Coverage of Ground-Based Optical Networks for Cislunar Space Monitoring*

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Abstract

To meet the requirements of cislunar space object monitoring and cataloging, research is conducted on networking strategies for ground-based optical equipment, with further analysis of the limitations of ground-based optical monitoring. First, based on the distances and motion characteristics of cislunar objects, the detectability of ground-based stations is preliminarily analyzed, and a station deployment strategy for key airspace near the Moon is proposed accordingly. Subsequently, the geometric, optical, and equipment-capability conditions involved in optical observation are precisely modeled, and evaluation metrics for the coverage capability of a monitoring network are proposed for search and discovery as well as catalog maintenance. Finally, a networking scheme design and coverage capability evaluation are carried out for Lenghu Astronomical Observatory in China, while continuous invisible periods and blind zones caused by factors such as the lunar phase cycle are analyzed and explained. The related research results can provide a reference for the deployment of ground-based optical monitoring equipment for cislunar space and the establishment of an integrated space-ground monitoring system.

Full Text

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Coverage of Ground-Based Optical Networks for Cislunar Space Monitoring*

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Abstract In response to the requirements of cislunar-space target monitoring and cataloging, this study investigates strategies for networking ground-based optical equipment and further analyzes the limitations of ground-based optical monitoring. First, based on the distances and motion characteristics of cislunar targets, the detectability of ground-based stations is preliminarily analyzed, and station-deployment strategies for key regions near the Moon are proposed accordingly. Then, the geometrical, optical, and equipment-capability conditions involved in optical observations are modeled in detail. With search and discovery as well as catalog maintenance as the objectives, evaluation metrics for monitoring-network coverage capability are proposed. Finally, focusing on astronomical sites at Lenghu in China, network-design schemes and coverage capability evaluations are carried out; meanwhile, the continuous non-visible periods and blind zones caused by factors such as the lunar phase period are analyzed and explained. The results of this research can provide a reference for the deployment of ground-based optical monitoring equipment for cislunar space and for the establishment of an integrated space–ground monitoring system.

Keywords Astronomical measurement; Earth; Moon; Method: numerical

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1 Introduction

Cislunar-space monitoring and cataloging are safeguards for the safety of cislunar-space activities[1–2]. Because optical telescopes have relatively high technological maturity and low operating costs, they have long been the principal means for monitoring and cataloging distant non-cooperative targets[3]. Existing ground-based optical monitoring systems are oriented toward near-Earth space targets within geostationary Earth orbit (Geostationary Earth Orbit, GEO), and cannot simultaneously meet monitoring requirements for the broader spatial extent of cislunar space, fainter targets, and avoidance of complex moonlight background[4]. At present, it is necessary to take into account the characteristics of cislunar-space targets and analyze the coverage capabilities and limitations of ground-based optical monitoring. On this basis, through such approaches as improving telescope detection capability, constructing monitoring networks, and developing other detection technologies, an integrated space–ground spatiotemporal-coverage monitoring system that satisfies the needs of cislunar-space monitoring can be formed.

Compared with near-Earth space, using ground-based optical telescopes to monitor faint moving targets in cislunar space faces multiple challenges[4–5]. First, the increased detection distance makes targets fainter; for the same target, the apparent magnitude is about 5 magnitudes higher than in near-Earth space. Second, most cislunar target orbits are located near the Earth–Moon line, so the influence of the moonlight background cannot be avoided. At the same time, the orbital motions of the Sun, Earth, and Moon introduce multiple periodic effects into the observing geometry, making the distribution of target-detection windows more complex. Finally, the high nonlinearity of orbital motion in cislunar space means that small perturbations in the initial state may cause large deviations in orbit prediction, significantly increasing the likelihood that a target will leave the field of view of the monitoring equipment and be lost after a non-visible interval[6]. At present, research on cislunar-space monitoring mainly focuses on the design of space-based constellations[7–12]. For ground-based optical monitoring, only the advantages of global station deployment along longitude have been discussed from the perspective of continuity in coverage time[13]; there remains a lack of in-depth analysis and full discussion of the capability level and limitations of ground-based optical monitoring systems from the standpoint of cislunar target cataloging requirements.

Aiming at the needs of cislunar-space target monitoring and cataloging, this paper, with respect to

Research has been carried out on networking strategies for ground-based optical equipment, and the limitations of ground-based optical monitoring have been further analyzed. First, based on the distances and motion characteristics of Earth–Moon targets, this paper preliminarily analyzes the detectability of ground-based stations and, on this basis, proposes a station-deployment strategy for key regions near the Moon. Next, for observations involving wide-field telescopes, it accurately models conditions such as geometry, optics, and equipment capability, and proposes coverage metrics for space targets with the goals of search, discovery, and catalog maintenance. Finally, focusing on China' s Lenghu astronomical base, it designs networking schemes and evaluates coverage capability, while also analyzing and explaining continuous periods of invisibility and blind zones caused by factors such as lunar phase cycles. This study can provide a reference for the deployment of ground-based optical monitoring equipment for Earth–Moon space and for establishing an integrated space-ground monitoring system.

2 Detectability Analysis

Ground-based optical observations are comprehensively affected by many factors, including the mutual motion relationships among the Sun, Earth, Moon, and target, the geographic location of the station, the physical properties of the target, and telescope performance. Together, these factors determine the detectability of a specific space target at a given epoch. If the physical properties of the space target and telescope performance are neglected, detectability is mainly determined by the geometric line of sight between the target and the station and by the phase angle. For Earth–Moon space targets, the relative positions of the Sun, Earth, and Moon exhibit different periodic variations, including the lunar orbital period, the Earth' s orbital period, and the period of variation in the lunar-orbit-celestial-equator inclination. Detectability is jointly affected by geometric visibility and illumination conditions; because their coupled effects are difficult to evaluate quantitatively, the problem is simplified here by treating it as the region in which the Moon moves in the sky. In addition, under the influence of Earth' s rotation, the station' s diurnally visible sky region has repeatability and representativeness. Based on the motion characteristics of Earth–Moon space targets, this chapter preliminarily analyzes the detectability of ground-based optical equipment and networks for Earth–Moon space from the two perspectives of visible sky region and observing-arc requirements, providing a reference for the deployment of ground-based monitoring equipment.

2.1 Visible Sky Region Analysis

To describe the detectability of a station with respect to a target, define the horizon angle θ: when a space target passes through the station' s horizon plane, the geocentric angle formed by the target and the station, as shown in Fig. 1(a). Here, θ is a function of orbital altitude. For space targets with orbital altitudes of 2×10^3 km (Low Earth Orbit, LEO), 2×10^4 km (Medium Earth Orbit, MEO), 3.6×10^4 km (GEO), 32×10^4 km (Earth-Moon L1), and 44×10^4 km (Earth-Moon L2), the corresponding values of the horizon angle θ are shown by the blue curve in Fig. 1(b). Fig. 1(c) gives the spherical triangle formed by the station position, the north celestial pole (P), and the target position, where the station longitude is λ_s, the latitude is ϕ_s, the longitude of the target' s sky position is λ_t, the latitude is ϕ_t, and $L \in [0^\circ, 360^\circ)$ is the station' s visible range angle along the right-ascension direction.

Fig. 1 Definition of the horizon angle (a), variations of the horizon angle and the mean angular velocity of a space target with orbital altitude (b), and schematic diagram of the spherical triangle formed by the station position, the north celestial pole, and the target position (c).

