Postprint of Simulation Study on GRO and LRO Occultation Events

Authors: Wang Shuzhi, Liu Congliang, Zhu Guangwu, Bai Weihua, Du Qifei, Sun Yueqiang, Xia Junming, Meng Xiangguang, Wang Xianyi, Zhao Danyang, Wang Dongwei, Cai Yuerong, Wu Di

Date: 2017-01-22T00:00:00+00:00

Abstract

The joint networking of GRO (Global Navigation Satellite System Radio Occultation) and LRO (Low Earth Orbit Radio Occultation) for Earth atmospheric sounding represents the primary development direction of radio occultation technology. This paper introduces the mathematical criteria for occultation events and conducts simulation analysis on the influence of main orbital parameters of LEO satellites on the quantity and global distribution of GRO and LRO occultation events. The research demonstrates that: the lower the satellite orbit, the greater the number of GRO occultation events; when the orbital inclination is between 30° and 75°, more GRO occultation events occur and global coverage is also greater; when utilizing polar-orbiting satellites for LRO occultation sounding, LRO occultation events are relatively uniformly distributed across various latitude bands. The research findings provide valuable reference for the joint constellation design of GRO and LRO.

Full Text

Simulation Study on GRO and LRO Occultation Events

Shuzhi Wang, Congliang Liu*, Guangwu Zhu, Weihua Bai, Qifei Du, Yueqiang Sun, Junming Xia, Xiangguang Meng, Xianyi Wang, Danyang Zhao, Dongwei Wang, Yuerong Cai, Di Wu

National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China

Abstract

Combining Global Navigation Satellite System Radio Occultation (GRO) and Low Earth Orbit Radio Occultation (LRO) for networked atmospheric sounding represents a primary development direction for radio occultation technology. This paper introduces the mathematical criteria for occultation events and conducts simulation analyses of how key LEO satellite orbital parameters affect the quantity and global distribution of both GRO and LRO events. The results demonstrate that lower LEO satellite altitudes yield more GRO events; when orbital inclination falls between 30° and 75°, GRO events are more numerous with broader global coverage; and when using polar-orbiting satellites for LRO sounding, LRO events distribute relatively uniformly across latitude bands. These findings provide valuable reference for the design of combined GRO and LRO satellite constellations.

Keywords: Radio occultation event, GRO, LRO, LEO, Orbital parameter

0 Introduction

Radio occultation (RO) technology originated from planetary atmospheric 探测 [1-3]. GNSS RO (Global Navigation Satellite System Radio Occultation, GRO) has since achieved substantial development, most notably through the COSMIC occultation constellation jointly launched by the United States and Taiwan. The COSMIC I constellation operated successfully for nearly a decade, and the COSMIC II program has already commenced [13], with its observational data widely applied in numerical weather prediction and global climate monitoring [4,5]. Concurrently, to effectively address remaining challenges in GRO technology such as water vapor ambiguity, nations worldwide have pursued LEO-LEO (Low Earth Orbit) inter-satellite occultation 探测 (LRO) as an important complement to GRO, proposing multiple LRO 探测 plans and conducting in-depth explorations toward combined GRO and LRO atmospheric sounding.

Major proposed LEO-LEO occultation plans include Europe' s ACE+ (Atmosphere and Climate Explorer) [6] and ACCURATE (Atmospheric Climate and Chemistry in the UTLS Region And climate Trends Explorer) [7], and the United States' ATOMMS (Active Temperature, Ozone and Moisture Microwave Spectrometer) [8]. All three plans have conducted feasibility studies for LRO and proposed the concept of combined GRO and LRO atmospheric sounding.

[Figure 1: see original paper] illustrates the schematic diagram of GRO and LRO occultation 探测, while presents the LEO satellite orbital parameters for the ACE+ plan [8].

LEO satellite orbit design constitutes one of the key challenges in implementing combined GRO and LRO atmospheric sounding. Domestic scholars have conducted simulation studies on how LEO orbital altitude and inclination affect the quantity and distribution of both GRO and LRO events [8-12], though most analyses have examined GRO and LRO events separately. Given the respective technical advantages of GRO and LRO, along with successful operational experience from GRO constellations such as COSMIC, networked GRO and LRO constellations represent the primary approach and development direction for enhancing radio occultation 探测 capabilities.

Addressing this need, this paper presents simulations of LEO orbital parameter effects on GRO events, models LRO event scenarios for LEO-LEO constellations, and analyzes how orbital inclination affects occultation events in combined GRO and LRO networked 探测.

