prediction data assimilation, RO events on 1 January 2026 were divided into four 6 h UTC windows: 00:00–06:00, 06:00–12:00, 12:00–18:00, and 18:00–24:00. Global [area-weighted surface coverage](#) ~~grid coverage~~ was calculated for each window at spatial resolutions of 0.5°, 1.0°, and 2.0°. Compared with daily statistics, [the 6 h area-weighted coverage](#) more directly characterizes short-term spatial continuity within a typical assimilation window. The results are shown in Fig. 5. For this one-day sample, mission-averaged coverage was broadly similar among the four UTC windows, although the temporal variability differed among missions. At 2.0° resolution, the mean coverage across all missions was [9.82%, 10.73%, 10.35%, and 10.31%](#)~~8.88%, 9.71%, 9.29%, and 9.15%~~ in the four successive windows, with corresponding total event counts of 23,462, 25,911, 24,442, and 24,587. YY-1 and TM-1 retained the strongest global coverage at the 6 h scale. The mean YY-1 coverage fractions at 0.5°, 1.0°, and 2.0° were [4.31%, 15.68%, and 46.08%](#)~~3.85%, 14.06%, and 41.88%~~, respectively, compared with [3.49%, 12.99%, and 40.62%](#)~~3.25%, 12.12%, and 38.24%~~ for TM-1. YY-1 reached the highest 2.0° coverage in the 06:00–12:00 UTC window ([49.77%](#)~~45.87%~~), whereas TM-1 remained more temporally stable, with 2.0° coverage ranging only from [39.53% to 41.63%](#)~~37.40% to 39.35%~~. Thus, even within 6 h windows, large constellations maintained high global ~~grid coverage~~[area-weighted surface coverage](#) and were the principal contributors to short-term global observational continuity. COSMIC-2, PlanetiQ, Spire, and FY-3 provided moderate 6 h coverage. Their mean coverage fractions at 0.5°, 1.0°, and 2.0° were [0.79%, 3.10%, and 11.48%](#)~~0.54%, 2.11%, and 7.83%~~ for COSMIC-2; [0.50%, 1.98%, and 7.54%](#)~~0.45%, 1.78%, and 6.80%~~ for PlanetiQ; [0.47%, 1.82%, and 6.71%](#)~~0.43%, 1.70%, and 6.33%~~ for Spire; and [0.40%, 1.57%, and 6.09%](#)~~0.35%, 1.40%, and 5.44%~~ for FY-3. COSMIC-2 coverage increased from [10.00%](#)~~6.82%~~ in the first window to more than [12.3%](#)~~8.4%~~ in the last two windows at 2.0° resolution, whereas FY-3 was comparatively stable, with 2.0° coverage ranging from [5.56%](#)~~to 6.34%~~~~5.05%~~ [to 5.59%](#). Spire showed stronger window dependence, with 2.0° coverage decreasing from [8.15%](#)~~7.83%~~ in the first window to [4.80%](#)~~4.43%~~ in the final window. Although these missions provided less coverage than YY-1 and TM-1, they still supplied important complementary observations within 6 h assimilation windows. Single-satellite and small-constellation missions generally provided low coverage within 6 h windows. At 2.0° resolution, the mean coverage fractions for GRACE-C/D, KOMPSAT-5, PAZ, and TerraSAR-X/TanDEM-X were [0.68%, 0.12%, 0.24%, and 0.38%](#)~~0.62%, 0.11%, 0.22%, and 0.37%~~, respectively. MetOp-B/A/C

325 and Sentinel-6A achieved slightly higher mean coverage, but only 1.91% and 1.78%~~1.75% and 1.54%~~, respectively. These
326 missions may provide useful spatial samples on a daily scale, but they still leave pronounced global gaps when used alone
327 within a 6 h data-assimilation window. Overall, the results indicate that 6 h coverage was governed primarily by event
328 abundance and constellation size, while orbital configuration affected how efficiently those events translated into spatial
329 coverage. Across the analyzed windows and resolutions, the Pearson correlation between mission event count and coverage
330 ranged from 0.994 to 0.999~~0.996 to 1.000~~. Large constellations therefore had a clear advantage at the 6 h scale, whereas
331 individual satellites and small constellations provided limited stand-alone coverage. Because the analysis was based on only
332 four windows from a single day, these findings should be interpreted as descriptive evidence for 1 January 2026 rather than as
333 proof of general independence from the UTC window. Multi-mission observations remain essential for improving global
334 continuity and reducing spatial gaps in short-window applications such as numerical weather prediction data assimilation.



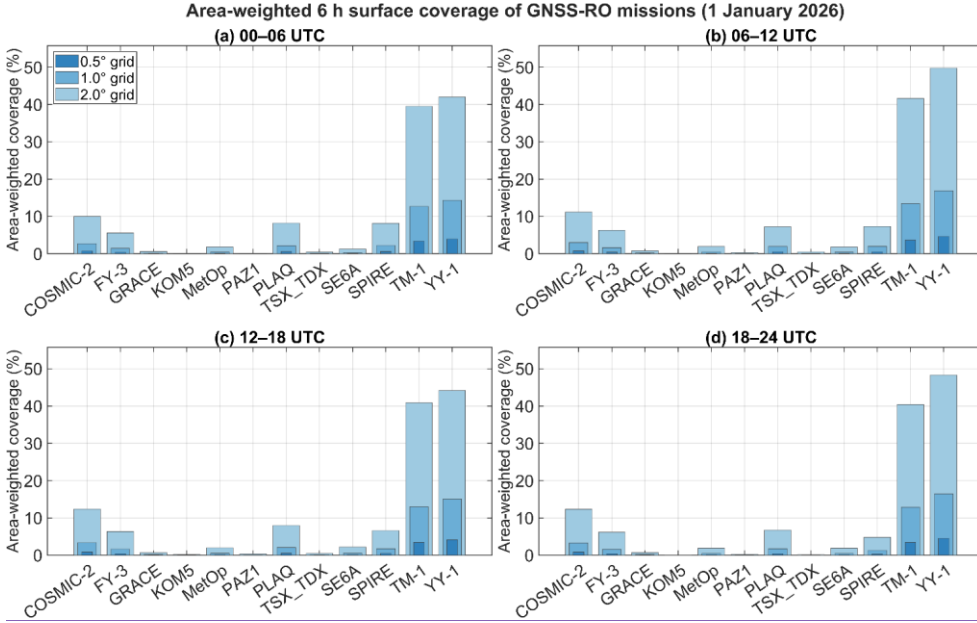


Figure 5. Area-weighted surface coverageCoverage of individual GNSS-RO missions within 6 h time windows on 1 January 2026.

