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Effect of Multiple GNSS Integration on the Number and Spatiotemporal Coverage of Radio Occultation Events

Congliang Liu ^{1,2,3,4,*}, Yueqiang Sun ^{1,2,3}, Weihua Bai ^{1,2,3}, Qifei Du ^{1,2,3}, Wei Li ^{1,2}, Xi Wang ^{1,4} and Peixian Li ⁴ 

¹ Chinese Academy of Sciences (NSSC/CAS) and Beijing Key Laboratory of Space Environment Exploration, National Space Science Center, Beijing 100190, China; syq@nssc.ac.cn (Y.S.); baiweihua@nssc.ac.cn (W.B.); dqf@nssc.ac.cn (Q.D.); liwei@nssc.ac.cn (W.L.); zqt2100204125@student.cumt.edu.cn (X.W.)

² Joint Laboratory on Occultations for Atmosphere and Climate (JLOAC), National Space Science Center, Beijing 100190, China

³ School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China

⁴ School of Geoscience and Surveying Engineering, China University of Mining and Technology-Beijing, Beijing 100083, China; lipx@cumt.edu.cn

* Correspondence: lcl@nssc.ac.cn; Tel.: +86-010-6255-7975

Abstract: The development of global navigation satellite systems (GNSSs) and multi-system compatible radio occultation (RO) techniques provides favorable conditions and opportunities for increasing the number of occultation events and improving their spatiotemporal coverage. The performance of the multiple GNSS RO event number, spatiotemporal coverage, and uniformity need assessments by robust and functional approaches. Firstly, a simulation system of RO events, which took the orbit perturbations into account, was established, and the concepts of global coverage fraction and uniformity of RO events were defined. Secondly, numerical experiments were designed to analyze the GNSS RO performances of a single-receiving satellite and satellite constellations under the condition of using current multiple GNSSs as transmitting satellite systems, in which the Earth was divided into $400 \times 400 \text{ km}^2$ grids. Finally, the number, timeliness, global coverage fraction, and uniformity of GNSS RO events for a single-receiving satellite and receiving satellite constellations were numerically calculated and analyzed. The results showed that ① multiple GNSS integration improved the number of GNSS RO events and their global coverage for a single polar-orbit satellite significantly, e.g., the 24 h multiple GNSS RO event number was about 7.8 times that of the single GNSS system, BeiDou navigation satellite system-3, while the corresponding 24 h global coverage fraction increased nearly 3 times. ② In the multiple GNSS integration scenario, the constellation composed of 12 polar-orbit low-Earth-orbit satellites achieved 100% RO event global coverage fraction within 24 h, of which the RO detection capability was comparable to the 100 Spire weather satellites and global positioning system (GPS) RO system. ③ More GNSS RO events of the polar-orbit constellations were distributed in the middle- and high-latitude zones. Therefore, multiple GNSS integration could increase the RO event number and global coverage significantly to benefit the global climate monitoring and global numerical weather prediction, and the polar-orbit constellations were more favorable to atmospheric detection in middle- and high-latitude regions.

Keywords: multiple GNSS; radio occultation; orbit and constellation parameters; event number; global coverage



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1. Introduction

Global navigation satellite system (GNSS) radio occultation (RO) is an atmospheric remote sensing technique that can deliver global coverage, all-weather capability, long-term stability, traceability to the international standard (SI) of time, high vertical resolution, and high-accuracy atmospheric profile retrievals, i.e., bending angle, refractivity, pressure, temperature, and humidity profiles [1–6]. Numerous studies have concluded that the GNSS

RO data played important roles in both global climate monitoring (GCM) [4,7–21] and global numerical weather prediction (GNWP) [16,22–27] applications.

Initially, the GNSS RO atmospheric detection technique was demonstrated by the proof-of-concept global positioning system/METeorology (GPS/MET) mission [28]. Subsequently, many GNSS RO missions have been implemented, including the Challenging Minisatellite Payload (CHAMP) [19,29–31], Gravity Recovery and Climate Experiment-A (GRACE-A) [29,32], and Meteorological Operational Satellite-A/B (MetOp-A/B) [33], which are single-receiving satellite (RS) constellations, and the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) [27,34,35], which is the first RS constellation with six low-Earth-orbit (LEO) satellites.

In the last decade, with the development of GNSS systems such as the Chinese BeiDou navigation satellite system (BDS), the European Galileo navigation satellite system (GALILEO), the Russian GLObal NAVigation Satellite System (GLONASS), and the U.S. GPS, the new GNSS RO missions have been commonly equipped with multi-GNSS RO receivers such as the FengYun-3C/-3D/-3E GNSS Occultation Sounder (FY-3C/-3D/-3E GNOS) [36–38], the COSMIC II, the Spire weather constellation [23,39], and so on.

In recent years, the emerge of regional navigation systems, e.g., Indian Regional Navigation Satellite System (IRNSS), Quasi-Zenith Satellite System (QZSS), etc., as well as the development of a spaceborne GNSS augmentation system has provided richer radio signals for RO atmospheric detection [40–44], which create more favorable conditions to meet the requirements of the GCM and GNWP applications with respect to the number of GNSS RO events, their global coverage, and timeliness.

Studies have indicated that more GNSS RO events with better spatiotemporal coverage are more beneficial for GCM and GNWP applications [7,45,46]. To meet the basic requirements of GNWP, about 20,000 global uniformly distributed GNSS RO events per day have been suggested, and the increase in daily GNSS RO events has obviously improved the GNWP accuracy [9,16,45,47]. This is the reason why the LEO satellite constellations and multi-GNSS RO techniques emerged and are developing so quickly. However, the orbit design and performance analyses of the GNSS RO missions have become more and more challenging [41,42].

To obtain more GNSS RO events and a better spatiotemporal distribution for particular areas, the impacts of LEO satellite orbital and constellation parameters on the GNSS RO event number and global distribution have been investigated [48–52]. The results showed that LEO satellite orbit inclination is a key parameter affecting the distribution of RO events along the latitude direction, and the number of GNSS RO events decreases with the increase in the LEO satellite orbit height [43,53]. Practical LEO satellite orbital and constellation parameters were designed and optimized for GNSS RO observations in particular regions such as a tropical zone [52], the Asia Pacific region [54], and an area in Egypt [55,56]. Recently, with the development of global and regional navigation satellite systems, the optimal design of LEO satellite constellations for multi-GNSS RO missions has become a research hotspot in the GNSS RO atmospheric detection field [47–49,57,58].