1 Mathematical Model for Occultation Events

A descending (or ascending) occultation event forms when signals transmitted from a satellite-borne transmitter pass through Earth' s atmosphere and are received by a receiver onboard a LEO satellite, scanning the atmosphere from top to bottom (or bottom to top) as the transmitter and receiver satellites move relative to each other. GNSS-LEO occultation 探测 utilizes LEO satellites to receive signals transmitted by GNSS satellites, whereas LEO-LEO occultation 探测 requires establishing a complete signal transmission-reception system, namely adding LEO satellites equipped with transmitters. Since various perturbation forces have minimal impact on satellite orbits over short timescales, they are not considered in this orbital simulation.

According to the definition of occultation events, specific geometric relationships between the transmitter and LEO satellites must be satisfied. Determining whether an occultation event occurs involves two main considerations: first, establishing whether the LEO and transmitter satellites satisfy the geometric relationship required to form an occultation; and second, verifying whether the line-of-sight between the LEO and transmitter satellites falls within the antenna field of view.

In the simulation, the receiver antenna has a half-power beamwidth of in the horizontal direction and in the elevation direction, with the receiver antenna boresight vector aligned with or opposite to the LEO satellite velocity vector. Based on these occultation criteria, the following mathematical model is established:

(1) Define _LR as the angle between the line from the LEO satellite to Earth' s surface tangent and the line connecting the LEO satellite to Earth' s center; define _TxRx as the angle between the line from the LEO satellite to the top of the 探测 atmosphere and the line connecting the LEO satellite to Earth' s center; define the angle between the line connecting the LEO receiver and transmitter satellites and the line connecting the LEO satellite to Earth' s center. The following condition should be satisfied: _min _TxRx _max ([Figure 2: see original paper]a).

(2) Define V_Rx as the velocity vector of the LEO receiver satellite, and let the projection of the line connecting the transmitter and receiver satellites onto the orbital plane along V_Rx be . Define as the angle between and V_Rx. The following condition should be satisfied: _max ([Figure 2: see original paper]b).

(3) Define the elevation angle as the angle between the line connecting the

transmitter and receiver satellites and the LEO-to-Earth-center line ([Figure 2: see original paper]c). The following condition should be satisfied: _max.

When all three conditions are satisfied simultaneously, an occultation event occurs. [Figure 2: see original paper]d illustrates a descending LEO-LEO occultation event.

Since LEO-LEO occultation 探测 employs X, K, and Ku band electromagnetic waves that are readily absorbed by Earth' s atmosphere, both transmitters and receivers use high-gain antennas with narrow fields of view. To satisfy these three necessary conditions for occultation events, the transmitting and receiving satellites for LRO 探测 must be deployed in orbits with different altitudes, small orbital plane inclination differences (approaching zero), and opposite motion directions. In this configuration, a transmitter-receiver LEO satellite pair can perform two descending and two ascending occultation observations per orbital period. [Figure 2: see original paper]d shows a descending LEO-LEO occultation event.

When the above three criteria are satisfied, an occultation event is confirmed, and the tangent point latitude/longitude, tangent point altitude above Earth' s surface, and occultation event start/end times can be calculated from satellite orbit determination data. Statistical analysis of the global distribution of occultation events over specified time periods can then be performed based on these spatiotemporal parameters.

2 Simulation of Occultation Events

This paper simulates occultation events for three scenarios: (1) the effect of orbital parameters of a single inclined-orbit LEO satellite on the quantity and distribution of GRO events; (2) simulation analysis of LRO event quantity and distribution for a constellation of six LEO satellites; and (3) analysis of how different orbital inclinations affect GRO event quantity and distribution when combining one inclined-orbit and one polar-orbit LEO satellite.

Since GPS and GLONASS satellite constellations are continuously evolving, with Galileo and BDS also completing their deployments, this simulation adopts nominal global navigation constellation configurations: 24 GPS satellites, 24 GLONASS satellites, 30 Galileo satellites, and 35 BDS satellites.

2.1 Simulation Analysis of GRO Events for a Single Inclined-Orbit LEO Satellite

In the simulation, the GRO receiver antenna parameters installed on a single inclined-orbit LEO satellite are configured as shown in .

** GRO Receiver Antenna Parameters**

First, we analyzed the effect of satellite orbital altitude on GRO events. [Figure 3: see original paper] shows the daily number of GPS occultation events acquired by a single LEO satellite as a function of altitude at an inclination of 50°.

The results indicate that as LEO satellite altitude increases from 400 km to 1600 km, the number of GPS occultation events decreases overall, dropping by over 30% at 1600 km. This demonstrates that lower LEO satellite altitudes are more favorable for GNSS-LEO limb sounding.