4 Joint distribution characteristics of global GNSS-RO missions

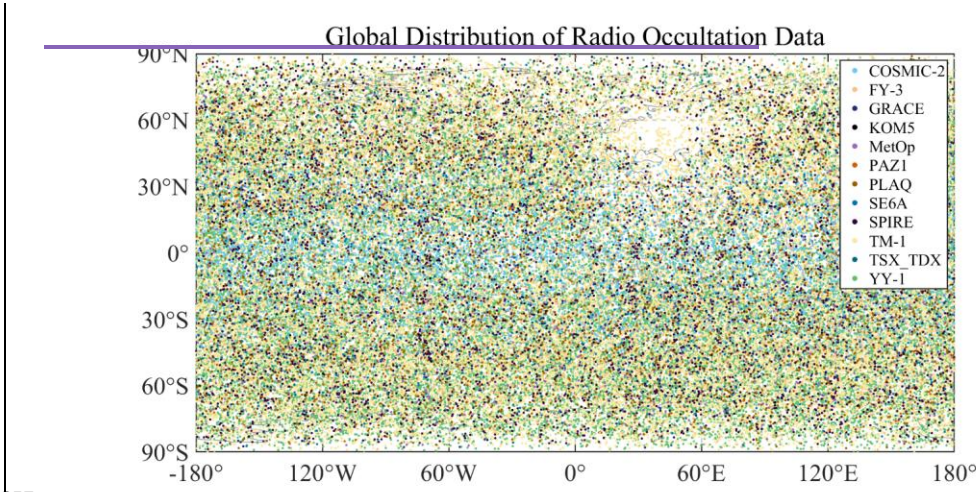
Observations from all missions analyzed in Sect. 3 were combined to evaluate the overall effects of multi-mission joint observations.

$$n_i^{joint}(r) = \sum_{k=1}^M n_{(i,k)}(r) \quad (56)$$

In Eq. (56), $n_{i,joint}(r)$ is the total number of RO events in the i th grid after combining missions at spatial resolution r , $n_{i,m}(r)$ is the number of events from mission m in the i th grid, and M is the number of missions included in the joint analysis.

343 **4.1 Joint global spatial distribution**

344 Figure 6 shows the enhanced spatial completeness achieved by combining observations from all missions on 1 January 2026.
345 The joint dataset contains 98,402 GNSS-RO events and provides substantially broader global sampling than any individual
346 mission. The complementarity is particularly evident at low latitudes and in polar regions. At low latitudes, observations from
347 the low-inclination FY-3G satellite and YY-1 satellites 18–20 complement the dense tropical sampling of COSMIC-2. Within
348 10° of the Equator, the combined dataset contains 10,979 events, accounting for 11.16% of the joint sample. Within 30°S–
349 30°N, COSMIC-2 contributes 4,565 events, while FY-3G and YY-1 satellites 18–20 contribute 471 and 1,826 events,
350 respectively, thereby strengthening the low-latitude observing capability. Polar sampling is also enhanced through the
351 complementarity of high-inclination and near-polar missions. A total of 21,762 events occur poleward of 60°, accounting for
352 22.12% of the joint sample, with YY-1, TM-1, PlanetiQ, Spire, FY-3, and other high-inclination missions jointly contributing
353 to high-latitude coverage. Overall, the combined dataset demonstrates clear latitudinal complementarity among missions:
354 COSMIC-2 and selected low-inclination satellites strengthen tropical coverage, whereas high-inclination and near-polar
355 missions improve sampling in polar regions. Localized data gaps near the Russia–Ukraine region are still visible in some
356 distributions and may be related to regional signal interference, quality-control screening, or data-reception limitations.



Global Distribution of Multi-Mission RO Events

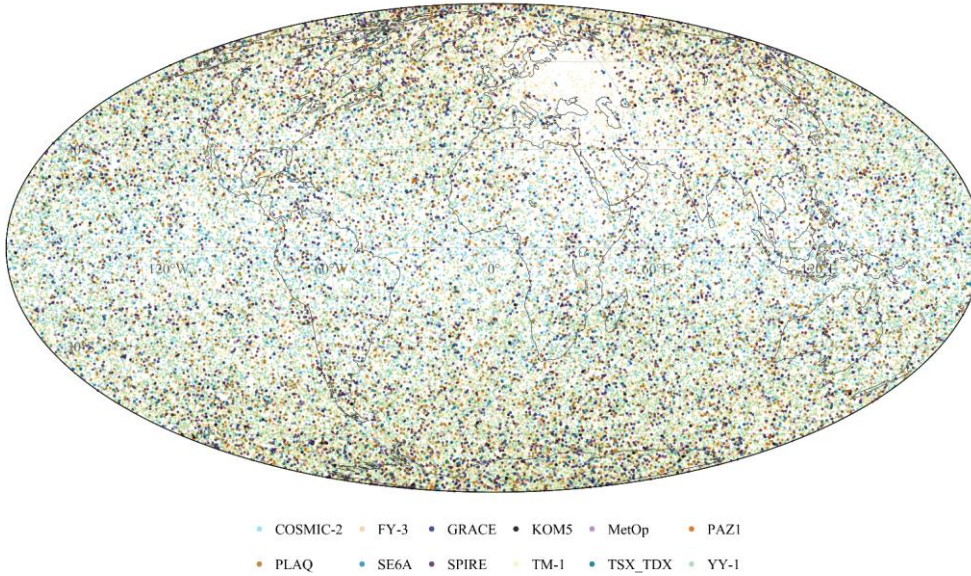


Figure 6. Global distribution of the combined radio occultation dataset on 1 January 2026.