Fig. 1 Definition of Horizon Angle (a), variations of Horizon Angle and mean angular velocity with orbital height (b), and diagram of the spherical triangle formed by the station position, north celestial pole and target position (c).

According to the definition of θ, the station's visible sky region is the range of sky in which the geocentric angle between the target and the station is smaller than the corresponding horizon angle; this range increases with orbital altitude. For Earth–Moon distances, θ is approximately 89°, and at a given moment the visible sky region of a single station approaches a 2π celestial sphere centered on that station. Fig. 2(a)-(c) respectively show the visible sky region at a given moment at Earth–Moon distance when the station is located in the equatorial region, a mid-latitude region, and a polar region; the horizontal axis is right ascension and the vertical axis is declination. The coverage ranges of two stations symmetric in latitude and differing by 180° in longitude are shown in the same figure using different colors.

As shown in Fig. 2, for stations in the equatorial and polar regions, the visible sky range along the right-ascension direction is a fixed constant, whereas mid-latitude stations exhibit a tendency for the range to decrease from the hemisphere containing the station toward the opposite hemisphere, and at specific

there are all-coverage regions and uncovered regions in declination. Given the station latitude ϕ_s, the declination ranges ϕ_f and ϕ_u corresponding to the station' s all-coverage region and uncovered region are, respectively:

$$\phi_f = \begin{cases} \phi_t \geq 180^\circ - \phi_s - \theta, \\ \qquad \phi_s \in [90^\circ - \theta, 90^\circ], \\ \phi_t \leq -180^\circ - \phi_s + \theta, \\ \qquad \phi_s \in [-90^\circ, \theta - 90^\circ], \\ \emptyset, \\ \qquad \phi_s \in (\theta - 90^\circ, 90^\circ - \theta), \end{cases} \tag{1}$$

$$\phi_u = \begin{cases} \phi_t \leq \phi_s - \theta, \\ \qquad \phi_s \in [90^\circ - \theta, 90^\circ], \\ \phi_t \geq \phi_s + \theta, \\ \qquad \phi_s \in [-90^\circ, \theta - 90^\circ], \\ (\phi_t < \phi_s - \theta) \cup (\phi_t > \phi_s + \theta), \\ \qquad \phi_s \in (\theta - 90^\circ, 90^\circ - \theta). \end{cases} \tag{2}$$

For a sky region with latitude ϕ_t lying between full coverage and no coverage ($\phi_t \in (-90^\circ, 90^\circ) \setminus (\phi_u \cup \phi_f)$, where "$\setminus$" denotes exclusion), the visible angular range L along the right-ascension direction can be obtained by applying the law of cosines to the spherical triangle shown in Fig. 1(c):

$$\cos(L/2) = \frac{\cos\theta - \cos(90^\circ - \phi_s)\cos(90^\circ - \phi_t)}{\sin(90^\circ - \phi_s)\sin(90^\circ - \phi_t)}, \qquad \phi_s \neq \pm 90^\circ. \tag{3}$$

Because the angle θ corresponding to the Earth-Moon distance is close to 90°, Eq. (3) can be approximated as

$$\cos(L/2) = -\cot(90^\circ - \phi_s)\cot(90^\circ - \phi_t). \tag{4}$$

Using Eq. (4), the station' s diurnal coverage duration for a target sky region with declination ϕ_t is calculated as $D = L/15$ h. Conversely, given the declination ϕ_t of the target coverage sky region and the required coverage duration D, the condition that the station' s geographic latitude must satisfy can be derived as

$$\begin{cases} \phi_s > \arctan[\cos(7.5D)\tan(90^\circ + \phi_t)], & \phi_t \in (0^\circ, 90^\circ), \\ \phi_s < \arctan[\cos(7.5D)\tan(90^\circ + \phi_t)], & \phi_t \in (-90^\circ, 0^\circ), \end{cases} \qquad D \in (0, 24). \tag{5}$$

From Fig. 2 it can be seen that a complementary two-station configuration with symmetric latitudes and longitudes differing by 180° can approximately cover 4π steradians at any time, with only an approximately 0.5° coverage gap at the junction of the two stations' visible sky regions. This two-station layout compensates for the spatiotemporal coverage limitations of a single station and, without considering the influence of other factors, achieves an effect close to all-time, all-sky coverage at Earth–Moon detection distances.

2.2 Analysis of Ground-Based Station-Deployment Strategies

The airspace within 15° of the Moon [14] is the key region of interest for Earth–Moon space monitoring. Considering the monthly variation of the Moon' s orbital motion in the right-ascension direction and the long-term variation of the inclination between the lunar path and the celestial equator within the range $18° \sim 28°$ [15], this paper defines the sky region with Earth–Moon-distance declination range $\phi_t \in (-43°, 43°)$ as the key region. On this basis, from the perspectives of visibility and coverage duration, a preliminary analysis of ground-based station-deployment strategies for the monitoring requirements of this region is carried out as follows:

Figure 2. Visible-sky range at one Earth–Moon distance; the stations are located at the equator (a), mid-latitudes (b), and polar regions (c).

Visible labels in the figure:

- (a) Observer 1: latitude 0°, longitude 0°; Observer 2: latitude 0°, longitude 180°; Uncovered area. Axes: Right Ascension/°, Declination/°.
- (b) Observer 1: latitude 45° N, longitude 0°; Observer 2: latitude 45° S, longitude 180°; Uncovered area. Axis: Right Ascension/°.
- (c) Observer 1: latitude 90° N, longitude 0°; Observer 2: latitude 90° S, longitude 180°; Uncovered area. Axis: Right Ascension/°.

Fig. 2 Visible sky at different latitudes at a distance of one Earth-Moon distance. Equator (a), Mid-Latitude (b), and Polar (c).

For the requirement of daily visibility of the key region. A single station within the latitude range of $\pm 47°$ on Earth can make the key region visible every day.

For the requirement that the daily coverage duration of the key region be D. Since the diurnal coverage length of an equatorial station for the entire key region is approximately

12 h. For the case in which D is less than 12 h, a single station located at latitudes near the equator can satisfy the coverage requirements for the entire key region; the latitude range $\pm\phi_s$ can be calculated from the value of D using Eq. (5). For the case in which D is greater than 12 h, dual-station or multi-station coordination is required at any geographic latitude to meet the coverage-duration requirement for the key region. When the site-environment requirements of optical observations are not considered and only the complementarity of geographic locations is considered, a complementary two-station configuration is the combination with the highest coverage efficiency.

For monitoring low-orbit targets, more stations need to be deployed along the ground-track projection to achieve relay observations. However, for the vast majority of space targets in cislunar space, the angular velocity of motion is slower than that of near-Earth targets, approximately 1/30 of Earth' s rotation rate, as shown by the red curve in Fig. 1(b). For a complementary two-station configuration, the relay observation of targets moving near the Moon can basically be realized under the effect of Earth' s rotation. For a single station, the intermittent data sampling achieved through Earth' s rotation can also satisfy the requirements of orbit calculation in terms of arc-length distribution. Therefore, for orbit-calculation requirements, deploying a single optical instrument within the corresponding latitude range on Earth for monitoring cislunar targets is a relatively cost-effective option. However, if factors such as weather, equipment status, and other influences on the observing window are considered, a complementary two-station scheme can more effectively increase coverage duration, improve monitoring stability and reliability, and reduce the risks introduced by uncertainties.