On the other hand, with the development of spaceborne communication and GNSS augmentation technologies, the next-generation LEO constellations with large numbers of satellites might tend to integrate the functions of satellite communication, satellite navigation, and satellite remote sensing in one system. Nowadays, LEO satellite constellations, e.g., Iridium, Spire, Starlink, China's Hongyan, etc., have been designed and implemented [40,44], which can provide more LEO satellites and navigation signal opportunities for GNSS RO atmospheric detection.

Large LEO constellation and multi-GNSS RO mission design and detection capability evaluation should consider the requirements of the GCM and GNWP applications. However, the traditional GNSS RO event descriptions and statistical approaches such as the global distribution of RO event locations and histograms of RO event numbers in specific latitude and longitude bins are too simple to quantitatively describe and analyze the GNSS RO spatiotemporal coverage and uniformity information.

In this paper, according to the requirements of the GCM and GNWP applications, GNSS RO event spatial and temporal distribution analysis approaches were proposed by defining the global coverage fraction (GCF) and uniformity coverage index (UCI), in which an equal-area projection method [59] was involved. Then, based on real navigation satellites' and designed LEO satellites' (constellations) orbit data, a simulation study was conducted to investigate the variation characteristics of the multi-GNSS RO event number, global coverage, and uniformity. Under the existing multi-GNSS conditions, the following scientific questions were analyzed: ① to what extent can the multi-GNSS integration improve the number of RO events and their global coverage fraction for a single polar-orbit LEO satellite? ② An RO constellation with how many polar-orbit LEO satellites can achieve the Spire/GPS RO system detection capability and thus can meet the GNWP's basic requirements in terms of the RO event number, timeliness, and global coverage fraction?

The structure of this paper is as follows: Section 2 introduces the GNSS RO event simulation and their detection capability assessment approaches, the satellite orbit datasets, as well as the experimental programs used in this study; Section 3 presents the key results of this study including the effects of the multi-GNSS integration on the single polar-orbit LEO satellite RO detection capability and the RO detection capabilities of the LEO constellations; Section 4 discusses the impacts of the orbital types on the GNSS RO event global distribution characteristics; finally, the main conclusions of this study are provided in Section 5.

2. GNSS RO Event Simulation and Assessment Approaches

2.1. GNSS RO Event Simulation

As shown in Figure 1, during a GNSS RO event active period, the transmitting signal ray path from the transmitting satellite (TS, i.e., the GNSS satellite), first passes through the atmosphere and is captured by the receiving satellite (RS, i.e., the LEO satellite); then, with the relative motion of the TS and RS, the atmosphere is vertically scanned and remotely observed [60]. The Earth's atmosphere bending angle of the GNSS L-band occultation signal is generally less than 1° , which has little effect on the RO tangent point position; thus, the signal path can be considered as a straight line in the RO event simulation and analyses [52]. An RO event occurs when the connecting line between the TS and RS and its tangent point with the atmospheric layers simultaneously satisfy a certain geometric relationship, and the mathematical criteria are as follows: ① the tangent point is between the TS and RS, ② the height of the tangent point is between the bottom and the top of the atmosphere (typically 0–120 km), and ③ the azimuth angle of the TS relative to the RS's running direction is within a particular range (i.e., in the receiving antenna view field ($\pm 40^\circ$) in this study); specifically, the azimuth angle of the TS relative to the RS running direction ranges were set as 0° – 40° and 320° – 360° for rising GNSS RO events and 140° – 220° for setting GNSS RO events [43].

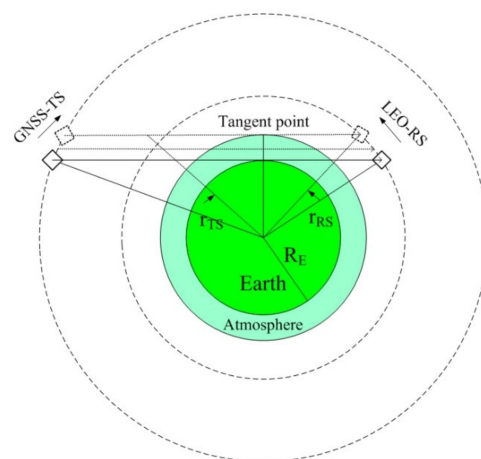


Figure 1. Occultation geometry between one GNSS transmitting satellite (TS) and one LEO receiving satellite (RS).

The unperturbed two-body orbits are always conic sections; therefore, the Earth orbits are commonly described as an ellipse by Keplerian elements, i.e., eccentricity (e), semimajor axis (a), inclination (i), longitude of the ascending node (Ω), argument of periapsis (ω), and true anomaly (ν). However, real Earth orbits have perturbations due to the gravitational pull of bodies other than the Earth, the nonsphericity of the Earth, atmospheric drag, relativistic effects, radiation pressure, electromagnetic forces, and so on. Therefore, in the simulation, RS and TS satellite positions and velocities were calculated from two-line element (TLE) sets through the simplified general perturbations-4/simplified deep space perturbations-4 (SGP4/SDP4) model propagator, which takes the general and deep space orbital perturbations into account [61]. Then, the TS and RS satellite positions and velocities at different epochs were used to calculate the RO geometric parameters, which involved the tangent point positions, in the following steps [60,62]:

Firstly, we calculated the latitude, longitude, and height of the occultation tangent point for each ray path using the TS and RS time and position data by the following formulas:

$$r_{TR} = r_{TS} - r_{RS} \quad (1)$$

$$\hat{n}_{TR} = (r_{TR}) / \|r_{TR}\| \quad (2)$$

$$R_T = \|r_{TS} \cdot \hat{n}_{TR}\| \quad (3)$$

$$r_{TP} = r_{TS} - \hat{n}_{TR} \cdot R_T = (X_{TP}, Y_{TP}, Z_{TP}) \quad (4)$$

$$\begin{cases} \varphi_{TP} = \arctan\left(Z_{TP}(N + h_{TP}) / \sqrt{X_{TP}^2 + Y_{TP}^2} / (N \cdot (1 - e_E^2) + h_{TP})\right) \\ \lambda_{TP} = \arctan(X_{TP}/Y_{TP}) \\ h_{TP} = Z_{TP} / \sin \varphi_{TP} - N \cdot (1 - e_E^2) \\ N = a_E / \sqrt{1 - e_E^2 \sin^2 \varphi_{TP}} \\ \varphi_{TP0} = \arctan\left(Z_{TP} / \sqrt{X_{TP}^2 + Y_{TP}^2}\right) \\ |\varphi_{TPi+1} - \varphi_{TPi}| \leq 10^{-12} \end{cases} \quad (5)$$

where r_{TR} is the vector from RS to TS, r_{TS} and r_{RS} are the position vectors of TS and RS, respectively, $\hat{n}_{TR}$ is the unit vector along the direction from RS to TS, R_T is the projection of the TS position vector on the RS to TS connecting line, r_{TP} is the position vector of the occultation tangent point, (X_{TP}, Y_{TP}, Z_{TP}) are the three-dimensional coordinates of the occultation tangent point in the Earth-centered Earth-fixed (ECEF) coordinate system, a_E is the equatorial radius of the Earth, e_E is the first numerical eccentricity of the ellipsoid, N is the distance from the surface back to the Z-axis intersection along the ellipsoid normal, and φ_{TP} , λ_{TP} , and h_{TP} are the latitude, longitude, and height of the occultation tangent point in the geodetic coordinate system, respectively, where φ_{TP} needs to be solved by iteration.

Secondly, we calculated the elevation angle E and azimuth angle A of TS relative to the RS running direction. The elevation angle E and the azimuth angle A of the TS relative to the RS running direction were defined in a Cartesian coordinate system with the RS mass center as the origin, which were computed by the following formulas [60,62]:

$$\begin{cases} x = v_{RS} \\ y = v_{RS} \times r_{RS} \\ z = x \times y \end{cases} \quad (6)$$

$$\sin E = z \cdot r_{TR} / (\|z\| \cdot \|r_{TR}\|) \quad (7)$$

$$r_A = r_{TR} - \|r_{TR}\| \cdot \sin E \cdot z / \|z\| \quad (8)$$

$$\cos A = r_A \cdot x / (\|r_A\| \cdot \|x\|) \quad (9)$$

where v_{RS} is the RS velocity vector and r_A is the projection of r_{TR} in the xy coordinate plane.

Finally, we determined whether a GNSS RO event occurred according to the three mathematical criteria of an occultation event and the results of the above two steps. If a

GNSS RO event occurred, then we stored its attributes including temporal and spatial data such as RO event ID number, starting and ending time, tangent point latitude, and longitude and height in the occultation table; otherwise, we continued to solve and determine whether an RO event occurred at the next epoch until the end of simulation.

2.2. Global Coverage Fraction and Uniformity of GNSS RO Events

Firstly, the Earth's surface is spatially divided by a grid into uniform meshes. Since the GNSS RO event positions are recorded by longitude and latitude, the Earth's surface can be divided into uniform grids of $M \times M$ (km^2) with latitude and longitude ($0^\circ, 0^\circ$) as the reference origin. In this study, the size of the uniform grids was set as $400 \times 400 \text{ km}^2$.

Secondly, according to the temporal order, the GNSS RO events are accumulated into corresponding grids sequentially by equal-area projection to obtain the GNSS RO spatiotemporal datasets. Specifically, it includes the following steps:

① Time normalization:

$$t = t_{ro} - t_0 \quad (10)$$

where t_{ro} is the RO event time and t_0 is the start time of the analysis period.

② The RO events are accumulated to corresponding grids by equal-area projection [59]:

$$col = k \cdot \frac{a_E \varphi \cos \lambda_0}{\sqrt{1 - e_E^2 \sin^2 \lambda_0}} \quad (11)$$

$$row = k \cdot \frac{a_E Q(\lambda) \sqrt{1 - e_E^2 \sin^2 \lambda_0}}{\cos \lambda_0} \quad (12)$$

where col and row are column and row index numbers in the divided grid matrix, respectively, k is the scale factor, a_E is the equatorial radius of the Earth, e_E is the first numerical eccentricity of the ellipsoid, φ and λ are the longitude and latitude of the RO tangent point, respectively, λ_0 is the scale reference latitude, and the expression of $Q(\lambda)$ is

$$Q(\lambda) = (1 - e_E^2) \left[\frac{\sin \lambda}{(1 - e_E^2 \sin^2 \lambda)} - \frac{1}{2e_E} \ln \left(\frac{1 - e_E \sin \lambda}{1 + e_E \sin \lambda} \right) \right] \quad (13)$$

③ Calculation of the global coverage fraction (GCF) in time series:

$$GCF = (S_{occ} / S_{tot}) \times 100\% \quad (14)$$

where GCF is the global coverage fraction of RO events, S_{occ} is the accumulated area of the grid cells visited by RO events, and S_{tot} is the total grid area, i.e., the entire Earth's surface in the given case of a global coverage fraction.

④ Calculation of the uniform coverage index (UCI) in time series:

In order to quantitatively assess the global coverage uniformity of RO events, the UCI was defined as

$$UCI(n) = (N_{\geq n} / N_{tot}) \times 100\% \quad (15)$$

where $N_{\geq n}$ denotes the number of grids with GNSS RO event-visited-times greater than or equal to n , and N_{tot} denotes the total number of grids. Therefore, UCI denotes the global coverage uniformity of occultation events when n is set as the average value of the number of RO events relative to N_{tot} .

2.3. GNSS and LEO Satellite Orbital Data

In this study, two-line element (TLE) format satellite orbital data were used for the GNSS RO event simulation. The GNSS satellites' and Spire weather satellites' orbital data were downloaded from the Current TLE (on 20 June 2021) via the link: <https://www.cesstrak.com/> (latest accessed date is 16 December 2021). A multi-GNSS TS system involves GPS Operational (30 satellites), GLONASS Operational (GLO, 27 satellites),

GALILEO (GAL, 26 satellites), BDS (50 satellites), satellite-based augmentation system (SBAS, 16 satellites), navy navigation satellite system (NNSS, 18 satellites), and Russian LEO navigation (RLNav, 9 satellites), as well as the Iridium NEXT constellation (IridN, 75 satellites) which has satellite navigation, positioning, and timing functions. Therefore, the selected TS system had 251 satellites in total. Due to the large number of multi-GNSS TS satellites, the satellite ID and major orbital roots of representative TS satellites are given in Table 1.

