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Summary of Lunar Constellation Navigation and Orbit Determination Technology

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Abstract: The Moon is the closest celestial body to the Earth. Its rich unique resources are an important supplement to the Earth's resources and have a profound impact on the sustainable development of human society. As large-scale exploration missions gradually progress, demands for communication, navigation, surveying and other services of lunar-space probes have significantly increased. Constellation navigation and orbit determination technology will become an indispensable part of future lunar exploration infrastructure. This article systematically analyzes the current status of lunar relay navigation satellite networks at home and abroad, summarizes the technical principles of single-satellite and constellation navigation and orbit determination, discusses the technical difficulties in lunar navigation constellation orbit determination and navigation, and analyzes possible solutions. Finally, the development trend of research on high-precision orbit determination and navigation methods for lunar navigation constellations is proposed.

Keywords: lunar exploration; precise orbit determination; autonomous navigation

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1. Introduction

Since the 21st century, lunar exploration has once again become a research hotspot. Countries around the world have launched lunar probes more than one hundred times. Space powers such as the United States and Europe have successively planned several unmanned/manned lunar exploration missions, including the Artemis program [1,2] and the Moon Village project [3], etc., with a view to ultimately realizing long-term residence on the Moon as well as the development and utilization of resources. With the successful implementation of China's Chang'e-5 mission [4], the three-step plan of 'orbiting, landing and returning' of the lunar exploration project was successfully completed. The lunar south pole exploration, lunar far side sampling return, and the construction of the international lunar research station have become the next direction for China's lunar exploration.

With the gradual launches of large-scale lunar exploration missions, the demand for high-precision navigation and positioning of lunar probes has become increasingly urgent. At present, the main methods of precise orbit determination for Earth–lunar space probes are via ground-based measurements, including radio ranging, velocity measurement, and interferometry. As the quantity of in-orbit lunar probes increases, ground measurement and control are facing daily increasing pressure, and are barely meeting the needs of long-term orbit determination for a large number of lunar probes. At the same time, for long-distance lunar probes, ground measurement and control have characteristics such as long time delays, weak signals, and the influence of unfavorable factors such as the problem that the far side of the Moon cannot communicate directly with the Earth due to blocking. It is difficult to achieve continuous, real-time and accurate navigation and positioning solely by relying on ground systems. Referring to the orbit determination capabilities of China's current lunar exploration projects, the orbit prediction accuracy of lunar probes is generally

in the order of several hundred meters, which cannot meet the orbit determination accuracy requirements of future lunar navigation constellations.

Meanwhile, in addition to the above-mentioned methods, the current lunar probe orbit determination methods also include satellite-ground laser measurement, GNSS signal measurement, astronomical navigation, etc. Among them, satellite-to-ground laser ranging has a high accuracy, but also has high requirements on the Earth's atmospheric environment and limited usage time.

GNSS can achieve real-time positioning. In [5], the estimated orbit is validated with SLR as the satellite is equipped with a laser retroreflector array (LRA). A 3D RMS of about 0.3 m accuracy levels is obtained for POD using SLR. Using a real-time onboard navigation filter, 1.1 m accuracy in 3D RMS was achieved while post-processing on the ground with flight data offered 0.7 m accuracy in 3D RMS. In [6], a POD solution based on the Schmidt–Kalman filter performed better in terms of accuracy than the standard Kalman filter using single-frequency GPS receiver data. POD accuracy is improved by about 6 cm compared to the standard Kalman filter. In [7], a consider Kalman filter (CKF)-based reduced-dynamic orbit determination (RDOD), or CKF-RDOD, approach was used. The results showed a satisfactory POD with approximately 1.5 m level of three-dimensional RMS error with the CKF-RDOD approach using GPS data and broadcast messages in real-time scenarios. For satellites on LEO orbits, Montenbruck et al. used a combined GPS/Galileo receiver to achieve precise orbit determination [8]. Ref. [9] used the Kalman filter algorithm for real-time POD, providing seven different solutions using the onboard and simulated data. At those distances, decimeter-level onboard orbit determination can be achieved. For deep space applications, GNSS faces challenges such as weak side-lobe signals, poor visibility and limited positioning accuracy. Combined with low-orbit constellations, joint high-, medium- and low-orbit fast and high-precision positioning has become the development direction of the next generation of intelligent location services.

Astronomical navigation includes methods such as angle measurement, velocity measurement, and ranging. Combined with orbital dynamics, real-time satellite positioning can be achieved. However, it also faces the problem of limited accuracy and low maturity of high-precision navigation instruments. Therefore, the existing single-satellite orbit determination method for lunar probes cannot meet the needs of future large-scale lunar resource development.

Future lunar exploration will be more complex and diversified, and using lunar constellation for exploration can effectively solve these problems. The lunar relay communication and navigation positioning systems will become a necessary part of the future lunar exploration infrastructure. Correspondingly, the lunar navigation and communication system architecture LunaNet [10], Project Moonlight [11,12], the Lunar Pathfinder Mission [13], the new hybrid data relay satellite CommStar-1 [14] and other plans for supporting lunar probe relay communications were proposed. China has also proposed its own 'Queqiao comprehensive constellation for communications, navigation and remote sensing' [15], which is planned to be completed in three phases to provide relay communications, navigation, positioning and timing services for cislunar space transfer and lunar surface exploration activities.

The lunar exploration constellation composed of Moon orbiters and relay satellites on the Earth–Moon balance point can achieve continuous coverage of specific areas of the lunar surface or even the entire lunar surface, and can provide necessary relay communication, navigation, positioning and other services for human beings to fully carry out lunar exploration in the future. Among them, the lunar orbit can achieve full lunar coverage and communicate with lunar targets at close range. Its orbital characteristics are similar to those of Earth satellites, so it is easy to apply. Compared to lunar orbit, the observation coverage on the libration point orbit is wider. Additionally, the L2 point of the Earth–Moon system keeps its position over the back of the Moon, so one satellite on libration points can provide a relentless lunar coverage equivalent to a lunar orbit constellation. The disadvantage is

that the libration point is farther from the lunar surface compared to the circumlunar orbit, resulting in insufficient communication timeliness and navigation accuracy.

The lunar space probe's demand for communications, navigation, surveying and other services has increased significantly. The construction of the communication and navigation remote sensing constellation will significantly improve the efficiency of lunar resource surveying, development and utilization while meeting the technical requirements of future exploration missions. In response to the demand for high-precision lunar navigation and orbit determination, this article first analyzes the principles of related technologies, research status, and key difficulties that need to be solved urgently. Finally, the future development trends are outlined, providing reference directions for the construction of future lunar navigation constellations.

2. Current Status of Lunar Relay Navigation Satellite Networks

In the 21st century, the strategic significance of lunar exploration activities has become increasingly prominent. Lunar resources include location resources, environmental resources, material resources, etc., which have huge development and utilization value. The world's major aerospace countries and organizations have successively planned several unmanned/manned lunar exploration missions, with the aim of ultimately realizing long-term residence on the Moon and the utilization of resources. China has continued to carry out scientific research and engineering practice in the field of lunar exploration. It has been undertaking a 'lunar exploration project' since 2004. The three-phase mission of 'orbiting, landing and returning' has been a complete success, and the subsequent four-phase lunar exploration mission is in full progress.

The south pole of the Moon has the largest and deepest impact basin in the solar system—the Aitken basin. There is also water ice at the north and south poles of the Moon. The poles and back of the Moon may contain rich resources and have greater exploration value. Exploration is the cornerstone of human exploration and research of the entire solar system. In previous lunar exploration missions as well as landing and sampling return missions on the front side of the Moon, the probe's measurement and control communication during each flight phase could rely on ground stations' support, so a dedicated communication and navigation satellite system was not developed. However, as lunar exploration activities progress towards the direction of long-term habitation and development, and the exploration values of the lunar poles, backside and other areas becomes more prominent, the issue of communication and navigation services for the cislunar space has garnered significant attention.

In previous lunar exploration missions, the number of probes in a single mission was limited, and measurements and control communications at each flight phase could be supported by ground stations. Therefore, there was no urgent need to develop a dedicated communication and navigation satellite system. As the value of lunar exploration becomes more prominent, the quantity of probes operating in the Earth–lunar space will increase rapidly, and the orbit determination of multiple probes will place a greater load on ground stations. It is also difficult to directly provide navigation support for the lunar south pole or lunar far-side probes due to the propagation characteristics of radio, the influence of lunar tidal locking and the impact of ground stations. On the other hand, future lunar resource development and other tasks will require more real-time high-precision positioning and speed control in the Earth–lunar space. Current orbit determination methods of lunar probes include satellite-to-ground laser measurement, GNSS signal measurement, astronomical navigation, etc. Among them, satellite-to-ground laser ranging is highly accurate, but also imposes high requirements on the Earth's atmospheric environment and limited usage time. GNSS can achieve real-time positioning, but has weak side-lobe signals, poor visibility, and limited positioning accuracy in deep space exploration [16]. Astronomical navigation includes angle measurement, velocity measurement, and ranging. Combined with orbital dynamics, real-time positioning of satellites can be achieved. However, it also faces the problem of limited accuracy and low maturity of high-precision navigation

instruments. Therefore, the existing single-satellite orbit determination method for lunar probes cannot meet the needs of future large-scale lunar resource development.

Future lunar exploration will be more complex and diversified. Using lunar constellations for exploration can effectively solve these problems and achieve continuous coverage of specific areas of the lunar surface or even the entire lunar surface, which can provide communication, navigation, positioning and other functional support for human beings to comprehensively carry out lunar exploration in the future. Therefore, the construction of lunar communication and navigation satellite systems has gradually become one of the most important planning contents of future lunar exploration by major space agencies. Foreign countries have proposed the LunaNet, Moonlight, Lunar Pathfinder and other special communication and navigation systems for lunar exploration. In 2022, China also launched the demonstration of a lunar communication and navigation system (constellation).

2.1. U.S. Lunar Navigation and Communication Plan

1. LunaNet

As the National Aeronautics and Space Administration (NASA) continues to explore the Moon and the solar system, the demand for powerful interstellar communication and navigation systems is also increasing [17]. To meet this growing demand, NASA is developing LunaNet, a flexible and expendable lunar navigation and communication system architecture that can provide network, positioning, navigation and timing (PNT) as well as scientific services to lunar exploration users [10]. With the LunaNet system, lunar probes or astronauts can access networks just like people on Earth. Each communication link can be connected to a larger network, allowing data transmission between any devices on the network.

The system architecture will offer users three services: network services, positioning, navigation and timing services, and scientific utilization services. After utilizing LunaNet, users will encounter an operational environment similar to Earth users. To provide the required navigation capabilities to lunar missions, LunaNet will provide the following data:

(1) Universal stable time and frequency reference source for achieving time synchronization between all elements of the entire network;
(2) Key measurement information obtained from each observable communication link, such as radiance or optimization;
(3) Observability of GNSS signals;
(4) Angle measurement of stars and celestial bodies for determining relative positions;
(5) Images of surface features nearby for relative terrain navigation;
(6) Broadcasting signals that transmit navigation data throughout the lunar environment, similar to GPS signals on Earth.

The LunaNet architecture is open, expandable, and interoperable. Lunar exploration missions can either be components or users of the LunaNet infrastructure, or even play both roles simultaneously. To satisfy future needs, NASA is exploring spacecraft designs including lunar relay satellites and small satellite constellations to expand the LunaNet infrastructure. These relay satellites or small satellites can carry payloads that provide PNT-related basic functions, such as ranging equipment, autonomous navigation processors, broadcast beacons and time reference source/distribution modules.

2. CommStar-1

On 9 January 2024, NASA once again postponed its manned lunar landing mission. The "Artemis 2" and "Artemis 3" missions will be postponed to September 2025 and September 2026 respectively, and one of the key technologies is high-speed communications between the Earth and the Moon. A new company called CommStar Space Communications has announced a plan to launch CommStar-1, a hybrid data relay satellite that can be used as private communications infrastructure for space missions.

The CommStar-1 relay infrastructure will be designed as a hybrid system for radio frequency and optical (laser) communications. CommStar-1 will be a larger communication platform than anything else currently considered for missions on the lunar surface or in

orbits around the Moon, capable of receiving and relaying signals between satellites and the Earth from its access points in the cislunar service area. CommStar-1 will provide active and always-on advanced data services at a distance of more than 362,102 km (225,000 miles) from the Earth, while its general location will be closer to the Moon.

The goal is to establish a space-based Cislunar Network Access Point (C-NAP), operating in a stable and diverse orbit, as a hybrid space-based platform (Earth–Moon, Moon) and a hybrid data communications relay to Earth.