3 Coverage Simulation of a Ground-Based Optical Monitoring Network

Cislunar-space monitoring is simultaneously affected and constrained by the physical characteristics of targets and the capabilities of observing equipment. Section 2 of this paper analyzed the coverage of ground-based optical monitoring for key regions near the Moon from the perspective of the visible sky region. This section fully considers target characteristics such as size and albedo, as well as the observing capability of ground-based optical telescopes, to establish a simulation model, select suitable detection targets, construct a coverage-evaluation indicator system, and calculate and comparatively analyze the coverage capabilities of a single station and of a network.

3.1 Optical Detection Model

When ground-based optical equipment detects cislunar targets, the following conditions usually need to be satisfied[^5]: there is no obstruction between the station and the target; the telescope operates at night when the sky background is relatively dark; the target is outside the lunar avoidance angle; and the target brightness is higher than the telescope' s limiting detectable magnitude. Converting the above conditions into a mathematical model, a detection function $F(\vec{r}_s, \vec{r}_t, t)$ is defined to represent the detectability state of the target relative to the station at a certain time t, where $\vec{r}_s$ and $\vec{r}_t$ denote the position vectors of the station and the target, respectively. The value of the detection function F is 0 or 1, indicating that the target is undetectable or detectable, respectively. Its expression is as follows:

$$F(\vec{r}_s, \vec{r}_t, t) = \begin{cases} 0, & h < h_0 \text{ or } \psi < \psi_0 \text{ or } \beta > \beta_0 \\ & \text{or } \theta^c < \theta_0^c \text{ or } M^t > M_0, \\ 1, & \text{else.} \end{cases} \tag{6}$$

In Eq. (6), h and β represent the altitude angles of the space target and the Sun, respectively; ψ denotes the angular separation between the Sun and the geocenter with the space target as the reference point; θ^c denotes the angular separation between the target and the Moon with the station as the reference point; and M^t is the apparent magnitude calculated by combining information such as target size and distance. h_0, ψ_0, β_0, θ_0^c, and M_0 are the thresholds of the corresponding characteristic quantities. Schematic diagrams of these characteristic quantities are shown in Fig. 3. In the figure, $\vec{L}_{\text{sun}}$ is the unit vector from the target toward the Sun, $\vec{r}_m$ is the lunar position vector, θ_e represents the geocentric angle between the target and the station, ϕ is the solar phase angle, i.e., the angular separation between the Sun and the station with the target as the reference center, and R_e denotes Earth' s radius. The calculation method for apparent magnitude is given in Section 3.1.3. By comparing these characteristic quantities with their corresponding thresholds, the detectability of the target is comprehensively determined. In Eq. (6), the various decision conditions are divided, according to their properties, into three categories: geometric conditions, optical conditions, and detection conditions. The following subsections introduce the calculation methods or prescribed values of the characteristic quantities and their thresholds in the formula by category.

3.1.1 Geometric Conditions Maintaining an unobstructed line-of-sight state between the space target and the station, and between the space target and the Sun, is a necessary condition for detectability. This condition includes the following two geometric constraints[^16]: the target is above the station horizon, and the target is outside Earth' s shadow and the Moon' s shadow. To reduce atmospheric effects, the target altitude angle being greater than a certain threshold h_0 is usually taken as a detection condition. At the same time, for computational convenience, the target-altitude-angle constraint is converted into a geocentric-angle constraint. θ_0 is the geocentric angle corresponding to h_0, and its calculation method is given in Eq. (7). According to the schematic diagram of Earth' s shadow shown in Fig. 3(b), the calculation of the Earth-shadow avoidance threshold ψ_0 is given in Eq. (8).

$$\theta_0 = \arccos\left(\frac{|\vec{r}_s|}{|\vec{r}_t|}\cos h_0\right) - h_0, \tag{7}$$

$$\psi_0 = \arccos\left(\sqrt{1 - \frac{R_e^2}{|\vec{r}_t|^2}}\right). \tag{8}$$

In Eq. (8), the lunar-shadow avoidance condition can be obtained by replacing the geocenter with the lunar center and replacing Earth' s radius with the lunar radius. The geocentric angle θ and angular separation ψ involved in this section can be obtained by calculating the included angles from the position vectors of celestial bodies, stations, and space targets defined in a unified coordinate system. The other angular separations mentioned below are calculated in the same way.

Figure 3 Schematic diagram of the ground-based optical detection model (a) and the Earth-shadow constraint (b)

Fig. 3 Schematic of ground-based optical detection model (a) and Earth shadow constraint (b)

3.1.2 Optical Conditions

Optical conditions refer to the skylight background produced by the Sun and the Moon. The detectability requirements must satisfy the following optical constraints: the Sun is below the station' s horizon, and the target is outside the Moon-avoidance angle. To obtain a better skylight background, the solar elevation angle is usually set to be smaller than a certain threshold β_0. In this paper, the condition that the solar elevation angle β should satisfy is converted into the condition that, with the station as the center, the angular separation between the Sun and station vectors is greater than $90^\circ + |\beta_0|$.

The lunar avoidance angle θ_0^c is an avoidance cone angle introduced to delimit the range affected by moonlight. Its value is usually set according to the lunar phase, telescope parameters, and target size, with a typical range of $1^\circ \sim 10^\circ$[17-18].

3.1.3 Detection Conditions

The detection capability of the equipment should satisfy the target-brightness requirement, and the limiting magnitude M_0 of the equipment is usually assumed reasonably. The formula for calculating the apparent magnitude of the target is[19]:

$$M^t = M^s - 2.5 \lg \frac{AC\rho(\phi)}{d^2}. \tag{9}$$

where $M^s = -26.73$ is the apparent magnitude of the Sun, A is the effective reflective area of the target, C is the mean reflectivity, and d is the distance between the target and the station. Treating the target as an ideal diffusely reflecting sphere, its effective reflective area is approximately equal to πr^2, where r is the radius of the sphere. The phase function $\rho(\phi)$ of a spherical target is calculated as[19]:

$$\rho(\phi) = \frac{2}{3\pi^2}\left[\sin\phi + (\pi - \phi)\cos(\phi)\right]. \tag{10}$$

3.2 Selection of Monitoring Targets

Two types of monitoring scenarios are assumed:

The airspace formed by a 30° cone along the Earth–Moon line, hereinafter referred to as the conical airspace.

Several major classes of periodic orbits near the Moon, including the southern and northern Halo orbit families near the L1 and L2 Earth–Moon libration points, the planar and vertical Lyapunov orbit families, and the DRO (Distant Retrograde Orbit) family.

The conical airspace is a key corridor connecting the Earth, the Moon, and the L1 and L2 libration points. This region carries the vast majority of Earth–Moon transfer trajectories, such as major space missions including the Artemis program and the Chang' e project, and is also an indispensable route for future activities such as Earth–Moon transportation and deep-space exploration. Periodic orbits near the Moon have unique dynamical characteristics and are ideal parking orbits for cislunar-space missions[20]. For example, the Chang' e-4 relay satellite "Queqiao" uses an L2 Halo orbit, successfully realizing communications relay on the far side of the Moon and providing important support for many deep-space exploration missions. Routine monitoring of targets in the conical airspace and on periodic orbits near the Moon is an important component of cislunar-space target cataloging.

3.2.1 Airspace Anchor Points

For ease of analysis, the conical airspace is discretized into static reference points in the Earth–Moon synodic coordinate system; these are called airspace anchor points, hereinafter referred to simply as anchor points. Each anchor point represents the surrounding airspace, and discretization transforms continuous-space coverage analysis into detectability analysis of anchor points.