Table 1. Main orbital elements of representative transmitting satellites from their TLE data files.

Satellite ID	Inclination/(°)	RAAN/(°)	Eccentricity	Argument of Perigee/(°)	Mean Anomaly/(°)	Height/(km)
BDS-3 (C59)	1	226.6	0.0003	356.3	149.4	35,787
BDS-3 (C38)	56	56.9	0.0019	191.9	341.8	35,787
BDS-3 (C19)	55.4	123.8	0.0012	293.4	66.5	21,528
GPS (13)	55.5	169.8	0.0048	53.4	307.1	20,182
COSMOS (2425)	64.8	255.3	0.0024	342.9	16.3	19,129
GSAT (E11)	56.8	31.2	0.0004	31.7	328.3	23,222
IRIDIUM (109)	86.4	129.2	0	92.1	268.1	778
COSMOS (2361)	82.9	112.9	0.0032	129.8	43.7	989
NNSS (19)	89.9	242.6	0.0171	349.6	10.2	1069
QZSS (184)	42.4	269.3	0.0758	269.1	89.6	35,787
QZSS (189)	0.02	188.6	0.0002	271.7	154.3	35,787

In this study, the LEO RS satellites mainly involved 12 designed polar-orbit satellites, a traditional meteorological satellite (MET), and Spire weather satellites. Currently, there are 114 Spire weather satellites in orbit, and about 100 Spire weather satellites have been carrying GNSS RO sounders for atmospheric sounding since 2016; thus, 100 Spire weather satellites were selected to form a RO constellation as the control experimental group. The satellite ID and major orbital roots of the LEO RS satellites are shown in Table 2, in which three representative Spire weather satellites are presented.

Table 2. Main orbital elements of the receiving satellites.

Satellite ID	Inclination/(°)	RAAN/(°)	Eccentricity	Argument of Perigee/(°)	Mean Anomaly/(°)	Height/(km)
RS01	93.6	151	0.0001	90	30	600
RS02	93.9	215	0.0001	90	150	600
RS03	94.6	330	0.0001	90	270	600
RS04	95.5	183	0.0001	90	90	600
RS05	96.6	245	0.0001	90	210	600
RS06	96.9	280	0.0001	90	330	600
RS07	96.5	330	0.0001	90	90	600
RS08	95.9	215	0.0001	90	330	600
RS09	95.3	151	0.0001	90	210	600
RS10	53	15	0.0001	90	330	600
RS11	53	60	0.0001	90	150	600
RS12	53	105	0.0001	90	30	600
MET	98.8	348.5	0.00004	185.7	174.4	827
Spire01	6	198.4	0.00134	155.9	204.1	635
Spire02	51.6	11.3	0.00001	327.4	32.7	388
Spire03	97.6	136.6	0.00224	296.5	63.4	524

2.4. Experimental Programs

Numerical simulation experiments of RO events were conducted by using the above-mentioned TLE orbit data of the GNSS transmitting and LEO receiving satellites to quantitatively analyze the following scientific questions under the existing multi-GNSS conditions.

① To what extent can the multi-GNSS integration increase the number of RO events and their global coverage fraction for a single polar-orbit LEO satellite?

② An RO constellation with how many polar-orbit LEO satellites can achieve the Spire/GPS occultation detection capability and thus can meet the GNWP's basic requirements in terms of the RO event number, timeliness, and global coverage fraction?

In the GNSS RO event simulation, the receiving satellites were divided into 6 groups, i.e., the single traditional meteorology LEO satellite (MET), 3-satellite constellation (RS01-03, 3RS), 6-satellite constellation (RS01-06, 6RS), 9-satellite constellation (RS01-09, 9RS), 12-satellite constellation (RS01-12, 12RS), and 100-satellite constellation (100RS), while the transmitting satellites were divided into 3 groups i.e., single GNSS systems of BDS-3 (30 satellites), GPS (30 satellites), and multi-GNSS (251 satellites). Then, GNSS RO systems combined with the abovementioned receiving and transmitting satellite groups were simulated, long time series of GNSS RO events were calculated by using the methods described in Section 2.1, and the ID number, latitude, longitude, and time of each RO event were stored in occultation tables for statistical analysis.

Specifically, the comparison of the MET/multi-GNSS and MET/BDS-3 RO system performance could be used to analyze the detection capability improvement of multi-GNSS for a single polar-orbit LEO satellite. The comparison of the 3RS/multi-GNSS, 6RS/multi-GNSS, 9RS/multi-GNSS, 12RS/multi-GNSS, and 100RS/GPS RO systems were used to analyze the detection capability of the polar-orbit LEO satellite constellations under the existing multi-GNSS status.

3. Results

3.1. Detection Capability Improvement of Multi-GNSS for a Single Polar-Orbit Satellite

In order to analyze the RO detection capability enhancement of a single polar-orbit satellite by the multi-GNSS integration, the GNSS RO events in five days from 21 to 25 June 2021 were simulated using MET and multi-GNSS satellites' orbital data. The global distribution of the MET/multi-GNSS RO events on 21 June 2021 is shown in Figure 2, in which the red triangles indicate MET/BDS-3 RO events, and the colorful dots indicate the RO events of different GNSS systems marked by the legends. From Figure 2, one can see that on 21 June 2021, there were 568 MET/BDS-3 RO events sparsely distributed on the Earth while there were 3783 MET/multi-GNSS RO events that occurred, and those RO events formed a more uniform and dense coverage of the Earth.