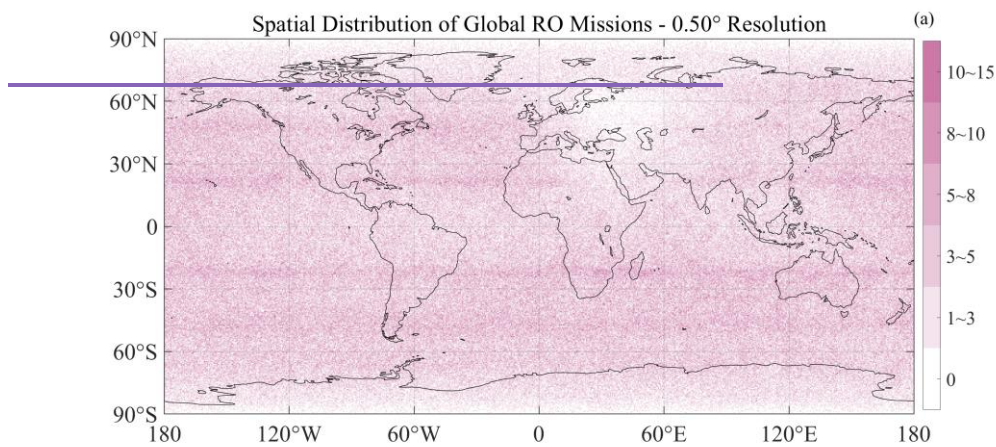
4.2 Joint global gridded distribution

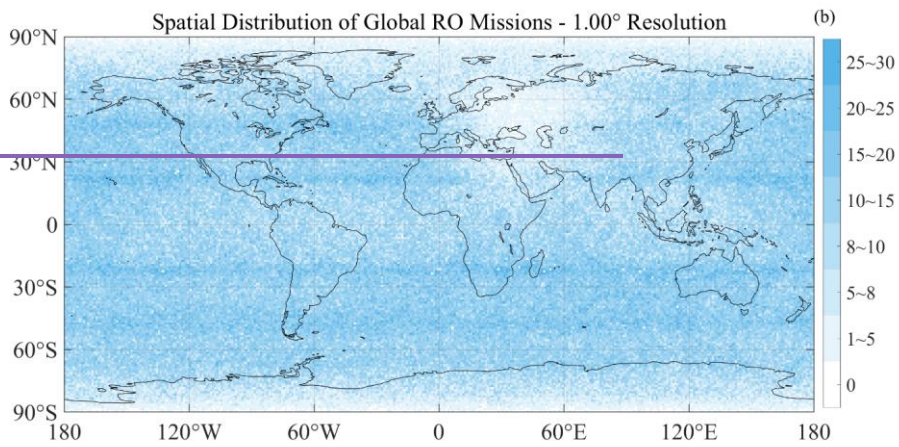
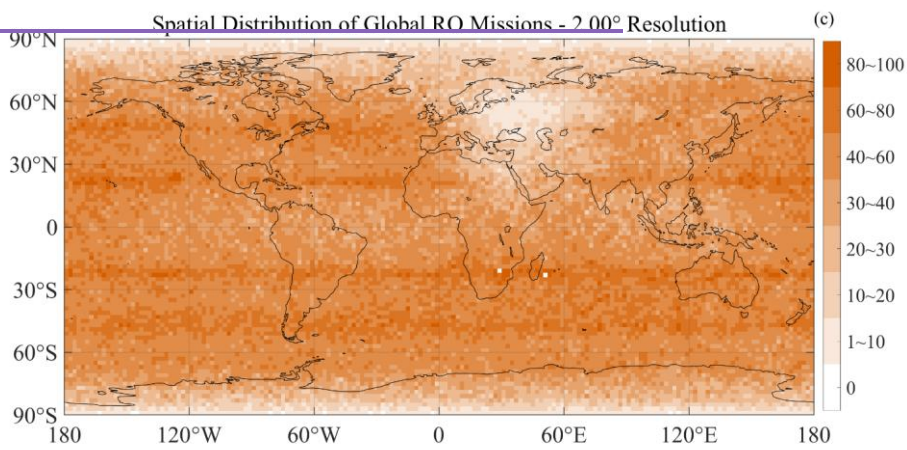
Figure 7 further illustrates the [event density](#) [event count per grid cell](#) and spatial continuity achieved by combining 679,854 RO events from all missions during 1–7 January 2026. At 0.5° resolution, 225,142 of the 259,200 global grids are occupied, corresponding to a [grid-cell occupancy fraction](#) [spatial coverage](#) of 86.86% and a blank-grid fraction of 13.14%; the [maximum density](#) [maximum event count in a grid cell](#) reaches 15 events per grid; [the corresponding area-weighted surface coverage is 92.08%, with an area-weighted blank fraction of 7.92%](#). Most occupied grids remain low to moderate in [density](#) [event-count](#), with 102,993 grids containing one to two events and 79,607 grids containing three to four events, whereas only 681 grids contain ten or more events. At 1.0° resolution, the blank-grid fraction decreases to 1.87%, [corresponding to a grid-cell occupancy fraction of 98.13% and an area-weighted surface coverage of 99.71 %](#) and the [maximum density](#) [maximum event count in a grid cell](#) increases to 38 events per grid. The largest [density class](#) [event-count class](#) is 10–14 events, comprising 22,559 grids, while 34 grids contain 30 or more events. At 2.0° resolution, the combined dataset provides nearly continuous global coverage, with 16,170 of 16,200 grids occupied, a blank-grid fraction of only 0.19%, [and an area-weighted surface](#)

372 coverage of 99.995% and a maximum density maximum event count in a grid cell of 113 events per grid. The dominant density
373 event-count class is 40–59 events, accounting for 7,205 grids, followed by 60–79 events in 2,294 grids; only three grids
374 contain 100 or more events. The heat-map distribution also exhibits clear zonal high-density event-count bands. Pronounced
375 dense regions appear near approximately 20°S and 20°N, while another relatively evident concentration occurs around 45°
376 latitude in both hemispheres. These banded structures indicate that, although multi-mission combination greatly improves
377 global spatial continuity, the final event-count event density pattern still reflects the combined influence of orbital inclination,
378 constellation geometry, and latitude-dependent sampling frequency.

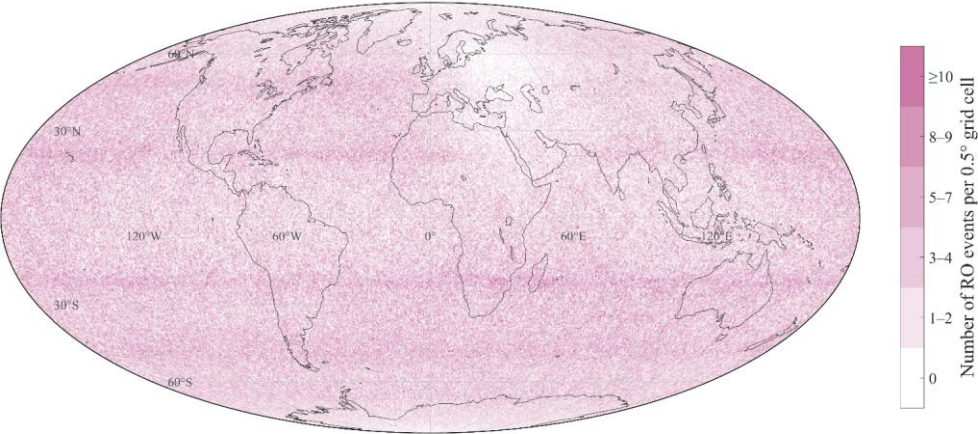
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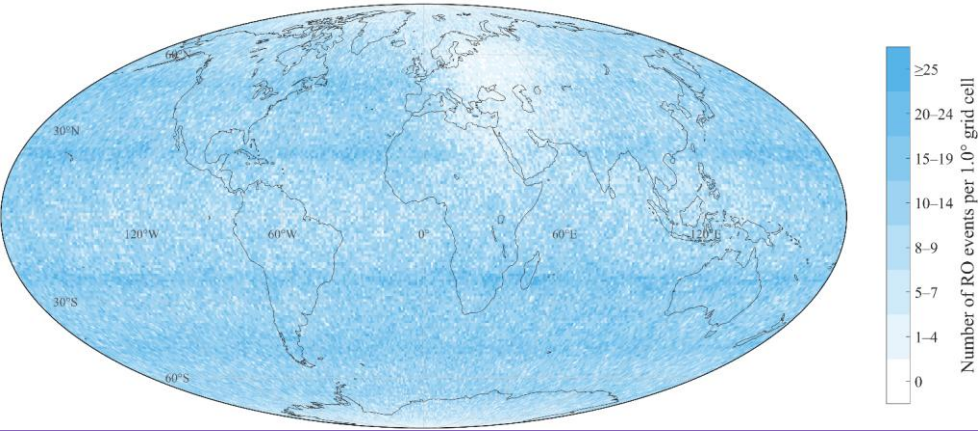