Therefore, when designing LEO satellite orbital altitude, lower altitudes should be selected when feasible. However, since RO performs limb sounding of the atmosphere below the receiver altitude, and many forecasting and research requirements must also consider ionospheric sounding altitudes, an orbital altitude of approximately 800 km is recommended for GNSS-LEO inclined-orbit LEO satellites in practical applications and simulation designs.

Second, satellite orbital inclination significantly affects GRO events. [Figure 4: see original paper] shows the daily number of GNSS-LEO occultation events and their global distribution for a single LEO satellite at 800 km altitude with inclinations of 0°, 20°, 30° (top row, left to right), 60°, 75°, and 90° (bottom row, left to right). Red dots indicate GRO event projections on Earth' s surface, while green lines represent coastlines. Additional simulations were performed for other inclination values, with statistical results presented in .

** Statistics of Occultation Event Quantities for Different Inclination Angles**

The results show that when orbital inclination is below 30°, the number of GNSS atmospheric occultation events is significantly lower than at other inclinations. For inclinations between 30° and 75°, the event count fluctuates within a small range with increasing inclination, with approximately 1550 events per satellite per day. From the perspective of event count and overall distribution, satellites at 30°, 70°, and 75° inclinations achieve higher detection numbers. Regarding global distribution uniformity of single LEO satellite daily GNSS-LEO occultation events, coverage gradually expands from equatorial regions toward the poles as inclination increases from 0° to 90°, with global coverage progressively improving.

2.2 Simulation Analysis of LEO-LEO Occultation Events

Since LEO-LEO occultation occurs between LEO satellites, orbital parameter configuration primarily aims to maximize LEO-LEO event quantity and distribution uniformity. This requires rapid changes in relative satellite positions and balanced distribution distances.

In the simulation, circular orbits are adopted. To adequately accommodate both GNSS occultation 探测 and ionospheric sounding, transmitter satellites are set at 800 km altitude and receiver satellites at 650 km altitude.

For orbital inclination, LEO-LEO event quantity peaks when the receiver satellite’ s inclination complements the transmitter satellite’ s inclination, reaching maximum when both transmitter and receiver inclinations are 90° [9]. Due to nodal precession caused by Earth’s non-spherical gravitational field, inclinations other than 90° produce different precession rates for the two satellite groups at different altitudes, preventing stable co-planar counter-rotating configurations. However, polar orbits at 90° inclination have zero nodal precession, maintaining stable orbital geometry. Therefore, LEO-LEO constellation inter-satellite occultation 探测 satellites are configured with 90° inclination (polar orbits).

For right ascension of the ascending node (RAAN), event count maximizes when the transmitter and receiver satellite RAANs differ by approximately 120° or 240° [9]. However, from an engineering perspective, since the altitude difference between transmitting and receiving LEO satellites is only a few hundred kilometers (unlike the >10,000 km difference in GNSS-LEO), the transmission angle is limited. To ensure the transmitted signal can be received by the receiver antenna, transmitter and receiver satellites should be positioned in opposite orbital planes, i.e., RAAN difference of 180° is optimal.

In the simulation analysis, six polar-orbiting satellites are configured in two groups (three transmitter satellites and three receiver satellites), uniformly distributed within each orbital plane at 120° phase intervals. The two groups share the same orbital plane but operate at different altitudes with counter-rotating motion. Orbital parameters are listed in .

** LEO-LEO Occultation Constellation Orbital Parameters**

[Figure 5: see original paper] shows global LRO event distribution and statistical results across latitude bands (with Earth uniformly divided into 10 latitude bands) for time periods of 24, 72, and 144 hours. Purple triangles indicate LRO event projections on Earth’ s surface, with upward triangles representing ascending occultations and downward triangles representing descending occultations; green lines show coastlines.

** Statistics of Orbital Inclination and Occultation Event Counts**

The results demonstrate that with the polar orbit configuration specified in , LRO events distribute relatively uniformly across the globe, achieving uniform global coverage as time accumulates.

2.3 Statistical Analysis of GRO Events for Combined Inclined-Orbit and Polar-Orbit LEO Satellites

To further analyze global coverage of GRO events in combined GRO and LRO 探测, we conducted statistical analysis of GRO events using one polar-orbit satellite and one inclined-orbit satellite.

In the analysis, Earth’ s surface was divided into 300 km × 300 km grids to analyze daily global surface coverage of GRO events for combined single inclined-orbit and single polar-orbit LEO satellites at various inclinations. Statistical results are presented in .

** Global Grid Coverage of Occultation Events for Different Inclination Satellites Plus Polar-Orbit Satellite**

The results indicate that when the inclined-orbit satellite' s inclination is below 30°, global coverage is significantly lower than at other inclinations. For inclinations between 30° and 75%, coverage variation is minimal.