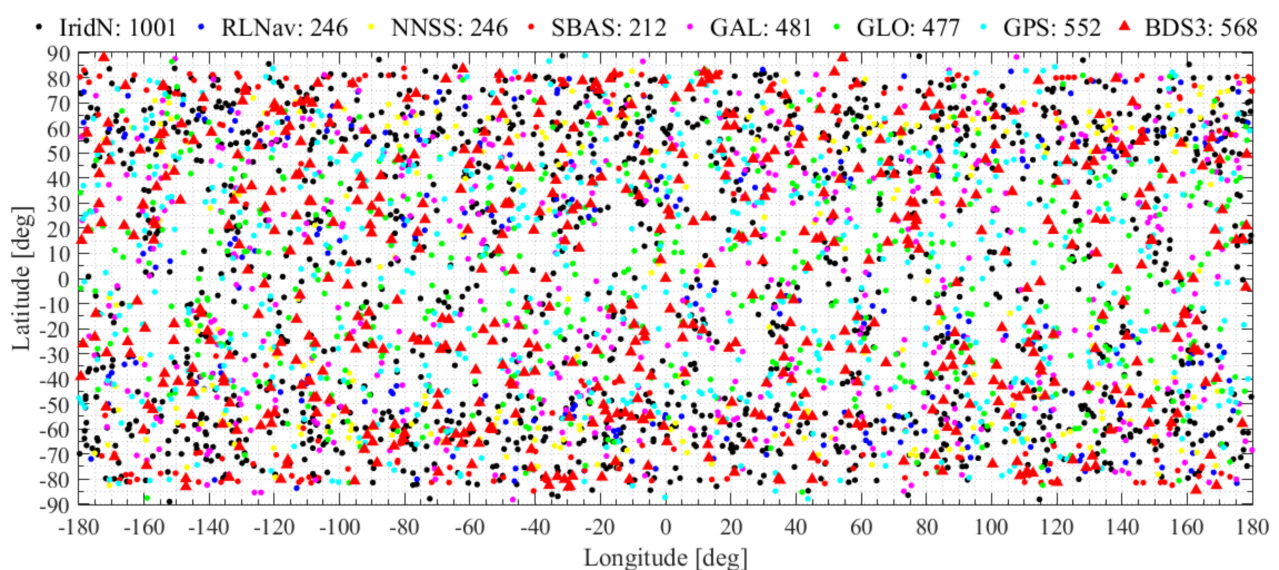


Figure 2. Distribution of the MET/multi-GNSS RO events on 21 June 2021.

To quantitatively analyze the spatial and temporal distribution of each GNSS system RO event, the time series of GCF and UCI of the GNSS RO events were calculated by using the methods introduced in Section 2.2. However, the equal-area projection distorts the world map by angle and length, and the most serious distortion is in the polar regions. The world map distortion makes it difficult to plot the RO events' global coverage using latitude and longitude coordinates. To show the RO events' distribution in a common way and avoid the RO events being counted many times, Figure 3 shows the number of RO event revisits using a $4^\circ \times 4^\circ$ latitude and longitude grid coordinate.

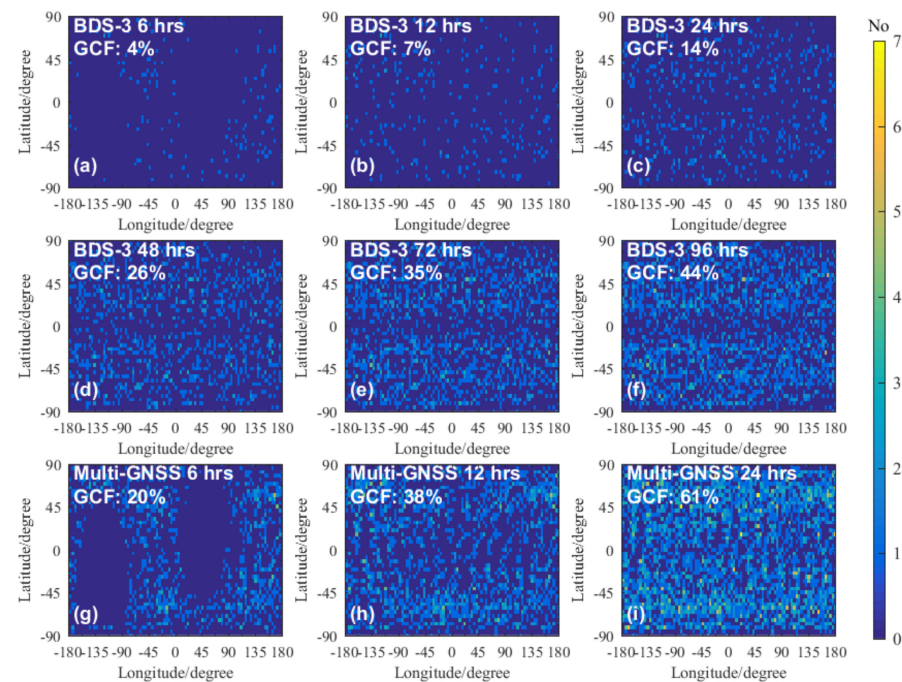


Figure 3. The global coverage of GNSS RO events for MET/BDS-3 and MET/multi-GNSS RO systems, illustrating the number of RO event revisits using a $4^\circ \times 4^\circ$ latitude and longitude grid coordinate.

To further explore the RO detection capability improvement of the integration of multiple GNSS for a single polar-orbit LEO satellite quantitatively, Figures 3 and 4 show the global coverage and the number trend beside the GCF trend of the occultation events for MET/BDS-3 and MET/multi-GNSS RO systems.

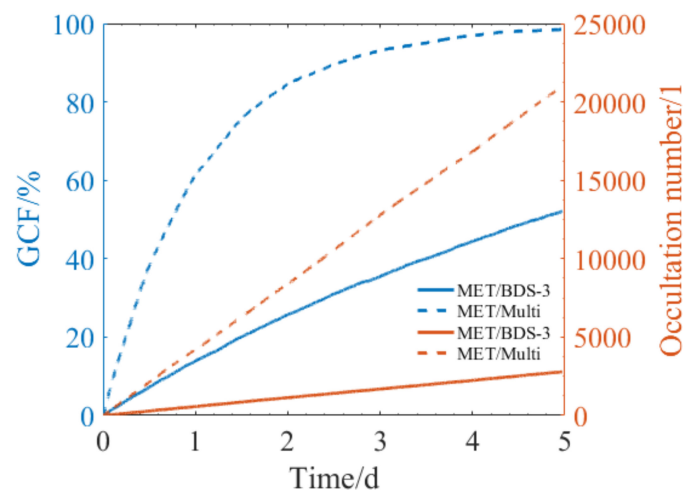


Figure 4. GNSS RO number and global coverage fraction trend for MET/BDS-3 and MET/multi-GNSS RO systems.