Global Multi-Mission RO Event Counts (0.5° Grid)



Global Multi-Mission RO Event Counts (1.0° Grid)



Global Multi-Mission RO Event Counts (2.0° Grid)

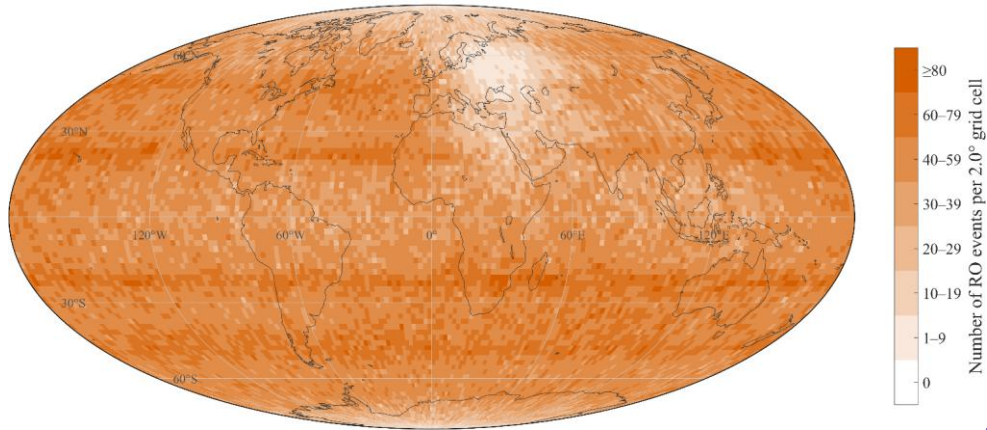


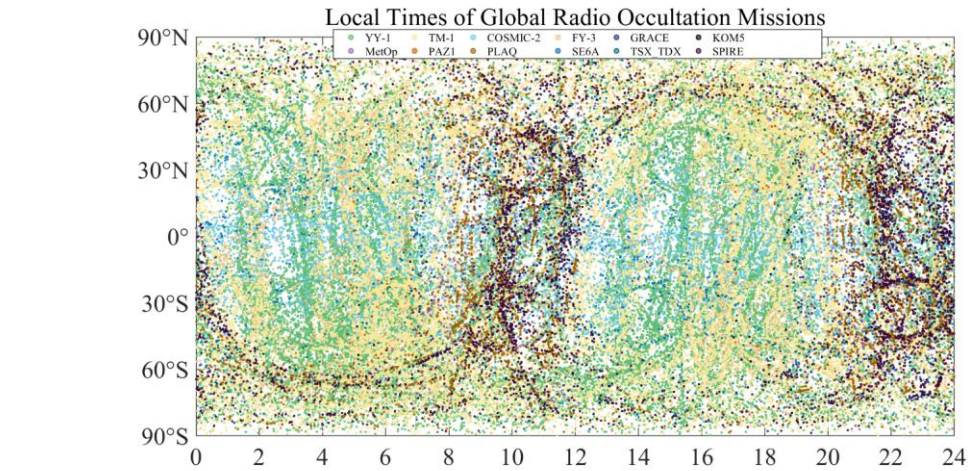
Figure 7. Gridded spatial distribution of the combined radio occultation dataset during 1–7 January 2026.

4.3 Joint global local-time distribution

Broad local-time coverage should not be interpreted as a requirement that every location be observed during every hour of a single day. Rather, it reduces dependence on mission-specific observation times and improves the representation of phenomena with diurnal variability. For NWP, observations distributed across successive local times provide sampling of an evolving atmospheric state within consecutive assimilation cycles. For climate applications, more stable local-time sampling reduces the risk that changes in the sampled portion of the diurnal cycle are aliased into long-term climate variations. For ionospheric and space-weather studies, local-time diversity is particularly important because electron density structures and equatorial irregularities can differ substantially between daytime, nighttime, and post-sunset conditions. Figure 8 shows that combining observations from multiple missions broadens and densifies the latitude–local-time distribution and reduces mission-specific sampling gaps on 1 January 2026. The joint dataset contains 98,402 RO events, of which YY-1 and TM-1 jointly contribute 76,897 events, accounting for 78.15% of the total. Owing to their large constellation sizes and relatively distributed local-time sampling geometry, YY-1 and TM-1 provide the main observational backbone for the combined dataset and substantially enhance global latitude–local-time continuity. FY-3 also contributes to a more balanced local-time distribution: the differing local-time designs of FY-3D, FY-3E, and FY-3F help spread observations across multiple time sectors, while the low-inclination FY-3G satellite provides additional sampling at low latitudes. COSMIC-2 and YY-1 satellites 18–20 further strengthen the low-latitude component of the combined distribution. Other missions exhibit more distinct mission-dependent local-time preferences. For example, near-polar or sun-synchronous missions such as PlanetiQ, Spire, MetOp, GRACE-C/D,

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404 KOMPSAT-5, PAZ, and TerraSAR-X/TanDEM-X tend to form localized or banded structures in specific morning, evening, or
405 nighttime local-time sectors, rather than providing uniformly distributed sampling on their own. Overall, the multi-mission
406 combination produces a more continuous local-time distribution than any single constellation or mission alone. Nevertheless,
407 the sampling remains nonuniform, with [event-densityevent count per grid cell](#) varying among latitude bands and local-time
408 sectors, reflecting the combined effects of constellation size, orbital configuration, and mission-specific sampling geometry.



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410 **Figure 8.** Local-time distribution of the combined radio occultation dataset on 1 January 2026.

411 **4.4 Joint coverage within 6 h time windows**

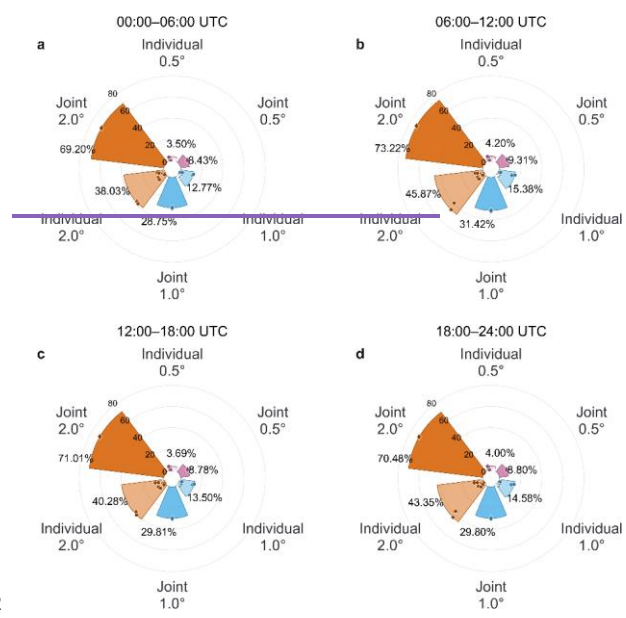
412 To assess joint coverage on the time scale commonly used for numerical weather prediction data assimilation, the multi-mission
413 analysis employed the same four 6 h UTC windows used in the individual-mission analysis. This consistent temporal
414 framework enables direct comparison between individual and combined RO observations within operationally relevant
415 assimilation windows.