[Figure 6: see original paper] shows the distribution of occultation events across latitude bands (with Earth uniformly divided into 18 latitude bands) for combined single inclined-orbit and single polar-orbit satellite 探测 at 800 km altitude with inclinations of 0°, 20°, 30° (top row, left to right), 60°, and 75° (bottom row, left to right).

The results show that for GRO events, total event count is lower and concentrated in equatorial regions when inclination is below 30°. For inclinations between 30° and 75°, event counts are higher and more uniformly distributed globally, with particular concentration in mid-latitude regions.

3 Conclusions

Based on the above simulation and analysis of GRO and LRO occultation events, the following conclusions can be drawn (quantitative results are presented in figures and tables throughout the paper):

(1) With fixed orbital inclination, lower LEO satellite altitudes facilitate limb sounding and produce greater numbers of GRO events. With fixed orbital altitude, GRO event counts are higher and more globally uniformly distributed when inclination falls between 30° and 75°.

(2) When inclined-orbit and polar-orbit LEO satellites conduct joint atmospheric sounding, global coverage is greater for inclinations between 30° and 75°.

(3) For LRO occultation 探测, configuring transmitter and receiver satellites in polar orbits readily satisfies the three mathematical criteria for occultation events, resulting in uniform global distribution of LRO events.

Furthermore, combined GRO and LRO 探测 enhances global occultation event coverage. These results provide theoretical reference value for constellation design in combined GRO and LRO networked atmospheric sounding missions.

References

[1] A. Kliore, D. L. Cain, S. Gerald et al., "Occultation experiment: results of the first direct measurement of mars' s atmosphere and ionosphere," *Science*, vol. 149, pp. 1243-1248, 1965.

[2] J. L. Elliot, and C. B. Olkin, “Probing planetary atmospheres with stellar occultations,” *Science*, vol. 24, pp. 89-123, 1996.

[3] A. Kliore, L. C. Dan, G. Fjeldbo et al., “Preliminary results on the atmospheres of io and jupiter from the pioneer 10 s-band occultation experiment,” *Science*, vol. 183, pp. 323-324, 1974.

[4] 王树志, 朱光武, 白伟华 et al., “风云三号 C 星全球导航卫星掩星探测仪首次实现北斗掩星探测,” 物理学报, vol. 64, no. 8, pp. 089301(1-8), 2015.

[5] 王大钊, 白伟华, 孙越强 et al., “ROPP 反演软件算法及其精度分析,” 空间科学学报, vol. 35, no. 3, pp. 350-355, 2015.

[6] S. Schweitzer, G. Kirchengast, M. Schwaerz et al., “Thermodynamic state retrieval from microwave occultation data and performance analysis based on end-to-end simulations,” *Journal of Geophysical Research*, vol. 116, no. D10, 2011.

[7] J. J. Harrison, P. F. Bernath, and G. Kirchengast, “Spectroscopic requirements for ACCURATE, infrared-laser occultation satellite mission,” *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 112, no. 14, pp. 2347-2354, 2011.

[8] 吕华平, 严卫, 王迎强 et al., “LEO-LEO 掩星事件仿真研究,” 遥感信息, vol. 30, no. 2, pp. 65-70, 2015.

[9] 杜晓勇, 符养, 薛震刚 et al., “卫星轨道参数对 LEO-LEO 掩星事件数量及分布影响的模拟研究,” 地球物理学报, vol. 50, no. 5, pp. 1289-1297, 2007.

[10] 徐晓华, 李正航, and 罗佳, “单颗 LEO 卫星轨道参数对 GPS 掩星事件分布和数量影响的模拟研究,” 武汉大学学报（信息科学版）, vol. 30, no. 7, pp. 609-612, 2005.

[11] 赵世军, 孙学金, 朱有成 et al., “LEO 卫星轨道参数对 GPS 掩星数量和分布的影响,” 解放军理工大学学报, vol. 3, no. 2, pp. 85-89, 2002.

[12] 王先毅, 孙越强, 白伟华 et al., “北斗掩星事件数量与分布的模拟研究,” 地球物理学报, vol. 56, no. 8, pp. 2522-2530, 2013.

[13] S. Y. Chen, C. Y. Huang, Y. H. Kuo et al., “Assimilation of GPS refractivity from FORMOSAT-3/COSMIC using a nonlocal operator with WRF 3DVAR and its impact on the prediction of a typhoon event,” *Terr. Atmos. Ocean. Sci.*, vol. 20, no. 1, pp. 133-154, 2009.