CommStar Space Communication hopes to use the new communications satellite as the primary communications infrastructure to serve the anticipated needs of government and commercial agencies from a low Earth orbit to the Moon and eventually beyond. CommStar-1 is designed to be the first satellite in a similar system. The specific design goals are as follows:

(1) Receive/distribute radio frequency and optical (laser) communications from the Moon, Earth, and cislunar space;
(2) Fully enable integration and interoperability with other space and terrestrial infrastructure—lunar, terrestrial, and cislunar space;
(3) Cloud-based data distribution, open architecture, software definition, and end-to-end user management;
(4) Realize communication between users and space;
(5) User data are distributed directly to different cloud storage facilities (hosts), corporate sites, and universities/laboratories through existing interconnections between space stations and ground stations.

2.2. ESA Lunar Navigation and Communication Program

The European Space Agency (ESA)'s Project Moonlight is committed to building a shared lunar communication and navigation constellation. This concept proposes to deploy a satellite network around the Moon to expand the coverage of reliable satellite navigation to provide manned and unmanned lunar explorations. The constellation will eventually be used by official and commercial lunar exploration missions. Moonlight will be operated as a commercial service to reduce the development difficulty and cost of lunar exploration missions.

Over the next decade, ESA aims to establish a common communication and navigation infrastructure for all lunar missions based on dedicated lunar satellites. Project Moonlight will support missions that cannot use Earth satellite navigation signals, such as landers on the far side of the Moon, and plans to achieve target positioning accuracy below 50 m.

Project Moonlight will build a Lunar Satellite Communication and Navigation System (LCNS) via global cooperation, based on lunar landers from various countries. It consists of near-lunar orbit satellites and lunar surface static ranging beacon stations. It deploys a constellation around the Moon to provide support to manned and unmanned lunar exploration activities.

Currently, ESA has a signed contract with Surrey Satellite Technology Limited (Guildford, UK), which will be responsible for developing the Lunar Pathfinder, the first commercial satellite for Project Moonlight. It is planned to be launched in 2026 and weighs approximately 208 kg. The satellite will carry out an eight-year mission to provide commercial relay services for lunar missions. It will also expand the operational limits of satellite navigation signals, aiming to verify that a commercial communication constellation can be built in the future.

The Lunar Pathfinder will carry out the first satellite navigation and positioning mission in the lunar orbit by equipping an advanced satellite navigation receiver. It plans to use a highly stable frozen large elliptical orbit above the Moon's south pole to focus on the south pole as the main exploration target. Several unmanned lunar landing missions and NASA's Artemis program all plan to go to the lunar south pole in the future. The Lunar Pathfinder will communicate with probes on the lunar surface and in orbit around the Moon via UHF and S-band, and relay communication signals to the Earth via X-band. The

signal is detected by a high-sensitivity receiver, and positioning accuracy of approximately 100 m will be achieved by using advanced space-borne orbit filters.

2.3. China's Lunar Navigation and Communication Plan

The general goal of China's Queqiao comprehensive constellation construction is to build a communication and navigation system that serves the lunar surface, lunar orbit, cislunar space and even deep space by 2045, and expand to the lunar Internet to support unmanned/manned lunar, and even deep space, exploration as cislunar space infrastructure. At the same time, it will support the construction of the Earth–Moon space economic zone, laying a technical foundation for the further construction of the interplanetary Internet and the realization of space power in the future.

The construction of the entire lunar communication and navigation system has been divided into three phases [18]:

(1) Phase I of the project (around 2030): Build a pilot constellation to support the fourth phase of the lunar exploration project, the international lunar scientific research station and other tasks.
(2) Phase II of the project (before 2040): Complete the basic constellation to realize regional navigation. It will serve manned lunar exploration, international lunar exploration, as well as the exploration of Mars and Venus.
(3) Phase III of the project (before 2050): Build an expanded constellation to achieve communication and navigation coverage on Mars and Venus, and serve the exploration of Mars, Venus, giant planets and the edge of the solar system.

Table 1 contains information on the current status of relay navigation satellite constellations, and introduces the leading institutions, project goals, navigation communication criteria and orbits of different constellations. The result shows that by deploying relay satellites in the cislunar space or lunar orbit, continuous coverage of navigation and communications for specific areas of the lunar surface or even the entire lunar surface can be effectively achieved, and the corresponding criteria can be achieved as well. In the future, the relay satellite network will be further applied in lunar exploration missions.

Table 1. Analysis of the current status of relay navigation satellite.

Project Name	Leading Institution	Project Objectives	Navigation Communication Criteria	Orbit
LunaNet	NASA	A flexible and scalable lunar communications and navigation architecture	Providing network services, positioning, navigation and timing services, and scientific utilization services near the Moon	Earth–Moon space
CommStar-1	CSC	Real-time relay optical laser communications between the Moon and Earth	It will provide real-time advanced data services within a distance of 360,000 km, via microwave and laser communications.	Orbit between Earth and the Moon
Moonlight	ESA	Establishing a lunar shared communication and navigation network	For manned missions, the target positioning accuracy at any location on the Moon can reach less than 50 m.	Orbit around the Moon
Lunar Pathfinder	ESA	The first dedicated navigation and communication satellite of Project Moonlight	For unmanned exploration missions 1: Achieve 100 m positioning accuracy 2: Communication to the Moon: UHF, S-band 3: Ground relay: X-band 4: Data rate: 0.5–2048 kbps 5: Communication protocol: CCSDS Proximity-1	Frozen large elliptical orbit around the Moon

Table 1. *Cont.*

Project Name	Leading Institution	Project Objectives	Navigation Communication Criteria	Orbit
Queqiao	China	Provide lunar relay, communication and navigation services	In view of the communication and navigation capability requirements of the fourth phase of lunar exploration, the International Lunar Research Station and subsequent lunar exploration missions will carry out research on the lunar communication and navigation satellite system, complete critical technologies such as lunar relay navigation satellite constellation planning, relay navigation network architecture and navigation algorithms, and establish an interoperable lunar relay navigation constellation to provide general relay communication and navigation services for targets on the lunar surface.	Circum Moon+ Libration point+ GEO Constellation

2.4. Other Countries

Japan was the first to successfully utilize lunar relay satellites in lunar exploration missions. In September 2007, Japan successfully launched the SELENE satellite, which consists of a main satellite and two sub-satellites. The primary mission of the main satellite and one sub-satellite is to measure the gravitational field of the Moon, while the other sub-satellite was responsible for relay communication with the Earth. The orbit of SELENE is a polar orbit with an orbital inclination of about 90°. The main satellite was in a circular orbit with an orbital altitude of 100 km. The relay satellite is in an elliptical orbit with a perigee altitude of 100 km and an apogee altitude of 2400 km. The mission saw the breakthrough of many new technologies and achieved a series of results. At the end, it successfully impacted the Moon in June 2009.

In 2014, OHB SE in Germany and the University of Stuttgart proposed a lunar relay communication satellite program operating at the Earth–Moon L4 and L5 libration points. The purpose is to provide support for unmanned and manned lunar probes, with an operating life of 10 years. In order to solve the problem of large-capacity data transmission, besides microwave relay links, laser communication links are also used.

3. Overview of Single-Satellite Navigation and Orbit Determination Methods

3.1. Radio Measurement Orbit Determination Technology

At present, ground-based measurement and orbit determination technology is the main precise orbit determination method for Earth–lunar space probes, including ground-based radio ranging, velocity measurement and interferometry.

1. Radio velocity measurement

According to the location of the oscillation source, Doppler velocity measurement is divided into one-way Doppler velocity measurement and two-way Doppler velocity measurement.

In unidirectional Doppler velocimetry, the oscillation source is mounted on the spacecraft. The downlink transmission signal is generated by the oscillation source on the spacecraft, and is received by the ground receiver after propagation and delay in space. The ground station calculated the spacecraft's radial velocity by measuring the frequency difference of the received signal relative to the nominal downlink transmitted signal. Therefore, the single velocity measurement equipment is simple and does not require uplink signals, so it is widely used in satellite navigation and positioning.

The oscillation sources of the two-way Doppler velocity measurement are configured at the ground measurement and control station. The system consists of a ground transmitter, a ground receiver, a transmitting antenna, a receiving antenna and a transponder on the spacecraft. It is also called interrogational velocity measurement. The ground control station transmits a highly stable frequency signal to the spacecraft, which is forwarded or reflected back to the ground observation point through the spacecraft's transponder. Comparing the return signal with the reference signal can determine the Doppler frequency shift (a change of two times) in the round trip of the signal, thereby obtaining the relative radial velocity of the spacecraft. Since a ground-based frequency standard is used as the reference signal for uplink and downlink signals for two-way Doppler velocity measurement, and the stability of the frequency source used by the ground station can reach an extremely high level, it can obtain much higher accuracy than one-way velocity measurement.

Doppler velocity measurement adopts an integral model. The relationship between the velocity measurement observation value and the receiving frequency is as follows [19]:

$$\dot{\rho} = \left(1 - \frac{f_R}{M f_T}\right) c \tag{1}$$

In the formula, $\dot{\rho}$ represents the radial velocity of the probe. f_R is the receiving frequency and the measurement quantity. f_T is the transmission frequency, which is generally known. c is the speed of light. The parameter M is the spacecraft transponder turnaround ratio, which is the ratio of the transmitted down-leg frequency at the spacecraft to the received up-leg frequency at the spacecraft. Note that these two frequencies are phase-coherent. The turnaround ratio M is a function of the uplink band at the transmitting station on Earth and the downlink band for the data point. Both of these bands are obtained from the data record for the data point on the OD file.

The transmitter frequency f_T at a tracking station on Earth can be constant or ramped. If it is a constant frequency, it is obtained from the record of the OD file for the data point. If the transmitter frequency is ramped, it is specified as a series of contiguous ramps. Each ramp has a start time, an end time, the frequency f at the start time and the constant derivative $\dot{f}$ of f (the ramp rate) which applies between the start time and the end time for the ramp. When the spacecraft is the transmitter, the frequency of the transmitted signal (for all one-way data types except GPS/TOPEX observables) is:

$$f_T = C_2 f_{S/C} \tag{2}$$

where $f_{S/C}$ is the S-band value of the spacecraft transmitter frequency and C_2 converts it to the transmitted frequency for the downlink band for the data point (obtained from the data record for the data point on the OD file).

2. Radio ranging

In ranging, continuous wave ranging signals can be divided into harmonic signals (such as sidetone signals) and non-harmonic signals (such as pseudo-code signals). Sidetone ranging uses 'sidetone' (a single-frequency sine wave) to modulate the sidetone with a fixed frequency as a baseband signal onto a carrier wave and transmits it to the target. The target forwards the signal to the receiving end to demodulate. After processing, by comparing the phase difference between the received signal and the transmitted signal, the total distance between the transmitting point, the target, and the receiving point can be obtained. Increasing the sidetone frequency can achieve high-precision ranging, and this method has a narrow bandwidth and high acquisition speed.

The basic principle of pseudo-code ranging is the same as that of sidetone ranging. The distance is calculated based on the relationship between the propagation delay of the ranging signal and the speed of light. The difference is that sidetone ranging uses phase difference to calculate distance, while pseudo-code ranging uses autocorrelation functions to measure delay. Pseudo-code ranging uses the long pseudo-code period as the

de-ambiguation signal and uses random chips as high-frequency sidetones. Ranging can be completed with only one signal.

Code-tone hybrid ranging is a hybrid system using pseudo-code and side-tone, which combines their respective advantages. It uses high-frequency sidetones to improve measurement accuracy and pseudo-code to decode distance blur.

The computed values of three-way ramped Sequential Ranging Assembly (SRA) and Planetary Ranging Assembly (PRA) range observables are calculated as follows [19]:

$$\rho_3(ramped) = \left[\int_{T_B}^{t_3(ST)_R} F(t_3)dt_3 - \int_{T_A}^{t_1(ST)_T} F(t_1)dt_1\right], \text{modulo} M \text{ range units} \quad (3)$$

The reception time $t_3(ST)_R$ in station time ST at the receiving electronics at the receiving station on Earth is equal to the data time tag TT. The corresponding transmission time $t_1(ST)_T$ in station time ST at the transmitting electronics at the transmitting station on Earth is calculated as follows:

$$t_1(ST)_T = t_3(ST)_R - \rho \quad \text{s} \quad (4)$$

ρ is the precision round-trip light time. The quantities T_B and T_A are zero-phase times at the receiving and transmitting stations, respectively. At T_B, the phase of the transmitter ranging code at the receiving station is zero. The phase of the transmitted ranging code at the transmitting station is zero at T_A. $F(t_3)$ and $F(t_1)$ are conversion factors at the receiving station and transmitting station, respectively, depending upon the uplink band and exciter type at the station.

