

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. 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% at 2.0° resolution. Multi-mission integration also broadens local-time 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.

28 **1 Introduction**

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

36 GNSS-RO originated with the GPS/MET demonstration mission in the late twentieth century. During its operation, GPS/MET
37 acquired extensive observations and successfully retrieved neutral-atmosphere profiles from 0 to 60 km, demonstrating the
38 feasibility of GNSS-RO atmospheric sounding (Rocken et al., 1997). Subsequent single-satellite missions, including CHAMP
39 (Wickert et al., 2001) and GRACE (Beyerle et al., 2005), advanced RO data processing, retrieval algorithms, and applications.
40 The six-satellite COSMIC-1 constellation, launched in 2006, enabled the first large-scale operational use of GNSS-RO
41 observations and substantially increased the number of global RO profiles, marking an important transition from technology
42 demonstration to operational application (Anthes et al., 2008). Later missions, including the MetOp series (Bonnedal et al.,
43 2010), the FY-3 series (Bai et al., 2014), COSMIC-2 (Schreiner et al., 2020), and Sentinel-6/Jason-CS (Donlon et al., 2021),
44 have provided stable observations and broadened the use of GNSS-RO in numerical weather prediction, climate monitoring,
45 and space-weather research. More recently, low-Earth-orbit small-satellite constellations and commercial missions such as
46 GeoOptics/CICERO, Spire, PlanetiQ, TM-1, and YY-1 have further increased the number and spatial sampling event-count of
47 RO events, creating a multi-source observing system that combines demonstration missions, operational meteorological
48 satellites, and commercial constellations.

49 Advances in low-Earth-orbit platforms, spaceborne GNSS receivers, and RO retrieval techniques have transformed GNSS-RO
50 from a small number of demonstration missions into a global system of concurrent missions and constellations. Differences in
51 orbital altitude, inclination, local-time configuration, constellation size, and received signal systems produce distinct global
52 distributions, latitudinal coverage patterns, local-time sampling, and observation densities. Low-inclination missions generally
53 enhance sampling at low and middle latitudes, high-inclination or near-polar missions improve middle- and high-latitude
54 coverage, and large or commercial constellations improve global coverage continuity through higher observation frequencies.
55 For global atmospheric monitoring and data assimilation, the value of RO data depends not only on the retrieval accuracy of
56 individual profiles but also on the spatiotemporal distribution of the observations. Insufficient sampling within particular
57 latitude bands, local-time intervals, or spatial grids can reduce the representativeness of a mission for weather systems, climate
58 background states, and regional atmospheric structures. Compared with a single mission, joint multi-mission observations
59 exploit complementary orbital configurations to reduce spatial gaps, improve uneven local-time sampling, and increase the

continuity and stability of global RO observations. A systematic assessment of individual and combined missions in terms of spatial coverage, grid density, and local-time distribution is therefore important.

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

For climate applications, stable sampling across latitude and local time is important because incomplete sampling of atmospheric variability, including the diurnal and semidiurnal cycles, can introduce sampling errors into gridded climate records. Changes in the composition and orbital configuration of the RO observing system may also introduce time-dependent sampling differences if they are not properly accounted for (Gleisner et al., 2020). For ionospheric and space-weather applications, electron density and ionospheric irregularities exhibit pronounced dependence on geomagnetic latitude and local time, particularly in the equatorial ionosphere after sunset (Hocke et al., 2002). Multi-mission integration is therefore valuable because complementary orbital configurations reduce spatial and local-time gaps. Nevertheless, the coverage metrics analyzed here describe observational availability and sampling representativeness rather than direct changes in forecast skill, climate-record uncertainty, or space-weather prediction performance. This study examines major global GNSS-RO missions, including 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. Using RO observations during 1–7 January 2026, we analyze their global spatial distributions, grid-based coverage characteristics, and local-time sampling patterns, and evaluate the improvement in global coverage obtained through multi-mission combinations.

2 Missions and data

2.1 GNSS-RO missions

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

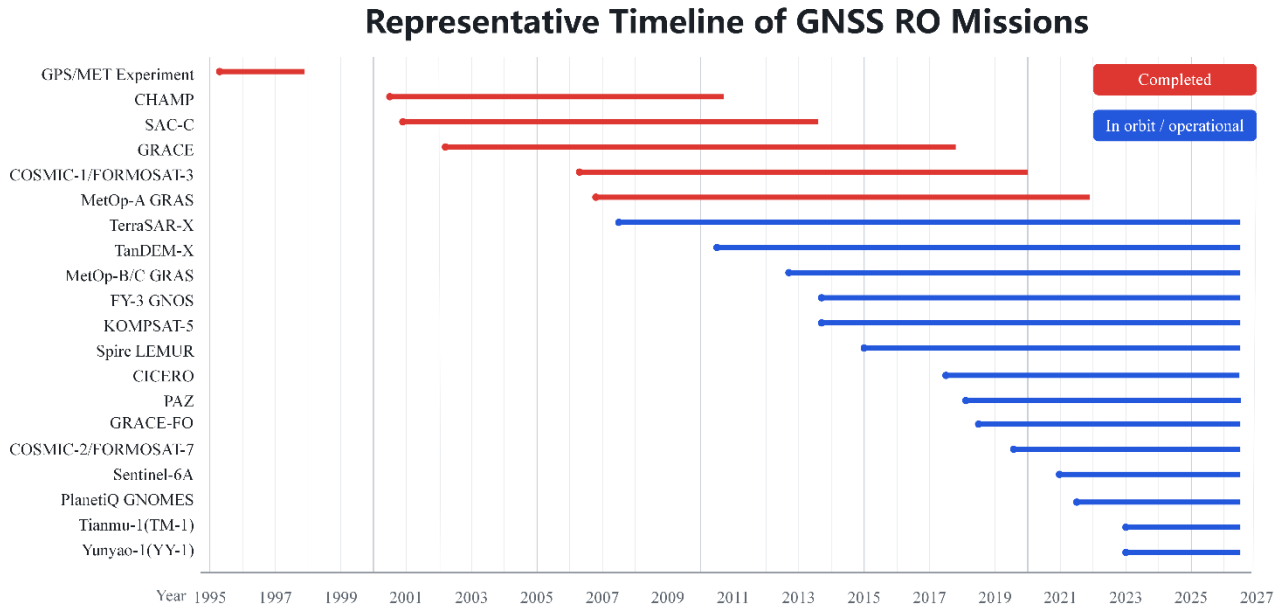


Figure 1. Development timeline of representative GNSS radio occultation missions.

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). 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 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(Zhang et al., 2022), 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.

The twin-satellite GRACE mission was launched in 2002 primarily to observe the Earth's gravity field and also carried GNSS receivers for RO observations. The satellites operated in near-polar orbits at approximately 500 km and an inclination of

approximately 89 degrees. GRACE RO data contributed to early studies of atmospheric structure and retrieval algorithms (Beyerle et al., 2005). The GRACE Follow-On (GRACE-FO; GRACE-C/D) twin-satellite mission continues the gravity-mapping mission of the original GRACE satellites (Kornfeld et al., 2019). Rising RO observations from GF1 and setting RO observations from GF2 have been continuously available since March 2020 and September 2021, respectively (Schmidt et al., 2020; Schmidt et al., 2022). The two-satellite system provides approximately 400 atmospheric profiles per day for climate applications and assimilation into numerical weather prediction models (Schmidt et al., 2022).