Figure 3a–f describe the global coverage situations of the MET/BDS-3 RO events that occurred in 6 h, 12 h, 24 h, 48 h, 72 h, and 96 h, respectively, while Figure 3g–i describe the global coverage situations of MET/multi-GNSS RO events that occurred in 6 h, 12 h, and 24 h, respectively. As shown in Figure 3, the GCF of RO events gradually increased with time accumulation, and the GCF values of MET/BDS-3 RO events that occurred in 6 h, 12 h, 24 h, 48 h, 72 h, and 96 h were 4%, 7%, 14%, 26%, 35%, and 44%, respectively, while the GCF values of the MET/multi-GNSS RO events that occurred in 6 h, 12 h, and 24 h were 20%, 38%, and 61%, respectively. Comparing the performance of the two RO systems, one can see that the GCF of MET/multi-GNSS RO events in 24 h was about four times that of the MET/BDS-3. Furthermore, the GCF of the MET/multi-GNSS RO events in 24 h was larger than that of MET/BDS-3 RO events in 96 h, and its maximum number of RO event revisits was also higher. However, as shown in Figure 3g, the GCF of 6 h MET/multi-GNSS RO events was only 20%, which could not meet the requirements of GNWP for RO data volume and timeliness.

There were two blank regions in the 6 h GNSS RO Figure 3a,g. These distinct performances of the GNSS RO event distribution and uniformity were caused by the limitations of the short time interval and LEO satellite number. The single meteorology LEO satellite's orbital period was about 1.69 h, which means it can only run about 3.55 circles around the Earth in 6 h; therefore, its track could not cover the entire Earth's surface in such a short time. Furthermore, the meteorology LEO satellite's orbit track and velocity were along the longitude direction, and the GNSS RO events occurred in the fore and back occultation antenna fields of view; therefore, the GNSS RO events distributed along the longitude as shown in Figure 3a,g.

Figure 4 illustrates the occultation number trend beside the GCF trend of the MET/BDS-3 and MET/multi-GNSS RO systems. As shown in Figure 4, the occultation numbers were proportional to time, and their growth rates were about 540 and 4200 events per day, respectively, while the 5 day cumulative occultation numbers were about 2700 and 21,000, respectively. The GCF increased with time accumulation, and the 5 day cumulative occultation GCFs were about 52% and 99%, respectively. Therefore, the multi-GNSS integration could significantly increase the occultation number and GCF of a single polar-orbit LEO satellite. Specifically, the occultation number and the growth rate of the MET/multi-GNSS RO system were about 7.8 times as many as those of the MET/BDS-3 RO system.

3.2. Comparing Polar-Orbit Constellation Detection Capability with the Spire Constellation

In order to explore the RO detection capabilities of the constellations with polar-orbit satellites and the Spire/GPS RO system including 100 Spire weather LEO satellites quantitatively, Figures 5 and 6 show the global coverage and the number trend beside the GCF trend of the RO events for 100RS/GPS, 6RS/multi-GNSS, and 12RS/multi-GNSS constellations in 6 h, 12 h, and 24 h.

As shown in Figure 5a–c, the GCF value of the 100RS/GPS RO events in 6 h reached 94% and formed a uniform global coverage, which could basically meet the requirements of the RO number and timeliness for the GNWP for which products are released in every 6 h. The 12 h and 24 h 100RS/GPS RO events' GCF values could reach 100%, and the number of RO event revisits for a single-grid cell in the mid-latitude zones could reach more than 40.

As shown in Figure 5d–f, the GCF values of 6RS/multi-GNSS RO events in 6 h, 12 h, and 24 h were 75%, 95%, and 99%, respectively, which were smaller than those of the 100RS/GPS system, and their global coverage uniformity was also poor compared with the 100RS/GPS system. Figure 5g–i show that the GCF values of the 12RS/multi-GNSS RO events in 6 h, 12 h, and 24 h were 90%, 99%, and 100%, respectively. Therefore, the 24 h GCF value of the 12RS/multi-GNSS RO events was comparable to the 100RS/GPS RO system. Regarding the number of the RO event revisits, the 12RS/multi-GNSS constellation performed higher in polar regions but lower in middle- and low-latitude zones than the 100RS/GPS RO system.