The first integral in Equation (3) is the phase of the transmitter ranging code at the reception time $t_3(ST)_R$ at the receiving electronics at the receiving station on Earth. The second integral in Equation (3) is the phase of the transmitted ranging code at the transmission time $t_1(ST)_T$ at the transmitting electronics at the transmitting station on Earth. It is equal to the phase of the received ranging code at $t_3(ST)_R$. The phases of the transmitter ranging code and the received ranging code at the reception time $t_3(ST)_R$ at the receiving electronics at the receiving station on Earth are measured in range units. The difference of these two phases is calculated modulo M range units, where M is the length of the ranging code in range units.

3. Very long baseline interferometry (VLBI)

VLBI technology is an important interferometry technology. It combines multiple radio telescopes hundreds or even thousands of kilometers away into a huge comprehensive aperture telescope. It is currently the highest-resolution astronomical observation technology and is widely used in the astrophysics, astrometry, geodesy and deep space exploration fields.

The measurement principle of the VLBI system of two base stations is shown in Figure 1. The distance between the radio source and the Earth is much longer than the distance between the two observation stations on the ground. Therefore, the radio signal emitted from the radio source can be considered parallel light when it reaches the Earth. The signal radiated by the same radio source at a certain time satisfies the interference conditions. In VLBI data processing, according to the radio signals received by each base station, the relative amplitude of the interference fringes, the time delay for radio signals radiated by the same radio source to reach each base station, and the change rate of the delay can be obtained. The correlation amplitude represents the intensity distribution information of the radio source, and the position information between base stations and the position information of the radio source can be calculated using the delay and delay rate.

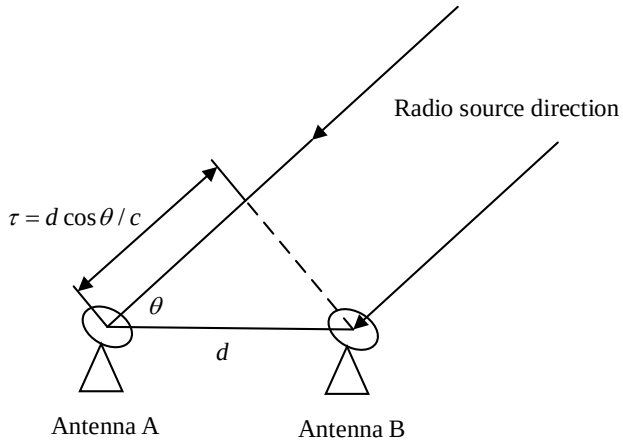


Figure 1. Schematic diagram of radio interferometry.

According to the geometric relationship shown in the figure, the time difference τ between two measuring stations receiving a certain wave front (for one of the measuring stations, it is the delay value) is [20]:

$$\tau = \frac{1}{c} d\cos\theta \tag{5}$$

The distance between the two base stations is d, which can be called the baseline. c is the speed of light. By performing multiple measurements of τ or $\dot{\tau} = \frac{d\tau}{dt}$ for multiple sources, the three components of the baseline and the location of the source can be solved.

3.2. Astronomical Navigation Technology

The exploration mission faces problems such as extended information transmission time, complex environment, and many unknown factors in space, which has higher demands on the autonomous navigation of the probe. Radio navigation methods based on ground station measurement and control are widely used in space exploration-related missions. However, due to problems such as transmission rate, transmission delay, and cumulative errors caused by orbital dynamics recursion, it is difficult to achieve real-time high-precision navigation with single ground-based deep space radio navigation. Therefore, with the development of exploration missions, navigation methods that combine more astronomical information such as images and spectra have become a research hotspot.

According to the differences in measurement methods, astronomical autonomous navigation methods are divided into three categories: angle measurement navigation, ranging navigation and velocity measurement navigation.

1. Astronomical angle measurement navigation

Astronomical angle measurement navigation uses optical images of target celestial bodies captured by navigation cameras and known celestial ephemeris, calculates the direction information of the probe relative to the navigation source using image-processing techniques, and finally combines navigation filter methods to achieve autonomous navigation, obtaining information such as the position, velocity and attitude of the probe in a certain coordinate system [21,22]. The astronomical angle measurement navigation method is widely used in deep space exploration missions, and its schematic diagram is shown in Figure 2. The height difference principle proposed by the French navigator Saint-Hillarie is the basis of astronomical angle measurement navigation. The earliest astronomical navigation method was designed based on this principle [23]. In the early stage of development, astronomical angle measurement navigation methods were mainly used as an auxiliary to terrestrial radio navigation methods. Subsequently, this technology has been continuously developed and improved, and has been successfully applied in several exploration missions [24–28]. Since the accuracy of astronomical angle measurement

navigation is greatly affected by distance, when the probe is far away from the navigation target, a small error in the angle estimate may lead to a large error in the probe position estimation after calculation. In actual exploration missions, this technology is generally used in the approach or capture phase when the probe is closer to the target celestial body.

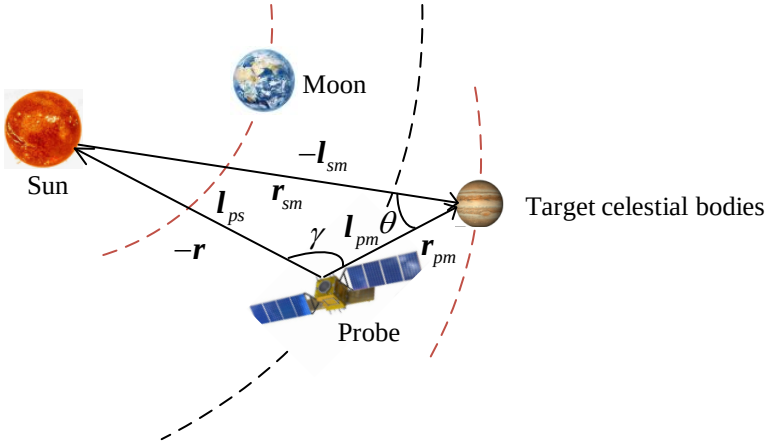


Figure 2. Schematic diagram of angle measurement navigation.

In the heliocentric inertial coordinate system, the geometric relationship is [29]:

$$\begin{aligned} \gamma &= \arccos(\boldsymbol{l}_{ps}\boldsymbol{l}_{pm}) \\ \theta &= \arccos(\boldsymbol{l}_{sm}\boldsymbol{l}_{pm}) \end{aligned} \tag{6}$$

Among them, $\boldsymbol{l}_{ps}$ is the sight vector of the sun relative to the probe, and $\boldsymbol{l}_{pm}$ is the sight vector of the target celestial body relative to the probe, which can be obtained through the measurement of the navigation sensor. $\boldsymbol{l}_{sm}$ is the direction vector from the sun to the target celestial body, which can be obtained by means of ephemeris calculation. The position of the probe in the inertial frame is:

$$\boldsymbol{r} = -\frac{\|\boldsymbol{r}_{sm}\|\sin\theta}{\sin\gamma}\boldsymbol{l}_{ps} = -\|\boldsymbol{r}_{sm}\|\sqrt{\frac{1-(\cos\theta)^2}{1-(\cos\gamma)^2}}\boldsymbol{l}_{ps} \tag{7}$$

That is:

$$\boldsymbol{r} = -\|\boldsymbol{r}_{sm}\|\sqrt{\frac{1-(\boldsymbol{l}_{sm}\boldsymbol{l}_{pm})^2}{1-(\boldsymbol{l}_{ps}\boldsymbol{l}_{pm})^2}}\boldsymbol{l}_{ps} \tag{8}$$

Among them, $\boldsymbol{l}_{ps}$ and $\boldsymbol{l}_{pm}$ can be obtained through navigation sensors and solar sensors, and their observation models are:

$$\begin{aligned} \widetilde{\boldsymbol{l}_{ps}} &= \boldsymbol{l}_{ps} + \boldsymbol{V}_{ps} \\ \widetilde{\boldsymbol{l}_{pm}} &= \boldsymbol{l}_{pm} + \boldsymbol{V}_{pm} \end{aligned} \tag{9}$$

Among them, $\boldsymbol{V}_{ps}$ and $\boldsymbol{V}_{pm}$ are the sight vector observation noises. Taking the $\boldsymbol{r}$ observed value as $\boldsymbol{Z}$, the observation equation is:

$$\begin{aligned} \boldsymbol{Z} &= -\|\boldsymbol{r}_{sm}\|\sqrt{\frac{1-(\boldsymbol{l}_{sm}\widetilde{\boldsymbol{l}_{sm}})^2}{1-(\widetilde{\boldsymbol{l}_{ps}}\widetilde{\boldsymbol{l}_{pm}})^2}}\widetilde{\boldsymbol{l}_{ps}} \\ &= -\|\boldsymbol{r}_{sm}\|\sqrt{\frac{1-[\boldsymbol{l}_{sm}(\boldsymbol{l}_{pm}+\boldsymbol{V}_{pm})]^2}{1-[(\boldsymbol{l}_{ps}+\boldsymbol{V}_{ps})(\boldsymbol{l}_{pm}+\boldsymbol{V}_{pm})]^2}}(\boldsymbol{l}_{ps}+\boldsymbol{V}_{ps}) \end{aligned} \tag{10}$$

For the above equation, Taylor expansion at $\boldsymbol{l}_{ps}$ and $\boldsymbol{l}_{pm}$ gives:

$$\boldsymbol{Z} = \boldsymbol{r} + \left(\frac{\partial \boldsymbol{r}}{\partial \boldsymbol{l}_{ps}} \boldsymbol{V}_{ps} + \frac{\partial \boldsymbol{r}}{\partial \boldsymbol{l}_{pm}} \boldsymbol{V}_{pm} \right) + o(\bullet) \tag{11}$$

Ignoring the higher-order small quantities in the observed quantities, then:

$$\boldsymbol{Z}_t = \boldsymbol{r} + \boldsymbol{V}(t) \tag{12}$$

Among them, the observation error is calculated as follows:

$$\boldsymbol{V}(t) = \frac{\partial \boldsymbol{r}}{\partial \boldsymbol{l}_{ps}} \boldsymbol{V}_{ps} + \frac{\partial \boldsymbol{r}}{\partial \boldsymbol{l}_{pm}} \boldsymbol{V}_{pm} \tag{13}$$

Among them, $\boldsymbol{V}_{ps}, \boldsymbol{V}_{pm}$ are measurement noises, which are generally treated as Gaussian white noise.

2. Astronomical ranging navigation

Astronomical ranging navigation is an autonomous spacecraft navigation method based on X-ray pulsar observations. X-ray pulsars will emit strong and stable periodic X-ray radiation. The difference between the time when the same pulse signal reaches the spacecraft X-ray detector and the time when it reaches the center of mass of the solar system predicted by the phase time model is used as the observation quantity to construct X-Ray pulsar navigation measurement equations. Combined with the speed of light, the plane where the spacecraft is located is obtained, which is the projected length of the distance from the spacecraft to the center of mass of the solar system in the direction of the pulsar, as shown in Figure 3. By detecting three pulsars at the same time, a geometric relationship can be constructed to calculate the space position of the spacecraft and achieve autonomous navigation. The radio pulse signal navigation proposed by Downs is the basis of astronomical ranging navigation [30]. The earliest autonomous navigation method of X-ray pulsars was designed based on this principle [31]. In the early stage of development, astronomical ranging navigation remained at the theoretical level. It was not until 2017 that NASA announced the implementation of the first space demonstration of X-ray pulsar navigation [32]. A series of subsequent tests also proved that this technology has the advantages of a stable navigation source signal, strong anti-interference and long application distance [33–36]. The key to follow-up research is the establishment of a pulsar library and effective on-orbit exploration technology of pulse signals.

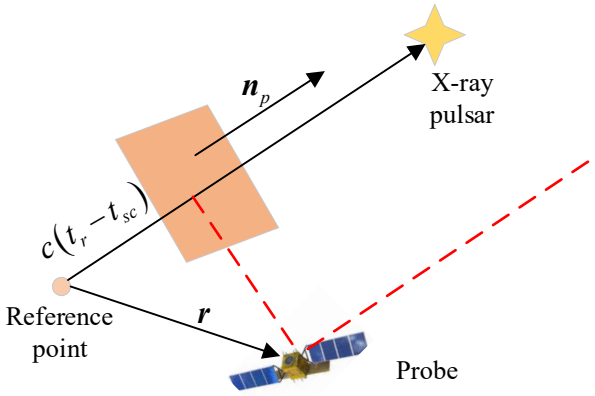


Figure 3. Schematic diagram of ranging navigation.