Figure 4 shows the distribution of anchor points in the Earth–Moon synodic system. The anchor-point positions are obtained using the following discretization method[14]: first, on the X-axis of the Earth–Moon synodic coordinate system, from twice the GEO altitude to the vicinity of the L2 point, and within the range of ± 0.25 LU on the Y- and Z-axes, 9 points are selected in each of the three axial directions at uniform step sizes. Thus, a total of 729 initial anchor points are obtained in three-dimensional space, where LU is the mean Earth–Moon distance. Then, screening···

located within the 30° cone about the Earth–Moon line. After checking them one by one, 305 anchor points satisfying the criteria were obtained.

3.2.2 Periodic-Orbit Parameters Figure 5 shows several selected major families of periodic orbits. For each family, 10 orbits with different amplitudes are specified; their amplitudes and periodic parameters are given in Table 1. For convenience in the study, serial numbers 1–10 are assigned to orbits in the same family in order of increasing amplitude.

3.2.3 Simulation Procedure For the assumed monitoring scenario, based on the current status of Earth–Moon space detectors and the relevant literature, assumptions were made regarding the shape, size, reflectivity, and other parameters of the anchor points and of the targets moving on periodic orbits [5]. The relevant parameters are listed in Table 2. Among them, the lunar avoidance angle was determined on the basis of measured data. Through statistical analysis of multiple sets of measured data from the Yao' an station and the Lenghu station for a satellite in a DRO orbit, it was found that, under conditions in which the target is visible during the full Moon, the minimum angular separation between the satellite and the Moon is approximately 1.5°. Considering the influence of the mutual motion of the Sun, Earth, and Moon on target detection, a one-year time scale was selected. In combination with ground-based optical detection conditions, the detectability of each anchor point or target by the observing station was simulated. The specific simulation procedure is as follows:

Fig. 4 Distribution of anchor points within the conical domain in the Earth–Moon synodic frame

Fig. 4 Anchor points within the conical domain in the Earth-Moon synodic frame

Fig. 5 Several major periodic orbits in the Earth–Moon synodic coordinate system. (a): southern and northern Halo orbits around L_1; (b): southern and northern Halo orbits around L_2; (c): DRO orbits; (d): planar Lyapunov orbits around L_1 and L_2; (e): vertical Lyapunov orbits around L_1 and L_2.

Fig. 5 Periodic orbits in the Earth-Moon synodic frame. (a): L1 Southern and Northern Halo Orbits, (b): L2 Southern and Northern Halo Orbits, (c): Distant Retrograde Orbits, (d): L1 and L2 Planar Lyapunov Orbits, (e): L1 and L2 Vertical Lyapunov Orbits.

Generate ephemeris data: Based on the Circular Restricted Three-Body Problem (CRTBP) model, generate ephemeris data in the J2000.0 celestial coordinate system for all anchor points and periodic-orbit targets over one year, with an ephemeris interval of 10 min.

Compute detectable arcs: In combination with the ground-based optical detection model and the specific simulation parameters in Table 2, compute, at each discrete time, the observing set—

···the detectability of the anchor points or targets by the equipment, and preliminarily determine the start and end times of each detectable arc segment within the simulation period.

Refine arc-segment boundaries: for each detectable arc segment, use the bisection method to iteratively correct its start and end times, and output the refined arc-segment time.

During the simulation process, we use analytical methods, the Newton–Raphson half-period shooting method, and orbit continuation to compute and generate periodic orbits near the Earth–Moon libration points under the circular restricted three-body problem. Meanwhile, based on equipment performance and the detection model, we simulate the observation data of cislunar-space targets obtained by the telescope.

Table 1 Periodic orbits with primary orbital parameters

Orbit type	Feature	Period/d	Amplitude/(10^3 km)
Halo	L1 Northern	10.61~12.10	0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70
Halo	L1 Southern	10.61~12.10	0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70
Halo	L2 Northern	12.84~14.83	0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70
Halo	L2 Southern	12.84~14.83	0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70
Lyapunov	L1 Planar	11.69 ~26.44	0.5, 1, 2, 5, 8, 10, 20, 30, 40, 50
Lyapunov	L2 Planar	11.69 ~26.44	0.5, 1, 2, 5, 8, 10, 20, 30, 40, 50
Lyapunov	L1 Vertical	12.02~17.28	1, 5, 10, 20, 30, 40, 50, 60, 70, 80
Lyapunov	L2 Vertical	12.02~17.28	1, 5, 10, 20, 30, 40, 50, 60, 70, 80
DRO	/	8.91~26.07	50, 60, 70, 90, 110, 130, 150, 170, 190, 200

Table 2 Modeling and physical parameters for simulation

Item	Parameter	Value
Time span	/	2025-01-01—2026-01-01
Target model	Shape and size	2-meter diameter sphere
Target model	Average reflectance	0.5
Detection model	Target altitude angle threshold h_0	9°
Detection model	Solar altitude angle threshold β_0	$-10°$
Detection model	Lunar exclusion angle θ_0^c	1.5°
Telescope capability	Limiting magnitude	21

3.3 Coverage Evaluation Metrics

This paper decomposes space-monitoring capability into three basic indicators for evaluation: coverage period, coverage duration, and continuous invisible period. These three indicators are evaluation metrics derived from single-target coverage. Coverage refers to whether monitoring equipment can cover a target, and its definition is closely related to the purpose of the space-monitoring mission. For the search and discovery of cislunar targets, this paper proposes a coverage condition: to search for and discover new targets and determine their initial orbits, a detection arc of a certain length is required. Therefore, this paper takes whether the length of the detection arc meets the requirement for batch target initial-orbit computation as the coverage condition.

For the problem of evaluating the coverage capability of N stations for I cislunar-space anchor points/targets within K days, assume that cislunar-space target i has j detectable arcs on the k-th day of the simulation period. Considering that optical monitoring is usually carried out in units of days, this paper also examines it in units of days

coverage of space targets; the j detectable arcs are detectable arc segments independently computed by N stations. Let $t_i^{k,j}$ denote the time interval of the j-th detectable arc of target i on day k, and let T_i^k denote the length of the union of all arc time intervals of target i on day k. For example, Fig. 6 illustrates the method for calculating the daily cumulative detectable arc length for different targets. In the figure, the horizontal axis is time and the vertical axis is the observed target ID. The visible arc segments of a target observed by station 1 and station 2 are denoted by $[A, B]$ and $[C, D]$, respectively, where the subscript number represents the target ID and the asterisk in the superscript is used to avoid duplication. For target 00001, whose arc segments overlap, and target 00002, whose arc segments do not overlap, the method for calculating the daily cumulative detectable arc length is shown in the figure.

Fig. 6 Calculation method for daily cumulative detectable arc length of a single target

Relevant literature and our preliminary exploration of initial orbit determination both indicate that, when the observed arc length of a cislunar space target is approximately 3 h or longer, the stability of initial orbit computation can be effectively ensured[21]. Therefore, the coverage of anchor point/target i on day k is expressed as:

$$D_i^k = \begin{cases} 0, & T_i^k \le 3 \text{ h}, \\ 1, & T_i^k > 3 \text{ h}. \end{cases} \tag{11}$$

Values of D_i^k equal to 0 and 1 indicate non-coverage and coverage, respectively. When space surveillance is aimed at catalog maintenance, according to previous exploratory studies, the 3 h arc length set in Eq. (11) can be relaxed to any observation length.