416 **Table 2.** Mean 6 h [area-weighted global surface coverageglobal-grid-coverage \(%\)](#) of individual RO missions and the combined
417 dataset at three spatial resolutions

Mission	0.5°	1.0°	2.0°
Combined dataset	9.898.831	33.2629.944	76.8070.978
COSMIC-2	0.790.538	3.102.108	11.487.833

FY-3	<u>0.400.354</u>	<u>1.581.404</u>	<u>6.095.435</u>
GRACE-C/D	<u>0.040.039</u>	<u>0.170.155</u>	<u>0.680.619</u>
KOMPSAT-5	<u>0.010.007</u>	<u>0.030.028</u>	<u>0.120.113</u>
MetOp	<u>0.120.111</u>	<u>0.480.443</u>	<u>1.911.752</u>
PAZ	<u>0.020.014</u>	<u>0.060.054</u>	<u>0.240.216</u>
PlanetiQ	<u>0.500.448</u>	<u>1.981.776</u>	<u>7.546.802</u>
TerraSAR-	<u>0.020.023</u>	<u>0.090.092</u>	<u>0.380.367</u>
X/TanDEM-X			
Sentinel-6A	<u>0.110.097</u>	<u>0.450.387</u>	<u>1.781.535</u>
Spire	<u>0.470.434</u>	<u>1.821.703</u>	<u>6.716.326</u>
TM-1	<u>3.493.247</u>	<u>12.9912.121</u>	<u>40.6238.236</u>
YY-1	<u>4.313.848</u>	<u>15.6814.056</u>	<u>46.0841.883</u>

To quantify the improvement in 6 h coverage achieved through multi-mission integration, the combined dataset was compared with the individual RO missions. Coverage was calculated separately for each spatial resolution and 6 h window on 1 January 2026 and then averaged across the four windows.



Multi-mission complementarity in four 6 h windows

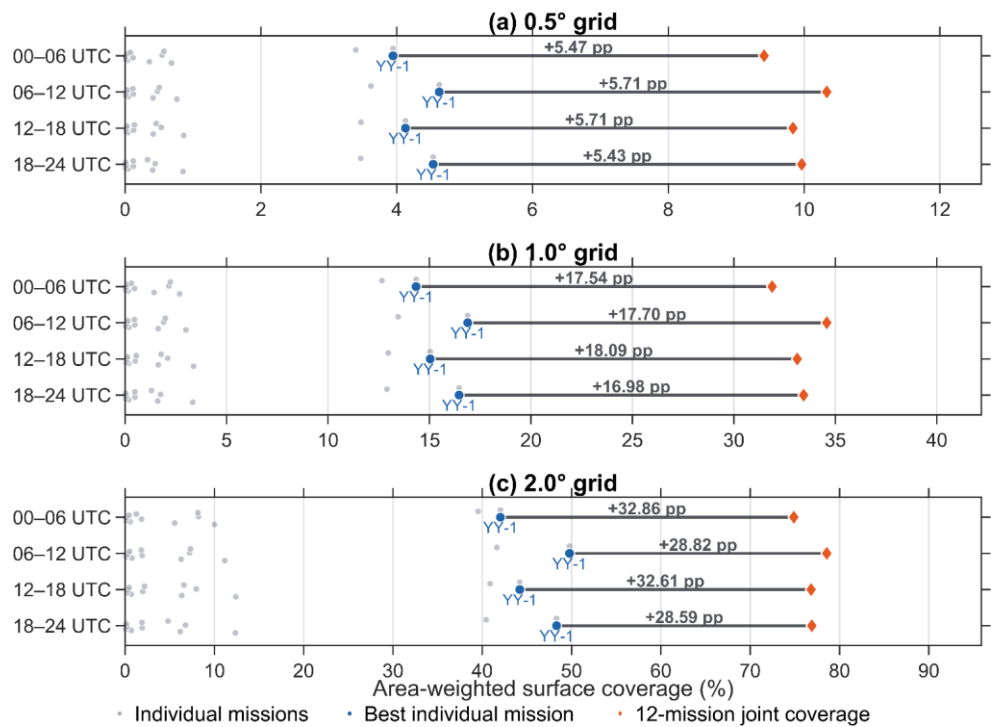


Figure 9. Global area-weighted surface coverage in four 6 h UTC windows on 1 January 2026

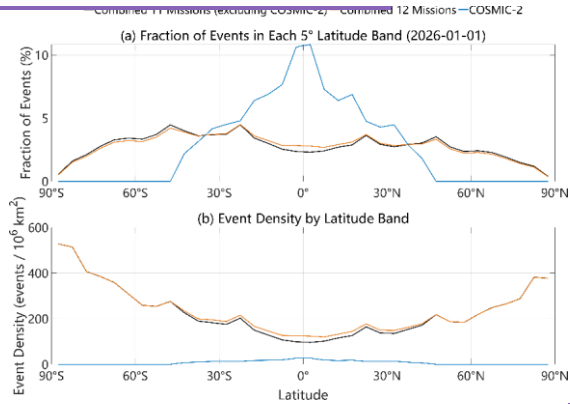
Figure 9 presents the results for individual windows, whereas Table 2 reports their four-window means. Averaged over the four windows, area-weighted joint coverage reaches 9.89%, 33.26%, and 76.79%~~joint coverage reaches 8.83, 29.94, and 70.98%~~ at 0.5°, 1.0°, and 2.0°, respectively. YY-1 remains the best-performing individual mission, with corresponding mean coverage fractions of 4.31%, 15.68%, and 46.08%~~3.85, 14.06, and 41.88%~~. Joint observations therefore provide absolute gains of 5.58, 17.58, and 30.72~~4.98, 15.89, and 29.10~~ percentage points relative to YY-1, equivalent to relative increases of 129.4%, 112.1%, and 66.7%~~129.5, 113.0, and 69.5%~~. Although the proportional improvement decreases as grid size increases, the absolute coverage gain becomes larger. These results demonstrate that complementary sampling among missions effectively fills additional spatial gaps and improves global observational continuity within 6 h data-assimilation windows.