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

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

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

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

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

136 Sentinel-6A is a joint European-US operational altimetry satellite launched in 2020 and equipped with a GNSS-RO receiver.
 137 Its non-sun-synchronous orbit has an inclination of approximately 66 degrees and provides complementary observations at
 138 low and middle latitudes (Paoletta et al., 2025).
 139 Spire Global operates a commercial constellation that collects GNSS-RO and GNSS reflectometry data using numerous
 140 LEMUR nanosatellites. More than one hundred satellites have been launched, forming one of the world's largest commercial
 141 GNSS-RO constellations. The satellites occupy multiple low-Earth-orbit planes, including several sun-synchronous planes, at
 142 altitudes of approximately 385-650 km. Orbital inclination and local solar time vary among launch batches (Masters et al.,
 143 2020).
 144 TerraSAR-X and TanDEM-X are German twin SAR missions that also support GNSS-RO and precise orbit determination.
 145 They operate in near-polar, sun-synchronous orbits with an inclination of approximately 97.44 degrees and a designed
 146 descending-node local time of 06:00 (Faller et al., 2007).
 147 Tianmu-1 (TM-1) is China's first commercial GNSS-RO meteorological constellation. It comprises multiple networked small
 148 satellites in low-Earth orbit at approximately 520 km and an inclination near 97 degrees. The receivers support GPS, BDS,
 149 Galileo, and GLONASS signals, substantially increasing global RO observation density (Li et al., 2025).
 150 Yunyao-1 (YY-1) is an important component of China's new generation of commercial GNSS-RO constellations. The planned
 151 system comprises 90 satellites equipped with GNSS-RO instruments by the end of 2026 (Fu and Li, 2021). Its design combines
 152 12 high-inclination orbital planes with six satellites per plane and six low-inclination planes with three satellites per plane. The
 153 constellation includes quasi-sun-synchronous orbits near 97 degrees and low-inclination orbits near 50 degrees at an altitude
 154 of approximately 500 km. This combination of orbital configurations further enhances coverage (Xu et al., 2025).
 155 To keep figure legends concise and clear, standardized abbreviations are used for several missions. Table 1 lists the full mission
 156 names and abbreviations used in this study.

157 **Table 1. Names and abbreviations of the 12 GNSS-RO mission systems included in the quantitative analysis.**

RO Constellation	RO Acronym	Specific Satellite (Data Directory)	RO Constellation	RO Acronym	Specific Satellite (Data Directory)
COSMIC-2	COSMIC-2	C2E1, C2E2, C2E4, C2E5, C2E6	FengYun-3	FY-3	FY3D,FY3E, FY3F, FY3G
,GRACE-C/D	GRACE	GRACE-C,GRACE-D	KOMPSAT-5	KOM5	KOM5
MetOp	MetOp	MetOp01, MetOp03	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	Yun Yao-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 Yun Yao 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.

3 Global distribution characteristics of individual missions

3.1 Coverage metrics and statistical methods

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

Because regular latitude–longitude cells decrease in physical area toward the poles, we distinguish between the grid-cell occupancy fraction and the area-weighted surface-coverage fraction. The grid-cell occupancy fraction is defined as

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

where N_r is the total number of latitude–longitude cells at resolution r , and I is the indicator function. This metric describes the fraction of grid cells containing at least one observation, but it does not account for the variation in physical cell area with latitude.

The area-weighted surface-coverage fraction is therefore defined as

$$C_A(r) = \frac{\sum_{i=1}^{N_r} A_i I[n_i(r) \geq 1]}{\sum_{i=1}^{N_r} A_i} \times 100\% \quad (2)$$

where A_i is the physical area of cell i . For a regular latitude–longitude grid,

$$A_i = R_E^2 \Delta\lambda (\sin \phi_{i,N} - \sin \phi_{i,S}) \quad (3)$$

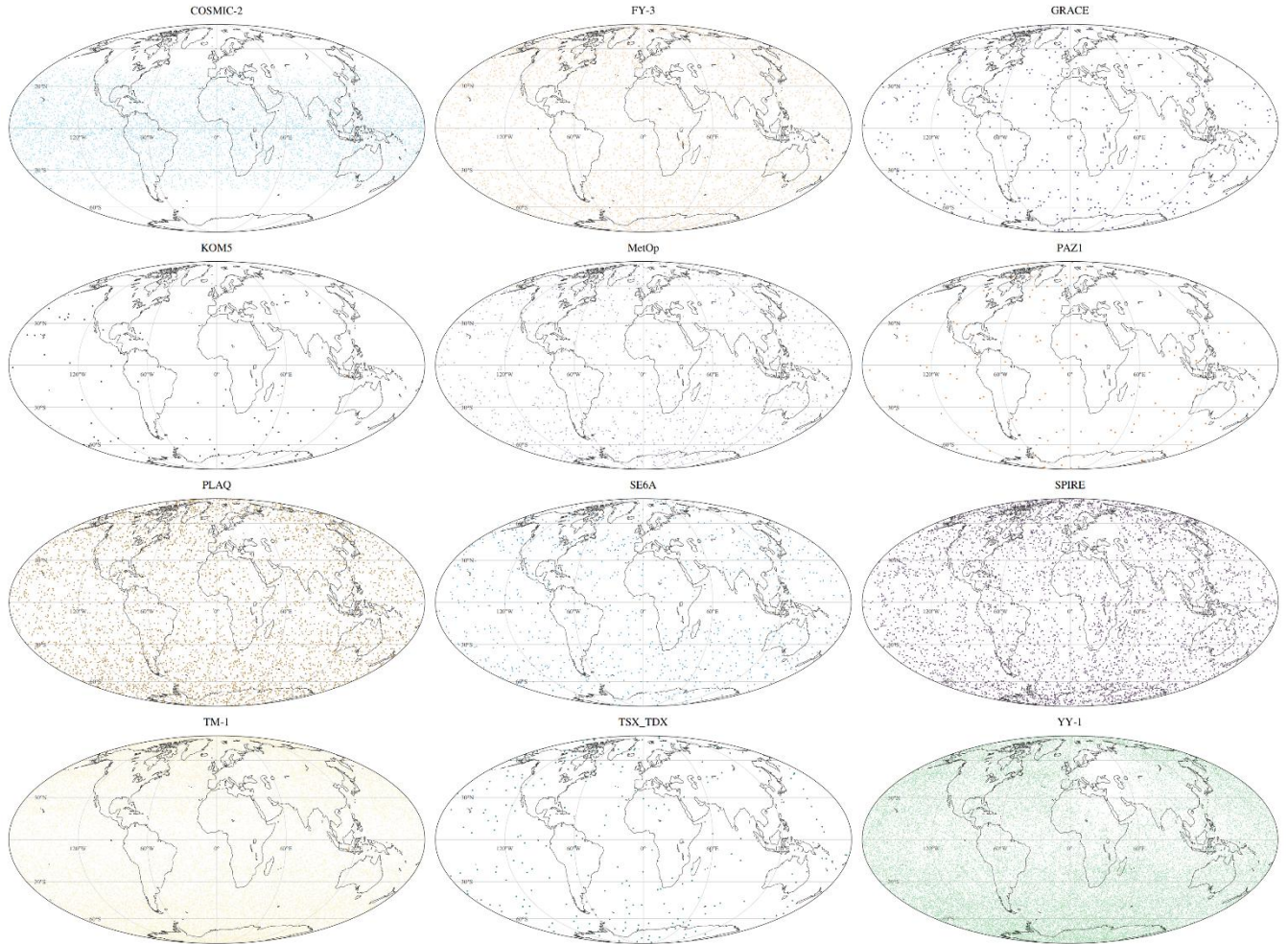
where R_E is the mean Earth radius, $\Delta\lambda$ is the longitudinal width of the cell in radians, and $\phi_{i,N}$ and $\phi_{i,S}$ are its northern and southern latitude boundaries. The corresponding area-weighted blank fraction is

$$B_A(r) = 100\% - C_A(r) \quad (4)$$

3.2 Global spatial distributions

GNSS-RO events occur at the tangent points of signal paths between GNSS transmitters and receivers aboard low-Earth-orbit satellites. Figure 2 presents the global distributions of GNSS-RO events 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 on 1 January 2026. During this one-day period, YY-1 produced the largest number of events (42,391), followed by TM-1 (34,506), reflecting their comparatively large constellation sizes; the analysis included 33 YY-1 satellites and 22 TM-1 satellites. COSMIC-2 recorded the third-largest total (5,613), followed by PlanetiQ (4,658), Spire (4,523), and FY-3 (3,699). The low-inclination FY-3G satellite and YY-1 satellites 18–20 provided valuable supplementary observations at low latitudes, with FY-3G contributing 471 events and YY-1 satellites 18–20 contributing 1,826 events within 30° S–30° N. Owing to its near-circular low-inclination orbit configuration, COSMIC-2 provided dense and nearly symmetric tropical coverage, with 2,295 and 2,270 events occurring within 30°S–0° and 0°–30°N, respectively. PlanetiQ and Spire produced broad latitudinal coverage, with moderately enhanced sampling in the middle-latitude bands. MetOp-B/C and Sentinel-6A produced 1,153 and 1,007 events, respectively, whereas GRACE-C/D, TerraSAR-X/TanDEM-X, and PAZ produced 401, 238, and 140 events, resulting in less distinct spatial patterns. KOMPSAT-5 produced the fewest events (73), resulting in a distribution too sparse to support the identification of a robust spatial pattern. Localized data gaps apparent in some mission distributions, particularly over the Russia-Ukraine region, may partly reflect regional GNSS interference. Using normalized RO signal-to-noise ratios at deeply occulted heights ($H_{SL} <$