Coverage period

The coverage period is the number of days during the simulation period for which the proportion of covered targets to the total number of targets satisfies a given numerical value. For multi-target monitoring, it is divided into three cases: full coverage, partial coverage, and zero coverage. Let the symbol B_k denote the number of covered anchor points on day k, with $B_k = \sum_{i=1}^{I} D_i^k$. During the simulation period, the proportion of the number of targets covered on day k to the total number of targets, $x = B_k/I$, forms a set S. Then the expression for the coverage-period metric C_1 is:

$$\begin{cases} C_1^{\text{full}} = \sum_{x \in S} \mathbb{I}(x = 1), \\ C_1^{\text{zero}} = \sum_{x \in S} \mathbb{I}(x = 0), \\ C_1^{\text{part}} = \sum_{x \in S} \mathbb{I}(x \ne 0 \text{ and } x \ne 1). \end{cases} \tag{12}$$

C_1^{full}, C_1^{zero}, and C_1^{part} denote the full-coverage period, zero-coverage period, and partial-coverage period, respectively. The indicator function $\mathbb{I}(x = 1)$ takes the value 1 when $x = 1$, and otherwise takes the value 0; the other expressions have similar meanings. The coverage ratio is the proportion of the coverage period within the simulation period.

Coverage duration

The coverage-duration metric C_2^k is the daily cumulative duration of detectable arcs for covered targets, and its expression is:

$$\begin{aligned} C_2^k &= \sum_{i=1}^{\tilde{I}} T_i^k, \\ \text{s.t.} \quad D_i^k &= 1. \end{aligned} \tag{13}$$

$\tilde{I}$ is the number of covered targets, and s.t. is the abbreviation of "subject to," indicating that the expression is a constraint.

Continuous invisible period

The continuous invisible periods constitute the set E_i formed by the intervals between two adjacent coverage events for a single target, expressed as:

$$
\begin{aligned}
E_i = \{\, k_m - k_n - 1 \mid m < n,\ k_m, k_n \in K,& \\
D_i^{k_m} = 1,\ D_i^{k_n} = 1,& \\
\text{and } D_i^{k_m+1} = 0,\ D_i^{k_m+2} = 0, \cdots,\ D_i^{k_n-1} = 0 \,\}.&
\end{aligned} \tag{14}
$$

The longest invisible period of the target is:

$$C_3^i = \max\{E_i\}.$$

3.4 Simulation Results Analysis

Based on the above model, we calculated the coverage performance of stations and station networks located at different latitudes. Considering the relative motion of the Sun, Earth, and Moon, one year was selected as the duration of the simulation calculation. Because the airspace anchor points are stationary points defined in the Earth–Moon synodic coordinate system, some anchor points located on the Earth–Moon line always fall within the lunar avoidance angle and cannot be detected, which prevents the conical airspace from achieving true full coverage. Therefore, the "full coverage" discussed in this paper is approximate full coverage—that is, full coverage outside the blind zone caused by the moonlight background; the description of the blind zone is given in Section 4.1.3.

3.4.1 Single Monitoring Station

Figure 7(a)-(c) shows the coverage of the conical airspace when the station is located, respectively, at mid-latitudes in the Northern Hemisphere, mid-latitudes in the Southern Hemisphere, and the equator. The horizontal axis represents the lunar phase cycle, and the vertical axis represents the number of days counted by category. Overall, the coverage performance of an equatorial station is better than that of mid-latitude stations, and its annual fluctuation amplitude is smaller. For the Northern Hemisphere station, the full-coverage period is better in winter than in summer, which is opposite to the trend for the Southern Hemisphere station. This phenomenon mainly reflects seasonal variation, namely the influence of the Sun' s changing position on the ecliptic on coverage. When the Sun is north of the celestial equator, the illumination time of Northern Hemisphere stations is longer; conversely, the illumination time of Southern Hemisphere stations is longer. Longer illumination time reduces the time available for ground-based observation and weakens coverage capability. The annual difference in day length at the equatorial station is very small, while the full-coverage period shown in Figure 7(c) also exhibits a slight fluctuation. Analysis indicates that this is caused by the coupled effect of lunar altitude and solar illumination simultaneously reaching favorable positions, forming two small local maxima around the summer solstice and winter solstice.

Figure 7 Variation of the coverage period of a single monitoring station for conical airspace with the lunar phase cycle. In each column, from top to bottom, the periods are full coverage, partial coverage, and zero coverage. (a): The station is located at mid-latitudes in the Northern Hemisphere; (b): the station is located at mid-latitudes in the Southern Hemisphere; (c): the station is located at the equator.

Fig. 7 Single-station coverage period variation for conical airspace across lunar cycles, displaying full, partial, and zero coverage periods in vertical columns (top to bottom). (a): Station located at mid-latitudes in the Northern Hemisphere, (b): station located at mid-latitudes in the Southern Hemisphere, (c): station located at the equator.

Zero coverage occurs within several days near the waning crescent and new Moon. At this time, the Moon lies between the Sun and Earth, and the airspace anchor points in the same direction as the Moon are visible only during daytime; ground-based telescopes therefore do not have observing conditions.

3.4.2 Complementary Dual Stations

Figure 8 shows the coverage of the conical airspace by complementary dual stations. Figure 8(a) corresponds to complementary dual stations at mid-latitudes in the Northern and Southern Hemispheres, while Figure 8(b) corresponds to complementary dual stations on the equator. In this subsection, the complementary dual-station configuration does not consider whether the actual environments of the stations are suitable for deploying optical monitoring stations; it focuses only on the influence of geographic complementarity on coverage. The seasonal fluctuation in the full-coverage period shown by the single monitoring stations in Figure 7 is compensated for and canceled under the complementary dual-station layout in Figure 8, and stable coverage is achieved in every lunar phase cycle.

The above results show that the coverage capability of equatorial stations is superior to that of mid-

latitude stations, whereas a complementary dual-station pair at mid-latitudes can almost completely compensate for the influence brought about by the latitude band, achieving a coverage capability nearly identical to that of an equatorial complementary dual-station pair. These conclusions supplement and corroborate the analysis of the visible celestial region in Section 2.1.

Fig. 8 Coverage performance of the complementary dual-station combination for conical airspace. (a): stations located in the northern and southern hemispheres; (b): stations located at the equator.

4 Simulation Analysis of Networking Schemes Based on the Qinghai Lenghu Station

This section takes the Qinghai Lenghu Astronomical Base in China as the starting point for studying monitoring-network configurations for cislunar space. With reference to high-quality optical monitoring site resources worldwide, various networking schemes are formed around the Qinghai station, and the coverage capability of each scheme is investigated. For the conical airspace considered in this paper, calculation using Eq. (4) shows that the Qinghai station provides about 6 h of coverage for the lowest latitudes of the conical airspace, exceeding the requirement of a 3 h detection arc length. To form a north–south complementary layout with the Qinghai station, three site resources in the mid- and low-latitude regions of the Southern Hemisphere are selected: Western Cape in South Africa, Limari in Chile, and Cocos in Australia. In addition, to form multiple sets of north–south complementary layouts, two sites at mid-latitudes in the Northern Hemisphere are selected: Andalusia in Spain and Hawaii in the United States. The site information and geographic distribution involved in the simulations in this paper are shown in Table 3 and Fig. 9.