3. Astronomical velocity navigation

Astronomical velocity measurement navigation uses the solar system and extrasolar stars as navigation sources. It obtains relative motion speed information by observing

the astronomical spectral frequency shift caused by the motion of the probe relative to the navigation source, and further calculates the velocity vector of the probe in space [37]. The schematic diagram is shown in Figure 4, whereby v_s, v_t are the velocity vectors of the star and the probe in the reference coordinate system. l_{ts} is the azimuth vector of the star relative to the probe. v_{ts} is the radial velocity of the probe relative to the star. v_{ts} can be derived from the spectral frequency shift amount $v_{ts} = c \bullet \frac{\Delta f}{f_r} = l_{ts}^T(v_s - v_t)$ and f_r is the reference spectral frequency. The basis of astronomical velocity measurement and navigation is the feasibility analysis of using the visible spectrum band and radio spectrum band of stars for velocity measurement proposed by Franklin [38]. Guo et al. further designed an astronomical speed measurement system based on the solar radial velocity and direction vector [39]. Subsequently, the program has been continuously developed and improved, and many scholars have completed a large amount of in-depth and detailed research work [40–42]. Velocity navigation initially obtains the speed information of the probe. In order to obtain the spatial position of the probe, the speed needs to be further integrated. When the integration time is long, there is a problem of accumulated error. Therefore, although this method is not limited by the probe distance, it is generally used for short-term autonomous navigation in actual exploration missions.

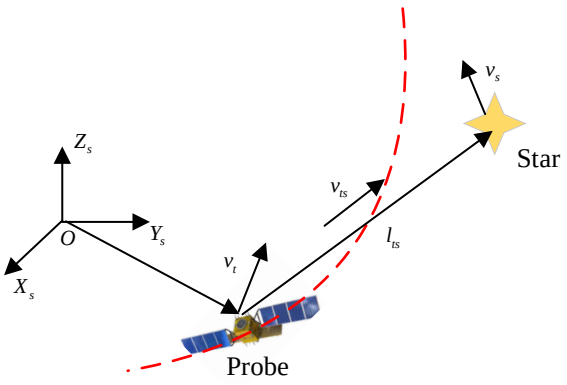


Figure 4. Schematic diagram of velocity measurement navigation.

There are obvious differences in the navigation sources, sensors used, measured information, navigation principles and performance characteristics of different navigation methods, so there are also differences in applicability. In practice, information obtained by multiple navigation methods is often fused through filtering to form a combined navigation system to further improve navigation accuracy.

3.3. Satellite-to-Ground Laser Measurement Technology

Satellite Laser Ranging (SLR) is currently the most accurate technology for precise satellite orbit determination and inspection. Its single ranging accuracy reaches centimeter level or even sub-centimeter level. The United States and the Soviet Union successively installed five sets of laser reflector arrays on the lunar surface, and collected a large amount of observation data as well as noting significant scientific achievements.

SLR is used to accurately measure the round-trip time interval of the laser pulse from the ground observation point to the satellite equipped with a corner reflector, expressed in terms Δt, to calculate the distance from the ground observation point to the satellite R. R and Δt have the following relationship [43]:

$$R = \frac{1}{2}c\Delta t = \frac{1}{2}cNT_0 \tag{14}$$

where c is the speed of light.

The schematic diagram is shown in Figure 5. ρ_{TP} is the satellite observation value vector and ρ_{TD} is the ground target calibration observation value vector. $\overrightarrow{OD}$ is the distance

value for ground target calibration and should be accurately measured by a ranging instrument during the construction of the ground target. $\vec{OF}$ is the distance vector of the ground center point, which should also be accurately measured during the construction of the ground center point. $\vec{PS}$ is the satellite center of the mass correction value vector, determined according to the shape of the satellite. dx is the system delay correction value, which is obtained by each measurement of the ground target. Laser ranging observation is to measure the distance from the ground reference point to the satellite. The ground reference point can be the intersection of the two axes of the telescope as the reference point, or the ground center point as the reference point.

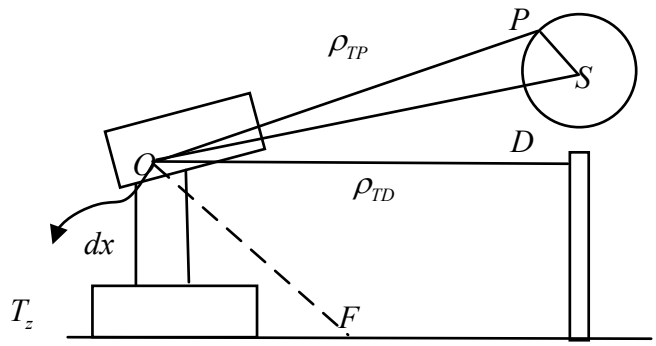


Figure 5. Schematic diagram of laser ranging.

The observation vector from the telescope reference point to the satellite's center of mass can be expressed as:

$$R_{OS} = \rho_{TP} + \vec{PS} - |\rho_{TD}| + \left|\vec{OD}\right| \tag{15}$$

The observation vector from the ground center point to the satellite's center of mass can be expressed as:

$$R_{FS} = \rho_{TP} + \vec{PS} - \vec{OF} - |\rho_{TD}| + \left|\vec{OD}\right| \tag{16}$$

3.4. GNSS Orbit Determination Technology

GNSS (Global Navigation Satellite System) orbit determination refers to the method of positioning and orbit determination of a spacecraft using a satellite navigation system. By transmitting a set of precise radio signals, which are received and processed by ground receivers, precise positioning and orbit determination are achieved.

The basic principles of GNSS orbit determination are that a spacecraft or mobile device receives signals from at least four satellites and calculates its position by measuring the time difference of these signals. This is because each satellite emits a precise signal that contains information about the satellite's own position and time. By receiving signals from multiple satellites, a GNSS receiver can calculate its distance from each satellite and use this distance information to determine its position.

Specifically, the GNSS orbit determination principle includes the following key steps:

(1) Satellite signal transmission: GNSS satellites emit signals that contain information about the satellite's own position and time. These signals travel through the air via radio waves and are picked up by ground-based receivers.
(2) Signal receiving and processing: After the ground receiver receives the signal transmitted by the satellite, it will process the signal. This includes amplifying, filtering, demodulating and other operations on the signal to extract useful information.
(3) Signal time difference measurement: By measuring the time difference between signals received from multiple satellites, the ground receiver can calculate its distance

from each satellite. This is accomplished by comparing the difference in the time it takes for the signal to arrive at the receiver.

(4) Positioning calculation: By measuring the distance between four or more known satellites and the GNSS receiver, the position of the receiver can be determined through distance intersection. Therefore, the positional information of the satellite which is equipped with the GNSS receiver can be obtained. There are many methods for calculating position, among which the triangulation method and the least squares method are the most commonly used.

As shown in the Figure 6, when the receiver only observes one satellite, it can only determine that the receiver is on a sphere with the geometric distance between the two satellites as the radius. When it observes two satellites, the two spheres intersect to form a circle, and the receiver position is located on this circle. When three satellites are observed, the three spherical surfaces intersect in pairs and form two points in space. One of the positions can be eliminated according to the conditions, and the receiver's position can be obtained. To actually determine the receiver's position, at least four satellites need to be observed. This is because the receiver's clock error is also an unknown parameter. Three types of observations can be obtained using GNSS receivers: pseudo range, carrier phase, and Doppler frequency shift. By analyzing the observations and processing the data, information on the status of the satellite can be obtained.

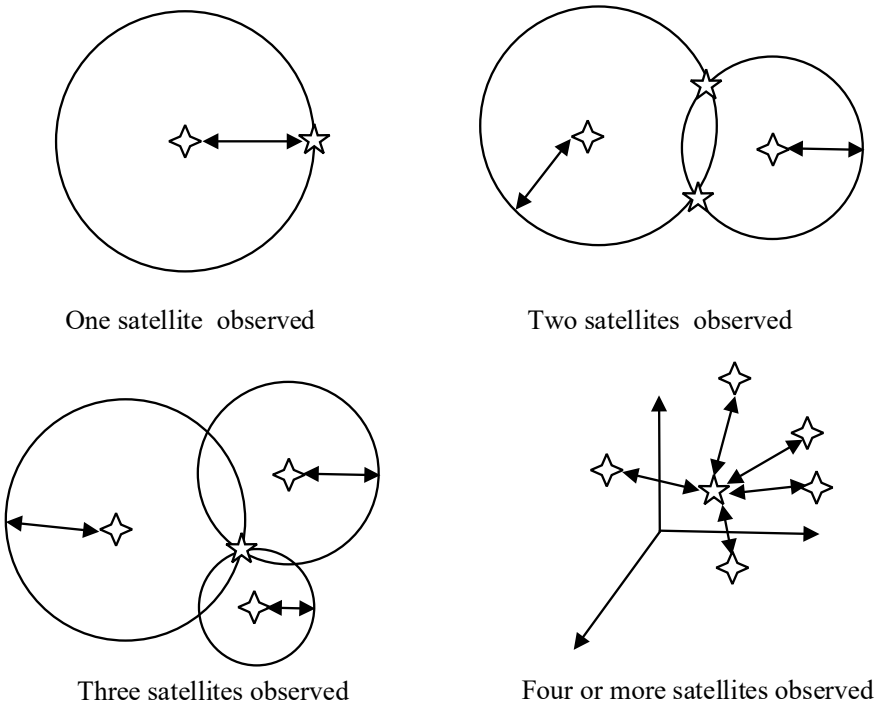


Figure 6. Basic principles of spaceborne GNSS orbit determination.

3.5. Navigation Data Processing Technology

A navigation algorithm, which can use the navigation information containing noise to achieve the state estimation of the target, is one of the most important directions in research into navigation technology methods. The first estimation algorithm used for satellite navigation is the least squares algorithm (LS). Least squares estimation uses the minimum sum of squares of the residuals as the risk function and does not make any assumptions about the observation sample. Because of its wide applicability and ease of operation, it is widely used in navigation calculations.

The parameters of interest, as well as the dominant error sources, are often time-varying. If these time variations can be modeled, the parameters can be resolved based on minimum mean squared error prediction, filtering and smoothing techniques [44]. Of the

various such techniques, the most commonly used filter methods in navigation research include the Kalman filter (KF) [45], extended Kalman filter [46], unscented Kalman filter [47] and improved algorithms based on these filter methods. The EKF algorithm is simple to calculate and easy to implement. However, due to errors introduced by the linearization process, the estimation accuracy of highly nonlinear problems is poor. Although the UKF algorithm avoids the linearization errors introduced in Taylor approximation, it is still based on the Gaussian assumption. Witternigg et al. provide a good example of filtering and processing in direct lunar transfers using UKF [48]. Whether it is KF, EKF or UKF, they all require relatively accurate a priori statistical information on the system model and measurement model noise, but any statistical information has a certain degree of distortion. When the prior noise statistics error is large, the accuracy of the navigation filter methods will decrease or even diverge. In order to reduce the influence of prior noise statistical information distortion on EKF and UKF, scholars have proposed the Sage–Husa filter [49,50], evanescent filter [51,52], robust adaptive filter [53–55], multi-model adaptive filter and other adaptive filter methods. The Sage–Husa [56] adaptive filter method calculates the observation residual or prediction residual by selecting the observations within an observation epoch interval, and then re-estimates the system noise covariance matrix Q and the measurement noise covariance matrix R. This method adaptively estimates system and measurement noise based on real-time measurement conditions, thereby improving the accuracy and reliability of sensor measurement data. Fagin proposed an evanescent filter algorithm [57] for system state model errors. Specifically, the method of determining the forgetting factor enables the filtering algorithm to still maintain a certain optimality when there is an error in the state model or the state is disturbed. Yang Yuanxi and others proposed a robust adaptive filter algorithm [58] to address the status and measurement anomalies existing in dynamic carrier navigation to improve the accuracy of dynamic carrier navigation. Mohamed et al. proposed multi-model based adaptive estimation (MMAE) from the perspective of model adaptation [59]. Compared with a single model, the multi-model adaptive estimation method estimates through a set of parallel filtering estimators, and calculates the model probability at all times, which meets the needs of changing noise sequences in this process and can achieve an adaptive effect.