201 140km), Wu (2024) identified enhanced jamming signatures over the Mediterranean, Eastern Europe, and the Middle East,
 202 with the enhancement extending toward Russia in 2022 and interpreted as likely related to the Russo-Ukrainian War. However,
 203 Wu detected jamming signatures rather than directly demonstrating a reduction in the number of retrieved atmospheric RO
 204 profiles. The gaps identified here may also result from quality-control screening, data transmission, or data-access limitations;
 205 therefore, their cause cannot be determined from the present dataset alone.



206
 207 **Figure 2. Global distribution of radio occultation events from individual missions on 1 January 2026. The distributions are shown**
 208 **using a Mollweide equal-area projection.**

209 3.3 Grid-based spatial distributions

210 Figure 3 presents the gridded counts of GNSS-RO events-during 1–7 January 2026 at spatial resolutions of 0.5°, 1.0°, and
 211 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-cell fractions of 41.60% and 39.28%, respectively, whereas all other missions retain blank-cell 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-cells and 16,089 nonzero grids, while YY-1 follows closely with 2.55% blank-cells and 15,787 nonzero grids. YY-1, however, exhibits the largest local 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 event-count range without saturation. Based on blank-grid fractions, nonzero-grid continuity, and maximum grid-level 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%, and 98.16%, respectively, indicating that their observations are still spatially discontinuous even after seven-day accumulation. Overall, the seven-day results show that TM-1 and YY-1 dominate the globalgridded event-count distribution, PlanetiQ, Spire, FY-3, and COSMIC-2 provide useful supplementary coverage with mission-specific spatial patterns, and the remaining smaller missions contribute more localized and sparse observations.

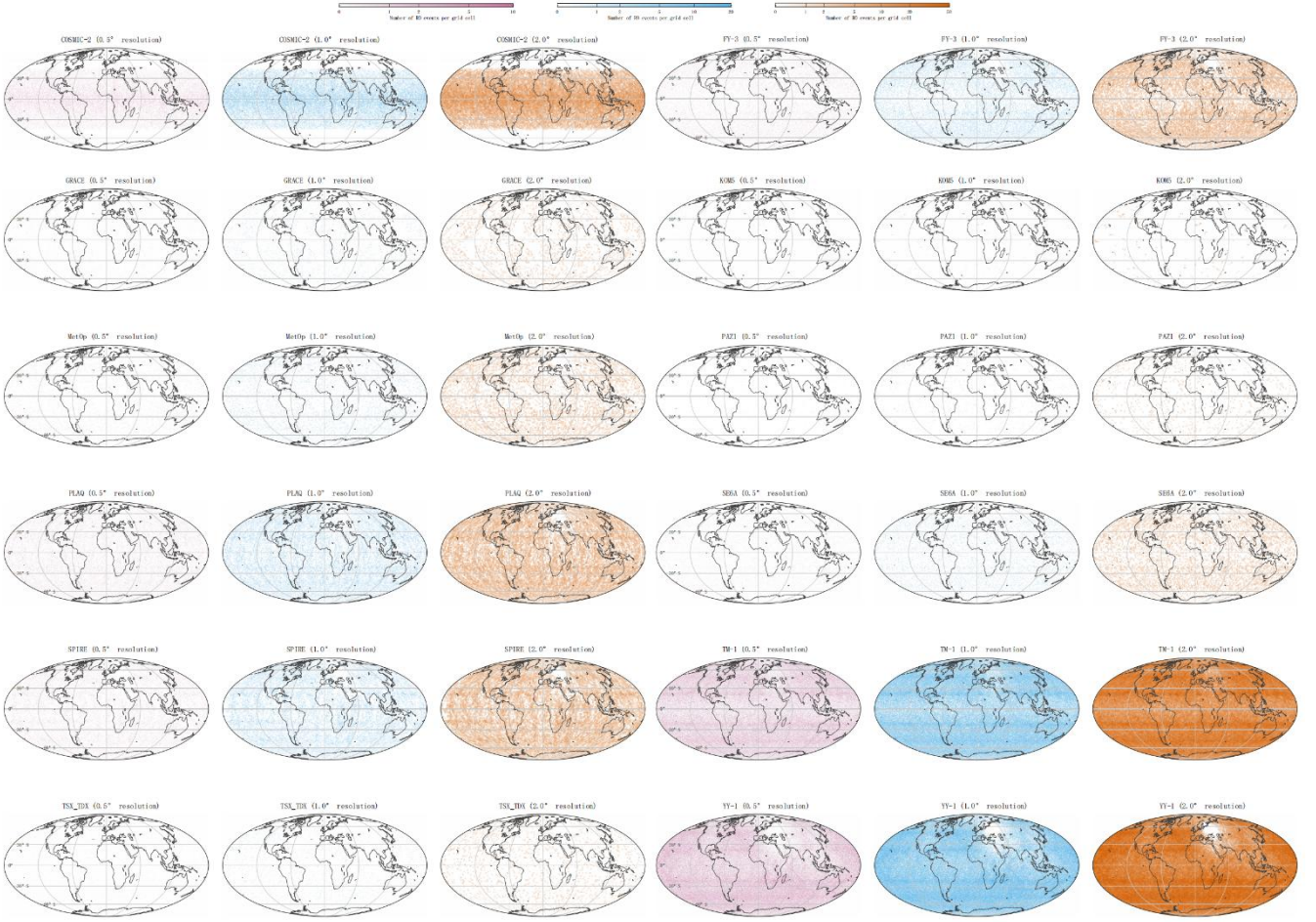


Figure 3. Gridded spatial distributions of radio occultation events from individual missions during 1–7 January 2026. Colors represent the raw number of events within each latitude–longitude cell and are not normalized by physical cell area.