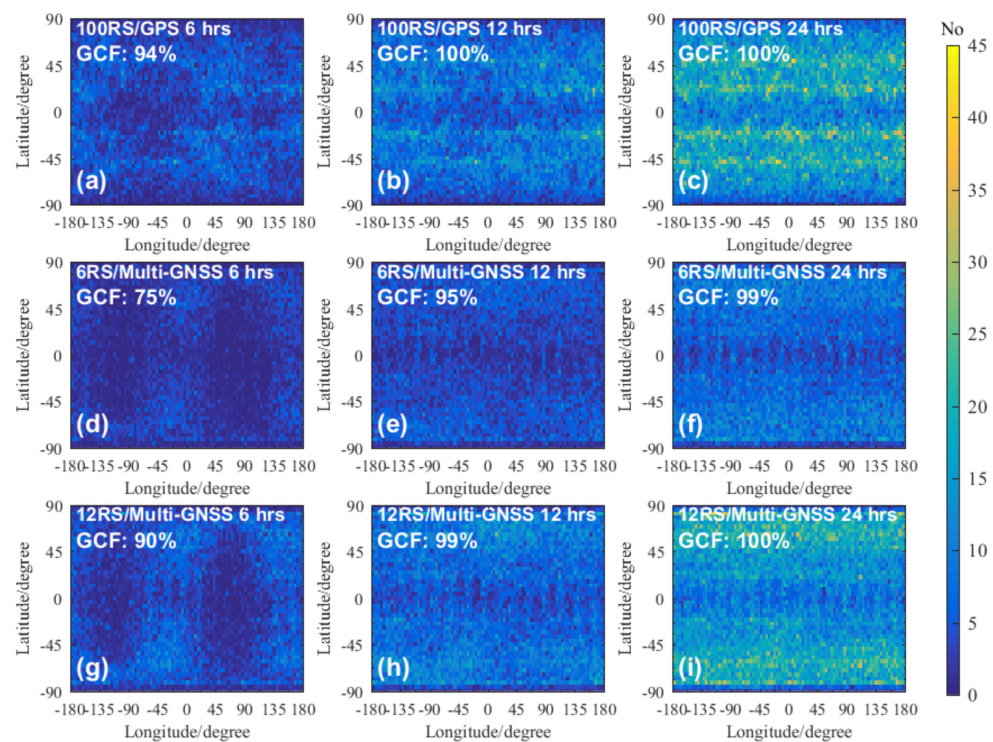


Figure 5. The global coverage of GNSS RO events for 100RS/GPS, 6RS/multi-GNSS and 12RS/multi-GNSS RO systems, illustrating the number of RO event revisits using a $4^\circ \times 4^\circ$ latitude and longitude grid coordinate.

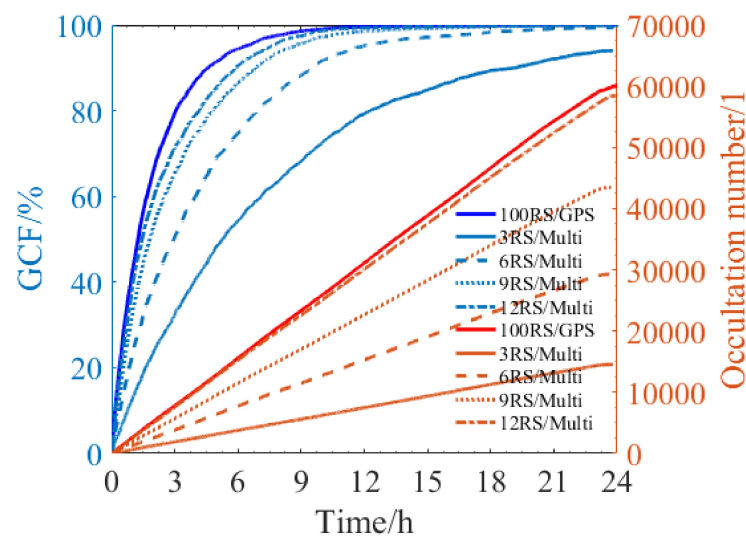


Figure 6. Occultation number and global coverage fraction trend of 100RS/GPS and polar-orbit RS constellation/multi-GNSS RO events.

Figure 6 illustrates the occultation number trend beside the GCF trend of the RO events for 100RS/GPS, 3RS/multi-GNSS, 6RS/multi-GNSS, 9RS/multi-GNSS, and 12RS/multi-GNSS RO systems within 24 h. As shown in Figure 6, with the increase in the number of polar-orbit RS satellites, the slope of the occultation number and GCF curves increased significantly; particularly, the curves of 12RS/multi-GNSS and 100RS/GPS RO systems were similar to each other, and in some time intervals, the corresponding occultation number lines and GCF curves overlapped. This indicates that in the multi-GNSS combination scenario, the RO detection capability of RS constellation composed of 12 polar-orbit LEO satellites was basically comparable to that of the 100RS/GPS RO system. Specifically, both

the 12RS/multi-GNSS and 100RS/GPS RO systems achieved a global coverage fraction of 100% in about 12 h, and the daily RO event numbers reached more than 60,000, which could meet the basic requirements of global numerical weather prediction for occultation data volume and timeliness.

Table 3 presents the RO events' global coverage fraction UCI(1) and global coverage uniformity UCI(m) data for the seven RO detection systems in 6, 12, and 24 h. From Table 3, one can see that in the single RS satellite scenario compared with the MET/BDS-3 constellation, the multi-GNSS combination significantly improved the RO event global coverage and uniformity, but the performance was still poor. Even in the multi-GNSS combination scenario, the limitation of the single RS satellite in terms of the RO event spatial and temporal distribution was obvious, which could not meet the requirements of the global numerical weather prediction and climate research.

Table 3. GCF and uniformity of radio occultation events.

	MET/BDS-3/(%)	MET/Multi/(%)	3RS/Multi/(%)	6RS/Multi/(%)	9RS/Multi/(%)	12RS/Multi/(%)	100RS/GPS/(%)
UCI6(1)	4	20	54	75	87	90	94
UCI6(m)	4	20	54	51	47	45	54
UCI12(1)	7	38	79	95	99	99	100
UCI12(m)	7	38	50	48	45	43	55
UCI24(1)	14	61	94	99	100	100	100
UCI24(m)	14	28	44	40	46	44	57

In the multi-GNSS combination scenario, when the number of the RS satellites increased from one to three, the UCI(1) and UCI(m) indices increased significantly. With the RS satellite number increase, the UCI(1) parameter increased monotonously, but the UCI(m) parameter showed a gradual decreasing trend with fluctuations. The UCI(1) parameter of the 12RS/multi-GNSS system was comparable to that of the 100RS/GPS RO system; however, the UCI(m) parameter of 12RS/multi-GNSS was smaller than that of the 100RS/GPS RO system. This indicates that although the global coverage fraction of 12RS/multi-GNSS RO events basically reached the level of 100RS/GPS RO system, the global uniformity of the 12RS/multi-GNSS system was worse than that of the 100RS/GPS RO system.

In summary, in the multi-GNSS combination scenario, the occultation constellation composed of polar-orbit RS satellites, with the increase in the number of RS satellites, the number and GCF values of RO events increased significantly. When the number of RS satellites increased to 12, the RO detection capability of the RS12/multi-GNSS RO system could reach that of the 100RS/GPS RO system; specifically, the 24 h RO events GCF could reach 100%, and the global coverage uniformity could reach more than 40%, which could meet the basic requirements of global numerical weather prediction in terms of the RO event number, timeliness, and global coverage fraction.

4. Discussion

From the results, one can see that the number and GCF of the 12RS/multi-GNSS RO events basically reached the level of the Spire/GPS RO system. However, the global coverage uniformity of the 12RS/multi-GNSS RO events was worse. As shown in Figure 5, compared with the Spire/GPS constellation, the number of the RO event revisits of the 12RS/multi-GNSS RO events was smaller at low latitudes and larger at high latitudes.