Depending on the model characteristics and noise characteristics of the navigation systems, the navigation filter algorithms used are also different. Applicable algorithms need to be designed for different navigation systems to improve the accuracy of state estimation. The navigation system will suffer external interference during operation, and this interference may have a greater impact on the state estimation results. Therefore, the stability of the algorithm also needs to be considered. In addition, the lunar navigation system has higher real-time requirements, and the calculation amount and convergence speed of the algorithm need to be considered. Therefore, it is necessary to comprehensively consider the estimation accuracy, stability, convergence and other performance parameters of the algorithm, in order to study the corresponding navigation algorithms and achieve the real-time high-precision autonomous navigation of lunar navigation system satellites.

4. Constellation Navigation and Orbit Determination Technology

4.1. Multi-Constellation GNSS Lunar Satellite Orbit Determination Method

Affected by the obstruction of the Earth–Moon double stars, the amount of visible satellites provided by a single GNSS constellation does not exceed four most of the time, which cannot meet the theoretical positioning requirements. This poses a challenge to multi-constellation integrated navigation technology. In recent years, in order to increase the quantity of visible stars and select satellites with better geometric structures through satellite selection algorithms to indirectly improve navigation and positioning accuracy [60], major aerospace countries have successively developed from single-constellation systems to multi-constellation GNSS combined systems. This field includes research on satellite selection algorithms for multi-constellation integrated navigation and research on positioning solution methods for multi-constellation integrated navigation.

Satellite selection algorithms are generally divided into the optimal satellite selection method and the suboptimal satellite selection method. The optimal satellite selection method calculates the geometric accuracy factors of all combined constellations and selects the combination corresponding to the minimum value as the result of satellite selection. The suboptimal algorithm selects satellites according to the actual needs of users by establishing an algorithm model for satellite selection. The accuracy is usually lower than that of the optimal algorithm, but the calculation complexity of the algorithm is low and the real-time performance is high.

In terms of the study of the optimal algorithm, Le proposed the weighted geometric accuracy factor method [61]. This method is based on the optimal algorithm and obtains its approximate optimal estimate by calculating the weighted geometric accuracy factor, which improves positioning accuracy. Most of the research is based on the suboptimal star algorithm and achieves rapid selection by proposing a suitable positioning error estimation model. Based on the cost function model of the suboptimal algorithm, Feng Biao et al. proposed a cost function model based on altitude angle and carrier-to-noise ratio weighting, which improved the efficiency of satellite selection [62]. The fast star selection algorithm [63] is based on the elevation and azimuth angle sorting method and the principle of uniform distribution of satellites for selection, which greatly reduced the selection time. Wang Ershen proposed a satellite selection algorithm based on chaotic particle swarm optimization, which can reduce the selection time to 37.5%, while the geometric accuracy factor error is less than 0.6 [64].

The multi-constellation combination positioning solution method is generally divided into centralized combination and distributed combination. The centralized combination method is a simple inheritance of the single-constellation positioning solution method. Commonly used centralized combination methods include solution methods based on least squares and solution methods based on the Kalman filter. For on-ground batch processing of GNSS observations, the solution method based on least squares uses Taylor expansion to linearize the observation equation, which requires a large number of calculations. It only solves for the user's current location and is suitable for static single-point positioning. There are no accuracy problems related to the use of the least squares approach. The accuracy of the dynamic models plays a crucial role in this case. For real-time application, a Kalman filter approach is preferred. The Kalman filter algorithm establishes a user motion trajectory model and smoothies the observation data to obtain position information with higher accuracy. Zhang Jie et al. applied the Cubature Kalman filter algorithm to satellite navigation positioning solutions, and recursively estimated the position of the receiver with time updates and measurement updates [65]. Zhang Jingxian et al. proposed a method based on the Kalman filter–RBF neural network to predict INS errors and compensate for them, thereby making up for the defect of GNSS lock loss and inability to navigate [66]. When the average position error is 3 m, accurate prediction can last for about 30 s.

In order to solve the problems of poor fault tolerance and difficulty in real-time calculation of centralized combination methods, some scholars have conducted research on distributed combination methods. The representative distributed combination method is a solution method based on the federated Kalman filter [67]. This algorithm designs federated filters by treating each GNSS system as federation members to improve positioning accuracy. Carlson proposed a multi-constellation combination solution method based on the Kalman filter and adaptive joint filter [68]. This method has good tracking performance and improves the positioning accuracy and stability of the system. Joint positioning technology uses the federated Kalman filter algorithm to design a joint positioning system and locate a single point [69]. Compared with the Kalman filter algorithm, the error in straight line distance is reduced by 9.54%, and the error in elevation is reduced by 53.43%.

4.2. Inter-Satellite Measurement Autonomous Navigation Method

The orbital information of the current global navigation satellite system is mainly measured on the ground, and then the satellite ephemeris is updated via ground stations.

In order to prevent ground stations from being destroyed during war, the United States first proposed the concept of autonomous navigation of navigation constellations, which uses the mutual ranging between navigation satellites in the navigation constellation. The American scholars Menn MD and Ananda MP designed an autonomous orbit determination scheme [70] and used 21 satellites for simulation demonstration. The results show that the system can operate autonomously for 180 days using UHF inter-satellite ranging based on the predicted ephemeris GPS constellation, and URE is better than 7.33 m. The Galileo system and the GLONASS system also have inter-satellite ranging autonomous navigation functions [71]. All Beidou-3 satellites are equipped with Ka-band inter-satellite link payloads to achieve autonomous orbit determination and satellite–ground joint orbit determination [72,73]. The inter-satellite link of Beidou-3 not only includes the construction of links between MEO satellites, but also includes the construction of links between GEO and MEO, IGSO and MEO and other links among satellites on different orbits, greatly improving the system's survivability and service performance [74,75]. Wei Zhang used the Starlink constellation to investigate the self-induced collision risk caused by malfunctioning satellites [76].

Research shows that because the Earth's gravity plays an absolutely dominant role in the orbital position of the Earth satellite, and the Earth's gravitational field itself has strong rotational symmetry, Earth satellites can only determine the size and shape of the satellite's orbit using only inter-satellite ranging observations. For relative pointing, the absolute position of the satellite in inertial space cannot be determined. There is an unobservable problem of the overall rotation and translation of the constellation, so it is impossible to determine the long-term autonomous orbit of the constellation. Regarding the constellation rotation problem, Abusali analyzed the impact of constellation rotation on orbit determination accuracy [77]. Liu Lin proposed a method of constraining the right ascension of the ascending node of the orbit to solve the rank deficiency problem [78]. Chen Jinping conducted simulation demonstration for the method of constraining the orientation parameters of the satellite orbital plane [79], and Tang Chengpan studied the situation with anchoring stations. Based on the centralized autonomous orbit determination of four test satellites, the radial overlap arc accuracy of IGSO satellites is better than 15 cm, and that of MEO satellites is better than 10 m [80]. Gong Xiaoying studied the joint orbit determination method based on anchoring stations [81]. Zhang Weixing et al. studied the impact of EOP forecast errors on autonomous orbit determination results [82]. Liu Jingnan et al. studied the algorithm and simulation results of autonomous orbit determination of navigation satellites [83]. Liu Wanke studied the simulation algorithm of satellite–ground joint orbit determination [84], and Zhao Deyong studied the weighting problem of joint orbit determination [85]. Song Xiaoyong studied the distributed autonomous orbit determination filter algorithm [86]. Li Zhenghang studied the impact of prior information error on autonomous orbit determination [87]. Cai Zhiwu et al. studied the rotation error analysis and control of navigation satellite autonomous orbit determination constellations [88]. Ruan Rengui studied the equipment time delay estimation method in joint orbit determination of navigation satellite inter-satellite/satellite-ground link [89]. Shuai Ping studied the time synchronization method of autonomous navigation [90]. Chen Zhonggui studied the critical technologies for autonomous operation of navigation satellite constellations based on the actual needs of China's regional tracking network [91].

In general, to achieve long-term autonomous navigation of near-Earth/near-Moon satellite constellations based on inter-satellite measurements, additional information needs to be introduced to determine the overall direction of the constellation in space, which cannot yet be called truly autonomous navigation.

4.3. LiAISON Autonomous Navigation Method

In the three-body problem, the gravitational influence of the third body can indirectly provide information about the direction to that third body, and with it the absolute orientation of the orbits. In other words, a halo orbit near the Moon is influenced very strongly

by both the Earth and the Moon and has a unique size and shape. Because of the strong asymmetry of the three-body force field, a halo orbit with that size and shape can only have a single orientation with respect to the Earth and Moon. This means that a spacecraft in a halo orbit can track a second spacecraft using crosslink range measurements and determine the absolute positions and velocities of both spacecraft simultaneously without any Earth-based tracking or mathematical constraints. In 2006, Hill et al. first started from the asymmetry of satellite motion acceleration functions and pointed out that under the influence of the third body gravity of the Moon, halo orbiting satellites near points L1 and L2 in the Earth–Moon system are most likely to only use interstellar ranging observations to determine the orbit autonomously. They proposed the concept of Joint Autonomous Satellite Orbit Navigation (LiAISON) [92,93]. Hill et al. also demonstrated the observability of autonomous orbit determination for libration point orbit satellites based on inter-satellite ranging information through covariance analysis. By comparing the autonomous orbit determination results of satellites with different libration point orbits, it was found that the farther away from the lunar orbital plane and the shorter the period, the higher the accuracy of autonomous orbit determination for libration point orbits [94,95]. By analyzing the evolution of random acceleration error over time and its influence on the autonomous orbit determination accuracy of the LiAISON method, Leonard conducted a systematic study on the autonomous navigation problem of manned exploration missions in the Earth–Moon space. JS Parker et al. also studied the specific application of inter-satellite measurement navigation in the combination of satellites orbiting Lagrange points and other types of satellites [96,97]. Villac et al. analyzed the orbit optimization problem in inter-satellite measurement navigation and its applications [96,98]. Starting from the correlation of the coefficient matrix, Duran et al. pointed out the key role of the introduction of Earth–Moon system libration point orbit satellites in improving the positive definiteness of the orbit determination matrix. Taking the lunar low-orbit satellite–Halo orbit satellite constellation as an example, they demonstrated the feasibility of the autonomous orbit determination method based on inter-satellite ranging data under the CRTBP (Circular Restricted Three-Body Problem) model [99]. Liu et al. studied the joint ranging autonomous orbit determination problem of the Earth–Moon system's libration point orbit and the large amplitude retrograde orbit with the lunar orbit, and pointed out that the Halo orbit with a larger vertical plane amplitude has better autonomous orbit determination accuracy and lunar coverage performance, while the large amplitude retrograde orbit has more advantages in stability than the Halo orbit [100]. Huang Yong et al. used a hybrid constellation composed of libration point probes, DRO probes and satellites as a typical scenario to analyze the autonomous orbit determination accuracy of the Earth–Moon space detector based on inter-satellite ranging, demonstrating the application of inter-satellite ranging technology on Earth. There is huge application potential in the construction of a lunar space navigation system [101].

As the Pathfinder mission of NASA's Gateway program, the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) was launched on 28 June 2022 [102], heading towards a near-linear halo orbit around the Moon to demonstrate the core technology components of the lunar autonomous positioning system, and to test the ranging ability between the CAPSTONE satellite operating in NRHO orbit and the LRO probe.

5. Outlook on Key Technologies for Lunar Constellation Navigation and Orbit Determination

5.1. Moon Reference Frames and Time Scales

In the cislunar space environment, due to the lack of clear geographical references, the traditional Earth coordinate often cannot meet the needs of precise positioning. The purpose of establishing the lunar reference frame is consistent with the purpose of establishing the Earth's reference frame, mainly to describe the position of the probe relative to the Moon. In addition to revolving around the Earth, the Moon also rotates. The intersection points of its

rotation axis and the lunar surface are the Moon's north and south poles, respectively. The great circle that is perpendicular to the rotation axis and intersects the lunar surface through the center of the Moon is the lunar equator. This is the basis for defining the Moon-fixed coordinate system. There are two commonly used definitions of the Moon-fixed coordinate system. One is the mean pole frame recommended by IAU, and the other is the principal axes frame defined by JPL; the origin of both is the Moon's center of mass. In the lunar gravity field, laser lunar data analysis and other dynamic research work, the principal axes frame is mainly used, but the analysis results such as the coordinates of the lunar surface retroreflector are often given in the mean pole frame.