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4.5 Sampling contribution of COSMIC-2 to the multi-mission observing systemPotential impact of COSMIC-2 retirement on joint GNSS-RO coverage

To quantify the sampling contribution of COSMIC-2 within the current multi-mission observing system, we conducted a diagnostic exclusion analysis by removing COSMIC-2 while retaining the other 11 mission systems. This analysis characterizes the sampling supplied by COSMIC-2 but does not constitute a forecast-impact or retirement-scenario experiment. Figure 10 shows the absolute and relative reductions in event counts by 5° latitude band after COSMIC-2 is excluded.To assess the potential impact of the planned retirement of COSMIC-2, the joint GNSS-RO dataset was re-evaluated after excluding COSMIC-2 and retaining the other 11 missions. Figure 10 compares the latitudinal distributions of the 11-mission dataset, the complete 12-mission dataset, and COSMIC-2 alone. The removal of COSMIC-2 has a distinctly latitude-dependent effect. Because COSMIC-2 is a low-inclination constellation, its contribution is concentrated in the tropical and subtropical regions, whereas the remaining missions largely preserve the mid- and high-latitude sampling structure. Within 5°S–5°N, the number of RO events decreases from 5,539 for the 12-mission dataset to 4,334 after removal of COSMIC-2, corresponding to a reduction of 1,205 events (21.75%). Thus, although the remaining 11 missions still provide extensive global sampling, the retirement of COSMIC-2 would noticeably weaken the latitudinal sampling densityevent-count near the Equator.

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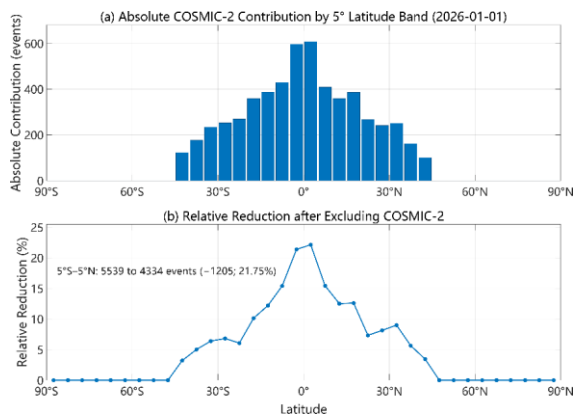
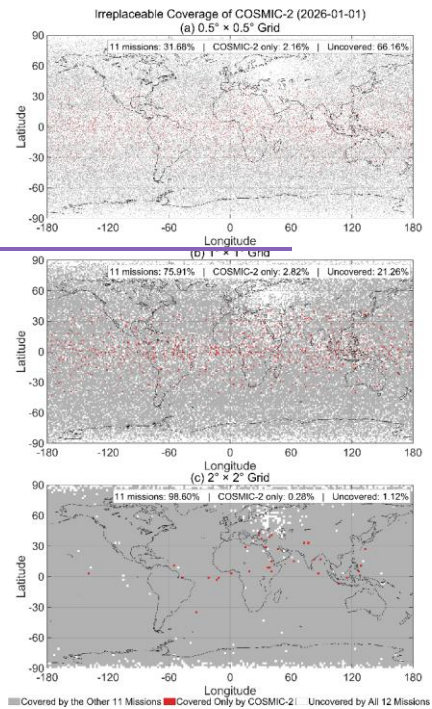


Figure 10. Sampling contribution of COSMIC-2 by 5° latitude band on 1 January 2026: (a) the absolute number of events removed when COSMIC-2 is excluded, $\Delta N = N_{12} - N_{11}$; and (b) the corresponding percentage reduction, $100\Delta N / N_{12}$. Latitudinal distributions of GNSS-RO events for the combined 11-mission dataset excluding COSMIC-2, the complete 12-mission dataset, and COSMIC-2 alone on 1 January 2026.

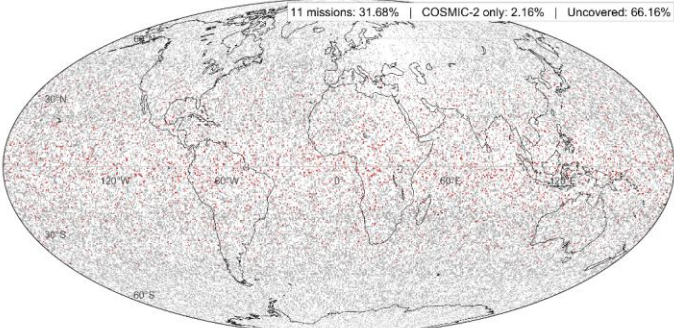
Figure 11 further illustrates the spatially irreplaceable contribution of COSMIC-2 at three grid resolutions: (a) $0.5^\circ \times 0.5^\circ$, (b) $1^\circ \times 1^\circ$, and (c) $2^\circ \times 2^\circ$. Gray grids are covered by the other 11 missions, red grids are covered only by COSMIC-2, and white grids are not covered by any of the 12 missions. At the finest 0.5° resolution, 3,797 grids, corresponding to an area-weighted 2.16% of the global area, are covered exclusively by COSMIC-2. These COSMIC-2-only grids are concentrated in the low- and middle-latitude belt, with a pronounced tropical contribution, confirming that the constellation provides coverage that cannot be fully replaced by the other missions at high spatial resolution. At 1° resolution, the COSMIC-2-only area-weighted surface-coverage fraction is 2.82% (1,233 grids), whereas at 2° resolution it decreases to an area-weighted surface-coverage fraction of 0.28% (31 grids) because the coarser grid aggregation merges many COSMIC-2 observations with coverage from the other missions. Overall, the multi-mission system remains highly resilient after excluding COSMIC-2, especially at coarse spatial scales; however, its retirement would lead to a measurable loss of independent high-resolution coverage and a clear reduction in equatorial RO sampling.

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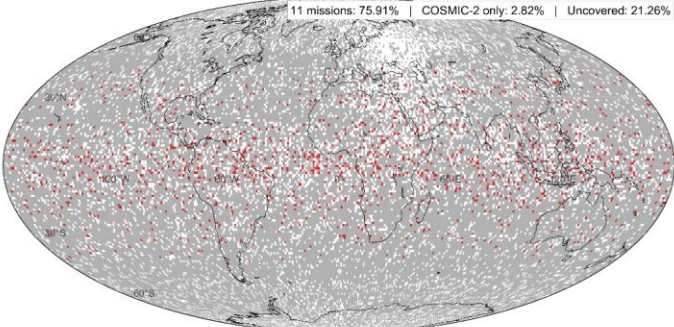
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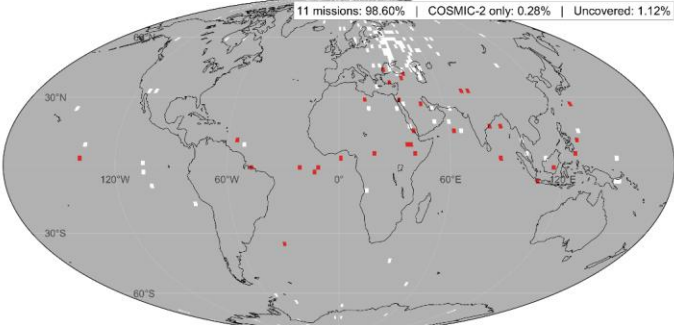
Irreplaceable coverage of COSMIC-2 (2026-01-01)
(a) $0.5^\circ \times 0.5^\circ$ grid



(b) $1^\circ \times 1^\circ$ grid



(c) $2^\circ \times 2^\circ$ grid



■ Covered by the other 11 missions ■ Covered only by COSMIC-2 ■ Uncovered by all 12 missions

Figure 11. Spatially irreplaceable coverage contribution of COSMIC-2 at 0.5°, 1°, and 2° grid resolutions on 1 January 2026.