Table 3 Locations of globally distributed critical optical monitoring facilities

Station name	Abbreviation	Longitude	Latitude	Region
Qinghai	N1	93.8°	38.5°N	Qinghai, China
Western Cape	S1	20.1°	33.9°S	Western Cape, South Africa
Andalusia	N2	357.3°	37.7°N	Andalusia, Spain
Limari	S2	289.2°	30.4°S	Limari, Chile
Hawaii	N3	203.6°	20.7°N	Hawaii, United States
Cocos	S3	96.9°	12.2°S	Cocos Islands, Australia

4.1 Coverage Analysis of Conical Airspace

4.1.1 Coverage Proportion Section 3.4 has already demonstrated the compensatory effect of mid-latitude north–south dual-station combinations on single-station coverage periods, and this will not be repeated here. Table 4 shows the coverage periods of the conical airspace when using, respectively, the Qinghai single station, north–south dual-station combinations including Qinghai, four-station combinations, and six-station combinations.

the proportions during the one-year simulation period. The coverage capability of the various networking schemes improved as the number of stations increased. The most significant improvement came from the north–south two-station combination strategy; the four-station and six-station combinations had a very limited effect on improving the full-coverage-period metric. For the optimal two-station combination $N1\&S2$, the average full-coverage period in each lunar phase cycle was about 20 d, and the average zero-coverage period was about 4 d.

Figure 9. Schematic diagram of the global distribution of important optical observation facilities

Fig. 9 Global geospatial distribution map of critical optical monitoring facilities

Table 4. Coverage proportions over the conical airspace for various networking schemes centered on Qinghai Station

Table 4 Coverage period of various networking deployment schemes centered on Qinghai station over conical airspace

Case	Station combination	C_1^{full}: d	C_1^{full}: percentage	C_1^{zero}: d	C_1^{zero}: percentage
Case 1	N1	168	46.0%	86	23.6%
Case 2	N1 & S1	239	65.4%	46	12.6%
Case 3	N1 & S2	243	66.5%	47	12.9%
Case 4	N1 & S3	224	61.3%	53	14.5%
Case 5	N1 & S1 & N2 & S2	245	67.1%	27	7.4%
Case 6	N1 & S1 & N2 & S2 & N3 & S3	250	68.5%	22	6.0%

4.1.2 Coverage duration

Figure 10 shows the daily coverage duration over the conical airspace for the Qinghai single station, the north–south two-station combinations including Qinghai, the four-station combination, and the six-station combination. Among them, Fig. 10(a) separately presents the three two-station combinations, while Fig. 10(b) shows the influence of changes in the number of stations on the coverage duration. The coverage duration of the Qinghai single station exhibits the superposition of short-period variations associated with the lunar phase cycle and long-period seasonal variations. For the short-period variation associated with the lunar phase cycle, the coverage duration approaches zero around the new moon, then increases rapidly and reaches a peak during the full moon, after which it falls rapidly again and enters the next lunar phase cycle. This phenomenon arises because optical observation of extremely dim targets depends strongly on solar illumination conditions; the cone point is near the Earth–Moon line, which is essentially consistent with the conditions under which the Moon obtains optimal illumination. Therefore, the coverage

Figure 10: Annual variation in daily coverage duration across different station combinations.

Figure 1: Figure 10: Annual variation in daily coverage duration across different station combinations.

duration follows a pattern consistent with the lunar phase cycle. The seasonal long-period variation is mainly related to the length of night jointly determined by the station' s geographic latitude and the season; the peak coverage duration in winter is significantly greater than that in summer. The night at Qinghai Station during the winter solstice and summer solstice···

approximately 15 h and 9 h, respectively. The maximum and minimum annual coverage-peak values are 3709 h and 2058 h, respectively, and the fluctuation amplitude of the coverage duration is roughly comparable to that of the night length.

(a)
(b)

Fig. 10 Annual variation in daily coverage duration for various station combinations over one year. (a): three dual-station combinations; (b): four station-combination schemes listed in Table 4.

Fig. 10 Annual variation in daily coverage duration across different station combinations. (a): Three dual-station combinations, (b): four station combinations in Table 4.

The seasonal fluctuation in the daily coverage duration of the Qinghai station is compensated in the dual-station and multi-station combinations. Figure 10(b) shows that the seasonal fluctuation of the N1 & S1 north–south dual-station combination is no longer significant, and the coverage duration of the six-station combination reaches the upper limit of daily coverage, achieving the effect of global station distribution for relay observations. Among the three dual-station combinations shown in Figure 10(a), the peak value of the coverage duration is positively correlated with the longitude difference between the two stations. For example, the longitude difference between the N1 & S2 stations is 164°, and the average daily coverage duration for each target is about 20 h.

4.1.3 Continuous Invisibility Period

Figure 11(a) and (b) respectively show the longest invisibility periods of some grid points in the conical sky region for the Qinghai station and the Western Cape station in South Africa. These grid points lie in the YZ plane where the Earth–Moon L2 libration point is located. In this plane, the grid points are farthest from Earth and are also the most numerous; some grid points may also be occulted by the Moon, making stable observation most challenging. The results show that, under single-station observation, the longest invisibility period of the grid points exhibits systematic variation. For the Qinghai station in China, its longest invisibility period increases from north to south, from 10 d to 19 d; the Western Cape station in South Africa shows the opposite trend. The systematic variation in the continuous invisibility period is caused by the coupling between station latitude and lunar orbital motion, and is consistent with the phenomenon shown in Section 2.1 in which the visible sky region of a mid-latitude single station decreases from one side of the station to the other. For stations in the Northern Hemisphere, northern grid points have higher positions in the sky and more easily satisfy the 3 h coverage condition, thereby forming a longer coverage period. The north–south dual-station combination can cancel the invisibility caused by geographical latitude. As shown in Figure 11(c), the longest invisibility period of the grid points is reduced to about 9 d, and no longer exhibits systematic variation.

It should be noted that, because of the influence of the moonlit background, the seven grid points on the Earth–Moon line that are more than 13×10^4 km from Earth always lie in the coverage blind zone. Moreover, this blind zone cannot be eliminated through multi-station networking, and is a blind zone for ground-based optical monitoring.

4.1.4 Coverage Conditions and Coverage Capability

This section further studies the influence of stricter coverage conditions on the coverage capability of the Qinghai station. Figure 12 shows the coverage of the conical sky region by the Qinghai station when the coverage conditions are set to 3 h and 5 h, respectively. Figure 12(a) and its local enlarged view show the difference in coverage duration, while Figure 12(b) and its local enlarged view show the difference in the number of covered grid points. The two local enlarged views both mark the vertical-axis data corresponding to day 153 under the two coverage conditions.

Around the full Moon, the peak coverage duration does not decrease, indicating that during these periods the cumulative daily arc length of the covered grid points can reach more than 5 h. During other periods, the 5 h coverage condition causes some grid points no longer to satisfy the coverage requirement and thus to be excluded. As shown in the local view of Figure 12(a), near the sixth lunar cycle, when the summer night length is shortest, the cumulative duration difference of the covered grid points approaches 1000 h. Similarly, the peak value of the number of covered grid points does not decrease, but the average number of daily covered grid points decreases significantly, with an average reduction of about 50; this leads to the full-coverage period

become shorter, and zero-coverage periods become longer. As shown in the enlarged view of Fig. 12(b), the maximum decrease in the number of anchor points covered in a single day is 250, and full coverage is achieved only on day 160; the zero-coverage period increases to twice its original length.