The orbit determination of the lunar probe and the orbit determination of the near-Earth spacecraft are consistent in principle. They are both based on satellite tracking observations containing errors, and use an approximate observation model to optimally estimate the initial state of the satellite. However, the central gravitational field of the lunar probe will change when it is flying in orbit. Therefore, the orbit determination process of the lunar probe involves more spatiotemporal reference frames, and the conversion between different coordinate systems and time systems is also more complicated. Regarding the scale of the lunar reference frame, it is conceptually defined as the scale of a local lunar frame in the sense of gravitational relativity. In practice, it can usually be determined by the speed of light c, the lunar gravitational constant GM and the relativistic correction model used in data processing.

Unified Moon reference frames will provide the necessary spatial benchmark for deep space exploration activities, allowing for more accurate data comparison and analysis between different missions. Therefore, the urgency of constructing different means such as protocol inertial reference frames, lunar and planetary ephemerides and Earth satellite dynamic reference frames to ensure that they can be easily implemented and realized in lunar exploration missions has become increasingly prominent. Specifically, it includes the use of VLBI, LLR (Lunar Laser Ranging), GNSS and other technologies to jointly monitor the lunar ephemeris and its rotation balance. In this way, the connection and conversion of three types of celestial reference frames can be realized with high precision under the framework of the general relativity gravity theory, providing a new, unified celestial reference frame support for human social activities within the Earth–Moon space.

Commonly used time scales can be divided into two categories: one is defined based on the rotation of the Earth, including sidereal time, solar time, etc. The second category is based on the International System of Units—atomic time seconds, including international atomic time (TAI) for practical applications, geocentric coordinate time (TCG) for theoretical research, and center of mass coordinate time (TCB). Geocentric ephemeris time (TT) and barycentric dynamical time (TDB) are related to this. When the lunar probe flies in the Earth–Moon transfer orbit or the lunar orbit, its coordinate time is defined in the solar system center of mass reference frame, that is, TDB. TDB and TT can be calculated by means of the following approximate formula [103]:

$$\begin{aligned} TDB &= TT + 0.001658 \times \sin g + 0.000014s \times \sin(2g) \\ g &= 357.53^\circ + 0.98560028^\circ \times (JD - 2451545.0) \end{aligned} \tag{17}$$

where g is the Earth's mean anomaly.

With the increase in global lunar exploration activities in the future, the current lunar surface timing method is unsustainable. How to unify the lunar area time and unify the lunar time scale becomes a problem. Therefore, it is necessary to set a time benchmark on the Moon that can be used by all parties to solve the problem of timekeeping on the lunar surface and the time difference between space projects of various countries.

What is more, for distances up to the Moon, the time scales play a major role and relativistic effects should be considered accurately. First order approximations are not enough. Such considerations apply to the time scales, GNSS-based orbit determination and use of Doppler measurements. For the orbit determination of lunar satellites, the first-order approximation is not sufficient, mainly because at long distances and high speeds (relative

to the Earth's orbit), relativistic effects become significant, which will affect the precision and accuracy of the measurements. First, gravitational time dilation. According to general relativity, clocks run slower in strong gravitational fields (such as near the Earth's surface) than in weak gravitational fields (such as the orbit of the Moon). This gravitational time dilation effect needs to be taken into account in more precise orbit determinations. In long-distance communications and measurements, relativistic effects cause time and frequency shifts. The signal round-trip time between the ground station and the lunar orbiter is longer, and any small errors will accumulate, causing the overall error to increase.

5.2. High-Precision Dynamic Model

In order to satisfy the high-precision requirements for the long-term operation of the lunar navigation system, high-precision dynamic modeling research on the lunar navigation constellation needs to be carried out in the future. High-precision modeling and characteristic analysis are the keys to ensuring the accurate implementation of engineering missions. Dynamic modeling such as third-body gravity, solar radiation pressure and the albedo effect, and jet unloading caused by the Earth and sun should be studied. Orbit stability and other conditions should be analyzed. For functional requirements of communication, navigation and positioning, timing, information services, scientific detection, and expanded applications of the comprehensive constellation, focusing on achieving full-month communication coverage and supporting subsequent unmanned and manned lunar exploration and other mission requirements, the Earth–Moon integrated constellation system track plan design and plan iteration optimization should be developed. Yi Qi et al. investigated trajectory corrections for lunar flyby transfers to Sun–Earth/Moon libration point orbits (LPOs) with continuous thrusts using an ephemeris model [104]. Muralidharan et al. investigated stretching directions in cislunar space to apply to departures and transfer design [105].

At present, a set of high-precision dynamic models have been established for the lunar probe, but the long-term forecast is still inaccurate. Accurate modeling of solar radiation pressure and the albedo effect, the jet unloading dynamic model, etc. are key links in providing long-term orbit recursion accuracy. However, at present, there are few relevant studies, and research needs to be carried out. For the configuration of the communication constellation, the design considerations are complex, the constraints are many, and the optimization is difficult. There is currently no definite conclusion, and optimization design work still needs to be carried out.

5.3. Multi-Source Ranging Fusion Technology

The high-precision orbit determination of the lunar navigation constellation is a prerequisite for providing users with high-precision navigation and positioning services. However, the existing 100 m level orbit determination accuracy in the near-lunar space cannot fulfill the meter-level orbit determination of the lunar navigation constellation itself in the future. Satellite-to-ground laser ranging and inter-satellite ranging are important means to improve orbit determination accuracy. These two methods have been used in precise orbit determination of near-Earth space navigation satellites. Near-lunar space and near-Earth space have many different characteristics, and there are huge differences in the geometric configuration of orbits. However, there are currently few studies on satellite-to-ground laser ranging and inter-satellite ranging and orbit determination in near-lunar space.

Satellite-to-ground laser ranging in near-lunar space is difficult, but once achieved, extremely high ranging accuracy can be achieved. At present, navigation systems such as GPS and BDS are actively considering using inter-satellite laser ranging to obtain greater inter-satellite information to further improve the accuracy of orbit determination and the accuracy of autonomous constellation navigation. The improvement of orbit determination accuracy using satellite-to-ground lasers and inter-satellite ranging has been fully demonstrated in near-Earth space. The world's major space powers are conducting demonstrations

on lunar navigation systems. How to use satellite-ground lasers and inter-satellite ranging to improve near-lunar space orbit determination accuracy is a development trend and key core technology in subsequent lunar navigation constellation and orbit determination.

5.4. Quantity Measurement Error Propagation Mechanism and Suppression

Quantity measurements in the system are affected by environmental noise, measurement technical errors, sensor noise, etc., and errors are inevitable. In order to improve observation accuracy, error sources that affect navigation performance should be properly analyzed and processed.

For example, for measurement errors, source model errors, spacecraft system errors, etc. in astronomical navigation, the system errors are compensated for via the extended state method and the epoch difference method. In addition, pulsar profile processing technology is also a key factor in improving accuracy, including period ambiguity problems, fast signal processing, the Doppler effect, phase delay, etc. An accurate model of pulsar observations can ensure the high positioning performance of the spacecraft. However, accurate observation models are usually nonlinear, and the filter method needs to be improved based on the characteristics of pulsar navigation to precisely estimate the position, velocity and other status information of the spacecraft. Velocity measurement navigation requires accurate modeling of the source-end errors of the astronomical spectrum, so the quality of measurement information should be significantly improved to ensure that the accuracy of the navigation system meets the demand.

Spaceborne GNSS observations must go through three phases of processing. These three phases also bring three error sources, which will directly affect the accuracy of multi-constellation GNSS satellite orbit determination. The errors come from the navigation satellite, the GNSS signal receiver as the receiving source, and signal propagation. It is necessary to effectively correct the observation errors to improve the quality of measurement information to ensure the calculated orbit satisfies the accuracy requirements.

Further research is needed on the mechanism and suppression methods of error propagation in the system, with a focus on studying the variation patterns of navigation measurement information error characteristics during the process of source end transferred to sensor processing, and constructing corresponding models. In terms of error suppression, the focus of research is on designing unique filter algorithms for different navigation methods and researching efficient and applicable filter algorithms.

5.5. Data Processing Filter Algorithm

Quantity measurements in navigation systems are affected by environmental noise, measurement technical errors, sensor noise, etc., and errors are inevitable. There are also errors in information estimated recursively using orbital dynamics models. It is necessary to design a proper navigation filter algorithm to deal with various errors. At the same time, in order to comprehensively utilize the advantages of various navigation methods, it is necessary to combine angle measurement, speed measurement, and ranging information and perform information fusion by means of filters.

For offline orbit determination, batch filter algorithms, such as the least squares filter, are commonly used to calculate the state quantity with the smallest sum of squares of the residuals of the objective function as the optimal estimate of the navigation parameters. The process is simple and efficient, and does not require prior statistical information of the state quantity. However, it is not applicable for the scenario of obtaining complex navigation parameters under the orbital dynamics model in real-time exploration missions. Traditional sequential filter algorithms for nonlinear systems are commonly used for real-time orbit determination tasks in astronomical autonomous navigation systems, including the extended Kalman filter, unscented Kalman filter, Cubature Kalman filter and other algorithms, which have the advantages of not requiring repeated iterations and fast processes. For information fusion in integrated navigation, federated filters are commonly used. Effective fusion of the valuations of each navigation subsystem via the information

distribution principle can improve the failure tolerance of the integrated navigation system to a certain extent.

Regarding the errors in the navigation system, the key to future research should satisfy the characteristics of the lunar exploration mission. Filter methods that achieve a balance between convergence, adaptability, stability, estimation accuracy and calculation amount should be designed.

5.6. Multi-Source Navigation Information Fusion and System Optimization

In future exploration missions, in order to meet navigation needs, establishing a lunar navigation constellation is the most reliable way for lunar users to obtain location services. Studying the integrated navigation performance including pulsars, star sensors, lunar surface beacons and other information sources is also the focus of the next step of research. For example, the high-precision information obtained by the star sensor is used to calibrate the navigation measurement information in some phases, and the distance and speed information provided by radio navigation are combined to improve the accuracy of the rendezvous and docking section. To combine multiple navigation methods, it is critical to design efficient fusion algorithms for multi-source information based on rich navigation measurement information.

In view of engineering constraints such as the nonlinear and highly time-varying orbital dynamic environment of lunar navigation satellites and unknown factors, the optimization selection criteria for inter-satellite measurement observations of lunar navigation constellations are proposed, and a navigation constellation optimization plan is proposed. By combining satellite ground measurement, astronomical measurement and other information, research is conducted on the quality evaluation and failure monitoring methods of combined autonomous navigation information, the unified method of spatiotemporal reference for multi-source navigation information and the fusion processing method of multi-source information. The optimal combined autonomous navigation scheme is constructed to satisfy the high-precision, real-time and highly reliable autonomous navigation requirements of lunar navigation satellites.

5.7. Libration Point Constellation Design

With the development of lunar exploration missions, lunar probes will likely operate in various lunar orbits and various lunar surface positions. The lunar constellation navigation system must be able to cover the entire lunar orbit and the entire lunar surface, and cooperate with ground measurement and control as well as application systems. It can realize continuous and uninterrupted navigation services for various lunar probes. The future lunar constellation navigation and orbit determination system will develop a constellation system composed of multiple orbiting satellites through phased and step-by-step construction, and ultimately form a full-lunar surface and full-time coverage capability.

Specifically, in the future, there will be navigation demands for the exploration of invisible areas and large-scale activities on the lunar surface. Therefore, it may be necessary to deploy multiple satellites on multiple libration point orbits and phases to form a certain configuration and form a moving point constellation which can meet the particular requirements, so it is necessary to study the optimal design of libration point constellations under various constraints. Secondly, it is necessary to design the lunar surface positioning and navigation based on the libration point constellation. On the one hand, the Earth–Moon libration point constellation is limited by the amount of satellites, and the coverage of the lunar surface is relatively sparse. Therefore, the positioning conditions on the Moon are far worse than the GNSS constellation method. At the same time, due to the unique motion characteristics, the Earth–Moon libration point constellation cannot directly used the GNSS method to evaluate the lunar surface positioning accuracy and constellation positioning performance. On the other hand, due to limitations such as the mass and power of spaceborne equipment, the performance and accuracy of the communication and navigation equipment of Earth–Moon libration point satellites will be lower than

that of ground teleoperation equipment, and the abnormality of their communication and navigation signals may also be higher than ground equipment. Therefore, it is necessary to study corresponding libration point navigation technologies and methods.