5-Comparison of GNSS RO retrievals with ERA5

5.1 Method for comparison with ERA5

ERA5 reference neutral atmospheric refractivity was calculated from pressure, temperature, and specific humidity using the Smith–Weintraub equation (Smith and Weintraub, 1953):

$$N = 77.6 \frac{p}{T} + 3.73 \times 10^5 \frac{e}{T^2} \quad (6)$$

where N is the neutral atmospheric refractivity in N-units, p is the total atmospheric pressure in hPa, T is the absolute temperature in K, and e is the water-vapor partial pressure in hPa. Water-vapor pressure was calculated from ERA5 specific humidity q as follows:

$$e = \frac{qp}{0.622 + 0.378q} \quad (7)$$

After calculating ERA5 reference refractivity profiles, the forward modeling method implemented in the Radio Occultation Processing Package (ROPP) was followed. The profiles were vertically interpolated at high resolution, and the corresponding impact parameters and refractive index gradients were calculated. ERA5 reference bending angles were then obtained using an Abel integral and compared with RO Level 1b bending angle products. First, the ERA5 refractivity profiles were logarithmically interpolated in the vertical, and refractive index was calculated as follows:

$$n(r) = 1 + N(r) \times 10^{-6} \quad (8)$$

In Eq. (7), $n(r)$ is refractive index, $N(r)$ is atmospheric refractivity, and r is the radial distance from the center of the Earth. The corresponding impact parameter is defined as follows:

$$a = n(r)r \quad (9)$$

Under the assumption of spherical symmetry, bending angle is calculated from the radial gradient of refractive index using the Abel integral (Fjeldbo et al., 1971):

$$\alpha(a) = -2a \int_{r_{\text{tp}}}^{\infty} \frac{d \ln n(r)}{dr} \frac{dr}{\sqrt{n^2(r)r^2 - a^2}} \quad (10)$$

In Eq. (10), $\alpha(a)$ is the bending angle associated with impact parameter a , and r_{tp} is the corresponding tangent-point radius. Relative error and root mean square error (RMSE) were used to quantify bending angle and refractivity retrieval errors. Relative error is defined as follows:

$$\delta X(z) = \frac{X_{\text{RO}}(z) - X_{\text{ERA5}}(z)}{X_{\text{ERA5}}(z)} \times 100\% \quad (11)$$

In Eq. (11), x represents bending angle or refractivity and z is geometric height.

To characterize systematic differences between each mission and the ERA5 reference, the mean bias was calculated at each geometric height level as follows:

$$Bias(z) = \frac{1}{N_z} \sum_{t=1}^{N_z} [\delta X_t(z)] \quad (12)$$

The overall error magnitude was additionally evaluated using RMSE:

$$RMSE(z) = \sqrt{\frac{1}{N_z} \sum_{t=1}^{N_z} [\delta X_t(z)]^2} \quad (13)$$

In Eq. (13), N_z is the number of samples included at height z .

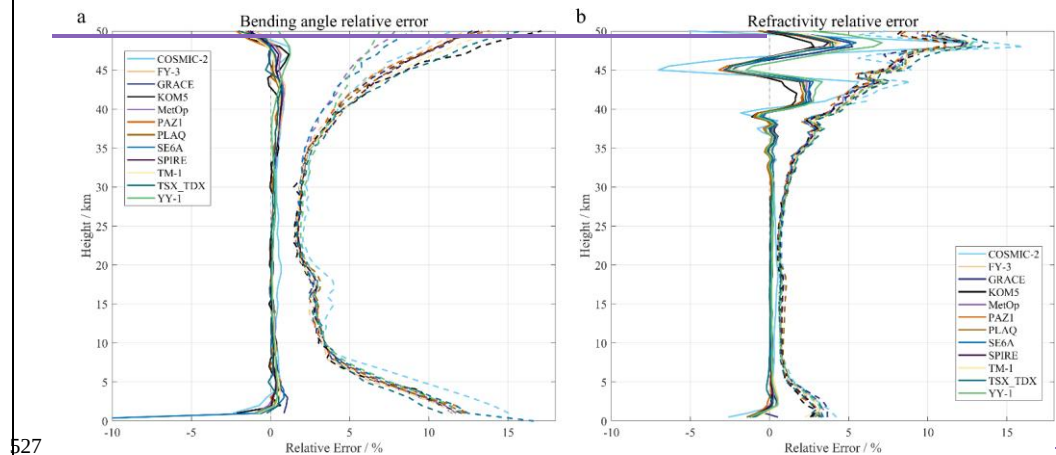
5.2 ERA5-based bending-angle and refractivity error analysis

Following the method described in Sect. 5.1, vertical profiles of bending-angle and refractivity errors relative to ERA5 were calculated for each mission (Fig. 12a):

Bending-angle errors propagate into the subsequent Abel inversion and are particularly sensitive to receiver tracking quality, orbit and clock corrections, residual ionospheric correction, and horizontal gradients in the lower atmosphere. Figure 12a shows distinct vertical error structures among the missions. Above approximately 47 km, all missions exhibit negative biases of varying magnitude. This common high-altitude tendency may arise because neutral-atmospheric bending becomes very small with increasing altitude, making relative error statistics increasingly sensitive to measurement noise, residual ionospheric effects, and orbit and clock correction errors. COSMIC-2 exhibits a pronounced positive bias in the middle atmosphere, with the most prominent feature occurring near 20 km. Its RMSE between 10 and 30 km is substantially larger than that of the other missions. Below 10 km, the RMSE increases progressively toward the surface and remains considerably larger than that of the other missions. These features may be related to the low-inclination orbit and predominantly tropical sampling of COSMIC-2. Strong horizontal inhomogeneity, high water-vapor content, and steep vertical moisture gradients in the tropics increase the likelihood of super refraction, multipath propagation, and unstable signal tracking. Sentinel-6A reaches its maximum positive bias at approximately 3–4 km. GRACE C/D maintains a positive bias throughout the lower atmosphere. The pronounced bending-angle error of Sentinel-6A at the lowest level may be attributed to the limited number of valid profiles, resulting in considerable statistical uncertainty. Owing to their relatively small sample sizes, the bending-angle error profiles of KOMPSAT-5, PAZ and TerraSAR-X/TanDEM-X are less smooth and subject to greater statistical uncertainty. For most other missions, mean biases in the middle and upper atmosphere remain close to zero, and RMSE varies relatively smoothly with height. In the lower troposphere, the missions exhibit negative biases of varying magnitudes because of strong moisture gradients, super refraction, multipath propagation, and other complexities in the near-surface propagation environment.