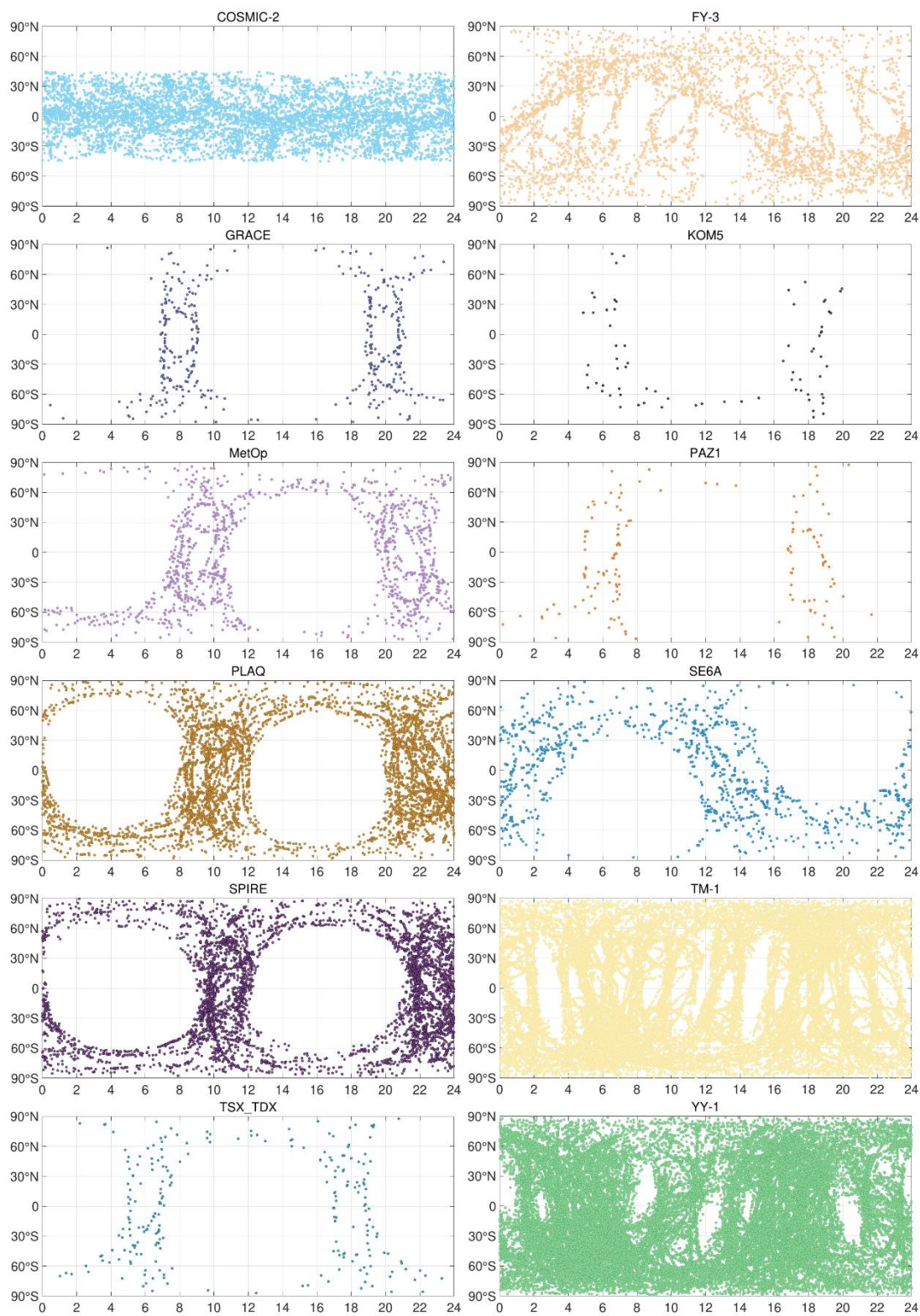
3.4 Local-time distributions

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:

$$LT = \left(UTC + \frac{\lambda}{15^\circ} \right) \bmod 24 \quad (5)$$

In Eq. (5), 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.

243 Figure 4 shows the local-time distributions of the global RO systems. The low-inclination COSMIC-2 configuration
244 provides broad local-time sampling at low and middle latitudes. The local-time distributions of FY-3D, FY-3E, and
245 FY-3F correspond to their descending-node local times, while low-inclination FY-3G produces curved bands that
246 supplement low-latitude sampling. Sentinel-6A exhibits a similar curved-band pattern. The near-polar GRACE-
247 C/D configuration produces nearly meridional distributions near 01:30, 11:30, 13:30, and 23:30 local time. Too few
248 KOMPSAT-5 events are available to identify a clear pattern. MetOp-B/C events cluster near 08:00-10:00 and 20:00-
249 22:00, while TerraSAR-X/TanDEM-X and PAZ events cluster near 05:00-07:00 and 17:00-19:00, consistent with
250 their approximately 06:00 descending-node local times. Spire events primarily occur near 10:00-12:00 and 22:00-
251 24:00. PlanetiQ has many events concentrated near 08:00-12:00 and 20:00-24:00, although the cause of this pattern
252 requires further investigation. TM-1 includes sun-synchronous satellites with different descending-node local times,
253 providing observations throughout the day but retaining gaps associated with LEO-GNSS geometry. Many YY-1
254 sun-synchronous satellites have descending-node local times between 02:00 and 08:00, producing concentrated
255 sampling, while YY-1 satellites 18-20 supplement low-latitude gaps. Overall, mission-specific orbital objectives
256 and local-time configurations produce pronounced sampling biases, particularly because many near-sun-
257 synchronous satellites are concentrated near 08:00-12:00 local time.



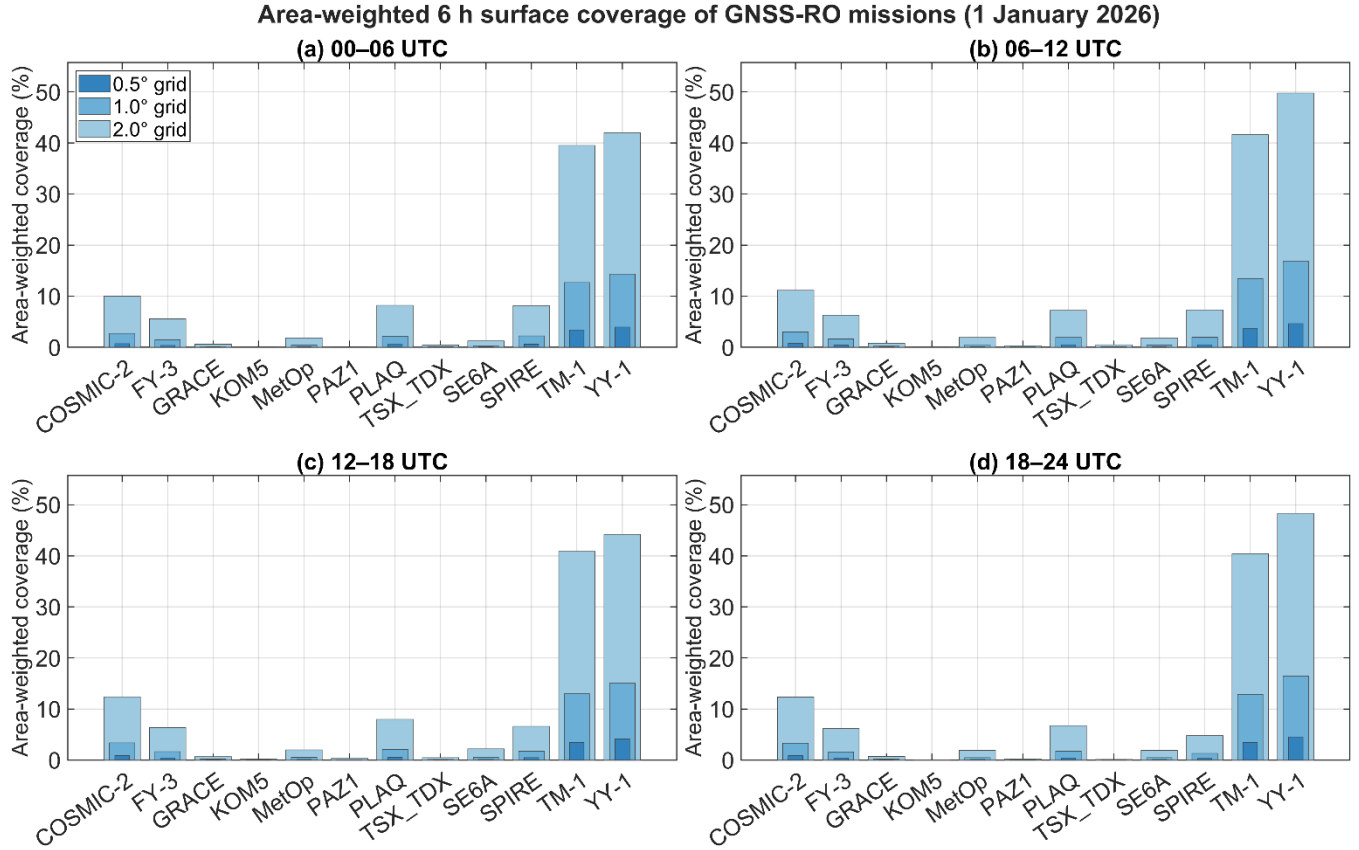
259 **Figure 4. Local-time distributions of radio occultation events from individual missions on 1 January 2026.**