Fig. 11 Maximum invisible duration of anchor points on the YZ plane containing L2 within the conical airspace; colors represent days. (a): Qinghai station, China (N1); (b): Western Cape station, South Africa (S1); (c): dual-station configuration of Qinghai, China (N1), and Western Cape, South Africa.

Fig. 11 Maximum invisible days of anchor points on the YZ plane at L2 in airspace, colors represent days. (a): Qinghai, China (N1), (b): Western Cape, South Africa (S1), (c): dual-station of N1 and S1.

Fig. 12 Comparison of the coverage performance of the Qinghai station, China (N1), under different coverage conditions. (a): coverage duration; (b): number of covered anchor points.

Fig. 12 Comparative coverage performances of the Qinghai station (N1) under different coverage conditions. (a): Daily coverage duration; (b): daily covering anchor points.

As the coverage conditions become more stringent, the coverage capability of the Qinghai station decreases sharply, which indirectly reflects the influence of soft capabilities such as orbit computation on the requirements for network layout: that is, when orbit computation imposes higher data requirements, the necessity of dual-station and multi-station layouts becomes more prominent.

4.2 Periodic-Orbit Coverage Analysis

4.2.1 Coverage Fraction

Fig. 13 shows the coverage of moving targets on selected periodic orbits by the Qinghai station. Each subfigure corresponds to one orbit family. The horizontal axis represents the index assigned to orbits of the same family in ascending order of amplitude, and the vertical axis represents the annual fraction of the coverage period. In the figure, bar charts in different colors indicate the coverage fractions obtained under different coverage conditions, while the curves connect the corresponding longest invisible periods of the orbits.

As with the conical airspace, this paper adopts the coverage condition $T_i^k > 3$ h to evaluate the Qinghai station' s coverage capability for detecting targets on periodic orbits. Overall, the coverage fractions of several main periodic-orbit families exhibit a trend of first increasing and then tending toward stability, with the coverage fractions stabilizing at around 60%. Specifically, the stabilized coverage fraction and the orbital amplitude required to reach that stable value differ among orbit families: because of their greater distance, the stabilized coverage fraction for orbits near L2 is slightly lower than that for orbits near L1; small-amplitude Lyapunov orbits lie entirely within the lunar avoidance angle, and their coverage fraction is zero; for the DRO orbit family, the ampli-

The amplitudes are all greater than 5×10^4 km, and the fluctuations in coverage percentage among the individual orbits are very small.

In contrast to the single Qinghai station, Fig. 14 shows the coverage capability of the Qinghai and Limari two-station network for periodic orbits; this combination is the optimal north–south two-station combination obtained in Section 4.1. The overall trend in the coverage percentages of several major periodic-orbit families is similar to that for the single-station case, but the stable value of the coverage percentage increases to about 75%. The coverage percentage for small-amplitude Lyapunov orbits remains zero.

Figure 13 Coverage of the selected periodic-orbit families in Table 1 by the Qinghai Station (N1) in China. The upper bar charts show the coverage percentage under the condition $T_i^k > 3$ h; the lower bar charts show the coverage percentage under the condition $T_i^k > 0$ h; the line charts show the maximum invisible period.

Fig. 13 Coverage performances of the Qinghai Station (N1) in China for the selected periodic orbit families in Table 1. The upper part of the bar charts represents the coverage percentage under the condition of $T_i^k > 3$ h, the lower part represents the coverage percentage under the condition of $T_i^k > 0$ h, and line charts represent the max invisible period.

For catalog maintenance of known targets, an observation of any duration on a given day is considered to cover the target; that is, the coverage condition is $T_i^k > 0$ h. Figures 13 and 14 also show, respectively, the coverage capabilities of the Qinghai station and the Qinghai & Limari two-station configuration for periodic orbits in catalog-maintenance tasks. Even when only the Qinghai single station is used, its coverage capability is comparable to that of the two-station combination under the 3 h coverage condition, and the improvement provided by the Qinghai & Limari two-station configuration is very limited. This result reflects the influence of differences in monitoring tasks on the requirements for network layout: from the perspective of catalog maintenance, a two-station combination does not provide additional coverage gains.

4.2.2 Continuous Invisible Period The results in Fig. 13 show that, under the condition $T_i^k > 3$ h, Qinghai

For a single station, among several major periodic-orbit families, the maximum invisible period for orbits whose coverage percentage tends to stabilize is about 15 d, while the DRO orbit family reaches 21 d. Overall, for several major periodic-orbit families, the relationship between the maximum invisible period and the orbital amplitude shows no consistent pattern, and differences also exist for the same orbit family under different coverage conditions. Only the DRO orbit family exhibits an increase with amplitude. This phenomenon results from variations in detection distance and illumination conditions as the target moves, among which the geocentric distance at apogee is the most significant influencing factor; therefore, the maximum invisible period shows a positive correlation with amplitude. Under the condition $T_i^k > 0$ h, the maximum invisible periods of most periodic-orbit families are between 7 and 10 d, while that of the DRO orbit family is about 16 d.

Figure 14. Coverage of the selected periodic-orbit families in Table 1 by the

Qinghai Station (N1) in China and the Limari Station (S2) in Chile as a dual-station system in the Northern and Southern Hemispheres.

Fig. 14 Coverage performances of the Qinghai Station (N1) in China and the Limari Station (S2) in Chile, as a dual-station system in the Northern and Southern Hemispheres, for the selected periodic orbit families in Table 1.

The dual-station results in Figure 14 show that the maximum invisible periods of several major periodic-orbit families all decrease, and the magnitude of the decrease is mainly related to the coverage condition. For $T_i^k > 3$ h, the decrease is about 5 d; for $T_i^k > 0$ h, the decrease is not significant.

Longer continuous invisible periods make target search and discovery more difficult. The dual-station combination significantly shortens the invisible period and improves coverage capability in target search-and-discovery scenarios. For catalog maintenance, however, the dual-station combination cannot improve the coverage percentage or the invisible-period metric.

4.2.3 Phase and Coverage Capability

The conclusions in the preceding subsections were obtained by selecting on each periodic orbit

The simulation was obtained by taking one target as the object. Although statistical results over a long time scale were fully considered, it is still necessary to evaluate whether these results can faithfully and comprehensively characterize the coverage of these periodic orbits. Therefore, the differences in coverage among targets with different phases on the same orbit must be calculated. Without loss of generality, we select a set of near-rectilinear halo orbits (NRHOs) to study the mechanism by which phase affects coverage capability, and also to investigate whether resonant orbits have specific phases that lead to longer continuous invisible periods. Within the southern and northern NRHO families near the L_2 point, one 4:1 resonant orbit and one 9:2 resonant orbit are selected, with corresponding orbital periods of 7.43 d and 6.53 d, respectively. Starting from the zero phase at apolune, one phase is selected every 1/10 of a period as the initial dynamical state of one target; thus, the four orbits generate a total of 40 targets.

Figure 15 presents the simulation results of the Qinghai Station for these targets. Figures 15(c) and 15(d) show the coverage of 10 targets on the 4:1 and 9:2 resonant northern NRHO orbits, respectively, while Figures 15(e) and 15(f) show the coverage of 10 targets on the 4:1 and 9:2 resonant southern NRHO orbits, respectively. In each subplot, the fluctuation in the coverage percentage among the 10 orbits is very small, indicating that phase differences have little influence on coverage capability. Excluding the phase factor, the coverage percentage of the Qinghai Station for southern NRHO orbits is about 10% lower, and the average maximum invisible period is 4 d longer; its coverage capability is therefore significantly weaker than that for the northern symmetric orbits.