5.8. Systematic Design for Deeper Space

The development of the lunar constellation should not only consider the needs of lunar exploration missions, but also take into account the relay communication and navigation and orbit determination requirements of other deep-space exploration missions, such as the exploration of Mars, asteroids and Jupiter. In order to achieve effective transmission of scientific data and provide reliable communication and navigation services, NASA has proposed a next-generation space Internet architecture, with the deep-space relay communication system as the main line to form an interplanetary network. The development of the lunar constellation system must also be comprehensively considered, coordinated, and utilized within the entire deep-space navigation system. At the same time, as a service guarantee system for subsequent exploration missions, the system must have a long service life, run for at least 10 years, and be able to provide services to more users, while also being easy to upgrade and maintain. The designers should strive to improve the system's cost–effectiveness ratio as much as possible.

6. Conclusions

Moon exploration activities will remain an important part of the future international deep space exploration field. The normal operation of missions such as manned Moon landings and the establishment of lunar scientific research stations will multiply the pressure on the ground measurement and control network. The world's major space countries have successively proposed construction plans for lunar communication and navigation constellations. High-precision orbit determination of navigation constellations is the premise and foundation for providing high-precision navigation services. This article systematically analyzes the current status of lunar relay navigation constellations at home and abroad, summarizes the technical principles of single-satellite and constellation navigation and orbit determination, discusses the technical difficulties in lunar navigation constellation orbit determination and navigation, and analyzes possible solutions. Finally, the development trend of research on high-precision orbit determination and navigation methods for lunar navigation constellations is proposed.

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References

1. Angelopoulos, V. *The ARTEMIS Mission*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 3–25.
2. Johnson, S.K.; Mortensen, D.J.; Chavez, M.A.; Woodland, C.L. Gateway—A communications platform for lunar exploration. In Proceedings of the 38th International Communications Satellite Systems Conference (ICSSC 2021), Arlington, WV, USA, 27–30 September 2021; IET: London, UK, 2021; Volume 2021.
3. Köpping, A.H. The moon village and space 4.0: The 'open concept' as a new way of doing space? *Space Policy* **2019**, *49*, 101323. [CrossRef]
4. Zhou, C.; Jia, Y.; Liu, J.; Li, H.; Fan, Y.; Zhang, Z.; Liu, Y.; Jiang, Y.; Zhou, B.; He, Z.; et al. Scientific objectives and payloads of the lunar sample return mission—Chang'E-5. *Adv. Space Res.* **2022**, *69*, 823–836. [CrossRef]

5. Sun, X.; Chao, H.; Chen, P. Real-time precise orbit determination of LEO satellites using a single-frequency GPS receiver: Preliminary results of Chinese SJ-9A satellite. *Adv. Space Res.* **2017**, *60*, 1478–1487. [CrossRef]
6. Montenbruck, O.; Swatschina, P.; Markgraf, M.; Santandrea, S.; Naudet, J.; Tilmans, E. Precision spacecraft navigation using a low-cost GPS receiver. *GPS Solut.* **2012**, *16*, 519–529. [CrossRef]
7. Yang, Y.; Yue, X.; Dempster, A.G. GPS-based onboard real-time orbit determination for LEO satellites using consider Kalman filter. *IEEE Trans. Aerosp. Electron. Syst.* **2016**, *52*, 769–777. [CrossRef]
8. Montenbruck, O.; Hackel, S.; Wermuth, M.; Zangerl, F. Sentinel-6A precise orbit determination using a combined GPS/Galileo receiver. *J. Geod.* **2021**, *95*, 109. [CrossRef]
9. Hauschild, A.; Montenbruck, O. Precise on-board navigation of LEO satellites with GNSS broadcast ephemerides. In Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020), Online, 22–25 September 2020.
10. Israel, D.J.; Mauldin, K.D.; Roberts, C.J.; Mitchell, J.W.; Pulkkinen, A.A.; La Vida, D.C.; Johnson, M.A.; Christe, S.D.; Gramling, C.J. Lunanet: A flexible and extensible lunar exploration communications and navigation infrastructure. In Proceedings of the 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 7–14 March 2020; IEEE: Piscataway, NJ, USA, 2020.
11. Giordano, P.; Malman, F.; Swinden, R.; Zoccarato, P.; Ventura-Traveset, J. The Lunar Pathfinder PNT experiment and Moonlight navigation service: The future of lunar position, navigation and timing. In Proceedings of the 2022 International Technical Meeting of The Institute of Navigation, Long Beach, CA, USA, 25–27 January 2022.
12. Zini, E.E. Precise Orbit Determination Techniques for a Lunar Satellite Navigation System. Master's Thesis, Politecnico di Torino, Torino, Italy, 2021.
13. Offord Harle, N.; Oates, C.; Bywater, S.; Cranstoun, C.; Friend, J.; Lay, G.; Schwarz, B.; Stevens, P.; Hufenbach, B.; Liuicci, F.; et al. Lunar comms and nav infrastructure–first data relay orbiter Lunar Pathfinder, operational in 2024, paves the way for full constellation by 2030s. *ASCEND* **2021**, *2021*, 4132.
14. Commstar Space Communications. Intention to Deploy Next-Generation Hybrid Data Relay Satellite Between the Earth and the Moon by 2023. 2020. Available online: https://commstar.space/news/commstar-space-communications-launch-announcement/ (accessed on 10 October 2020).
15. Ma, L.; Xie, P.; Liu, D.; Wu, Y. Research on the Influence of China's Commercial Spaceflight on the Economic and Social Development of the Regions Along the Belt and Road. *New Space* **2019**, *7*, 223–234. [CrossRef]
16. Palmerini, G.B.; Sabatini, M.; Perrotta, G. En route to the Moon using GNSS signals. *Acta Astronaut.* **2009**, *64*, 467–483. [CrossRef]
17. Flanegan, M.; Gal-Edd, J.; Anderson, L.; Warner, J.; Ely, T.; Lee, C.; Shah, B.; Vaisnys, A.; Schier, J. NASA lunar communication and navigation architecture. In Proceedings of the SpaceOps 2008 Conference, Heidelberg, Germany, 12–16 May 2008.
18. Xu, M.; Wang, S.; Zhao, W. Why did Chang'e build a Magpie Bridge before exploring the moon? *Nanfang Daily* **2024**, *A08*. [CrossRef]
19. Moyer, T.D. *Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation*; John Wiley & Sons: Hoboken, NJ, USA, 2005.
20. Lin, K. Lectures on Space Geodesy—Lecture 8 Very Long Baseline Interferometry (Part 1). *Bull. Surv. Mapp.* **1983**, *02*, 43–47.
21. Hornig, A.; Homeister, M. TYCHO: Demonstrator and operational satellite mission to Earth–Moon-Libration point EML-4 for communication relay provision as a service. *Acta Astronaut.* **2015**, *108*, 156–170. [CrossRef]
22. Chen, X.; Xu, J.; Zhang, X.; Zhang, W. Research on the filter algorithm for integrated autonomous navigation based on angle and velocity measurementin deep space. *Sci. Sin. Phys. Mech. Astron.* **2022**, *52*, 214509. [CrossRef]
23. Xue, X.; Zhang, H.; Kong, D. A review of astronomical autonomous navigation technology for deep space exploration. *Astron. Res. Technol.* **2017**, *14*, 382–391.
24. Battin, R.H. *An Introduction to the Mathematics and Methods of Astrodynamics*; Aiaa: Reston, VA, USA, 1999.
25. Duxbury, T.C.; Born, G.H.; Jerath, N. Viewing phobos and deimos for navigating mariner 9. *J. Spacecr. Rocket.* **1974**, *11*, 215–222. [CrossRef]
26. Bhaskaran, S.; Desai, S.; Dumont, P.; Kennedy, B.; Null, G.; Owen, W., Jr.; Riedel, J.; Synnott, S.; Werner, R. *Orbit Determination Performance Evaluation of the Deep Space 1 Autonomous Navigation System*; NASA: Washington, DC, USA, 1998.
27. Mastrodemos, N.; Kubitschek, D.G.; Synnott, S.P. Autonomous navigation for the deep impact mission encounter with comet tempel 1. *Space Sci. Rev.* **2005**, *117*, 95–121. [CrossRef]
28. Ma, P.B.; Baoyin, H.X.; Mu, J.S. Autonomous navigation of Mars probe based on optical observation of Martian moon. *Opt. Precis. Eng.* **2014**, *22*, 863–869.
29. You, W. Multi-Vector Fusion Mechanism and Estimation Method for Astronomical Velocity Measurement and Navigation in Deep Space Exploration. Ph.D. Thesis, Harbin Institute of Technology, Harbin, China, 2020.
30. Downs, G.S. *Interplanetary Navigation Using Pulsating Radio Sources*; No. JPL-TR-32-1594; NASA: Washington, DC, USA, 1974.
31. Sheikh, S.I. *The Use of Variable Celestial X-Ray Sources for Spacecraft Navigation*; University of Maryland: College Park, MD, USA, 2005.
32. Wang, H. NASA has completed the world's first space validation of XNAV. *Chin. J. Space Sci.* **2018**, *38*, 277–278.
33. Zheng, S.; Ge, M.; Han, D.; Wang, W.; Chen, Y.; Lu, F.; Bao, T.; Chai, J.; Dong, Y.; Feng, M.; et al. Test of pulsar navigation with POLAR on TG-2 space station. *Sci. Sin. Phys. Mech. Astron.* **2017**, *47*, 099505. [CrossRef]