260 **3.5 Coverage within 6 h time windows**

261 To assess coverage on the time scale commonly used for numerical weather prediction data assimilation, RO events on 1
262 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
263 area-weighted surface coverage was calculated for each window at spatial resolutions of 0.5°, 1.0°, and 2.0°. Compared with
264 daily statistics, the 6 h area-weighted coverage more directly characterizes short-term spatial continuity within a typical
265 assimilation window. The results are shown in Fig. 5. For this one-day sample, mission-averaged coverage was broadly similar
266 among the four UTC windows, although the temporal variability differed among missions. At 2.0° resolution, the mean
267 coverage across all missions was 9.82%, 10.73%, 10.35%, and 10.31% in the four successive windows, with corresponding
268 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
269 scale. The mean YY-1 coverage fractions at 0.5°, 1.0°, and 2.0° were 4.31%, 15.68%, and 46.08%, respectively, compared
270 with 3.49%, 12.99%, and 40.62% for TM-1. YY-1 reached the highest 2.0° coverage in the 06:00–12:00 UTC window
271 (**49.77%**), whereas TM-1 remained more temporally stable, with 2.0° coverage ranging only from 39.53% to 41.63%. Thus,
272 even within 6 h windows, large constellations maintained high global area-weighted surface coverage and were the principal
273 contributors to short-term global observational continuity. COSMIC-2, PlanetiQ, Spire, and FY-3 provided moderate 6 h
274 coverage. Their mean coverage fractions at 0.5°, 1.0°, and 2.0° were 0.79%, 3.10%, and 11.48% for COSMIC-2; 0.50%, 1.98%,
275 and 7.54% for PlanetiQ; 0.47%, 1.82%, and 6.71% for Spire; and 0.40%, 1.57%, and 6.09% for FY-3. COSMIC-2 coverage
276 increased from 10.00% in the first window to more than 12.3% in the last two windows at 2.0° resolution, whereas FY-3 was
277 comparatively stable, with 2.0° coverage ranging from 5.56% to 6.34%. Spire showed stronger window dependence, with 2.0°
278 coverage decreasing from 8.15% in the first window to 4.80% in the final window. Although these missions provided less
279 coverage than YY-1 and TM-1, they still supplied important complementary observations within 6 h assimilation windows.
280 Single-satellite and small-constellation missions generally provided low coverage within 6 h windows. At 2.0° resolution, the
281 mean coverage fractions for GRACE-C/D, KOMPSAT-5, PAZ, and TerraSAR-X/TanDEM-X were 0.68%, 0.12%, 0.24%, and
282 0.38%, respectively. MetOp-B/C and Sentinel-6A achieved slightly higher mean coverage, but only **1.91% and 1.78%**,
283 respectively. These missions may provide useful spatial samples on a daily scale, but they still leave pronounced global gaps
284 when used alone within a 6 h data-assimilation window. Overall, the results indicate that 6 h coverage was governed primarily
285 by event abundance and constellation size, while orbital configuration affected how efficiently those events translated into
286 spatial coverage. Across the analyzed windows and resolutions, the Pearson correlation between mission event count and
287 coverage ranged from 0.994 to 0.999. Large constellations therefore had a clear advantage at the 6 h scale, whereas individual
288 satellites and small constellations provided limited stand-alone coverage. Because the analysis was based on only four windows
289 from a single day, these findings should be interpreted as descriptive evidence for 1 January 2026 rather than as proof of

290 general independence from the UTC window. Multi-mission observations remain essential for improving global continuity
 291 and reducing spatial gaps in short-window applications such as numerical weather prediction data assimilation.

292



293

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

295 **4 Joint distribution characteristics of global GNSS-RO missions**

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

$$n_i^{joint}(r) = \sum_{k=1}^M n_{(i,k)}(r) \quad (6)$$

298 In Eq. (6), $n_{i,joint}(r)$ is the total number of RO events in the i th grid after combining missions at spatial resolution r , $n_{i,m}(r)$
 299 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.

300 4.1 Joint global spatial distribution

301 Figure 6 shows the enhanced spatial completeness achieved by combining observations from all missions on 1 January 2026.
302 The joint dataset contains 98,402 GNSS-RO events and provides substantially broader global sampling than any individual
303 mission. The complementarity is particularly evident at low latitudes and in polar regions. At low latitudes, observations from
304 the low-inclination FY-3G satellite and YY-1 satellites 18–20 complement the dense tropical sampling of COSMIC-2. Within
305 10° of the Equator, the combined dataset contains 10,979 events, accounting for 11.16% of the joint sample. Within 30°S –
306 30°N , COSMIC-2 contributes 4,565 events, while FY-3G and YY-1 satellites 18–20 contribute 471 and 1,826 events,
307 respectively, thereby strengthening the low-latitude observing capability. Polar sampling is also enhanced through the
308 complementarity of high-inclination and near-polar missions. A total of 21,762 events occur poleward of 60° , accounting for
309 22.12% of the joint sample, with YY-1, TM-1, PlanetiQ, Spire, FY-3, and other high-inclination missions jointly contributing
310 to high-latitude coverage. Overall, the combined dataset demonstrates clear latitudinal complementarity among missions:
311 COSMIC-2 and selected low-inclination satellites strengthen tropical coverage, whereas high-inclination and near-polar
312 missions improve sampling in polar regions. Localized data gaps near the Russia–Ukraine region are still visible in some
313 distributions and may be related to regional signal interference, quality-control screening, or data-reception limitations.