Figure 12b shows the refractivity retrieval errors for the same period. Between 5 and 35 km, mean refractivity biases are generally below 1% and centered near zero, indicating stable retrievals for most missions. COSMIC-2 exhibits a small positive

514 bias between 10 and 30 km, consistent with its bending-angle error characteristics. Apart from COSMIC-2, the retrieval
 515 accuracy of the different missions is broadly consistent between 10 and 35 km. Inter-mission differences become more
 516 pronounced in the lower troposphere, particularly below 5 km. PAZ develops a negative bias at a higher altitude than the other
 517 missions, possibly because its dual-polarization RO mode tracks only setting occultations. Below 10 km, TerraSAR-
 518 X/TanDEM-X exhibits a vertical error structure distinct from those of the other missions: a negative bias first appears at
 519 approximately 3–5 km, followed by a positive bias near 2.5 km, which subsequently shifts back to a negative bias toward the
 520 surface. Most other missions show a positive bias followed by a negative bias toward the surface, reflecting the combined
 521 effects of complex near-surface moisture structures, multipath propagation, and signal truncation. GRACE-C/D shows a small
 522 positive bias at the lowest level, although the underlying cause remains unclear. Above 35 km, all missions exhibit a broadly
 523 consistent vertical variation in refractivity bias, while COSMIC-2 has the largest overall bias magnitude. This common upper-
 524 level behavior may reflect the propagation of bending-angle biases into the refractivity retrievals, as well as errors associated
 525 with upper-level reference fields or retrieval initialization. Differences in sampling and atmospheric representativeness among
 526 orbital configurations may further modulate the magnitude of these biases.



528 **Figure 12.** Vertical profiles of mean relative bias (solid lines) and relative root mean square error (dashed lines) for (a) bending angle
 529 and (b) refractivity from individual GNSS-RO missions relative to ERA5.

530 **56 Conclusions and outlook**

531 This study compared the spatial distributions, grid coverage, local-time sampling and 6 h coverage and retrieval
 532 characteristics of 12 GNSS-RO mission systems using observations collected during 1–7 January 2026. The results

demonstrate that constellation size, event abundance, and orbital configuration jointly determine the observational capabilities of individual missions. Large constellations provide the strongest global spatial continuity, low-inclination missions enhance tropical and subtropical sampling, and high-inclination and near-polar missions provide complementary observations at middle and high latitudes. Consequently, no single mission can reproduce the spatial and temporal sampling characteristics of the complete multi-mission observing system.

On 1 January 2026, the combined dataset contained 98,402 RO events, of which YY-1 and TM-1 contributed 78.15%. Their large observation volumes formed the backbone of the global distribution, while COSMIC-2, FY-3G, and the low-inclination YY-1 satellites strengthened tropical sampling. Over the full seven-day period, the combined dataset comprised 679,854 events. Its global [grid-cell occupancy fraction](#)~~grid coverage~~ reached 86.86%, 98.13%, and 99.81% at resolutions of 0.5°, 1.0°, and 2.0°, respectively, [while the corresponding area-weighted global surface-coverage fractions reached 92.08%, 99.71%, and 99.995%](#). Although the integrated dataset provided nearly continuous global coverage at the two coarser resolutions, its ~~event density~~[event count per grid cell](#) remained spatially nonuniform, with pronounced zonal structures associated with orbital inclination, constellation geometry, and latitude-dependent sampling frequency.

At the 6 h scale relevant to numerical weather prediction data assimilation, event abundance was strongly correlated with grid coverage. Multi-mission integration substantially improved short-window spatial continuity, achieving [76.79% mean area-weighted surface coverage](#)~~70.98% coverage~~ at 2.0° resolution compared with [46.08%](#)~~41.88%~~ for YY-1, the best-performing individual mission. The combined observations also broadened sampling across the 24 h local-time cycle and reduced gaps among latitude bands, demonstrating the benefits of complementary orbital configurations. [These improvements indicate greater observational availability and sampling representativeness for downstream applications. However, their effects on NWP forecast skill, climate-record uncertainty, and space-weather prediction were not directly evaluated in this study and require application-specific experiments.](#)

~~Comparisons with ERA5 indicate that both bending-angle and refractivity retrievals from most missions show broadly consistent performance in the middle and upper atmosphere. For bending angle, mean relative biases for most missions remain close to zero at middle and upper levels, although a common negative tendency appears above approximately 47 km, where the weak neutral-atmospheric signal increases the sensitivity of relative errors to measurement noise and residual retrieval errors. COSMIC-2 exhibits a pronounced positive bias near 20 km and larger RMSE values between 10 and 30 km, while its errors increase markedly toward the surface. These features are likely associated with its predominantly tropical sampling, where strong moisture gradients, super-refraction, multipath propagation, and unstable tracking conditions are more common. Refractivity retrievals are broadly consistent between 10 and 35 km, with mean biases generally below 1%, whereas larger inter-mission differences occur in the lower troposphere and at upper levels. Missions with relatively few valid profiles also exhibit greater statistical uncertainty. Multi-mission applications should therefore consider both sampling complementarity and mission-specific retrieval accuracy when developing quality control and observation-weighting strategies.~~

565 Because the present analysis covers only seven days and the 6 h assessment is based on four windows from a single day, the
566 results represent a short-term observational snapshot. Future work should extend the analysis to longer periods, quantify
567 seasonal and regional variability, and evaluate optimized mission combinations in numerical weather prediction and climate
568 applications. [Future work will extend the analysis to longer periods and different seasons and regions. Subject to data](#)
569 [availability and experimental resources, we also plan to evaluate the application-level consequences of changes in COSMIC-](#)
570 [2 sampling through dedicated data-assimilation or data-denial experiments for NWP, longer-term sampling-error analyses for](#)
571 [climate applications, and targeted assessments of ionospheric and space-weather products.](#)
572

573 **Code and data availability**

574 The data and code supporting the findings of this study are available from the corresponding authors upon
575 reasonable request. Access to the original data is subject to the data-sharing policies of the Information Center.

576 **Author contributions**

577 LWQ and CR contributed equally to the conceptualization, methodology, formal analysis, visualization, and
578 preparation of the original draft. XN and MXG contributed to the conceptualization, supervision, and project
579 administration. LM and LY contributed to data curation and validation. YGL, HXQ, ZXG, and SYQ contributed to
580 the interpretation of the results and the review and editing of the manuscript. All authors discussed the results and
581 approved the final manuscript.

582 **Competing interests**

583 The authors declare that they have no conflict of interest.

584 **Disclaimer**

585 [].

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