To investigate the RO event distribution characteristics of the polar-orbit RS constellations in the multi-GNSS combination scenario, all high-orbit TS satellites (i.e., Geosynchronous Orbit (GEO) and Inclined Geosynchronous Orbit (IGSO) satellites) from the existing GNSS satellites, the MEO (Medium Earth Orbit) satellites from the BDS-3 constellation, and the Iridium NEXT constellation were selected to represent the high-orbit, medium-orbit, and low-orbit TS satellites, respectively, for a 24 h RO event simulation analysis. The occultation events' global coverage and GCF values for eight representative

RO systems of MET/GEO, MET/IGSO, MET/MEO, MET/LEO, 12RS/GEO, 12RS/IGSO, 12RS/MEO, and 12RS/LEO are given in Figure 7.

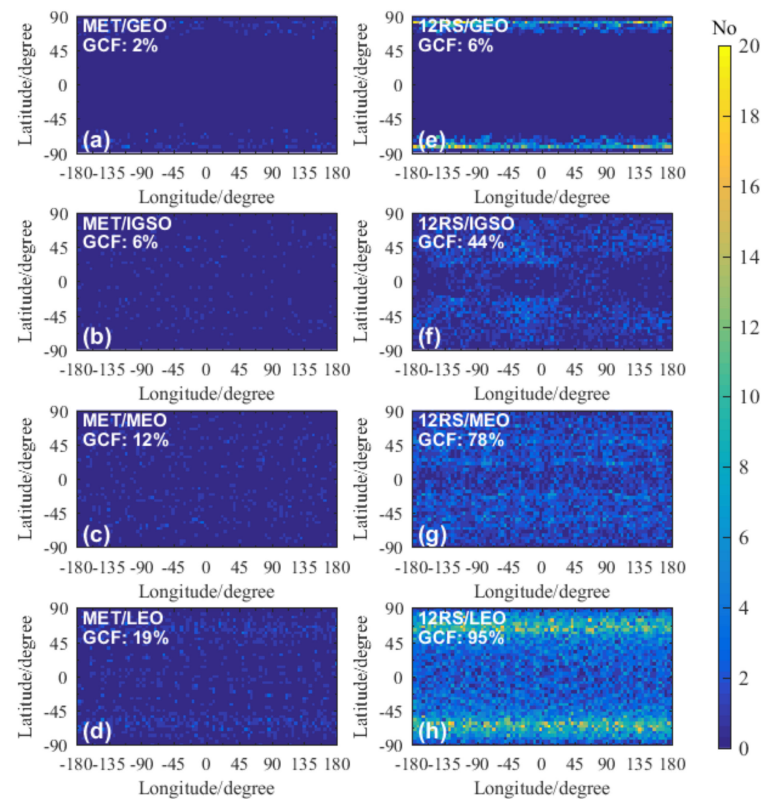


Figure 7. The global coverage of GNSS RO events for MET/GEO/IGSO/MEO/LEO and 12RS/GEO/IGSO/MEO/LEO RO systems, illustrating the number of RO event revisits using a $4^\circ \times 4^\circ$ latitude and longitude grid coordinate.

As shown in Figure 7, the polar-orbit RS/GEO RO events were mainly distributed in the polar regions, increasing the number of RO event revisits in these regions; however, there were almost no RO events located in the middle- and low-latitudes zones (i.e., the area between $\pm 60^\circ$). Therefore, the polar-orbit RS/GEO RO events were beneficial to the climate change monitoring in the polar regions. The polar-orbit RS/IGSO RO events were unevenly distributed in both latitudinal and longitudinal directions, with more events occurring at middle- and high-latitude regions. The global distribution of polar-orbit RS/MEO RO events was more uniform. The polar-orbit RS/LEO RO events could cover the Earth globally, and there were more RO events in high-latitude areas than in middle- and low-latitude areas. Therefore, a constellation with polar-orbit RS satellites could form a global RO event coverage and was more beneficial for middle- and high-latitude region atmospheric monitoring.

In this paper, we analyzed the detection capabilities of all abovementioned GNSS RO systems for the occultation event number and their spatiotemporal distribution level, which represent the maximum detection capability of those RO systems. Practically, not all the GNSS RO events' atmospheric products can be retrieved from the raw RO observation data successfully with high precision; thus, the low quality and even failure of the RO products retrieval can somehow reduce the RO systems detection capabilities for GCM and GNWP applications. The GNSS RO retrieval and quality control were not the focus of this study, and it may be investigated in our future work.

5. Conclusions

The improvement of the number and global coverage fraction of RO events for a single polar-orbit RS satellite by the multi-GNSS integration, as well as the RO detection capability of the polar-orbit satellite constellations under the conditions of the existing multi-GNSS were quantitatively analyzed. The main conclusions were as follows.

For a polar-orbit RS satellite, compared with the BDS-3, the multi-GNSS integration increased the number of RO events and their growth rate by 6.8 times while increasing the 24 h and 5 day RO events' GCF values by 3 times and 1 time, respectively.

In the multi-GNSS scenario, the RS constellation of 12 polar-orbit satellites could reach the detection capability of the Spire/GPS RO system, and the global coverage fraction of 24 h RO events could reach 100% while the global coverage uniformity could reach 44%, which could meet the basic requirements of global numerical weather prediction in terms of the RO event number, timeliness, and global coverage fraction.

The RO events of polar-orbit RS satellites and constellations with GEO, IGSO, and LEO navigation satellites as TS systems contributed more to the coverage in the middle- and high-latitude regions; thus, they were beneficial to the atmospheric sounding in middle-latitude and polar regions.

According to the requirements of global numerical weather prediction and climate monitoring, a simulation study on the effect of multiple GNSS integration on the number, global coverage fraction, and uniformity of RO events was conducted. In this study, polar-orbit satellites and constellations were designed, and 100 Spire weather satellites were selected to form the receiving satellite systems, in addition to the GNSS, regional navigation satellite system, and Iridium NEXT constellations that were selected to form the multi-GNSS transmitting satellite systems. The assessment approaches and quantitative results were significant to provide references for the design of GNSS RO constellations, receivers, and satellite platforms in the multiple GNSS scenario.

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