314

Global Distribution of Multi-Mission RO Events

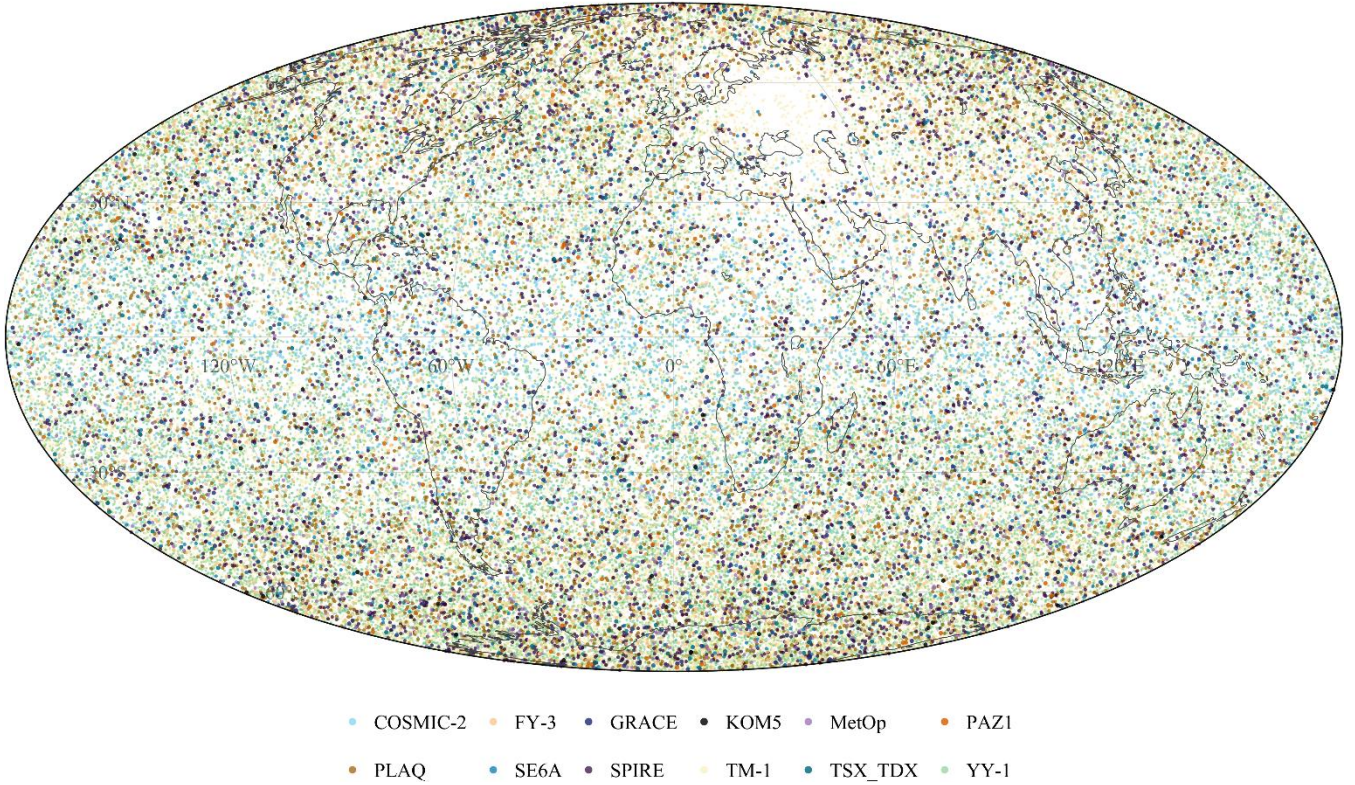


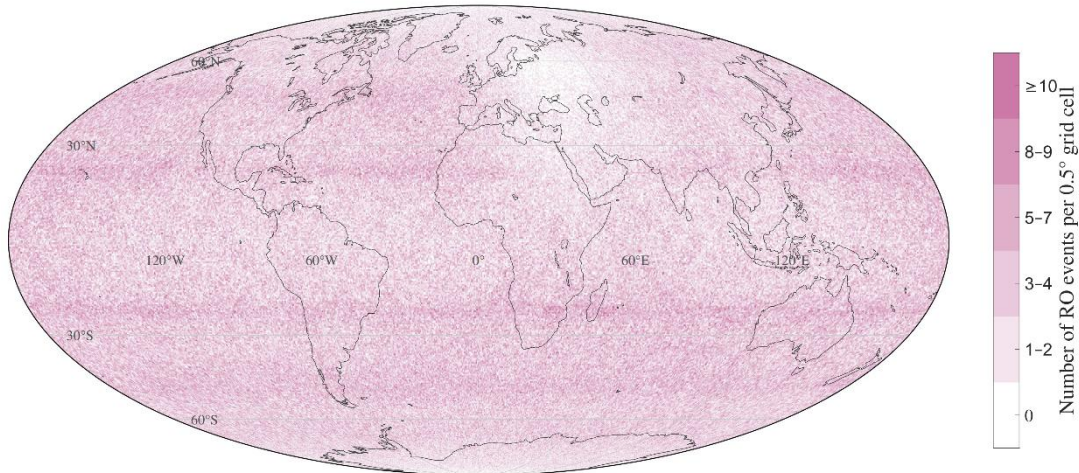
Figure 6. Global distribution of the combined radio occultation dataset on 1 January 2026.

4.2 Joint global gridded distribution

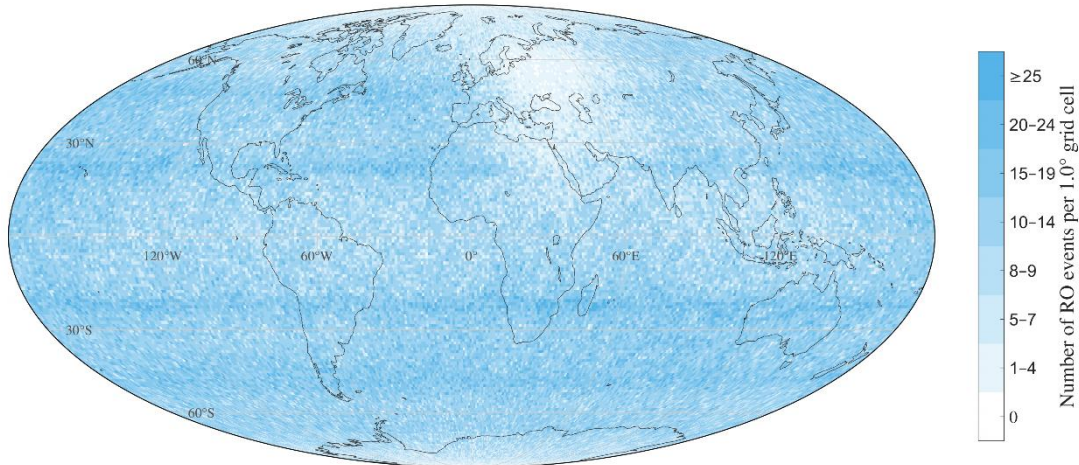
Figure 7 further illustrates the event count per grid cell and spatial continuity achieved by combining 679,854 RO events from all missions during 1–7 January 2026. At 0.5° resolution, 225,142 of the 259,200 global grids are occupied, corresponding to a grid-cell occupancy fraction of 86.86% and a blank-grid fraction of 13.14%; the 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 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 event count in a grid cell increases to 38 events per grid. The largest 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 coverage of 99.995% and a maximum event count in a grid cell of 113 events per grid. The dominant event-

329 count class is 40–59 events, accounting for 7,205 grids, followed by 60–79 events in 2,294 grids; only three grids contain 100
330 or more events. The heat-map distribution also exhibits clear zonal high-event-count bands. Pronounced dense regions appear
331 near approximately 20°S and 20°N, while another relatively evident concentration occurs around 45° latitude in both
332 hemispheres. These banded structures indicate that, although multi-mission combination greatly improves global spatial
333 continuity, the final event-count pattern still reflects the combined influence of orbital inclination, constellation geometry, and
334 latitude-dependent sampling frequency.

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)

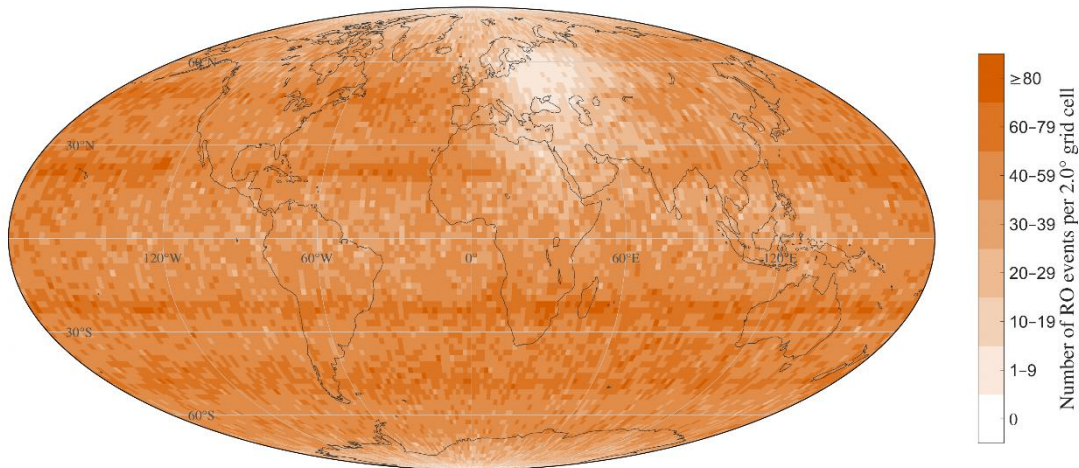


Figure 7. Gridded spatial distribution of the combined radio occultation dataset during 1–7 January 2026.