34. Lin, Q.; Huang, L.; Shuai, P. TOA estimation methods for the observation data based on the X-ray Pulsar-based Navigation-1 (XPNAV-1) satellite. *Chin. Space Sci. Technol.* **2017**, *38*, 1–7.
35. Zheng, S.J.; Zhang, S.N.; Lu, F.J.; Wang, W.B.; Gao, Y.; Li, T.P.; Song, L.M.; Ge, M.Y.; Han, D.W.; Chen, Y.; et al. In-orbit demonstration of X-ray pulsar navigation with the Insight-HXMT satellite. *Astrophys. J. Suppl. Ser.* **2019**, *244*, 1. [CrossRef]
36. Shuai, P.; Chen, S.; Wu, Y.; Zhang, C.; Li, M. Navigation principles using X-ray pulsars. *J. Astronaut.* **2007**, *06*, 1538–1543.
37. Zhang, W.; Chen, X.; You, W.; Zhang, W.; Fang, X. New autonomous navigation method based on redshift. *Shanghai Aerosp.* **2013**, *30*, 32–33+38.
38. Franklin, R.G.; Birx, D.L. A study of natural electromagnetic phenomena for space navigation. *Proc. IRE* **1960**, *48*, 532–541. [CrossRef]
39. Guo, Y. Self-contained autonomous navigation system for deep space missions. *Spacefl. Mech.* **1999**, *1999*, 1099–1113.
40. Yim, J.; Crassidis, J.; Junkins, J. Autonomous orbit navigation of interplanetary spacecraft. In Proceedings of the Astrodynamics Specialist Conference, Denver, CO, USA, 14–17 August 2000.
41. Liu, J.; Fang, J.C.; Yang, Z.H.; Kang, Z.W.; Wu, J. X-ray pulsar/Doppler difference integrated navigation for deep space exploration with unstable solar spectrum. *Aerosp. Sci. Technol.* **2015**, *41*, 144–150. [CrossRef]
42. Ning, X.; Gui, M.; Fang, J.; Liu, G.; Dai, Y. A novel differential Doppler measurement-aided autonomous celestial navigation method for spacecraft during approach phase. *IEEE Trans. Aerosp. Electron. Syst.* **2017**, *53*, 587–597. [CrossRef]
43. Zhang, H. Research and Implementation of Key Technologies for Improving Space Target Laser Ranging Capability. Master's Thesis, Shandong University of Science and Technology, Qingdao, China, 2020.
44. Verhagen, S.; Teunissen, P.J. Least-squares estimation and Kalman filtering. In *Handbook of Global Navigation Satellite Systems*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 639–660.
45. Kalman, R.E. A new approach to linear filtering and prediction problems. *J. Basic Eng.* **1960**, *82*, 35–45. [CrossRef]
46. Bucy, R.S.; Senne, K.D. Digital synthesis of non-linear filters. *Automatica* **1971**, *7*, 287–298. [CrossRef]
47. Julier, S.J.; Uhlmann, J.K. Unscented filtering and nonlinear estimation. *Proc. IEEE* **2004**, *92*, 401–422. [CrossRef]
48. Witternigg, N.; Obertaxer, G.; Schönhuber, M.; Palmerini, G.B.; Rodriguez, F.; Capponi, L.; Soualle, F.; Floch, J.J. Weak GNSS signal navigation for Lunar exploration missions. In Proceedings of the 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2015), Tampa, FL, USA, 14–18 September 2015.
49. Zhang, C. Research on adaptive filter methods. *Chin. J. Aeronaut.* **1998**, *S1*, 97–100.
50. Wei, W.; Qin, Y.; Zhang, X.; Zhang, Y. Improvement of Sage-Husa algorithm. *J. Chin. Inert. Technol.* **2012**, *20*, 678–686.
51. Xia, Q.; Sun, Y.; Zhou, C. Optimal adaptive algorithm of vanishing Kalman filter and its application. *J. Autom.* **1990**, *03*, 210–216.
52. Qian, H.; Ge, L.; Yu, P. Multi-evanescent factor Kalman filter and its application in SINS initial alignment. *J. Chin. Inert. Technol.* **2012**, *20*, 287–291.
53. Duan, S.; Sun, W.; Wu, Z. Application of error-resistant adaptive EKF in INS/GNSS tight combination. *J. Univ. Electron. Sci. Technol. China* **2019**, *48*, 216–220.
54. Yang, Y.; He, H.; Xu, T. On dynamic adaptive filter. *Acta Geod. Cartogr. Sin.* **2001**, *04*, 293–298.
55. Yang, Y.; Ren, X.; Xu, Y. Main progress in the theory and application of adaptive robust filter. *J. Navig. Position.* **2013**, *1*, 9–15.
56. Sage, A.P.; Husa, G.W. Adaptive filter with unknown prior statistics. In Proceedings of the Tenth Joint Automatic Control Conference, Boulder, CO, USA, 5–7 August 1969. No. 7.
57. Fagin, S.L. Recursive linear regression theory, optimal filter theory, and error analysis of optimal systems. In *IEEE International Convention Record*; No. Part 1; IEEE: Piscataway, NJ, USA, 1964; Volume 12.
58. Yang, Y. *Adaptive Dynamic Navigation and Positioning*; Surveying and Mapping Press: Beijing, China, 2006; pp. 10–40.
59. Mohamed, A.H.; Schwarz, K.P. Adaptive Kalman filter for INS/GPS. *J. Geod.* **1999**, *73*, 193–203. [CrossRef]
60. Qiao, D.; Zhou, X.; Li, X. Analytical configuration uncertainty propagation of geocentric interferometric detection constellation. *Astrodynamics* **2023**, *7*, 271–284. [CrossRef]
61. Le, L. Star selection algorithm for GNSS/pseudolite combined positioning. *Electron. Test* **2020**, *13*, 41–43+73.
62. Feng, B.; Chai, H.; Pan, Z.; Wang, M.; Yang, K. An improved star selection algorithm for integrated navigation systems. *Eng. Surv. Mapp.* **2018**, *27*, 26–31.
63. Peng, S.; Guo, C.; Liu, F. Research on fast star selection algorithm in Beidou/GPS dual-mode positioning. *GNSS World China* **2017**, *42*, 11–14.
64. Wang, E.; Jia, C.; Qu, P.; Huang, Y.; Pang, T.; Bie, Y.; Jiang, Y. Beidou/GPS integrated navigation star selection algorithm based on chaotic particle swarm optimization. *J. Beijing Univ. Aeronaut. Astronaut.* **2019**, *45*, 259–265.
65. Zhang, J.; Li, J.; Hu, C. Satellite navigation and positioning solution method based on Cubature Kalman filter. *J. Univ. Chin. Acad. Sci.* **2021**, *38*, 532–537.
66. Zhang, J.; Yang, Y.; Qian, F. Research on GNSS/INS error feedback correction based on Kalman filter-neural network prediction. *Electron. Des. Eng.* **2015**, *23*, 103–105.
67. Carlson, N.A. Federated square root filter for decentralized parallel processors. *IEEE Trans. Aerosp. Electron. Syst.* **1990**, *26*, 517–525. [CrossRef]
68. Wu, L.; Sun, Y.; Chen, C. Multi-constellation integrated navigation adaptive information fusion filter algorithm. *Aerosp. Control* **2010**, *28*, 38–42+62.

69. Zhang, Y.; Jiang, X.; Yang, W.; Liu, J.; Wei, Y. Research on joint positioning technology of GNSS systems based on Kalman filter. *Electron. Meas. Technol.* **2021**, *44*, 109–113.
70. Menn, M.D.; Bernstein, H. Ephemeris observability issues in the global positioning system (GPS) autonomous navigation (AUTONAV). In *Proceedings of 1994 IEEE Position, Location and Navigation Symposium-PLANS'94*; IEEE: Piscataway, NJ, USA, 1994.
71. Guo, S.; Cai, H.; Meng, Y.; Geng, C.; Jia, X.; Mao, Y.; Geng, T.; Mao, Y.; Zhang, Y.; Xie, X. Beidou-3 navigation and positioning technology system and service performance. *Acta Geod. Cartogr. Sin.* **2019**, *48*, 810–821.
72. Li, Z.; Xin, J.; Guo, R.; Li, X.; Tang, C.; Tian, Y. Feasibility analysis of autonomous satellite navigation based on Beidou inter-satellite link. *Geomat. Inf. Sci. Wuhan Univ.* **2022**, *47*, 55–60.
73. Shao, R.; Chang, J.; Lin, X.; Tan, S.; Gong, W.; Lin, B. An orbit determination algorithm suitable for extended users between Beidou-3 satellites. *Chin. Space Sci. Technol.* **2024**, *44*, 106–113.
74. Yang, Y.; Yang, Y.; Hu, X.; Tang, C.; Zhao, L.; Xu, J. Comparative analysis of the accuracy of two orbit determination modes of Beidou-3 satellite. *Acta Geod. Cartogr. Sin.* **2019**, *48*, 831–839.
75. Zhou, Y. Research on Key Technologies for Autonomous Orbit Determination of User Spacecraft Based on the Beidou Interstellar Link. Ph.D. Thesis, National University of Defense Technology, Changsha, China, 2020.
76. Zhang, W.; Wang, X.; Cui, W.; Zhao, Z.; Chen, S. Self-induced collision risk of the Starlink constellation based on long-term orbital evolution analysis. *Astrodynamics* **2023**, *7*, 445–453. [CrossRef]
77. Abusali, P.A.M.; Tapley, B.D.; Schutz, B.E. Autonomous navigation of global positioning system satellites using cross-link measurements. *J. Guid. Control. Dyn.* **1998**, *21*, 321–327. [CrossRef]
78. Lin, L.; Liu, Y. On the problem of deficient rank in autonomous orbit determination with star-to-star relative measurements. *J. Spacecr. TTC Technol.* **2000**, *19*, 1–4.
79. Chen, J.; Jiao, W.; Ma, J.; Song, X. Research on autonomous orbit determination of navigation satellites based on inter-satellite ranging/orbit orientation parameter constraints. *Geomat. Inf. Sci. Wuhan Univ.* **2005**, *05*, 439–443.
80. Tang, C. Fusion of Multiple Observation Data to Calculate High-Precision Broadcast Ephemeris of Beidou Navigation Satellites. Master's Thesis, University of Chinese Academy of Sciences, Beijing, China, 2016.
81. Gong, X. Research on Centralized Autonomous Real-Time Orbit Determination and Time Synchronization Method of Beidou System. Ph.D. Thesis, Wuhan University, Wuhan, China, 2013.
82. Zhang, W.; Liu, W.; Gong, X. Analysis of the impact of EOP forecast errors on autonomous orbit determination results. *J. Geod. Geodyn.* **2011**, *31*, 106–110.
83. Zhao, Q.; Liu, J.; Ge, M. Research on precision orbit determination theory and software of GPS navigation constellations and low-orbit satellites. *Geomat. Inf. Sci. Wuhan Univ.* **2005**, *30*, 1.
84. Liu, W. Method Research and Simulation Calculation of Navigation Satellite Autonomous Orbit Determination and Satellite-Ground Joint Orbit Determination. Ph.D. Thesis, Wuhan University, Wuhan, China, 2008.
85. Zhao, D.; Zhou, H.; Wang, Z. Joint orbit determination data fusion modeling and optimal weighting algorithm based on multi-source observations. *J. Syst. Simul.* **2008**, *10*, 2515–2519.
86. Song, X. Research on Orbit Determination of COMPASS Navigation Satellite. Ph.D. Thesis, Chang'an University, Xi'an, China, 2008.
87. Li, Z.; Huang, J. *GPS Measurement and Data Processing*; Wuhan University: Wuhan, China, 2005; pp. 40–42.
88. Cai, Z.; Han, C.; Chen, J. Constellation rotation error analysis and control of long-term autonomous orbit determination of navigation satellites. *J. Astronaut.* **2008**, *02*, 522–528.
89. Ruan, R.; Feng, L.; Jia, X. Equipment delay estimation method in navigation satellite-ground/inter-satellite link joint orbit determination. *Acta Geod. Cartogr. Sin.* **2014**, *43*, 137–142+157.
90. Shuai, P.; Qu, G. Time synchronization technology for autonomous navigation of navigation constellations. *Acta J. Astronaut.* **2005**, *06*, 768–772.
91. Chen, Z. Research on Key Technologies for Autonomous Operation of Navigation Satellite Constellations Based on Inter-Satellite Links. Ph.D. Thesis, National University of Defense Technology, Changsha, China, 2012.
92. Hill, K.; Born, G.H.; Lo, M.W. Linked, Autonomous, Interplanetary Satellite Orbit Navigation(LiAISON) in Lunar Halo Orbits. *Adv. Astronaut. Sci.* **2006**, *123*, 2369–2388.
93. Hill, K.; Parker, J.; Born, G.; Demandante, N. A lunar L2 navigation, communication, and gravity mission. In Proceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Keystone, CO, USA, 21–24 August 2006.
94. Hill, K.; Parker, J.; Born, G.H.; Lo, M.W. Low-cost lunar communication and navigation. In *CCAR White Paper 5*; 2006. Available online: https://www.researchgate.net/publication/237404072_LOW-COST_LUNAR_COMMUNICATION_AND_NAVIGATION (accessed on 17 June 2024).
95. Hill, K.A.; Born, G.H. Autonomous orbit determination from lunar halo orbits using crosslink range. *J. Spacecr. Rocket.* **2008**, *45*, 548–553. [CrossRef]
96. Parker, J.; Anderson, R.; Born, G.; Fujimoto, K.; Leonard, J.; McGranaghan, R. Navigation between geosynchronous and lunar L1 orbiters. In Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, Keystone, CO, USA, 21–24 August 2006.
97. Parker, J.S.; Leonard, J.M.; Anderson, R.L.; Born, G.H. LiAISON-supplemented navigation of a crewed vehicle in a lunar halo orbit. In Proceedings of the AAS/AIAA Astrodynamics Specialist Conference, Hilton Head, SC, USA, 11–15 August 2013; No. AAS 13-776.

98. Hesar, S.G.; Parker, J.S.; Leonard, J.M.; McGranaghan, R.M.; Born, G.H. Lunar far side surface navigation using linked autonomous interplanetary satellite orbit navigation (LiAISON). *Acta Astronaut.* **2015**, *117*, 116–129. [CrossRef]
99. Du, L. Inter-satellite ranging and orbit determination of Halo-lunar orbit under circular restricted three-body problem. *Acta Geod. Cartogr. Sin.* **2013**, *42*, 184–190.
100. Liu, P.; Hou, X.Y.; Tang, J.S.; Liu, L. Application of two special orbits in the orbit determination of lunar satellites. *Res. Astron. Astrophys.* **2014**, *14*, 1307. [CrossRef]
101. Huang, Y.; Yang, P.; Chen, Y.; Li, P.; Zhou, S.; Tang, C.; Hu, X. Interstellar ranging and autonomous orbit determination of the Earth-Moon space probe. *Sci. Sin. (Phys. Mech. Astron.)* **2023**, *53*, 132–144.
102. Cheetham, B.; Gardner, T.; Forsman, A.; Kayser, E.; Clarkson, M. Capstone: A unique CubeSat platform for a navigation demonstration in cislunar space. In Proceedings of the ASCEND 2022, Las Vegas, NV, USA, 24–26 October 2022; p. 4382.
103. Li, X. Research on Precise Orbit Determination of Lunar Probes Using Combined Orbit Measurement VLBI, USB and Space VLBI Technology. Ph.D. Thesis, Wuhan University, Wuhan, China, 2016.
104. Qi, Y. Anton de Ruiter. Trajectory correction for lunar flyby transfers to libration point orbits using continuous thrust. *Astrodynamics* **2022**, *6*, 285–300. [CrossRef]
105. Muralidharan, V.; Howell, K.C. Stretching directions in cislunar space: Applications for departures and transfer design. *Astrodynamics* **2023**, *7*, 153–178. [CrossRef]

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