Figure 15. Coverage performance of the Qinghai Station (N1) in China for resonant NRHO orbits at the L_2 point. (a): schematic of phase selection for the 4:1 resonant northern NRHO orbit; (b): schematic of phase selection for the 4:1 resonant southern NRHO orbit; (c): coverage of the 4:1 resonant northern NRHO orbit; (d): coverage of the 9:2 resonant northern NRHO orbit; (e): coverage of the 4:1 resonant southern NRHO orbit; (f): coverage of the 9:2 resonant southern NRHO orbit.

Fig. 15 Coverage performances of the Qinghai Station (N1) in China for the resonant NRHO at L_2 point. (a): 4:1 resonant northern NRHO phase selection, (b): 4:1 resonant southern NRHO phase selection, (c): coverage of the 4:1 resonant northern NRHO, (d): coverage of the 9:2 resonant northern NRHO, (e): coverage of the 4:1 resonant southern NRHO, (f): coverage of the 9:2 resonant southern NRHO.

The difference in the coverage capability of the Qinghai Station for northern and southern NRHO orbits also reflects the need for ground-based monitoring stations to be deployed separately in the Northern and Southern Hemispheres. Under the condition $T_i^k > 0$ h, the influence of station geographic latitude on the coverage percentage and invisible period can be neglected.

5 Summary and Discussion

The orbital motion and observational geometry in cislunar space differ greatly from those in near-Earth space. The ground-based optical observations currently established for near-Earth space

The monitoring system cannot be applied to cislunar space monitoring. Therefore, it is necessary to analyze the deployment strategy of ground-based optical monitoring networks on the basis of the requirements and characteristics of cislunar space monitoring. This paper first starts from the cataloging requirements of cislunar space objects; based on the distance and motion characteristics of cislunar targets, it analyzes the relationship between station geographic latitude and the observable sky region, and discusses strategies for networking ground-based optical monitoring stations. Then, with precise modeling of ground-based optical detection, the effectiveness of a north–south station deployment and networking strategy is verified by simulation over a one-year timescale. Finally, taking the Lenghu Astronomical Base in Qinghai, China, as an example, a cislunar space monitoring network analysis is carried out. Multiple station-site resources distributed worldwide are selected to form different networking schemes with the Qinghai station, and the coverage capability of each scheme is evaluated on the basis of simulation results and coverage metrics.

Cislunar space objects are distant and move slowly, and the requirements for ground-based optical monitoring station deployment and networking differ significantly from those for near-Earth space. Without considering factors such as lunar phase, moonlight background, and equipment capability, the visible sky region of a single ground-based station at cislunar distance is approximately a 2π

space centered on the station; a complementary two-station configuration with symmetric latitudes and longitudes differing by 180° can approximately achieve full-time, full-region coverage. For the 15° region near the Moon that is a focus of cislunar space monitoring—corresponding to the range between declinations ±43° on the celestial sphere at one cislunar distance—a single station within the latitude range of ±47° on Earth can meet the daily visibility requirement for the key region. Deploying a single station within the latitude range calculated by formula (5) can satisfy the requirement for visible duration D in the key space region, while a complementary two-station configuration with symmetric latitudes and longitudes differing by 180° is the most effective solution for achieving a visible-duration requirement greater than 12 h.

The simulations carried out on the basis of the above analytical conclusions show that, for the discovery search of cislunar objects, the full-coverage periods of the Qinghai single station for the conical space region along the Earth–Moon line account for 46% of the one-year simulation period. A north–south two-station network can significantly improve coverage capability; among such schemes, the China Qinghai & Chile Limari combination has the highest coverage proportion, about 66%. The north–south four-station combination and six-station combination that include the Qinghai station provide only slight improvements in the coverage-proportion metric. For several major classes of periodic orbits, the coverage proportion of the Qinghai single station stabilizes at around 60% as the amplitude increases, while the Qinghai & Limari two-station combination improves it to about 75%. For catalog maintenance of targets in several major classes of periodic orbits, the coverage proportion of the Qinghai single station can reach about 75%, and the north–south two-station configuration does not significantly improve the coverage proportion. Overall, for the search and discovery of space objects near the Moon, the two-station network composed of Qinghai, China, and Limari, Chile, has the best coverage effectiveness; for catalog maintenance of cislunar targets, the Qinghai single station can meet the basic coverage requirements.

Orbit determination based on target monitoring is an important link in implementing catalog management of cislunar targets. At the same time, the requirements of orbit determination for monitoring-data length, data volume, and data distribution also determine the layout and allocation strategy of monitoring resources. This paper simplifies this requirement relationship and calculates ground-based optical monitoring coverage-evaluation metrics for different data-length requirements. By comparing changes in metrics for the same monitoring network, it preliminarily analyzes the influence of different orbit-determination requirements on monitoring-network coverage capability. On the one hand, in the conical-space coverage scenario for new-target search, an increase in data length leads to a significant decline in monitoring-network coverage. On the other hand, the simulation results for coverage of various types of orbits in the two scenarios of new-target search and catalog maintenance show that different mission scenarios have different requirements for orbital coverage and therefore require different monitoring-network deployment strategies.

However, whether for the search and discovery of new targets or for catalog maintenance of known targets, continuous unobservable intervals are one of the important factors affecting the effectiveness of target cataloging. First, for monitoring targets near the Earth–Moon line, the relative motion of the Sun, Earth, and Moon leads to continuous unobservable intervals around the new Moon; when factors such as target distance and elevation angle are taken into account, the duration of such continuous unobservable intervals may increase, and they cannot be eliminated or effectively shortened by complementary ground-based two-station configurations or even by global station deployment. Second, the space region near the Earth–Moon line is always within the range affected by moonlight for ground-based optical monitoring, forming a coverage blind zone. Because ground-based optical monitoring cannot avoid the above difficulties, integrated space–ground joint monitoring is an inevitable trend in cislunar space-object monitoring. By developing space-based and lunar-based monitoring systems, it is possible to compensate for the coverage blind zones of ground-based monitoring, expand diversified observation geometries, and improve the responsiveness of situational awareness. In summary, the analysis in this paper of the coverage and limitations of ground-based optical monitoring will further provide a reference for research on orbital design and optimized resource-scheduling design for space-based systems.

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Coverage of Ground-based Optical Network for Monitoring Cislunar Space

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ABSTRACT Driven by the need for monitoring and cataloging objects in Cislunar space, this paper investigates the networking deployment schemes of ground-based optical devices, while also examining their coverage limitations. The article first analyzes the observability of ground-based stations based on the distance and kinematic characteristics of Cislunar objects, proposing station layout strategies focused on key regions near the Moon. Subsequently, the paper numerically models geometric, optical, and equipment capability conditions related to optical observation, then proposes metrics to assess coverage capabilities for the tasks of object search and discovery, as well as catalog maintenance. Finally, this study takes China' s Lenghu Astronomical Base as an example to design networking deployment schemes and evaluate their coverage capabilities, while also analyzes and explains the continuous invisible periods and blind spots caused by factors such as the lunar phase period. This research provides valuable insights for the deployment of ground-based optical monitoring devices and the development of an integrated space-ground monitoring system.

Key words astrometry, Earth, Moon, methods: numerical

Note: Figure translations are in progress. See original paper for figures.