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

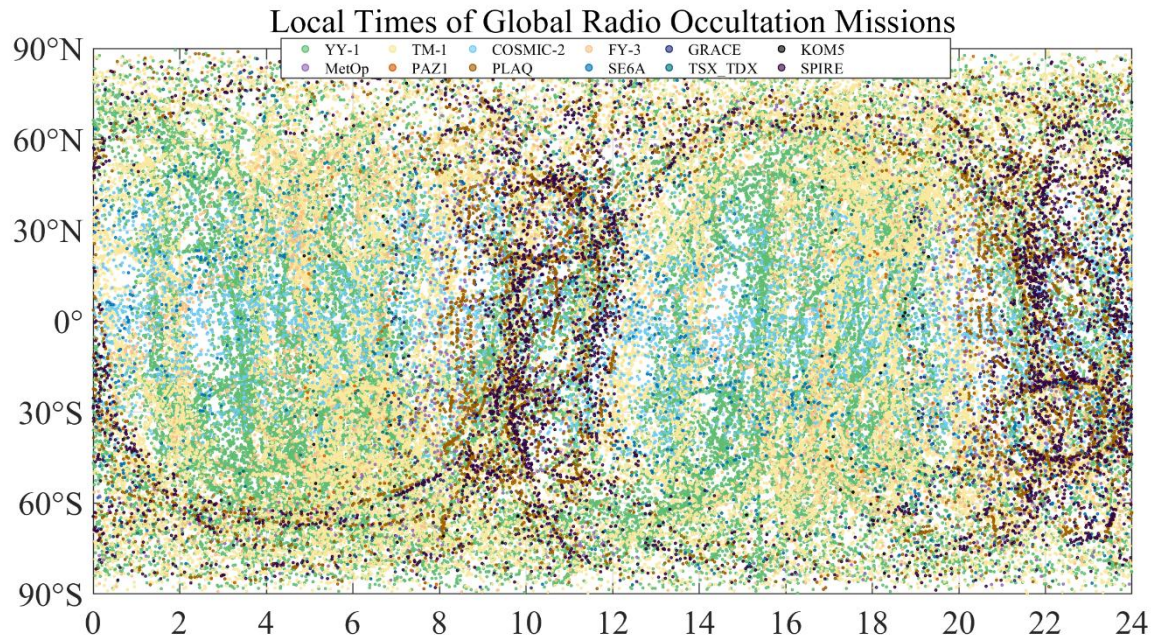


Figure 8. Local-time distribution of the combined radio occultation dataset on 1 January 2026.

4.4 Joint coverage within 6 h time windows

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

Table 2. Mean 6 h area-weighted global surface coverage (%) of individual RO missions and the combined dataset at three spatial resolutions

Mission	0.5°	1.0°	2.0°
Combined dataset	9.89	33.26	76.80
COSMIC-2	0.79	3.10	11.48
FY-3	0.40	1.58	6.09
GRACE-C/D	0.04	0.17	0.68
KOMPSAT-5	0.01	0.03	0.12

MetOp	0.12	0.48	1.91
PAZ	0.02	0.06	0.24
PlanetiQ	0.50	1.98	7.54
TerraSAR-	0.02	0.09	0.38
X/TanDEM-X			
Sentinel-6A	0.11	0.45	1.78
Spire	0.47	1.82	6.71
TM-1	3.49	12.99	40.62
YY-1	4.31	15.68	46.08

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

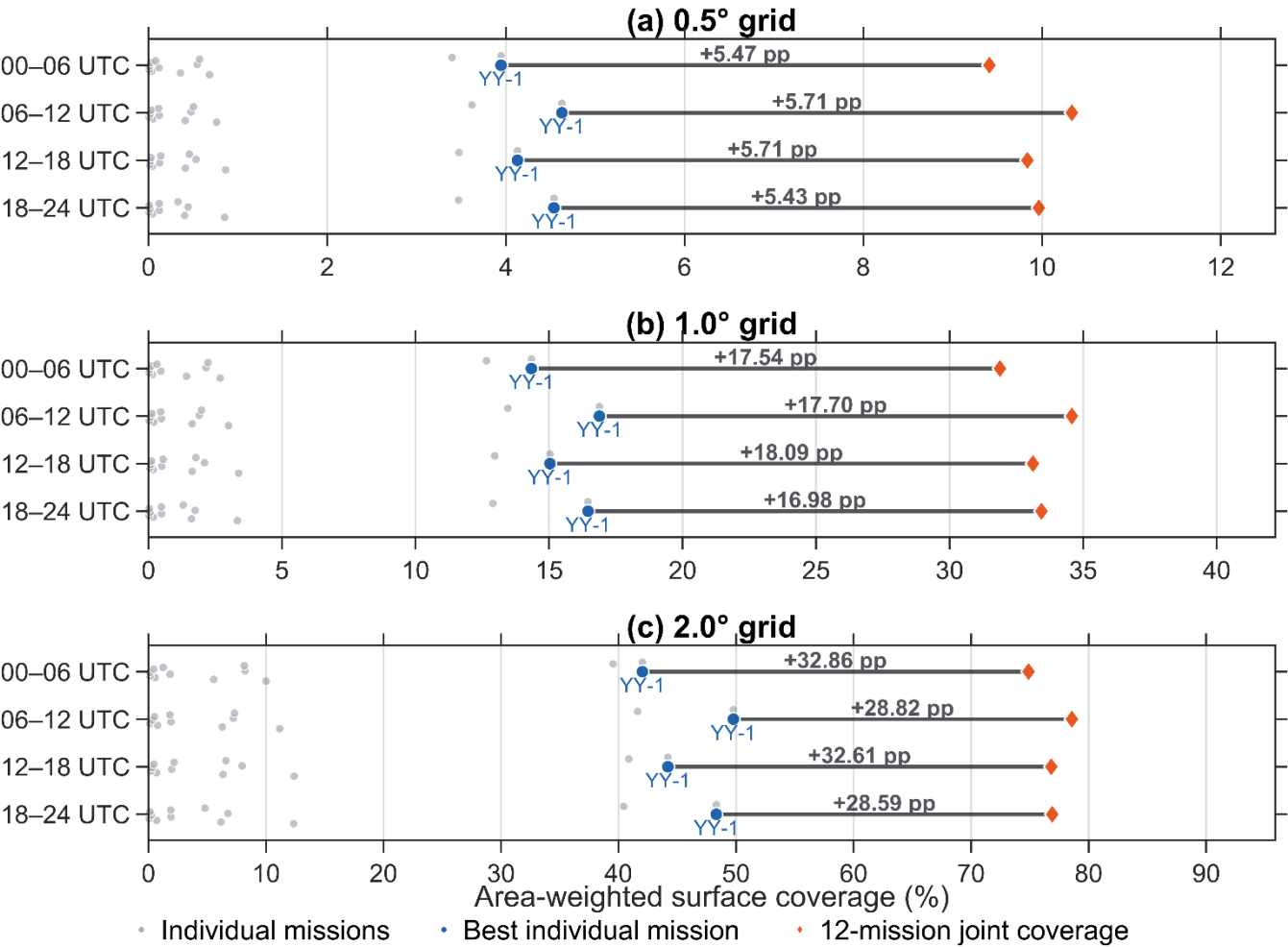
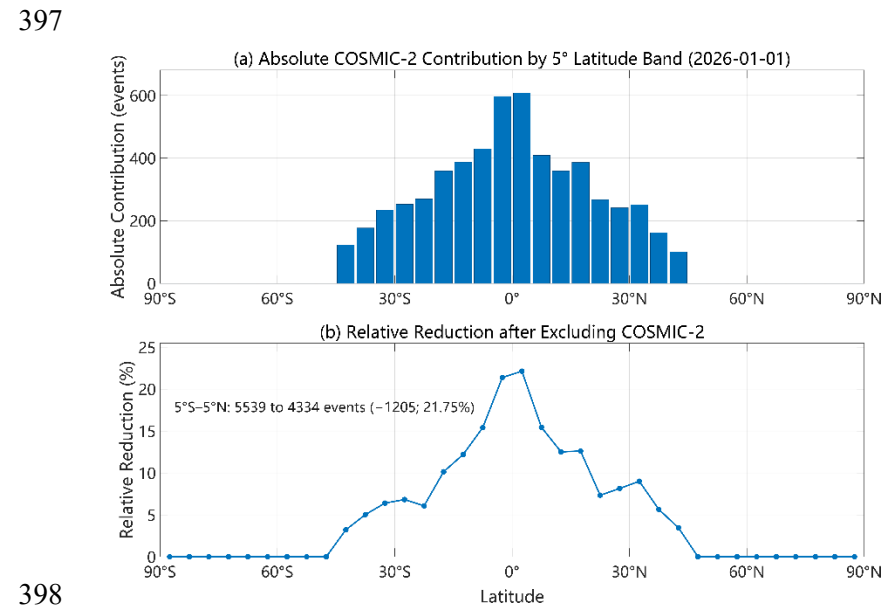


Figure 9. Global area-weighted surface coverage in four 6 h UTC windows on 1 January 2026

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% 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%. Joint observations therefore provide absolute gains of 5.58, 17.58, and 30.72 percentage points relative to YY-1, equivalent to relative increases of 129.4%, 112.1%, and 66.7%. 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.

386 4.5 Sampling contribution of COSMIC-2 to the multi-mission observing system

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



398 **Figure 10. Sampling contribution of COSMIC-2 by 5° latitude band on 1 January 2026: (a) the absolute number of events removed**
 399 **when COSMIC-2 is excluded, $\Delta N = N_{12} - N_{11}$; and (b) the corresponding percentage reduction, $100\Delta N / N_{12}$.**
 400

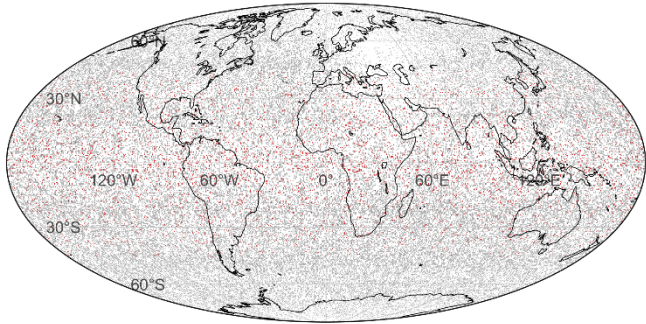
401 Figure 11 further illustrates the spatially irreplaceable contribution of COSMIC-2 at three grid resolutions: (a) $0.5^\circ \times 0.5^\circ$, (b)
 402 $1^\circ \times 1^\circ$, and (c) $2^\circ \times 2^\circ$. Gray grids are covered by the other 11 missions, red grids are covered only by COSMIC-2, and white
 403 grids are not covered by any of the 12 missions. At the finest 0.5° resolution, 3,797 grids, corresponding to an area-weighted
 404 2.16% of the global area, are covered exclusively by COSMIC-2. These COSMIC-2-only grids are concentrated in the low-
 405 and middle-latitude belt, with a pronounced tropical contribution, confirming that the constellation provides coverage that
 406 cannot be fully replaced by the other missions at high spatial resolution. At 1° resolution, the COSMIC-2-only area-weighted

407 surface-coverage fraction is 2.82% (1,233 grids), whereas at 2° resolution it decreases to an area-weighted surface-coverage
408 fraction of 0.28% (31 grids) because the coarser grid aggregation merges many COSMIC-2 observations with coverage from
409 the other missions. Overall, the multi-mission system remains highly resilient after excluding COSMIC-2, especially at coarse
410 spatial scales; however, its retirement would lead to a measurable loss of independent high-resolution coverage and a clear
411 reduction in equatorial RO sampling.
412

Irreplaceable coverage of COSMIC-2 (2026-01-01)

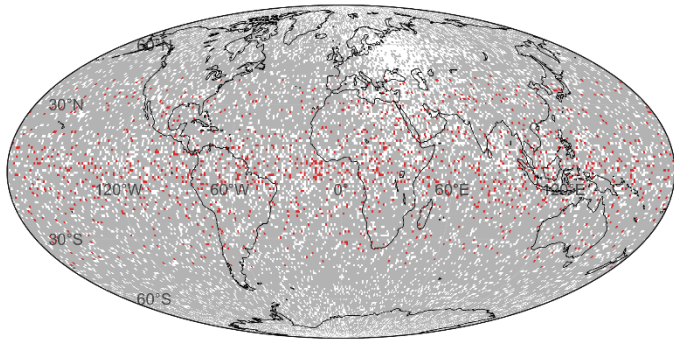
(a) 0.5° × 0.5° grid

Other 11: 31.68% | COSMIC-2 only: 2.16% | Uncovered: 66.16%



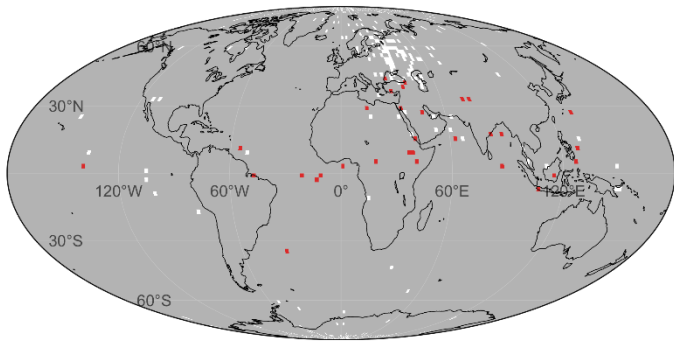
(b) 1° × 1° grid

Other 11: 75.91% | COSMIC-2 only: 2.82% | Uncovered: 21.26%



(c) 2° × 2° grid

Other 11: 98.60% | COSMIC-2 only: 0.28% | Uncovered: 1.12%



Other 11 missions covered COSMIC-2 only Uncovered by all 12

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

415 **5 Conclusions and outlook**

416 This study compared the spatial distributions, grid coverage, local-time sampling and 6 h coverage of 12 GNSS-RO mission
417 systems using observations collected during 1–7 January 2026. The results demonstrate that constellation size, event abundance,
418 and orbital configuration jointly determine the observational capabilities of individual missions. Large constellations provide
419 the strongest global spatial continuity, low-inclination missions enhance tropical and subtropical sampling, and high-
420 inclination and near-polar missions provide complementary observations at middle and high latitudes. Consequently, no single
421 mission can reproduce the spatial and temporal sampling characteristics of the complete multi-mission observing system.

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

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

438
439 Because the present analysis covers only seven days and the 6 h assessment is based on four windows from a single day, the
440 results represent a short-term observational snapshot. Future work should extend the analysis to longer periods, quantify
441 seasonal and regional variability, and evaluate optimized mission combinations in numerical weather prediction and climate
442 applications. Future work will extend the analysis to longer periods and different seasons and regions. Subject to data
443 availability and experimental resources, we also plan to evaluate the application-level consequences of changes in COSMIC-
444 2 sampling through dedicated data-assimilation or data-denial experiments for NWP, longer-term sampling-error analyses for
445 climate applications, and targeted assessments of ionospheric and space-weather products.

447 Code and data availability

448 The radio occultation datasets used in this study were obtained from the National Meteorological Information
449 Center of the China Meteorological Administration, comprising (1) global atmospheric profiles acquired under the
450 WMO Global Telecommunication System (GTS) exchange agreement and subject to WMO data sharing and
451 exchange policies, and (2) operational RO products from the commercial small-satellite constellations “Tanmu-1”
452 and “Yunyao-1”, both of which have been admitted into the CMA integrated observation system in accordance with
453 the Administrative Measures for the Admission and Exit of Meteorological Data Products and processed via the
454 Tianqing meteorological big data cloud platform; these data are further governed by the CMA License Agreement
455 for the Use of Meteorological Data, WMO GTS distribution rules, and the intellectual property clauses of the
456 respective commercial satellite operators, meaning the authors are not authorized to redistribute them, and eligible
457 researchers may register at data.cma.cn, sign the required license agreement, and apply for access. The code
458 developed in this study is archived at Zenodo repository under DOI: 21866427. Access is currently restricted as the
459 code forms part of an ongoing follow-up research project. The full codebase will be made publicly accessible under
460 the same DOI upon completion of the related series of studies, estimated by 1 year. In the meantime, the code is
461 available from the corresponding author upon reasonable request.

462 Author contributions

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

468 **Competing interests**

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

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478 **References**

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